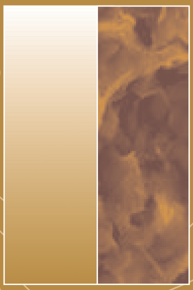
Report Series



Dossier 2005 Argile

Tome

Architecture and management of a geological repository

December 2005

ANDRA

Agence nationale
pour la gestion des déchets radioactifs

The present English version is a translation of the original "*Dossier 2005 Argile*" documentation written in French, which remains ultimately the reference documentation.

In order to be consistent through the various documents, while the word ''storage'' (''*entreposage*'' in French) refers only to temporary management (in terms of concept and facility), ''disposal'' (in term of concept) and ''repository'' (in terms of facility or installation) refers to long term management of high level long lived radioactive waste (''*stockage*'' in French for these words).

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The study approach

1.1 Purpose of this volume within the Dossier 2005 Argile

The Law of 30 December 1991 Loi n° 91-1381 du 30 décembre 1991 relative aux recherches sur la gestion des déchets radioactifs. conferred on Andra the task of assessing the feasibility of a high-level, long-lived waste (HLLL waste) repository in a deep geological formation. This volume of the Dossier 2005 Argile reports on the results of the study from the standpoint of the architecture and management of such a repository. It is based on the characteristics of the clay formation studied in an underground research laboratory located in the Meuse and Haute-Marne departments.

The feasability study sought to assess if it would be possible to build a repository which could be operated and managed in a reversible manner, closed and monitored and then evolve without any further human invention. It covers the entire inventory of existing French HLLL waste (classified as B or C) or waste which is to be produced in the short and medium term future (as well as, on an exploratory basis, spent fuel which has not necessarily been reprocessed). It aims to ensure that the safety of staff and public, and environmental protection, are not compromised at any time.

To assess feasibility, Andra has selected a potential respository architecture that meets expectations and is industrially realistic. The repository design is based on available knowledge and technology.

The architecture studied does not in any way freeze the definition of a potential repository. The technical options set out in this document, chosen as being as simple and robust as possible, show that solutions are conceivable. They should not be regarded as optimized solutions, either in technical/economic terms or from the safety standpoint. They may be developed further if action is taken on the project after 2006.

This architecture was also the basis used to analyse repository safety, particularly its behaviour and evolution at different time scales. Two other volumes of the Dossier 2005 Argile address the phenomenological evolution of a repository and its safety assessment (Figure 1.1.1). All three volumes are based on reference knowledge documents and a number of thematic technical documents. The reference knowledge documents concern the Meuse/Haute-Marne site, waste packages (description and inventory model), the repository's constituent materials, waste package behaviour (release model) and radionuclide behaviour. The thematic technical documents particularly relevant to this volume concern the specifications for and design of the main repository components (waste packages and cells) and conceptual modelling of phenomena to be taken into account in designing repository reversibility (e.g. thermal load).

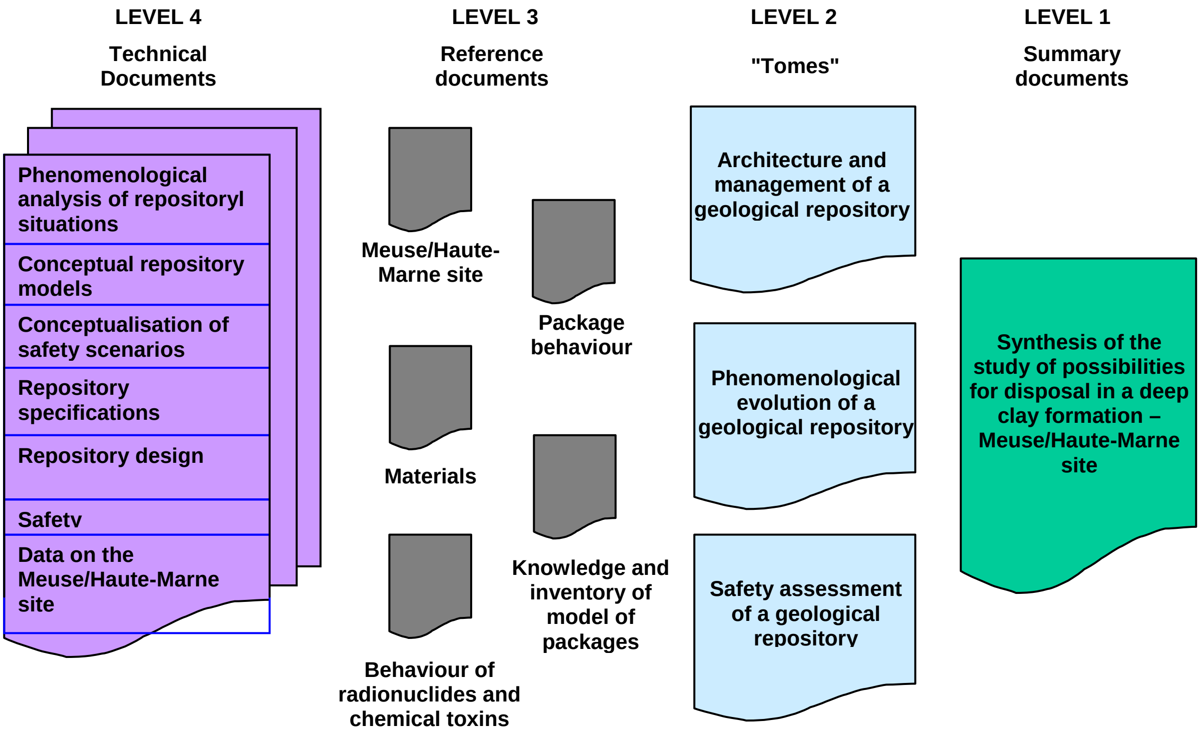

Figure 1.1.1 General structure of the Dossier 2005 Argile

Note that it is not the purpose of this initiative to allocate a particular site for the repository. It seems to be premature at this stage to identify a repository site. Andra has therefore made sure the results obtained at the laboratory site are transposable to a wider area. Only transposability will ensure that the results do not depend on the specific features of a particular location within a given zone.

1.2 Main stages of the design study

Andra has taken an iterative approach to studying geological disposal. As research has developed since the Act of 30 December 1991, knowledge of packages, the geological study site and the main phenomena to be taken into account in repository design have advanced simultaneoulsy.

The period 1994-1996 was spent on geological surveys at sites identified by the consultation mission led by Member of Parliament Christian Bataille. The task was to check that the sites had no features that would exclude them in light of the Basic Safety Rule III 2 f. [2]. At the close of this phase an application was submitted for authorization to create underground laboratories, including one at the Meuse/Haute-Marne site.

Alongside these surveys, initial research on repository concepts was conducted. This led to the selection of *initial design options* in 1997. These options addressed the questions the first safety studies had raised, particularly with regard to the long-term behaviour of packages and engineered barriers.

Studies conducted on that basis led to the selection of *preliminary concepts.* These took into account the different types of waste, the knowledge of the clay formation acquired through the surface-based surveys, and the uncertainties that were unresolved at that stage. The preliminary concepts were designed to explore a fairly wide range of options so as to address the different scientific and technical problems regarding technological feasibility, safety and reversibility. The outcome was a choice of repository geometries, materials and operating and maintenance methods.

From 1999 to 2000, a safety analysis – the "initial safety verification" – was carried out on the preliminary concepts. This enabled Andra to test the analysis methods and identify important points to examine from the safety angle, knowledge to develop further and design aspects to improve on. Alongside the analysis of post-closure safety, an initial assessment of operating risks was carried out. The preliminary concepts were also analysed for reversibility. The results of the studies were put together in an interim dossier issued in 2001.

At the same time, research was conducted to find ways to improve the concepts technically and economically. In particular, alternative options were introduced to make the repository more compact.

In 2002, the lessons drawn from the 2001 Clay dossier were used to select the technical options on which the 2005 dossier is based. This selection favoured a simple, robust concept for each type of package, in the light of current knowledge. For example, options for which there were industrial analogies were adopted, as these can provide useful feedback from experience.

Andra then drew up technical requirements specifications setting out the functional needs and technical choices for the components.These specifications constituted a basic data input for the engineering studies conducted between 2002 and 2005, the behaviour studies and the safety analysis.

The purpose of the engineering studies conducted since 2002 has been to describe the main components of a repository architecture in greater detail and check capability to build and operate them. When the Meuse/Haute-Marne underground laboratory was built, the studies were progressively fitted to the new data acquired at the site.

With these engineering studies, Andra systematically sought out industrial analogies in the nuclear and mining industries and major civil engineering structures. The purpose was to gather feedback from industrial experience relevant to a nuclear waste repository. This involved working with major engineering firms specialising in those fields. In addition Andra has not only thought in terms of the French situation. Andra's concepts have been compared with those of counterpart organisations in other countries through technical exchanges and co-operation programmes.

For the most part, at this stage the technological demonstration aspect has been addressed only by factoring in experience feedback. However, tests have been conducted on particular points such as disposal packages and maintenance principles, for which operating experience feedback and experience from tests conducted in other countries did not seem sufficient.

Overall, the repository feasibility assessment presented in this dossier is based on the results of studies and other work aimed at knowledge acquisition, and the synthesis of those results in the form of usable models. Alongside the surveys and characterisation studies conducted from ground level at the Meuse/Haute-Marne site during the building of the underground laboratory and then in the laboratory drifts, research was conducted on the geosphere and biosphere, and on rock behaviour using samples. A major scientific knowledge acquisition programme was conducted on the physical-chemical behaviour of the packages' constituent materials and the radionuclides they contain, and of the materials used to build a repository in a clay environment.

The repository architecture was also modelled. The modelling involved recording the phenomena occurring in the repository,describing changes in waste packages, repository components and the geological environment and their physical and chemical interactions. The models allowed to dimension the engineered structures. However, their main function was to address the behaviour of the repository at long timescales (from a century to hundreds of thousands of years). Experience feedback and the results of short-term experiments are not a sufficient basis for addressing such long-term behaviour.

The long-term safety analysis is a way of checking the capability of the system as a whole to meet the objectives of radiological protection laid down under Basic Safety Rule III.2.f [2], and assess its robustness with regard to the uncertainties of very long timescales.

1.3 An iterative approach

Andra has adopted an iterative approach for its research, the repository architecture being gradually more precisely defined as knowledge accumulates. The principle of the process is shown in the next figure.

In particular, it meets a recommendation on long-term safety in Basic Safety Rule III.2.f, which stipulates that *"the quantitative objectives for barrier confinement performance can only be validly set after an iterative process incorporating experience acquired during the repository safety study"*.

Each iteration involves knowledge acquisition and a study of architecture concepts that are consistent with this knowledge. With the available knowledge, models can be used to understand the behaviour of the concepts studied.

These elements are the basis of a safety analysis. The safety analysis concerns the long-term functions of the repository, which are its distinctive features, and its operating safety.

The lessons from the safety analysis then act as input data for the next iteration: uncertainties in the knowledge base that need to be reduced as a matter of priority, design guidelines etc.

This approach ensures that safety is taken into account at the very earliest design stage. In this way (i) choices can be progressively steered towards solutions that are increasingly robust with regard to uncertainties in knowledge and (ii) preventive and protective measures against identified risks can be introduced.

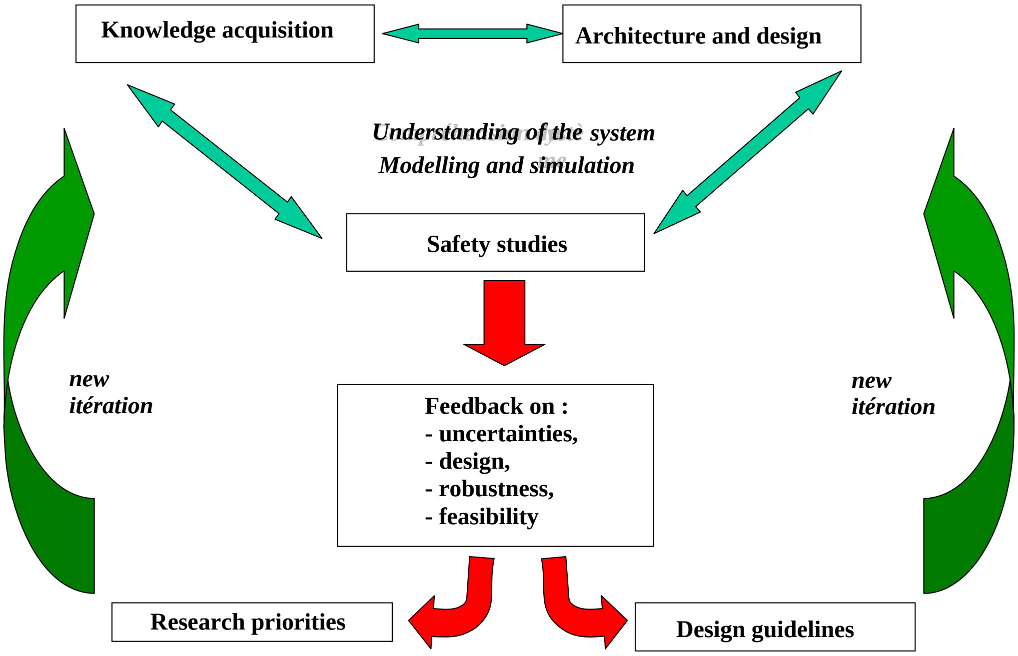

Figure 1.3.1 The iterative study process

1.4 Structure of the volume

This document particulary refers to the preliminary design studies for a potential repository, which include several closely linked strands.

They begin by identifying the functions of a repository with regard to safety objectives and the reversibility requirement. The technical options for fulfilling these functions are then identified and studied. These elements are presented in summary form in Chapter 2.

A meticulous inventory of waste focussed on in the study was drawn up and summarised in an “inventory model”.The results of this work are set out in Chapter 3.

Among the essential technical options, the core of the repository concept is the nature of the waste packages inventoried and the design of the underground engineered structures intended to receive them. These elements are presented in Chapters 4 and 5 respectively.

The supplementary physical components concern the layout of the underground engineered structures, the access structures (shafts and connecting drifts) and the surface installations. These elements are presented in Chapters 6, 7 and 8 respectively. The description of the underground structures includes the devices to be installed to close the repository (backfill and seals). The surface installations are considered only briefly, as they are analogous to installations at existing nuclear facilities. In additec to describing a disposal facility, the study sought to verify that the technical resources for industrial operation of such a facility exist. These resources are described in Chapter 9.

Reversibility has been taken into account not only in the architecture design presented here but also in the repository operating rationale. The factors that combine to make disposal reversible are set out in Chapter 10. In particular, this chapter highlights the need to master the repository's phenomenological behaviour and describes the associated technical measures.

Another aspect, inseparable from the design of a repository architecture for industrial operation, is security and nuclear safety during building and operation. In this connection a preliminary risk analysis and a study of hypothetical accident situations have been conducted. The results of this study are presented in Chapter 11. The rationale of this study is similar to the conventional approach, but differs in that the institutional context is not an application to build a basic nuclear facility. It therefore concentrates on problems specific to disposal and does not exhaustively cover safety arrangements that are already well known in another context.

To conclude the volume, Chapter 12 summarises the main lessons of the technical feasibility study for a repository, incoporating the rationale of reversibility and taking safety objectives into account. It makes suggestions for additional research that could be conducted after this study.

2

General description

This chapter gives an overview of the architecture and management of a reversible disposal system.

It describes the main characteristics of the waste to be disposed of and the functions the repository must fulfil over time. The main purpose of these functions is to protect the environment and future generations from any risks generated by the waste. They also incorporate a reversibility requirement.

The chapter then describes the geological situation for which disposal feasibility has been studied.

It also briefly describes the technical options for fulfilling the repository's functions and the principles on which those options are based. These technical options concern the waste disposal containers and the architecture of the repository.

The chapter ends with a summary recapitulation of the role each repository component plays in fulfilling the required functions.

2.1 Waste studied

The waste studied (called High Level and Long Lived, or HLLL waste) contains both short-lived radionuclides, usually in large quantities (high level), and long-lived radionuclides[1] in medium to very large quantities.

The main danger of long-lived radionuclides is from ingestion, exposing living tissue to α radiation; the half-life[2] of some isotopes is more than a hundred thousand years.

A high proportion of HLLL waste also has high γ radiation activity, which means that humans must be protected from external exposure.

The β-γ activity in HLLL waste decays fairly quickly. After a few decades, nuclear fuel contains only a few per cent of the radioactivity it displayed when unloaded from the reactor.

The energy generated by radioactivity is mainly converted into heat. The radiation is absorbed by the waste package's constituent matter and, to a lesser extent, the matter in its immediate vicinity. A few centuries later, when the β-γ radioactivity has largely decayed, the residual radioactive energy (from the long-lived isotopes) is very low and the amount of heat produced is no longer significant.

The decrease in β-γ activity over time suggests that for the most highly radioactive waste there should be an interim period between production and disposal. This can be achieved with temporary storage facilities. During this period the heat produced by the waste diminishes, and this affects the dimensioning of the disposal installations and their footpint in the host formation.

2.1.1 Origin and properties of HLLL waste

HLLL waste is produced by the nuclear power industry, research activities and national defense. To study disposal possibilities, Andra drew up an "inventory model" consolidating data and hypotheses on HLLL waste [3]. It takes future waste into account as well as existing waste.

Nuclear power industry waste mainly comes from spent fuel unloaded from nuclear power reactors. At present Cogema reprocesses this fuel in its plants at La Hague. In reprocessing, the uranium and plutonium are separated from the residue – fission products, minor actinides and the mechanical structures of the fuel assemblies (cladding sections, end cap parts).

For the disposal study, all waste produced by existing nuclear power stations has been taken into account, based on a hypothetical average of forty years in operation for each reactor.

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[1] Long-lived isotopes include (i) fission and activation products produced, respectively, by the division of heavy atoms such as uranium and plutonium during fission in a reactor, and neutron absorption by materials (mainly metals) present in the reactor, (ii) actinides, consisting of uranium and heavier atoms formed when uranium captures neutrons.

[2] The half-life of an isotope is the time required for 50% of the amount of the isotope present to decay (i.e. to be spontaneously transformed into another element, whether radioactive or stable). An isotope is said to be long-lived if its half-life is strictly longer than 30 years.

The study takes various production scenarios into account. They have been selected to cover a wide range of waste types, including hypothetical types, and so address a range of different disposal problems. One family of scenarios includes continued reprocessing of spent fuel unloaded from reactors. Another assumes that reprocessing is halted. It is not the aim of these scenarios to prefigure an overall industrial plan but to examine how a repository architecture can take into account different possible methods of management at the back end of the nuclear power cycle. The waste producers – EDF, CEA and Cogema – were closely involved in drawing up these scenarios.

The scenarios considered take into account the spent fuel – which are not regarded as waste. Assuming they are not reprocessed, they will have to be studied from the standpoint of waste management methods. They could be spent MOX fuel (mixed uranium and plutonium oxide) from recycled plutonium, or UOX enriched uranium fuel.

In addition to spent fuel and reprocessing residues, there is operating waste from nuclear reactors (control rods) and waste from operating and maintaining the reprocessing facilities ("technological" waste; replaced or obsolete parts contaminated by radioactive materials, liquid effluent, etc.).

There is also waste from the Marcoule facility, now closed, which reprocessed fuel from the early natural uranium graphite-moderated gas-cooled reactors.

Most HLLL waste from activities other than power generation (research, defence) is technological waste.

There are also small quantities of spent fuel from research or military installations. Making no predictions as to future reprocessing of this waste, their possible disposal has been taken into account.

2.1.2 Conditioning of HLLL waste

Conditioning waste involves (i) solidifying and immobilising waste produced in dispersible form (usually liquid) (ii) placing the waste in a container to facilitate handling and storage at industrial facilities.

The inventory of HLLL waste covers two types of waste:

- waste that has already been produced, is currently stored at production sites and may or may not be conditioned;
- waste yet to be produced, either conditioned according to existing operating methods at nuclear facilities, or according to alterante programmes not yet precisely known, and which will depend among other things on future power generation and fuel cycle strategies.

To draw up the inventory, it was assumed[3] that all waste was conditioned. This implies knowing, or making assumptions about, the properties and conditioning and packaging methods of existing waste that has not yet been conditioned, and future waste, and the numbers and volumes of primary waste packages to be considered ("primary waste packages" are the objects delivered to a repository).

The producers were substantially sollicited in identifying the different types of waste and defining conditioning methods (whether already existing or adopted as reference hypotheses). The result is quite a wide range of families of primary waste packages that differ in terms of radiological content, the heat released owing to the presence of certain radionuclides, the physical-chemical properties of the waste or conditioning materials, and waste package size.

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[3] However, the possibility of conditioning spent fuel assemblies directly at the disposal site is considered.

HLLL waste packages are usually divided into the following categories, each with its own disposal issues (or questions):

- Class B waste has low to medium β-γ activity and therefore releases little or no heat. It regroups the longest number of waste. Their total radioisotope inventory is relatively small compared to other packages waste, and is distributed over a large volume.
- Class C waste consists of fission products and minor actinides separated out during fuel reprocessing. Their high β-γ activity causes considerable heat release, which declines over time mainly due to the radioactive decay of the medium-lived fission products (cesium-137, strontium-90). This waste is conditioned by incorporating it in a glass matrix. Glass has a particularly high and long-lasting confinement capacity provided the physical-chemical properties of the environment are favourable. Because of the high concentration of long-lived radionuclides in vitrified C waste packages, the high temperature and the physical-chemical behaviour of the immobilisation material, disposal conditions need to be specially adapted. Existing and possible future C packages are divided into sub-groups C0, C1, C2, C3 and C4 depending on their composition. C0 (old waste such as that stored at the Marcoule site) is markedly less exothermic than the others.

Spent fuel is also highly radioactive and therefore releases considerable heat. This is due to the presence of fission products having average half-lives, as well as that of plutonium and americium (stemming mainly from plutonium decay), in the bother two responsible for a slower decline if heat release. Other features are the large size of fuel rods unloaded from nuclear power reactors if they are to be disposed of as they are, and a larger amount of fissile products, raising the question of criticality risk. There are two types of commercial spent fuel, CU1 (UOX fuel) and CU2 (MOX fuel) which are highly exothermic. Fuel that might come from research and defence reactors (CU3 type fuel) are considerably less exothermic.

Chapter 3 gives a more detailed description of primary HLLL waste packages, their radiological content, heat release and physical-chemical properties.
In each of the above waste classes, the different families of HLLL wate packages have been grouped into a smaller number of representative "waste package types". This is in order (i) to make a more thorough study by limiting the number of cases to be specifically addressed, while not ignoring the diversity of the packages, (ii) to propose as far as possible a standardisation of the engineered structures and means employed in a disposal facility. Using this approach it is possible to study a disposal solution for each package inventoried, irrespective of whether other types of waste are being disposed of.

2.2 Functions of a reversible disposal facility

The functions of a repository have been identified by a functional analysis perfomed by conventional methods [4]. This ensures that all expected functions are taken into account.

The basic purpose of long-term management of high-level, long-lived waste (HLLL waste) is to protect human health and the environment against the associated risks. The solution offered by a repository is to confine the waste to the geological formation studied. The waste is passively confined for a long period of time; periods studied extend to millions of years.

Strong demand has been expressed for reversible disposal if a repository were to be constructed. Andra has taken this into account in its repository concepts, particularly by designing a flexible method of repository management.

Operating a repository would involve several industrial activities. These could concern a time scale on the other of a century, with is not uncommon to other human endeavors. As with any other industrial facility, they must be performed in such a way as to protect man and the environment.

The ability of a repository to protect man from the risks associated with the waste can be assessed in relation to particular safety objectives. These objectives have been defined both for the industrial operating phase and for the long term.

2.2.1 Long-term safety functions of a repository

The basic objective of a deep geological repository is summarised in Basic Safety Rule RFS III.2.f [2]: "*The protection of man and the environment in the short and long term is the fundamental aim assigned to a deep geological formation waste repository.*"

Protection is achieved by preventing the dissemination of the radionuclides contained in the waste without relying, in the long term, on maintenance or surveillance [5]. The safety rule states that *"It [the protection of man and the environment] must be assured for the risks linked to the dissemination of radioactive substances in all the situations taken into account without relying on institutional control, which cannot be foreseen with certainty beyond a limited period"*.

To prevent the dissemination of radionuclides at different timescales, a deep geological repository is assigned a number of safety functions, which complement each other to optimise the system's overall performance. By providing a degree of redundancy, they give better resistance against failure or external disturbance.

A deep geological repository protects the waste from erosion and most human activities which, on the hundreds of thousands of years timescale, only affect the uppermost layers of the earth (§2.3 and [6] – Volume 3).

Deep below the surface, underground water is the main carrier providing radionuclide transportation. The repository (i) resist water circulation, (ii) limits radionuclide release and immobilises them within the repository (in effect "protecting" the waste), and (iii) delays and reduces the migration of any radionuclide released by the waste [7].

To achieve this, the greatest possible benefits are taken from the favourable properties of the Callovo-Oxfordian argillites – low permeability, water retention capacity, geochemical properties, hydrogeological environment (see section 2.2). The age of the formation, its tectonic stability and the depth of the repository's location suggest that these favourable properties will remain stable over the timescales studied here (from a thousand years to several hundred thousand).

It is therefore advisable to preserve the favourable properties of the geological surroundings by controlling possible disturbance due to the excavation and operation of underground disposal structures, the materials brought in and the presence of the waste, especially the thermal load it generates.

After the end of the operating and observation phase, a repository's safety functions are passive functions requiring no human intervention.

Some functions are only useful at a late stage. This applies particularly to the repository's ability to limit the migration of radionuclides. This will only really come into play once the packages have begun to release radionuclides. During the period when these functions are available but not yet needed, they are referred to as "latent functions".

2.2.1.1 Countering the circulation of water in the repository

Deep geological formations are saturated with water. Water circulating in the vicinity of the waste is the main factor liable to deteriorate the packages and enable radionuclides to be released inside the repository. Circulating water could then potentially carry radionuclides beyond the repository.

The first set of functions is therefore designed to counter the circulation of water in the repository. Broadly speaking this means:

- limiting the water flux in contact with the repository, coming either from the host formation itself or from the overlying geological formations through which the access structures pass4;
- strongly limiting the velocity of water circulation between the repository and the overlying and underlying formations.

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[4] On the Meuse/Haute Marne site, the overlying geological formations arepoor aquifers and hence the water flow is limited there.

For a transitory period after the underground disposal installations are closed, they gradually become saturated with water again [8]; at this stage the general direction of flow is towards the installations and the second of the above functions is latent.

After that, once the underground installations are resaturated, the hydraulic pressures gradually readjust. Water then circulates according to its natural hydrogeological gradient. The flow of water is strongly limited by the low permeability of the repository's host formation.

The architecture and seal arrangements of the disposal system can also contribute to this function.

2.2.1.2 Limiting the release of radionuclides and immobilising them in the repository

As the possibility of water reaching the waste cannot be excluded in the long term, it is important to limit the release of radionuclides and chemical toxins into the water by immobilising them in or very near the waste.

To achieve this, a first goal is to have waste packages that prevent the dispersion of radionuclides, e.g. due to the properties of the matrix that incorporates the radionuclides or those of the containers in wich the waste is emplaced. Alteration by water of the waste and its conditioning is limited by placing them in a favourable physical and chemical environment.

The corresponding functions depend on the type of waste – B waste, vitrified C waste or spent fuel.

For B waste, the repository protects the metal parts it contains from corrosion by providing a chemically favourable environment (reducing potential, pH 10 to 12.5). For bituminised B waste, disposal conditions help to protect the bitumen's confinement properties durably [9] by keeping temperatures between 20 and 30 C, by preserving the geometry of the embedded waste and by controlling the pH of water reaching the bitumen (pH 10 to 12.5).

For vitrified C waste, a primary function is to prevent water coming into contact with the glass during the period when the temperature is relatively high, which lasts about a thousand years at most [10]. In light of current limits of scientific knowledge (or understanding) any release of radionuclides should ideed be avoided as long high temperatures prevent a reliable description of radionuclide behaviour [11]. Another purpose is to protect the glass, since currently accepted behaviour models indicate that glass becomes more readily altered at increasing temperatures [9].

After the thermal phase, the aim is to limit alteration of the glass (a) by reducing the possibility of dissolved species transport in the vicinity of the glass to favour a chemical balance between glass and water, and (b) by controlling pH (preferably between 7 and 9) since the solubility of silica, the main ingredient in glass, is sensitive to this factor.

For spent fuel too it is necessary to prevent water reaching the assemblies during the thermal phase. Beyond that, to limit dissolution of the fuel the aim is to control dissolved species transport near the assemblies and the chemistry of the water (neutral to alkaline pH, reducing conditions).

For all types of waste, once alteration of the packages by water has begun, though weakened by the functions just described, the disposal conditions are designed to limit the mobility of the radionuclides.

This function concerns elements that may dissolve in water when the waste is altered. A large proportion may remain solid or be reprecipitated, thanks to the reducing geochemical conditions (complemented by pH control); only a few radionuclides (particularly iodine-129 and chlorine-36) are insensitive to these favourable geochemical conditions.

It also concerns any radionuclides suspended in water as microparticles (coilloidal particles can form during alteration of the packages or precipitation of radionuclides, or may already exist in the medium and sorb dissolved radionuclides). The geological environment ensures a physical filtration function allowing to immobilize these particles.

Lastly, the physical-chemical properties of some B waste can lead to the formation of complexing species during alteration by water; in solution in water, these species may increase the mobility of some radionuclides. The impact of such chemical disturbance will be limited by keeping potential sources of complexing species away from other waste wherever possible.

2.2.1.3 Delaying and reducing migration of radionuclides towards the environment

To protect man and the environment from any radionuclides or toxic chemicals released by the waste, one function of the repository is to delay and reduce the flow released.

To achieve this, migration of radionuclides dissolved in water is controlled by diffusion, dispersion and retention within the repository's host formation [12]. To this end, the argillite properties of the Callovo-Oxfordian formation offer a low permeability, a low diffusion coefficient and a high retention capacity. Dissolution in water of radionuclides released as gas makes it possible to manage them in the same way.

Radionuclide migration can also be delayed inside certain repository components. This can also help to reduce the potential impact on man and the environment.

Radionuclides that might be released beyond the repository's host formation will disperse in the long term in surrounding geological formations before reaching the environment accessible to humans.

2.2.1.4 Preserving the favourable properties of the geological environment, limiting disturbance caused by the repository

To make it possible to use all the favourable properties of the Callovo-Oxfordian formation for the purposes described above, the repository is designed and built in such a way as to limit any disturbance it may cause to the geological environment.

One function is to dissipate the heat generated by the radioactivity of the waste. If heat release raises temperatures in the rock above 100°C, complex coupled processes can be generated. If temperatures are too high for too long, irreversible mineralogical changes can occur in the Callovo-Oxfordian argillite. Studies suggest that a thermal stress of 100°C for 1000 years followed by 70°C for 10,000 years causes little or no irreversible change.

To stay within an operating range where the phenomena are known and to reduce damage to the argillite, the aim is to keep the temperature of the argillite within these values. In practical terms, the thermal design of the repository aims to limit tempertures to 90°C at the contact between the disposal cell and the argillite and verify that the temperature is well below 70°C at the 10,000 year timescale. This function particularly concerns vitrified C waste and spent fuel.

Another important function is concerned with the mastery of the mechanical deformation of the host formation. The argillaceous nature of the rock studied limits its mechanical resistance in the event of deformation. Opening underground cavities in a medium subject to natural mechanical stresses due to the weight of overlying rock causes deformation in the surrounding rock. During the excavation and operation of the cavities, ground supports and lining support the rock and therefore limites its deformation. In the very long term, new deformations could occur and would alter the linings (chemical alteration in particular). The intensity of deformation in the rock is therefore related to the volume of remaining empty space in the packages and the engineered structures.

An additional cause of deformation with highly radioactive packages is thermal expansion of the materials due to heat released by the waste.

If deformation is greater than the rock's resistance it can cause local damage, thus more or less increasing permeability according to the extent of the damage (microfissures, fractures) (see below, § 2.3.2.3 and [13]). A major objective is therefore to limit the mechanical deformation caused by the repository, in order to prevent or limit the intensity and extent of damage to the rock and so avoid weakening the safety functions of preventing water circulation and slowing and reducing migration of radionuclides.

It should also be ensured that hydrological and chemical disturbance (desaturation of the geological medium during construction work, introduction of oxygen and various materials), which may be coupled with mechanical disturbances, does not cause prejudicial damage to the geological environment.

Lastly, since some packages contain fissile material, the repository must remain in a sub-critical configuration, taking account of the potential displacement of matter and long-term changes in the materials.

2.2.1.5 Safety functions over time

The chart below summarises all the safety functions available over time. For each period considered, it distinguishes between functions that are directly effective in protecting humans and the environment, and latent functions. The latent functions can help to protect humans and the environment in the event that an effective function is weakened.

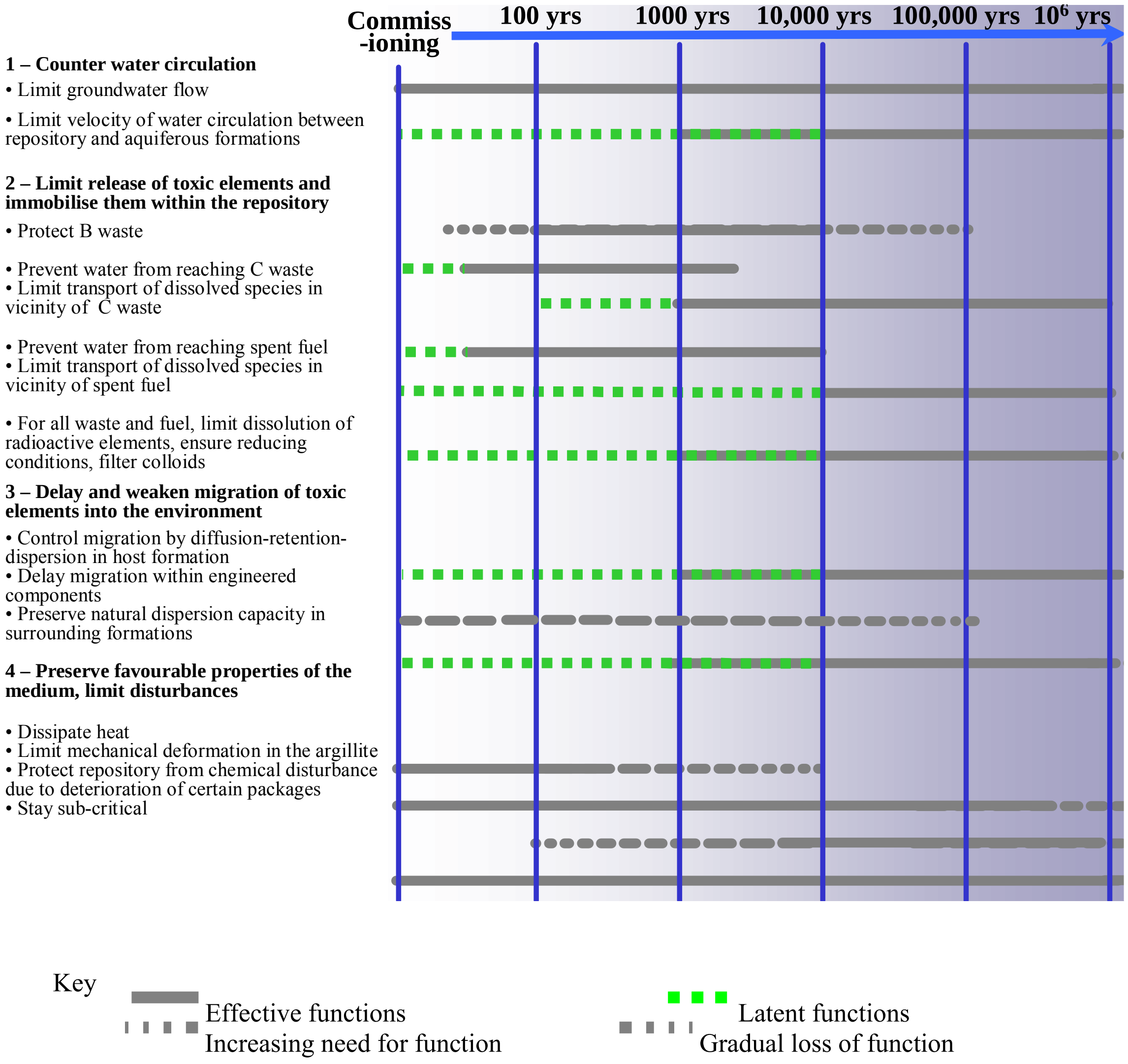

Figure 2.2.1 Safety functions over time

2.2.2 Reversibility and stages in repository implementation

The Act of 30 December 1991 makes provision for a study of repository reversibility. At the government's request, the National Review Board (CNE) submitted a report on reversibility in June 1998 [14]. In December 1998, the government published a declaration stressing that research should adhere to the reversibility paradigm [15].

There are a number of reasons arguring in favor of reversibility, and analysis of these reasons has informed the search for technical solutions. As a result, the need to define reversibility more broadly than the ability to withdraw waste packages from the repository ("retrievability") became apparent. Reversibility can be defined as the possibility of progressive, flexible management of the disposal process, leaving future generations free to make their own decisions in the matter.

The Nuclear Energy Agency (NEA) of the Organisation for Economic Cooperation and Development (OECD) introducted a clear distinction between retrievability and reversibility, showing in what respects reversibility has a broader scope of action than retrievability [16]. The international group of experts that wrote that report particularly highlighted the link between reversibility and a prudent, flexible, stage-by-stage approach that is part of good practice.

In light of the above, the disposal process can be broken down in successive stages. The point is to provide as much flexibility as possible in the management of each stage, for instance by allowing for a period of waiting and of monitoring, before deciding to move on to the next stage – or to move back to a prior stage.

Reversibility can be assessed by (i) the ability to withdraw packages from the repository, (ii) the ability to act on the disposal process, and (ii) the possibility of modifying engineered structure design in the course of the process.

Reversibility provides a repository management solution that gives leeway for each generation concerned to address its own needs.

2.2.2.1 Compliance with the reversibility requirement

The reversibility requirement implies providing for openness in decision-making in the long-term management of radioactive waste. Prudent decisions are to be preferred, leaving options open to future generations' decision makers,without coercing them by technical constraintes, albeit while maintaining an active management approach. In this way reversibility leaves the way open for negotiating between technical options and social issues [17].

This approach to reversibility may come within the province of the precautionary principle ([18], [19]). Maintaining reversibility and developing the means to achieve it is motivated by a prudent management approach to action in an uncertain context, particularly owing to the long period over which radioactive waste must be managed.

Applying the precautionary principle also means adopting an attitude of scientific modesty. It means acknowledging the uncertainties and unknowns of a given moment, considering the timescales involved. During implementation of a reversible disposal process, one can envisage the possibility of monitoring over long periods for comparison with model results, updating knowledge, providing new information to aid decision-making, and so building confidence in the system as a whole.

2.2.2.2 Safety and reversibility

Although its implementation will involve future generations, the design of a repository must be robust enough to protect man and the environment over the long term, and this is its primary purpose. No compromises with regard to safety are allowed while taking into account reversibility.

Safety and reversibility are both founded on an attitude of modesty, recognising the existence of uncertainties and managing them with due regard for the rights of future generations. Safety requires that robust technical options be taken at the repository design stage, and reversibility implies prudent management of the repository.

The uncertainties of our present state of knowledge have been systematically taken into account in the choice of technical options described further on in this report.

Measures that might be at least partly justified by reversibility considerations must not impair safety functions. No technical measure that might significantly disturb safety relevant feature has been added solely for the purposes of reversibility. Such a measure would bring reversibility and safety into conflict, and in that case safety would take precedence. For example, introducing materials wich might cause a new type of disturbance, or a significantly greater disturbance than those already existing for other reasons, can not be justified soley for reasons of reversibility.

2.2.2.3 Organisation of the stage-by-stage disposal process

If it is decided to build a disposal facility, the first stage of its operational life will be the building of ground-level service installations and the engineered structures for access to the host geological formation, and preparation of the underground disposal installations.

This will be followed by an operating and monitoring stage when the waste packages are placed in the repository. For the sake of flexibility, the duration of the operating and monitoring stage should not be set in advance: it could last a century or several centuries.

Allowing for reversibility means, first and foremost, flexible management of the disposed waste packages, comparable to temporary storage.

But a repository is also designed to allow closure and thus a passive evolution[5]. Closure mainly consists of filling in and sealing the undergound installations.

Flexibility therefore implies gradual closure. This opens the way to progressively reducing the level of reversibility as decisions are taken.

The construction, operating and closure of a repository are therefore organised in stages, which can be implemented independently for each class of waste.

The first stage is the construction of a repository module, in which the packages are then placed.

Closure is designed as a gradual process in several stages: closure of modules, closure of access to modules, to the disposal installations for the class of waste concerned, and finally of the underground installations as a whole. Deconstruction of the surface installations[6] may begin, in part, before closure of the underground installations is finished, and be terminated afterwards.

The first stages of the operating phase are similar to temporary storage, which would be implemented undergound. However, unlike a purpose-built temporary storage facility, many of the elements required for long-term safety functions are already present and can be monitored in situ.

Because of the modular design of the installations, they can be built in successive phases. This gives greater freedom of choice in managing the development of the repository.

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[5] After closure, the safety functions decribed above are fulfilled without the need for human intervention.

[6] This operation includes deconstructing surface installations and definitive cleanup of surface spill.

The stage-by-stage approach to repository management has been studied internationally. Under European Union auspices, concerted action on the reversibility of the repository concepts studied in national programmes has shown that dividing the disposal process into stages is useful for analysing and understanding this issue and providing a progressive framework for decisonmaking [20]. Stage-by-stage disposal design is also being considered in the United States, where the National Research Council (NRC) suggests adaptive staging offering decision makers the widest possible range of options at each stage [21]. The NRC emphasises the advantages of this approach over linear staging, from the technical, as well as from the social, political and economic standpoints.

2.2.2.4 Ability to withdraw deposited packages, ability to act on the disposal process, design reversibility

Progressively, as choices are made and the closure process moves on from stage to stage, the degree of reversibility could diminish. The technical options presented later in this document are designed to make this reduction as gradual and as well-controlled as possible.

The ability to withdraw packages is assessed right up to the loading of the packages onto vehicles for transport to other sites. During the first operating stages, packages are retrieved in the same way as with temporary storage, simply by reversing the emplacement process. As the closure stages progress, the ability to withdraw packages implies the ability to re-open and unseal the installations.

The ability to act on the process is the possibility for future operators to manage each stage flexibly. This concerns the time technically possible before moving on to the next stage or backtracking, and the ability to keep installations in good condition. Monitoring the behaviour of the disposal installations provides support for the management of the disposal process by providing information about the state of and changes in the repository.

New engineered structures can be designed or redesigned as the staged development of the disposal installations progresses. Design will have the benefit of experience and knowledge acquired during operation and monitoring of earlier structures, and of technical progress achieved elsewhere. It can also take into account data from the social, technological and scientific environment.

Note that reversible management of the repository requires long-term knowledge management, both for scientific knowledge and knowledge of the technical configuration of the repository.

An analysis of reversible repository management (ability to act as the process advances, ability to withdraw packages) is presented in Chapter 10.

2.2.3 Emplacement of waste packages

The emplacement of waste packages involves industrial activities [22]. These consist of (i) taking delivery of primary packages from waste producers (ii) physically placing them inside the Callovo-Oxfordian host formation and (iii) managing those packages as well as the (repository) installations.

The industrial operating processes involve risks, particularly due to handling radioactive materials. The public, staff and the environment must be protected.

2.2.3.1 Receiving the primary waste packages

The primary waste packages delivered to the repository site will be sent from production or storage sites via the road or rail network. The transfer casks and transport systems will then have to be received, unloaded and sent back to the production or storage sites[7].

Prevention of the dissemination of radioactive materials includes inspections on the transfer casks[8] and transport systems, the possibility of decontaminating these items and managing the radioactive waste and effluents arising from these operations.

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[7] The returned transfer casks will generally be empty. They may however be filled with waste packages if a decision is made to refrain from unloading transfer casks or to destock packages (following their withdrawal from the repository).

The protection and inspection of nuclear materials contained in the installation [23] will be noted in particular.

2.2.3.2 Placing the waste packages in the Callovo-Oxfordian argillites

In order to place the waste packages in the argillites, underground installations must firstly be made within the scope of the gradual development of the repository.

This implies surveying the volumes of argillites which will receive the packages by checking that the local properties of the argillites are good and, if necessary, by adjusting the data used to design the engineered structures. This survey can be completed in stages as the repository is developed, with each stage providing additional knowledge specific to each repository zone created. Conventional methods of geological surveying are used.

Next the new repository facilities and the engineered structures serving the repositories are excavated. This involves excavating the argillite, loading it (muck removal) and extracting it to the surface and stockpiling the excavated material, while maintaining the possibility of using the extracted argillite later to backfill the underground installations.

Finally, these repository installations must be equipped by preparing, taking underground and installing the equipment required for operation and that contributing to the safety functions.

Furthermore, the primary conditioning of the waste (in other words, as carried out by the producers), may have to be supplemented to facilitate operation or perform safety functions after closure. In the technical options presented below, it is assumed that the additional packaging is carried out at the repository site.

Finally, the packages thus prepared must be transferred to their repository location while it is ensured that operating personnel are protected against the risks of external and internal exposure to ionising radiation.

At each stage in the process, the various objects made are characterised by a report of each object which is completed and saved in order to populate and update the repository knowledge base.

Among the support functions to all of these activities, two appear particularly important:

- ventilating the installations to enable intervention by personnel [24], and control potential risks linked to the build-up of gases (especially hydrogen generated by radiolysis of the materials in certain B waste packages);
- supporting the underground caverns mechanically to provide dimensional stability, ensure safety and limit argillite deformation.

2.2.3.3 Managing the installations

The installations are managed according to the reversibility paradigm presented earlier. Management covers maintenance of the installations, monitoring and the possibility of withdrawing packages from the repository, once again while limiting radioactive dissemination.

The possibility of closing the underground installations implies preparing the backfilling and sealing materials, taking them to the bottom, and then constructing the closing structures.

2.2.3.4 Operational nuclear safety functions

The industrial activities presented above imply the implementation of "operational safety functions" that are comparable to usual nuclear facility practices, whilst taking the underground nature of the repository into consideration.

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[8] If spent fuel is received, an inspection will especially be carried out to ensure that there are no ruptured bare rods inside the transfer casks.

First and foremost, the radioactive materials must be confined to prevent their dissemination. In particular, releases of gaseous radionuclides liable to be given off by certain wastes will be limited as far as possible and monitored ([25] ,[26]). The contamination monitoring systems also relate to this objective.

The operators and the general public must also be protected from radiation. This is done by interposing fixed or portable protection screens, keeping operators away from sources of radiation and managing their period of exposure.

Another objective relates to criticality- safety. This objective was mentioned earlier for the long term, and naturally applies from the moment when the packages are received. It involves avoiding a criticality accident, the consequences of which could in particular undermine the confinement and radiation protection functions [27]. The objective is achieved by monitoring fissile materials, geometries and, if applicable, the interposition of neutron-absorbing materials.

The need to evacuate gases (especially radiolysis gases) and the thermal power emitted by certain waste packages, with a view to limiting the temperature levels in the installations, will also be noted. Ventilation contributes to this during operation.

In addition, functions relating to the underground nature of the package disposal operations must be taken into account. This is particularly the case for the mechanical stability of the engineered structures and ventilation of the installations.

2.2.4 Objectives regarding the protection of men after closure

The level of human protection, with regard to the risk induced by radionuclides, can be assessed by the individual committed[9] effective[10] dose, for the prolonged exposure of a person belonging to a critical group, i.e. a group of individuals potentially subjected to greatest exposure. An objective can therefore be set which will make it possible to assess the capability of the repository design to protect man from radionuclide risks.

For the post-closure period, Basic Safety Rule n° III.2.f notes that the radiological impact of a repository shall not exceed ¼ millisievert per year (mSv p.a.) for a reference scenario covering a series of probable natural events [2]. In any event, the aim is to make this value as low as reasonably achievable.

This value of ¼ mSv p.a. represents a fraction of the public individual exposure limit (1 mSv p.a.) adopted by the International Commission on Radiological Protection (ICRP) and Euratom Directive 96/29, excluding individual exposure for medical purposes and to natural radioactivity [28]. By way of an illustration, remember that individual exposure to natural radioactivity represents an average of 2.4 mSv p.a. in France, resulting from the inhalation of radon given off by the soil, the ingestion of food and drink (notably containing potassium 40), external irradiation through the floors and walls of homes, and finally cosmic radiation[11].

The human protection objective covers a very long period following closure of the repository. For the overall safety approach, the RFS recommends distinguishing between two periods when carrying out studies into the very long-term behaviour of a repository:

up to ten thousand years, a period for which radiological impact forecasts can be made objectively due to the stability of the geological medium;

beyond ten thousand years, a period for which conservative estimates may be proposed using pessimistic values given the gradually increasing level of uncertainty over time.

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[9] The "committed" dose takes account of the continuous effect of tissue irradiation by a radionuclide ingested into the body.

[10] Apart from the energy supplied to the material in the form of radiation, the "effective" dose takes account of the relative harmfulness of that radiation and the sensitivity of the organs or tissues irradiated.

[11] Exposure during medical examinations (radiographie, etc.) represents a dose of 1.6mSv per year

It should also be checked that the design of a repository meets environmental protection criteria concerning its impact beyond issues of radioactivity (notably the chemical toxicity of elements which may be contained in certain wastes or introduced with repository construction materials). As a result, the use of labile toxic elements in the construction of packages and the repository installations are particularly avoided. It will also be noted that the safety functions of a repository actually help reduce the impact of toxic elements on the environment.

2.2.5 Protection of men during repository operation and observation

The public and personnel must be protected from the radiological risks associated with the industrial activities. For the operating phase, Andra has adopted an individual annual dose of less than ¼ mSv as a public protection objective. For workers directly assigned to jobs under ionising radiation conditions and therefore benefiting from reinforced follow-up, the objective is to limit the annual individual dose below 5 mSv p.a.

Man must also be protected from other harmful effects potentially generated by the operation of a repository [29], especially:

exposure to dust,
exposure to potentially toxic gases,
exposure to high temperatures (particularly caused by the heat given off by the waste),
accidental risks (see chapter 11 – Operational safety: fire, explosion, falling blocks or collapse in underground installations, electrical hazards, etc.).

Finally, environmental protection constraints during industrial operation (groundwater and surface water [30], air [31], landscape and, for information at this stage, the vicinity, soils, fauna and flora) will be noted.

2.3 The geological context of the Meuse/Haute-Marne site – the Callovo-Oxfordian formation

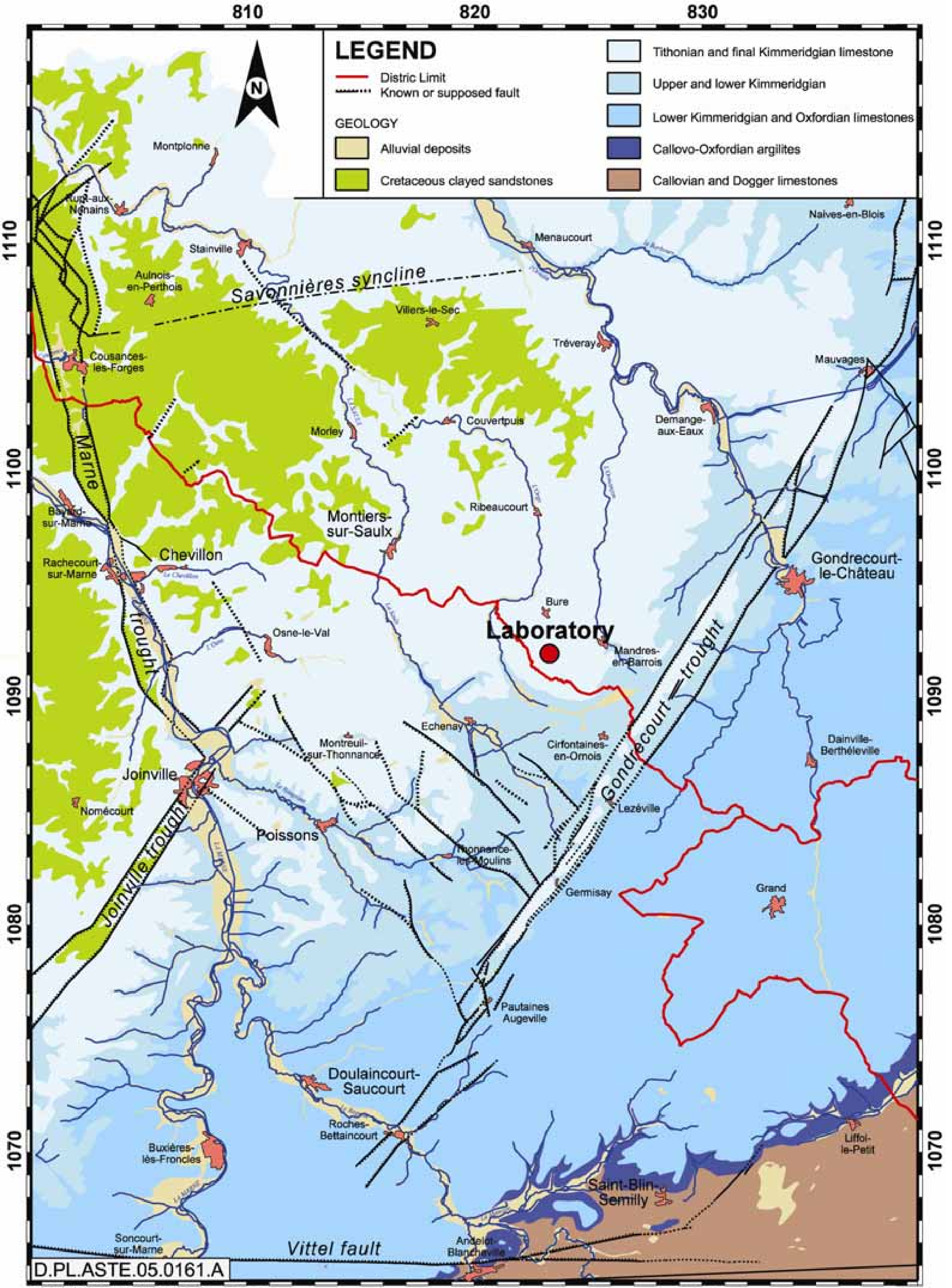

Figure 2.3.1 Geological map of the Meuse/Haute-Marne sector

This section provides a global introduction to the geological context of the Meuse/Haute-Marne site, plus the various results obtained on the properties of Callovo-Oxfordian argillites.

As indicated above, the characteristics of the clay formation, studied in particular by the underground research laboratory, contribute significantly to the achievement of the repository safety functions. The main characteristics in this respect are its thickness, continuity, permeability, retention capacity and geodynamic stability. The hydrogeological context on a larger scale also plays a part in the assessment of long-term repository performance.

The study of waste emplacement in a repository and the control of disturbance are also based on knowledge of other characteristics of the host formation: dip, depth and mechanical and thermal behaviour.

2.3.1 General presentation of the sector studied

Geologically speaking, the Meuse/Haute-Marne site belongs to the eastern rim of the Paris Basin; the lowest point of this basin corresponds to the Ile de France region. In the zone studied, the Paris Basin consists of alternating layers of predominantly clay sediment and limestone; these layers were deposited between 250 million and 135 million years ago ([6] - Volume 1).

In detail, the sedimentary series more particularly concerned by the study comprises, from the bottom up (and from east to west at the outcrops):

- the Dogger limestone formation resting on Liassic marls and clays,
- the Callovo-Oxfordian argillite formation,
- the middle to upper Oxfordian limestone formation,
- Kimmeridge marls,
- at the outcrop at the location of the site, Tithonian limestone (known as Calcaire du Barrois),
- a few superficial Argilloarenaceous Cretaceous deposits thinly covering the highest points of the topography.

These sedimentary layers have a simple, monoclinal structure with a slight, regular dip of 1 to 1.5 degrees to the north-west.

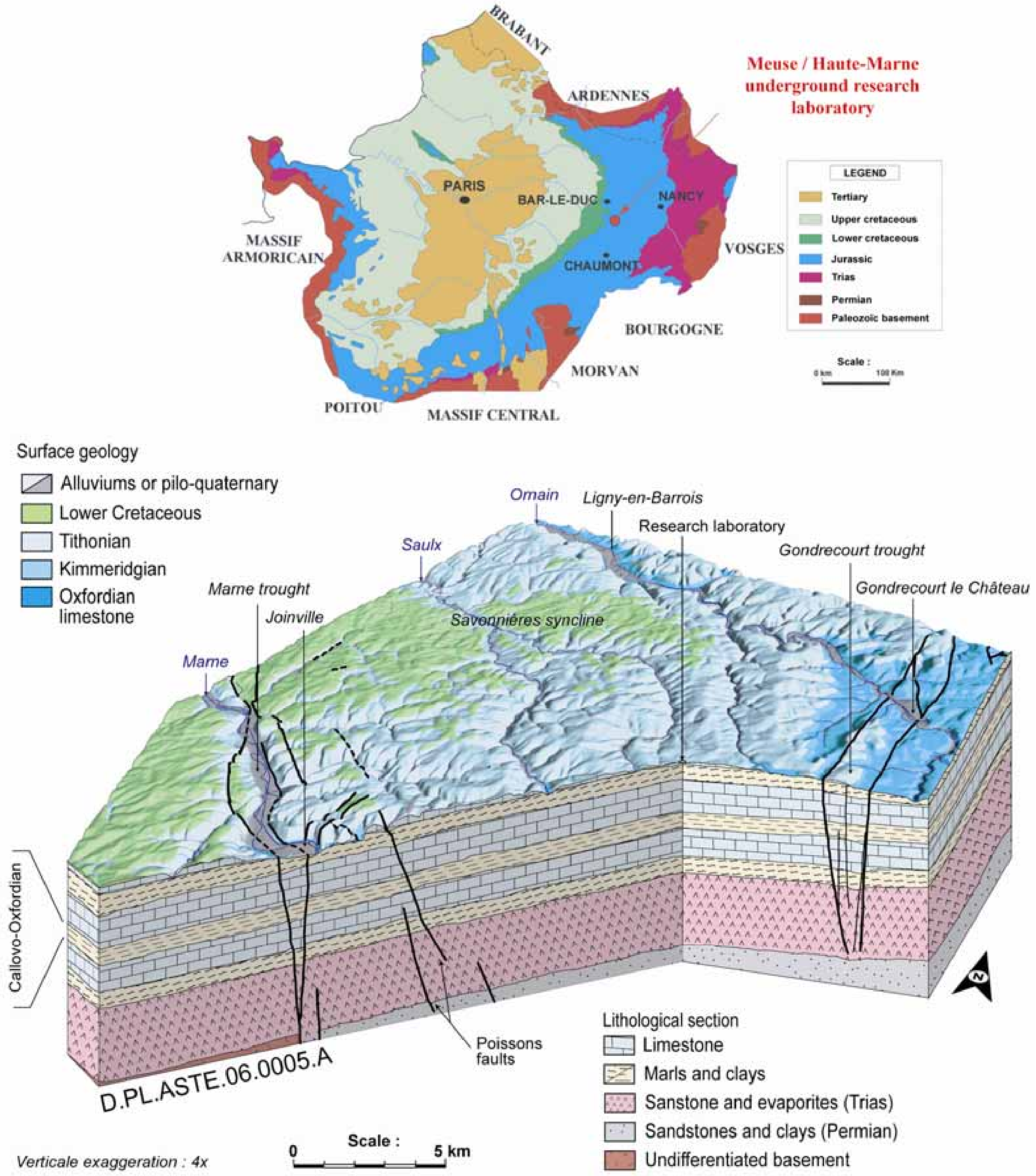

Figure 2.3.2 3D geological block diagram of the Meuse/Haute-Marne sector

Within the sedimentary series, the clay formation studied is the Callovo-Oxfordian argillite formation. This layer originates from the sedimentation of detritic materials (clay minerals amounting to up to 60% by mass and fine quartz) and carbonates in a relatively calm sea. It covers a large geographical extent.

Research has led to the definition of a so-called transposition zone, covering an area of some 200 km^2, inside which the properties observed on the Meuse/Haute-Marne site seem to be able to be transposed. This zone has been delimited particularly by locating it away from faults in the sector (Marne fault, Gondrecourt rift, etc.).

In this zone, the Callovo-Oxfordian is a homogeneous layer of low permeability, the top of which is found at a depth ranging from 420 metres (corresponding to the laboratory site) to over 600 metres following the direction of the dip. Its thickness also varies gradually from 130 metres in the South to 160 metres in the North of the zone.

Vertically, the proportions of the main mineralogical phases vary and are structured into three sedimentary sequences[12]. The upper sequence is characterised by higher carbonate content.

The Callovo-Oxfordian argillites were laid down between 158 and 152 million years ago. The deposited sediments were gradually compacted over a period of some fifteen million years under the weight of subsequent deposits (at least 500 metres of sediment); water was expelled during this process. At that time, the argillites had acquired properties similar to those observed today, with movements of fluids and ions becoming very slow. The large-scale tectonic events which subsequently affected the whole of the Paris Baris, in the Cretaceous and Tertiary, did not cause any significant disturbance to the geological medium.

The Callovo-Oxfordian is bound by two large limestone formations, the underlying Dogger formation and the overlying calcareous Oxfordian formation, both containing porous sedimentary horizons where water flows. However, these horizons have low permeability and are aquifers in the hydrogeological sense (they do not represent a water resource).

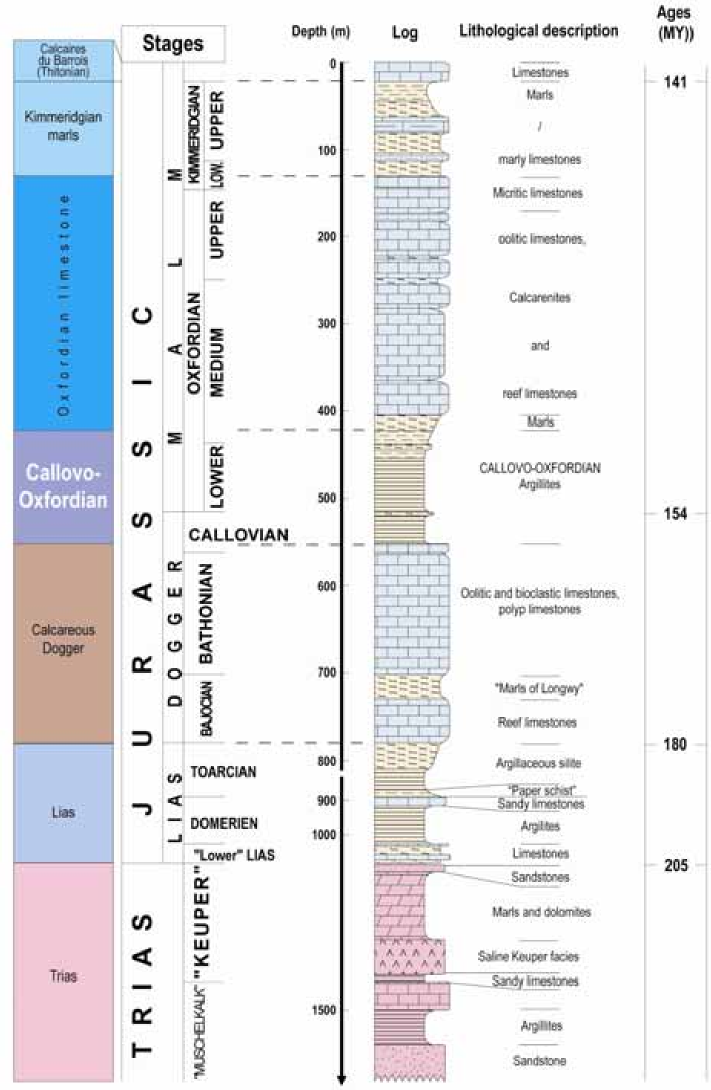

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Figure 2.3.3 Geological cross-section at the site of the underground research laboratory

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[12] These sequences express slight cyclic variations in the relative marine level at the time when the layer was deposited.

2.3.2 Properties of the Callovo-Oxfordian argillite formation

This paragraph presents the decisive characteristics of the Callovo-Oxfordian argillites: geochemical, mechanical, thermal, permeability and transport characteristics. Firstly, the considerable homogeneity of the formation will be noted as indicated by the various bore-holes drilled in the sector. Moreover, numerous investigations have not revealed any faults within the Callovo-Oxfordian.

2.3.2.1 Water flow and solute transport in the Callovo-Oxfordian

Owing to its textural properties, permeability of the Callovo-Oxfordian is low through its entire depth ([6] - Volume 1). Based on the various measurements carried out on samples and in situ, permeability ranges from 5.10^{-14} metres per second (m/s) to 5.10^{-13} m/s.

This permeability, combined with the small differences in hydraulic head on either side of the formation, means that vertical flows are very slight within the layer. It is due to a very small rock pore size and to the interactions between pore water and minerals. In actual fact, the porosity contributing to this flow (kinematic porosity) corresponds to the fraction of free water in the rock: approximately half of total porosity.

When an underground cavern is excavated in the formation studied, the water flow rate drained by this cavern is almost nil due to the low permeability of the argillites. As long as this cavern is ventilated, water will only be encountered in the form of vapour in the ventilation air and will not exist in liquid form.

Water flows circulating naturally by convection in the Callovo-Oxfordian formation being particularly low, diffusion into the pore water is the predominant transport mechanism of species in solution here.

The small pore dimensions determine tortuous transfer paths and, therefore, low diffusion coefficients. These coefficients are relatively uniform through the entire depth of the layer reflecting its lithological and textural homogeneity. The effective diffusion (De) coefficient values ([6] - Volume 1) have been assessed at:

- De = 5.10-12 m²/s for an accessible porosity value of 5% in the case of anions,
- De = 2.5.10-10 m²/s for an accessible porosity value of 18 % in the case of cations.

Diffusion may be accompanied by other processes. Even so, the displacement speeds of species in solution corresponding to these phenomena are very slow and negligible with regard to diffusion.

Different water salinities have been observed in the Callovo-Oxfordian and bounding formations: 3 to 4 grams per litre (g/l) in the interstitial water of the argillites, around 4 g/l in the Dogger, and 0.9 g/l in the calcareous Oxfordian ([6] - Volume 1). High salinity of the interstitial water in the Callovo-Oxfordian indicates an absence of hydraulic exchanges with water-bearing formations. It confirms the low permeability of the argillites and the very slow displacement of ions in solution.

The Callovo-Oxfordian formation comprises a very small number of microstructures which, in most cases, were clogged by calcite or celestine from the start of the argillite compaction phase. Investigations conducted at the site have shown that the average spacing between these structures is around thirty metres in the upper part (where behaviour is more fragile), and hectometric in the rest of the layer.

The hydraulic tests carried out have indicated that these microstructures have no impact on the permeability of the layer.

2.3.2.2 Geochemistry of the geological medium

The Callovo-Oxfordian is a naturally reducing medium; this property is particularly favourable in limiting the corrosion of metallic materials and the release of radionuclides (§ 2.2.1.2).

During the operation of underground structures, ventilation will cause an oxidation phenomenon in the vicinity of the wall. This phenomenon will also concern the argillite excavated rock extracted to the surface. However, argillites contain minerals (pyrites in particular) and organic matter which react with oxygen, which will limit this phenomenon to a very slight thickness.

After closing underground structures, the interstitial water of the argillites which will percolate towards these structures may transport chloride ions; the interaction of these ions with the materials emplaced in the structures (steel and concrete) is considered in the assessment of their long-term degradation.

Argillites can also act as effective buffers to alkaline disturbance, such as that which would be induced by the gradual degradation of concrete structures over time.

2.3.2.3 Mechanical properties and excavatability

The mineralogical composition of the Callovo-Oxfordian argillites confers them relatively high strength strong for an argillaceous rock and limited deformability, whereas; damage occurs above a certain load threshold and whereas they are prone to fearing (brittle). Their high clay mineral content limits the reversible deformation threshold, attenuates the brittle behaviour (plasticity), tends to reduce the breaking strength of the rock and confers a significant viscous behaviour (long-term creep).

As far as short-term mechanical behaviour is concerned, the simple compressive strength of argillites averages 21 megapascals (MPa) in the middle of the formation studied ([6]- Volume 2)[13].

It will be noted that this strength is comparable to that of rocks where major underground work has been carried out, under similar conditions. A particular example is the Chamoise motorway tunnel in the French Alps (see Figure 2.3.4) which, at a depth of approximately 400 metres, passes through an argillaceous rock of the same age, with simple compressive strength of 20 to 35 MPa [32], [33]).

The modulus of elastic deformation of Callovo-Oxfordien argillites ranges from 3 000 to 5 000 MPa – within the same range of values as the argillaceous rock traversed by the Chamoise tunnel (3 000 to 6 000 MPa).

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[13] It will be noted that this strength is only slightly lower than that of common construction-grade concrete (30 MPa).

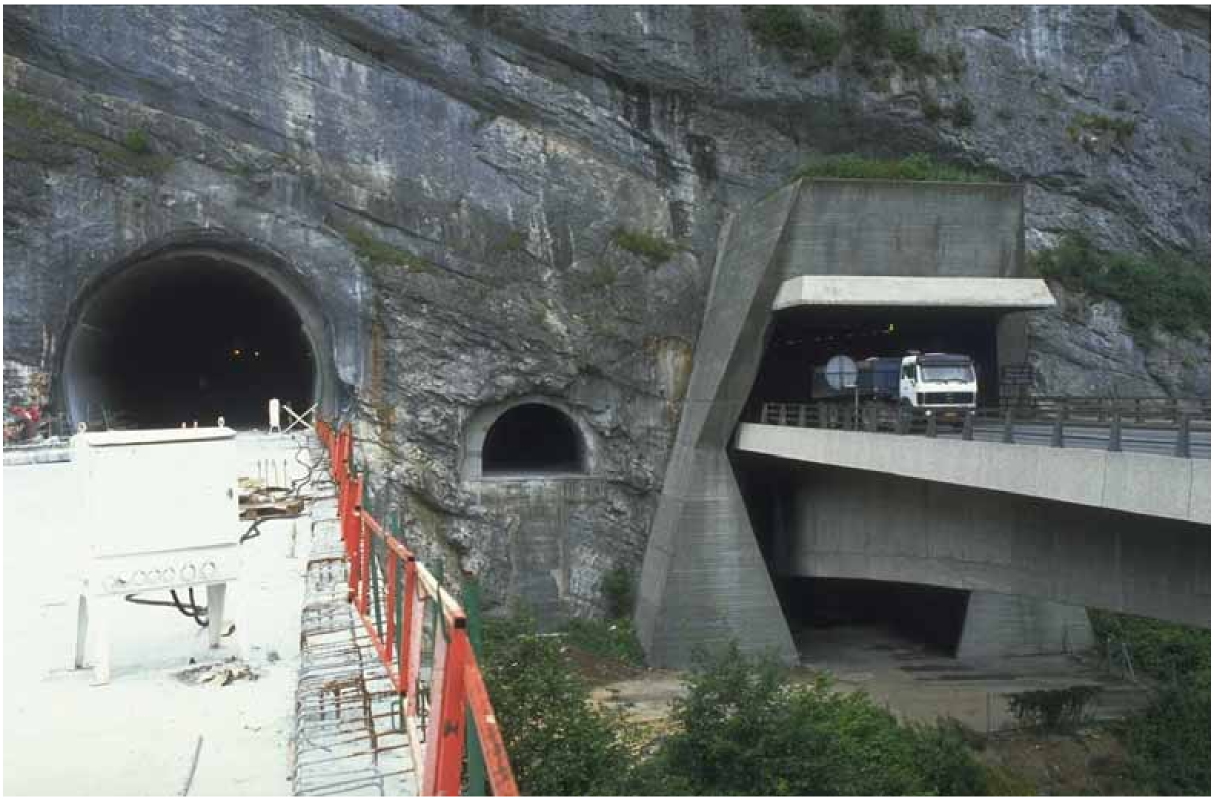

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Figure 2.3.4 *Entrance to the Chamoise tunnel (left, tube under construction; centre, exploratory drift; right, tube in operation)*

The strength of the argillites is to be compared with the natural mechanical stresses within the formation studied. The vertical stress is equal to the weight of the rock: 12 MPa at the location of the underground research laboratory. The major horizontal stress is, on average, oriented North 155° East in the Callovo-Oxfordian and is slightly higher than the vertical stress. The minor horizontal stress is equal to the vertical stress.

In such a natural stress field, the opening of a underground cavity generates a stear stress at the wall (i.e. a stress parallel to the wall) that is close to the machanical strenght of the argillites. Therefore, the behaviour of the formation studied is at the threstold between the appearance and non-appearance of fractures in the argillites in immediate proximity to the structures. In particular, threstold effect translates into a sensitivity of the mechanical response of the argillites to the installation depth of the structures. In any event, by using ground support for the argillites during excavation (§ 2.2.3.2), the risk of blocks falling during construction is avoided. Other constructive provisions, discussed below, allow to prevent the long-term safety functions of a repository from being affected by the possible appearance of a fractured zone.

Figure 2.3.5 View of the Meuse/Haute-Marne underground research laboratory drift at -445 m

Subjected to deviator stress (i.e. non-isotropic stress), the argillites deform gradually towards a more isotropic stress state. This deferred behaviour mechanism (creep) is slow; a creep deformation rate of 10^{-3} to 10^{-4} per year has been measured on water-saturated samples after two to three years under constant deviator stresses of 5 to 15 MPa ([6] - Volume 2)[14]. The deferred behaviour of the argillites will result in the gradual build-up of pressure on the underground structures. The liners of the underground excavations, and in the longer term all of the materials filling the excavations, will be able to absorb the resulting stresses and to control damage to the rock.

The ventilation of underground structures causes gradual desaturation of the surrounding argillites. As a result, their water content is reduced and a gaseous phase is formed in the rock pores. Desaturation increases rock stiffness and strength and slows down deferred deformations considerably, or even suspends them, for as long as the argillite remains unsaturated [6] - Volume 2).

The upper levels of the Callovo-Oxfordian formation have greater strength than the median levels of the formation (30 MPa on average). Damage here is naturally slight, as shown by the observations made in the shaft of the underground research laboratory. This element represents an advantage for the sealing of shafts at a possible repository installation.

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[14] By way of comparison, Boom clay, studied in Belgium for a possible repository (Hadès underground laboratory, Mol site), has a considerably higher creep rate: it varies from 0.06 to 0.3 per year under deviator stress of 2.25 to 2.75 MPa [34].

2.3.2.4 Thermal characteristics

The geothermal temperature within the Callovo-Oxfordian formation is 22°C at the depth of the underground research laboratory. The temperature rises with depth at a rate of 2.3°C per hundred metres, starting from a temperature near the ground surface, stable over time, of 10°C, which is low for the French context. Seasonal cycles or cycles of limited duration are, in fact, quickly absorbed at a shallow depth. Only climate cycles covering longer periods (glacial-interglacial cycles of 100 000 years) have an impact of a few degrees at 500 metres ([6] - Volume 2).

The Callovo-Oxfordian argillites present anisotropic thermal conductivities, with the anisotropy resulting from the bedding corresponding to the deposit of sediments. Parallel to the stratification, thermal conductivity varies from 1.9 to 2.7 watts per metre and per degree Celsius (W/m C) depending on the carbonate content of the horizon in question. It varies from 1.3 to 1.9 W/m°C at right-angles to the stratification. It will be noted that these thermal conductivities are averages for a rock. By way of comparison, a granite will be a greater heat conductor with conductivity of 2.5 to 4 W/m°C [35]. These values are however sufficient for heat evacuation by the rock.

An increase in argillite temperature has no significant effect on the mechanical strength and short-term deformation of the rock for temperatures below 70°C. It increases the deferred deformation rates and amplitudes of argillites, without considering the effects of desaturation [6] - Volume 2).

2.3.3 Hydrogeological context

The hydrogeological pattern for the Meuse/Haute-Marne sector is characterised by a succession of geological layers, some calcareous, some argillo-marlaceous, with contrasting hydrogeological properties and, as indicated above, with a very wide geographical extent. The limestone formations are water-bearing in certain areas of the Paris Basin, but their hydraulic transmissivity generally appears to be low over the sector studied [6] - Volume 1).

To the west and south of the laboratory, the tectonic structures (Marne rift, Poissons fault and other faults of lesser importance) may be deeply rooted in the Hercynian basement and probably contain gouge zones facilitating water circulation locally.

The more recent Gondrecourt rift has experienced strike-slip and extension movements, which could also have facilitated the circulation of fluids, but the current orientation of the stresses would rather tend to close the faults forming the rift.

In the Calcaire du Barrois (Tithonian) forming the surface of the plateau, the flows are mainly localised within the karst network[15], which essentially extends in its upper part along the Marne valley towards the north-west over many kilometres, at relatively high speeds (over 10 kilometres per year). These limestones are isolated from the underlying formations notably by the 140-metre thick argillo-marlaceous layer of the Kimmeridgian. The main natural outlets are the springs in the Saulx and Ornain valleys.

The Oxfordian limestone consists of a vertical succession of horizons with permeability ranging from 3.10^{-12} to 10^{-8} m/s ([6] - Volume 1). This formation is recharged with water primarily via the outcrops to the east and south of the site (at a distance of some 6 km from the Meuse/Haute-Marne laboratory).

In the Oxfordian limestone, the horizontal hydraulic head gradient is limited over the sector studied to a fraction of one percent. As a result, the flux and speed of the water circulating horizontally are low. All in all, the Oxfordian does not represent a water resource locally.

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[15] Karst network: series of cavities, varying widely in size, and natural underground drifts occurring in limestone areas which are created as rocks are dissolved by rainwater containing carbon dioxide.

In the Dogger, bore-hole tests have showed low permeability (10^{-8} m/s in the greatest water-producing levels). No water-producing level of regional extent has been identified. Water recharge takes places mainly via the outcrops about thirty kilometres to the east of the site. There is no natural outlet to this formation in the sector studied.

2.3.4 Geo-prospective evolution

The long-term evolution of the geological environement, like its past evolution on geological time scales, is the result of the climate at the ground surface, as well as the internal geodynamic evolution of the plates forming the earth's crust.

2.3.4.1 Climatic evolution and consequences

Since the beginning of the Quaternary Period, oscillating climate cycles succeed each other, responding to astronomic parameters, with alternating glacial and interglacial periods. Periodically, the surface soils are frozen to a significant depth for a long time (permafrost) at the Meuse/Haute-Marne site (40 to 50% of the time over the last 130,000 years). The frost penetrates to a depth of around a hundred metres. The deeper Callovo-Oxfordian formation is not therefore directly affected by frost ([6] – Volume 3). Notwithstanding the influence of the greenhouse effect which could slow down this evolution, permafrost could reappear in around 100 000 years' time.

These climate cycles result in a periodical boost to surface erosion. The main erosion phenomena are the incision of valleys and the removal of limestone plateaux which modify the surface flows through the evolution in the karst networks and possible river captures.

These phenomena have left marks on the landscape (alluvial terraces, for example) which make it possible to estimate their rate. The laboratory site is situated on a plateau zone away from the major valleys and located at the head of a secondary hydrographic network, where erosion is slower. The gradual disappearance of the Calcaire du Barrois (Tithonian) is possible beyond a period of 500 000 years.

2.3.4.2 Long-term geodynamic stability

The only tectonic movements anticipated are limited to the region's faults (Marne faults to the west and the Gondrecourt-le-Château rift to the south-east). Outside of these zones, no deformation of the geological layers is expected ([6] - Volume 3). The high geodynamic stability of the region explains the practically aseismic character of the sector on a historical time scale.

2.3.4.3 Seismic uncertainty

According to historical accounts or more recent records, no earthquake exceeding 3.5 in magnitude has been related or identified in the zone close to the Meuse/Haute-Marne sector (the Calcaire du Barrois (Tithonian) plateau between the Marne and Meuse valleys). The nearest known historical earthquakes were located over 60 kilometres from the site (essentially in the Vosges) and presented a magnitude ranging from 3 to 6.

In order to dimension the structures in accordance with regulations, a safety margin computed earthquake may be defined for the repository operating period. The magnitude of this earthquake (magnitude of 6 at a distance of 25 km from the site) is conservatively determined by increasing the magnitude of the strongest known historical earthquake in the zone and moving the focus from the place of occurrence to the closest point to the site. This earthquake is characterised by maximum acceleration of approximately 0.15 g (1.5 m/s^2) at the depth of the repository and approximately 0.2 g (2 m/s^2) at the surface. The difference is linked to the amplification of the movement on propagation of the seismic waves at the surface ([6] - Volume 3, [6]).

To assess the very long term impact of an earthquake, the maximum physically possible earthquake is determined for the configuration of the nearest faults to the site, by assuming that they are active (length, rooting depth and segmentation). Current simulations give this earthquake a magnitude of 6.1 at a distance of 6 kilometres from the laboratory site and at a depth of approximately 12 kilometres. Such an earthquake would cause maximum acceleration of approximately 0.3 g at the repository depth ([6] - Volume 3, [36]).

Although the safety margin computed earthquake and maximum physically possible earthquake characteristics are highly conservative, their amplitude remains moderate in comparison with those of earthquakes currently occurring around the edge of the Mediterranean Sea.

2.4 Principles of repository architecture design

A repository installation would consist of disposal cells (underground caverns), excavated in the argillite formation, containing waste disposal packages. These waste packages consist of primary waste packages, as conditioned by waste producers, supplemented by an over pack according to repository requirements.

The architecture studied contains disposal cells for various categories of waste within specific repository zones. The repository zones for B waste, C waste and, if applicable, spent fuel are therefore physically distinct from each other. This arrangement is envisaged to offer independence in terms of (i) the management of the various types of waste and (ii) the behaviour of each zone, in view of the specific characteristics of the waste contained [37]. The extent of the underground footprint for the B waste repository zone is 100 hectares for the inventory presented in chapter 3. For C waste (and spent fuel, if applicable), the footprint depends on the scenarios studied and the length of storage time prior to disposal in the repository. Indeed, preliminary storage reduces the thermal power of the waste when it is emplaced in the repository and therefore helps to reduce the footprint of the corresponding underground installations. Therefore, assuming 60 to 70 years' preliminary storage for C waste (depending on package types), the corresponding repository zone has a footprint of 500 hectares in a fuel (UOX and MOX) retreatment scenario (see chapter 6).

For cell construction, waste emplacement and reversible management of the installations, access is gained via vertical shafts between the surface and the repository level, then via connecting drifts between these shafts and the repository zones. While attempting to restrict the number of such structures, four vertical shafts are required to fulfil all of the functions presented in section 2.1.4. These shafts can be used for all types of waste in the repository.

During the operating phase, the waste is received and the disposal packages prepared in surface installations. These installations include workshops and offices supporting the underground work and operation. Excavation crushed rock are stockpiled in a specific zone called a crushed rock disposal. Its footprint depends on the volume of crushed rock and the hypotheses adopted for its geometry; it could be around 100 hectares for a fuel (UOX and MOX) retreatment scenario.

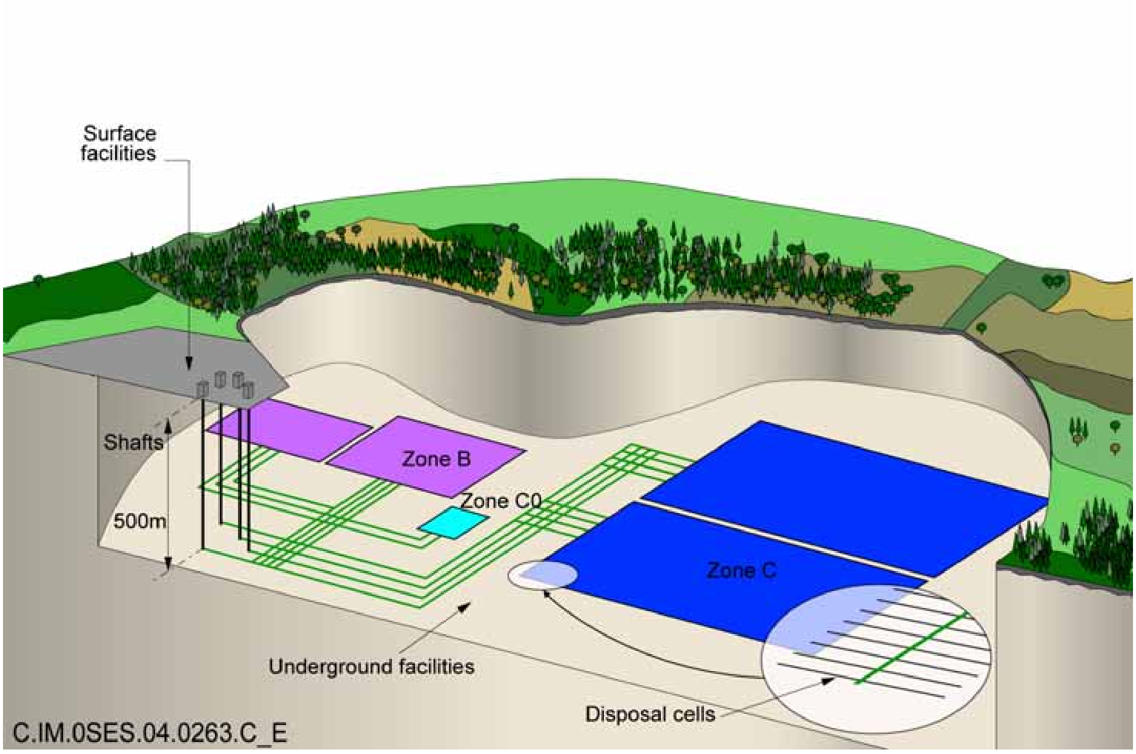

Figure 2.4.1 View of a repository architecture in operation

The design of the surface installations is similar to existing industrial facilities (see chapter 8 for further details).

The underground installations and disposal packages are more specific elements. After a presentation of key elements governing their design, the following sections globally describe the options proposed for the disposal cells and waste packages for each category of waste, and a possible arrangement for the repository zones, shafts and connecting drifts.

The technical feasibility of these installations and disposal packages depends on engineering studies and dimensioning with an appropriate degree of detail. In general, these studies are based on existing industrial experience supplemented in relevant areas by technological testing.

2.4.1 Key elements in the design of underground installations and waste disposal packages

The technical options proposed for the design of underground installations and waste disposal packages fulfil three needs expressed above:

long-term safety functions (section 2.1.2),
reversibility and flexibility of operation (sections 2.1.3 and 2.1.4),
personnel and operational safety (section 2.1.5).

These needs are accompanied by a quest for compactness.

2.4.1.1 Design and long-term safety

In order to control water flows, radionuclide release and migration to the environment, and the disturbance caused by the repository, several measures structuring the architecture are adopted.

- **Positioning of the repository in the middle of the geological formation**

The underground installations are embedded in the geological formation in such a way as to harness its favorable properties to form a barrier to water circulation and radionuclide migration. In order to maximise the thicknesses of argillite located above and below the repository, underground installations with a low vertical extent, organised on a single level located in the middle of the Callovo-Oxfordian layer are envisioned. The layout of these underground installations may be globally adapted to the dip in the layer, up to 1.5°[16]([6] - Volume 1).

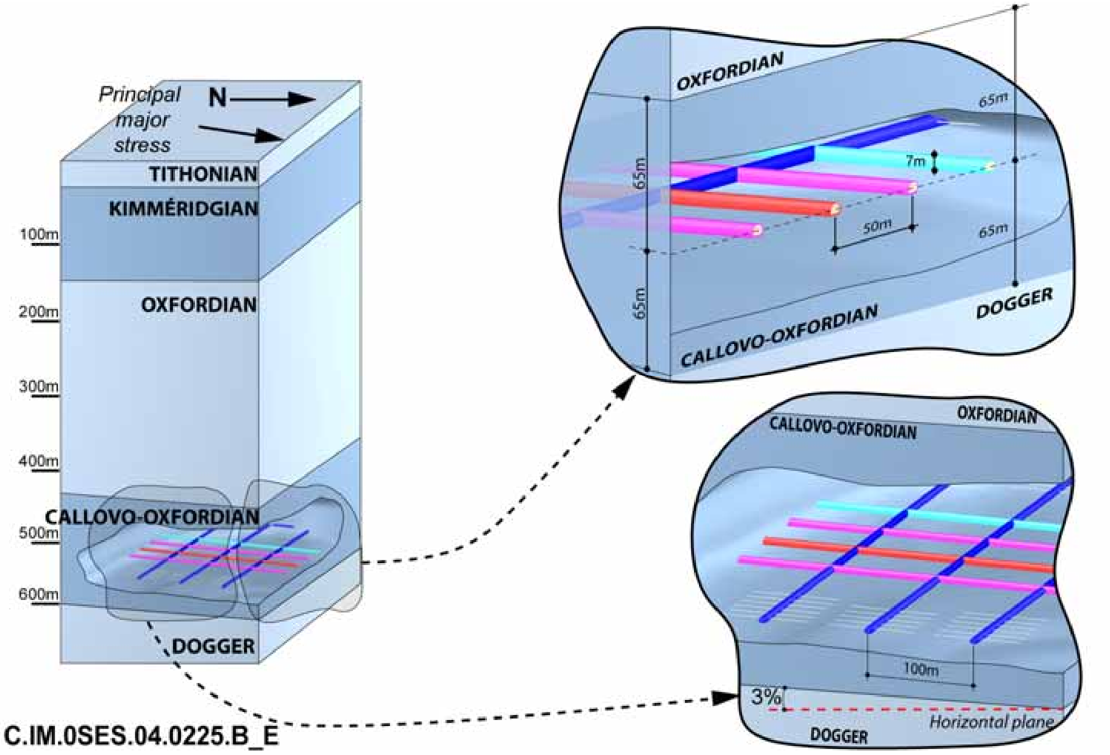

Figure 2.4.2 *Positioning of the repository in the layer. For illustration purposes, the depth and thickness of the clay formation correspond to the location of the underground research laboratory.*

- **Structures limiting the mechanical disturbance of the geological environment**

The underground structures are designed in such a way as to limit geomechanical disturbance not only during construction and operation, but also following the closure of the repository (cf. § 2.2.1.4).

The common profile of the various underground structures (disposal cells and access drifts) is generally circular or pseudo-circular[17]. Their excavated diameter is limited in accordance with our knowledge of argillite and the experience of comparable underground works. A liner is designed to provide lasting mechanical support. Furthermore, in accordance with frequent practice in underground works, a distance between two adjacent structures of at least five times their diameter has been adopted to boost their mechanical stability.

Backfilling the access drifts at the end of the operating phase helps limit the residual empty space. Such a measure avoids the creation of possible mechanical damage in the argillites in the very long term, following the loss of liner integrity [38].

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[16] Corresponding to a slope of approximately 3%.

[17] In an isotropic stress field, a circular section represents the most stable, least disturbing configuration for an underground structure.

● A dimensional design limiting thermal disturbance

The geometric configuration of the underground installations is designed to limit the temperature in the repository. In concrete terms, it has been decided to limit the temperature to 90°C in contact with the rock (or the buffer where the concept includes one). The concepts studied are based on heat dissipation by conduction through the rock. In this framework, the essential dimensional design parameters are the number of waste disposal packages per disposal cell and the space between the cells. The footprint of repository zones for vitrified C waste and spent fuel, depending on the thermal power given off by the waste packages when they are emplaced, is therefore a direct result of thermal considerations.

Moreover, we have opted to move B waste, especially bituminised waste, at a sufficient distancefrom exothermic waste to protect it from heat.

● Multiple sealing of underground installations and a dead-end architecture

When the repository is closed, the cells, connecting drifts and shafts must be sealed. Low-permeability, swelling clay plugs are used for this purpose. These seals oppose water circulations along these structures. They limit the water flow rate and the circulation velocity of this water.

Special systems have been studied to guarantee a continuous seal between the plug and the argillites and to interrupt, if necessary, the argillite zone fractured in the immediate vicinity of the excavation (see section 7.7).

The excavation of the engineered structures can lead to the creation of a damaged zone in the excavation wall which is expressed in different ways. In this respect, the following is notable:

- A fractured area in the immediate vicinity of the engineered structure. This occurs if the breakdown threshold, which corresponds to the maximum mechanical strength of the rock, is exceeded; It is characterised by the appearance of fractures, which are connected to a greater or lesser extent, and are susceptible to increase the permeability of the rock;
- A microfissured zone. This is formed when the fissuring threshold is exceeded either immediately in the wall of the structure (if the fractured zone is not formed) or behind the fractured area. It is the result of mechanical unloading related to the excavation of the engineered structures: the resulting deformations manifest themselves in the form of diffuse micro-cracking which is not very connected. The fact that the microfissures are not very connected limits the increase in permeability.

Effects accompanying the progress of the excavation may also occur. In this case, oblique shear fracturing to the axis of the drift may appear ahead of the excavation face. As these shear fractures are intersected by the drift as it progresses, only the extremities exist in the wall, forming a network of "chevrons", the length of which is close to that of the microfissured zone.

Beyond the microfissured zone is a zone described as being mechanically "influenced" it is the site of limited modification of the field of constraints and deformations that do not affect the properties of the rock (its permeability in particular).

To increase seal effectiveness, we have opted to orient the cells and the drift sections designed to be sealed parallel to the major principal geomechanical stress. This arrangement reduces the extent of the damaged argillite zone in the vicinity of the structure [38]. Andra has also sought to minimise the section of the structures to be sealed. Indeed, the greater the diameter, the greater the extent of the damaged zone, particularly the fractured part, if any. The excavated diameter of the connecting drifts has been limited to approximately seven metres which is still compatible with the equipment and material transfers and ventilation flows along these drifts (see chapter 7).

Furthermore, to limit the possibilities of convection phenomena in the repository, especially in the case of a seal failure, it has been decided to place all architectural elements in a dead-end. This provision particularly concerns possible water flux from overlying formations. It prevents a circulation from being established through the repository under the effect of a horizontal hydraulic head gradient.

The architecture presented is characterised by the following arrangements:

- the disposal cells described below are “blind” tunnels,
- the groups of cells have a “dead-end” topology. A series of cells is therefore accessed via a small number of close, parallel drifts as shown in Figure 2.4.3,
- overall, the repository is itself in a dead-end with all shafts grouped together on a single side of the repository.

The multiple seals and the possibility of a dead-end architecture complement the favourable hydrogeological characteristics of the site (low permeability of the studied formation and slight hydraulic head gradients in this and the overlying formations) in limiting the flow rates and velocity of the water within the repository in a particularly robust manner.

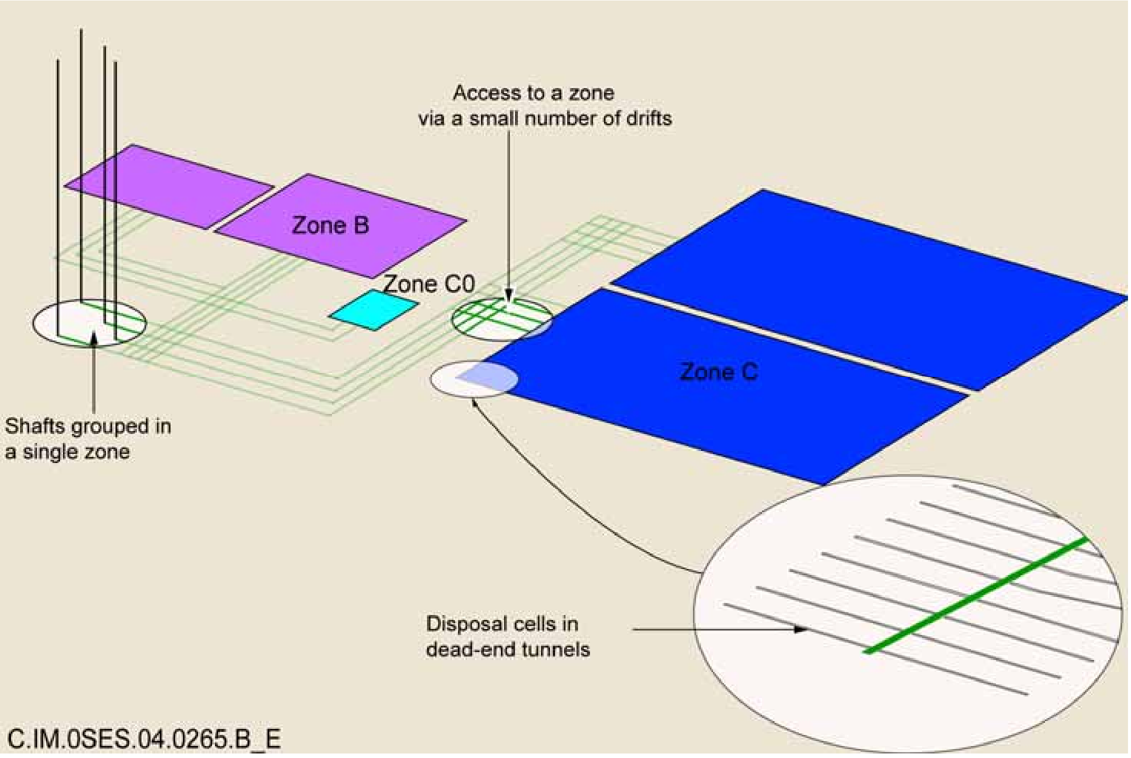


Figure 2.4.3 Principle of a series of dead-end cells

- **A favourable physical and chemical environment for waste**

The design of the disposal cells, particularly the choice of constituent materials, aims to offer a favourable physical and chemical environment to the waste packages. This intends to control their alteration over time in order to limit the release of radioactive elements in the presence of water [9].

In this respect, the concrete planned for the B waste disposal cells is a material which is favourable to the physical and chemical protection of waste and to the retention of certain radionuclides.

In the case of vitrified C waste, the use of concrete is not envisaged in the vicinity of the packages as the alkaline conditions which it would create could accelerate glass alteration. Only metallic materials have been considered.

- **Repository module separation**

The repository zones are compartmentalised to reduce the quantity of waste and radionuclides that could be affected in a failure or intrusion situation. In this respect, each repository module consisting of a cell or a group of cells can be rendered independent of the others by a sufficient horizontal distance between modules and by seals closing the access or connecting drifts.

2.4.1.2 Design, reversibility and flexibility of operation

As a result of the principle of reversibility being taken on board and research being carried out into an industrially realistic design for an installation intended to be managed on a century time scale, the repository operator is offered adaptive management flexibility.

- **Modularity of the underground installations**

The modularity of the architecture promotes flexible management of the installations. In particular, it provides potential for action on the disposal process (construction and operation by phases) and allows for the design and method of operation to be changed on the basis of feedback.

In this respect, each repository zone can be constructed and operated progressively in successive groups of cells. It is expected that these groups of structures will be constructed and filled with waste packages over a period of a few years (generally between two and four years according to the assumptions considered on the throughput of packages).

- **Durable structures and disposal packages**

Due to the principle of reversibility, preference is given to materials and design arrangements promoting the durability of the structures and the disposal packages.

- **Waste package emplacement favouring retrievability**

The waste package disposal facilities and processes are designed with the aim of simplifying any waste package retrieval operations which may be decided by future generations. Preference is notably given to the use of similar means to the ones used for emplacement. As a result, clearances for handling purposes that can be durably maintained are provided between the packages and/or between the packages and the cell walls. These clearances are minimised, however, with a view to limiting geomechanical disturbance as indicated above.

2.4.1.3 Design, personnel safety and operational safety

Operational safety considerations aim to offer the repository operator a safe strategy and techniques for the implementation of activities relating to construction, the transfer of waste packages to their disposal cell and the closure of the underground installations.

They form an important data component in the design of the access drifts. They also govern the design of equipment and processes for transferring and emplacing the packages in the cells.

- **Coactivity management**

The possibility of constructing further repository modules while the site is in operation leads to a nuclear type activity (operation) being carried out simultaneously with a civil engineering type activity (construction). To avoid interference between these two activities characterised by the throughput of materials and different types of risks, specific drifts per type of activity are opted for in the design. By specialising the drifts, transfers of vehicles, people and materials and ventilation flows can be separated. Similarly, by arranging the repository zones into successive cell subassemblies, it is possible to conduct just a single activity at any given time within each subassembly.

- **Standardised disposal packages**

The design of the disposal packages is aimed at facilitating their management and, in particular, at standardising their handling operations by eliminating the wide diversity in the primary packages that they contain, particularly in the case of B waste. Such standardisation reduces the number of handling devices and therefore makes the operating process simpler and safer. This enables the number of disposal packages to be placed in the cell to be limited to around two to ten per day, all categories of waste combined, according to the scenarios and assumptions regarding primary package throughput.

- **Waste disposal package transfer under radiological protection**

Due to their irradiating character, the waste disposal packages are transferred from the surface installations to the disposal cells by means of devices providing radiological protection for personnel (shielded transfer transfer casks). Docking systems installed at the head of the cell guarantee continued radiological protection for personnel during waste package emplacement oeperations in the disposal cell. Package handling equipment is designed in such a way that, in the event of a breakdown, assistance can be provided while still assuring this radiological protection.

2.4.1.4 Quest for compactness for the underground installations

The design and dimensioning of the underground installations are conducted with the aim of controlling the total excavated volume and the footprint of the surface stockpile. The compactness of the repository is the result of a compromise between thermal and geotechnical requirements (which give priority to small, spaced out structures), the technological requirements of disposal in cells (which limit the length of the cells) and the quest for repository module separation.

Compactness is motivated by:

- a reduction of the excavated volume, limiting implementation costs and the volume of crushed rock to be stockpiled on the surface,
- optimum use of the underground footprint in the Callovo-Oxfordian,
- simplification of the drift network, facilitating the operation.
- As a result, the principle of irradiating waste repository chambers with simple geometry has been selected for B waste, while horizontal cells, in tunnels, are preferred for C waste and spent fuel.

2.4.2 Waste disposal packages and cell design

2.4.2.1 Waste disposal packages and cells for B waste

The B waste category covers a highly diverse range of primary packages in terms of conditioning, geometry and radiological and chemical content.

The concern with simplifying operating methods has led to the design of standardised disposal packages which group together one to four primary packages in a parallelepipedal concrete container weighing approximately 6 to 25 tonnes and measuring from 1.2 to 3 metres – see section 4.1 for further details. Radiological protection is not incorporated into the container as it would require an extra thickness of concrete and adversely affect the compactness objective. The contribution of disposal package concrete to the limitation of radionuclide release in the long term has been studied for exploratory purposes [41].

The disposal cells are subhorizontal tunnels limited in length to approximately 270 metres – a detailed description is provided in section 5.1. As B waste packages are only slightly exothermic, if at all, the excavated diameter of the cells is essentially the result of the geotechnical analysis and the compactness target. It is limited to 12 metres at most.

The concrete drift liner gives the engineered structure mechanical stability. Selected first and foremost for its mechanical qualities and its durability favourable to reversibility, the liner concrete also provides chemical protection for the packages and contributes to radionuclide retention. Its inner section is a rectangular shape and delimits a repository chamber in which the packages are stacked over several levels.

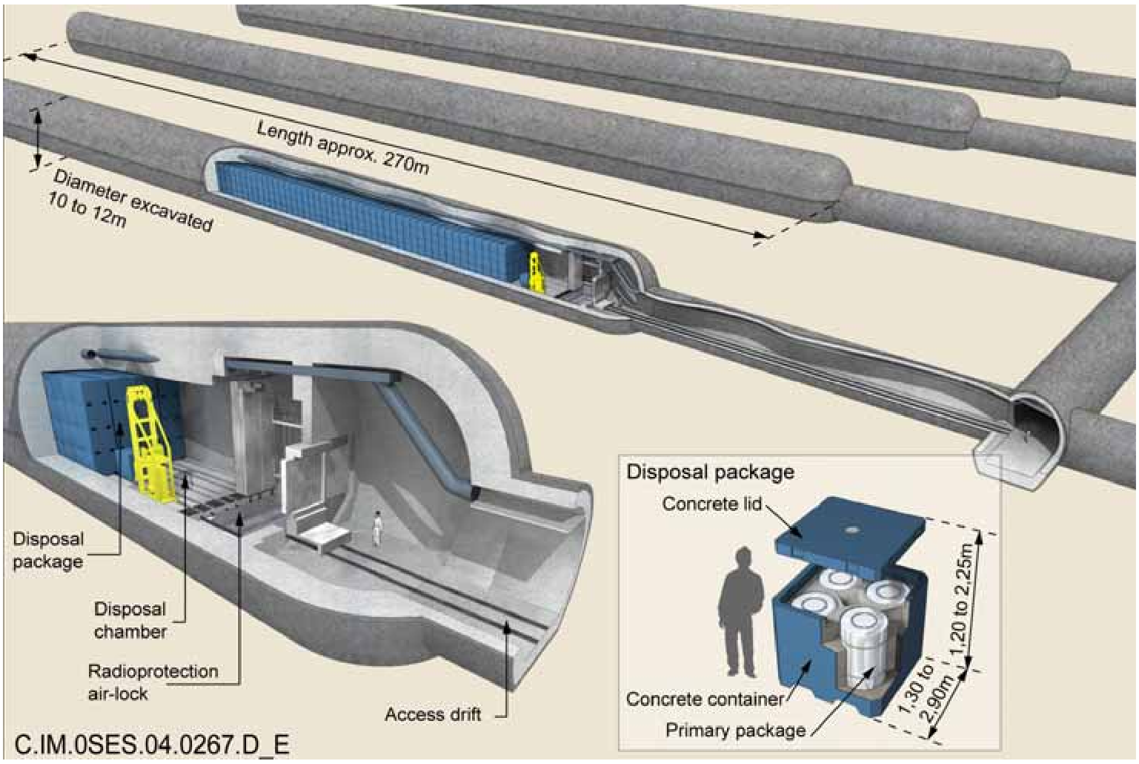


Figure 2.4.4 B waste disposal cell in operation

The repository chamber forms an irradiating volume in which packages are handled by remotely operated equipment described in chapter 9. The head of the cells is equipped with a radiological protection chamber enabling the disposal packages to be extracted from the shielded transfer casks and protecting the operators liable to be present in the access drift.

When the cell is closed, it does not appear to be necessary to fill in the gaps between packages in the repository chamber, which facilitates the closure operations and the possible future retrieval of the waste packages. Owing to the emplacement and retrieval techniques used, these gaps are limited to just 5% of the volume of the chamber. On the other hand, the volume occupied by the radiological protection chamber is filled in and the access drift is sealed with a swelling clay plug. Each B waste cell constitutes, in the long term, a module isolated from the others.

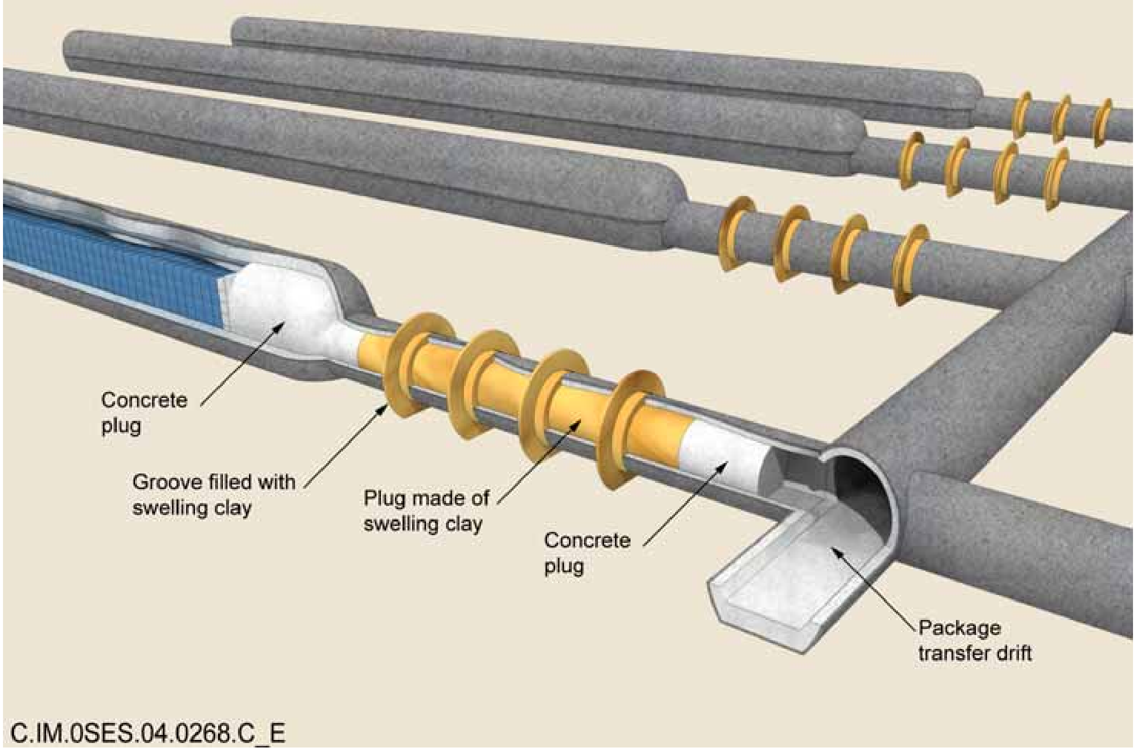


Figure 2.4.5 Sealed B waste disposal cell

2.4.2.2 Waste disposal packages and cells for vitrified C waste

To prevent the inflow of water onto the waste during the thermal phase, each primary package of vitrified waste is placed in a watertight over-pack throughout this phase. This over-pack is made of non-alloy steel with an effective thickness of 55 millimetres, dimensioned very conservatively to withstand corrosion for a thousand years. A detailed description of the over-pack is provided in section 4.2. The mass of the standard disposal package is almost 2 tonnes (package types C1 to C4).

The design of C waste disposal cells is the result of (i) the search for a physical and chemical environment suited to the packages, and (ii) the thermal design associated with heat dissipation by conduction through the rock. As a result, the thermal load per unit of surface area is limited not only on a repository scale but also on a cell scale.

C waste disposal cells are dead-end, horizontal bore-holes with an excavated diameter of approximately 0.7 metre. At this stage, their length has been limited to around 40 metres, a length considered reasonable in view of construction and handling techniques – see section 5.2. They have a metallic sleeve which supports the argillites and enables package handling for their emplacement and possible future retrieval. They contain from 6 to 22 disposal packages..

Packages characterised by moderate thermal power may be disposed side by side – this is the case of package type C0.

For packages with higher thermal power (package types C1 to C4), a conceivable storage period prior to emplacement in the repository has been determined in order to limit thermal disturbance. The duration of this storage period is 60 to 70 years depending on the package. After such a storage period, the residual thermal power of these packages still requires them to be separated by spacers in a single disposal cell. In any case, we have yet to conduct an optimisation process at this stage.

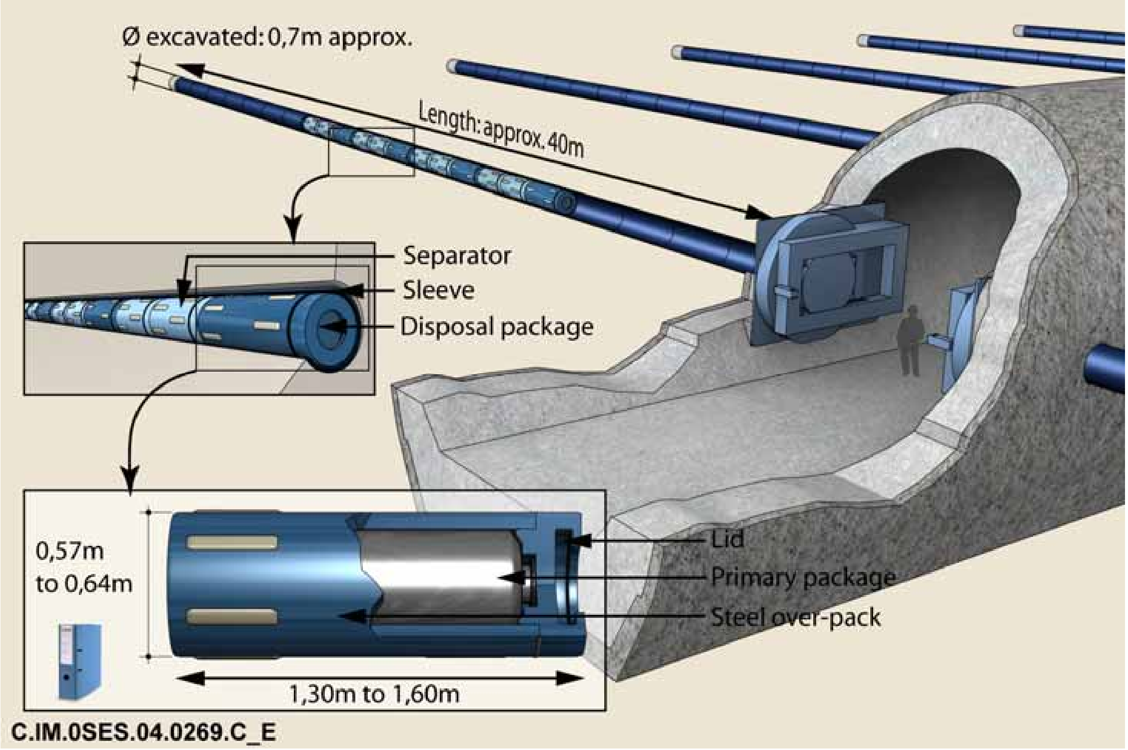


Figure 2.4.6 Vitrified C waste disposal cell

On closure, the cell is sealed by a swelling clay plug held mechanically by a concrete retaining plug.

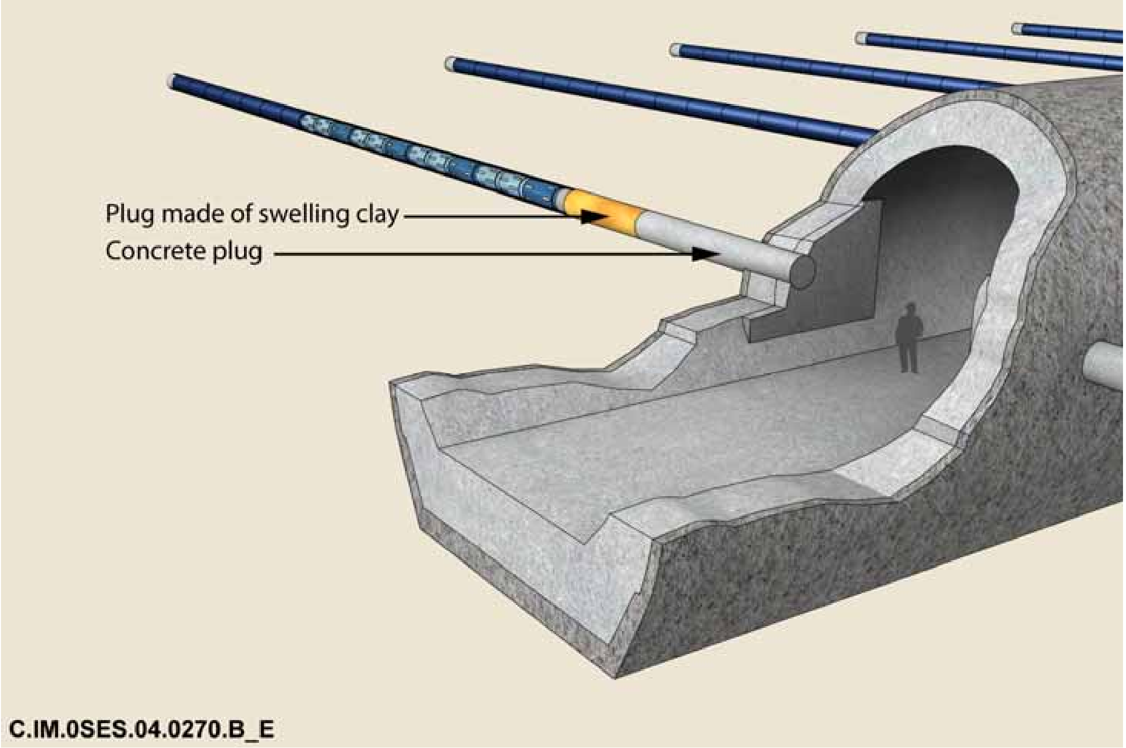


Figure 2.4.7 Sealed C waste disposal cell

2.4.2.3 Waste disposal packages and cells for spent fuel

The disposal packages designed for spent fuel comprise a cylindrical envelope of non-alloy steel. The thickness of this envelope must guarantee leaktightness during the thermal phase. For fuel types CU1 (UOX) and CU2 (MOX) discharged from electricity-generating pressurised water reactors (PWR), a minimum leaktightness period of the order of 10 000 years has been adopted. The thickness has been conservatively determined (approximately 110 mm for container CU1).

The number of assemblies in each package depends on the type of spent fuel and, in particular, the heat released – see section 4.3. For PWR fuels, the packages studied contain one (in the case of MOX – package type CU2) or four assemblies (in the case of UOX – package type CU1). Moreover, the disposal package design ensures that the risk of criticality is controlled over the various time scales. Figure 2.4.8 (inset) illustrates the largest disposal package studied (43 tonnes, outer diameter approximately 1.3 metres, length 5.4 metres).

Like C waste disposal cells, the spent fuel cell design is dependent on thermal design criteria. These cells are horizontal tunnels, some 45 metres long, in which the disposal packages are emplaced – see section 5.3. In the case of PWR fuels releasing considerable heat (1000 to 1500 watts per package after pre-disposal storage of 60 to 90 years), the disposal packages are spaced apart with spacers and each tunnel contains three of four packages.

For the design of spent PWR fuel disposal cells, the insertion of a swelling clay buffer (engineered barrier) between the packages and the geological formation has been adopted. The aim is to safeguard against uncertainties in the thermomechanical behaviour of the cell, caused by a relatively slow decrease in the heat released from the spent fuel. Where water resaturates the cell, this option enables a continuous, low-permeability medium to be formed around the packages by exploiting the capability of certain clays to swell considerably in the presence of water, and accept a high deformation rate. This barrier will limit, locally, the transport of dissolved species and thereby favour the control the physical and chemical environment of the fuel. It makes it possible to manage the uncertainties existing at this stage regarding the thermo-hydro-mechanical evolution of the argillites located in proximity during the thermal phase. The excavated diameter of the disposal cell corresponding to this configuration is around 3 metres. The engineered swelling clay barrier is provided with an axial internal sleeve to enable the introduction and possible future withdrawal of the packages.

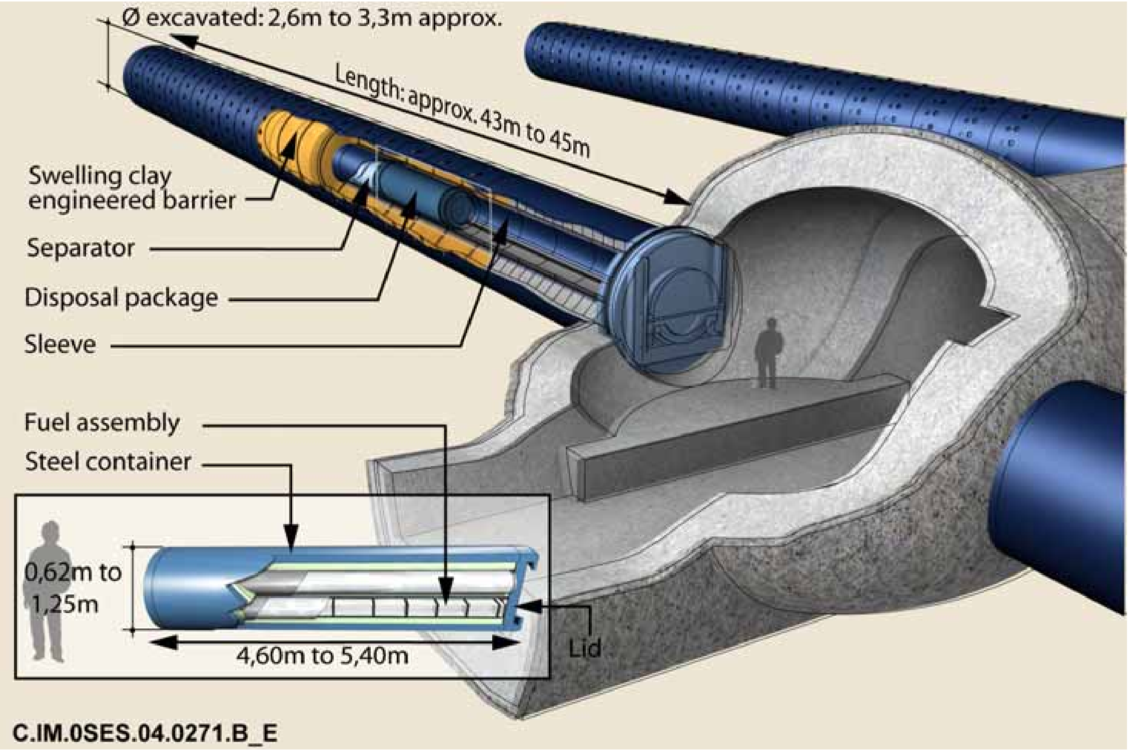


Figure 2.4.8 Spent fuel (UOX or MOX) disposal cell in operation

The spent fuel disposal cells are closed by the emplacement of a swelling clay plug held by a concrete retaining plug.

For spent fuel releasing a more moderate amount of heat (fuel type CU3), the disposal packages and cells would be similar to those described above for vitrified C waste.

It will be noted that the study of an engineered swelling clay barrier for spent PWR fuel could be transposed to C waste (and fuel type CU3).

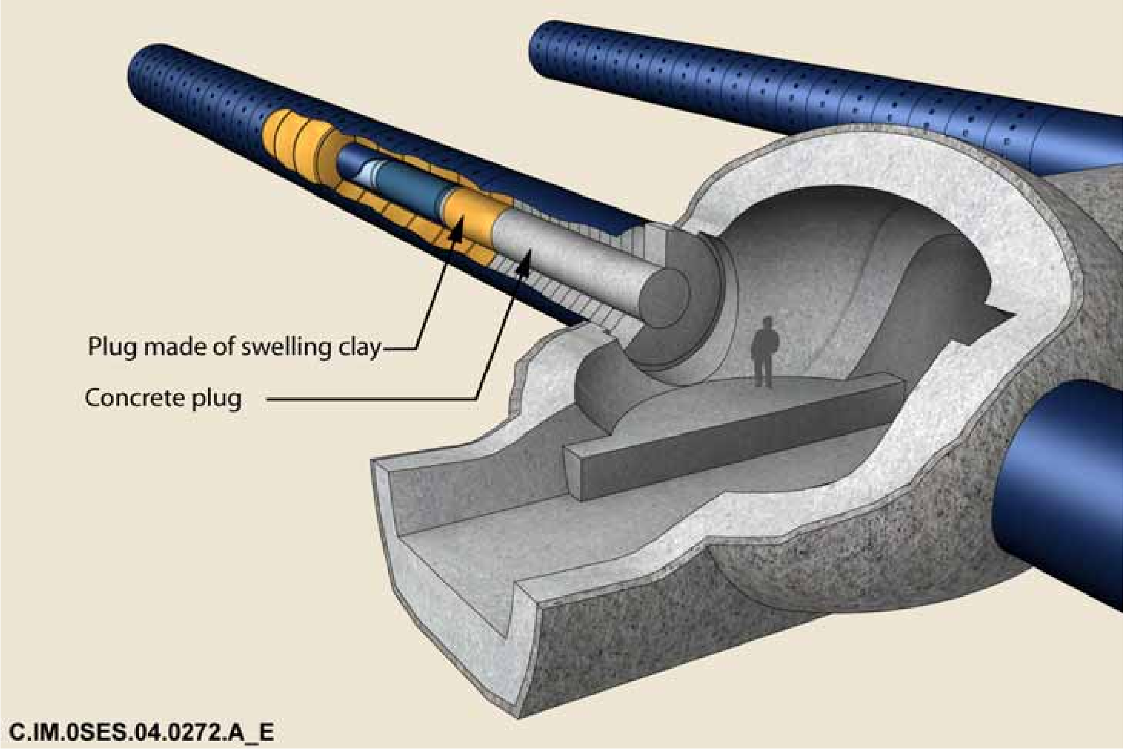


Figure 2.4.9 Sealed spent fuel disposal cell

2.4.3 Overall configuration of the underground installations

The disposal cells for the various categories of waste are organised in an overall architecture. This architecture comprises various levels formed by (i) the independent repository zones for the various categories of waste, (ii) groups of disposal cells illustrating the gradual construction of these zones, and (iii) the actual disposal cells.

Furthermore, the architecture comprises shafts and connecting drifts: these structures provide access to the repository modules for the purpose of construction in the first instance, followed by transport of the waste packages, observation and, if the decision is taken, closure.

2.4.3.1 Shafts and connecting drifts

A series of four shafts links the surface installations to the repository level in the geological formation studied (these shafts are described in detail in chapter 7):

- a personnel transfer shaft, dedicated to the transfer of personnel and small equipment, and to the inflow of fresh air into the underground installations;
- a construction shaft dedicated to the transfer of crushed rock, backfill, other materials and equipment. This shaft also forms an air inlet;
- a shaft specially allocated to the transfer of disposal packages (placed in radiation protection transfer casks) and empty transfer casks;
- an exhaust shaft for the air extracted from the underground installations.
- As a variant, a ramp is conceivable for construction, rescue or package transfer functions.

The repository modules can be accessed from the shafts via a set of structured connecting drifts. To enable waste package emplacement activities and new module construction activities to coexist safely, the connecting drifts are allocated to specific functions:

- some connecting drifts serve the construction worksites and are equipped with railway lines or tracks for plant mounted on tyres. They are designed for the transfer of worksite personnel, mining equipment, broken rocks and construction materials;
- other drifts are for the transfer of disposal packages;
- finally, some drifts are specifically dedicated to ventilation air return.

If and when a decision is taken to close the repository modules, the connecting drifts and shafts are sealed.

2.4.3.2 Repository zones

The design of the repository zones is essentially the outcome of the strategy to give the repository a modular feature. By adopting the principle of modularity, the various repository zones concerned can be made and operated in a gradual, flexible manner. This is the underlying principle for the creation of repository modules consisting of one or more disposal cells. The repository zones are also designed according to safety considerations and notably ventilation in case of fire. Finally, geotechnical considerations have led to the engineered structures being spaced apart by a distance equivalent to approximately five times their diameter to guarantee their mechanical stability.

When a decision is taken to close the repository, the various components of the repository zone (disposal cells, access drifts and connecting drifts) are sealed by means of low-permeability, swelling clay plugs and backfilled with the excavation broken rocks from the argillite formation. This process is implemented gradually in successive stages. In the long term, the seals fulfil a separating function in the repository zone.

In the B waste repository zone, a repository module consists of a single disposal cell served by an access drift oriented along the cell axis. The disposal cells dedicated to packages containing organic matter are kept away from the other cells in order to limit the impact of chemical disturbance that may be caused by alteration of this organic matter in the long term.

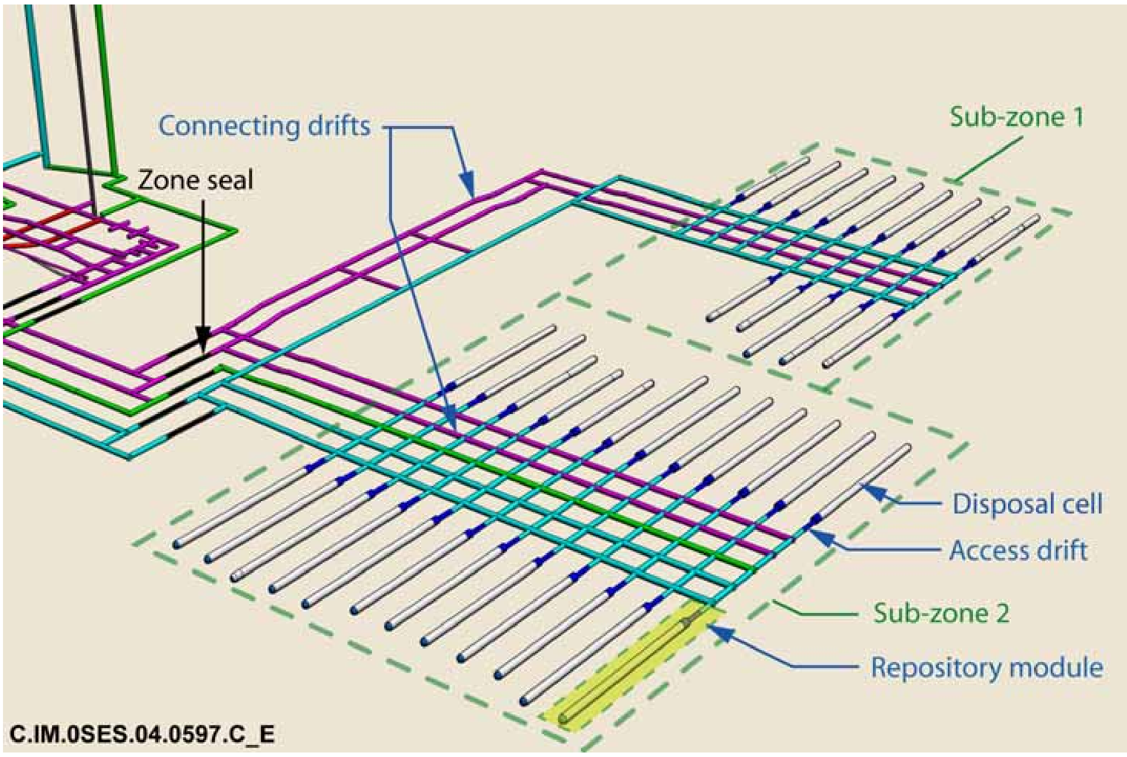


Figure 2.4.10 Organisation of the B waste repository zone

The figure above illustrates the possibility of separating the repository zone into two sub-zones according to whether they contain organic matter or not.

In the repository zone for vitrified C waste (or spent fuel), a module consists of several dozen disposal cells. The cells are served by access drifts, oriented at right-angles to the cells. The space between the cells, essentially resulting from the consideration of thermal phenomena, is designed to ensure adequate heat dissipation.

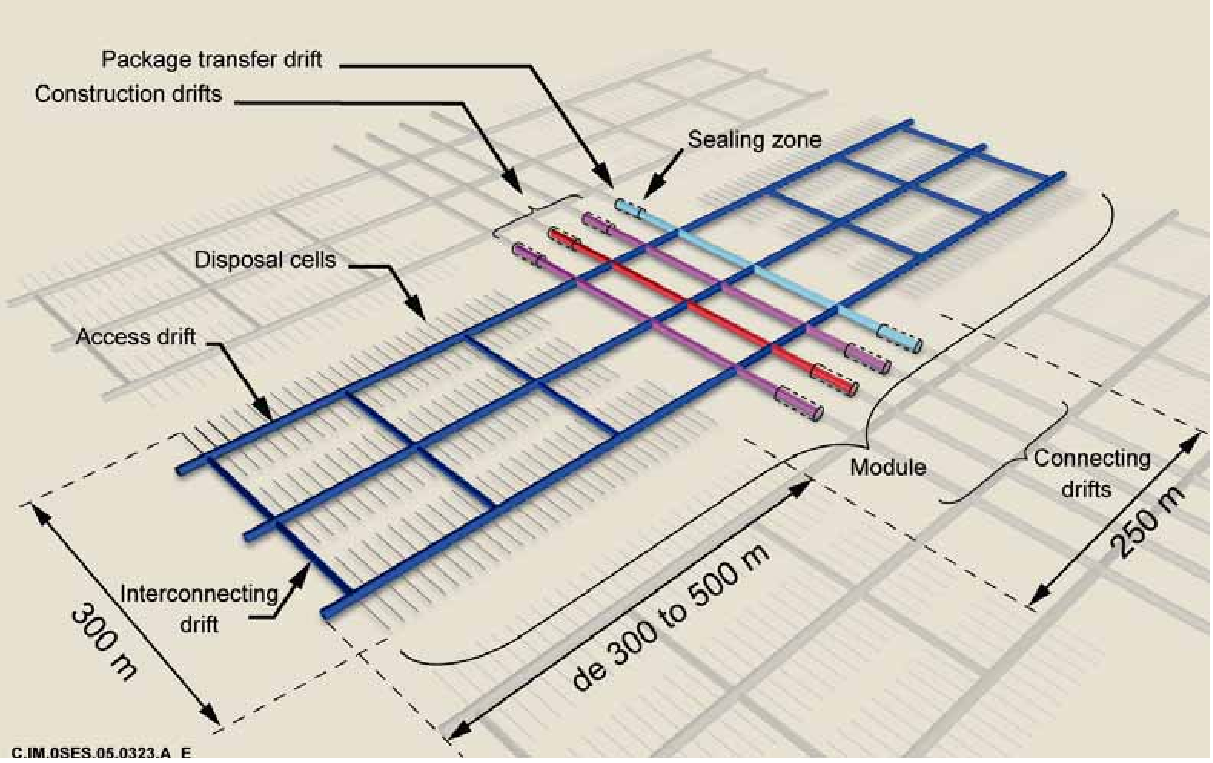


Figure 2.4.11 C waste (or spent fuel) repository module

2.5 The role of the various components of a repository

This section summarises the relationships between the components of a repository and the functions described in section 2.1, for the operation and observation of a repository, then in the long term. Through these functions, the needs fulfilled by each of the components or manufactured means described in chapters 4 to 10 are introduced. These needs will be detailed in the corresponding chapters.

In addition to the waste disposal packages and major architectural components (repository modules, connecting drifts, shafts, multiple seals and surface installations), operational means used to construct new modules, emplace the packages and manage the installations in a reversible manner are covered.

2.5.1 Role of components for the reversible emplacement of waste packages

Certain components are justified solely by the industrial operations of waste package emplacement.

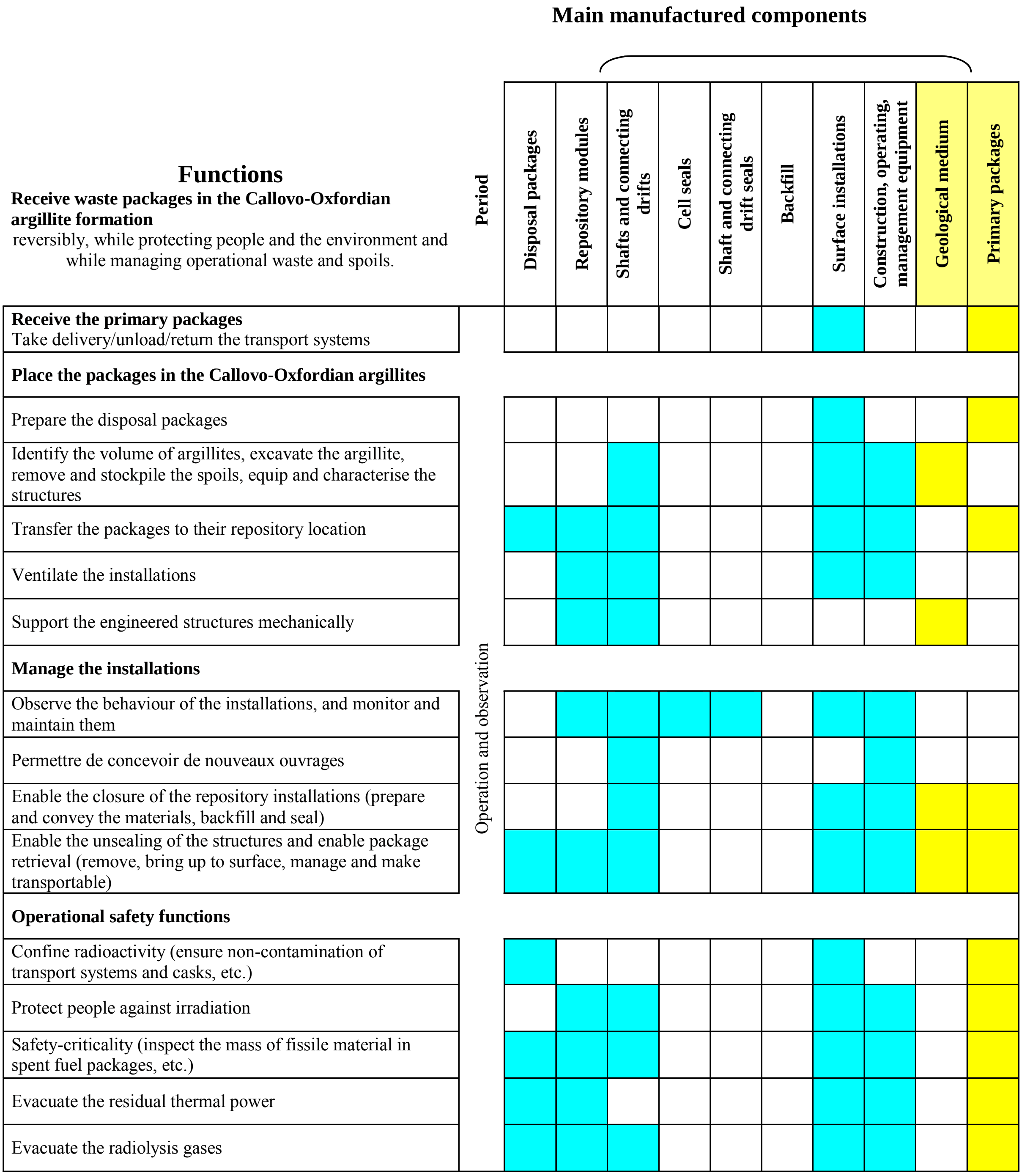
For instance, surface installations and equipment used for the construction, operation and reversible management of the installations have no long-term safety function. Surface installations should be dismantled or reused for other purposes following closure, with the possible exception of the broken rock disposal. The equipment used for the construction, operation and management of the installations will be removed where necessary on closure, so as not to affect long-term safety.

Similarly, the shafts and connecting drifts are only necessary for the construction and reversible operation of a repository. However, these components will remain after closure. If the decision is taken to close the repository, these shafts and drifts will be sealed and backfilled. Their design must therefore take account of long-term safety functions, identified in the next paragraph.

As for the waste disposal packages and repository modules, they contribute to both operational functions and post-closure safety functions.

Table 2.5.1 identifies the manufactured components of a repository which contribute to a greater or lesser extent to the various industrial functions involved in the implementation of a repository. It also identifies the functions where the study must take account of the characteristics of the geological medium or the primary waste packages.

Table 2.5.1 Emplacement of waste packages and repository components



Main manufactured components

Functions **Receive waste packages in the Callovo-Oxfordian argillite formation** reversibly, while protecting people and the environment and while managing operational waste and spoils.	**Period**	**Disposal packages**	**Repository modules**	**Shafts and connecting drifts**	**Cell seals**	**Shaft and connecting drift seals**	**Backfill**	**Surface installations**	**Construction, operating, management equipment**	**Geological medium**	**Primary packages**
Receive the primary packages Take delivery/unload/return the transport systems	Operation and observation							🟦			🟨
Place the packages in the Callovo-Oxfordian argillites											
Prepare the disposal packages								🟦			🟨
Identify the volume of argillites, excavate the argillite, remove and stockpile the spoils, equip and characterise the structures				🟦				🟦	🟦	🟨	
Transfer the packages to their repository location		🟦	🟦	🟦				🟦	🟦		🟨
Ventilate the installations			🟦	🟦				🟦	🟦		
Support the engineered structures mechanically			🟦	🟦						🟨	
Manage the installations											
Observe the behaviour of the installations, and monitor and maintain them			🟦	🟦	🟦	🟦		🟦	🟦		
Permettre de concevoir de nouveaux ouvrages				🟦					🟦		
Enable the closure of the repository installations (prepare and convey the materials, backfill and seal)				🟦				🟦	🟦	🟨	🟨
Enable the unsealing of the structures and enable package retrieval (remove, bring up to surface, manage and make transportable)		🟦	🟦	🟦				🟦	🟦	🟨	🟨
Operational safety functions											
Confine radioactivity (ensure non-contamination of transport systems and casks, etc.)		🟦						🟦			🟨
Protect people against irradiation			🟦	🟦				🟦	🟦		🟨
Safety-criticality (inspect the mass of fissile material in spent fuel packages, etc.)		🟦	🟦	🟦				🟦	🟦		🟨
Evacuate the residual thermal power		🟦	🟦					🟦	🟦		🟨
Evacuate the radiolysis gases		🟦	🟦	🟦				🟦	🟦		🟨

Key:

🟦 Contribution of a manufactured component to a function

🟨 Function where the study takes account of the characteristics of the geological medium or the primary packages

The figure below presents a simplified overview of the industrial operations of receiving, preparing and transferring the packages, followed by closing, illustrating the role of certain components in these operations.

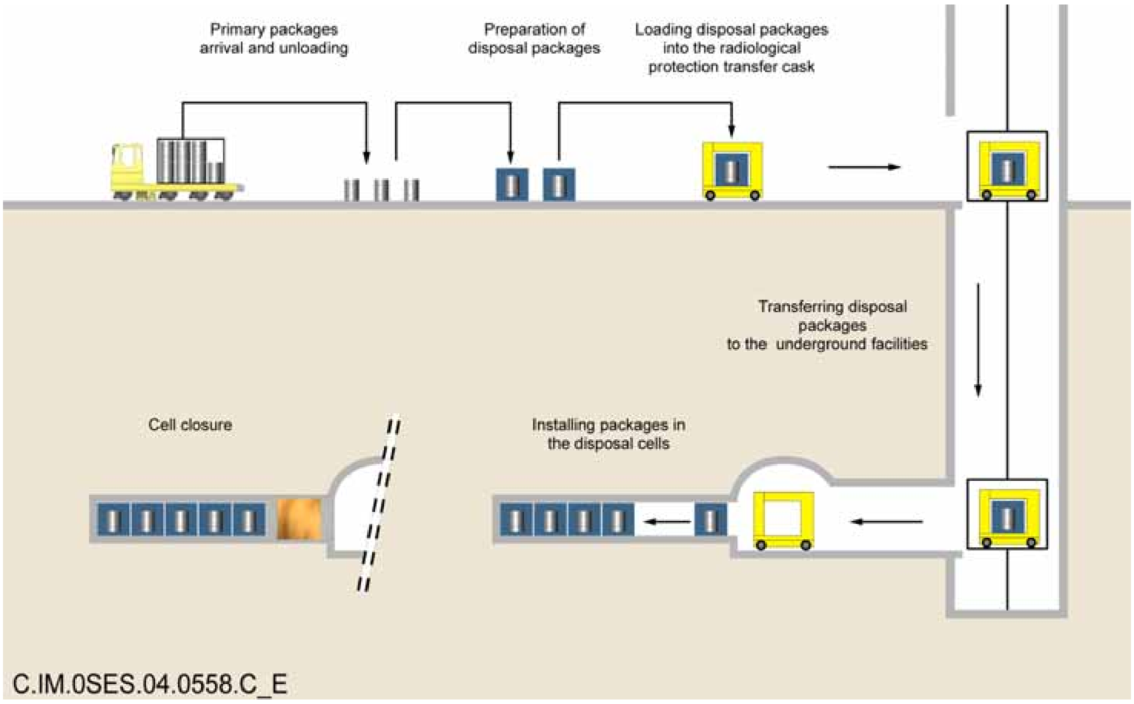


Figure 2.5.1 Overview of operation and closure

2.5.2 Role of the repository components with regard to its long-term safety functions

For the main long-term safety functions, the repository design aims to harness as far as possible the beneficial properties of the clay formation. In particular, this objective is conveyed by the architectural arrangements proposed such as, for example, installation in the middle of the geological formation and the dead-end architecture. In addition, technical arrangements are aimed at limiting disturbance in the geological environment, notably through appropriate dimensioning of the disposal packages and cells, and control of the materials introduced into these structures. Finally, manufactured components can make a more direct contribution to certain safety functions, in a complementary or redundant manner with the geological environment. This is the case, for example, of materials used in the disposal cells or to seal the engineered structures.

Table 2.5.2 identifies, for the various repository safety functions, the manufactured components which contribute to these functions, either directly or by harnessing the beneficial properties of the geological environment. It also indicates the functions where the study needs to take account of the characteristics of the geological environment or the primary waste packages. Some manufactured components are designed to carry out one function as a matter of priority, even if they can be called on for others. In such cases, their main function is identified by a cross.

Table 2.5.2 Long-term safety functions and repository components

Functions **Protect man and the environment against the dissemination of radioactive substances** by taking account of probable natural events and hypothetical situations, by protecting the environment from other impacts (chemical)		**Period**		**Main manufactured components**								
			Disposal packages	**Repository modules**	**Shafts and connecting drifts**	**Cell seals**	**Shaft and connecting drift seals**	**Backfill**	**Surface installations**	**Construction, operation, management equipment**	**Geological medium**	**Primary packages**
Isolate waste from surface erosion phenomena and ordinary human activities		After closure		🟦							🟨	
Oppose water circulation Limit water flows and circulation velocity				🟦	🟦	🟦	X				◆	
Limit the release of toxic elements and immobilise them in the repository												
B waste	Protect metallic waste from corrosion	After closure	🟦	🟦							🟨	🟨
	Protect embedding bitumen (bituminised waste): temperature, deformation, pH	All	🟦	🟦							🟨	🟨
C waste (vitrified)	Prevent inflow of water onto glass during thermal period	Thermal period	X								🟨	🟨
	Limit aqueous alteration of glass, transport of dissolved species to vicinity, pH	After closure		🟦		🟦					🟨	🟨
Spent fuel	Prevent inflow of water onto assemblies	Thermal period	X								🟨	🟨
	Limit aqueous alteration of ceramic, transport of dissolved species to vicinity	After closure		🟦		🟦					🟨	🟨
Limit the dissolution of toxic elements, ensure reducing chemical conditions			🟦	🟦		🟦					◆	
Filter the colloids				🟦		🟦					◆	
Delay and attenuate the migration of toxic elements to the environment												
Monitor migration by diffusion, retention and dispersion into the host formation		After closure		🟦	🟦	🟦					◆	
Delay the migration of toxic elements into the engineered components		All	🟦	🟦		🟦					🟨	
Preserve the capacity of natural dispersion into surrounding geological formations		After closure									🟨	
Preserve the beneficial properties of the geological medium												
Limit mechanical deformation in the Callovo-Oxfordian argillites		All	🟦	🟦	🟦	🟦	🟦	X			🟨	🟨
Dissipate heat (essentially vitrified C waste and spent fuel)			🟦	🟦							🟨	🟨
Protect disposal modules from chemical disturbance caused by the alteration of certain packages				🟦		🟦	🟦				🟨	🟨
Remain sub-critical (spent fuel, vitrified C waste type C4, B waste types B3/4/5)			🟦	🟦								🟨
Separate the repository modules				🟦			🟦					🟨

Key:

🟦 Contribution of a manufactured component to a function

X Main function of a component

◆ Function harnessing a beneficial property of the geological medium

🟨 Function where the study takes account of the characteristics of the geological medium or the primary packages

3

High-level long-lived waste

This chapter describes the primary waste packages that are considered for the geological repository feasibility study. It draws particular attention to their diversity. It is based on the results of the work carried out jointly between Andra and the producers concerning (i) surveying, and (ii) collecting and structuring the knowledge.

Firstly it sets out the waste production scenarios underpinning the inventory considered. The survey of existing waste is based on knowledge of past and present processes, production reports for each facility, identification of storage sites and control of their contents. In considering future waste, hypotheses have been formulated concerning the continuation of production by the various facilities. For waste from nuclear power plants, several scenarios have been selected to cover the various possible situations: ongoing reprocessing of spent UOX fuels consistent with current industrial practice, reprocessing of URE and MOX fuels, possible increase in the heat rating of vitrified C waste and the exploratory hypothesis of direct disposal of UOX, URE and MOX fuels.

This chapter then sets out the primary waste package characteristics for each existing or planned family surveyed, on the basis of the relevant knowledge collected by the producers.

It also provides an inventory model [3] which forms the basis for constructing all the design and dimensioning studies for the repository. The model brings together all the various waste families by defining "waste packages types" covering each a more or less important range, varying in extent, of primary waste packages. The notion of waste package types is an essential element structuring the technical options considered in response to the diversity of primary waste. It is therefore a key to reading the following chapters.

Finally, the chapter sets out the hypotheses concerning waste disposal volumes over time for various scenarios.

3.1 Waste production: the study scenarios

The activity sectors producing the greatest volume of waste studied come within the nuclear power industry (EDF electricity-generating reactors, COGEMA fuel reprocessing plants, MELOX plant producing MOX fuels) or research and national defence activities (CEA centres).

The study must also consider waste produced upstream of the cycle, during uranium ore processing operations, and end-of-life radioactive objects from various industrial and medical activities.

Currently, spent fuels removed from pressurised water reactors (58 of these are currently operated) are reprocessed in the La Hague plants, except for URE and MOX fuels, prepared from reprocessed uranium and plutonium respectively, which at present are stored in pools [39].

Reprocessing operations produce various types of waste, either directly resulting from spent fuels (fission product solutions and minor actinides, fuel assembly cladding waste), or linked to the use of facilities for maintenance operations (technological waste resulting from replacement of parts and other equipment) or radioactive effluent treatment (sludge). Currently, wastes are conditioned in-line in the UP2-800 and UP3 plants at La Hague. In previous-generation plants (UP2-400 at La Hague and UP1 at Marcoule, now shut down), where fuels from various reactor generations were reprocessed, especially the first-generation NUGG (Natural Uranium-Graphite-Gas), part of the waste was stored in unconditioned form in specific facilities. However, with the exception of Umo solutions currently stored at La Hague (see Section 3.2.2.1), it should be noted that all fission product solutions, as well as effluent sludge at Marcoule, have been conditioned.

In addition, the operation of electricity-generating nuclear reactors requires systems for starting up and controlling the reactors. After a certain time these are replaced and become waste. This mainly concerns neutronic poison and control rod assemblies and, to a lesser extent, waste such as source clusters and metal parts (thimbles and pins for example). All waste currently produced is stored in pools close to the reactors.

Research carried out at the CEA, especially on behalf of the French nuclear power programme, and the routine operation and maintenance of its facilities, are other sectors that have produced a wide range of waste. Most of this waste, made up of intermediate-level solid and liquid effluent waste, has been conditioned using immobilisation materials and packages of various types and geometry.

Finally, activities linked to national defence produce intermediate-level technological waste.

For the repository studies, the package inventory (in terms of type and quantity) includes all waste already produced as well as waste that may be produced through operating existing nuclear facilities. With regard to future production, this implies the need to formulate waste production and conditioning hypotheses, especially concerning management of nuclear power plants.

Currently 58 pressurised water reactors, commissioned between 1977 and 1999, are operated to produce electricity. The tonnage of nuclear fuels removed from these reactors over their total operating period is estimated at 45,000 metric tons of heavy metal (tHM). This estimation is based on a combination of hypotheses concerning (i) the average lifetime of units (forty years), (ii) power production (16,000 terawatt-hours total production), (iii) the gradual increase of the "burnup" ratio of fuels in the reactors[18]. The fuel types considered and the corresponding average burnup ratio is as follows:

- three generations of uranium oxide fuels: UOX1, UOX2, UOX3, irradiated respectively at 33 gigawatt-days per metric ton of fuel (GWd/t), 45 GWd/t and 55 GWd/t, on average;
- fuels containing recycled uranium (URE) irradiated on average at 45 GWd/t;
- mixed uranium oxide and recycled plutonium oxide fuels (MOX) irradiated at 48 GWd/t on average.

On this basis, four nuclear fuel management scenarios were selected for the studies. The principle behind these scenarios is to include various possible industrial strategies without singling out any of them for special priority. This process makes it possible to consider a very wide range of waste types and examine the technical aspects of the various packages.

The first three scenarios, designated as S1a, S1b and S1c, correspond to continued reprocessing of spent fuels removed from EDF reactors. Scenario S1a supposes that all these fuels (UOX, URE and MOX) are reprocessed. This scenario includes the hypothesis of incorporating fission product mixtures and minor actinides from UOX and MOX fuels in glass. Also, for study purposes, it is assumed that a very small part of the plutonium from reprocessed UOX fuels is incorporated in some packages. This scenario therefore covers a variety of vitrified C package typologies. In scenarios S1b and S1c, MOX fuels are not reprocessed, allowing the hypothesis of their direct disposal to be explored. Scenarios S1b and S1c have been separated in order to study, in scenario S1b, the possibility of increasing the waste concentration in glass, compared with the packages currently produced; this greater concentration would result in a slightly greater release of heat from the packages. Finally, a fourth scenario, designated as S2, which supposes that reprocessing is stopped, is used for the exploratory study of direct disposal of UOX and URE fuels, as well as the MOX fuels considered in scenarios S1b and S1c. In this scenario the fuels are considered to be waste, which, we should recall, is not the case at present.

To be able to estimate the quantity of waste produced, scenarios S1a, S1b and S1c are based on the following distribution of various types of fuels removed from existing reactors: 8,000 tHM of UOX1 (33 GWd/t), 20,500 tHM of UOX2 (45 GWd/t), 13,000 tHM of UOX3 (55 GWd/t), 800 tHM of URE (45 GWd/t) and 2,700 tHM of MOX (48 GWd/t). In scenarios S1b and S1c, the direct disposal study concerns all the 2,700 tHM of spent MOX fuels.

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[18] The burnup of a nuclear fuel assembly expresses the energy produced in the reactor by the fissile material that it contains (uranium oxide or mixture of uranium and plutonium oxides)

Scenario S2 takes the hypothesis that reprocessing of some of the UOX fuels will continue until 2010 (8,000 tHM of UOX1 and 8,000 tHM of UOX2), but will cease after this date. Suspending the recycling of uranium and plutonium changes the overall distribution of the types of fuel removed from the reactors. Direct disposal of non-reprocessed fuels will then involve 29,000 tHM, including 12,500 tHM of UOX2, 14,000 tHM of UOX3, 500 tHM of URE and 2,000 tHM of MOX.

As stated in Chapter 2, the studies concern conditioned waste. Conditioning processes have therefore been defined for existing unconditioned waste as well for future waste. The hypotheses adopted take the industrial processes currently implemented by the producers: vitrification, compaction, cementation and bituminisation.

The scenarios considered also allow a robust approach for the repository study in light of possible management changes downstream of the cycle.

In addition to these scenarios, the question of management of spent fuels from French reactors other than the EDF's pressurised water reactors (especially research and military reactors) was also considered. In all events, their reprocessing will only produce a marginal quantity of waste compared with the waste from reprocessing EDF fuels. For exploratory purposes, the possibility of direct disposal of these fuels was given special attention, without predicting the choices concerning their management.

3.2 Description of the primary waste packages

After surveying the types of waste and defining their conditioning process, a large variety of primary package families emerge (61 in total). They differ from one another in their chemical and radiological content, heat rating and radiation level which depend on the presence of certain radionuclides, the type and geometry of their package and their quantity.

This section describes these various primary packages. In addition to making the basic distinction between category B waste (intermediate-level long-lived waste generating little or no heat), category C waste (vitrified high-level waste) and spent fuels, the packages are grouped according to the similarity of the disposal problems they present.

3.2.1 Primary B waste packages

The survey of existing and forecast B waste reveals a wide diversity of types of waste, depending on its source and the processes that produced it.

The following paragraphs provide a description of these types of waste and their actual or predicted conditioning processes. From here on, wastes have been grouped essentially on the basis of their type and conditioning method, into the following seven sets: activated metal waste from nuclear reactors, bituminised liquid effluent treatment sludge, cemented or compacted technological waste, cemented or compacted cladding waste, cladding and technological waste in drums, sources, and radium- and americium-bearing waste.

3.2.1.1 Activated metal waste from nuclear reactors

The first set of B waste comes directly from electricity-generating reactors. This is operating waste from the existing pressurised water reactors (PWR) and activated waste from the SUPERPHENIX fast neutron reactor.

PWR neutronic poison and control rod assemblies represent more than eighty percent of the total weight of activated waste. Each assembly contains twenty-four fuel rods suspended from a support system which fits into the locations left for this purpose in the fuel assemblies (see Figure 3.2.1).

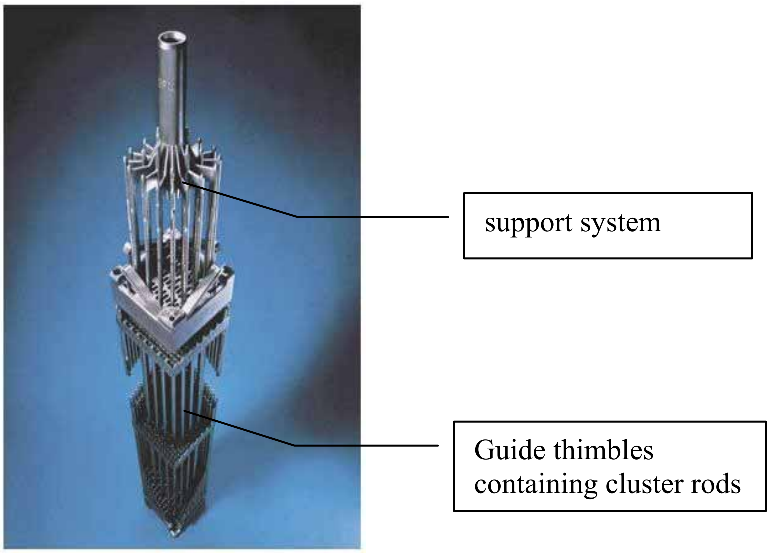

Figure 3.2.1 *PWR fuel assembly with its rods*

The neutronic poison rods are used during reactor start-up (first operating cycle) to control excess reactivity due to the use of entirely new fuel; they are removed during the following cycles and therefore become waste. The control rods are used to control the reactor power level and its immediate shut-down if necessary. They are replaced after several cycles in the reactor and also become waste.

Some rods contain neutron-absorbing materials: boron, in the form of PYREX glass for the neutronic poison rods, boron carbide (B_4C) and/or an alloy of silver, indium and cadmium (SIC) for control rods. The number of rods containing these materials depends on the reactor.

Other activated wastes from PWRs include metal waste, mainly dead-end tubes, known as core instrumentation system (CIS) thimbles fitted on the underside of the reactor vessel. These tubes are used to insert the neutron probes required to control the nuclear reaction. They are replaced, if necessary, after a certain period of use and then become waste.

These various types of reactor operation waste have specific chemical and radiological characteristics distinguishing them from other types of B waste. Their specific chemical nature is due to the nature of the materials making up some of the waste. More specifically, control rods add significant quantities of SIC alloys and B_4C, whereas other types of B waste generally contain none of these. The radiological activity is due solely to activation products formed by neutronic activation of the elements and impurities contained in the waste materials during their time in the reactor. These activation products are located inside the materials and are therefore unlikely to be dispersed. Among them, the activation products that contribute most to the radioactivity of the waste are, in decreasing order, nickel 63 (^{63}Ni) which is a long-lived isotope (half-life 100 years), then iron 55 (^{55}Fe) and cobalt 60 (^{60}Co) which are short-lived isotopes.

The high radioactivity of ^{60}Co has thermal consequences. This waste therefore belongs to category B, with the highest heat rating in relative terms (roughly 20 Watts per package when the packages are produced, taking the conditioning hypotheses set out below). Since this is largely due to cobalt, the residual heat rating of the package drops rapidly as the cobalt decays. As an illustration, the heat rating is divided by 2 after 5 years of cooling, by 3.5 after 10 years of cooling and by 6 after 15 years of cooling. Another consequence of this radiological inventory is the high level of radiation of the packages. Thus, the equivalent ß-γ dose rate in pseudo-contact with the package (i.e. at a distance of 5 centimetres) is roughly 50 sieverts per hour (Sv/h), at the time of its production. This is mainly attributable to ^{60}Co, but also to silver-108m (^{108m}Ag) whose half-life is 420 years, and remains at a relatively high level even after 10 years' cooling (around 15 Sv/h).

The conditioning hypothesis considered in the study [19] is compaction of the waste placed in holders[20], then transfer to small sizes stainless steel containers known as "Standard Compacted Waste Containers" (CSD-C) (see Figure 3.2.2).

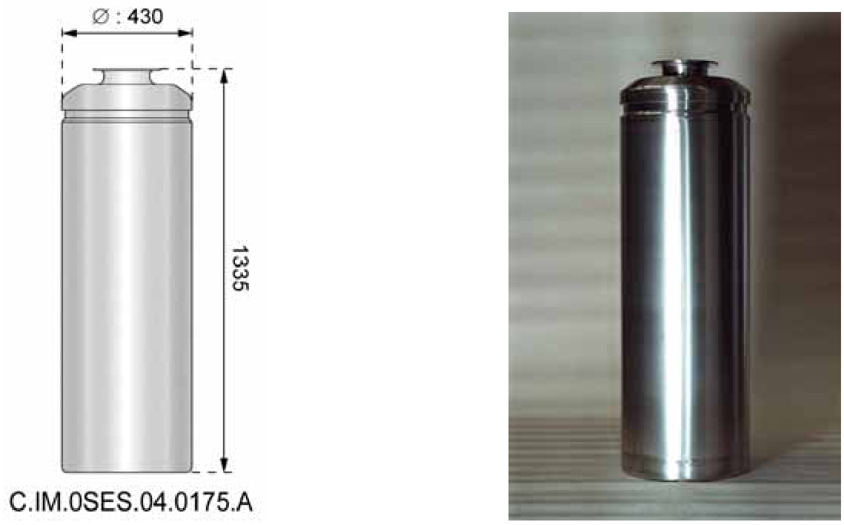

Figure 3.2.2 Standard compacted waste containers (CSD-C)

The conditioning hypothesis assumes a weight of 400 kilograms of waste per package, made up of a mixture of different types of activated waste in the following proportions: 5% neutronic poison rods, 78% control rods and 17% various metal wastes. The weight of the finished package is around 510 kilograms.

It should be noted that these pakages contain no organic materials and are not liable to produce gas (hydrogen) by radiolysis.

3.2.1.2 Bituminised liquid effluent treatment sludges

The second group of B wastes comes from radioactive liquid effluents resulting from the operation of fuel reprocessing facilities. The effluents considered here are generated at various stages of fuel reprocessing and during work carried out on equipment and facilities (decontamination, flushing). These effluents are collected in treatment stations where they are decontaminated by chemical processes before discharge. The residual waste is then recovered in the form of sludges.

In the STEL effluent treatment station at Marcoule and STE3 at La Hague, opened in 1966 and 1989 respectively, this sludge has been conditioned by embedding in bitumen, which is then put in carbon steel drums. On the other hand, sludges from effluents produced and chemically treated at La Hague STE2 (Effluent Treatment Station No. 2) from 1966 to 1990 have been gradually stored in tanks and silos at the plant, awaiting conditioning. The planned conditioning method for these sludges is also embedding in a bitumen matrix.

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[19] An alternative conditioning mode, not dealt with here, is being studied at EDF

[20] Large rods and CIS thimbles are cut into sections before being placed in compaction holders

The bitumen-embedded materials consist of dry extract, obtained by drying the sludge, 70/100 refinery bitumen, surface-active additive, and a small quantity of residual water. The average composition of the embedded waste, expressed as percentage weight, is as follows:

- Dry extract of sludge: 39% of the weight of the embedded waste. This dry extract is itself made up of a mixture of insoluble and soluble salts, in proportions that vary according to the source of the sludge;
- Bitumen: 58% of the weight of the embedded waste;
- Surface-active agent: 1% of the weight of the embedded waste;
- Water: 2% of the weight of the embedded waste.

The radioactivity of the waste comes from traces of activation products, fission products and actinides evenly distributed in the mass of the embedded waste. Among these, short- or intermediate-lived radionuclides represent a large part of the radioactivity of the packages. However, they release much less radiation that those described in the previous paragraph: the equivalent ß-γ dose rate in pseudo-contact with the package is one sievert an hour at most. As a result of their relatively low radioactivity, they do not release heat.

The specific nature of these packages derives mainly from the chemical nature of the conditioned waste, which contains a high load of salts and organic matter. Radiolysis of bitumen and of water results in the production of gases, mainly hydrogen, as well as traces of carbon monoxide and dioxide and methane (for hydrogen produced through bituman radiolysis, 1 to 2 litres[21] per year, for STE3 and STEL packages, 9 to 10 litres a year for STE2 packages).

Another difference is that the bitumen-embedded packages do not all have the same geometry. A first group, representing 45% of the inventoried packages, consists of stainless steel primary drums of 238 litres (STE3/STE2) and 245 litres (STEL from October 1996 onwards). These packages are illustrated in Figure 3.2.3.

238-litre stainless steel drum (STE3/STE2)

245-litre stainless steel drum (STEL)

Figure 3.2.3 STE3/STE2 and STEL stainless steel drums

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[21] At atmospheric pressure

The second group of packages (55% of the inventoried bitumen packages) consists of 428-litre stainless steel drums, also known as "EIP" overdrums[22]. These drums (see Figure 3.2.4) are used as overdrums for primary non-alloy steel drums produced at the STEL between 1966 and October 1996.

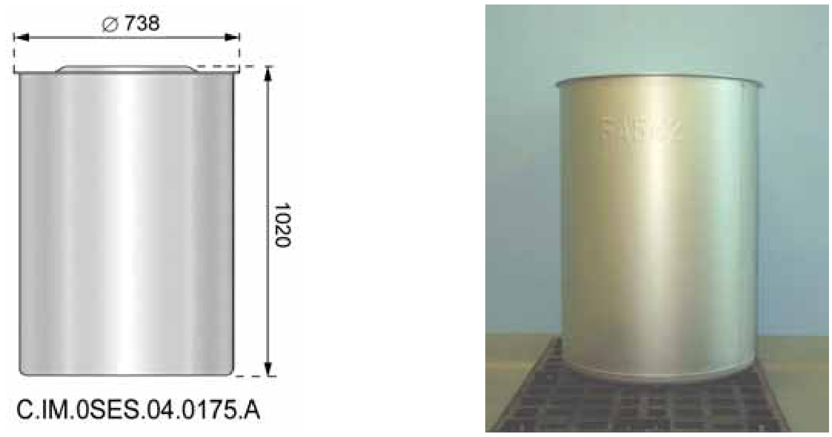

Figure 3.2.4 Stainless steel drum used as overdrum for primary non-alloy steel drums

The study takes the hypothesis that the interstitial gap between the two drums is completely filled with a non-compressible material, such as mortar, in order to limit the long-term mechanical deformation in the repository.

On average, the weight of conditioned waste per package is 220 to 240 kilograms, including roughly 90 kilograms of dry extract and 130 kilograms of bitumen. The average weight of the finished packages is 240 kilograms for STE3/STE2 and STEL packages and 330 kilograms for STEL packages with overdrum.

3.2.1.3 Cemented or compacted technological waste

A third group of waste is technological waste resulting from the operation and maintenance of nuclear facilities by COGEMA and the CEA. This consists mainly of various kinds of solid waste (various metals, organic materials), but also includes filtration sludges and evaporation concentrates. This group also includes various waste produced at Marcoule such as graphite, ion-exchanger resins and zeolites. The radiological activity of waste, especially of technological waste, is usually due surface contamination of the waste by fission products and/or activation products and/or actinides.

The conditioning process for this waste depends on its production site and/or its type. The problems posed by these waste packages are therefore linked essentially to the diversity (i) of their chemical content, itself linked to the type of waste and the conditioning matrices used, and (ii) of container shapes and materials. The chemical nature of some packages also makes them liable to produce gases, chiefly hydrogen, by radiolysis. These packages do not generate heat.

The various existing and planned technological waste packages can be grouped into nine subsets, taking into account the types of waste, the conditioning processes and the containers.

A first subset of these packages comprises 1000-litre concrete containers, manufactured by the CEA, containing low-contamination sludges, debris, earth and sands immobilised in a cement-bitumen matrix. Following degradation, some of these concrete containers have been installed in non-alloy steel containers (see Figure 3.2.5). These two package shapes are considerably larger than those described in earlier paragraphs; on average, they weigh around 3.2 metric tons. There are very few of these packages (90 in total). As a precaution, with no precise data available, the possibility of hydrogen production by radiolysis of the matrix water was considered.

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[22] The French term EIP, meaning multipurpose storage, refers to the storage facility set up at the Marcoule site which will eventually contain all the B waste packages of this site.

Figure 3.2.5 Non-alloy steel container used as overdrum for 1000-litre concrete containers

A second subset of packages, from the COGEMA La Hague site, contains technological or pulverulent waste consisting of a mixture of resins, zeolites, diatoms and graphite, conditioned in a cement matrix inside cylindrical fibre-reinforced concrete containers, known as CBF-C'2 (see Figure 3.2.6). It should be noted that technological waste was conditioned between 1990 and 1994 in asbestos-cement containers, which were replaced from 1994 onwards by fibre-reinforced concrete containers. Both types of container have the same geometry. The weight of the finished containers varies from 1.5 to 3 metric tons, with an average of around 2.4 metric tons. The technological waste is made up of metal or organic materials. The equivalent ß-γ dose rate in pseudo-contact (5 cm) with the packages is around 0.5 Sv/h, for the packages releasing the most radiation. For these packages, production of hydrogen by radiolysis of the organic matter and cement matrix water is taken into account; this production is from 1 to 2 litres[23] a year.

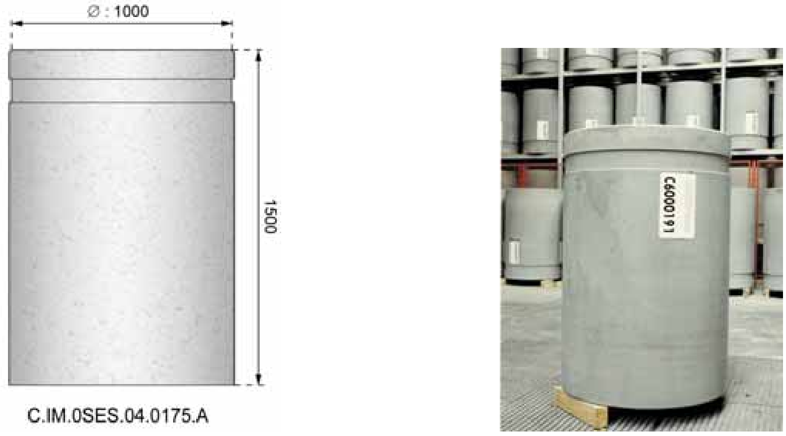

Figure 3.2.6 Cylindrical fibre-reinforced concrete container (CBF-C'2)

A third subset of packages, manufactured by the CEA, consists of 1800-litre concrete containers filled with various metallic and organic waste conditioned in a cement-bitumen matrix or in mortar. All of these packages were produced between 1964 and 1987: 25% of the concrete containers have been repaired (resurfacing) and following degradation 75% have been installed in non-alloy steel containers (see Figure 3.2.7). These packages are also very large.

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[23] At atmospheric pressure

Figure 3.2.7 Non-alloy steel container used as overdrum for 1800-litre concrete containers

The weight of the packages varies from 2.7 metric tons to 6.8 metric tons. The number of these packages is still low (180 in total). As with the previous subset, potential production of hydrogen by radiolysis of the organic matter and matrix water also needs to be considered. It is important to note that these packages do not release radiation; they can therefore be handled with operators present.

A fourth subset of packages, manufactured by the CEA, comprises drums of filtration sludges (still being produced) or of cemented evaporation concentrates (production stopped), conditioned in 500-litre concrete containers (see Figure 3.2.8). As things currently stand, this packaging process is taken as the reference hypothesis for the drums produced at the CEA Valduc centre containing either sludges, concentrates or a mixture of cemented sludges and concentrates. It should be noted that the use of mortar to immobilise waste drums in concrete containers was stopped 1996.

The weight of the finished packages varies from 770 to 920 metric tons.

As with the waste referred to in Paragraph 3.2.1.2 (bituminised sludge), these packages differ from the other technological waste packages by the chemical nature of the conditioned waste, especially the presence of salts. Once again, potential production of hydrogen by radiolysis of the matrix water has to be considered. These packages, like those of the previous subset, do not release radiation.

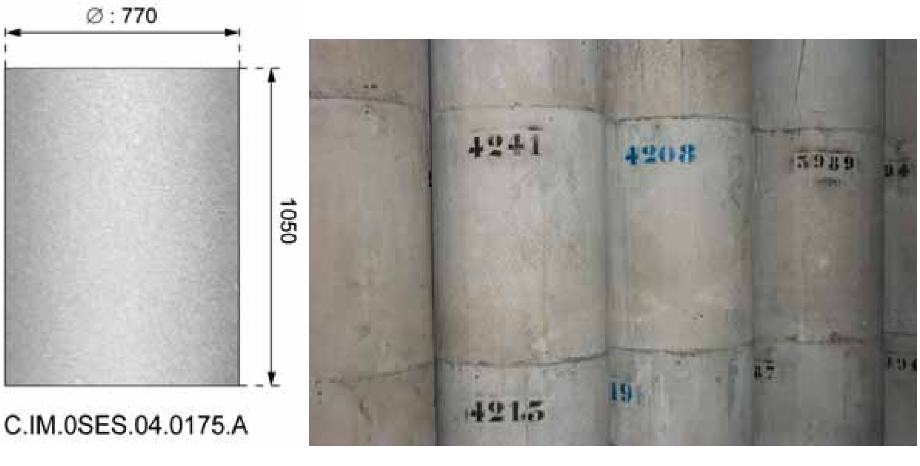

Figure 3.2.8 500-litre concrete container

A fifth subset of packages consists of solid waste and sludge that will be conditioned in the future CEDRA and AGATE facilities of the CEA. The hypothesis currently adopted is conditioning of the waste in CBF-C'2 fibre-reinforced containers. It is also supposed that mortar will be used to immobilise the waste in the containers. As a precaution, the potential hydrogen production by radiolysis of water in the mortar is considered. Once again, these packages do not release radiation.

A sixth subset of packages contains various technological waste, known as alpha waste, mainly contaminated by plutonium during the manufacture of MOX fuels or reprocessing of spent fuels (especially for the conditioning of plutonium). The most representative waste, in terms of nature and flow, is waste from the manufacture of MOX fuels in the MELOX plant (Marcoule). This is composed of organic waste, filters and various predominantly metallic waste from glove boxes. The planned conditioning process is compaction of the waste then transfer to standard compacted waste containers (CSD-C) in the ACC shop of the La Hague plant. The exact mixture of the waste mentioned above in the packages depends on the hypotheses selected. The average weight of the finished packages is 635 kilograms. As with other containers, the presence of organic matter in the packages means that the production of hydrogen by radiolysis of this matter must be considered. These packages do not release radiation.

A seventh subset of packages contains pulverulent waste from the COGEMA plant at Marcoule. The waste comes either from the water filtration systems (ion-exchanger resins, zeolites, diatoms and pool sludge), or from mechanical processing of fuels (graphite). The planned conditioning method is embedding in a cement matrix and transfer to 428-litre stainless steel drums (EIP drums: see Figure 3.2.9). The exact mixture of the waste mentioned above in the drums depends on the hypotheses selected. The average weight of the finished packages is 720 kilograms. Potential production of hydrogen by radiolysis of the water in the matrix concrete must be taken into account. The equivalent ß-γ dose rate in pseudo-contact (5 cm) with the packages is low at roughly 0.05 Sv/h.

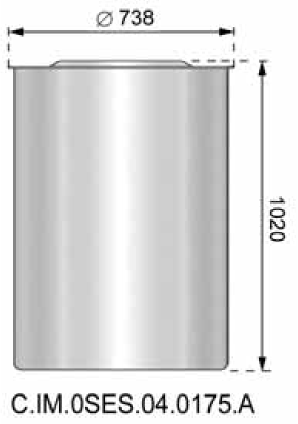

Figure 3.2.9 EIP stainless steel drum

An eighth subset of packages, manufactured by the CEA, contain intermediate-level solid technological waste from shielded cells, mainly contaminated with ß-γ emitters. The waste is conditioned in compacted form in 500-litre steel containers (see Figure 3.2.10). It should be noted that changes have been made since the packages were first produced, concerning (i) the conditioning matrix used to immobilise the waste in the containers: intially a cement-bitumen matrix, then from 1990 a cementitious material, (ii) the material used for the container: the non-alloy steel used initially was replaced by stainless steel from 1994.

Figure 3.2.10 500-litre stainless steel container

In this subset, the waste consists of various materials, especially metals, organic matter and glassware, mixed in the same package. The average weight of the finished packages is 925 kilograms for those immobilised by a cementitious material and 850 kilograms for a cement-bitumen matrix. Given the chemical content of the packages, potential production of hydrogen by radiolysis of the organic matter and conditioning matrix water also needs to be considered. The equivalent ß-γ dose rate in pseudo-contact (5 cm) with the packages is roughly 0.2 Sv/h.

The ninth and last subset of technological waste packages, manufactured by the CEA, contains solid waste contaminated mainly by α emitters. Depending on its dimensions, the waste is conditioned, in compacted or non-compacted form, in 870-litre non-alloy steel containers (see Figure 3.2.11).

As with the 500-litre steel containers above, two waste conditioning matrices – initially a cement-bitumen matrix, then from 1990 a cementitious material – have been used in succession since the packages were first produced. It should be noted that this package subset also includes some packages of cemented concentrates initially conditioned in 700-litre steel drums, then reconditioned in 870-litre containers.

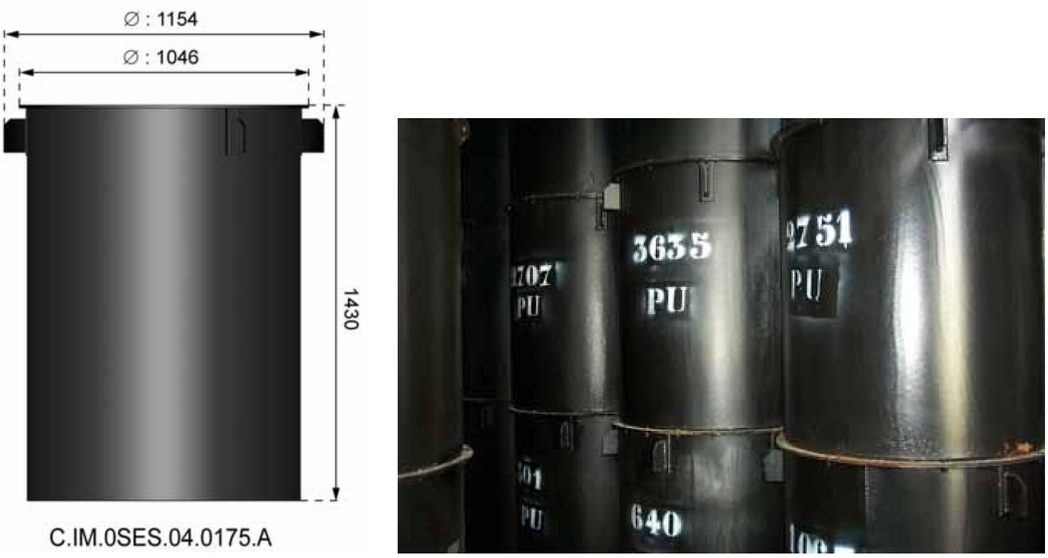

Figure 3.2.11 870-litre non-alloy steel container

The conditioned waste comprises various materials (metals, organic matter, glass, debris, etc.) mixed in the same package. The average weight of the finished packages varies between 1.6 and 2.3 metric tons, depending on the content (compacted or non-compacted, conditioning with overdrums). Given the chemical content of the packages, once again potential production of hydrogen by radiolysis of the organic matter and conditioning matrix water must be considered. These packages do not release radiation.

The main characteristics of the nine subsets of cemented or compacted technological waste packages are summarised in Table 3.2.1.

Table 3.2.1 *Summary of the main characteristics of subsets of cemented or compacted technological waste packages*

Package subset	Overall volume of the package (m^3)	Container material	Embedding or immobilising matrix	Presence of metallic materials	Presence of organic matter
1	1	Concrete	Cement-bitumen	None	x
2	1.2	Fibre-reinforced concrete or asbestos cement	Cement	x	x
3	1.8 3.2 or 3.8 with overdrum	Concrete or non-alloy steel	Cement-bitumen or mortar	x	x
4	0.5	Concrete	Cement	None	x
5	1.2	Fibre-reinforced concrete	Mortar	x	x
6	0.18	Stainless steel	None	x	x
7	0.428	Stainless steel	Cement	None	x
8	0.5	Non-alloy or stainless steel	Cement-bitumen or cementitious material	x	x
9	1.22	Non-alloy steel	Cement-bitumen or cementitious material	x	x

3.2.1.4 Cemented or compacted cladding waste

This type of waste comes from spent fuel reprocessing in the COGEMA plants; it relates to the metallic framework components in the fuel assemblies. This waste is separated from recyclable nuclear materials (uranium, plutonium) and from fission products and minor actinides when reprocessing commences during fuel shearing and dissolution operations.

This waste is commonly known as "hulls and end caps" in pressurised water reactor fuel assemblies. The hulls are the cladding from the fuel rods, recovered in lengths of around three centimetres long, from which the nuclear material has been extracted by being dissolved in acid. The end caps are the parts located at both ends of the fuel assembly.

The cladding waste under consideration here has come from reprocessing operations in the COGEMA plants at La Hague. They include (i) waste produced during previous reprocessing operations of NUGG and PWR fuels, today stored in silos and pits, and (ii) waste from current and future reprocessing operations of the various types of PWR UOX and MOX fuels, defined in the design scenarios given in Section 3.1.

There are several types of materials in cladding waste: magnesium-zirconium and magnesium-manganese alloys for the NUGG fuels; zirconium-tin (zircaloy 4) or zirconium-niobium (M5 alloy) alloys, stainless steels and nickel alloy for the PWR fuels. Following the conditioning hypotheses indicated below, some packages also contain technological waste formed of metal only (non-alloy and stainless steels) or a metallic-organic mixture. The mass of this technological waste represents around ten per cent of the total mass of conditioned waste per package.

Radiological activity is due (i) to activation products from neutron activation of the alloy components and impurities making up the component materials of the assembly structures during their time in the reactor and spread in the mass of these materials, and (ii) contamination by fission products, impurity activation products and actinides found in the oxidised layer covering the internal surface area of the cladding lengths that held the fuel. This contamination is also caused by traces of undissolved substances that may be left after the waste has been rinsed. The radiological contribution from technological waste found in some packages is negligible compared with that of the cladding waste.

Package thermicity is mainly caused by cobalt-60. A decrease in cobalt results in some packages losing their thermicity given the age of the waste.Other packages have a heat rating in the order of around thirty watts when they are produced, but this drops rapidly after a few years, in conjunction with the decrease in cobalt. These changes are illustrated in Figure 3.2.12.

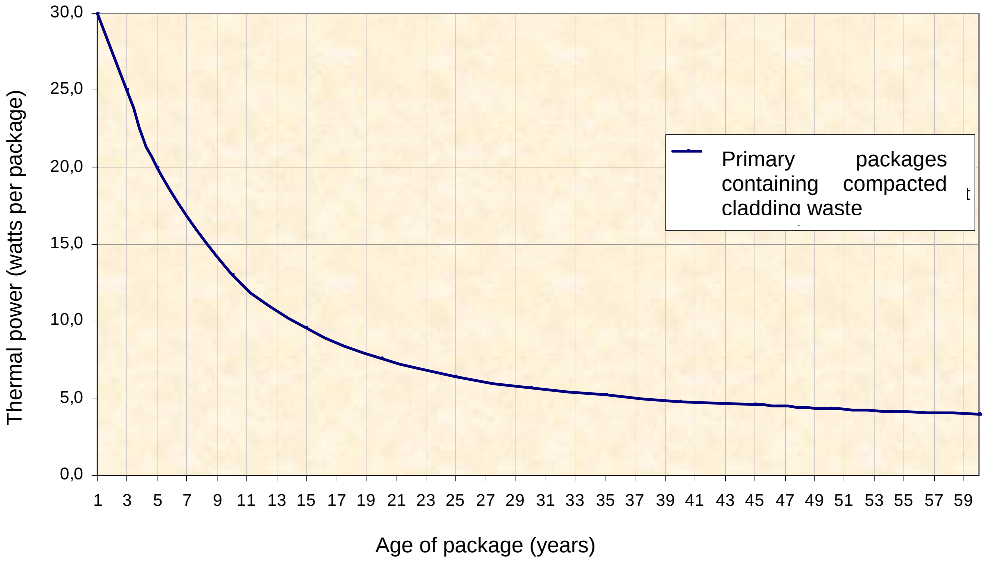

Figure 3.2.12 *Changes in residual heat rating in cladding waste primary packages from PWR UOX, enriched recycled uranium and MOX fuels*

- **Cemented cladding waste**

The cladding waste from the PWR fuel assemblies is initially cemented into huge stainless steel drums. This process was applied between 1990 and 1995, then replaced in 2002 by waste compacting, in the Hull Compacting Workshop at La Hague.

Packages produced between 1990 and 1995 are called *drums of cemented hulls and end caps* (see Figure 3.2.13).

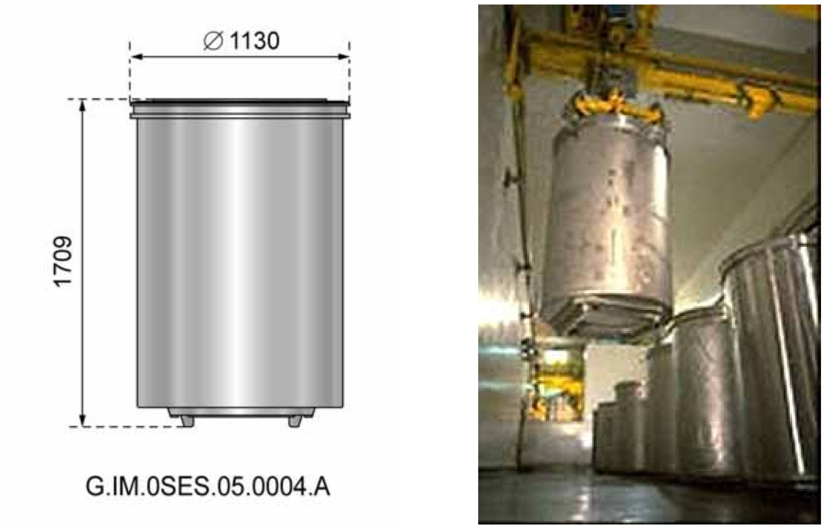

Figure 3.2.13 1,800-litre, stainless steel drum containing cemented cladding waste.

They contain an average of 776 kilograms of cladding waste, made up of 80.7% zirconium-tin (zircaloy 4) alloy, 15.9% stainless steel and 3.4% nickel alloy. The package weight (drum + waste + matrix) is 3.5 tonnes on average. The residual heat rating in the packages from the cobalt-60 is today in the order of around ten watts. It will be about three watts by 2025. The equivalent β-γ dose rate in pseudo-contact with the packages (5 cm) is currently in the order of 4 Sv/h; it will be in the order of 0.5 Sv/h by 2025. Water radiolysis in the cementing matrix produces hydrogen.

- **Compacted cladding waste**

As indicated previously, a new method of conditioning cladding waste was introduced on the La Hague site in 2002. This involves compacting waste placed preliminarily in claddings, before being moved to stainless steel containers (CSD-C). The compacting process is applied to cladding waste produced from NUGG and PWR fuels reprocessed previously and now stored in silos and pits, and cladding waste produced from current and future reprocessing operations of fuel unloaded from the PRW reactors. As mentioned above, some packages also contain compacted technological waste from the site's operating and/or maintenance shops. Given the diversity and nature of the flows of waste in question, distinction is made between four sub-assemblies of compacted cladding waste packages (CSD-C).

The first package sub-assembly contains cladding waste from UOX, enriched recycled uranium and MOX fuel reprocessing mixed with metallic and organic technological waste. The hypotheses adopted are (i) fuel reprocessing on average eight years after unloading from reactors and (ii) average weight of 420 kilograms of conditioned waste per package (including compacting claddings). Based on these hypotheses, the heat rating of the packages, calculated for an envelope radiological inventory of the various waste flows mentioned above, is around 30 watts. Thermal decay of these packages is given in Figure 3.2.12. Package irradiation levels, initially around fifty sieverts per hour (Sv/h) is in the order of 15 Sv/h after a ten-year cooling period. The radiolysis of the organic waste in the packages made up of technological waste produces hydrogen. Note also that radioactive elements other than tritium (with the symbol T or ^{3}H), carbon-14 (^{14}C), chlorine-36 (^{36}Cl), argon-39 (^{39}Ar) and krypton-85 (^{85}Kr). The finished packages weigh approximately 520 kilograms.

Like the previous packages, t*he second package sub-assembly* contains a mixture of UOX, enriched recycled uranium and MOX cladding waste and technological waste. It differs from the first in the type of technological waste, here formed of metallic materials only. Unlike the first sub-assembly packages, it does not therefore generate hydrogen through radiolysis. However, there is a risk of the waste releasing traces of radioactive gases (^{3}H, ^{14}C, ^{36}Cl, ^{39}Ar and ^{85}Kr). This raises the question of their containment as close to the waste as possible; this issue is dealt with in Chapter 4.

The other package characteristics (heat rating, equivalent dose rate, weight) are otherwise identical to the first sub-assembly.

The third package sub-assembly only contains cladding waste from PWR fuels reprocessed in the past and now stored. The packages weigh 725 kilograms on average. Given the age of the waste, the packages do not transfer heat. Their irradiation level is around 5 Sv/h; it will be around 1 Sv/h by 2025.

The third package sub-assembly only contains cladding waste from NUGG fuels reprocessed in the past and now stored. The finished packages weigh 350 kilograms on average. Given the age of the waste, the packages do not transfer heat. Their irradiation level is also lower than for the previous sub-assemblies, namely around 0.4 Sv/h.

Table 3.2.2 summarises the principal characteristics of the four sub-assemblies of compacted cladding waste packages.

Table 3.2.2 Summary of principle characteristics of sub-assemblies of compacted cladding waste packages

Package sub-assembly	Cladding waste materials	Presence of technological waste	Presence of organic matter	Production of gas by radiolysis (H_2)	Thermicity, irradiation level when packages produced
1	Zirconium-tin or zirconium-niobium alloys, stainless steels, nickel alloy	x	x	x	Packages transfer little heat, extremely irradiating
2	Ditto sub-assembly 1	x	None	None	Packages transfer little heat, extremely irradiating
3	Zirconium-tin alloy, stainless steels, nickel alloy	None	None	None	Packages do not transfer heat, moderately irradiating
4	Magnesium-zirconium or magnesium-manganese alloys	None	None	None	Packages do not transfer heat, only slightly irradiating

3.2.1.5 Cladding and technological waste placed in drums

This groups waste produced on the COGEMA Marcoule site and currently stored, excluding bitumen waste and cemented pulverulent waste described above. It includes (i) operating waste from the Marcoule vitrification shop, (ii) cladding waste from fuels reprocessed in the UP1 plant and (iii) operating and maintenance technological waste from the Marcoule site facilities.

The waste is placed in stainless steel drums. Note that the modalities for limiting the residual voids inside the primary packages have yet to be defined.

A first package sub-assembly contains technological waste from operations in the Marcoule vitrification shop (AVM). The waste formed of equipment, tools and various steel parts is deposited in a stainless steel container of similar geometry to the AVM vitrified waste containers. The packages weigh 160 kilograms on average and may weigh as much as 320 kilograms (excluding waste immobilisation material). Radiological activity corresponds to contamination of the waste surface area. These packages do not transfer heat and have an irradiation level of around 0.05 Sv/h.

A second package sub-assembly contains fuel cladding waste. The waste is temporarily conditioned in stainless steel drums known as EIP drums (from the French acronym for multi-purpose storage facility). The packages hold aluminium and stainless steel cladding waste or magnesium-alloy cladding waste. They weigh less than 300 kilograms on average (excluding waste immobilisation material). Packages containing aluminium and steel cladding waste have a heat rating in the order of 10 watts, mainly attributable to cobalt-60; this will be 0.5 watts at most by 2025. The package irradiation level is 25 Sv/h, becoming 2 Sv/h by 2025.

The packages containing the magnesium alloy cladding waste do not transfer heat. Their irradiation level, attributable to two isotopes, barium-137m (^{137m}Ba) and europium-154 (^{154}Eu), is 3 Sv/h, becoming around 2 Sv/h by 2025.

A third package sub-assembly contains technological waste made up of a mixture of metallic materials and organic matter or metallic materials alone. The temporary conditioning method is also to place the waste in EIP drums.

The packages containing metallic and organic waste weigh 90 kilograms on average (excluding waste immobilisation material). They do not transfer heat and are not irradiating. Hydrogen release from radiolysis of the organic matter should be taken into account.

The packages containing the metallic technological waste do not transfer heat nor produce gas. Their irradiation level is around 0.05 Sv/h, becoming around 0.02 Sv/h by 2025. The finished packages weigh 240 kilograms on average, excluding waste immobilisation material.

Table 3.2.3 summarises the principal characteristics of the three sub-assemblies of the cladding and technological waste packages.

Table 3.2.3 Summary of the characteristics of the cladding and technological waste placed in drums

Package sub-assembly	**Overall package volume (m^3)**	**Presence of metallic waste**	**Presence of organic waste**	**Production of gas by radiolysis (H_2)**	**Thermicity, irradiation level when packages produced**
1	0.175	x	None	None	Packages do not transfer heat, only slightly irradiating
2	0.428	x	None	None	Nil or average thermicity, average or high irradiation level depending on packages
3	0.428	x	x	x	Packages do not transfer heat and are not irradiating

3.2.1.6 Sources

This waste groups PWR source rods and sealed sources for industrial use.

Source rods are operating waste from PWR reactors, similar to the variety of active metallic waste described in Section 3.2.1.1. Forming part of the rods contained in the primary and secondary source clusters, they are used to raise the flow level to a threshold that may be detected by neutron counters during reactor start-up. Primary source rods containing a californium capsule are unloaded at the end of the first cycle, whilst secondary source rods, made up of an antimony-beryllium mixture, go through several irradiation cycles before being scrapped. The primary source clusters unloaded from 900 MW reactors are reprocessed to recover the californium capsules and are therefore not considered waste (and are therefore not included in the inventory). The total weight of waste for conditioning is less than two tonnes.

The conditioning hypothesis retained for the study is, like for the other PWR activated waste, shearing then compacting of the source rods before being placed in a CSD-C container. Note that the source rod conditioning will produce a maximum of four CSD-C.

The sealed sources for industrial use contain radioactive material with very different properties, activities and periods. Several thousand sources were conditioned in concrete containers between 1972 and 1984, which were then reconditioned into metallic containers. The packages known as "source blocks" are currently stored on the CEA site at Cadarache (see Figure 3.2.14). These are large sized packages weighing between 6.0 and 9.2 tonnes.

Figure 3.2.14 Source blocks

Several thousand other sealed sources are also stored today at various facilities. They cover a very wide range of radioactive isotopes, activities and varying periods. All sources for a period higher than or equal to that of cesium-137 (equal to thirty years) have been adopted for consideration in the study, consistent with the waste accepted for surface disposal at the Aube facility. The conditioning hypothesis envisaged at the moment is to cement the sources into EIP drums.

3.2.1.7 Radium and americium waste

This groups various types of waste including radiferous lead sulphate, items for medical use and lightning rods. Taking this waste into account in the HLW/ILW-LL inventory remains exploratory, however. *Radiferous lead sulphates* come from uranium ore processing in the Bouchet plant. The waste is placed initially in metallic drums that have been reconditioned successively for storage purposes. The hypothesis adopted for the studies is the recovery of primary radiferous lead sulphate drums for conditioning in EIP drums. Note that the modalities for limiting the residual voids inside the primary packages have yet to be defined.

Items for medical use are needles and very small metallic tubes, each containing a few milligrams of radium. The radium is incorporated in a solid, insoluble but pulverulent chemical form (sulphate or chloride). The history of the radium industry shows that about a hundred grams of radium have been extracted, including around fifty grams used in the manufacture of items for medical use. Note that the items for medical use (a total of some 5,000) can be conditioned in a single EIP drum.

As a precaution, consideration is also given to lightning rods that contain radium or americium. Already used for a few radium lightning rods, compacting has been adopted as the conditioning solution, followed by cementing the lightning rod heads in 870-litre, non-alloy steel containers. The packages contain around 200 lightning rod heads on average, both radium and americium, and have an activity in the order of 10 gigabecquerels (GBq). They weight 2 tonnes on average.

3.2.2 Primary vitrified C waste packages

Vitrified waste is a product of spent fuel reprocessing. This includes mainly fission products and minor actinides (neptunium, americium and curium) formed by nuclear reaction and contained in the spent fuels, which are separated from the uranium and plutonium during the reprocessing operation. They are separated and incorporated into a glass matrix. The manufactured glass is poured at temperature into a stainless steel container. Radiological activity is spread homogenously through the mass of vitrified waste.

Vitrification has been developed in several pilot French facilities operated by the CEA, including the pilot PIVER facility now halted, then implemented industrially in three shops operated by COGEMA: Marcoule Vitrification Shop (AVM), started in 1978, and vitrification shops R7 and T7 at La Hague, started in 1989 and 1992 respectively.

Vitrified waste characteristics, particularly their activity and heat rating, depend on several parameters: (i) initial characteristics of solutions of fission products and minor actinides from fuel reprocessed in these facilities, (ii) varying degrees of concentration of fission products in the glass and (iii) the age of the waste.

It was therefore decided to make a distinction between several vitrified C waste package groups, respectively (i) the oldest glass productions (§ 3.2.2.1), (ii) current glass productions or those planned in the short term (§ 3.2.2.2), (iii) provisional glass productions, including UOX/MOX glass and UOX glass with the hypothesis of incorporating a small fraction of plutonium (§ 3.2.2.3).

Figure 3.2.15 illustrates the heat rating levels of these various package groups.

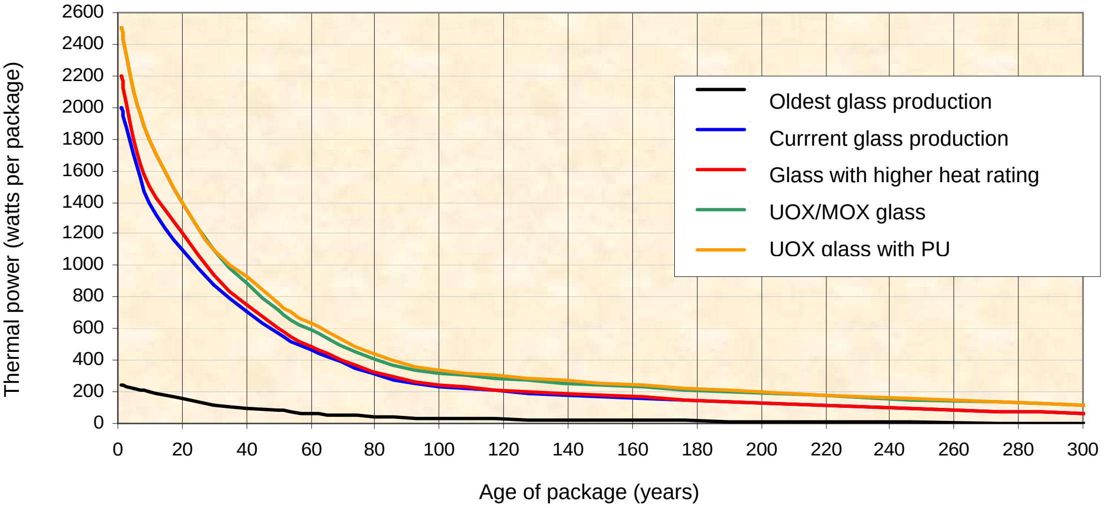

Figure 3.2.15 Heat ratings of vitrified waste packages

3.2.2.1 Glass packages from former productions

This package group includes (i) glass packages containing solutions of fission products from the reprocessing of fuel from Natural Uranium Graphite Gas reactors (Sicral-type NUGG fuels) and fuels from the Phénix rapid neutron reactor in the PIVER facility, (ii) glass packages containing solutions of fission products known as UMo, produced by NUGG fuels recovered previously on the COGEMA La Hague site and now stored and (iii) glass packages produced since 1978 in the COGEMA Marcoule vitrification shop (AVM glasses), containing fission products and actinides produced mainly by reprocessing of NUGG fuels. The majority of packages are of the latter type.

These packages differ in their chemical content, depending on the composition of the glass matrix used, their radiological content and subsequently their heat rating, and in container geometry.

PIVER packages, produced between 1969 and 1981, are predominantly formed of NUGG glasses. The vitrified waste is conditioned in stainless steel containers of the same diameter but with different heights (see Figure 3.2.16).

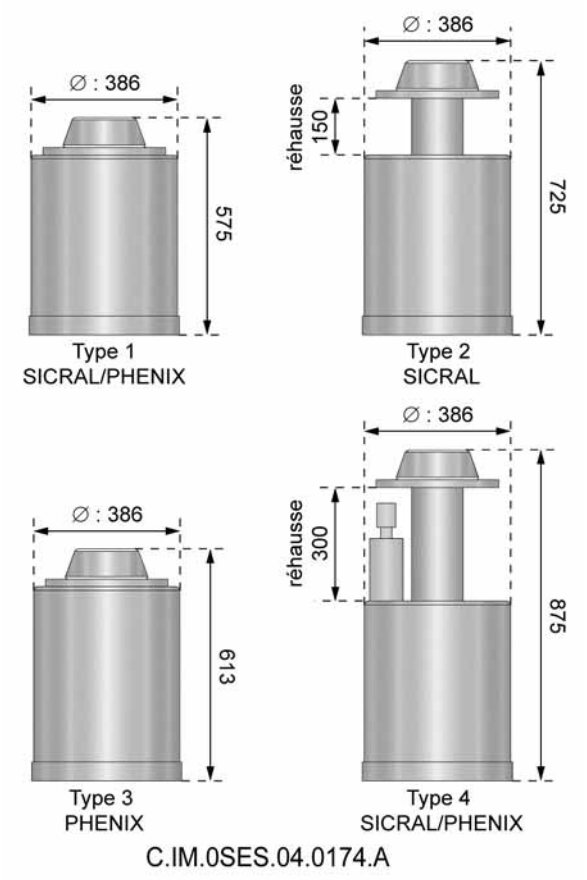

Figure 3.2.16 PIVER containers

These are low-capacity packages (39 or 45 litres depending on the type of container) containing glass weighing between 20 and 120 kilograms. An average weight of 72 kilograms of vitrified waste per package has been adopted for the study, with a total average weight of 90 kilograms for a full package (vitrified waste + container).

The radiological activity of the packages has decreased considerably given their date of production. It continues to be dominated by two medium-life fission products - strontium-90 (^{90}Sr) and cesium-137 (^{137}Cs). These generate residual thermal release, currently on the order of about thirty watts per package. The equivalent β-γ dose rate in pseudo-contact (5 cm) with the package is around 70 Sv/h, becoming around 45 Sv/h by 2025.

The UMo glass waste packages correspond to future conditioning of solutions of existing fission products; these are produced by NUGG fuels recovered in the COGEMA UP2-400 plant at La Hague. The chemical nature of the solutions requires a specific glass to be formulated and modifications to process equipment, particularly the vitrification furnace. Following the hypotheses adopted, the average weight of the conditioned waste is 400 kilograms per package. Strontium-90 and cesium-137 also play an important role here in the radiological activity of the packages, although this has decreased tremendously given the age of the solutions. Subsequently, the residual thermal release is currently around 70 watts per package. The equivalent β-γ dose rate in pseudo-contact (5 cm) with the package is around 15 Sv/h, becoming around 10 Sv/h by 2025.

This waste will be conditioned in a stainless steel container identical to the one used today in the COGEMA R7 and T7 vitrification shops at La Hague.Figure 3.2.17 illustrates this container, called the Standard Vitrified Waste Container (CSD-V).

Figure 3.2.17 Standard Vitrified Waste Container (CSD-V)

The AVM glass waste packages group all the vitrified waste produced since 1978 in the COGEMA vitrification shop at Marcoule. As indicated above, the vitrified solutions come in the main from reprocess NUGG in the site's UP1 plant. Note that four different glass formulations exist for one or more vitrification campaigns.

The vitrified waste is conditioned in a stainless steel container illustrated in Figure 3.2.18.

Figure 3.2.18 AVM vitrified waste containers

The average weight of each package is 410 kilograms, including 360 kilograms of vitrified waste. The packages' heat rating comes principally from medium-lived fission products, ^{90}Sr et ^{137}Cs. A heat rating of 155 watts by 2025 has been adopted for the study. Note that this heat rating is higher than for the previous packages; it is nevertheless significantly less than those of the C packages presented below. The equivalent β-γ dose rate in pseudo-contact (5 cm) with the package, around 235 Sv/h, will be around 150 Sv/h by 2025.

3.2.2.2 Vitrified waste packages from current productions or those planned in the short term

These packages contain solutions of fission products produced by reprocessing PWR UOX/enriched recycled uranium fuels in the COGEMA La Hague plants, conditioned as glass in a so-called CSD-V stainless steel container (see Figure 3.2.17). It is assumed that production and conditioning of the waste will occur after an average fuel storage time of eight years, after unloading from the reactors. The conditioned waste weighs 400 kilograms on average per package.

A first group of waste packages relates to current industrial productions from a heat transfer viewpoint. Following the hypotheses adopted, the vitrified waste is made up of a mixture of solutions of fission products from UOX1 (average combustion rate of 33 GWj/t), UOX2/enriched recycled uranium (average combustion rate 45 GWj/t) and UOX3 (average combustion rate 55 GWj/t) fuels.

A second group of waste packages relates to packages with a slightly-increased heat rating. The vitrified waste is made up of a mixture of solutions of fission products from UOX2/enriched recycled uranium and UOX3 fuels, with, as previously, average combustion rates of 45 GWj/t and 55 GWj/t respectively.

The heat ratings of these packages are illustrated in Figure 3.2.15 (blue and red curves). They raise the question of storage time before being placed in a repository and of repository module design, to limit the temperature to acceptable levels (see Chapter 2); this issue is dealt with in Chapter 5.

The equivalent β-γ dose rate in pseudo-contact (5 cm) with the packages is about 240 Sv/h, after a sixty-year cooling period.

3.2.2.3 Future hypothetical wastepackages

These waste packages relate to potential glass productions on the COGEMA La Hague site. These packages have been defined in the scenarios adopted for the study on the assumption that production and conditioning of the waste will take place, as for the previous glasses, after an average fuel storage period of eight years, after unloading from the reactors. Note that other possibilities could be envisaged.

Here also, the conditioned waste weighs 400 kilograms on average per package. The containers are similar to the ones presented above (CSD-V).

A first waste packages describes glasses produced by conditioning solutions of fission products from UOX and MOX fuels. Their make-up is defined as a mixture of 15% MOX and 85% UOX2.

A second waste packages describes vitrified waste from reprocessing UOX fuels, which contains a small additional plutonium load. The plutonium incorporation rate in the glass is fixed specifically at one percent, about 4 kilograms per package. The incorporated plutonium comes from the UOX2 fuels.

The heat ratings produced by these packages are illustrated above in Figure 3.2.15 (green and orange curves).

The equivalent β-γ dose rates in pseudo-contact (5 cm) with the packages will be 235 Sv/h for the UOX/MOX glasses and 265 Sv/h for the glasses with plutonium respectively, after a sixty-year cooling period.

3.2.3 Spent fuel

Spent fuels taken into account stem from the PWR reactors, as well as from halted plants and research reactors (NUGG, EL4) and fuels produced by national defence activities. Remember that these are taken into account in the study in the event they were to be considered as waste, assuming a halt in reprocessing; which is not current strategy in France.

Under scenario S2, the fuel typologies considered (see Section 3.1) are: UOX2 and enriched recycled uranium (45 GWj/t), UOX3 (55 GWj/t) and MOX (48 GWj/t).

Conditioning for assemblies has been studied (see Chapter 4, § 4.3). This allows for a receipt of bare assemblies or those placed in claddings prior to receipt.

3.2.3.1 PWR fuel assemblies

The reference fuel assembly corresponds to an advanced second-generation FRAGEMA assembly with thicker guide thimbles and zirconium alloy cladding. It is illustrated in Figure 3.2.19. It is called AFA-2GE for the PWR 900 MWe reactors and AFA-2LE for the PWR 1300 MWe and 1450 MWe reactors.

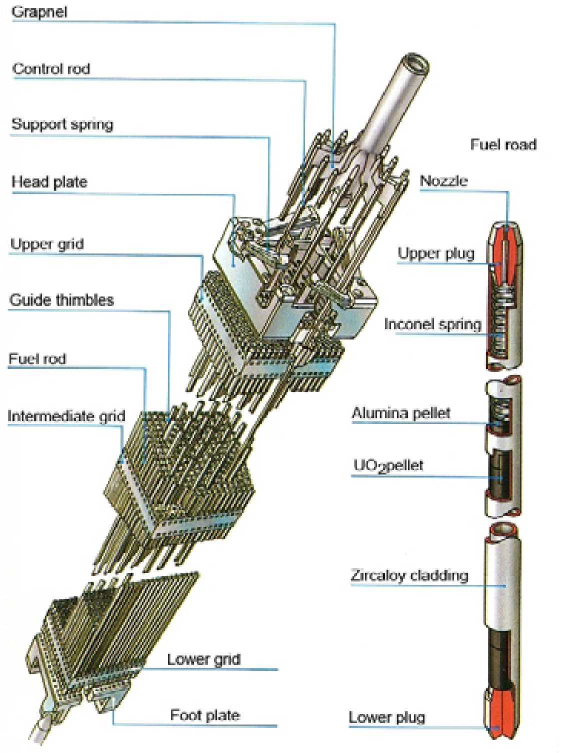

Figure 3.2.19 PWR fuel assembly

The assembly comprises a rigid metallic structure (skeleton) supporting 264 geometrically-identical rods distributed through a square lattice of 289 compartments.

The skeleton is made up of the following components:

- 2 fabricated end pieces, fixed by guide thimbles at each end, maintaining the position in the core;
- 24 tubes to guide the cluster rods (guide thimbles) and support the grids making up the structural framework;
- 1 central instrumentation tube with the sole task of guiding a flow measurement micro-chamber;
- 8 (AFA-2GE) or 10 (AFA-2LE) spacing grids to hold the rods axially and radially using a soft-hard stop assembly.The fuel rod is made up of:
- closed cylindrical, metallic cladding closed top and bottom by two welded plugs (the upper plug has a pressurisation hole which is plugged after the rod is filled with helium);
- stack of fuel pellets 95% of the way up the rod;
- a helical spring in the upper part of the fuel pellet stock holding it axially during handling operations.

The AFA-2GE and AFA-2LE assemblies have identical configuration (lattice 17x17 with 12.6 mm intervals, section 214 mm x 214 mm), but different total lengths: 4.12 metres for AFA-2GE and 4.87 metres for AFA-2LE (dimensions after irradiation). Material weights vary according to the type of fuel and type of assembly. They are given Table 3.2.4.

Table 3.2.4 Weight of PWR fuel assemblies (per material and total weight)

Assembly	Material weight per assembly (in kilograms)				Total weight of assembly) (in kilograms)
	Ceramic fuel	**Zirconium alloy (rod cladding)**	**Nickel alloy (end piece springs and grids)**	**Stainless steel (end pieces, rod springs, etc.)**	
AFA-2GE UOX/URE	521.2 (UO_2)	125.6	2.1	16.4	665
AFA-2LE UOX	608.1 (UO_2)	146.2	2.5	19.5	775
AFA-2GE MOX	513.9 ($(U\text{-}Pu)O_2$)	125.6	2.1	18.1	660

One of the problem areas of the fuels with respect to the disposal study, in common with vitrified C waste, is their considerable thermal release linked to their radiological inventory. One difference compared with vitrified waste is the major contribution made by plutonium to fuel thermicity; this results in a longer heat transfer phase, due to the period of the involved isotopes, mainly americium-241 (^{241}Am), a daughter product of plutonium-241 (^{241}Pu).

Changes over time in the residual heat rating of the UOX and MOX assemblies, after unloading from the reactors, is illustrated in Figure 3.2.20

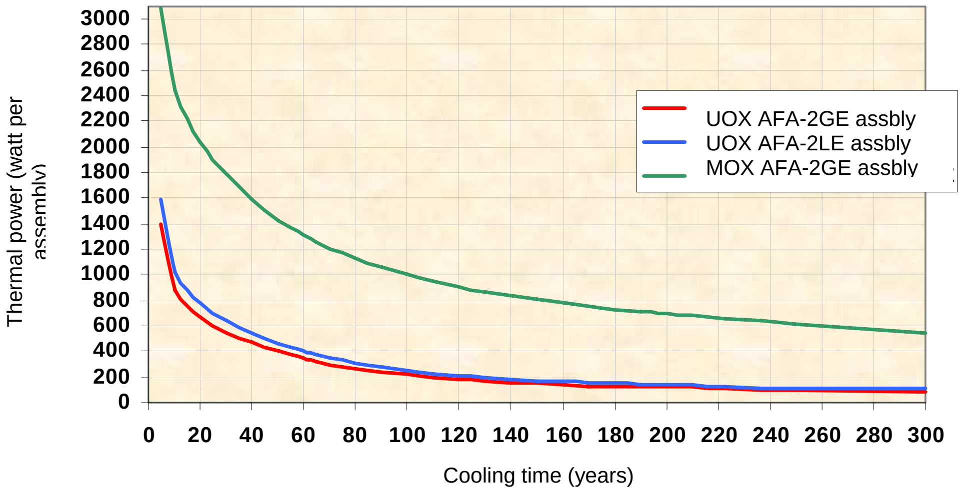

Figure 3.2.20 Changes in residual heat rating of UOX and MOX fuel assemblies

In the previous figure, the heat ratings are deducted from the UOX and MOX fuel radiological inventories. For noted UOX AFA-2GE and UOX AFA-2LE assemblies, an envelope inventory has been defined for a mixture of UOX2, UOX3 and enriched recycled uranium fuels. For the studies, note that the PWR spent fuel disposal packages group four assemblies for the UOX AFA-2GE or UOX AFA-2LE fuels (see Chapter 4, § 4.3).

3.2.3.2 CEA fuels (research and national defence reactors)

Alongside the scenarios described above, the CEA fuels are quite diverse. They include (i) fuels from NUGG reactors, (ii) fuels from the EL4 heavy water reactor, (iii) fuel elements from the Célestin reactors installed at Marcoule and (iv) nuclear propulsion fuels from land-based reactors or those on board ships.

The NUGG fuels correspond to a residual tonnage of non-reprocessed fuels, around 15 tonnes. They are currently conditioned in cylindrical claddings 88 or 130 mm in diameter and equal to 655.5 mm high. These claddings contain a very small amount of waste, 9 or 18 kilograms on average depending on the type of cladding. They have a particularly low heat rating of around 3 watts maximum.

The EL4 fuels represent about 50 tonnes of heavy metal. The fuel element is in the form of a 19-rod cluster fitting tightly in an ATR structure (alloy of zirconium with copper and molybdenum). The rods are made up metallic cladding in a zirconium-copper alloy and contain uranium oxide pellets very slightly enriched with uranium-235 (1.28% or 1.41% depending on the rods). The initial weight of the uranium oxide is 10.6 kilograms per cluster. The EL4 fuel clusters are currently conditioned in stainless steel claddings about 100 mm in diameter and 1100 mm long. Each cladding contains two clusters placed on top of each other. Their heat rating is also very low (maximum 10 watts per cladding).

The Célestin fuel elements are made up of metallic plates containing enriched uranium, mounted on a metallic structure. They are conditioned in stainless steel claddings around 340 mm in diameter and 1100 mm long. Each cladding holds six fuel elements representing a total heat rating of 120 watts maximum.

The nuclear propulsion fuels are made up of (i) oxide fuels based on sintered uranium oxide plates and (ii) metallic fuels based on highly enriched metallic uranium. These latter fuels are no longer used.

In both cases, the fuel takes the form of an assembly made up of several bundles. The bundles are separated from the assembly and conditioned in identical diameter claddings (340 mm approximately, like the claddings containing the Célestin fuel elements), but of different lengths to suit the bundle dimensions. Each cladding contains four or six bundles from the same type of fuel assemblies. The heat rate here is at most in the same order of magnitude as for the AVM vitrified waste packages described above (155 watts).

3.3 Inventory model

All the preceding data and hypotheses on the primary waste packages have been collated in an "inventory model", for systematic use in the study.

This inventory model organizes the diversity of primary waste packages (presented in section 3.2) into a tree-live structure. This structure groups those packages raising similar (waste management) issues. To cover the characteristics of the primary packages thus grouped, the inventory model defines "waste package types" that are representative of these groups.

The tree-live nomenclature adopted to identify the waste package types will be used throughout the following chapters. It has three levels. Level 1 differentiates in traditional fashion between the various package categories (B waste, C waste and spent fuels identified by the letters "CU") that present their own issues given their radiological content (type and quantity) and thermal consequences (thermal release levels and changes over time). Various types of packages are identified within each of these categories, particularly for category B waste, based on waste type (sludge, technological waste, cladding waste from fuel assemblies, etc.) and conditioning methods (compacting, bituminisation, cementation). Breaking down level 1 packages into one or even two additional levels provides greater detail on the variability of primary waste packages for design study, modelling and repository safety evaluation purposes. The following criteria are taken into account to differentiate between level 2 or level 3 waste package types: physico-chemical characteristics of the conditioned waste (in connection with the waste material and conditioning matrices), heat rating and irradiation levels of the packages (in connection with the radiological inventory) and container characteristics (dimensions, materials). Note that for waste package types encompassing a wide range of primary package families, such as the B3 waste package type, a second level in the tree is created to group packages initially based on the type of package materials (concrete, steel) and whether or not the conditioned waste is homogenous.

The physico-chemical characteristics of the conditioned waste have tremendous influence on the design choices, so that the packages are placed in favourable environmental conditions to limit their alteration over time. They determine the initial and long-term containment capability of the packages and disturbances potentially caused by their degradation. These disturbances include (i) the release of products likely to increase the solubility of the radionuclides or complex a significant number, (ii) the production of gas by radiolysis or corrosion of materials and (iii) the formation of potentially aggressive species on the surrounding materials. Packages containing organic waste are singled out. Gaseous releases are input data for the study of the ventilation of facilities, disposal packages and for the risk analysis in the operating and observation phases.

Container characteristics (dimensions, weights, gripping systems) are important parameters in designing disposal packages, architectures and operating methods.

The thermal data are used for (i) thermal design of the repository and (ii) an assessment of its behaviour. The irradiation level of the packages plays a part in designing the radiological protection methods, based on the radiological protection objectives adopted.

The inventory model defines the number of primary waste packages for each waste package type taken into account in the study, including their total volume, for every scenario S1a,b,c and S2 introduced in Section 3.1.

3.3.1 Choice of waste package type, nomenclature used subsequently

The various groups of primary packages presented in Section 3.2 differ in (i) the thermal release level of the packages (B waste with nil to moderate thermicity, vitrified C waste and spent fuels with greater thermicity) and (ii) the waste type and conditioning methods.

Sixteen reference packages have thus been identified at level 1 of the inventory model hierarchy tree by the package grouping possibilities. These include:

- eight B waste reference packages, graded B1 to B8, corresponding to Sections 3.2.1.1 to 3.2.1.7, differentiating between cemented cladding waste and compacted cladding waste (§ 3.2.1.4);
- give vitrified C waste reference packages, graded C0 (§ 3.2.2.1), C1 and C2 (§ 3.2.2.2), C3 and C4 (§ 3.2.2.3);
- two PWR spent fuel reference packages, graded CU1 and CU2 (differentiating between UOX and MOX fuels, § 3.2.3.1), to which is added reference package CU3 (grouping all the other fuels with a far lower thermal release).

As indicated above, some of these reference packages are sub-divided, into level 2 and level 3 reference packages.

Thus, B2.1 and B2.2 reference packages single out packages with different geometries.

B3 reference packages, grouping a wide range of package families, are listed on two levels. Package groupings at level 2 have been defined based on the materials used for the containers and the homogenous or heterogeneous nature of the conditioned waste:

- B.3.1: heterogeneous waste contained in concrete envelopes;
- B.3.2: homogenous waste contained in concrete envelopes;
- B.3.3: heterogeneous waste contained in metallic envelopes;

The level 3 reference package listing corresponds to the taking into account of the chemical nature of the waste, the risk of hydrogen production and the package dimensions (level 3 reference packages associated respectively with level 2 reference packages: B.3.1, B3.2 and B.3.3 are classified by ascending size order):

- B3.1.1, B3.1.3, B3.2.1, B3.2.2, B3.3.2: packages potentially generating hydrogen;
- B3.1.2, B3.3.1, B3.3.3, B3.3.4: packages containing organic matter and generating hydrogen.

Distinction is made between the B5 reference packages based on the type of waste and associated characteristics (chemical, radiological, heat transfer):

- B5.1/B5.2: these reference packages differ from other cladding waste conditioned in CSD-C in their higher thermicity and also the presence of technological waste. These reference packages can therefore be used to study two potentially different CSD-C populations according to their technological waste content: B5.1 reference packages cover technological waste containing organic matter; B5.2 reference package contains none;
- B5.3: this is cladding waste only, with no organic matter, very low thermicity of the waste given its age;
- B5.4: this reference package stands out due to the nature of the waste (magnesium), no organic matter and no thermicity.

Distinction is made in B6 reference packages in the waste type and materials and the envelope geometries:

- B6.1: different envelope geometry from the B6.2 to B6.5 reference packages (B6.2 to B6.5 envelopes are identical);
- B6.2: cladding waste made up of steel, zircaloy and nickel alloy;
- B6.3: magnesium cladding waste;
- B6.4: packages containing organic technological waste and generating hydrogen;
- B6.5: packages containing metallic technological waste only.

Distinction is also made between B7 and B8 reference packages based on the waste type and materials and the envelope geometries.

Reference packages C0.1, C0.2 and C0.3 separate the C0 reference packages based on the type and chemical composition of the vitrified waste, its radiological and heat transfer characteristics and the package dimensions.

The reference packages and their titles are given in Table 3.3.1. Reference is also made to the paragraphs discussing these reference packages in the previous section.

Table 3.3.1 *List of reference packages in the inventory model*

Reference packages	Cat.	Lev.1	Lev.2	Lev.3	Titles of waste grouped in the reference packages	Description
Activation product waste	B	B1			CSD-C containing activation product waste from PWR and fast reactors	§ 3.2.1.1
Bituminised waste		B2	B2.1		238- and 245-litre bitumen drums	§ 3.2.1.2
			B2.2		428-litre bitumen drums	§ 3.2.1.2
Technological and miscellaneous waste cemented or compacted		B3	B3.1	B3.1.1	1,000-litre concrete containers, reconditioned or not in metallic containers	§ 3.2.1.3
				B3.1.2	Concrete containers (CAC and CBF-C'2) containing miscellaneous technological waste	§ 3.2.1.3
				B.3.1.3	1,800-litre concrete containers containing miscellaneous waste	§ 3.2.1.3
			B3.2	B3.2.1	500-litre concrete containers (sludge and concentrates)	§ 3.2.1.3
				B3.20.2	1,200-litre concrete containers (CBF-C"2) containing CEDRA and AGATE waste	§ 3.2.1.3
			B3.3	B3.3.1	Standardised container for compacted waste (CSD-C) containing alpha waste	§ 3.2.1.3
				B3.3.2	EIP drums containing cemented pulverulent waste	§ 3.2.1.3
				B3.3.3	500-litre steel containers containing miscellaneous waste	§ 3.2.1.3
				B3.3.4	870-litre steel containers containing miscellaneous waste	§ 3.2.1.3
Cemented cladding waste		B4			Drums of cemented hulls and end pieces	§ 3.2.1.4
Compacted cladding waste with or without technological waste		B5	B5.1		CSD-C containing a mixture of hulls and end pieces and technological waste (including organic waste)	§ 3.2.1.4
			B5.2		CSD-C containing a mixture of hulls and end pieces and metallic technological waste	§ 3.2.1.4
			B5.3		CSD-C containing PWR (HAO) cladding waste, with no technological waste	§ 3.2.1.4
			B5.4		CSD-C containing magnesium cladding waste	§ 3.2.1.4
Cladding and technological waste placed in drums		B6	B6.1		180-litre steel containers containing AVM operating waste	§ 3.2.1.5
			B6.2		EIP drums containing metallic cladding waste	§ 3.2.1.5
			B6.3		EIP drums containing magnesium cladding waste	§ 3.2.1.5
			B6.4		EIP drums containing metallic and organic technological waste	§ 3.2.1.5
			B6.5		EIP drums containing metallic technological waste	§ 3.2.1.5
Sources		B7	B7.1		Source blocks	§ 3.2.1.6
			B7.2		CSD-C containing PWR primary and secondary source rods	§ 3.2.1.6
			B7.3		EIP drums containing sealed sources	§ 3.2.1.6
Radon and americium waste		B8	B8.1		EIP drums containing radiferous lead sulphate drums	§ 3.2.1.7
			B8.2		870-litre steel containers containing lightning rod heads with radium or americium	§ 3.2.1.7
			B8.3		EIP drums containing items for medical use	§ 3.2.1.7
Vitrified waste	C	C0	C0.1		PIVER vitrified waste	§ 3.2.2.1
			C0.2		UMo vitrified waste	§ 3.2.2.1
			C0.3		AVM vitrified waste	§ 3.2.2.1
		C1			"Current thermal" UOX/enriched recycled uranium vitrified waste	§ 3.2.2.2
		C2			"Future thermal" UOX/enriched recycled uranium vitrified waste	§ 3.2.2.2
		C3			UOX/MOX vitrified waste	§ 3.2.2.3
		C4			UOX + Pu vitrified waste	§ 3.2.2.3

The study of the following reference fuels is added to these waste reference packages

PWR EDF fuels	CU	CU1			PWR UOX and enriched recycled uranium spent fuels	§ 3.2.3.1
		CU2			PWR MOX spent fuel	§ 3.2.3.1
CEA fuels		CU3	CU3.1		NUGG and EL4 spent fuels	§ 3.2.3.2
			CU3.2		Célestin spent fuels	§ 3.2.3.2
			CU3.3		Nuclear propulsion spent fuels	§ 3.2.3.2

3.3.2 Number and volume of primary waste packages considered

In the framework of the scenarios presented in section 3.1, the number of reference packages is quantified by the inventories and waste production forecasts established by producers and assessed by Andra based on data provided.

For forthcoming waste, excluding reprocessing of spent fuels, Andra has added dimensioning margins to take uncertainties into account. Note that disposal possibilities for some waste packages under other disposal solutions have not been taken into account so as to have cautious estimations available.

For past production, inventories are based on data established by the producers. Inventories for reprocessing waste are deduced from the hypothetical electricity production by the facilities.

The number and volume of B waste packages taken into account in the studies are presented in Table 3.3.2 and Table 3.3.3. The number and volume of C reference packages are given in Table 3.3.4 . The volumes indicated are volumes of conditioned waste with the hypotheses formulated below.

Table 3.3.2 Overall quantitative data, in number and volume of packages, for B waste reference packages

Reference package	**Production sites**	**Scenario S1a**		**Scenario S1b**		**Scenario S1c**		**Scenario S2**	
		Number	**Volume (m^3)**	**Number**	**Volume (m^3)**	**Number**	**Volume (m^3)**	**Number**	**Volume (m^3)**
B1	**EDF**	**2 560**	**470**	**2 560**	**470**	**2 560**	**470**	**2 560**	**470**
B2	COGEMA La Hague	42 000	10 000	42 000	10 000	42 000	10 000	42 000	10 000
	COGEMA Marcoule	62 990	26 060	62 990	26 060	62 990	26 060	62 990	26 060
Total B2		**104 990**	**36 060**	**104 990**	**36 060**	**104 990**	**36 060**	**104 990**	**36 060**
B3	CEA	15 060	13 370	15 060	13 370	15 060	13 370	15 060	13 370
	COGEMA La Hague	9 890	10 470	9 890	10 470	9 890	10 470	7 340	7 750
	COGEMA Marcoule	7 990	3 420	7 990	3 420	7 990	3 420	7 990	3 420
Total B3		**32 940**	**27 260**	**32 940**	**27 260**	**32 940**	**27 260**	**30 390**	**24 540**
B4	**COGEMA La Hague**	**1 520**	**2 730**	**1 520**	**2 730**	**1 520**	**2 730**	**1 520**	**2 730**
B5	**COGEMA La Hague**	**42 600**	**7 790**	**39 900**	**7 300**	**39 900**	**7 300**	**13 600**	**2 490**
B6	**COGEMA Marcoule**	**10 810**	**4 580**	**10 810**	**4 580**	**10 810**	**4 580**	**10 810**	**4 580**
B7	**EDF/CEA/Andra**	**3 045**	**1 440**	**3 045**	**1 440**	**3 045**	**1 440**	**3 045**	**1 440**
B8	**CEA/Andra**	**1 350**	**775**	**1 350**	**775**	**1 350**	**775**	**1 350**	**775**

Table 3.3.3 Detail of number and volume of B2, B3, B5, B6, B7 and B8 reference packages

Reference package	**Scenario S1a**		**Scenario S1b**		**Scenario S1c**		**Scenario S2**	
	Number	**Volume (m^3)**	**Number**	**Volume (m^3)**	**Number**	**Volume (m^3)**	**Number**	**Volume (m^3)**
B2.1	46 930	11 210	46 930	11 210	46 930	11 210	46 930	11 210
B2.2	58 060	24 850	58 060	24 850	58 060	24 850	58 060	24 850
Total B2	**104 990**	**36 060**	**104 990**	**36 060**	**104 990**	**36 060**	**104 990**	**36 060**
B3.1.1	90	90	90	90	90	90	90	90
B3.1.2	8 690	10 250	8 690	10 250	8 690	10 250	6 440	7 590
B3.1.3	180	690	180	690	180	690	180	690
Total B3.1	**8 960**	**11 030**	**8 960**	**11 030**	**8 960**	**11 030**	**6 710**	**8 370**
B3.2.1	5 730	2 800	5 730	2 800	5 730	2 800	5 730	2 800
B3.2.2	1 260	1 490	1 260	1 490	1 260	1 490	1 260	1 490
Total B3.2	**6 990**	**4 290**	**6 990**	**4 290**	**6 990**	**4 290**	**6 990**	**4 290**
B3.3.1	1 200	220	1 200	220	1 200	220	900	160
B3.3.2	7 990	3 420	7 990	3 420	7 990	3 420	7 990	3 420
B3.3.3	1 700	850	1 700	850	1 700	850	1 700	850
B3.3.4	6 100	7 450	6 100	7 450	6 100	7 450	6 100	7 450
Total B3.3	**16 990**	**11 940**	**16 990**	**11 940**	**16 990**	**11 940**	**16 690**	**11 880**
Total B3	**32 940**	**27 260**	**32 940**	**27 260**	**32 940**	**27 260**	**30 390**	**24 540**
B5.1	7 940	1 450	7 400	1 350	7 400	1 350	2 140	390
B5.2	31 760	5 810	29 600	5 420	29 600	5 420	8 560	1 570
B5.3	2 500	460	2 500	460	2 500	460	2 500	460
B5.4	400	70	400	70	400	70	400	70
Total B5	**42 600**	**7 790**	**39 900**	**7 300**	**39 900**	**7 300**	**13 600**	**2 490**
B6.1	180	30	180	30	180	30	180	30
B6.2	930	400	930	400	930	400	930	400
B6.3	7 550	3230	7 550	3 230	7 550	3 230	7 550	3 230
B6.4	1 200	510	1 200	510	1 200	510	1 200	510
B6.5	950	410	950	410	950	410	950	410
Total B6	**10 810**	**4 580**	**10 810**	**4 580**	**10 810**	**4 580**	**10 810**	**4 580**
B7.1	41	155	41	155	41	155	41	155
B7.2	4	0,7	4	0,7	4	0,7	4	0,7
B7.3	3 000	1 285	3 000	1 285	3 000	1 285	3 000	1 285
Total B7	**3 045**	**1 440**	**3 045**	**1 440**	**3 045**	**1 440**	**3 045**	**1 440**
B8.1	1 100	470	1 100	470	1 100	470	1 100	470
B8.2	250	305	250	305	250	305	250	305
B8.3	1	0,4	1	0,4	1	0,4	1	0,4
Total B8	**1 350**	**775**	**1 350**	**775**	**1 350**	**775**	**1 350**	**775**

Table 3.3.4 Overall quantitative data, in number and volume of packages, for C waste reference packages

Reference package	Production sites	Scenario S1a		Scenario S1b		Scenario S1c		Scenario S2	
		Number	Volume (m^3)	Number	Volume (m^3)	Number	Volume (m^3)	Number	Volume (m^3)
C0.1	CEA	180	10	180	10	180	10	180	10
C0.2	COGEMA La Hague	800	140	800	140	800	140	800	140
C0.3	COGEMA Marcoule	3 140	550	3 140	550	3 140	550	3 140	550
Total C0		**4 120**	**700**	**4 120**	**700**	**4 120**	**700**	**4 120**	**700**
C1	**COGEMA La Hague**	**4 640**	**810**	**4 640**	**810**	**38 350**	**6 710**	**4 640**	**810**
C2	**COGEMA La Hague**	**990**	**170**	**27 460**	**4 810**	**0**	**0**	**5 920**	**1 040**
C3	**COGEMA La Hague**	**13 320**	**2 330**	**0**	**0**	**0**	**0**	**0**	**0**
C4	**COGEMA La Hague**	**13 250**	**2 320**	**0**	**0**	**0**	**0**	**0**	**0**

Table 3.3.5 shows the state of existing B and C waste volumes at the end of 2003, waste that is already conditioned is distinguished from that which is yet to be conditioned. The table also presentswaste volumes still to be produced under scenario S1a.

Table 3.3.5 State of B and C waste volumes produced at end of 2003, conditioned or otherwise, and still to be produced (scenario S1a)

	Reference package	Waste volume produced by 2003 (m^3)		Waste volume to be produced (m^3)
		Conditioned	Unconditioned	
B	B1	0	250	220
	B2	27 790	7 620	650
	B3	13 895	4 910	8 455
	B4	2 730	0	0
	B5	135	530	7 125
	B6	0	4 580	0
	B7	155	1 285	0
	B8	15	760	0
Total volume of B waste (m^3)		44 720	19 935	16 450
C	C0	540	140	20
	Other glasses	880	0	4 750
Total volume of C waste (m^3)		1 420	140	4 770

Quantitative data relating to PWR fuels are found in Table 3.3.6.

Table 3.3.6 Number of PWR fuel assemblies

	Production sites	**Number of PWR fuel assemblies**			
		Scenario S1a	**Scenario S1b**	**Scenario S1c**	**Scenario S2**
"Short" UOX AFA-2GE assembly, type CU1	EDF	0	0	0	27 200
"Long" UOX AFA-2LE assembly, type CU1		0	0	0	26 800
Total UOX assemblies, type CU1		**0**	**0**	**0**	**54 000**
"Short" MOX AFA-2GE assembly, type CU2	EDF	0	5 400	5 400	4 000
Total MOX assemblies, type CU2		**0**	**5 400**	**5 400**	**4 000**

Furthermore, 5,810 primary claddings are to be considered for type CU3 fuels, if appropriate.

3.4 Primary waste package reception flux hypothesis

To study operating resources in a potential repository, and the drifts and access shafts, flow hypotheses for packages received on a repository site have been established, consistent with the total numbers of packages listed.

As a reference, an annual reception rate of 5,000 primary waste packages has been envisaged for B waste. This corresponds to emplacement of the waste packages inventory into the repository over a forty-year period. With the exception of some packages produced late, particularly the B1 reference package, note that all or the vast majority of the other reference packages will already have been produced by 2020.

Chronologically, the C0 reference packages will be the first vitrified C waste packages available technically for repository disposal in view of their heat rating. 400 packages per year is the rate adopted for the hypothesis, corresponding to a resorption of storage facilities over ten years or so.

It is assumed that the other vitrified C waste packages (C1, C2, C3 and C4 in scenario S1a, C1 and C2 in scenarios S1b and S2, C1 only in scenario S1c) will be stored temporarily before final disposal, to allow their heat rating to decrease. The studies presented in Chapter 5 suggest a reasonable temporary storage period of 60 to 70 years under the concepts studied and heat transfer criteria currently being considered.

In any event, the hypothesis of an annual reception rate of 600 C1 to C4 reference packages (700 packages per year for C1 reference packages under scenario S1c) will permit resorption of storage facilities at a rate allowing for the packages contained therein to show a consistent heat rating, given the decrease in radioactivity. This corresponds to a resorption of storage facilities over about fifty years.

CU2 fuels identified in scenarios S1b, S1c and S2 will be received as appropriate after a currently-estimated temporary storage period of at least 90 years, at an annual rate of 150 assemblies. Their resorption will take place over about forty years under scenarios S1b and S1c (or thirty for scenario S2). Lastly, for CU1 fuels (scenario S1), the study considers the hypothesis of 1,650 assemblies per year.

Note that an annual reception rate of 400 primary claddings can be envisaged for CU3 fuels, corresponding to a resorption of storage facilities over about fifteen years.

4

Waste disposal packages

This chapter has a dual purpose. Firstly, it describes the reasons behind B and C waste over-packing and the functions of a spent fuel disposal container. Secondly, it describes their design principles and their justifies that manufacture, handling and performances are realistic.

The primary design motivations for a waste disposal package are linked to their reliability and to the standardisation of handling equipment in underground facilities. They also relate to the potential contribution of a waste disposal package to reversible repository management. Lastly, the disposal packages contribute to the long-term safety functions, particularly in protecting waste from processes susceptible to cause their alteration and by controlling radionuclide release.

This chapter describes the packing solutions studied for all waste categories. It shows that a concrete over-pack, regrouping several primary waste packages, is a suitable solution for B waste. It also shows why a metallic container seems more relevant for C waste and spent fuels. Include steel offers excellent resistance to temperature and total, reliable watertightness over long periods.

This chapter also presents the results of the real-scale waste disposal package demonstrator programme for B waste and spent fuels.

4.1 B disposal waste packages

B primary waste packages vary tremendously in size, shape, characteristics and handling methods.

Compactness, ease of handling and reversible repository management are all objectives that gave rise to the question of over-packing for B waste, thus simplifying the operating processes in underground facilities.

These considerations were shared with the Atomic Energy Commission (CEA), itself dealing with a similar problem in their long-term storage study. As result, a joint container solution was reached for long-term storage and for disposal. Note that this opens up the possibility of receiving on a repository site waste already contained in "storage and disposal" packages, as described below, rather than as the primary waste packages described in Chapter 3.

4.1.1 Discussion of principal issues

4.1.1.1 Interest of over-packing for B waste

Chapter 2 introduced the search for compactness in the repository architecture (§ 2.4.1.4). This research resulted in a disposal cell design with waste packages occupying the excavated area in the best way possible, by being placed close together. This has a strong influence on the package emplacement process.

The majority of B waste packages are irradiating (see § 3.2.1). To protect man against radiation from waste while allowing access to the B waste disposal cells, the disposal package must be either very thick to attenuate this radiation sufficiently (for example, one metre-thick concrete), or structures providing radiological protection must be built close to the waste disposal packages. Neither of these options, however, make optimum use of the excavated volume.

Andra thus adopted irradiating cells: as soon as a first waste package is introduced, operator presence in the majority of cells is banned. Operations taking place in these cells are therefore controlled automatically or remotely.

The choice of irradiating cells reinforces the interest in making underground operations as simple as possible: this involves encouraging the automation of repetitive actions, particularly package emplacement, and performing these operations with excellent operating safety. Faced with a technical problem, human intervention will be made difficult, if not impossible, by the radiation; the intervention will therefore be performed via remote control.

For emplacement of the waste packages in the cell, the search for simplicity and reliability anticipates two conditions: (i) reduced flux of objects to be handled and (ii) little physical difference in the objects introduced into the same cell.

The residual voids in the cells after emplacement of the waste packages also need to be minimised or filled. Indeed, the ultimate resorption of these voids is likely to cause deformation to the argillite, which should be limited in order to contain the extent of a potentially fissured argillite zone in the vicinity of the cell.

Large packages with simple, regular geometry and just enough clearances for handling purposes contribue to preventing the need for filling; this simplifies operations in the cell whilst controlling deformations in the argillite.

Lastly, simple emplacement processes and not having to fill the residual voids between the packages are two particularly favourable factors in reversibility, making it easier to retrieve the disposed packages.

Overall, the B primary waste packages do not unite these conditions for compactness and repository reversibility. Firstly, they come in large numbers and at a high flux rate (B waste represents around 200,000 primary packages, for a volume of 80,000 cubic metres, see Section 3.4 and [3]). Secondly, given their diverse origins and the history of the facilities producing them, the B primary waste packages have very different characteristics (see Section 3.2 and [3]). By way of example, the primary packages vary in diameter and height from 0.4 m to 1.6 m and from 0.7 m to 1.7 m respectively. They weigh between 0.3 and 9 tonnes. Package materials are as diverse as carbon steel, stainless steel and concrete. Lastly, more than ten gripping systems specific to each origin facility exist, including some that are incompatible with the objective of limiting handling clearances.

Thus the first interest in waste over-packing is to simplify waste disposal and its possible retrieval and make both more reliable: firstly, grouping smaller primary waste packages in higher-capacity disposal packages reduces the flow of objects being transferred in shafts and drifts, then handled into the cells; secondly, over-packing standardises the dimensions and handling methods of these objects. In order to limit long term deformations in the argillite, it minimises the residual empty spaces in the cell and therefore avoids having to filling in situ residual clearance around the primary packages. Lastly, it can contribute to reversibility through the choice of materials unlikely to alter greatly in repository conditions, which will facilitate the eventual retrieval in a period of at least one hundred years.

4.1.1.2 Other issues relating to waste disposal package design

A variety of questions linked to operational and long-term safety must be taken into account in the over-packing design.

- **Waste produced gas management**

The organic matter contained in some waste, the bitumen coating on the B2 packages (see § 3.1.2) and the water used in mixing mortar and cement of a large number of primary packages (see § 3.2) undergo a radiolysis phenomenon. This phenomenon is triggered by radiation issued by the radionuclide content in the waste; it slowly produces gas, mainly hydrogen. This production phenomenon exists in reference packages B2, B3, B4, B5.1, B6.4, B7.1, B8.1 and B8.2. An accumulation of the hydrogen produced must therefore be prevented in the disposal package. To achieve this, the disposal package must be capable of evacuating the hydrogen produced by the waste in question.

In addition, some waste can release traces of radioactive gas, such as tritium (^{3}H), krypton-85 (^{85}Kr), chlorine-36 (^{36}Cl), carbon-14 (^{14}C), radon-222 (^{222}Rn), iodine-129 (^{129}I) or argon-39 (^{39}Ar). Reference packages B1 and B5 are concerned mainly (see 3.2). Dissemination should be prevented as far as possible. In the event there is no risk of the waste package producing hydrogen by radiolysis (like the B5.2 reference packages especially), the aim is to contain these gases as close to the source as possible. Some primary containers like the CSD-C (B1 and B5.2) can be made leaktight before being placed in the disposal package, by welding a plug to the vent[24].

- **Accident situation management**

Waste package behaviour in accident situations during emplacement in the repository must also be taken into account. In this respect, the waste disposal package will contribute to limiting the dispersion of radioactive materials during a fall or fire.

- **Control of long-term chemical interactions**

Over the longer term, checks should be made that the chemical interactions between the materials making up the over-pack, the waste itself, and the argillite are controlled.

In B2 reference packages, the waste in the form of salts is closely mixed with a bitumen matrix. In this case, the radionuclides they contain will be released concomitantly with the uptake of water by the bitumen coating, the solubilisation of the salts and their diffusion in the permeable zone. A pH between 7 and 12.5 is sought to encourage the durability of the bitumen coating [40][25].

For other reference packages, B1, B4, B5, B6 and B7, part of the radionuclides present are the result of activation of the materials making up the waste. These activation products are found physically inside the metal; they are released from the waste concomitantly with the corrosion of the metal. An alkaline pH slows down steel corrosion [40].

Overall, an alkaline pH in the cell is favourable to the retention of certain elements (americium, curium), by reducing their solubility.

- **Temperature**

Some B waste has low exothermicity, linked mainly to the activation products. The heat rating of reference packages B4 and B6 is less than 5 watts per primary waste package when they are placed in the repository (even very much less for some B3 and B2 in particular). B1 and B5 reference packages are more exothermic. Their rating can vary between 5 and 15 watts per primary package when being placed in the repository. Repository compactness, as related to disposal package design and their arrangement in the cells, must therefore be checked to ensure that the ensuing is not excessive with respect to the ability in describing the material changes (see Chapter 5).

In this context, the containment capability or B2 waste is linked to maintaining the mechanical integrity of the bitumen coating. The rheological characteristics of the bitumen coating, however, are only preserved if the coating temperature remains below 30°C. Note nevertheless that this criterion only has a slight actual influence on the disposal package design, given the very low thermal release by these packages.

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[24] This can be done when leaving the industrial storage facility or on entering the repository surface facilities; it is suitable given the small amount of gas produced by radiolysis in these packages (no organic matter).

[25] This corresponds to the validity domain of the models adopted to describe the changes in these packages and the release of radioactive elements.

- **Safety-criticality**

Some B waste (particularly reference packages B3, B4, B5 and B6) come from spent fuel reprocessing and therefore contain traces of fissile materials. The repository design must ensure sub-criticality in all circumstances.In this context, the B5 reference packages present the most constructing design factors with respect to their potential fissile material content. As for the heat transfer phenomenon, the package design is linked to the cell design from the sub-criticality perspective, particularly as pertains to spacing between packages (see Chapter 5).

4.1.1.3 Investigation into calling on the retention capability of the disposal package

An analysis of the spread of radiological activity in the B waste shows the interest, for some of the waste to study the possibility,of calling on the disposal package for the retention of certain activation or long-lived fission products (niobium-94 (^{94}Nb), zirconium-93 (^{93}Zr), césium-135 (^{135}Cs), etc.). Such a performance in the long term (at the scale of 10,000 years) may be particularly interesting for the B5.2 (hulls and end caps without organic matter) and B1 (activated waste) reference packages, that represent a major part of the B waste inventory for the radionuclides listed above; note that these waste primary packages do not require the disposal containers to be permeable to gas (see above), for they contain no organic matter (see Section § 3.2).

In order to reinforce the confinement capacity of the disposal container, the latter must limit solute transportation. This means that it does not crack under the effect of the mechanical load liable to be applied in the long term. Therfore, the mechanical properties of such a package must be greater than those of a standard package. The set objective is to withstand a mechanical pressure of 12 MPa, corresponding to the long-termground pressure, assuming there to be a rupture in the cell lining.

4.1.2 Design principles adopted

The design of the disposal package is linked to the disposal cell design and the related handling equipment. Consistency in the "package-cell-handling" combination is justified as much by needs for operating safety and reversibility as by long-term safety.

4.1.2.1 Over-packing options envisaged

Several key parameters govern the identification of technical options for B waste over-packing. The disposal package may be cylindrical or parallelepipedal. The package material may be concrete, steel or a "noble" metal (copper, titanium, etc.). The package size and weight may be limited, particularly to allow stacking over several levels in the disposal cell, or conversely without constraints in a repository where no stacking exists. The possible combinations of these parameters are illustrated by the four options presented in Figure 4.1.1:

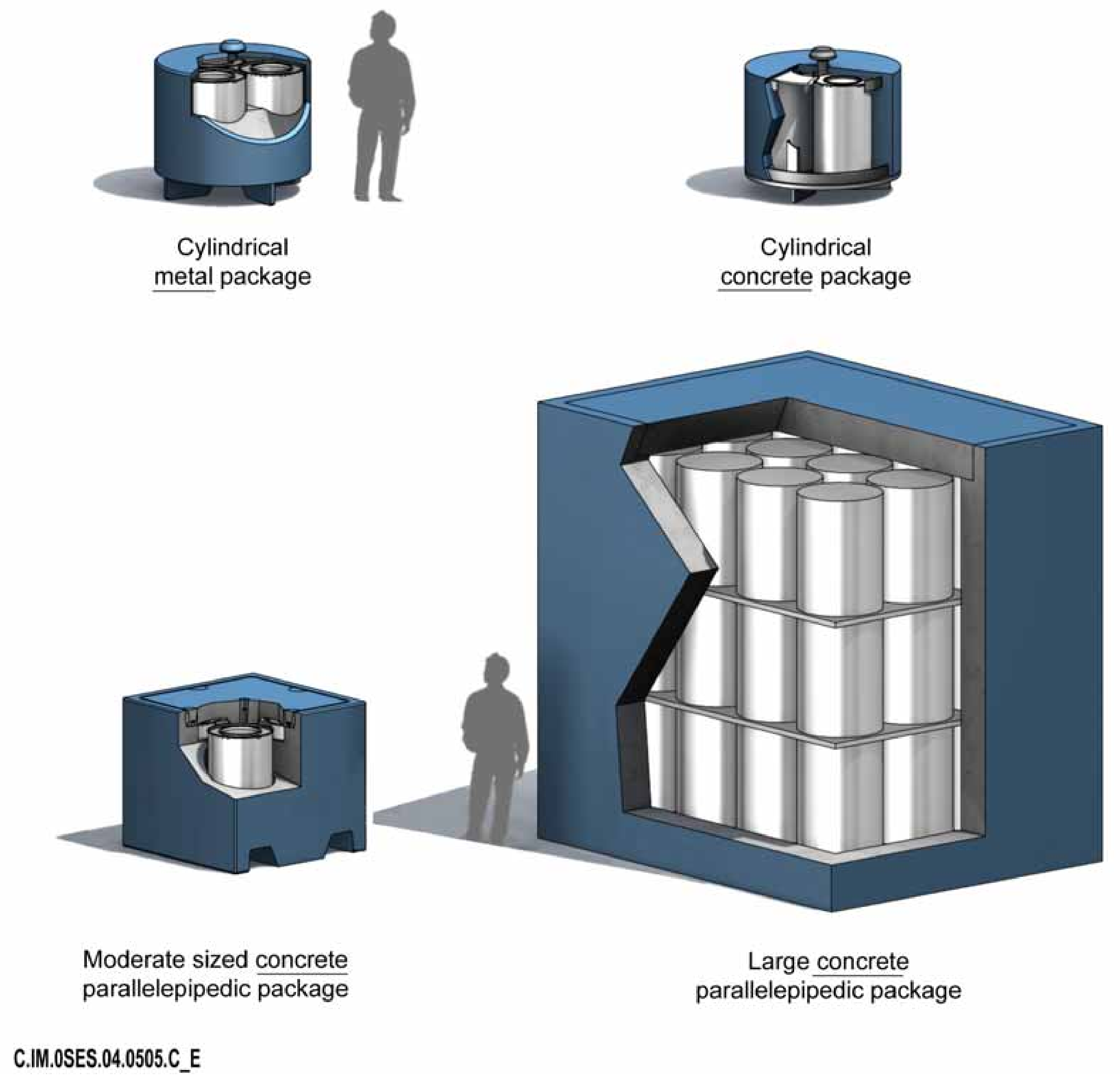

Figure 4.1.1 Options envisaged for B waste disposal package

- **"Cylindrical metal package" option**

In this first option, a cylindrical metal basket forms the package framework. The internal voids are filled with concrete. This package is stackable. In the case of bitumen packages (reference B2.1), this type of disposal package holding three primary packages will weigh around four tonnes, for an external diameter of about 1.4 metres and a height of 1.3 metres.

- **"Cylindrical concrete package" option**

This option is a steel basket holding three primary packages set in concrete. There is a minimum amount of steel. This package is stackable. In the case of bitumen packages (reference B2.1), this type of disposal package holding three primary packages will weigh around three tonnes, for an external diameter of about 1.4 metres and a height of 1.3 metres.

- **"Parallelepipedal, mid-size concrete package" option**

This option consists of a parallelepipedal, mid-size concrete box with cylindrical housings adjusted to the primary packages. This package may be stacked over several levels in the disposal cell. In the case of bitumen B2.1 reference packages, this type of disposal package grouping four primary packages has dimensions close to a cube with sides of 1.5 metres and weighs approximately 7 tonnes.

- **"Parallelepipedal, large concrete package" option**

This option is for a large parallelepipedal concrete box that cannot be stacked in the cell.

The thickness of the external wall could be sized to reduce the dose rate on contact to a value compatible with operator presence around the disposal packages; Andra has therefore been able to use this option to examine an alternative to irradiating cells, whilst seeking the simplification of operating processes.

In the case of the bitumen B2.1 packages, this type of non-irradiating disposal package, containing 60 primary packages (superposed over three levels) weighs in the order of 110 tonnes. It will be 4.4 metres long, 3.7 metres wide and 3.9 metres high.

4.1.2.2 Comparison of options

- **Waste disposal package shape**

A cylindrical shape has the major disadvantage of leaving fairly large residual voids between the disposal packages, even when they are in contact with one another. A parallelepipedal shape, however, responds more favourable to concerns over compactness and minimising voids. Regularity in clearance between the packages after emplacement limits the void rate and avoids the need for backfilling. This assumes that the waste disposal package is a solid object, limiting the internal voids around the primary packages.

- **Material used in the waste disposal package**

The primary waste packages are surrounded by concrete in all the options presented above. This is an ideal material for large volume use, given its strength and relatively low density.

The question is raised over the interest in adding a metallic envelope, as in the first option above. This type of addition is not justified with respect to the mechanical integrity of the package, given the durability and strength of concrete. Such an option could be effective with respect to the containment of gaseous radionuclides released by some primary packages; a leaktight seal for the primary container would appear simpler, however.

Note that the alkaline environment produced by concrete seems overall favourable to limiting the release of radionuclides into the geological medium. This assumes nevertheless limiting the pH to 12.5 to remain within the validity domain of the models describing the release. In addition, the concrete formulation should limit the amount of water and organic matter contained in the concrete, particularly with respect to the radiolysis mechanism and resultant gas production (hydrogen).

- **Dimensions and weight**

Large containers offer several advantages. The number of objects requiring handling underground can be reduced and transfer flows in the cell minimised. In addition, as these packages are not stacked in the cell, the overhead clearance remains low during handling operations. There is virtually no risk of falling. Lastly, the incorporation of radiological protection as in the option presented above negates the need for a transfer transfer cask in the connecting drifts and the installation of a radiological protection air lock at the cell head.

They are less favourable to the search for compactness, however, than the stackable containers. The section in the access drifts to the cells may have to be increased to deal with the container size, which may also present a handicap for transfer through a shaft.

The "stackability" of mid-size packages optimises the geometric shape of the "cell-package" combination, resulting in greater repository compactness. They are more suitable for transfert through a shaft and allow to optimise the access drift cross section.

4.1.2.3 Solution adopted

The solution adopted is a concrete, parallelepipedal container. It weighs less than about 25 tonnes. It can group up to four primary waste packages per waste disposal package [41].

The external geometry of the container is standardised according to a limited number of models. Its width and height are limited to 2.5 metres. Its length (dimension sideways to cell) may exceed 2.5 metres, but no more than 3 metres, for some primary packages. It is stackable over several levels in the disposal cell.

The parallelepipedal shape allows to minimise the external residual voids and at the same time facilities possible retrieval with the simple, robust handling methods used for the emplacement. The solid concrete design inside the disposal package ensures that the residual voids around the primary packages are virtually negligible.

Concrete also provides mechanical integrity for a period of at least one hundred years with respect to possible package retrieval.

For primary packages releasing hydrogen through radiolysis, the risk of excessive accumulation in the container can be avoided by creating vents in the over-packing. Note also that as long as the concrete is in a dry atmosphere, the porosity alone of the concrete will evacuate the hydrogen sufficiently.

Lastly, the disposal package is not designed to guarantee radiological protection with respect to external exposure to radiation.

- **Grouping of primary waste packages and standardisation of disposal containers**

Waste disposal package standardisation meets the need for simplicity and reliability in operation and the limiting of the flow of parcels to be handled, while respecting package grouping possibilities in the cells based on their physico-chemical and radioactive characteristics. Thus all the diverse B waste in the inventory presented in Chapter 3 may be disposed of based on seven dimensional classes of waste disposal package.

Most disposal packages (over 80%) have standardised lengths and heights of between 1.5 and 2.1 metres. These disposal packages all contain four primary packages.

The other disposal packages (under 20%) are larger. They are between 2.5 and 2.9 metres long and 1.7 and 2.4 metres high. These disposal packages contain four primary packages, or only one or two in the event the primary waste package are very large.

- **Make-up of a standard disposal container**

A disposal container (Figure 4.1.2) is made up of two, pre-fabricated concrete components: a body and a lid.

The body has internal partitions forming the compartments adjusted to the primary package shape. The clearance between the internal diameter of each compartment and the external diameter of the primary package is sufficiently large (functional clearance) to emplace the primary packages and sufficiently small (small residual void) not to require filling once the primary package is in place. This approach favours the possible recovery of the primary packages and avoids filling operations in an irradiating environment.

Once the primary packages are in place, the detachable lid fits into the container body.

The principle for handling the disposal containers in the cell was chosen for its consistency with the objective of minimising the cell section and limiting the voids. Crane and gantry crane handling was thus discarded, for it would require an area in the upper part of the cell that could not then be used for disposal. The principle adopted is gripping the bottom using a type of fork-lift truck (see section 9.3.2), which implies the needs for designing openings in the base of the container.

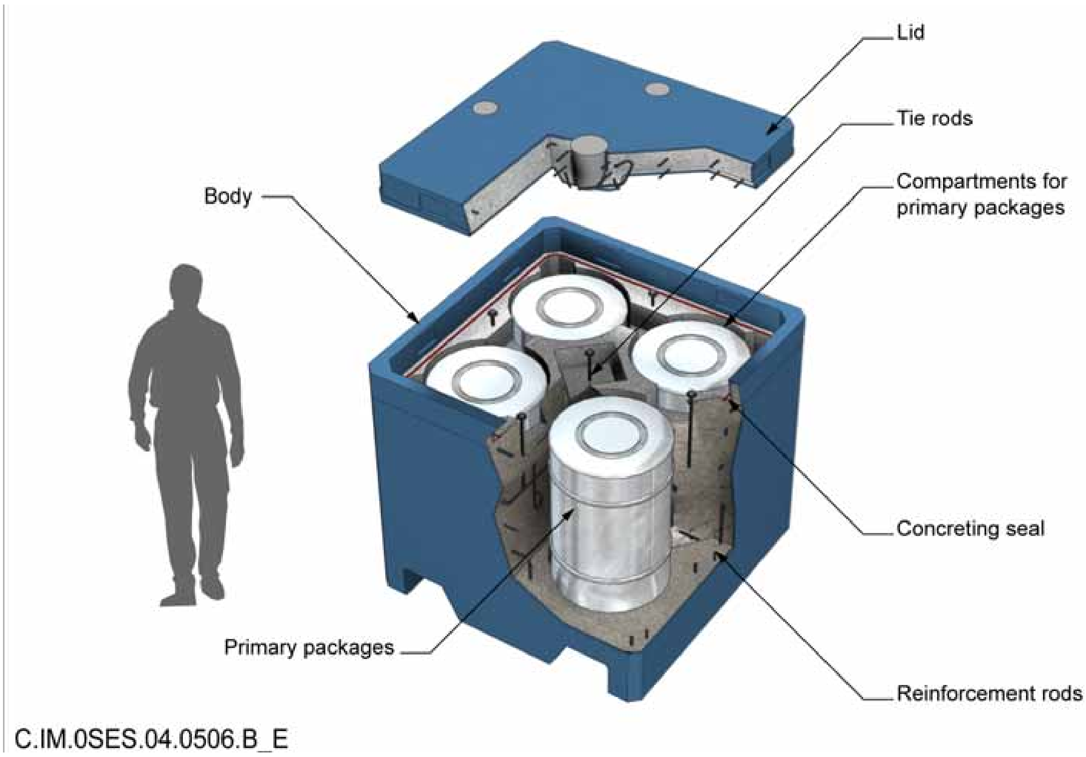

Figure 4.1.2 Standard disposal container (illustration for B2 reference package)

- **Variant on the possibility of calling on the retention ability of concrete in the waste disposal package**

A variant to this container has also been studied, which would call on the long term retention ability of the disposal package concrete (see § 4.1.1.3.). This variant only concerns primary waste packages that do not release gaseous elements (hydrogen in particular).

This variant would thus serve to delay the migration of radionuclides during a very long period (scale of several thousands of years). To achieve this, low permeability and a low diffusion coefficient at package scale are necessary, as well as long-term mechanical integrity. This leads to the quest for a compact concrete (low porosity). Low porosity limits both dissolved radionuclide transportation and concrete degradation. Concrete degradation is reduced even more as it is difficult for the water and the dissolved species to move through it.

One possible method of producing this variant (Figure 4.1.3) is to include a pre-fabricated body with housings adjusted to the size of the primary packages, as for the standard package. However, the pre-fabricated lid of the standard package is replaced by lids (or plugs) poured into each individual housing once the primary packages are in place.

The performance of the long-term disposal container are not only based on the thickness and performances of the concrete used, but also on the quality of the connection between the body and the poured lid. From this latter point of view, the adoption of small lids sized to each housing (diameter in the order of 600 mm) could limit the problems of recovery and fissuring.

The dimensions and weight of this variant are similar to a standard package.

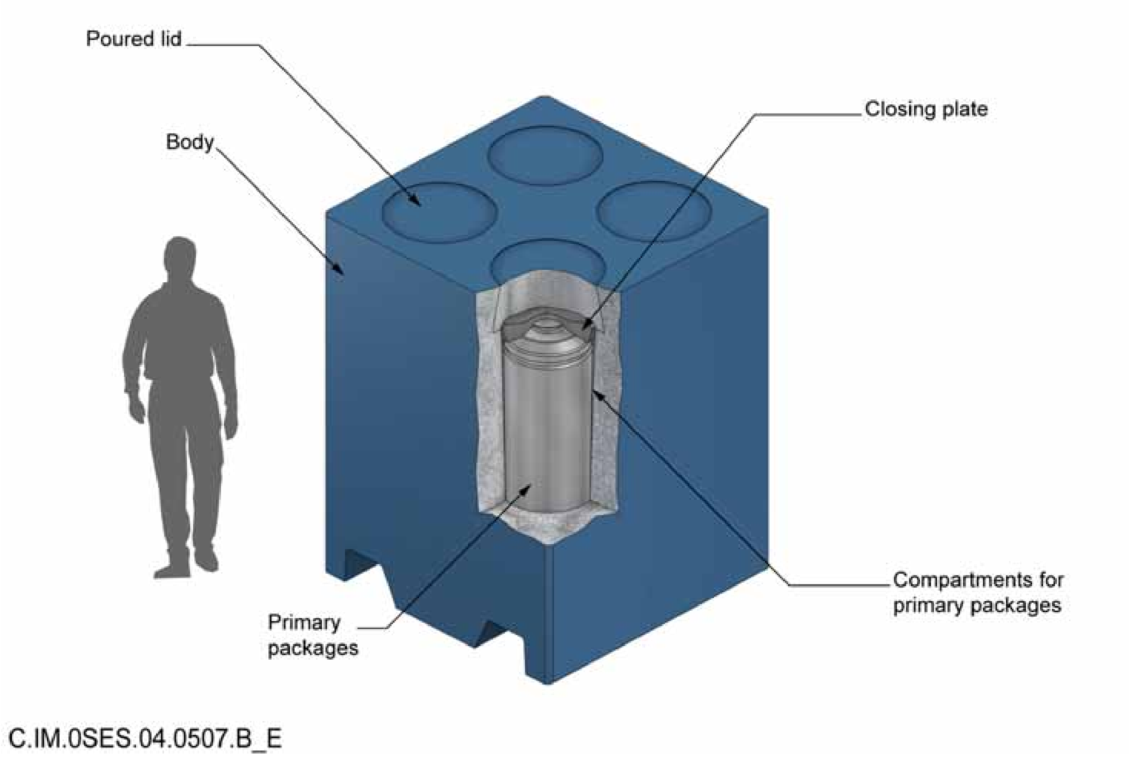

Figure 4.1.3 Disposal container with reinforced retention ability (illustration of B5 reference package)

4.1.2.4 Comparison with the options studied in other countries

The solution adopted by Andra is similar to the B waste package concepts studied in Japan and Switzerland.

- **Options studied in Japan (RWMC)**

The Japanese agency RWMC is carrying out a research and development programme on conditioning waste equivalent to the French category B in disposal packages, particularly bitumen waste and the hulls and end pieces. Three disposal package concepts are being studied at the same time:

- a concrete, parallelepipedal-shaped package
- a carbon steel package (one cylindrical, one parallelepipedal)
- a package coated with a titanium alloy.

For the concrete package concept, RWMC has formulated two types of needs leading to two variants of this package.

The first variant ("package 1" [42]) satisfies a mechanical integrity need for about 100 years. This disposal package comprises a pre-fabricated, reinforced concrete box with a lid held by bolts. The primary waste packages are placed in contact with each other inside the disposal package and the internal voids are filled with a filling mortar with sufficient porosity for hydrogen to circulate. Its dimensions correspond to a cube with sides of about 2 metres. It weighs between 30 and 35 tonnes depending on the type of waste. It contains sixteen primary containers (CSD-C) or eighteen 220-litre drums containing bituminized sludges (nine drums superposed on two levels).

The second variant ("package 2" [43]) only relates to compacted hulls and end caps (CSD-C). It satisfies a containment need of 60,000 years. This disposal package consists of a metallic compartment containing six primary packages, poured within a ultra high-performance fibre-reinforced concrete monolith (200 MPa). The internal voids in the metallic compartment are filled. Its dimensions correspond to a cube with sides of about 1.8 metres. It weighs 13 tonnes. The package is designed to resist isostatic stress of 13.5 MPa.

This design has given rise to a technological demonstration programme. Monoliths without fissuring containing dummy, non-irradiating waste packages have been produced at reduced scale (600 mm) by continuous poring of ultra high-performance concrete.

- **Swiss design (Nagra)**

The Opalinus Clay project [44] run by the Swiss agency Nagra[26] relates to a B type waste (known as intermediate level waste ILW) repository feasibility study in a clay medium.

Nagra also envisages waste over-packing in a concrete disposal container. The packages being considered are parallelepipedal concrete boxes stackable over 2 to 3 levels. Their dimensions correspond to a cube with sides of about 2.40 metres. They hold nine primary packages of compacted hulls and end caps (CSD-C) or eighteen 220-litre drums containing bituminized sludges.

The primary waste is placed in a pre-fabricated box. Mortar is used to fill the voids in the disposal container and to create a lid poured over the waste.

The hydrogen produced by radiolysis or corrosionis evacued through a free volume corresponding to concrete porosity of 25%.

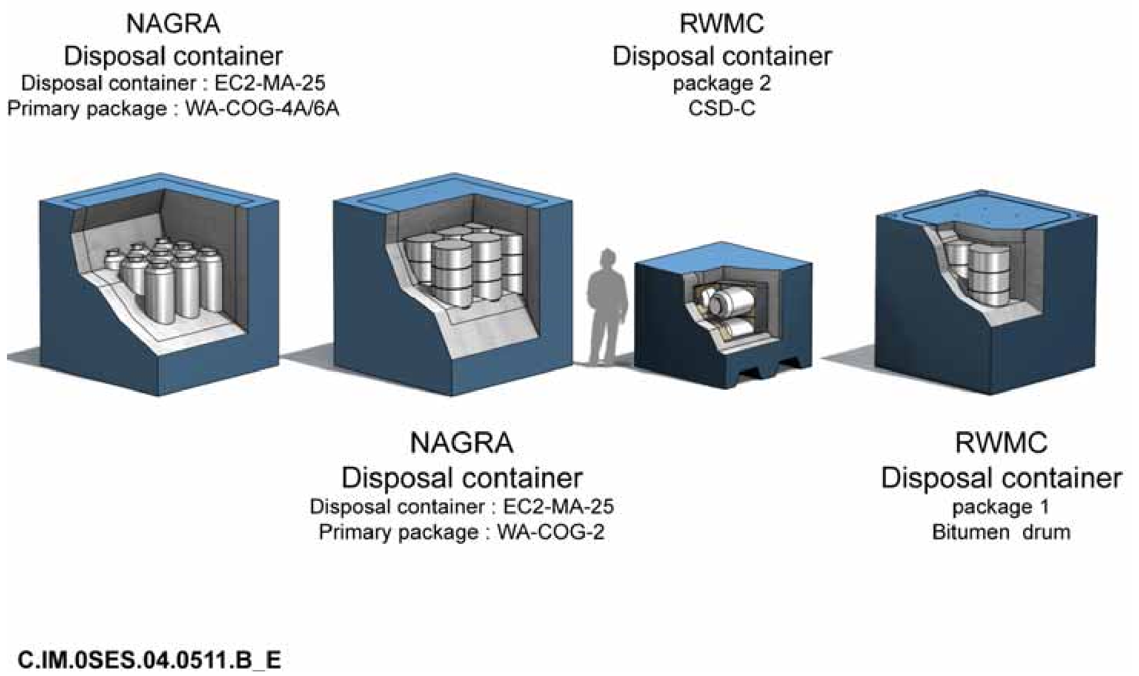

Figure 4.1.4 Waste disposal containers studied by RWMC and Nagra

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[26] National Cooperative for the Disposal of Radioactive Waste

4.1.3 Description and design of a standard container

This section describes the design parameters for the solution adopted for the standard container in greater detail. The disposal container presented here satisfies both the needs of a repository expressed previously and those of long-term storage, which is the waste management path studied by the CEA. It has therefore been designed by joint CEA and Andra collaboration. The mechanical design and the compatibility of the object with the handling processes are presented [41].

4.1.3.1 Description

The container body and lid are pre-fabricated in reinforced, concrete[27] which also containers as small amont of fibres. The fibre content (25 to 30 kg/m^3) prevents heterogeneous fissuring of the concrete from shrinking during curing; shrinking can then only be caused by micro-fissures spread homogenously, that will not weaken the object.

To limit risks of corrosion and improve the mechanical durability of the container, stainless steel has been adopted for the reinforcements and fibres. Note that in a repository situation, the very low humidity expected in the cells while oxidising conditions are prevalent would nevertheless limit the risk of corrosion of non- or low-alloy steels reinforcements and fibres or in steel casting for the fibres.

The body is in high-performance concrete with 75 MPa compressive strength and the lid in 60 MPa high-performance concrete. The lid consists of a plate placed on the inside sill of the side walls in the body (Figure 4.1.5), with five bushings (1 central and 4 around the edge) to carry the bolts fixed in the body (see below).

To evacuate the hydrogen produced by the vast majority of the primary packages, vents can be added to the top of the container body. These vents comprise a cylindrical opening reserved during the pre-fabrication of the container body and are located on the two opposing faces of the container, to allow the hydrogen to be diffused outside the disposal package.

A second hydrogen evacuation method is also taken into account in the container design, to ensure compatibility with the long-term storage specifications. This involves diffusion through the concrete in the lid. The result is a specific concrete being chosen for the lid with its thickness limited to 150 mm at this stage. These specific lid characteristics make it permeable to hydrogen without the need to provide vents for long-term storage[28]

To close the container, the lid is keyed mechanically to the body using a cementitious material poured into a groove formed between the body and the lid. Filling the lid bushings with the cementitious material seals the bolts to the lid. The sealed bolts help to unite lid and body and minimise the risk of the lid being torn off during a fall.

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[27] Variants limiting the reinforcements, but with added fibre content have also been studied. A first variant thus consists of a fibre-reinforced body with over 50 kg/m^3 fibre contact and a reinforced, lid containing a small amont of fibre. The over all dimensions, body geometry and reinforced lid remain unchanged. A second variant with no reinforcement would require a concrete lid thicker than 150 mm, which is incompatible under current knowledge with hydrogen being evacuated through the concrete porosity (long-term storage situation).

[28] At this stage in the studies, it is considered that the vents are blocked during storage and freed if necessary when the container enters the repository.

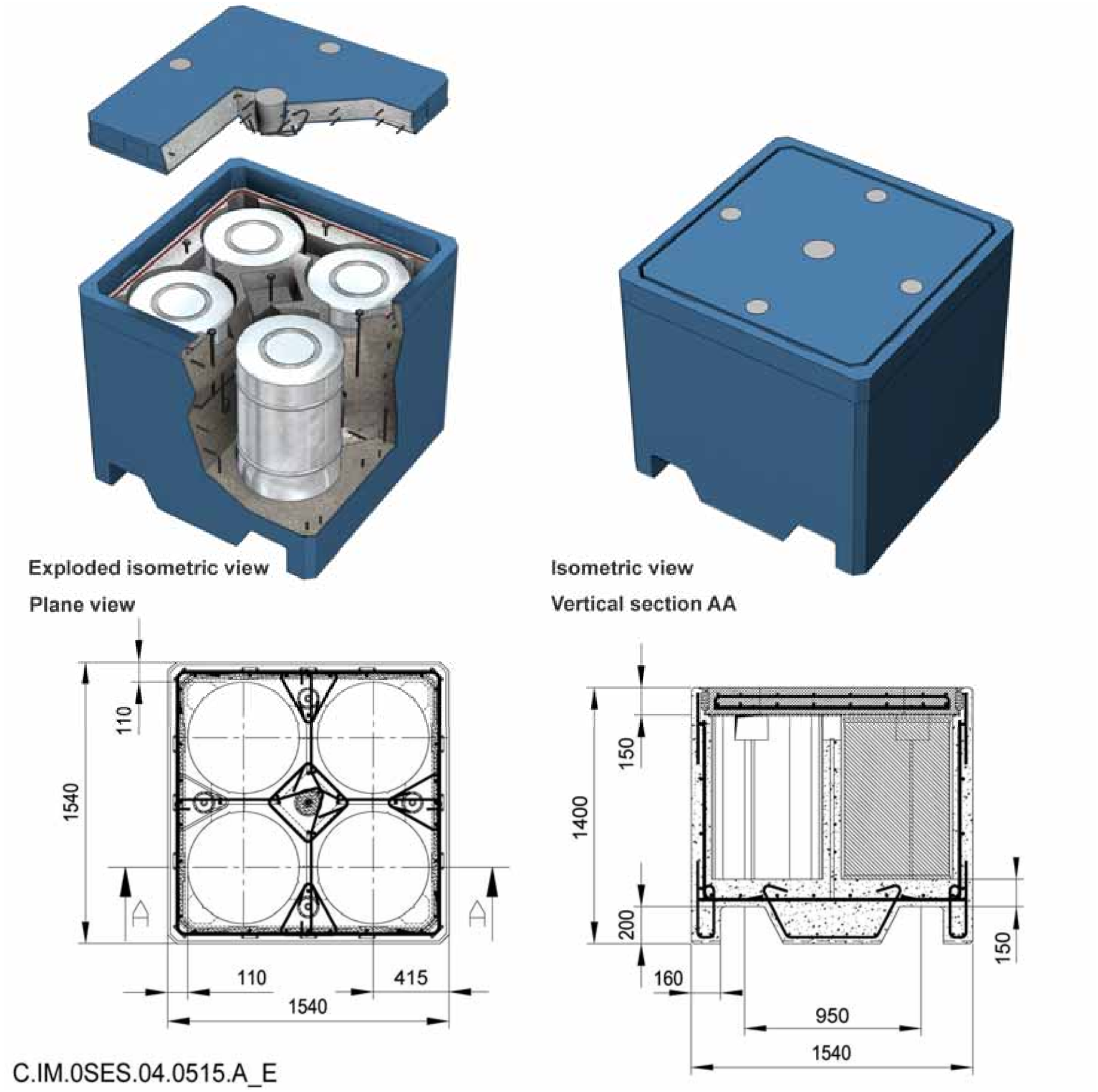

Figure 4.1.5 Standard disposal container (illustration for B2.1 packages types)

4.1.3.2 Mechanical design

Under normal repository conditions, the mechanical load to be resisted by the standard packages corresponds to their stacking in the waste disposal cell. A vertical misalignment of 20 mm between two successive packages is also taken into account. This load situation leads to verifying that the concrete package walls are dimensioned correctly, but generates no requirement for the lid.

Static dimensioning calculations have been carried out based on the Eurocode 2 rules [45].. The dimensioning element for the body is the zone under tensile stress in the vertical walls, given the acceptance of the stacking misalignment. The minimum thickness for the concrete walls (110 mm) is defined so that the reinforcements may be installed and coated with concrete. Given the choice of a high-performance, reinforced concrete with 75 MPa compressive strength for the body, the wall strength capacity at its minimum thickness is far superior to the forces induced by the loads [41].

As indicated above, the behaviour of the waste disposal package should also be assessed in a situation of falling in the cell. It should be verified, therefore, that deformations to the primary waste packages are sufficiently small to maintain the containment of the radioactive materials and that, in the case of an eventual loss of containment, this is compatible with the evacuation possibilities through the ventilation system.

To achieve this, dynamic simulations of the fall have been produced by a finite-element calculation with an assessment of the load resulting from the impact. A reducing coefficient of behaviour is applied to constraints produced by the finite-element calculation, to take account overall of the dissipation of energy linked to local crushing. This coefficient is established by analogy with seismic behaviour studies. Simulations have been performed on waste disposal packages with and without reinforcements. The results of these calculations show that primary waste package containment is maintained for the majority of packages, with slight damage to some primary waste packages, and that the waste disposal package lid does not open even when damaged (see § 11.8). A fall test programme for container demonstrators is in progress in 2005 to confirm the conclusions of these simulations.

4.1.3.3 Handling interface

The principle of package handling in the repository waste disposal cells is based on using a type of fork-lift truck (see § 9.3.2). The forks take hold of the disposal container via two housings set into the package thickness. The cross sections for the fork housings are standardised at 200 millimetres by 200 millimetres approximately.

The inter-axial distance between the forks may be standardised. Two types of packages are envisaged from this viewpoint. The lighter packages (weighing between 6 and 15 tonnes) holding four primary packages (as packages B2 and B5) have a standardised inter-axial distance between forks of 950 millimetres. The heavier packages (between 15 and 25 tonnes approximately) holding one, two or four primary packages have a standardised inter-axial distance between forks of 1,600 millimetres.

4.1.4 Variant with enhanced retention capability

As indicated in § 4.1.2.3, the study of a variant aims to evaluate the possibility of making use over the long term of the waste disposal package concrete retention capability.

One possible method of producing this variant is described below, based on the B.5.2 waste package type (package with hulls and end caps and compacted metallic technological waste), representative of the most active B waste packages containing long-lived activation and fission products (^{94}Nb, ^{93}Zr in particular).

4.1.4.1 Description

This variant differs from the previous one in that it uses a single formulation of concrete for all the package components, there are no steel reinforcements, these is reinforcement by fibres and it has a specific closing method. The lack of steel reinforcement favours the durability sought for this container but implies a higher fibre content to ensure mechanical strength.

The method considered for production of this variant is to include a pre-fabricated body with compartments adjusted to the size of the primary packages, comparable to the standard package. The container is closed by four independent lids poured into the upper part of each of the four housings in the body. Prior to pouring the lid, a pre-fabricated, conical plug (with the purpose of blocking the functional clearance) is placed above the primary package in each housing. Using pre-fabricated plugs simplifies any eventual recovery operation of the primary packages and guarantees a good mechanical connection above the residual voids in the housing.

The pre-fabricated body and the four poured lids are manufactured from a same high-performance concrete with stainless fibres (90 MPa minimum, see below). Stainless is chosen to limit the risks of corrosion.

This variant is illustrated below (Figure 4.1.6). It is about 1.50 metres wide and long and 2 metres high (package type B5.2). Its total weight (full container) is around 12 t.

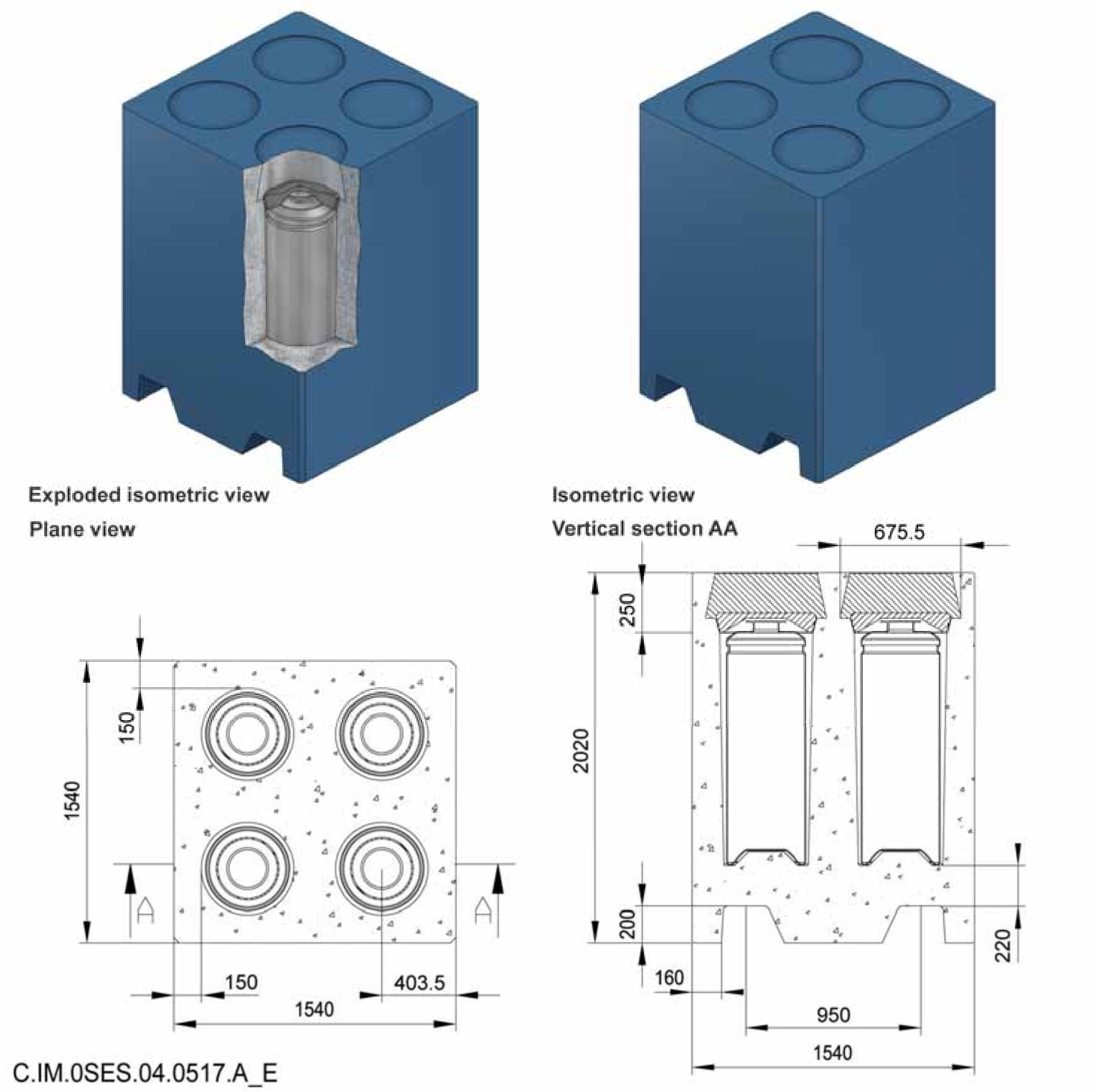

Figure 4.1.6 *Variant of container with reinforced retention capability (illustration of B5.2 package type)*

A perpective of an alternative container manufacture, called a monolith, may also be considered. It would be made up of a continuum of high-performance concrete poured in a single operation around the primary waste packages. The uniformity of the pouring could thus prevent discontinuities from construction joints between the container body and closing lids.

An option for the manufacturing of such an object could lie in using a concrete with accelerated curing from using a suitable admixture; this would give the concrete sufficient mechanical strength to support the primary packages during manufacture. Specific questions on this manufacturing option relate particularly to the concrete formulation, the principle of holding the packages in their correct position during the pouring operation and controlling the so-called "hindered" recovery to prevent fissures forming.

As indicated above, the Japanese agency RWMC has studied this type of solution and produced successfully a demonstrator at 1/4 scale with a metal, parallelepipedal basket. The concrete used is Ductal® high-performance, fibre-reinforced concrete.

4.1.4.2 Enhanced retention capacity

For durable mobilisation of the concrete retention capacity, a concrete must be defined which has very good intrinsic properties in terms of density, and the state of cracking linked with conditions of prefabrication and package closure must be controlled.

In terms of material, the considered concrete mix airs at high performances (permeability less than 2.10^{-13} m/s, diffusion coefficient less than 2.10^{-13} m²/s, and porosity of 10 % at most). A thickness of 150 mm has been selected.

Particular attention must be paid to the junction of each housing between the body of the container and the concrete cast during the second phase. Design provisions have been studied to provide a good body/lid connection: limiting the diameter of the cast lids, reducing any shrinkage which could generate microfissures, a circular shape avoiding particular zones, choice of profile for the interface based on feedback from existing packages (packages of waste showing low and medium activity disposed at the Aube Centre). A programme of tests on this junction is being performed in 2005 to make sure that there are no weak points.

4.1.4.3 Mechanical design

Compared with the standard package, removing all reinforcement reduces tensile strength, which becomes the most restrictive characteristic for design. It is therefore a good idea to limit tensile stress liable to create cracks or propagate them, and to reinforce the intrinsic characteristics of the fibrous concrete by increasing the quantity of fibres (55 kg/m^3 to 90 kg/m^3 depending on the type of fibres chosen) and the compactness of the concrete. A minimum resistance of 5 MPa in traction/deflection is the target.

The principle of housings with separate cast lids provides an adequate structure which limits tensile stress in the concrete (limiting amplitude and the extent of the zone subject to tensile forces above the package housing).

Mechanical design is based on a pressure load to be applied uniformly to the container. Waste disposal containers will be loaded gradually in the long term, depending on the evolution of the waste disposal cell sleeve and argillite creep. An isotropic pressure of 12 MPa has been set for package design. This value is considered to set the limit of uniform loading which may be applied in the long term[29].

Design calculation was conducted according to Eurocode 2 regulations [45], in particular as pertains to selecting penalising safety factors used to take into account geometric faults and operating tolerances for the containers, plus an extra safety ageing factor which incorporates deterioration of the concrete in the long term[41].

The application of these very severe conditions for compression and traction stresses means that a high performance concrete (HPC) with a compression strength of 90 MPa is preferred, to ensure that the traction-compression criterion is met at every point with an additional safety margin. The high value of dimensioning stress used (12MPa) means increasing the thickness of inner partitions (220 mm) and outer walls (150 mm already specified to delay radionuclides) relative to the standard disposal package (inner partitions and side walls around 110 mm thick) to reinforce the mechanical strength of the structure. This element favours the choice of separate lids which will reduce the space taken by lids above the housings.

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[29] For this load, the stresses engendered when the packages are emplaced, due to faulty alignment by 20 mm noted in the previous section, appear negligible relative to the 12 MPa exerted in the long term.

4.1.5 The concrete used for disposal containers

The material requirements deduced from current standards in the concrete construction field [46] generally include mechanical considerations and secular durability of the structures.

Within the context of container studies, Andra and the CEA have followed these standards; they have also completed them with stricter requirements. The solutions given here are therefore based on scientific studies concerning the durability of concrete on the centennial scale [47] [48]. These studies, including laboratory tests, have been conducted since the beginning of the 1990s, both in France and abroad. Industrial suitability checks are subsequently made of the adopted solutions.

The concrete used for disposal packages consists of four groups of materials:

- cement, mineral additions and water;
- admixtures;
- granulates (sands and gravels);
- reinforcements and/or metal fibres.

This section is devoted to defining the characteristics of each of them. It presents the respective contributions to global package performance.

4.1.5.1 Technical translation of expected performances

It will be noted first of all that there is strong coherence between the durability of concrete and its retention capacity. Indeed, to meet its objectives, concrete needs to be very compact (low porosity), with a very low diffusion coefficient and reduced permeability (no open porosity or cracking). These qualities promote concrete durability because they protect the concrete from penetration by water and hence prevent chemical alteration reactions engendered by the presence of water. They are also favourable to retention potential.

The ability to use the material and obtain the best possible quality initial condition (i.e. with cracking as limited as possible in opening and in length) depends on:

- low hydration heat;
- limited endogenic shrinkage;
- adequate relaxation of constraints generated early on by deformations blocked in the structure.

Apart from the above characteristics, concrete durability also depends on preventing concrete pathologies such as alkaline silica and alkaline granulate reaction, sulphate attack, hydrolysis and carbonation [47].

The consequences of a reaction between certain granulates (containing amorphous or poorly crystallised silica) and the alkaline interstitial concrete solution are that the reactive silica dissolves. This leads to the creation of a gel, which is more or less crystallised, with a larger volume than the initial reagents. The concrete can crack under the effect of this expansion. In the same way, the consequences of sulphate attack can be measured in terms of mechanical deterioration of the concrete. Indeed, precipitation of expansive compounds (mainly sulphate-aluminates) leads locally to mechanical stresses which exceed the material's capacity, thus creating severely cracked zones. The choice of non-reactive granulates and cements with a limited concentration of tricalcium aluminates (C_3A) helps control these pathologies.

The main consequence of hydrolysis of cement materials is loss of the acid-base buffering capacity by dissolution of the main concrete hydrates. This leads to a major loss of mechanical properties. One way of limiting propagation of this concrete deterioration front is to use materials which are not very permeable. Concrete carbonation, negligible as long as the environment is not resaturated, has the initial consequence of limiting concrete transfer properties (lowering porosity) and thus limiting propagation of the deterioration front by hydrolysis, for example. But eventually, this "passivating" layer is destroyed by other concrete deterioration phenomena, in particular the solubilising action of water [30]. Here again, by choosing concretes with low permeability, the zone affected by carbonation of package concrete can be limited in extent.

The materials used for the concrete are chosen on the basis of the above information. Note that this choice does not apply to the formula used for the standard container lid, defined specifically to promote the diffusion of hydrogen.

4.1.5.2 Cement, mineral and water addives

- **Cement and mineral additives**

The recommended cement is the "mixed" type. It is characterised by a ternary composition (e.g.: CEM V or CEM I with added silica fume and fly ash). This choice reduces hydration heat and produces concrecte with a better developed microstructure. This produces more compact, less porous, less permeable concretes.

The concentration of tricalcium aluminate clinker (C_3A) is limited to less than 5%. This choice[31] minimises physical disorder (risk of cracking) due to exothermicity of the tricalcium aluminate (C_3A) hydration reaction.

The quantity of alkaline elements (K and Na) in the cement, adjuvants and other constituents is as low as possible, to limit the risk of silica alkaline reaction (level of alkaline Na_2O not exceeding 0.6%).

The class of cement resistance to obtain a high performance concrete (HPC) class of concrete must be at least 42.5 Mpa.

- **Water dosage and ratio of total water to total cementitious material**

The weight ratio of total water (W) to total cementitious material (e = cements plus mineral additives) must be less than 0.40. To ensure that this is the case, apart from using a reasonably maximised dose of cementitious material, water (W) must also be minimised. A reasonable quantity of cementitious material, in line with taking into account an aggressive environment and current normalisation, is within the range of 300 to 550 kg/m3.

This choice makes a significant contribution to obtaining highly compact concrete, i.e. minimising porosity. This provides better protection from chemical attack and improves mechanical and confinement performances.

The low dose of water also helps limit the hydrogen source term by radiolysis of the envelope, particularly for disposal containers holding primary irradiating packages type B1 and B5 in particular.

4.1.5.3 Admixtures

For implementation, admixtures must be used. They compensate for the low water content, providing the concrete with the fluidity required for pouring. However, since admixtures are mostly organic materials, the dosage must be adjusted to limit the quantity of complexing species likely to influence radionuclidesolubility and sorption.

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[30] However, this carbonation phenomenon will take place essentially at the interface between B waste disposal cells and the geological medium and will not concern the packages directly.

[31] The cements selected to meet this objective are PMES (Cured sulphated seawater*)* which also provides a weapon to combat sulphate attack.

4.1.5.4 Granulates

The choice of granulates (sands and gravels) results from the objective of preventing alteration phenomena due to alkali silica reaction.

Considering the time scales considered, particularly for the variant with reinforced retention capacity, the granulate must be a physicochemically stable limestone. Dolomitic limestones (containing Magnesium), or limestones with a high alkaline content, must be avoided. The limestone granulates envisaged must contain at least 95% calcium carbonate ($CaCO_3$). The impurities constituting the remaining 5% must also be free of any alkali silica reaction.

The diameter of granulates must be limited (dimensional classification less than 12.5 millimetres) to improve the concrete's mechanical strength and density. The granular section can also be refined to improve the concrete's density to improve performance and facilitate concrete casting (injection, possibility of pumping). Finally, the granulates must be non-reactive.

4.1.5.5 Fibres and possible reinforcement

Fibres and any reinforcement used aswer the mechanical reinforcement and durability needs of the container.

The use of stainless steel reinforcement rods and/or fibres avoids the risk of cracking linked to the expansion of non-alloy steel corrosion products. It should be noted that the level of concentration of chlorides in the water, which is likely to reach packages in a disposal context, will have no effect on stainless steel corrosion.

The addition of fibres to the concrete improves the quality while reducing the risk of microcracking and provides characteristics of ductility and tensile strength. A tensile strength of 5 MPa has therefore been targeted.

However, the role of fibres only helps to stop crack initiation under traction if the physical properties of the concrete matrix are such that the material has high levels of ductility. Otherwise, the fibres only absorb the stress after cracking has started.

4.1.5.6 Formulation, industrial implementation tests and performance obtained

Several concrete formulations have been developed in the laboratory, then tested using industrial suitability tests. During these tests, particular attention was paid to the "pumpability" of the concrete, linked to the size of the granulate and dimension and shape of the fibres. A self-placing concrete was therefore sought, which does not need vibration to position it.

Two types of formulations were developed:

- an initial formulation basis was defined using CEM I with the addition of 10% silica fume on the one hand and limestone filler or fly ash on the other, for a total mass of cementitious material close to 500 kg/m3 and between 170 and 200 kg/m3 of water. The W/C ratio obtained is less than 0.35. Granulates and sands are Boulonnais limestone for a total mass of around 1700 kg/m3. The fibres are stainless steel hooked fibres for 30 kg/m3 (or 56 kg/m3 for the variant without reinforcement).
- a second formulation basis was defined using CEM V with the addition of 5% silica fume for a total mass of cementitious material close to 500 kg/m3 and a mass of water between 170 kg/m3. The water/cementitious material(W/C) ratio obtained is less than 0.35. The fibres are stainless steel straight fibres for 85 kg/m3.

Furthermore, the specific formulation for the lid of the standard package (hydrogen porosity) was developed on the basis of CEM I with limestone filler but no silica fume and only 25 kg of stainless steel hooked fibres.

The formulations developed and used to produce demonstration models allowed to reach the fixed objectives.

4.1.5.7 Evolution of pH in a disposal situation

The choice of materials and development of the formulations presented above means that a target pH for fresh concrete can be set at 13, which will rapidly fall to around 12.5 once the concrete has matured. Then, depending on the evolution of the concrete and its chemical breakdown, particularly by hydrolysis, the pH will fall very slowly to a pH of about 10.5 in degraded state [48].

4.1.6 Manufacturing techniques

This section presents manufacturing techniques, in the factory and in the surface of installation of repository, selected for standard disposal packages on the one hand and the variant investigating improved retention capacity [41] on the other.

These techniques were implemented to produce scale 1 demonstration containers with artificial primary packages. The work was carried out jointly by Andra and the CEA in 2004 and 2005. For the standard container, two variants have been produced (fibrous reinforced body, and fibrous non-reinforced body) based on B2.1 primary waste packages. For the variant with increased retention capacity, the container with prefabricated body and cast lid for primary packages B5.2 were produced. The manufacturing processes presented here are based on these demonstration models.

Measurement and testing programmes carried out on manufactured objects made it possible to monitor the evolution of the concrete used at a young age and to evaluate the performance of the container - lid bonds as well as the consequences of a package falling or being dropped.

4.1.6.1 Manufacture of standard prefabricated disposal packages

- **General manufacturing principles**

The principle for manufacturing standard packages consists of maximising the number of stages involved in a non-irradiating context, so that the quality of manufacture can be checked as simply as possible and manufacturing costs optimised.

Two types of elements are prefabricated in the factory in a non-irradiating context: bodies and lids.

The other manufacturing operations are performed in irradiation cells:

- loading primary packages;
- closing disposal packages (by concreting joints or cementitious material);
- maturing the body/lid closure seal in buffer storage (for 28 days);
- package inspection before emplacement in the waste disposal cell.

- **Prefabrication process for lids and bodies**

The lids and bodies are prefabricated in a special unit including a concrete plant and a production shop for managing the process, its control and repeatability.

Manufacturing operations consist of moulding the body and lid, then after about 24 hours of prestorage in the moulds, they are stripped and the objects cured, following application of a concrete curing product. Figure 4.1.7 presents the steel moulds produced for standard container demonstration models.

Figure 4.1.7 Body mould for standard container (B2)

The manufacturing processes used for prefabricated moulded fibrous concrete containers are already used in the nuclear industry, where they have been used for more than 15 years. To date more than 45 000 waste disposal containers have been delivered to the nuclear operators COGEMA and CEA. Furthermore, the technology used for moulded reinforced concrete containers has also been used for more than 15 years by EDF for collecting operational waste from French nuclear power plants, at a rate of about 1 200 to 1 500 packages per year.

The method of moulding containers for B type packages, described above, is already used by SOGEFIBRE, in particular for producing CBF-K type cubical containers.

The manufacturing process is no different whether the body of the container is made simply with fibres or with fibres and reinforcement. The only difference is in the prior positioning of the reinforcement rods in the mould.

Figure 4.1.8 and Figure 4.1.9 display the first operations performed to produce these demonstrators and the first standard containers produced as a result.

Figure 4.1.8 Installation of cores in the standard B2 package mould before casting

Figure 4.1.9 Standard container demonstrators.

- **Installation of primary waste packages in an irradiating cell**

Primary packages are handled in a similar method to that used by operators of the nuclear installations from which these primary packages come (see § 9.1.3). Provision is made inside the container to enable grippers for primary packages to pass through.

- **Closing standard waste disposal packages**

Closure is an important aspect of the standard container manufacturing process. The process used consists of closing the package by "hydraulic concrete jointing" between the lid and body. Concrete jointing provides a mechanical link and seal between the lid and the body and prevents the lid from being torn off. It is produced via a groove, several centimetres wide, between the body and the lid, which has a profile which prevents the lid from being ripped off. Fresh concrete is cast in this groove.

At the current stage, the selected solution of a concrete lid, fixed with a concrete seal, is providing important feedback. Concrete jointing is a process widely used on fibrous concrete packages currently used at the Aube Centre (CBF-C1C, CBFK, …). This classic technique has been used since 1990 on Cogema fibrous concrete containers. To date, 8 000 CBF-K packages have been manufactured at La Hague and Marcoule (through put of 400 packages per year). About 200 CBG-K packages have been produced on CEA sites (mainly in Grenoble).

This procedure was also tested as part of the demonstration programme.

4.1.6.2 Manufacture of waste disposal packages with reinforced retention capacity

As in the previous case, the container is put together in two stages. In the first step, the body is manufactured outside a nuclear context. In the second step, the primary waste packages are loaded and closed in an irradiating cell.

Once the primary packages are installed in the body, a packing plug is placed in each individual housing. Each one is then closed by casting concrete. These small closure lids are matured in a buffer storage area (for 28 days) to obtain adequate performances and stabilisation of the concrete so that the container can undergo quality control before being transferred to the repository.

The process of casting lids onto prefabricated bodies benefits from a great deal of industrial feedback; it has been in use since 1990 by COGEMA and EDF for packages showing low and medium activity disposed of at the Aube Centre.

This technique was used by COGEMA to produce more than 35 000 packages in 15 years (CBF-C1 and CBF-C2). It requires a special workshop (AD2 at La Hague) for filling and closing the containers. A similar technique is used by EDF to produce packages for the surface disposal centre [C1PG or C4PG (formulation type F44, reinforced concrete)].

In the context of demonstrator production, and Figure 4.1.10 and Figure 4.1.11 show cores being placed in the exterior mould before the body is casted and the first containers produced.

Figure 4.1.10 Installation of cores in the standard B5 package mould before casting

Figure 4.1.11 Demonstration model of container with reinforced retention capacity

4.2 C waste disposal packages

When reprocessing spent fuel, minor actinids and fission products are separated and incorporated in the glass. In the long term, glass contributes to the safety of the repository. Installed under favourable conditions, it strongly limits the release of the radionuclides it contains with a lifetime of at least one hundred thousand years.

However, during the first few hundred years, the decay of fission products and actinids having average half-lives engenders significant local heating. The mastery of phenomena during this so-called "thermal phase" begs the question of primary waste package disposal in their existing condition or of the advantage of placing them in an over-pack prior to disposal. Based on the current state of knowledge, Andra has chosen the second option.

This chapter describes the scientific considerations which led to this choice, the different technical responses envisaged and the option preferred at this stage of study.

With the aim of evaluating feasibility, it also includes the dimensions of the over-pack and manufacturing techniques based on tried and tested industrial practices.

4.2.1 Description of the main questions

4.2.1.1 Need for an over-pack

To understand the justification of studying an over-pack, we should first remember that the primary package consists of a glass matrix inside a stainless steel envelope. The need for an over-pack results from phenomenological aspects of the so-called "thermal" phase during which the temperature of the package falls gradually after rising to a maximum or "thermal peak"[32]. The phenomena characterising this phase increase the alterability of the glass matrix, influence the behaviour of the radionuclides it contains and weaken the stainless steel envelope of the primary packages with respect to corrosion [37].

Concerning the alterability of the matrix, glass dissolution models take into account (i) a control of the alteration process kinetics by silica dissolution, main constituent of glass and (ii) radionuclide release governed by dissolution congruent[33] with that of the silica. For C1 to C4 type packages, the model preferred for its robustness given strength at the current state of knowledge, consists of two phases. During the first phase, the initial dissolution speed [V_0] results from geochemical imbalance between the glass and its environment. During the second phase, silica saturation of the waste environment is reflected in a slowing of dissolution towards a residual speed [V_R]. For C0 type packages, the dissolution regime according to the initial speed is assumed to continue for a long time. These two speeds, V_0 et V_R, depend on temperature: between 50°C and 90°C, the initial speed of dissolution increases by a factor of 30, the residual speed by a factor of about 15[34][40].

Concerning the behaviour of radionuclides likely to have been released, the question of mastering the thermodynamic phenomena governing chemical equilibria must be considered. Indeed, the physicochemical phenomena involved are temperature-sensitive. Element solubility may be increased or decreased when the temperature increases. The physical data which determine the speciation[35] of an element in solution are known in a temperature range which is currently theoretically limited to 50-60°C. In practice, it is considered that uncertainty in extrapolating speciation evaluated on the basis of equilibrium constants acquired at 25°C, is understood up to 80°C. The temperature also influences sorption mechanisms at solid phase interfaces, as well as the transport of chemical species in water by diffusion (in particular via the "Soret" effect); the speed of diffusion increases with temperature.

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[32] For information, this peak is 100°C at most on the surface of the package.

[33] Congruence means that the same dissolution speed is used for all the species in the glass.

[34] Note also that the description of the passage from V0 to VR may show increasing uncertainty with temperature, because of the extrapolation of thermodynamic data available governing the behaviour of chemical species in solution and at the interface between the liquid and solid phases (sorption mechanisms).

[35] Radionuclide speciation in solution is evaluated on the basis of mass action, enthalpic and heat capacity constants. The last two parameters are particularly difficult to measure directly in temperature; this leads to considering for the speciation models a reactional enthalpy that is independent of temperature and a heat capacity of zero; as a corollary to this, this approximation limits the range of validity of these models..

Finally, since the phenomena described above are linked to the presence of water in contact with the waste, we should investigate the time at which water can actually reach the glass and dissolve the radionuclides. The presence of condensed water from the argillites in the cells, cannot be excluded in the long term [8]. On contact with the primary container, this water would be likely to undergo radiolysis due to the high radioactivity of the waste, leading to a high potential for oxidation. Under these conditions, a risk of penetration of the primary container by corrosion cannot be excluded on a scale of several tens of years. If water comes into contact with the glass at an early stage, this could lead to initiation of radionuclide dissemination.

In conclusion, the sensitivity of glass alterability to temperature, the relative uncertainty of radionuclide behaviour above 80°C, and the risks of the stainless steel envelope being penetrated by corrosion have led Andra to prefer the option of an over-pack to prevent water from reaching the glass at least during the thermal phase, i.e. the phase during which the temperature in the core of the glass is higher than about 50°C.

4.2.1.2 Other needs relative to over-packs linked to safety functions

When the over-pack has lost its sealing function, it should also be ensured that the package environment helps to limit dissolution of the glass and the release of radionuclides.

In practice, it must be verified that chemical interactions between the materials constituting the over-pack, glass constituents[36] and surrounding clay materials can be understood.

Furthermore, it must be verified that there is no criticality risk linked to traces of fissile materials left in C waste packages by reprocessing (C0, C1, C2, C3) or to the presence of fissile materials (C4).

4.2.1.3 Operational needs relative to over-packs

Management of C waste exothermicity, with the aim of making good use of the underground area, has led to Andra preferring a repository architecture which uses horizontal tunnels, as indicated in chapter 2. The over-pack must be designed to be compatible with emplacement operations in horizontal tunnels. Within the terms of reversible repository management, it should also be ensured that it can be removed for at least a century.

4.2.2 Selected design principles

4.2.2.1 Options considered

Several key parameters govern the design of the over-pack: the type of materials, method of assembling the over-pack components and the number of primary packages per over-pack.

Concerning the choice of materials, a metallic envelope is used to guarantee water-tightness during a long-term thermal phase (on the scale of a thousand years).

Several families of metallic materials have been envisaged. A "noble" metal such as titanium or a passivable alloy (based on nickel, chromium or manganese) could be used in thin layers (20 to 30 mm). Copper, for which behavioural data on corrosion under deep water conditions are available [49], may also be considered. However, copper could only be envisaged in association with another metallic material such as steel or cast iron to ensure the mechanical strength of the disposal package, as was the case of the container studied in Sweden by SKB [49] for spent fuel. Finally, thinck (around 50 to 60 mm) non-alloy or low-alloy steel provides another solution. Non-alloy steel is a strong metal routinely used, for which general corrosion processes are well understood.

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[36] This particularly concerns silica sorption by over-pack alteration products and their effects on the change from initial speed to residual speed of glass dissolution (See § 4.2.1.1).

Concerning the method of assembly, the need for water-tightness means that full-penetration welding must be used. From this point of view, various welding processes have been envisaged. They are split into two families: welding with filler metal (TIG "Tungsten Electrode with Inert Gas", MIG, MAG "Metal Electrode with Inert or Active Gas", YAG / Laser processes) and welding without filler metal (Electron Beam and Friction). It will be noted that at the current state of knowledge, sealing by insertable joints does not appear to be compatible with the objective of higt durability.

Concerning the number of primary packages per over-pack, one or two primary packages can be considered in view of considerations of mass and handling in the access shaft and underground drifts.

4.2.2.2 Comparison of the options envisaged and justification of choice

- **Choice of material constituting the over-pack**

"Noble" metals such as copper or titanium are thermodynamically stable under the reducing chemical conditions of the repository. Chromium, nickel or manganese based alloys are capable of passivation through the surface formation of a fine corroded layer which protects the rest of the metal. For thousand-year durability, Andra has performed particularly in-depth studies of passivable alloys from among these materials. However, these high-performance materials appear to be sensitive to environmental conditions (hyperoxidating conditions generated by radiolysis of water, temperature, the presence of aggressive species, particularly chlorides), and could suffer corrosion by pitting, wich would require a probabilistic approach to resistance against localised corrosion.

Non-alloy steels have the disadvantage of being corrodable under repository conditions. However, the process involved in the corrosion of non-alloy steel is now well understood. Concerning aqueous corrosion, a set of experimental results and models show that generalised corrosion is the dominant mechanism in the medium and long term. The speed of generalised corrosion, reflecting the thickness of corroded metal over time, can be quantified on the basis of models which have been validated experimentally. Localised corrosion by pitting or increvices, can be seen in these materials, particularly in the presence of oxygen, but experimentally, the speed of localised corrosion observed in the short term falls faster than that of generalised corrosion so that its relative importance decreases over time. Finally, the risks of specific corrosion such as corrosion under stress or hydrogen embrittlement, remain secondary relative to other corrosion mechanisms. Archeological analogues in iron dating back more than 2000 years support the evaluation of corrosive processes and provide a temporal reference as to the durability of steels over a significant time scale [47].

Moreover, models of non-alloy steel corrosion are tolerant to water chemistry, so that they require less precision in environmental chemical conditions [47]. They are also tolerant with respect to composition of the metal, its structural status and surface condition. This element considerably limits the risk that consequential faults will deteriorate the tightness and durability of the object, in particular along the welds.

Finally, non-alloy steels display very good weldability and provide excellent feedback about welding techniques, tested on thick samples.

In conclusion, non-alloy steel was preferred at this stage, because of the controlled, predictable nature of its corrosion process and because it is easy to weld.

- **Method used for welding over-pack components**

Processes using filler metal such as TIG (Tungsten Inert Gas), MIG (Metal Inert Gas) and MAG (Metal Active Gas) require several successive welding passes. Using these methods leads to long welding times, making these processes unsuitable for welding very thick parts. They also engender considerable extension of the heat-affected zone.

The YAG Laser (Yttrium Aluminium Garnet) process is a recent process using filler metal. Its application to thick steel is still in the development stage[37]. On the other hand, this process has industrial references for welding thin steel up to 10 millimetres (Tokaï Muraï factory in Japan, MOX workshop in Cadarache, Atalante installation at Marcoule).

The friction welding process is a process without filler metal, currently being developed in Sweden by SKB for welding copper-based containers. At present, this process does not appear to be directly transposable for welding thick steel.

Electron beam (EB) welding is performed in a vacuum, without filler metal. This process has many advantages. At first, it is a process which has been industrially tested on thick metals, up to 200 millimetres. Concerning the quality of the welds produced, the thermally affected zone (TAZ) of metal by the heat of welding is of limited extent.This process also displays metallurgical qualities of the TAZ close to those of the base material, which is favourable with respect to corrosion. Vacuum welding particularly limits the risk of cold-cracking. Concerning operational implementation, the possibility of welding with a single pass limits the time needed and the lack of filler metal is favourable for application in an irradiation cell. Finally, the process can easily be automated.

In conclusion, of all these processes, at this stage Andra prefers the electron beam (EB) process in view of the advantages listed above. This preference does not exclude reconsideration of this choice at a later date.

- **Number of primary packages per over-pack.**

It can technically be envisaged to place one or more primary packages in the over-pack, before lowering the disposal package into the underground installations. However, the thermal coupling which would result from the installation of two primary packages side by side, would limit flexibility in terms of managing heat emissions. Indeed, for disposal of C1 to C4 type packages (see chapter 3) after a storage period of 60 to 70 years, it seems that it would be necessary to redistribute the heat sources as evenly as possible by distancing the primary packages from each other (this point is developed in chapter 5). Finally, increasing the number of primary packages per over-pack would lead to more complex operations during emplacement in the waste disposal cells[38].

In conclusion, Andra prefers the over-pack option at this stage, notably for the flexibility it provides in terms of managing heat emissions from the waste.

4.2.2.3 The solution selected

The solution selected for its simplicity and robustness in the light of current knowledge and techniques, is that of an individual over-pack made of 55 mm thick non-alloy steel [50]. The over-pack consists of a body and a lid made of the same material. After inserting the primary packing into the body, the lid is welded onto it using the electron beam method. The whole unit can then be transferred to the underground repository.

The thickness selected for the body and lid results from the double considerations of durable water-tightness and mechanical stresses. Concerning corrosion, it includes a "consumable" part which is the thickness affected by generalised corrosion during the period under consideration.

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[37] This development takes place within the terms of the CLFA (Franco-German Laser Cooperation); it particularly focusses on welding of pipelines and the "vacuum vessel" in the ITER reactor project; it is also being considered by the CEA for producing long-term storage containers.

[38] An alternative over-pack would involve making the disposal cell lining durably water-tight (see chapter 5), the basic function of this lining being to provide mechanical support. This concept, called a "collective over-pack" would involve producing sections of lining of the necessary thickness and welding them (as well as the end parts) in situ, through the entire thickness. This option provides less guarantee of the quality of the object produced than would the option of producing the over-pack in a surface workshop. Furthermore, in the configuration in which disposal packages are separated from each other for thermal reasons, this solution would require a greater volume of steel than individual over-packs.

The cylindrical shape of the over-pack minimises the spaces inside the disposal package, because it matches the shape of the primary package. The inserts filling the spaces formed by the profile of the head and base of the primary package also help to minimise functional clearances between the primary packaging and the over-pack.

It is envisaged to fit disposal packages with ceramic sliding runners, avoiding direct steel/steel contact between the over-pack and the sleeve of the disposal cells. This facilitates installation operations as well as any eventual removal, by improving the possibility of sliding the package during horizontal handling within the cell. Along with the handling resources presented in section 9.3.3, it also helps limit clearance around the packages. It also maintains a space between the package envelope and the cell sleeve in the long-term, thereby avoiding the danger of the confined zone promoting the development of localised over-pack corrosion.

The gripping system built into the lid can also be designed to limit residual clearances outside the package. This design is illustrated in Figure 4.2.1.

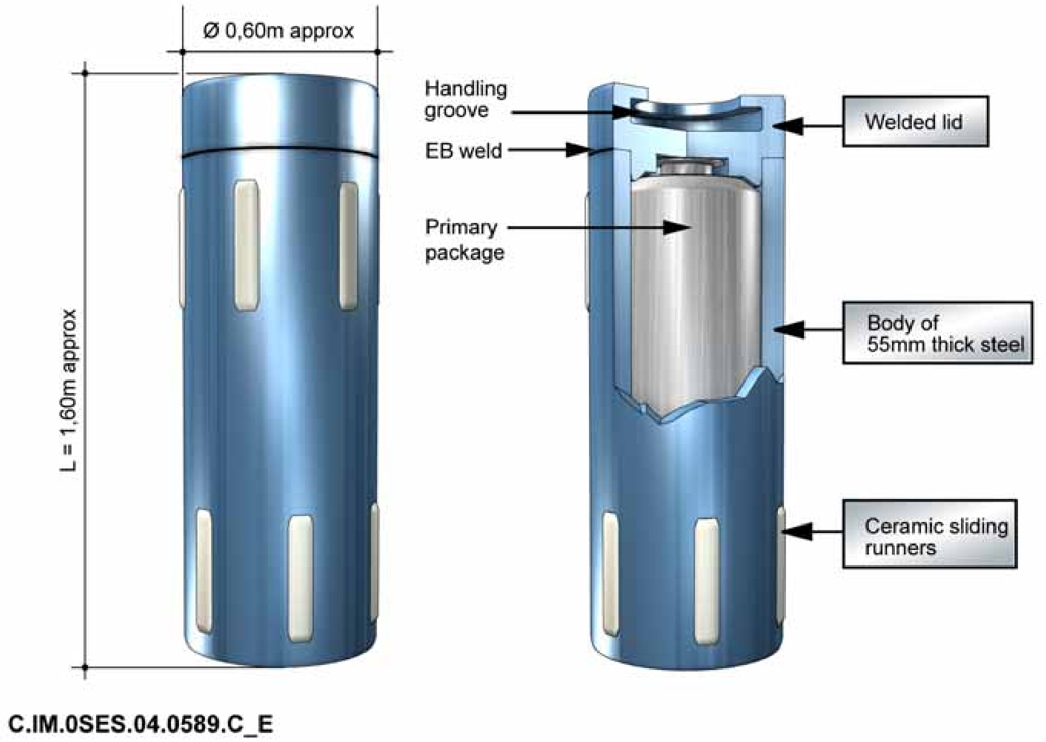

Figure 4.2.1 Principle of the C waste over-pack

4.2.2.4 Comparison with options studied in other countries

Most of the studies performed in other countries consider completing the primary packages of vitrified waste with an over-pack.

In Japan [51] and Switzerland [44], it is planned to use thick non-alloy or low-alloy steel. The durability objectives are similar to those selected by Andra. The thicknesses envisaged, however, are greater; this is because the choice was made to prevent radiolytic corrosion by significantly reducing the radiation level at contact with the packages. The dimensioning conceived by Andra (see below) does not exclude this kind of corrosion, which is explicitly taken into consideration in the durability estimation of the object. The concept developed in Japan also has a further radiological protection function allocated to the container.

In the United States [52], the "Yucca Mountain" project envisages a container consisting of two concentric envelopes, an internal one made of 50 mm thick stainless steel, to guarantee mechanical strength, and an outer envelope made of 20 mm thick nickel alloy (Inconel 22), to ensure resistance against corrosion. These materials meet the physicochemical environmental conditions specific to the Yucca Mountain project. This container, which is larger than the Andra one, (diameter) could hold several primary packages of waste (HLW) equivalent to vitrified C waste.

4.2.3 Description, performance

This section describes the design parameters of the selected solution in greater detail. It justifies the dimensions with respect to the durability performance required, and shows that the object is compatible with the handling processes.

4.2.3.1 Detailed description

Two disposal packages, of standard dimensions, can be used to cover all the primary packages of C waste presented in chapter 3:

- a so-called "short" geometry (1291 millimetres long, for an overall diameter of 655 millimetres) corresponds to C0.1 (PIVER vitrified waste) and C0.3 (AVM vitrified waste) type packages.
- a so-called "long" geometry (1 607 millimetres long for an overall diameter of 590 millimetres) corresponds to C0.2 type packages (CSD-V R7/T7 /UMo), and C1 to C4 from the La Hague factories.

The mass of these disposal packages varies between 1 645 kilogram (package type C0.1) and 1 965 kilograms (package type C0.2 and C1 to C4). This mass includes the primary package and all the over-pack constituents, described in detail below.

- **The body**

The body of the over-pack consists of a cylindrical shell with an effective thickness of 55 millimetres, used to ensure a water-tightness for a millennium (see below). This envelope is fitted with ceramic sliding runners. If these sliding runners are embedded, the thickness of the envelope will be increased by 10 millimetres, to avoid degrading the integrity of the effective thickness. The base has an effective thickness of 77 or 83 millimetres depending on the type of package. It can be manufactured in a single piece, without welding, so that the body has a built-in base.

After comparing various possible grades[39], the material chosen was non-alloy steel type P235. Its low carbon content gives it good weldability. Its structure is not very sensitive to cold-cracking during welding, because of its low elastic limit. It does not require preheating or heat treatment before or after welding. Although it is a commonly used steel, its mechanical characteristics are adequate to ensure the object's mechanical strength. Finally, its mechanical characteristics are favourable to controlling certain risks (particularly corrosion under stress and hydrogen embrittlement).

- **The lid**

The lid is made of the same grade of steel as the body. It is thicker than the base because its effective thickness is increased by about 100 millimetres to create a handling interface. This handling interface consists of a machined groove to enable the over-pack to be gripped by a grab. A hollow shape provides a greater weight-bearing area and consequently better load distribution than a "mushroom" type protruding shape. The internal shape of the lid, shown in Figure 4.2.2 match the upper profile of the primary package to help limit the void fraction.

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[39] Including, in particular, low-alloy steel 16MnD5 used for pressurised water reactor tanks.

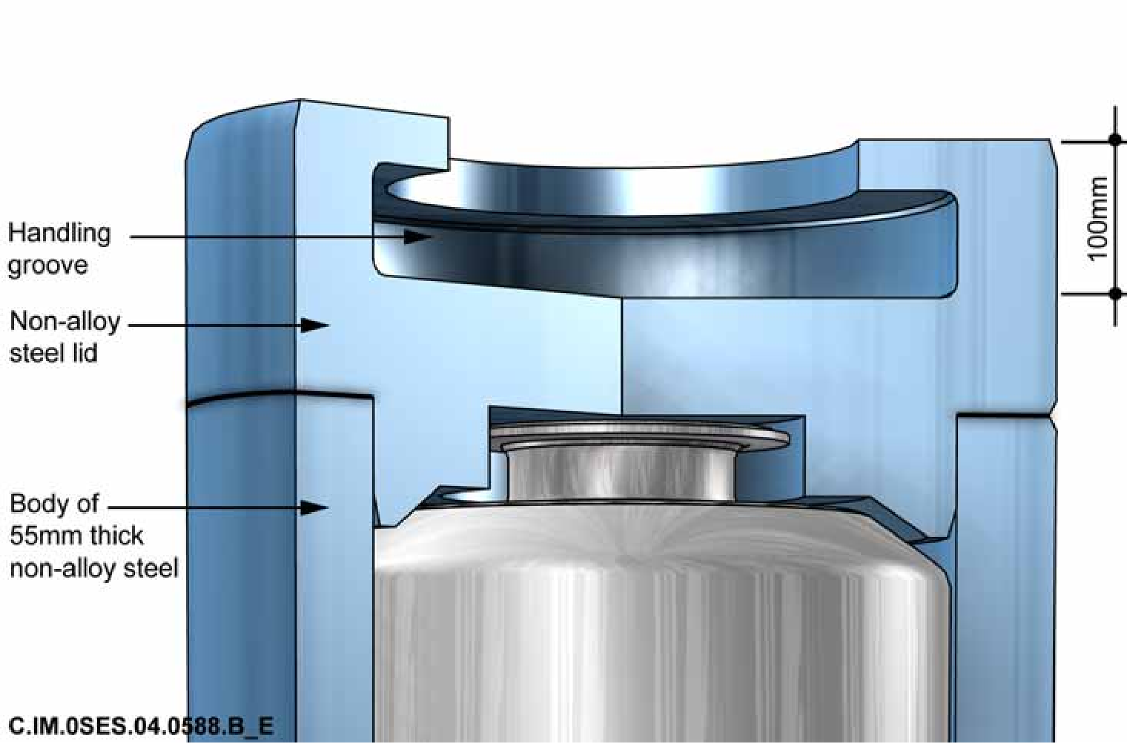

Figure 4.2.2 Details of the disposal package lid (C0.2, C1 to C4 R7/T7)

- **Ceramic sliding runners**

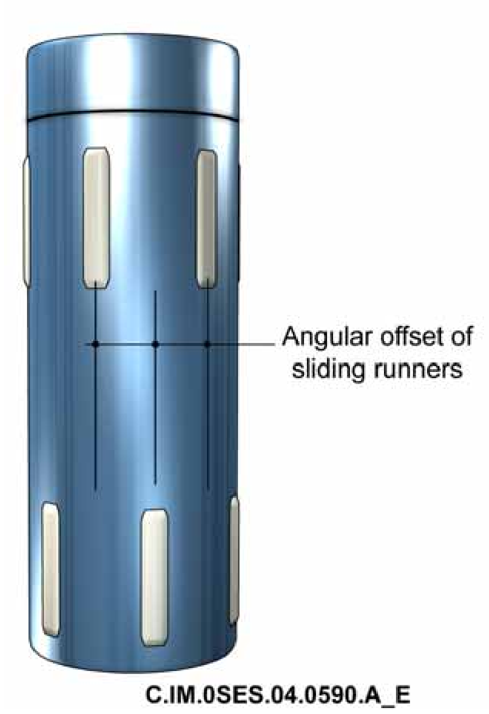

Figure 4.2.3 Sliding runners distribution

The over-pack is fitted with ceramic sliding runners installed longitudinally. Each sliding runner may consist of a metallic part coated with a fine layer of ceramic, or be a solid ceramic block. The sliding runners are fitted to the over-pack in two sets of six. Each set has an angular offset of 30 degrees, as shown in Figure 4.2.3. The sliding runners are mounted so that when there is pressure on the sleeve intrados, three sliding runners are always in direct contact with the cell sleeve.

4.2.3.2 Performances

- **Thickness of the envelope and lifetime**

The over-pack described in the previous section, has a degree of water-tightness in a disposal situation, designed to last at least a millenium.

This period covers the thermal phase, during which the core temperature of the glass exceeds 50°C. Indeed, the thermal phase[40] is evaluated to last about 150 years for C0 type packages, about 500 years for C1/C2 type packages and about 1 000 years for C3/C4 type packages (see Figure 4.2.4). These evaluations result from three-dimensional digital modelling of heat conduction in the repository (this modelling and its input data are described in section 5.2). They are based on (i) the age of 60 to 70 years on entering the repository, for C1.C2 and C3.C4 packages respectively, (ii) a configuration of disposal cells and overall architecture dimensioned[41] for a maximum temperature of 100°C at the interface between the disposal packages and the cell [10].

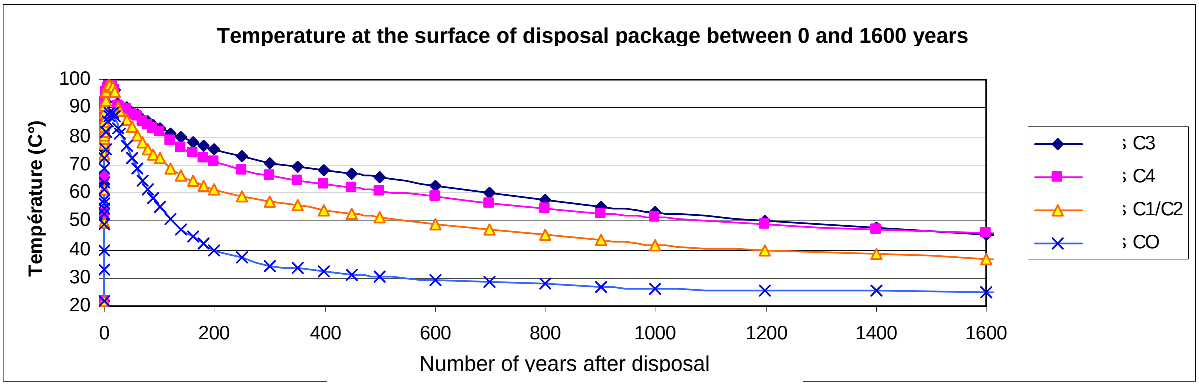

Figure 4.2.4 Evolution over time of the temperature of vitrified waste containers

To ensure water-tightness over at least a millenium, dimensioning of the effective thickness of the over-pack is based on the sum of the following two terms:

- a thickness of 28 millimetres for the shell and 50 millimetres for the base and the lid, to guarantee the object's resistance against the mechanical stresses likely to be exerted over this scale of time;
- an extra thickness of 27 millimetres, defined by a penalising method, corresponding to loss of substance due to generalised corrosion.

- **Mechanical dimensions**

The dimensions of the over-pack are such that it can resist stresses linked to vertical handling in surface installations and during transfer and horizontal handling when being inserted into the disposal cell. This point will be covered in section 4.2.3.3.

In the disposal cell, as long as it has an intact sleeve, the packages are not subjected to any mechanical stress. However, eventually the sleeve will corrode and gradually lose its mechanical strength. Deferred rock deformations will close the clearance between the rock and the sleeve and then exert slowly increasing pressure on the sleeve (estimated at a maximum of about 5 MPa at 300 years [13]).

A transient thermomechanical stress generated by the release of heat from the packages is added to the pressure, wich is due to creep and to the resaturation of the argillites. After several centuries, the temperature tends to even out in and around the cell. The thermomechanical stress has then fallen (from a maximum of 4 MPa to a residual value estimated at about 1.6 MPa [13]).

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[40] The duration of the thermal phase increases with the maximum temperature in the repository. It also depends on the age of the waste on installation in the repository. The thermal phase is also sensitive to the modularity of the storage zone: it falls with the increased volume of each module and the distances between modules.

[41] The concepts studied are based on heat dissipation by conduction in the rock

When the sleeve loses its strength, it deforms and the thrust of the terrain is then transmitted to the disposal packages. After 1 000 years, and conservatively not taking into account the partial dissipation of terrain thrust, the total radial pressure applied to the packages is more than 12 MPa (weight of the ground at 500 metres).

In an axial direction, the natural stress, which is stronger than the radial stress, accentuates the effect of deferred deformation at the disposal cell end. However, this effect is localised and covered by the margins allowed for the determination of radial pressure.

Andra has therefore decided to dimension the over-pack to withstand a pressure of 12 MPa applied uniformly to the walls after a loss of 27 millimetres of metal corresponding to generalised corrosion (see below).

The allowable material stresses (P235 steel) are 360 MPa for the tensile limit and 200 and 185 MPa of elastic limit for temperatures of 20°C and 55°C respectively. Thicknesses of 28 millimetres in the wall and about 50 millimetres for the base will respect these acceptable stresses. In fact, dimension calculations show that the tensile stresses exerted on the shell are lower (around 100 MPa [50]).

- **Duration of watertightness**

Generalised corrosion is the main process to be taken into account in the corrosion of non-alloy steels [53].

In this context, three successive periods can be distinguished during the life of a package in a disposal situation: an initial period with no corrosion, a transient period of corrosion under oxidizing conditions and, finally, a period of corrosion under anoxic conditions.

Initial period

Initially, the relative humidity in the cell is low because of the exothermicity of the packages, so that a film of water does not form on the packages and corrosion is not triggered. However, the temperature is sufficiently low (less than 100°C) for corrosion by oxygen gas[42] to be ignored.

Transient period (oxidation and/or resaturation)

As soon as the relative humidity of the atmosphere in the cell exceeds a critical value[43], a film of water is formed in contact with the package and corrosion may begin. The predominant oxidating species during this phase is oxygen dissolved in water.

Oxygen renewal is limited by constructive provisions (fast installation of a leaktight cover at the head of the cell). It is also preferentially consumed by the corrosion of metallic elements encountered before the package, in particular the sleeve. Therefore, this phase will be of short duration, if it occurs at all (around ten years) [53]. During this phase, the speed of progress of the corrosion of disposal packages depends on the kinetics of the phenomena[44] and takes into account the protective role of the layer of corrosion products. On the basis of corrosion tests performed in a clay environment, a semi-empirical law gives generalised corrosion speeds of several tens of µm/year at most.

Anoxic period

Once the oxygen is consumed, the environment becomes anoxic once more, as it was at first, and aqueous corrosion (by water reduction) in an anoxic medium becomes predominant.

The thickness of the over-pack limits radiolytic corrosion due to oxidating species, such as H_2O_2 ("oxygenated water") which would be created by water radiolysis under the effect of radiation.

---

[42] Several hundreths of microns per year at most

[43] Aqueous corrosion cannot start as long as the atmospheric humidity in the cell remains below a "critical relative humidity" between 40% and 70%, depending on the composition of the atmosphere.

[44] Redox reaction and oxygen transport linked to resaturation.

The speed of generalised corrosion observed under these conditions during long-term corrosion tests (several years) falls over time because the protective function of the layers of corrosive products is reinforced. The average speeds observed in samples tend to be very low, between 3 and 5 µm/year for a temperature of 50 to 90°C, with instantaneous speeds lower than one µm/year after a few years.

Applying conservative hypotheses, a thickness of 27 millimetres dedicated to corrosion provides for 4 000 years of watertightness of the overpack.

4.2.3.3 Compatibility with handling methods

Dimensions relative to the mechanical strength of the over-pack, subjected to external pressure of 12 MPa and its corrosion resistance on a millenium time scale having been established, the package must also be compatible with the handling methods used, presented in chapter 9.

Three main configurations of the over-pack handling cycle are taken into account for design and dimensioning. The first is the vertical handling of the package during temporary storage operations prior to its transfer to the package transfer shaft. The second corresponds to emplacing the package in the disposal cell. Finally, the third one refers to the hypothesis of an eventual retrieval of the packages.

- **Taking into account vertical handling operations in surface installations**

At the end of production, disposal packages in surface installations are stored vertically. They are then removed and inserted into a radiological protection transfer cask for transfer to the underground installations. During these operations, the height above the ground during handling is about 1.60 metres. Within the context of these operations, dimensioning consists of calculating the thickness of the handling interface and verifying the package's resistance to falling.

The allowable stress (116 MPa) in the material used for the over-pack handling groove is defined by the calculation rules used for lifting devices, produced by the European Handling Federation (FEM) as 2/3 of the elastic limit. The dimensions of this groove give it a robust character with respect to all the stresses induced by handling operations and beyond, during the mechanical loading it will experience in a disposal situation.

Several cases of dropped packages have been simulated, notably an angular fall from a height of 1.6 metres, which is the height above ground during handling operations in surface installations. These calculations were used to verify package integrity.

- **Taking into account operations for placing packages in the waste disposal cell**

The principle for transferring C disposal packages to a disposal cell, as illustrated in Figure 4.2.5, is carried out by sliding the package in the cell sleeve using a pusher robot.

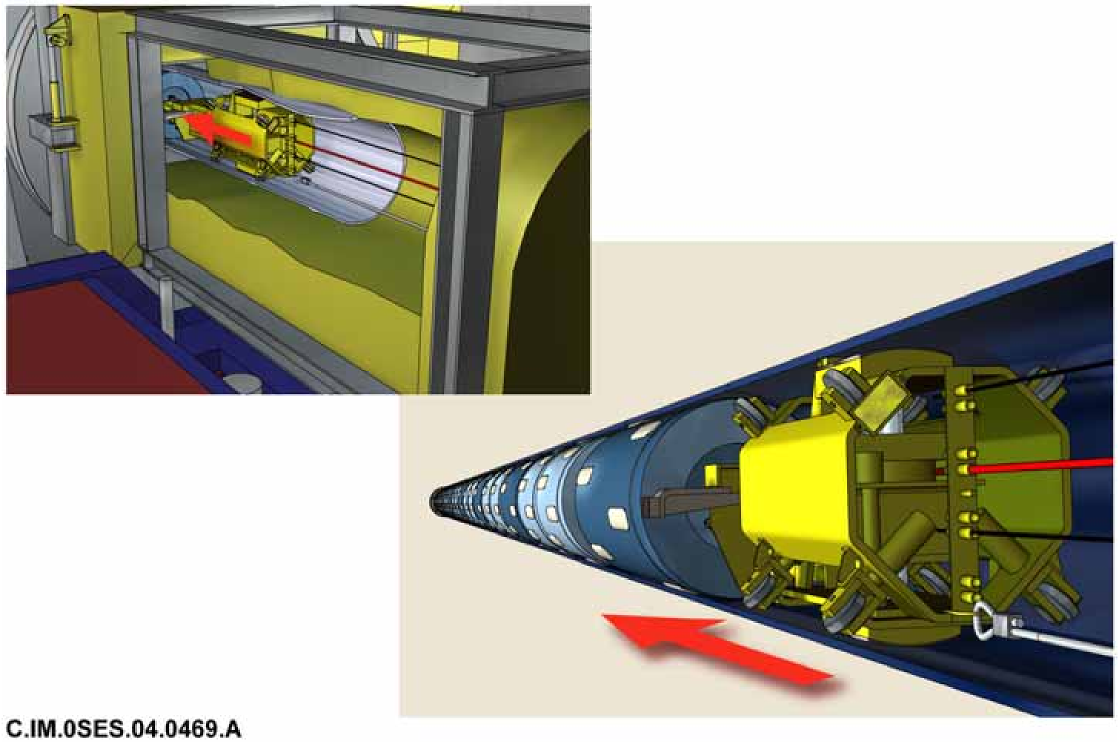

Figure 4.2.5 Principle for emplacement of C disposal packages into a waste disposal cell

The sliding is achieved by friction between the ceramic sliding runners and the metallic sleeve intrados. The essential function of these sliding runners is to facilitate sliding and limit the thrust required. By avoiding direct steel/steel contact between the package and the sleeve, the sliding runners also avoid damaging the body during pushing operations.

The choice of ceramic is largely inspired by its industrial use in other fields such as aeronautics or the automobile industry. This material is interesting because of its good friction coefficient, resistance to wear and resistance to compression.

- **Taking into account an eventual retrieval operation**

Within the context of an eventual retrieval of the package, we considered a case where generalised corrosion of disposal packages and the cell sleeve would have a negative effect on this operation.

For dimensioning the groove for gripping packages in this situation, we used the hypothesis that generalised corrosion (2mm)[45] affects all the outer surfaces of the handling groove. Taking this situation into account when dimensioning consists of making sure that it is possible to grip the packages and exert a significant tensile force to overcome the friction and sticking engendered by corrosion. The calculation gives a maximum applicable force, corresponding to the elastic limit, of about 40 tonnes. Reaching the breaking strain should theoretically lead to the development of a tensile force of about 85 tonnes, although with a risk of damaging the handling groove which could destroy it.

It should also be noted that the ceramic sliding runners on the container limit the risk of "sticking" due to corrosion products between the package and the sleeve.

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[45] 2 mm of corrosion engenders an excess thickness of swollen products of 3 mm relative to the initial dimensions (the total thickness of corrosion products is therefore 5 mm). The geometric dimensions of the groove take this corrosion thickness into account so that the central residual space is enough to allow deployment of the fingers of a specific gripping tool.

4.2.4 Manufacturing techniques

This section details the envisageable techniques used to manufacture the disposal packages based on existing industrial analogues.

Manufacture will take place in two phases. The first phase concerns the factory production of over-pack components; a particular aspect is the installation of sliding runners on the body of the object. The second phase includes installation of the primary package of vitrified waste in the over-pack and closure of the disposal package by full penetration welding of its lid. This second phase is performed in a succession of shielded cells.

4.2.4.1 Manufacture of the container and its lid in the factory

The components to be manufactured are a body made of non-alloy steel (P235) equipped with ceramic sliding runners, and a lid. Various techniques can be envisaged and they have been tried and tested industrially, for dimensions and thicknesses at least equal to those of the over-pack [50]. At the end of a comparative analysis, two of them appeared to be particularly suitable.

The first consists of forging a shell, then attaching a base. To produce the shell, an initial rough machined blank is obtained from an ingot and then drilled. This blank is rotated on a calibrated mandrel inside the blank. It is then stamped from the outside to increase its external diameter. Forging seals any faults in compactness of the initial ingot and produces parts with a fine structure free of compactness faults. This technique was used to produce a demonstration model of a spent fuel disposal container (See § 4.3.4.1). The base is produced separately, using methods such as static moulding, stamping, forging or cut and welded laminated sheets. The shell and base are then assembled by full penetrations welding to form the body of the container.

The second technique consists of producing the body in a single part, by drilling and drawing. This technique has the advantage of avoiding welding the base. The internal cavity of the container is obtained by deformation of the metal. Drilling – drawing consists of obtaining a tube from an ingot. The ingot which is removed from the oven is hot-drilled using a drill with a vertical press to obtain the inner diameter, then drawn by rolling, using a horizontal press in an extrusion die to obtain the required outer diameter and length (see Figure 4.2.6 and Figure 4.2.7). The part then undergoes heat treatment and is machined to achieve the final dimensions.

Figure 4.2.6 Ingot – Drilling - Drawing

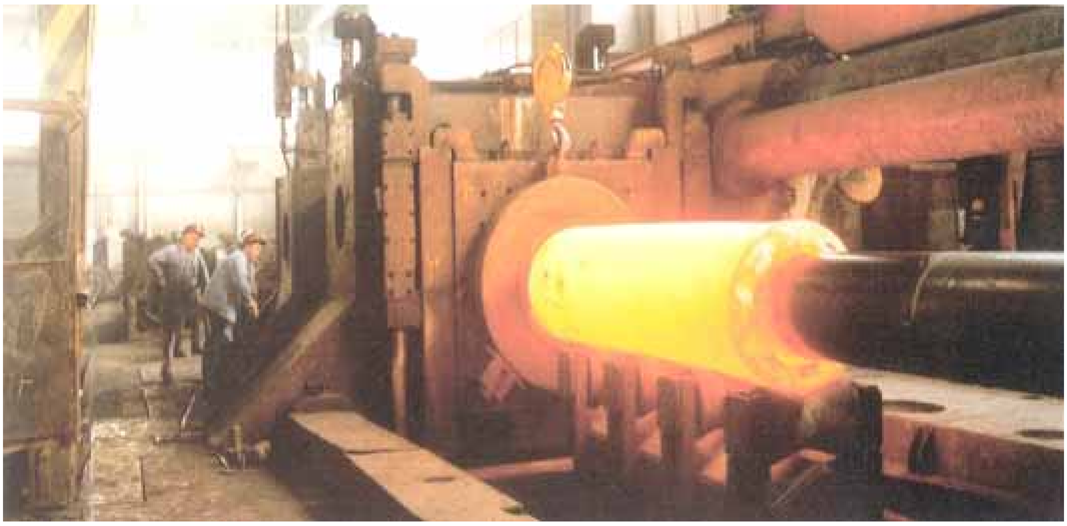

Figure 4.2.7 Drawing in an extrusion die using a mandrel and a horizontal press

These two techniques are tried and tested industrial methods used to obtain good metallurgical properties in the object produced.

4.2.4.2 Manufacture and integration of ceramic sliding runners

- **Manufacture and performance of ceramic sliding runners**

At this stage, corundum (alumina Al_2O_3), or doped corundum (Al_2O_3 + ZrO_2, Y_2O_3) appeared to be appropriate materials due to their mechanical characteristics and their insulating property. Workshop tests using a test bench demonstrated greater robustness of solid ceramic sliding runners compared to ceramic projected onto a metal base. The sliding runners used for these tests are illustrated in Figure 4.2.8: from left to right a solid ceramic sliding runner, a cast ceramic sliding runner and the metal base used as a support for ceramic projection.

Figure 4.2.8 Ceramic sliding runners

The test bench illustrated by Figure 4.2.9 permitted alternate movements simulating stress on the sliding runners during package pushing operations (loading and application duration). A rated vertical load of 1 metric ton can be applied to a sliding runner (Figure 4.2.10) [46].

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[46] Over-pack design results in it resting on 3 ceramic sliding runners during cell emplacement. This configuration is the most stable representation and therefore the most probable one for the package in the cell, both during the pushing phase (even if it is not always the same sliding runner supporting the loads), and at rest. In this tripod configuration, maximum static load supported by one of the sliding runners can be half of total package weight, or about 1 metric ton.

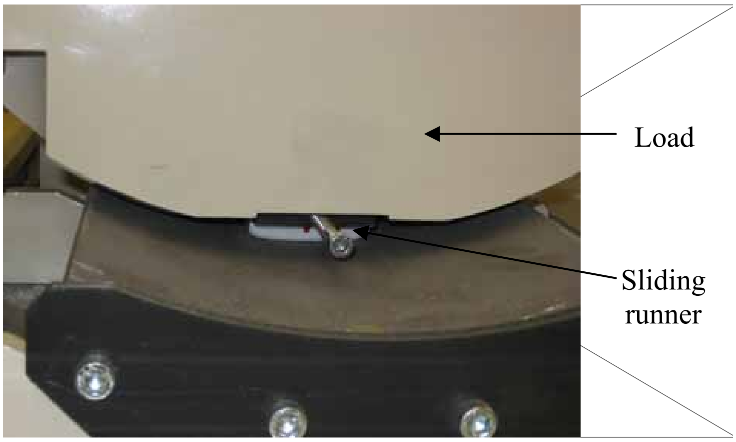

Figure 4.2.9 Sliding runner test bench

Figure 4.2.10 Loaded sliding runner

Tests carried out with a solid ceramic sliding runner demonstrated that the metal track underwent slight marking without metal detachment and that the load required for pushing was steady and stabilised at a value of half of the displaced weight, i.e. a friction factor of 0.5.

For this type of ceramic, the sliding runners are shaped by pressing powder and then sintering i.e. raising to high temperatures for consolidation. After cooling, machining is required so that the part complies with rated dimensions. The part can be quite complex in shape. The material obtained has homogenous characteristics with no residual stress.

- **Method for integrating ceramic sliding runners into disposal packages**

Integration of sliding runners in disposal packages must not affect the rated thickness of 55 mm of steel. This imposes an extra thickness of about 10 mm for installation of sliding runner emplacements. Two integration methods are possible: (i) direct bonding [47] of solid ceramic sliding runners in these machined emplacements with defined tolerance to obtain good mechanical resistance (especially resistance to shearing stress generated by friction applied to the metal sleeve), (ii) welding of sliding runners of composite ceramic/metal type [48] inserted in these emplacements. The advantage of the metal part is that it can be welded to the extra steel thickness on the over-pack.

4.2.4.3 Disposal package assembly

Disposal packages are assembled in a shielded cell:

- The first operation consists of loading the primary package of vitrified waste into the container. Functional clearance provides ease of vertical loading by freeing up container manufacture tolerances and tolerances related to the primary package.
- The lid is then placed on the container body. The ensemble is then inserted into an enclosure where the vacuum is effected, an operation required for electron beam welding. The container is then rotated and orbital welding of the lid is carried out. Figure 4.2.11 shows a welding enclosure under vacuum conditions and Figure 4.2.12 the electron beam welding process.

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[47] Using high performance industrial glue.

[48] Firstly, solid sintered ceramic is produced then mechanically added to a metal base in order to obtain the composite ceramic/metal sliding runner.

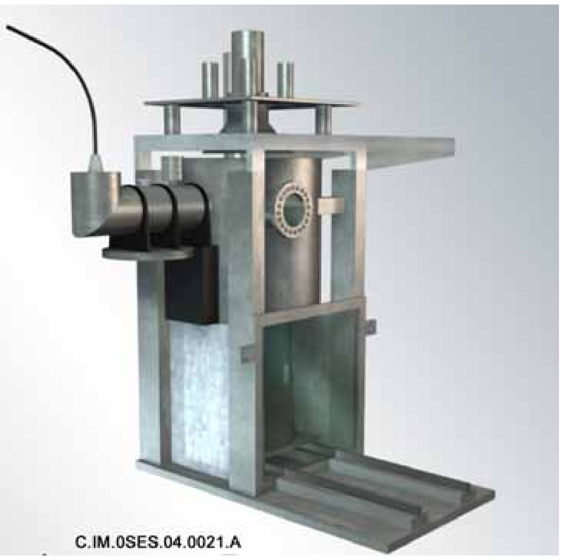

Figure 4.2.11 Welding enclosure under vacuum conditions

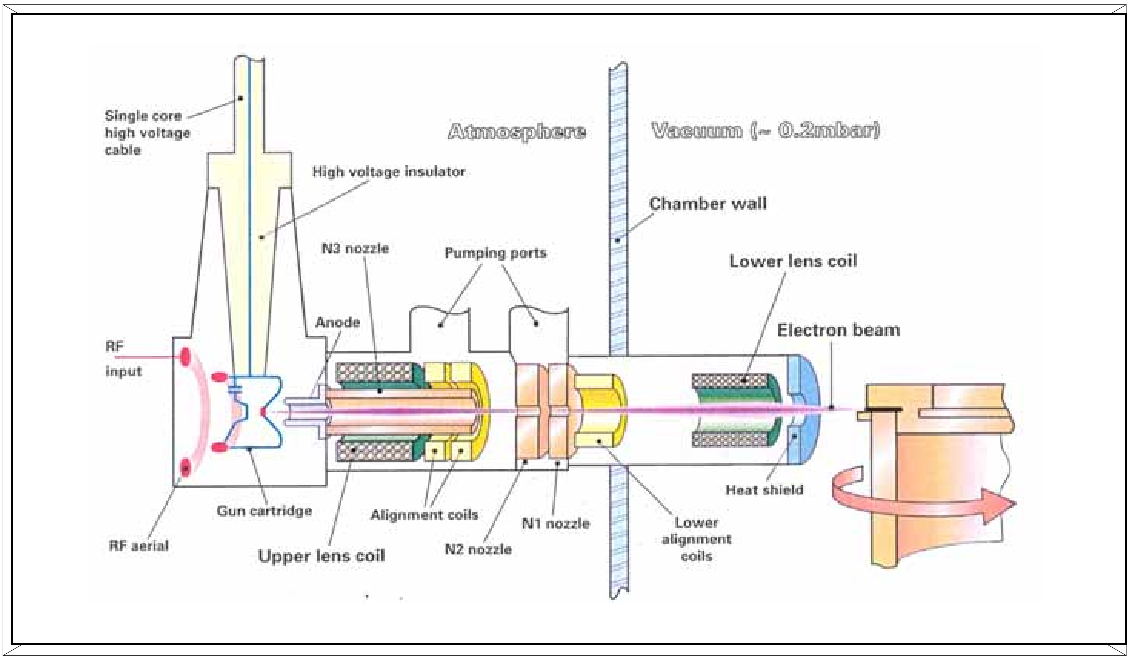

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Figure 4.2.12 Electron beam welding procedure diagram

For welding process control, important parameters can be recorded during the operation. Once welding has been completed, the welds are then tested, with the disposal package placed in another shielded cell.

An appropriate weld surface test procedure, routinely used by manufacturers, consists of visual inspection with video camera. Other procedures can be considered, namely liquid penetrant testing and magnetic particle testing, but they are more difficult to apply in an irradiating cell.

A tried and tested volumetric examination procedure is based on use of ultrasound.

It is worth mentioning that electron beam welding and weld testing resources were used to make the demonstrators for spent fuel disposal packages, with the same grade of steel as that envisaged for C waste repository containers (see section 4.3).

4.3 Spent fuel disposal packages

To start with, it should be pointed out that spent fuel is not considered as waste. A repository container is presented here for exploratory purposes for spent fuel of types CU1, CU2 and CU3, in the case of these not being reprocessed.

This chapter presents the scientific and technical aspects to be considered in the design of such a repository container, the various technical responses to be envisaged and the option favoured at this stage of research.

It also presents the design basis of this container and manufacturing techniques for feasibility assessment.

4.3.1 Presentation of main issues

For pressurised water reactor (PWR) fuel assemblies (CU1 and CU2), two initial spent fuel conditioning options are considered: bare or in individual cladding. Both these options offer flexibility of management upstream of disposal. Individual cladding under consideration is that determined by research on long-term storage of spent fuel carried out by the CEA.

Other fuel assemblies (of CU3 type) are normally conditioned in cladding in installations upstream.

4.3.1.1 Need for watertightness and durability

Water seepage in fuel assemblies causes corrosion of cladding and metal parts (end caps and grids), dissolving of labile activity and alteration of fuel pellets.

Metallic material corrosion speeds vary depending on the type of materials. Corrosion speeds are increased by temperature and radiolysis.

Irradiated uranium oxide pellets (UO_2), containing most of the fuel activity, are degraded by dissolving in the presence of water. Water radiolysis which generates localised hyperoxidising agents such as oxygenated water (H_2O_2) is likely to initially accelerate dissolvation.

In addition, as previously indicated for vitrified waste, the behaviour of radionuclides dissolved in water is affected by temperature.

These factors lead to the use of waterproof containers so that spent fuel does not come into contact with water at least during the heat transfer phase. A minimum duration of 10,000 years has been adopted for container watertightness as regards CU1 and CU2 types and a duration of a thousand years for CU3 types.

4.3.1.2 Other nuclear safety related issues

As spent fuel contains a mass of residual fissile material, container design must ensure the elimination of risks of criticality. When unloaded from the reactor CU1 type fuel (UOX) contains a mass of residual fissile material of 10 kg composed of 4 to 5 kg of ^{235}U and at least 4 kg of ^{239}Pu whereas CU2 type fuel (MOX) contains about 20 kg of residual fissile material including more than 80% plutonium, especially 12 kg of ^{239}Pu[49]. These fissile material masses require in-depth analysis based on the disposal package geometry and the characteristics of fuel assembly environment. This analysis must cover all repository container lifetime phases especially concerning extremely long-term conditions, taking into account changes over time in fissile material masses, of disposal package geometry and component materials and of the environment.

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[49] As a reminder, Pu239 critical mass is 510 g.

4.3.1.3 Operating requirements

In a similar way to C waste, Andra has adopted horizontal tunnels for repository architecture for the study. Spent fuel packages are able to be handled horizontally for transfer to underground drifts and placement in disposal cells. Within the framework of reversible repository management, these packages should be able to be removed for at least a hundred years.

4.3.2 Design principles adopted

4.3.2.1 Choice of technical options

In the same way as for C waste over-packs, leaktightness is ensured by a metal shell. From amongst the various categories of metal materials presented in section 4.2, non-alloy steel has been adopted for the same reasons.

In the same way as for C waste, material thickness determines leaktightness duration. Container closure with electron beam has also been adopted. It is worth mentioning that this process offers the advantage of minimising thermally affected zone extension and provides metallurgical qualities close to those of the base material concerning corrosion phenomena.

In order to comply with repository heat transfer design basis criteria, package capacity is restricted to four PWR fuel assemblies of CU1 type (UOX/URE) and one MOX fuel assembly (CU2).

The choice of a low package capacity thus restricts the mass, so that it remains in a scope covered by industrial experience feedback for shaft transfer.

Another important design choice is to limit residual voids within the package. For packages containing more than one assembly, this leads to a massive object containing compartments adjusted to assembly dimensions.

Several solutions for obtaining this object have been envisaged. Manufacture of a single-piece container made of cast steel with moulded emplacements, incurs the risk of obtaining a heterogeneous structure. However, forged steel single-piece manufacturing would provide a more homogeneous structure but machining of square emplacements for bare assemblies over such lengths is not technologically feasible at this stage. It seems too difficult to manufacture a steel shell and separate insert, which would be obtained from foundry and shrink fitted into the shell, for such dimensions, and this would result in deformations and stress too difficult to control. Simple mechanical fitting would result in significant clearance which would eventually have to be filled in. Therefore, direct pouring of a cast iron insert into the shell, after installation of a mould composed of steel tubes to form the emplacements, is the solution adopted.

Cast iron is of sufficient mechanical resistance for the insert to withstand long-term strain on the container.

It should be pointed out that cast iron was also chosen by SKB in Sweden (see below and [49]) for spent fuel container insert manufacture.

4.3.2.2 Solution adopted

The solution adopted at this stage consists of two models of cylindrical containers made of non-alloy steel composed of a body and a welded lid using the electron beam method. These two models differ in their external diameters and internal layout related to the number of fuel assemblies they contain and their conditioning mode (bare or in cladding) [54].

The first model (Figure 4.3.1) is large in diameter (about 1,250 mm with a thickness of 110 mm of steel) and contains four fuel assemblies of CU1 type (UOX/URE) representing total thermal power of about 1600 W, after storage of about 60 years once unloaded from the reactor.

The second model (Figure 4.3.2) is small in diameter (about 600 mm with a thickness of 120 mm of steel)and contains only one assembly. For CU2 type fuel (MOX), the thermal power of such a container is about 1100 W, after storage of approximately 90 years once unloaded from the reactor. This second model can also house UOX fuel whose reactivity concerning criticality risks is higher than that of standard spent fuel (see below).

For CU3 type fuel, the disposal package is similar to those developed for C0.3. The number of claddings placed in such a container results in thermal power of less than 150 W (identical for C0 type packages): ten claddings for CU3.1.1 type fuel, five claddings for CU3.1.2 and one cladding for CU3.2 and CU3.3.

The large diameter model illustrated by Figure 4.3.1 is equipped with a cast iron insert holding four emplacements (of square or circular section depending on whether the assembly is clad or not). This insert ensures container mechanical resistance during gradual loading and contributes to criticality risk control by separating the assemblies.

Design of small diameter containers is similar to that of C waste overpacks, but with increased thickness of steel as illustrated by Figure 4.3.2. The steel shell cylindrical cavity makes it possible to house the assembly directly (bare or in cladding).

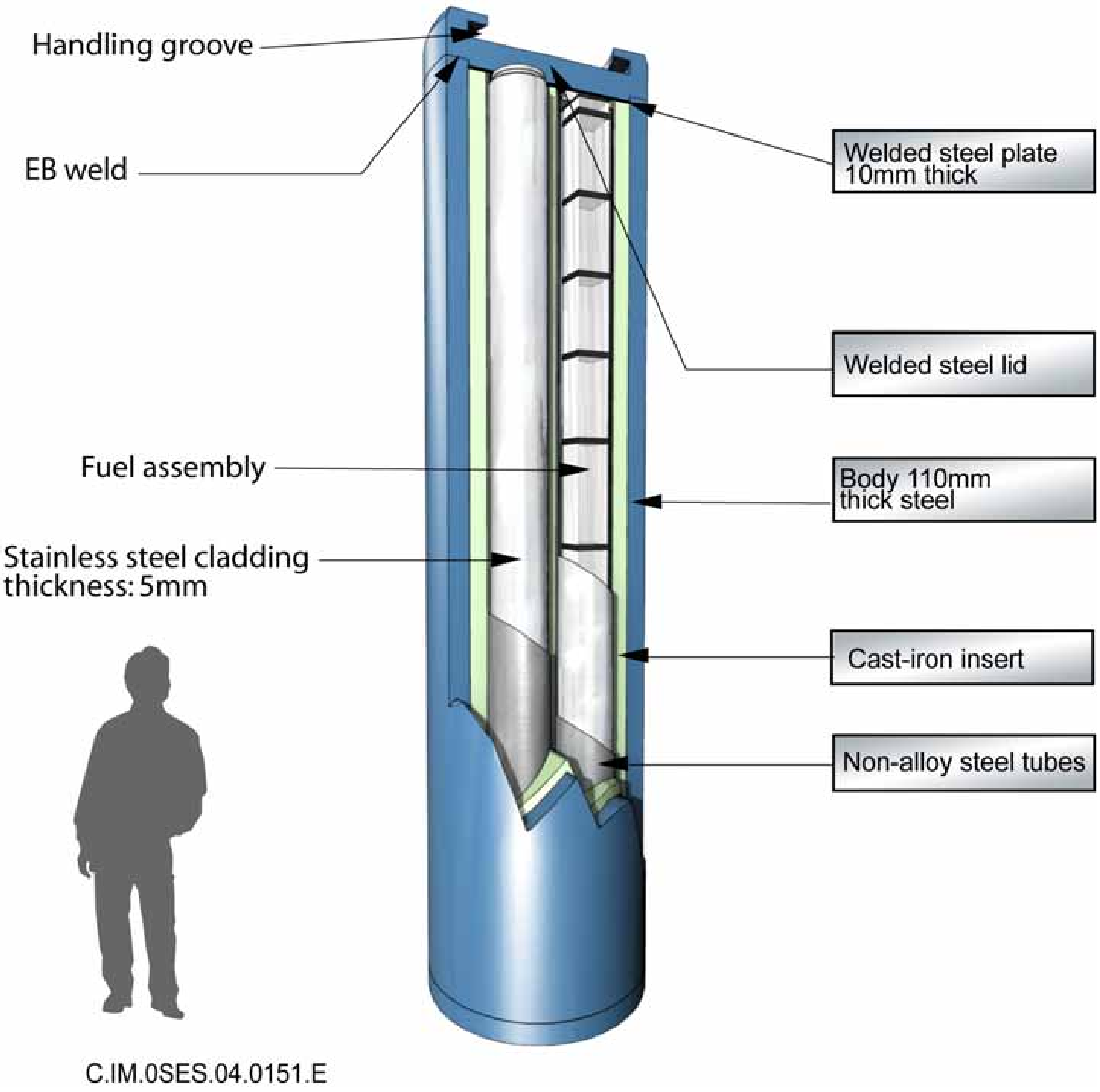

Figure 4.3.1 Large diameter disposal package, 4 UOX or URE assemblies

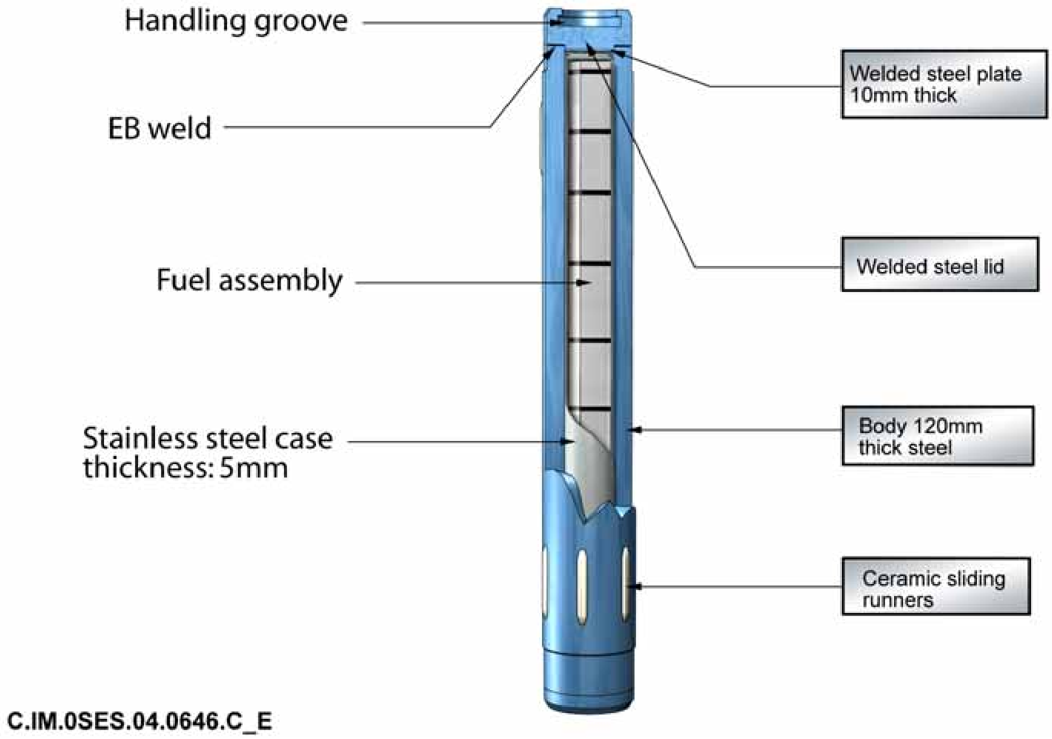

Figure 4.3.2 Small diameter disposal package, 1 assembly (UOX or MOX)

4.3.2.3 Comparison with solutions developed abroad

In the reference concept of Nagra (Switzerland) [44], spent fuel assemblies are placed in a container by 4 or 9 (depending on whether they have been unloaded from pressurised water reactors (PWR) or boiling water reactor (BWR)). This container is made of steel with a diameter of 1,050 mm and thickness of 150 mm and is designed to last for 1,000 to 10,000 years. One variant considers a container made of copper with insert in steel, or possibly in ceramic. This variant increases durability by an order of magnitude.

In Sweden, the KBS-3 project [49] located in a granitic environment, envisages a copper container 50 mm thick with a cast iron insert which can take 4 PWR assemblies or 12 BWR assemblies. Target watertightness duration for this container is more than 100,000 years.

In Finland, the project is similar to the Swedish KBS-3 project. Canada and Spain also envisage designing a copper container.

In the United States [52], the container envisaged for spent fuel for the « Yucca Mountain » project is similar in principle to that of HLW (an internal envelope in stainless steel about 50 mm thick to provide mechanical resistance and an outer envelope in nickel alloy about 20 mm thick to provide corrosion resistance). This container with larger dimensions (diameter of about 2,100 mm) and significantly heavier (up to 75 metric tons depending on the models) than those studied by Andra can take a high number of fuel assemblies (about twenty).

4.3.3 Description and performance

This section provides further details on design parameters of the adopted solution for CU1 and CU2 type fuel. It justifies the design basis, as pertains to expected durability and demonstrates the compatibility of the object with handling procedures.

Regarding waste packages for C0.3 type spent duel, see section 4.2.3 and more specifically those aspects potaining to C0.3 type waste packages. Repository containers are indeed in external diameter and steel thickness, with length adapted to that of the various assembly claddings.

4.3.3.1 Description

Two categories of disposal packages, having standardised dimensions, cover all spent fuel of CU1 and CU2 types presented in section 3.

- **Large diameter disposal package (4 assemblies)**

This package with a standard diameter of 1255 mm and length varying between 4500 and 5400 mm and weight between 35 and 43 metric tons according to configuration (short or long assembly [50], bare or clad assemblies) is composed of two main parts: a body equipped with an insert and a lid as well as an intermediate component known as the closure plug.

Container body

The disposal package body of large diameter is composed of a cylindrical shell in non-alloy steel (P235) of rated thickness of 110 mm and a bottom of the same rated thickness and material to fulfil leaktightness requirements during 10,000 years. A thickness of 20 mm is added to the rated thickness of the bottom to act as a root face for electron beam welding.

In the body (see § 4.3.4 below), a cast iron insert is poured equipped with four emplacements each designed to receive one fuel assembly.

Insert emplacements illustrated by Figure 4.3.3 and Figure 4.3.4 have geometry adapted to the components to be inserted, so as to limit residual voids in the disposal package:

- bare assemblies are placed in emplacements of square section;
- assemblies in individual cladding are placed in emplacements of cylindrical section.

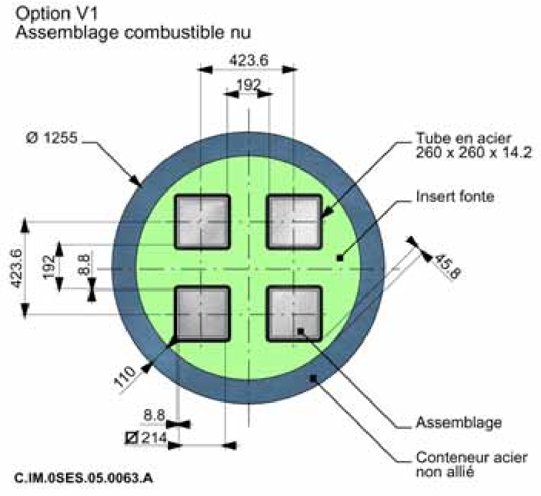

Figure 4.3.3 Square emplacements for four bare spent fuel assemblies

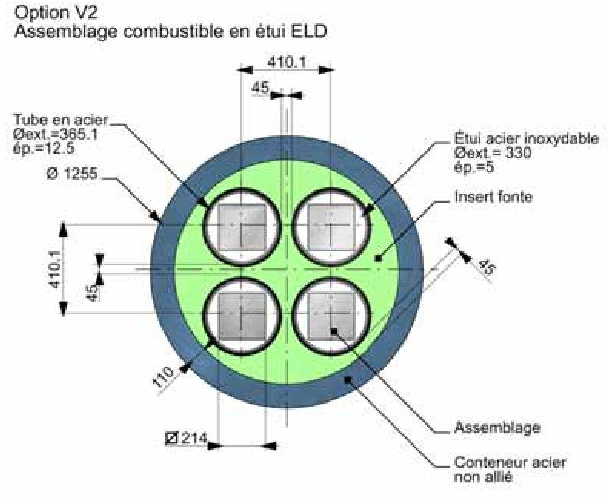

Figure 4.3.4 Cylindrical emplacements for four spent fuel assemblies in individual cladding

Minimum thickness of the insert between the emplacements and the shell is defined taking into account the limits of the manufacturing process applied (foundry). It is evaluated at about 40 mm. This value has been adopted for both variants (square emplacements and circular emplacements) and is sufficient to ensure mechanical resistance of the insert when loaded (see below).

This minimum thickness is also applied to the distance between emplacements.

---

[50] Short assemblies have come from EDF 900 Mwe reactors and long assemblies from EDF 1300/1450 MWe reactors (cf. § 3.2.3.1)

For the sake of standardisation, the outer diameter of the variant for bare assemblies (square emplacements) is identical to that of the other variant. Square emplacements have thus been distanced from each other, which favors package safety-criticality.

Intermediate closure plug

The closure plug is composed of a disk 10 mm thick (made of the same grade of steel as the shell) placed on the top of the insert and welded directly onto the inner part of the steel shell (above the insert emplacements). It restricts the void volume created during electron beam welding operations[51]. It is worth mentioning that it also limits risks of contamination of surface installations and particularly the welding unit when the container is definitively closed.

The lid

The lid with details illustrated in Figure 4.3.5 is made of the same grade of steel as the envelope, with total thickness of about 280 mm. This thickness includes resistance to corrosion, formation of a root face required for electron beam welding and a handling interface comparable to that of the C waste package lid, but with dimensions adapted to package mass.

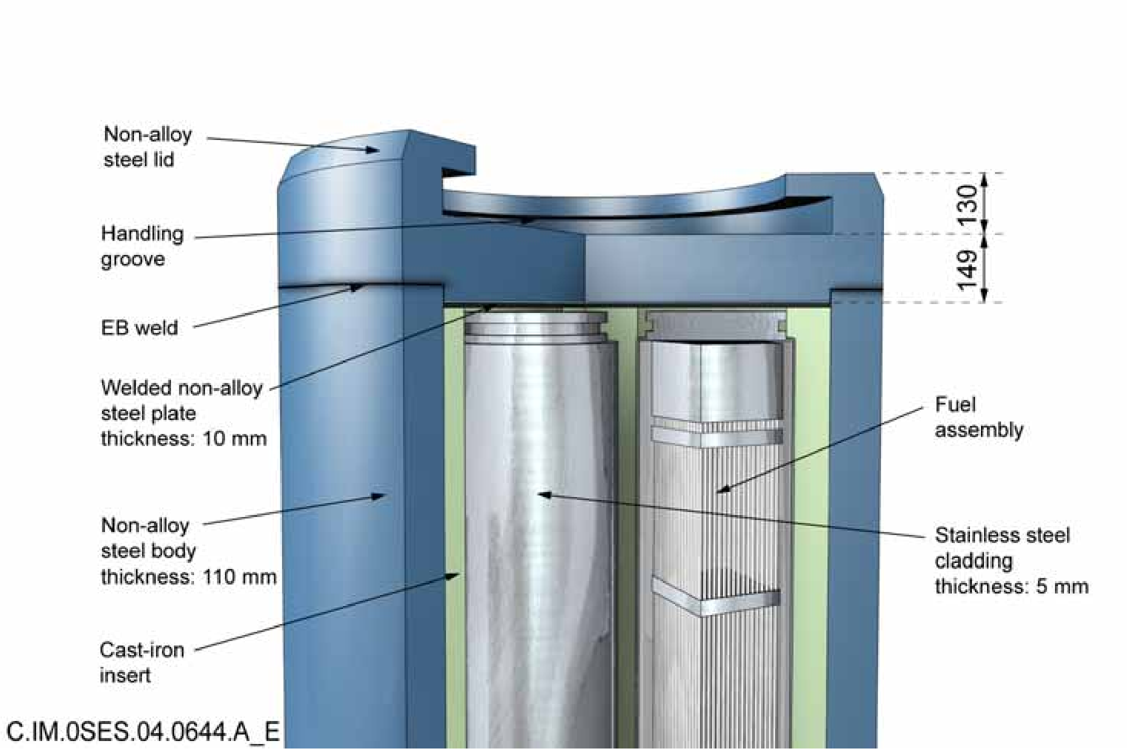

Figure 4.3.5 Detail of container and lid (container with cladding)

- **Small diameter disposal package (1 single assembly)**

This package with a standard over all diameter of 620 mm, with length varying between 4500 and 5400 mm and weight between 8 to 10 metric tons according to the configuration (short or long assembly, bare or clad) is composed of the same parts: a body (without insert) with a lid and closure plug.

This package has a similar diameter to vitrified waste disposal packages but it is about three times longer and four times heavier. Concerning its diameter, the process envisaged for placing it in the disposal cell is the same as that adopted for C packages (sliding onto the cell sleeve by pushing and use of ceramic sliding runners).

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[51] No vacuum is set up for the assemblies as it would adversely affect heat removal.

For both variants, the small diameter disposal package body (bare and individually cladd assembly) is composed of a single cylindrical shell made of non-alloy steel (P235) with rated thickness of 120 mm as illustrated in Figure 4.3.6 and Figure 4.3.7, and of a welded built up bottom with rated thickness of 150 mm made of the same material. Rated thickness is slightly higher than that of the large diameter package as it not only has to ensure leaktightness for 10,000 years (corrosion thickness) but also provide container mechanical resistance (see below). An additional thickness of 20 mm reinforces the rated thickness of the bottom to be used as a root face for electron beam welding.

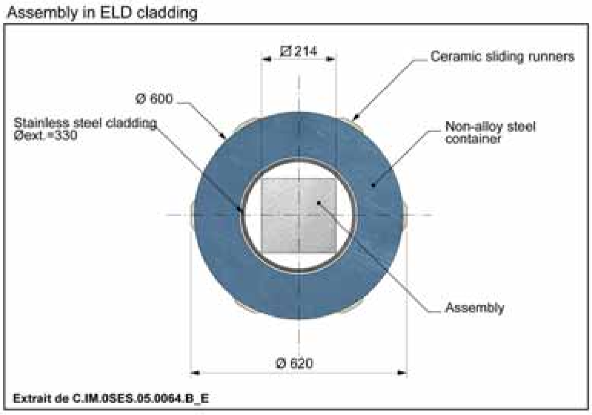

Figure 4.3.6 Emplacement for clad assembly

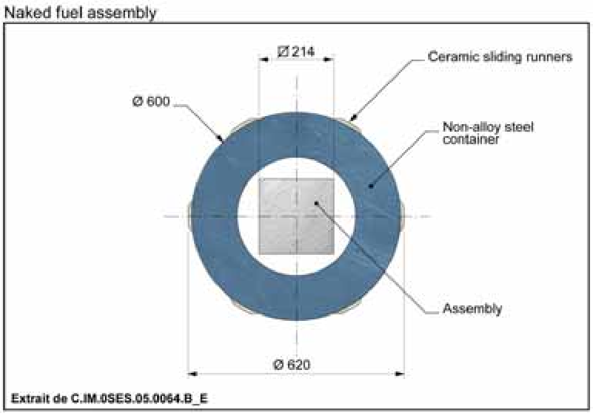

Figure 4.3.7 Emplacement for bare assembly

As for large diameter containers, the assembly emplacement is closed with a plug which is also a welded disk 10 mm thick.

- **The lid**

The lid has a total thickness of about 265 mm to fulfil the same functions as for large diameter containers as well as mechanical resistance.

4.3.3.2 Performances

This section reports on studies conducted to justify container design basis as regards objectives of durability (leaktightness and mechanical resistance) and safety-criticality.

- **Steel thickness and lifetime**

As in the case of C waste, thermal phase duration, i.e. the duration required for package temperature to go below about 50 °C, depends on three related parameters: (i) maximum repository temperature [52], (ii) fuel age when placed in the repository (iii) and repository zone architecture.

With temporary storage prior to disposal for CU1 and CU2 types of fuel of 60 years and 90 years respectively, thermal design basis of disposal presented in section 5.3 results in maximum thermal phase duration of a few thousand years [10]. Package temperature evolutions over time are presented in Figure 4.3.8.

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[52] As a reminder: 100 °C at repository container surface and 90 °C on contact with the engineered barrier based on swelling clay, see chapter 5.

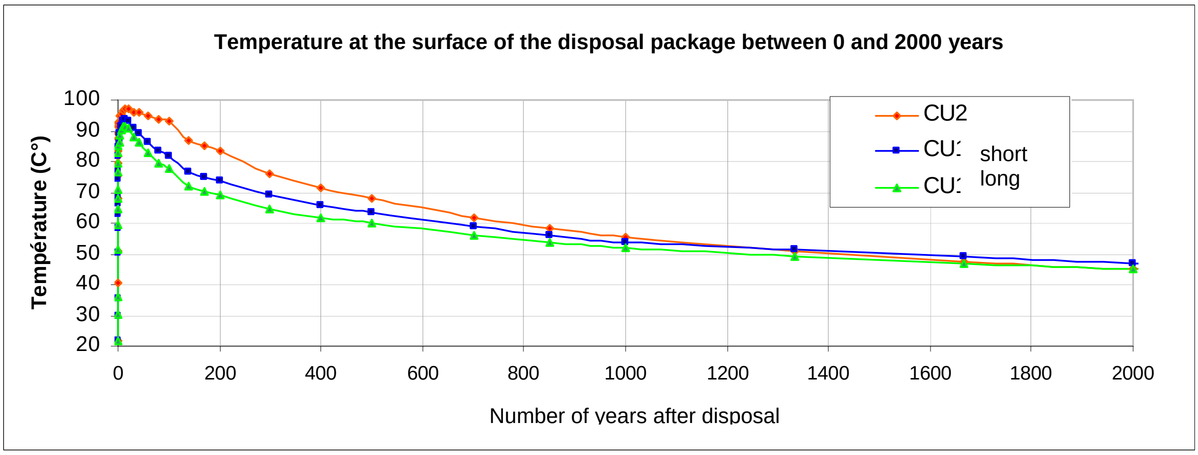

Figure 4.3.8 Spent fuel package temperature evolutions over time

Steel thickness to withstand corrosion has been determined based on the same models as for the C waste overpack, by adopting a penalising approach (see section 4.2.3.2). By the end of 10,000 years, the thickness affected by general corrosion is estimated at 90 mm.

In the case of large diameter repository containers, the shell thickness of 110 mm contains this thickness of general corrosion. Residual thickness of 20 mm combined with insert presence guarantees leaktightness of the shell subjected to mechanical stress for this duration (see below).

In the case of small diameter repository containers, the rated steel thickness of 120 mm results, in a manner similar to C waste containers, from the sum of the following two terms:

- a thickness of 30 mm ensures resistance to mechanical stress effective at this time scale.
- an extra thickness of 90 mm corresponding to assessed loss of substance due to general corrosion.

● Mechanical design basis

In the long term, it is considered that spent fuel containers will be gradually loaded after loss of the one sleeve integrity and argillite convergence. The design basis adopted a pressure that is 50% higher than are considered for C waste over-packs. This margin allows to guard against effects associated with the comparatively longer duration of leaktightness required for spent fuel containers. Such effects may be potentially higher thermo-mechanical stress, due to slower radioactive decay (actinides) and taking into account geostatic stress anisotropy.

CU1 and CU2 containers are therefore mechanically designed to take into account pressure of 18 MPa uniformly applied to their walls [13].

In the case of large diameter containers, the shell is supported by the solid insert. Calculations carried out for both variants (emplacements with square or circular section depending on whether the assemblies are bare or in cladding) show that pressures exerted by the deformed shell result in stress on the insert being much lower than the cast iron yield strength limit.

In the case of small diameter containers, the thickness assigned to mechanical resistance is sufficient for the shell material to remain within elastic regime.

- **Safety-criticality [55]**

Criticality calculations [55] have shown the packages to be sub-critical whatever the moderation conditions in the package and surrounding neutronic reflection, taking into account fuel assembly burn-up rate (burn-up credit[53]).

The solution of four assemblies per container covers about 99% of the UOX spent fuel quantitative inventory considered in the studies (this involves the estimated part of fuel with a burn-up rate higher than or equal to the rate considered for criticality assessment). Fuel assemblies with too low a burn-up rate to allow for a satisfactory demonstration of sub-criticality in packages with four assemblies can be conditioned safely in small diameter packages with one assembly.

Assessment of the sub-critical property of all these packages takes into account conditions resulting from long-term changes to the fuel assemblies, container (geometric modification to the emplacements due to gradual corrosion of the insert) and its environment.

4.3.3.3 Compatibility with handling equipment

In a similar way to C waste disposal packages, three container handling cycle configurations were considered in design and dimensioning. The first one corresponds to vertical handling of disposal packages during container operations and temporary storage prior to transfer to underground installations.The second one corresponds to placing in disposal cells. The third one is related to possible removal of packages, while taking into account same corrosion of the latter, to be cautions.

- **Taking into account vertical handling operations in surface installations**

Handling groove dimensions defined for handling in waste disposal cells (see below) are large enough to withstand stress related to vertical handling operations in surface installations.

Concerning resistance to falling, calculations with finite elements have been made for vertical falls onto an infinitely rigid surface, so as to determine permissible fall height, characterised by plastic deformation of less than 22 %. These calculations show that below a height of 5.90 m for the “without cladding” option and 6.40 m for the “with cladding” option there is no containment rupture. The lid is not damaged and preserves its gripping function. Deformations to fuel assembly emplacements are localised and do not result in plastic deformations likely to damage fuel assemblies and prevent them from being removed from the container. These heights are much greater than elevation envisaged in the installations (about 3 metres).

- **Taking into account operations for placement in waste disposal cells**

Weight and diameter of large diameter packages (CU1) result in favouring the principle of transfer using air cushions as illustrated in Figure 4.3.9 (c.f. chapter 9).

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[53] The burn-up rate considered is 40 GWj/t for an assembly initially enriched at 4,5%

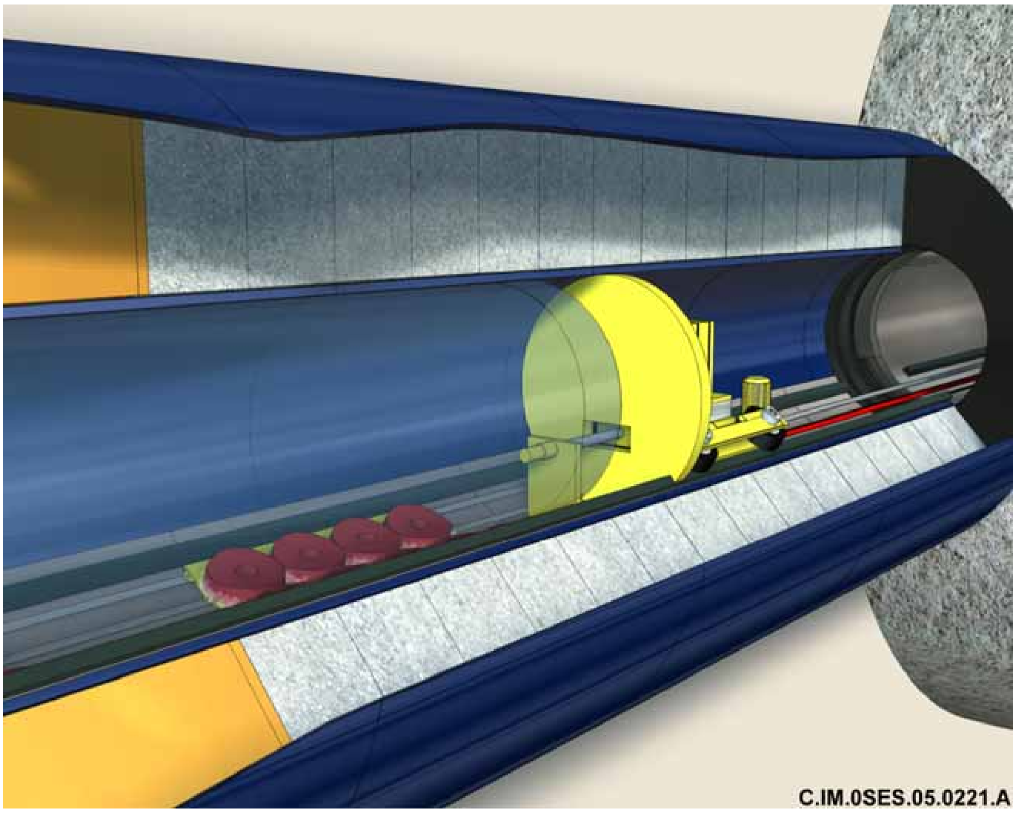

Figure 4.3.9 Placement in cell of a large diameter package using an air cushion

This procedure does not require any special technical measures for disposal packages.

However, for small diameter disposal packages (CU2 and CU3), the principle of disposal cell transfer adopted is similar to that of C waste packages (with nearly the same diameter), namely sliding packages in the cell sleeve using a pusher robot.

In the same way as for C packages, the sliding movement is carried out through ceramic sliding runner friction on the metal sleeve.

- **Taking into account on eventual retrieval**

In the same way as for C waste packages, maximum load applicable to the handling groove was determined for removal of packages from disposal cells, taking into account corrosion thickness (2 m). The calculation provides a maximum applicable load, corresponding to the yield strength limit of about 800 kN for large diameter packages and 500 kN for small diameter packages. Rupture stress corresponds to a traction load of twice that amount.

4.3.4 Disposal package manufacture technique

This section presents disposal package manufacture techniques for spent fuel of CU1 and CU2 types[54] These techniques have been full size tested within the framework of demonstrators[55]. These correspond to disposal packages containing 4 assemblies of UOX 1 300 MWe type in its two management variants (bare assemblies and assemblies in cladding) as presented in Figure 4.3.10.

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[54] For SF3 type fuel, the topic is covered in section 4.2.4

[55] This programme was implemented in 2004 and 2005 together with the CEA and EDF

As for C packages, manufacture is carried out in two phases. The first one consists of the in-plant manufacture of container components. The second phase consists of placing the fuel assemblies received bare or in individual cladding in the container, welding of the plug inside the body and closing the disposal package by welding its lid with electron beam. This second phase must be carried out in a succession of shielded cells for protection against exposure to radiation.

4.3.4.1 Plant manufacture of containers and lid

Figure 4.3.10 The two versions of large diameter container with cylindrical and square emplacements

As mentioned above, the components to be manufactured are the shell made of non-alloy steel (P235) 110 mm thick, the insert equipped with four emplacements (cylindrical or square), the bottom, lid and intermediate plug. For small diameter containers, this involves a shell made of non-alloy steel (P235) with rated thickness of 120 mm, a bottom, a lid and an intermediate plug.

The various techniques analysed (c.f. section 4.2) for the manufacture of C waste over-pack body are also envisaged for the spent fuel repository container body. As for the manufacture of the C over-pack body, two techniques have been identified as particularly appropriate: (i) forging of the shell and welding of the built-up bottom (ii) drilling-drawing to obtain a body in one single piece with integrated bottom.

At this stage, due to large package dimensions and to facilitate insert manufacture, the technique adopted for demonstrators uses a built-up bottom welded onto a shell obtained from forging a block of steel.

Shell forging is illustrated in Figure 4.3.11, with photographs taken during demonstrator manufacture.

Figure 4.3.11 Manufacturing stages of shell in non-alloy steel

The figure on the left shows the blank placed under a press which carries out forging operations and the figure on the right shows the finished product machined to final specifications.

4.3.4.2 Insert manufacture for large diameter packages

The grade of cast iron is selected to facilitate manufacture. Care was taken to limit the cast iron shrinkage during cooling after casting, so as to minimise clearance between the steel shell and insert (for overall mechanical performance)[56].

Direct pouring of the cast iron into the steel envelope was selected because it can minimise the clearance more easily.

The first stages of production of the cast iron insert consist of making a set of four tubes, illustrated in Figure 4.3.12, as part of the demonstrator programme.

Figure 4.3.12 Preparation for insert casting

After the tubes are put together using welded spacers; the ensemble is vertically lowered into the casting shaft, then each tube is filled with sand.

Once the forged shell has been placed around the four tubes, a pouring basin is placed at the top of the shell to spread the melted cast iron inside the shell.

Casting operations carried out for the demonstrator are illustrated in Figure 4.3.13.

Figure 4.3.13 Insert casting

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[56] The type of cast iron is grey iron (GJL150) (G for moulded part, J for cast iron, L for graphite structure and 150 for resistance in MPa) with carbon and silicon content favoring graphite expansion to limit steel/cast iron interface clearance.

Melted cast iron is directed into a ladle which tips over and pours it into the pouring basin.

After cooling and machining of the container body ends, a dimensional inspection makes sure that the emplacements inside the insert are in compliance geometrically to receive the assemblies, as illustrated by the photographs in Figure 4.3.14 for demonstrators.

Figure 4.3.14 Dimensional inspections

On the left, there is a template with assembly dimensions for checking the clearance area of each emplacement along its entire length; other dimensional inspections are carried out (on the right). Ultrasound testing confirms the slight clearance between the insert and steel shell.

4.3.4.3 Welding of the bottom and associated non-destructive testing

Welding of the bottom onto the shell and associated testing can be carried out in a similar way to lid welding (electron beam).

4.3.4.4 Disposal package assembly and closing

The next part of disposal package manufacture takes place in a shielded cell.

The first operation consists of loading bare or clad assemblies into container emplacements. Functional clearances make it easy to load vertically.

The closure plug can then be placed above the insert, the container is rotated and the plug is welded on for an MIG type procedure using a welding robot. The lid is placed on the container body, then the whole is partially inserted in an enclosure where the vacuum is effected, an operation required for electron beam welding. The container is then rotated and orbital welding of the lid is carried out.

Testing procedures are comparable to those used for C waste disposal packages (see section 4.2).

The complete full scale welding of a cover was carried out in the context of the technological demonstration programme. Figure 4.3.15 shows a polished cross-section of a sample taken from an overlying zone. No macroscopic or microscopic fault was observed in the useful thickness of the bond area between the shell and the lid.

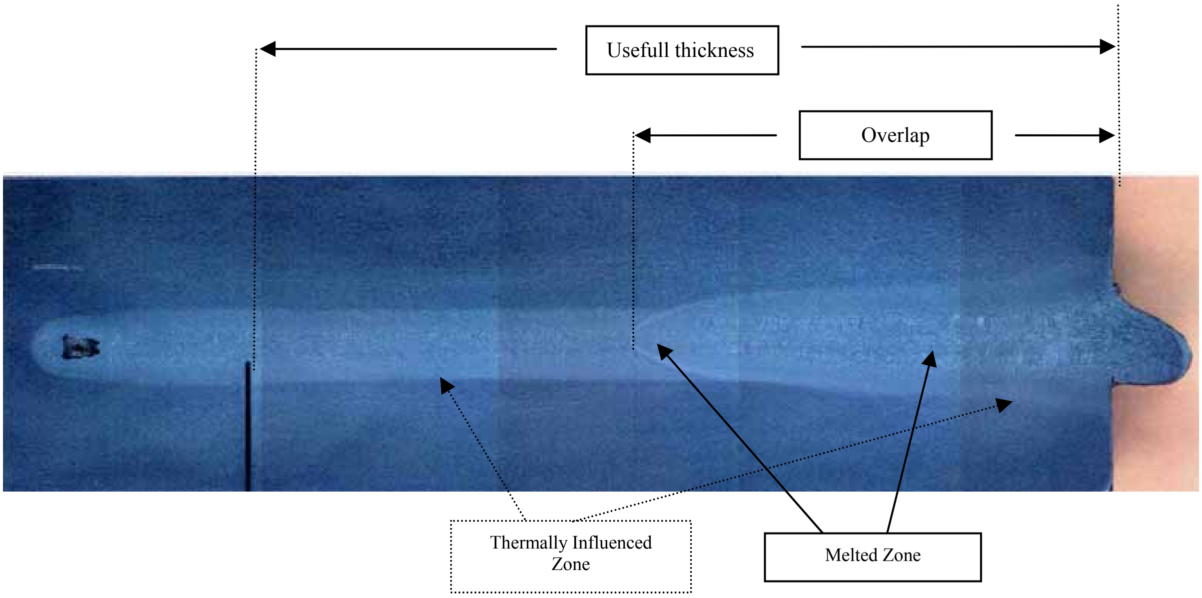

Figure 4.3.15 polished cross-section of a sample taken from an overlying zone

5

Repository modules.

The purpose of this chapter is to explain the design of repository modules as regards their designated functions, and to demonstrate suitability in terms of construction, performances, monitoring, reversibility and closure. As a reminder, a repository module comprises one or more disposal cells along with drifts providing access to them, and that the term disposal cell refers to a basic unit in which disposal packages are placed.

This chapter first of all explains the functions to be fulfilled and the design principles considered for each category of waste. It shows how design takes into account long-term safety measures, in particular, protection of packages within a favourable physical and chemical environment, immobilisation of radionuclides and any toxic matter they contain, and control of disturbances in argillites brought about by works in progress. This chapter also explains how specific design measures allow for reversible management of modules.

A specific set of principles governs choice of materials, their durability and long-term behaviour. In the various design options selected for disposal packages, concrete is the chosen material for B waste. Concrete is well suited to the construction of large-scale structures, and also helps increase retention in the case of certain radionuclides. Concrete is not, however, the preferred material for C waste disposal cells (or for spent fuel). Metallic materials, whose behaviour at temperature is better understood over time, are preferred.

This chapter then provides detailed description of structures along with justification of their design basis. It deals with the mechanical stability of structures excavated into argillites and control of mechanical disturbances incurred. Dimensioning is based on a depth of 500 m. Greater depths (a maximum of 630 m in the transposition zone) raises no particular problems. Its consequences are examined in the safety assessment [56]. Module dimensioning is also related to repository compactness objectives, with appropriate configuration being the goal as regards waste volume and corresponding volumes of argillites to be excavated. The various possible construction techniques are explained, along with the reasons why Andra has chosen the one it has.

Finally, this chapter explains the method for closing modules, which reconciles (i) need for low permeability (ii) ability to carry out the operation with maximum ease, and (iii) retaining the ability to reverse the process.

5.1 B waste repository modules

This section presents basic design principles chosen for B waste repository modules and provides their rationale. For purposes of comparison, it takes a look at concepts studied in other countries.

Repository module components – a cell, its access drift and its equipment – are then described, along with results of calculations of the cell mechanical, thermal and thermo-mechanical dimensioning. In particular, it is shown how long-term safety measures as well as package emplacement and reversibility are taken into account in choice of materials and design, and the rationale behind arrangement of cells according to waste types is explained. Finally, this section provides a description of construction and closing techniques.

5.1.1 Presentation of main issues

The elements underlying design of B waste repository modules are essentially governed by the number of primary waste packages, the radiation property displayed by the majority of them and the physico-chemical characteristics of the waste and its conditioning.

They also include operational safety and reversibility requirements.

5.1.1.1 Quest for repository compactness

A simple answer as regards regrouping and standardisation of disposal packages has been brought to bear upon the variety of primary packages, regrouping them in parallelepipedic concrete disposal packages [57], as described in Chapter 4. At the same time, total B waste package volume involves design of compact repository modules to minimise amounts of rock to be excavated for disposal of the entire inventory.

This quest for compactness must nevertheless be compatible with control of rock damage, temperature, and the sub-critical state of some packages.

5.1.1.2 Safety during works phase

Design of B waste disposal cells must allow:

- ensurance of mechanical stability of structures during operation,
- protection of personnel against radiation,
- management of gases which may be emitted by certain packages.

- **Ensuring mechanical stability of structures**

When package disposal operations commence, the cell must be inaccessible due to package irradiating properties. Any lining maintenance operation therefore requires temporary removal of disposed packages. In order to simplify disposal management, it has been decided to design lining to ensure cell mechanical stability throughout package emplacement and after, with a view to reversibility. Multi-century durability is targeted.

- **Protecting personnel from radiation**

During package emplacement, maintenance and monitoring operations, operating personnel must be protected against direct radiation from packages and also from radiation caused by the very small quantities of radioactive gases some of them may emit.

- **Evacuating gases**

Most B waste produces hydrogen by radiolysis of material it contains. As well as the above-mentioned need to protect personnel against radioactive gases, special attention must be paid to control of risks associated with the presence of hydrogen in the air inside cells and drifts.

5.1.1.3 Long-term safety

Regarding the long-term safety measures described in section 2.1.2, cell design contributes to:

- conserving favourable environmental conditions by limiting disturbances due to disposal,
- temperature control,
- maintenance of sub-critical state for B packages containing traces of fissile elements,
- control of water circulation around and within modules and cells,
- splitting up of disposal so as to limit radiological effects in certain hypothetical situations,
- protection of primary and disposal packages from physico-chemical alterations which could accelerate their deterioration,
- retention of certain radionuclides.

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[57] It is worth mentioning that these disposal packages have no role of biological shielding in the quest for compactness.

- **Limiting disturbances of argillites**

Disturbance of argillites due to disposal are largely mechanical in nature. Digging out of cells causes disturbances of argillites around the structures,. and structure design must aim to control extension of such disturbances, and particularly to prevent it occurring in the short and long term. Disturbances of mechanical origin are micro-cracks, fractures even, appearing in the excavation walls during the digging of cells in argillites. They can have a considerable effect on the permeability of the immediate geological environment. Such disturbances, located on the walls to an approximate depth of a half radius[58] after digging [57], may spread in the long term, following lining rupture (after a thousand years or so). Such spreading, caused by delayed action (of a viscous nature) on the part of the argillites, only occurs when deformation of argillites on the walls reaches threshold level**.** Controlling spread involves limiting maximum possible rock deformation.

In order to do this, it would appear necessary to limit spacing within cells (chiefly between disposal packages), as well as limiting voids within the disposal packages themselves. Furthermore, areas of rock disturbed may be limited by appropriate choice of excavating methods, and by disposal cell geometry and orientation [57].

It should be pointed out that disposal may also disturb rock chemically, due to introduction of air or of exogenous materials. Sizes of such disturbances, especially those of alkaline type, have been assessed in order to verify their limited nature [7] [58].

- **Temperature control**

As is the case for disposal packages, temperature limitation within the cells is caused by:

- the need to control changes in cell lining materials,
- the need to be able to predict behaviour of radionuclides in the repository.

In the case of concrete, temperature control is of considerable importance. Here, progressive changes due to temperature depend jointly upon temperature levels and temperature rise duration. Study of physics and chemical properties of cement materials show the existence of a temperature threshold affecting the material chemical changes (carbonation, hydrolysis). As long as temperature remains below this threshold, physics and chemical properties, especially permeability, change in a reversible manner or remain constant. Above the threshold, certain cement paste hydrates become unstable: major mineralogical modification would therefore lead to irreversible changes in concrete physics and chemical properties. Moreover, there are uncertainties regarding chemical properties at these temperature [48].

Temperature and overheating duration must be limited as much as possible. A maximum temperature of 70°C has been adopted.

In the special case of cells containing B2 waste (bitumens), a much lower temperature limit, 30°C, has been adopted to maintain the rheological properties of the bituminous bed .

It is worth mentioning that the above criteria are in line with the findings of current thermo-hydromechanical modelling, as well as with knowledge of radionuclide behaviour as regards solubility and sorption.

- **Maintaining sub-critical states for B packages containing traces of fissile elements**

Some B waste contains traces of fissile elements. Dimensioning of cells related to that of disposal packages should guarantee that all packages and installations stay sub-critical, not only by initial geometrical configuration, but also by taking into account long-term alteration phenomena in materials that could lead to local increases in concentration of fissile material. Dimensioning parameters involved are largely governed by spacing between packagesand their arrangement.

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[58] Zone with micro-cracking at 500m in depth for circular excavations and oriented in parallel to major horizontal stress.

- **Controlling water circulation around and within cells**

Construction and use of underground structures create disturbances of natural hydraulic systems. The resaturation phase for B cells lasts several tens of thousands of years and more [8]. After establishment of a new hydraulic balance, control of water circulation seeks to minimise flow of water likely to circulate in the cell and to limit flow speed. Design seeks in particular to reduce flows of water coming from access structures. Cell geometry along with means of access and closure must help to minimise such flows.

- **Splitting up disposal**

Splitting up disposal space into modules limits the effect on population and environment of any possible failure after repository closure.

- **Protecting waste from physico-chemical attack**

Protection of waste is aimed at limiting release of radionuclides. In practice, this consists of limiting corrosion of B waste containing activated parts made of stainless steel or alloys containing nickel, zirconium or magnesium (i.e. B1, B4, B5, B6 and B7 packages) and of limiting alteration of bitumen in B2 packages.

When water is present (that is to say, after cell closure and resaturation), physico-chemical conditions of alkaline pH within the cell help limit anoxic corrosion of metallic waste.

In addition, the right environmental conditions lead to pH levels below 12.5 in cells containing B2 packages, limiting alteration of bituminous beds, in conjunction with the temperature limitation already mentioned above.

- **Contribute to retention of certain radionuclides**

In conjunction with the rock itself, lining materials employed within the cells can also help immobilise certain radionuclides in the repository, through the physico-chemical conditions they impose in the cell[59].

5.1.1.4 Taking reversibility into account

Reversibility is taken into account in structure design, which must incorporate factors to ensure flexible repository management, as well as to simplify any possible future package retrieval operation. Such factors mainly concern structure durability and functional clearances.

Structure durability guarantees maintenance of functional clearances between packages and cell walls for at least a century. It also contributes to disposal package durability (already mentioned in Chapter 4). Maintenance of handling clearances and of package integrity provides great cell management flexibility, and makes any possible future package retrieval operation as simple as their original placement, as long as the cell is not sealed.

5.1.2 Cell design principles adopted

5.1.2.1 Several options considered and compared

Key design parameters for a B waste disposal cell concern cell geometry, arrangement of packages within the cell and handling of packages. Disposal cell design is inseparable from disposal package design and handling systems.

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[59] Thus, alkaline pH encourages insolubility of nickel, americium and curium. Cement also has a capacity to retain neptunium and plutonium.

- **Cell geometry: Medium to wide diameter tunnels or large cavities**

Cell geometry is governed by the need for compactness, geo-technical conditions and package characteristics.

The above-mentioned need for compactness points design towards high-capacity disposal structures consequently of large size. B waste being either non-exothermic or virtually so, packages can be disposed side-by-side in large numbers, a fact which encourages this orientation towards large-scale structures. Maximum size for the various options considered is in the twenty metre range, with virtually circular tunnel-type geometry (Figure 5.1.1) or large cavity or silo-type geometry (Figure 5.1.2).

It is also necessary to decide what constitutes reasonable size keeping in mind constraints related to construction, mechanical behaviour and conservation of undisturbed argillites above and below the structures.

The cell size of 10 to 12 m finally decided upon reconciles these two aspects.

- **Horizontal or vertical handling**

The choice between vertical and horizontal handling of packages greatly influences cell design.

For vertical handling, an apical space must exist along the entire length of the cell to allow for developments in handling tools (Figure 5.1.2 and Figure 5.1.4). This space, which cannot be used for disposal, reduces cell compactness.

For horizontal handling, it is possible to transport packages sideways (Figure 5.1.1 and Figure 5.1.3). This configuration, which allows the whole cell section to be used for disposal, fosters design compactness.

The quest for compactness together with the choice of structures excavated to the order of 10 to 12 m in diameter have led to opting for horizontal handling of packages.

- **Arrangement of disposal packages in guide tubes or in piles**

As regards arrangement of packages within cells, two major methods were compared.

The first consists of disposing packages in guide tubes. Installation of tubes in the cell and filling of spaces between tubes is done during construction. Several ways of installing the tubes have been considered: metallic tubes with poured concrete or prefabricated concrete components with hexagonal ‘beehive’ cross-section (Figure 5.1.1). The second solution results in major reduction of spacing between disposal tubes, and therefore greater compactness. However, the components must be aligned one against the other lengthwise to create concrete tubes for package disposal. It is thus possible to obtain considerable compactness by so equipping 10 or 11 metre diameter cells. However, with horizontal configuration, installation of packages in guide tubes requires rather complex handling methods in the access drift to get packages up to the tubes (up to around 9 m above the apron) and then push them into place. Moreover, this method of package placement may require limiting cell length.

The second method consists of piling and juxtaposing packages with nothing between them in order to obtain maximum compactness. To do this, a parallelepipedic disposal chamber is set up in the excavated cell during application of concrete lining. Chamber dimensions are adapted to disposal package dimensions (themselves parallelepipedic) in order to minimise space between packages and between packages and walls. This arrangement requires high-precision handling tools for package installation, but which poses no problem given existing means. With horizontal configuration, it results in very good repository compactness. Furthermore, minimising spaces in the disposal chamber avoids having to fill them up when closing the cell, and thus facilitates any future retrieval of packages.

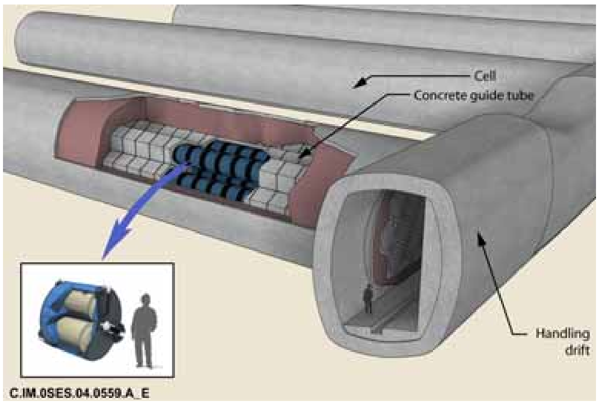

Figure 5.1.1 Tunnel with horizontal guide tubes

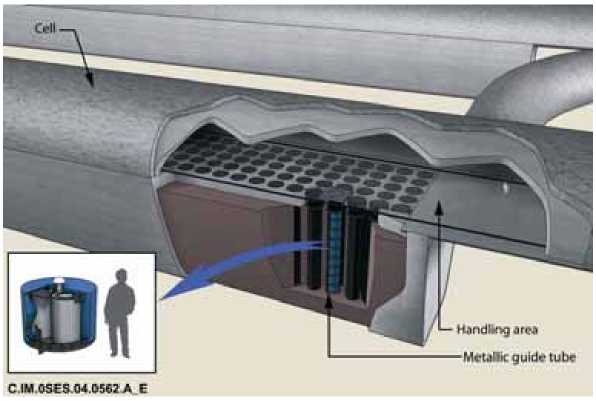

Figure 5.1.2 Cavity with vertical guide tubes

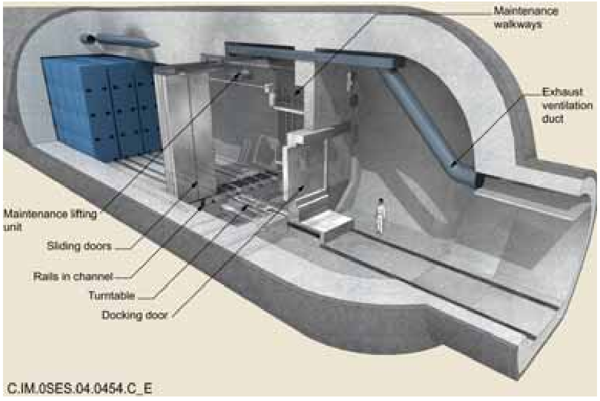

Figure 5.1.3 Tunnel for parallelepipedic disposal packages (horizontal handling)

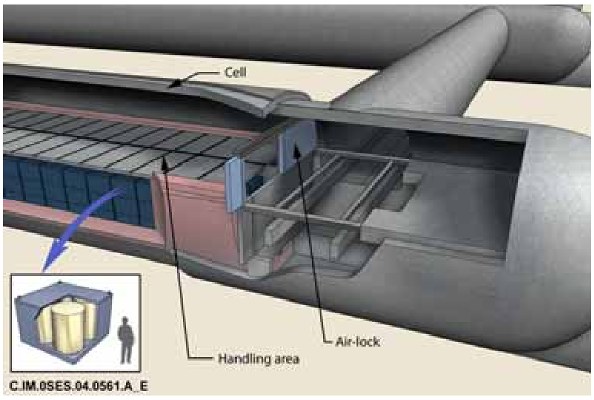

Figure 5.1.4 Tunnel for parallelepipedic disposal packages (vertical handling)

- **Summing up**

In conclusion, the choice (Figure 5.1.3) described below corresponds to the concept of parallelepipedic disposal packages piled in a parallelepipedic chamber, with horizontal handling.

5.1.2.2 The solution adopted

- **General**

The chosen disposal cell is a sub-horizontal, dead-end tunnel, with a useful length of approximately 250 m[60] and an excavated diameter of between 10 and 12 m. The tunnel is concrete-lined. This cell consists of an irradiating chamber in which the packages are disposed of using a remote-controlled lift truck. The cell head is equipped with a radiological protection chamber for protecting personnel when extracting a disposal package from its protective transfer cask. The cell is ventilated throughout its period of service for evacuating gases generated by the packages.

The cell is linked to the connecting drift network via a small diameter access drift.This drift will be sealed when the cell is closed.This concept is illustrated by Figure 5.1.5 which shows the cell in operational configuration and Figure 5.1.6 which shows the cell in sealed configuration.

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[60] This useful length is associated to a total length of around 270 m, including disposal cell head and far end.

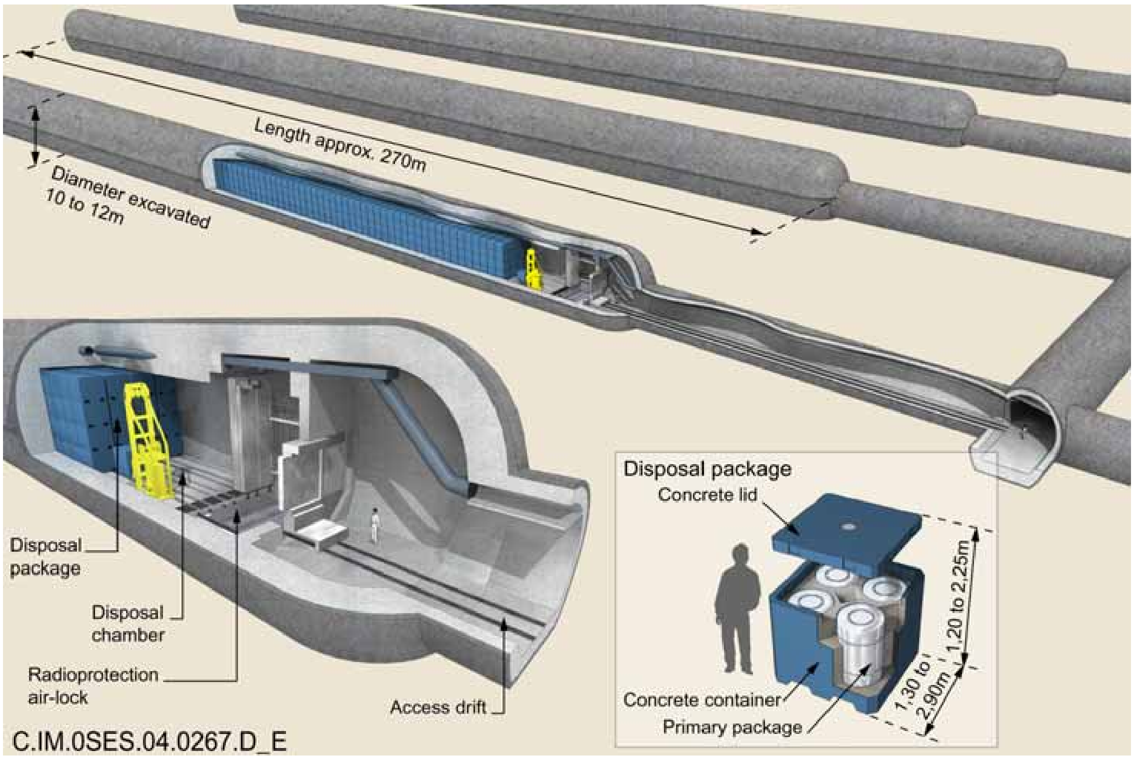

Figure 5.1.5 *B waste disposal cell in operating configuration*

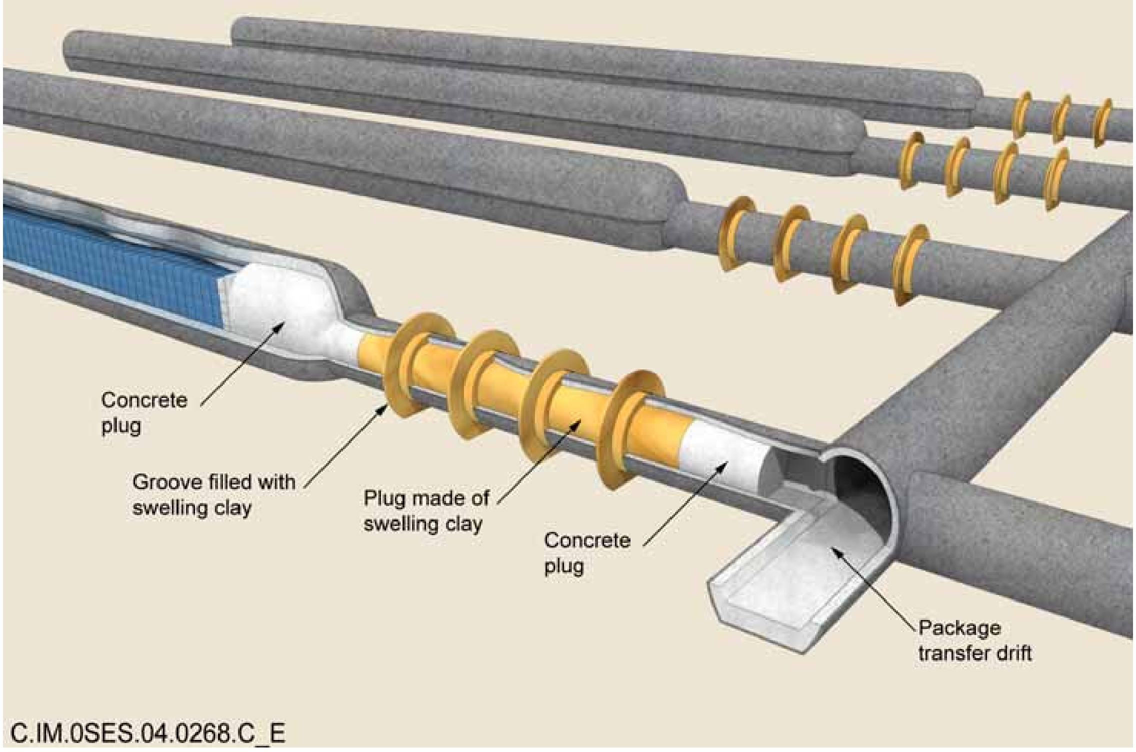

Figure 5.1.6 *Sealed B waste disposal cell*

- **The geometry and orientation of the cell**

Defining the diameter of the cell body is based on balancing the need for maximum compactness with the requirement of constructability of the cell within the constraints of the mechanical behaviour of the geological formation and any residual uncertainties. The first requirement favours a cell that is as large as possible, while the second would lead to the adoption of a small structure. As stated earlier, a diameter of 10 to 12 m was regarded as a reasonable compromise. This dimension corresponds to the dimensions frequently encountered in road or rail tunnels beneath a thick rock cover, with a hundred-year lifetime, as for example the Chamoise tunnel excavated in a rock similar to the argillites [59].

At this stage in the studies, a useful cell length of the order of 250 m has been adopted. This length seems to be a reasonable compromise between the compactness of the repository, the flexibility and progressiveness of repository management, the adaptability of cells to the wide variety of packages, the constraints of handling and the inclusion of the cells in the argillite layer.

The cell has a pseudo-circular cross-section and is aligned parallel to the major horizontal stress. This configuration creates a quasi-isotropic stress state around the body of the cell and the access drift where the future seal will be, and minimizes the mechanical disturbances caused during excavation.

The dead-end nature of the cell restricts water circulation within the cell in situations where a seal is defective (cell seal or other seals).

Cells are at least five excavated diameters apart, to minimize any mechanical interference between cells and to ensure the long-term stability of the whole area. It was further confirmed that this cell and repository zone geometry was compatible with compliance with temperature criteria (30 °C for reference package B2 and 70 °C for other packages), ignoring the favourable effect of ventilation.

- **Nature of the cell lining**

The cell body is basically characterized by a concrete lining. Choosing concrete meets the need for mechanical stability in the structure left without maintenance for a period of at least a hundred years, since concrete is a geomaterial, easy to use and stable over the period in question. Its chemical degradation (by hydrolysis and carbonation) is slow under repository conditions [48]. The lining concrete is not reinforced, so that its durability is not dependent on steel corrosion.

Moreover, as stated earlier, concrete has a favourable impact regarding the immobilization of certain radionuclides and regarding the corrosion of metal waste.

- **Form of the cell lining**

In order to restrict mechanical deformation of the geological formation in the long term, the residual space left after package emplacement has to be reduced as much as possible. A conventional solution for limiting these spaces would be to fill the cell's residual spaces with a granular or cement-based material after package emplacement. However, this solution has a double drawback: it requires an additional operation complicated by the irradiating nature of the packages and it increases the difficulty of possible removal of packages, since they would be blocked in by the fill material.

The solution adopted takes into account the need to limit the residual spaces and the need to keep a permanent functional clearance for a period of at least a hundred years (to allow reversible repository management). The principle adopted during construction consists in adding an additional volume of concrete to the lining segment[61] for ensuring mechanical stability, in such a way that a disposal chamber of rectangular cross-section is formed, of a size adapted to the form of the package stack. The tens of centimetre clearances between packages thus meet the two conditions mentioned above. These clearances actually produce an inter-package space of less than 5%, with respect to the excavated section [57].

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[61] Quasi-circular in shape

- **Airlock at cell head and radiological protection**

For the radiological protection of personnel, the cell head is fitted with an airlock separating the entrance drift from the cell body.

- **Cell access drift and seal**

The cell access drift linking the cell and the connecting infrastructure, is designed to accommodate the seal for closing the cell. To help achieve the best performance from the seal, this drift has a useful diameter reduced to 5 or 6 m, according to the size of the packages to be disposed of in the cell, and its support and lining are designed specifically so as to limit any mechanical disturbances at the seal, as in the case of the seals in connecting drifts. The length of this entrance drift (some fifty metres) is determined by the space needed for forming the seal and its retaining plugs.

- **Cell arrangement**

In order to improve the compactness of the repository and simplify operation, grouping together some reference packages (in particular those small in number) can avoid the construction of several short-length cells and thus reduce the overall space requirement of the disposal area. However, to prevent chemical interactions between packages capable of damaging retention properties in and around the cells, packages containing organic matter are disposed of separately in other packages [37].

- **Cell ventilation**

The filler concrete includes longitudinal ventilation ducts for ventilating the cell throughout its operation until it is sealed. This facility meets the need to control gases. This ventilation also helps reduce the temperature in the initial years of package disposal.

- **Summary of requirements and adopted solutions**

The contribution of the various cell components to the functions of disposal is summarized in Table 5.1.1. [7], [22].

Table 5.1.1 Functions and main Components of B cell (or module)

Functions	**Period**	**Concrete lining**	**Cell Section**	**Seal in the access drift**	**Cell airlock**
Transferring the packages to their repository location	Operations		**X**		
Mechanically supporting the structures	Operation and monitoring	**X**	x		
Protecting man against radiation	Operation and monitoring				**X**
For retrieving disposal packages	Operation and monitoring	**X**	**X**		
Preventing water circulation	After closure			**X**	
Restricting the release of radionuclides and immobilizing them in the repository	After closure	**X**		x	
Delaying and reducing the migration of radionuclides	After closure			x	
Limiting mechanical deformation in the Callovo-Oxfordian argillites	After closure	x	**X**		
Splitting up the repository	After closure			**X**	

Legend: **X** essential component in performing a function
x contribution of a component to a function

* Module separation of the repository does not, strictly speaking, constitute a safety function, but is a device adopted with safety objectives in mind

5.1.2.3 Solutions adopted abroad

Several countries are studying underground repository solutions for similar waste to French category B waste, in clay type environments.

In Switzerland, NAGRA[62] is studying the feasibility of an underground repository in an argillite with mineralogical characteristics similar to that of the Bure site, but with stronger mechanical properties. The concept adopted is a tunnel whose dimensions are around 9 m high by 7 m wide. The disposal packages are stacked in these tunnels on 2 or 3 levels. NAGRA has not chosen to minimize the spaces between the packages and the disposal cell and has preferred to fill the gaps with a mortar after emplacement of the packages (Figure 5.1.7). The cell is then closed with a concrete plug [44].

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[62] National Cooperative for the Disposal of Radioactive Waste

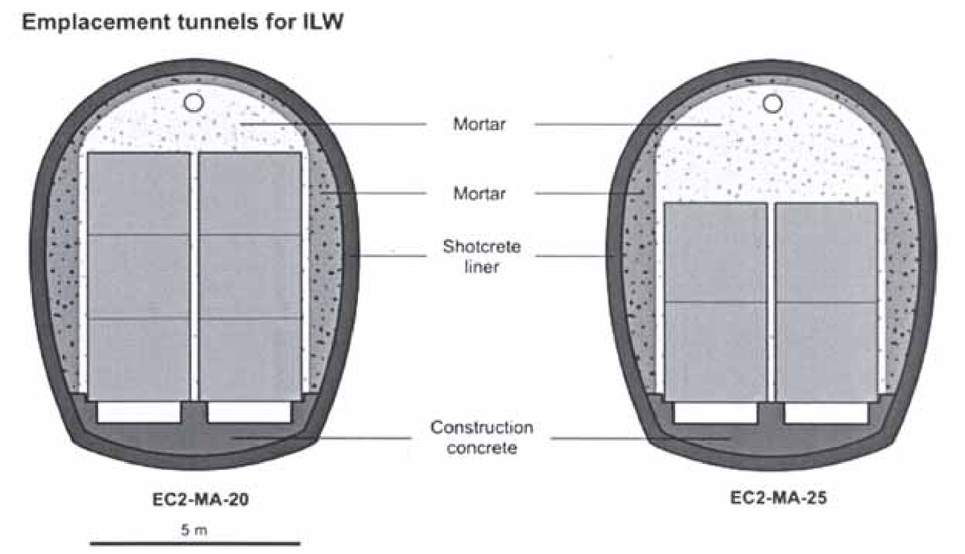

Figure 5.1.7 Diagram of the concept adopted by NAGRA (Switzerland)

In Belgium, the concept adopted by ONDRAF[63] consists in placing "monoliths" (concrete disposal packages containing several primary packages) in drifts with a diameter adjusted to the diameter of the monoliths, that is, 3 to 4.5 m (Figure 5.1.8). The aim of this small excavated diameter is to adapt to the properties of the Boom clay, which is more clayey and much more plastic than the argillites of Meuse/Haute-Marne. The emplacement clearances between the monolith and the drift lining are minimized; they do not require filling.

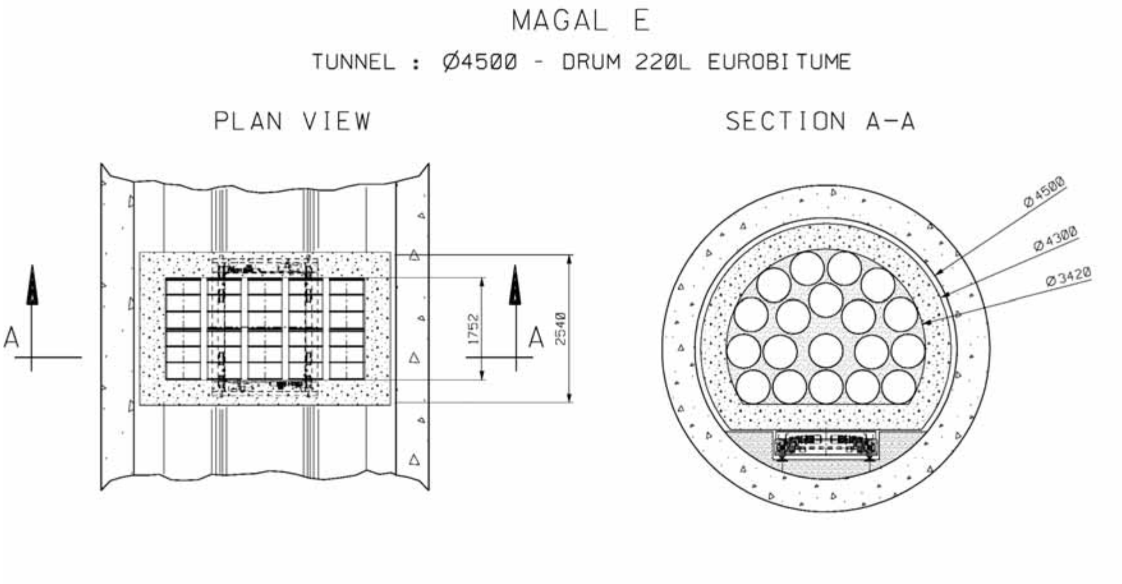

Figure 5.1.8 Diagram of the concept adopted by ONDRAF (Belgium)

In Japan, the concept adopted for a generic sedimentary site is a tunnel of circular cross-section with a useful diameter of 10 m. The space between the packages and the tunnel lining is filled in after package emplacement. Several kinds of material are considered[60].

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[63] National Agency for Radioactive Waste and Enriched Fissile Materials

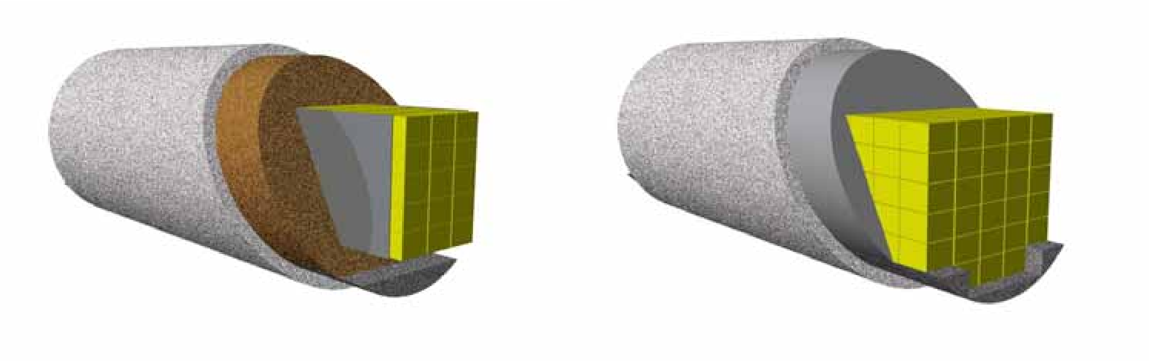

Figure 5.1.9 Diagram of the concept adopted by JNC (Japan) on a sedimentary site

In Germany, the Konrad project is aimed at disposing of non-exothermic radioactive waste in a calcareous marl layer of an old iron mine (Konrad in Lower Saxony). The primary packages are grouped into non-irradiating cylindrical or parallelepipedal disposal packages (see section 4.1.2). The disposal chambers are either existing chambers that have possibly been widened and/or lengthened, or new chambers. They are approximately 7 m wide and 6 m high. They may be up to 1000 m long. The packages put in place using a lift truck are stacked on 3 levels. After filling up a length of 50 m of disposal cell, a concrete wall is erected to isolate this cell section and spaces in this section are filled with a cement-based material by pumping.

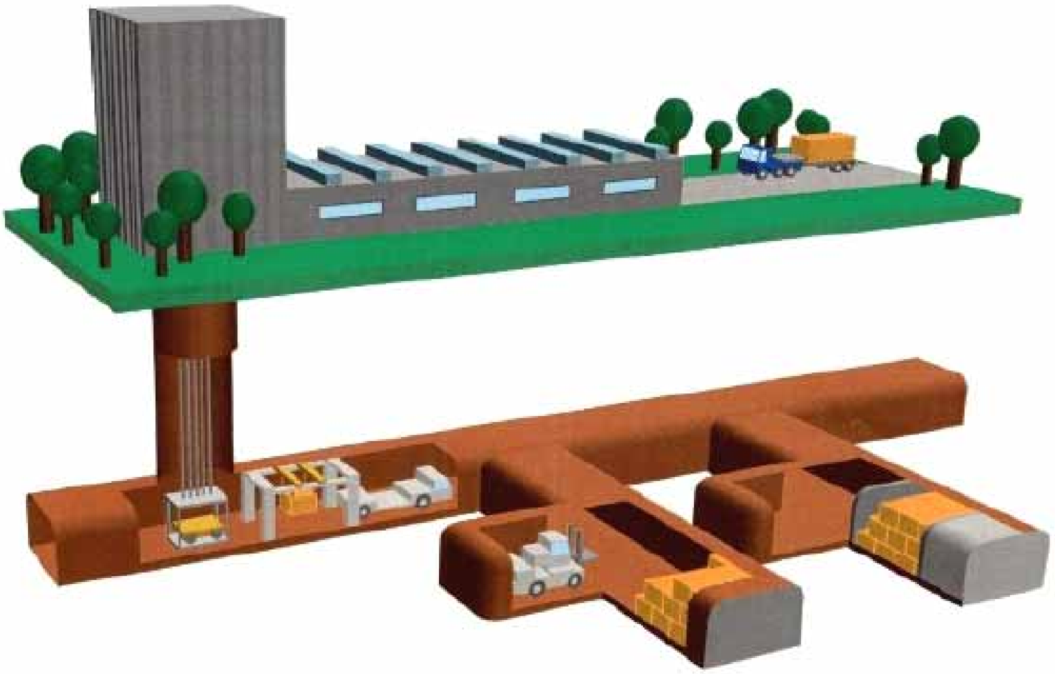

Figure 5.1.10 Diagram of the disposal concept adopted by DBE (Germany) at the Konrad site

This summary shows that the cell concepts studied abroad for B type waste or similar in sedimentary rocks display similarities with the concept envisaged by Andra.

The cells are horizontal tunnels with dimensions of the same order of size as that of the cells studied by Andra (up to 10 or 15 m). There are differences in lining due to the mechanical behaviour of the various host rocks.

Some foreign concepts mentioned above include filling in spaces, whilst others, like Andra's, favour minimizing such spaces through a suitable choice of disposal cell geometry and means of maintenance.

5.1.3 Description and dimensioning of the cell and access drift

This section is devoted to describing the cell and its equipment in operating configuration, together with the access drift. It also sets out the main results of the mechanical dimensioning calculations and shows how considerations relating to the integrity of the geological medium, the physical and chemical environment of the packages, the emplacement of the packages and the safety of the repository are taken into account in the choice of materials and design [61].

5.1.3.1 Overall characteristics

The description of the design principles of the B waste disposal cell given previously highlighted the existence of three parts:

- the useful part (or body) containing the disposal packages,
- the head, which is dedicated to extracting the packages from their transfer transfer cask and to the radiological protection of personnel during repository emplacement operations[64],
- the access drift where the cell seal will be placed.

The useful part comprises three main elements (Figure 5.1.11). The ground support and lining[65] ensure the stability of the cell. The slab and its equipment enable the transporter to move and take up the weight of the packages. Finally, the tubes set in the top part of the lining are used for ventilating the cell.

The cell’s dead end consists of a tympanum and a porous wall for ventilation. The cell head is equipped with an airlock for the transfer of packages between the radiological protection transfer casks and the irradiating cell body inaccessible to personnel.

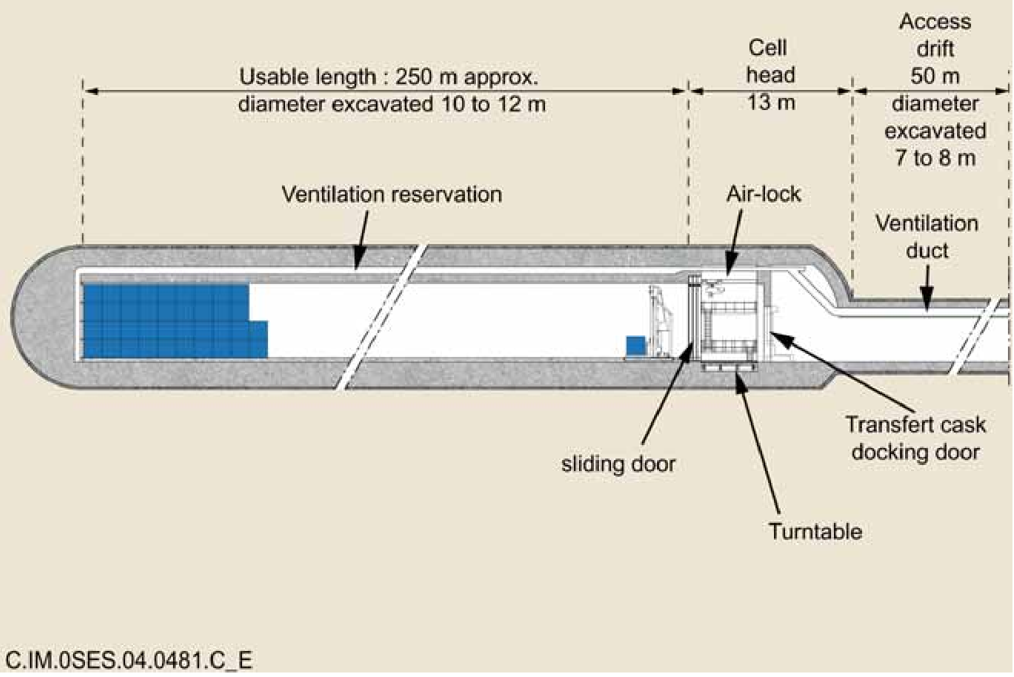

Figure 5.1.11 B cell in operation

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[64] Except for cells containing less irradiating packages, which do not need an airlock.

[65] The ground support, fitted as the excavation progresses, ensures the stability of the excavation during the construction work. The purpose of the lining is to maintain this stability over a long period (several centuries)

5.1.3.2 Detailed description of the cell in operating configuration

- **Description of the useful part of the cell**

The useful part of the cell is a drift with an excavated diameter of 10 to 12 m. The form of the excavation is quasi-circular or horseshoe-shaped, in order to best fit the different package dimensions, so as to minimize the volumes excavated and the volumes of concrete, while only stressing the lining concrete in compression. To extend the maximum lifespan of the cell structure, the amounts of steel are reduced to the minimum to avoid possible corrosion.

Figure 5.1.12 illustrates the various components of the useful part of the cell.

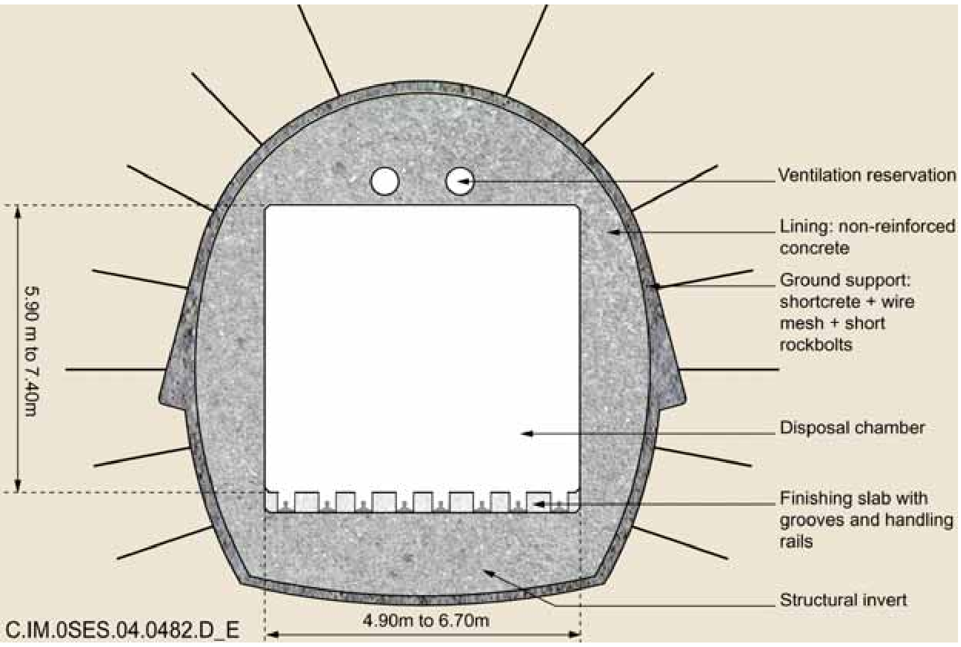

Figure 5.1.12 Main section of a B cell

The cell's ground support is designed to ensure worksite safety while minimizing long-term disturbances. To minimize disturbance in the argillite and restrict the introduction of metal components into the cell as much as possible, the ground support consists of short steel rockbolts, 2.40 m in length, which do not therefore exceed the extent of the microfissured clay zone[66]. A steel welded mesh and B40[67] glass fibre reinforced shotcrete, 25 cm thick, complete the device. This solution was preferred over more conventional solutions such as metal arches or 5 m long bolts, which would have penetrated much farther into the rock and possibly enlarged the damaged argillite zone at the walls. In the event standard equipment is used, the diameter of the cell makes it necessary to excavate and support the section of the cell in two phases. Owing to ground support installation constraints, the drift side walls must be widened at mid-height. The use of specific equipment would make it possible to excavate and support the cell in the middle of the section and would prevent these "elephant's feet" from forming.

The lining and the filler concrete, although having different functions, are cast as a single assembly for reasons of construction. The lining (with structural slab) is only subjected to compressive stress and is not reinforced (Figure 5.1.13). Preliminary dimensioning gives this structural ring a thickness of approximately 70 cm for a B60 concrete. The filler concrete forms the boundary of the rectangular disposal chamber. Dry joints[68] are used in the filler concrete so as not to interfere with the stresses in the structural ring. Stainless steel hangers locally reinforce the filler concrete.

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[66] Composite glass fibre - resin rods could be used as a variant, and/or a resin seal.

[67] Concrete whose simple compressive strength is 40 MPa

[68] Grooves made in the concrete and left empty

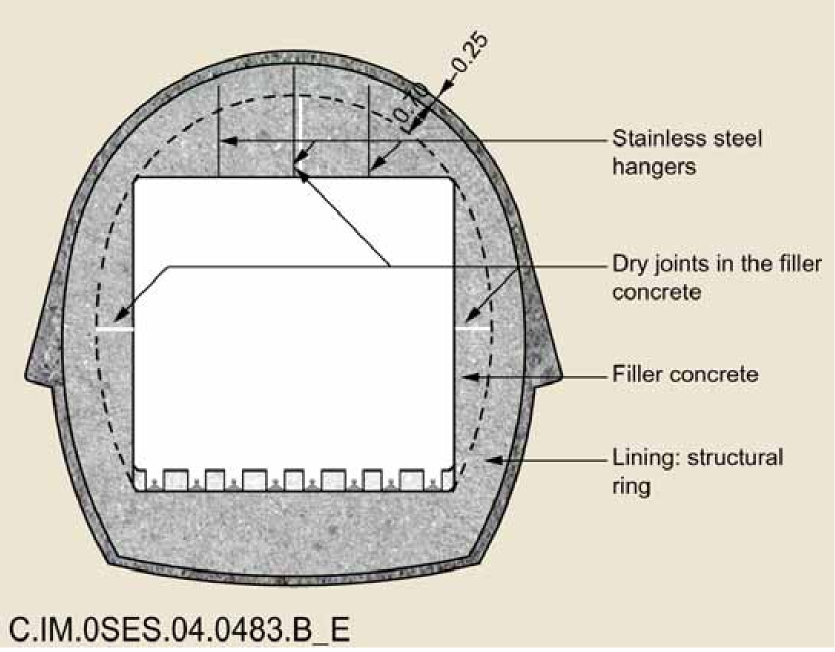

Figure 5.1.13 *Structural ring and filler concrete*

The slab is not reinforced and is integral with the lining. It is fitted with rails for handling packages.

Two ventilation ducts 600 mm in diameter are arranged in the filler concrete (Figure 5.1.14). The cell end is specifically equipped for the needs of ventilation. It is equipped throughout the section with a wall pierced by holes, which, due to its high aeraulic strength and the position of the holes, is capable of regulating airflow in the cell. The ventilation ducts behind this wall ensure air return in the cell.

The cell end is spherical in shape. The ground support comprises 2.40 m long sub-horizontal rockbolts and 25 cm of shotcrete. The concrete lining is lightly reinforced at the junction of the end and the main section.

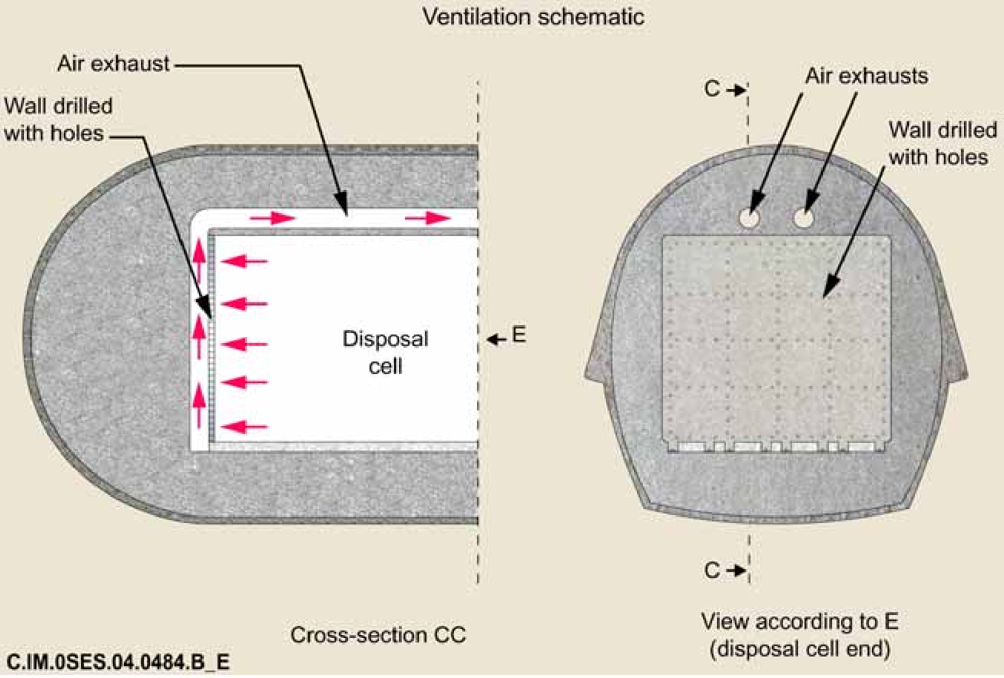

Figure 5.1.14 *Longitudinal and cross section of the cell end*

- **Arrangement of packages in the cell**

All the disposal packages placed in the same cell have the same dimensions[69]. According to their size, they are arranged on 3 or 4 levels and over 2 to 4 columns in the crosswise direction of the cell (Figure 5.1.15). A clearance of 15 cm is left between the top of the packages and the roof of the handling chamber. A clearance of 10 cm is left crosswise between the package columns and between the packages and the vertical walls of the handling chamber. The clearances are reduced to the minimum in the longitudinal direction. These clearances are sufficient for package handling and cell ventilation.

With this spacing, the gaps between packages represent approximately 5% of the excavated section of the cell. It should be noted that it would be possible to reduce these gaps still further by inserting a filler block about ten centimetres thick above each stack of packages, and by reducing the spacing between package columns through improving the precision of the handling system.

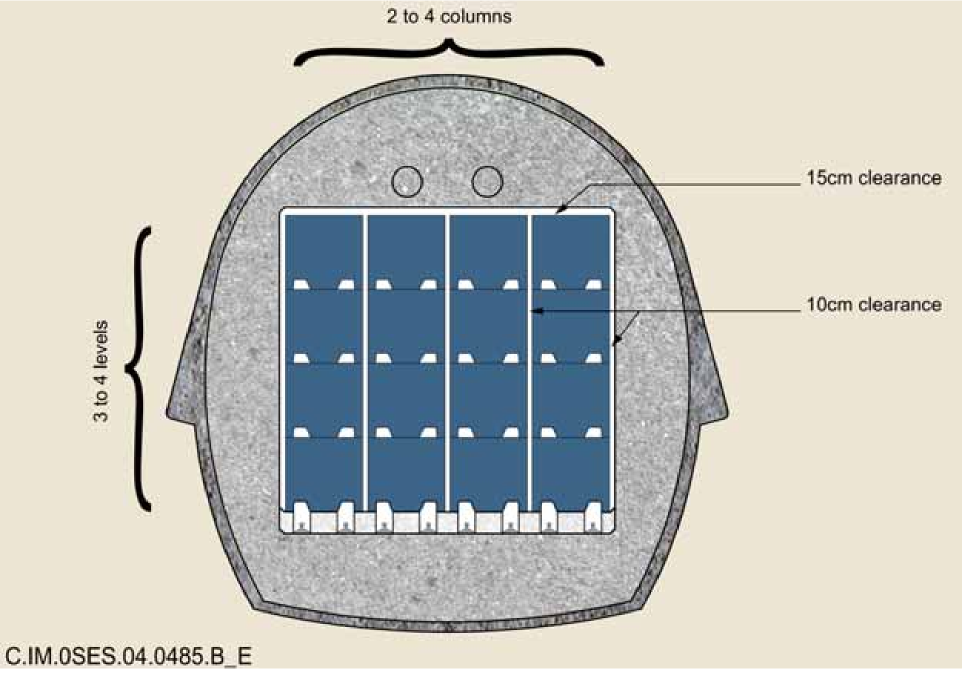

Figure 5.1.15 Arrangement of packages in the cell

- **Description of the equipment of the cell head (before sealing)**

B cells are equipped with an airlock at the cell head (Figure 5.1.16). Its function is to provide radiological protection for personnel during operations for extracting packages from their transfer transfer cask and disposal (or withdrawal). The handling equipment used for these operations is remotely controlled from outside the airlock.

The airlock is formed by two doors. The outer door (on the access drift side) is equipped with a window onto which the transfer transfer cask is docked. This door is also used for the exit and entry of the handling truck in the airlock. The inner door (on the cell body side) is formed of several sliding panels for the passage of this same truck for transferring packages to their repository location in the cell. The airlock thus formed between the two doors is fitted with a moving floor and a rotating table, which enable the handling truck to manoeuvre in a restricted space.

The airlock is ventilated via ducts connected to the pipes in the cell body and via shielded baffles in the airlock doors.

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[69] In some instances, packages of the same height and width (crosswise to the cell) but of different lengths (lengthwise to the cell) can be used. In this case, the packages are arranged by homogeneous zones within the cell.

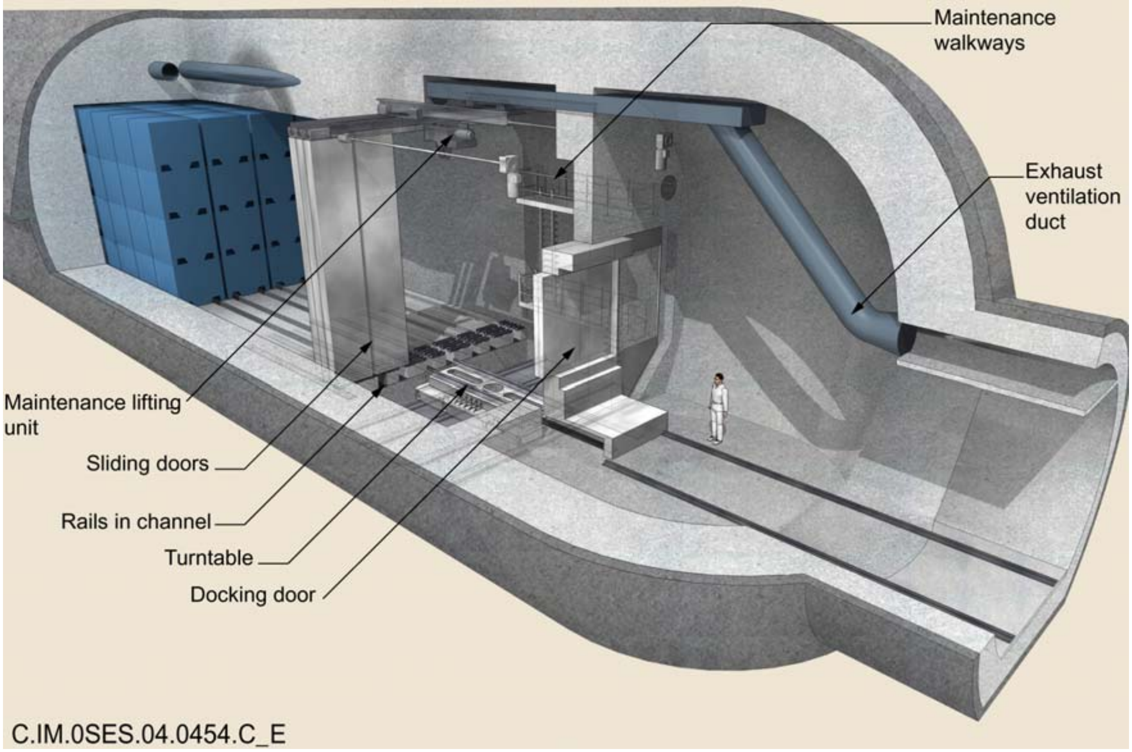

Figure 5.1.16 B cell airlock

5.1.3.3 Description of the access drift

The cell access drift is the area where the cell is to be sealed. Accordingly, the design of this drift is very similar to that of a drift section to be sealed such as that described in Chapter 7 (section on "*Closure of Underground Installations*"). The only special feature of the access drift lies in adapting its useful diameter to the size of the packages to be disposed of. The useful diameter is thus between 5 and 6 m along the cells, according to the packages that will be placed in them.

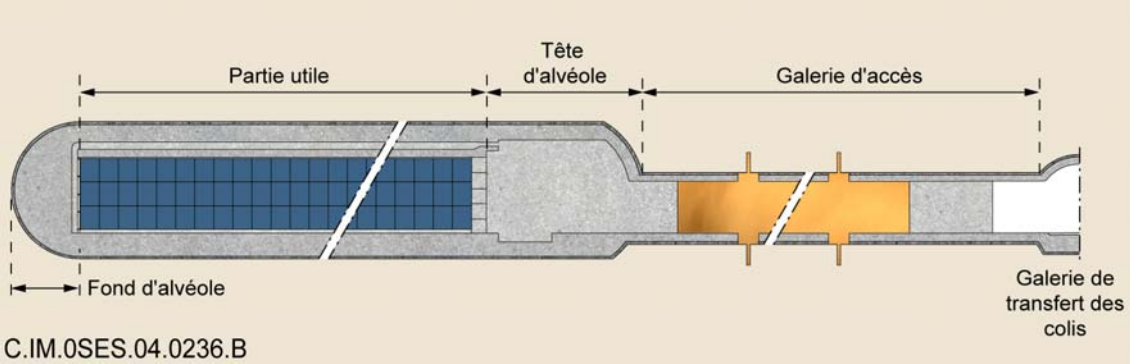

Figure 5.1.17 Cross-section through the B cell and the access drift after sealing

5.1.3.4 Thermal Behaviour of disposal cells

B waste is non- or only slightly exothermic. Some disposal packages (B5.1 and B5.2) have a low residual heat rating, of the order of 50 W for a disposal package containing four primary ten-year-old packages (cf. Figure 3.2.13, Chapter 3).

Although this aspect is not a very decisive factor in the design and layout of B waste cells, thermal models were created to check that the maximum temperature was well below 70°C. These models did not take into account the favourable effect of ventilation, so that the design is independent of the choice of management and in particular of the duration of ventilation after disposal. The main hypotheses adopted for these thermal dimensioning studies are the same as for the thermal dimensioning of C waste cells (see section 5.2), i.e. mainly heat transfer by conduction and radiation, neighbouring cells simultaneously filled with the same exothermic packages and an initial rock temperature of 22°C.

The models show that, for packages disposed of at 10 years of age, the maximum temperature in the cell always remains below 70°C and drops back below 50°C at the end of about a century.

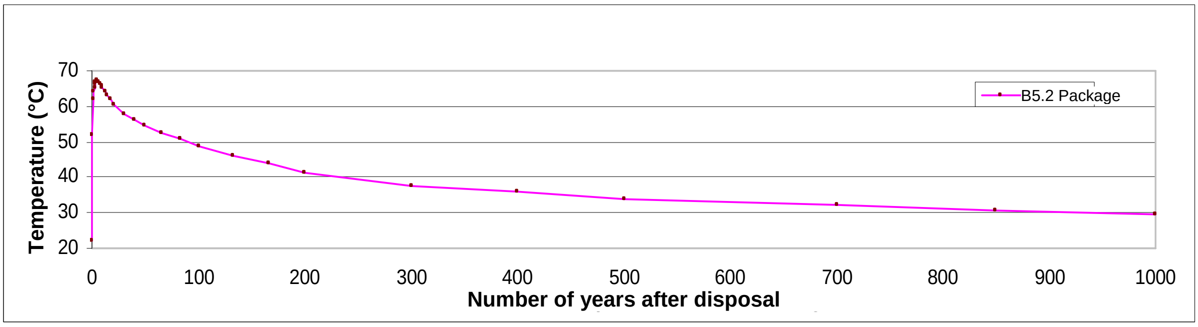

Figure 5.1.18 *Temperature in a cell of B5 .2 type packages placed at 10 years, without taking ventilation into account*

Ventilation helps restrict heating in the cell (before and after closure). Ventilated air with a flow rate of $3m^3/s$ can remove 80 to 90% of the heat released by B5 packages. Thus the maximum temperature for these packages could be permanently kept below 50°C by ventilating the cell for approximately 25 years[70].

5.1.3.5 Mechanical dimensioning of the cell

- **Dimensioning of the cell ground support and lining**

The mechanical dimensioning of the cells consists mainly in defining the ground support and the lining in the main section. The ground support is dimensioned so as to ensure the safety of the construction site over a maximum period of a year. The lining is dimensioned so as to ensure its mechanical stability over a period of at least a century, in accordance with usage for civil engineering structures such as road or rail tunnels [61].

Thermal effects are limited to a few cells.

The studies further show that seismic resistance is not a major design factor [57].

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[70] Without ventilation, the heat builds up in the terrain near the cell, whereas ventilation removes it outside for good. Consequently, after shutting down the ventilation, the temperature still remains below what it would have been without a ventilation phase.

Geotechnical hypotheses adopted

The instantaneous behaviour of argillites can be modelled using an elastoplastic law with the appearance of irreversible plastic deformation before rupture. Dimensioning calculations do not require taking this complex behaviour into account; simplifications according to standard engineering practice are accepted for these. Argillites in particular are treated as being elastic until peak resistance, then as behaving in a perfectly plastic way after rupture. The adopted characteristics, deduced from laboratory tests by adopting the lower limits of the results obtained (20% quartile) are as follows:

- Simple compressive strength of the rock mass (Rc): 12 MPa
- Cohesion: 4.5 MPa
- Internal angle of friction: 25°
- Young's modulus: 3,800 MPa

The choice of this behaviour model (elastic - perfect plastic) with minimum properties, leads to a maximizing evaluation of the stresses on the ground support and lining.

The deferred behaviour of the argillites subject to an anisotropic stress is of the viscoplastic type, which means that the rock is deformed slowly when subjected to this stress. In order to be conservative, no minimum stress value that might halt this deferred deformation has been introduced: the rock is therefore assumed to deform until it reaches an isotropic stress state. The viscoplastic law adopted is of the Lemaître type. The characteristics assigned to this law, resulting from the conservative extrapolation of laboratory tests, lead to predicting relatively high deferred deformations for this kind of rock (of the order of 1.2% deferred convergence for an unlined tunnel over 100 years). The favourable effect of the desaturation of the rock in the vicinity of the cell, which slows down the deferred deformations and improves the mechanical characteristics of the rock, was not taken into account, whereas this phenomenon could emerge not only before the closure of the cell, but also over several centuries after[71].

The initial stresses are assumed to be isotropic in the plane perpendicular to the cells, with a natural stress *in situ* of 12 MPa at 500 m depth.

Calculation principle and dimensioning criteria

In order to take into account the uncertainties in estimating the stresses to which the structure is subject and regarding the characteristics of the materials employed, the method used is that recommended by regulations such as the Eurocode [45].. This method uses safety factors for taking into account the uncertainties in estimating the stresses exerted on the structure to be dimensioned and regarding the characteristics of the materials used.

Two kinds of numerical calculations were performed: finite element calculations, which can be used to take into account the detailed geometry of the structure, and, as a check and for sensitivity studies, calculations by the conventional convergence-confinement method[72], which is a simplified approach applicable to a structure of circular cross-section.

The concrete strengths taken into account were chosen cautiously, taking the ageing of the concrete into consideration, as is normally done, through the use of safety factors defined by standard engineering practice. In fact, the concrete of a cell is subject to a physical and chemical environment more favourable than the concretes considered in establishing standard practice, which are subject to bad weather conditions and seasonal variations of temperature.

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[71] The rock is desaturated for several tens of centimetres under the effect of ventilation. Resaturation occurs after ventilation stops. This resaturation is very slow due to the very low permeability of the argillite.

[72] The convergence-confinement method uses the force-deformation curves of the lining (or of the ground support) and the terrain. The equilibrium of the lining-terrain system is found at the intersection of these two curves.

Connection between ground support and lining - summary of the problem

The role of the ground support is to ensure the safety of the worksite during the construction phase. The role of the lining is to ensure the stability of the structure throughout the period of operation.

The dimensioning of the ground support must enable it to withstand instantaneous deformations directly associated with the progress of excavating the drift, and deferred deformations due to the viscous behaviour of the rock, before the lining is installed. The dimensioning of the lining must enable it to resist deferred deformations after its installation.

Delaying fitting the lining offers the advantage of encouraging the expansion of the terrain, thus limiting the forces to be subsequently taken up by the lining, but the drawback of prolonging the functioning period of the ground support, which must consequently be reinforced. A compromise must therefore be found.

The viscoplastic law adopted means deferring fitting the lining in order to avoid using overly large amounts of concrete. Fitting the lining 6 months after the excavation is proposed. The ground support is dimensioned to last for a year, thus allowing a flexibility of several months for fitting the lining.

Using a cautious approach, and following normal practice, the contribution of the ground support to the long-term stability of the structure has not been taken into account in the dimensioning of the lining.

Results for the ground support

The results below apply to the following ground support options: for safety reasons the bolts are fitted just behind the face, while the shotcrete is cast some ten metres from the face, since, according to the calculations, the shotcrete is not stable if it is set very close to the face.

The 2.4 m long rockbolts are installed close to the front in a 1.5 m x 1.5 metre pattern and are combined with the welded mesh. They provide a shallow anchorage inside the microfissured argillite. The length of these bolts must be finalized taking into account underground laboratory tests in particular.

The B40 shotcrete is designed with a thickness of 25 cm at the cell for a waiting time of one year. This thickness would only be 15 cm for a waiting time of 6 months.

Results for the lining

The results given here correspond to a lining fitted at 6 months and dimensioned, like current large civil engineering structures, for a lifetime of about a hundred years. For a drift with an excavated diameter of 10.50 m (average value over all the cells), and in the shape of a horseshoe, using B60 concrete, we obtain a thickness at the cell of 70 cm. The thickness is 95 cm in the side walls. The thickness of the concrete reaches 1.40 m at the junction between the sidewalls and the base slab, which is the most stressed zone.

With the chosen shape, the lining is stressed only in compression and therefore does not need any reinforcing bars.

Analysis of the durability performance of the lining

Figure 5.1.19 shows the change in the load exerted by the terrain on the lining as a function of time. We see that the pressure exerted by the terrain on the lining is of the order of 3.5 MPa at 100 years. The increase in pressure after this century is less than 0.5 MPa per century[73]. The lining could theoretically withstand a pressure of the order of 8 MPa. We find that the margins of safety and dimensioning used allow for the cell to be stable over several centuries, in association with the slow rate of increase in the pressure of the terrain on the lining.

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[73] The choice of conservative values to represent the deferred deformations of the argillites means overestimating the pressure undergone by the lining at 100 years and its increase after that.

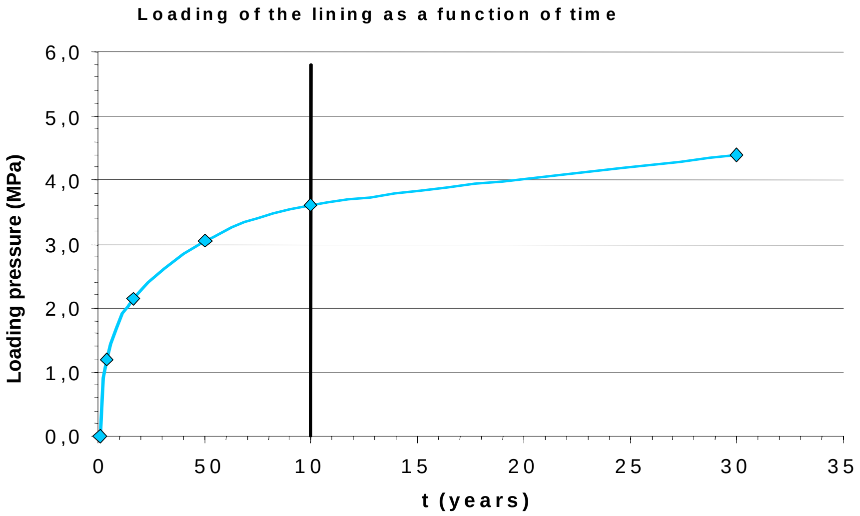

Figure 5.1.19 *Change in the loading of the lining as a function of time*

Sensitivity of dimensioning to hypotheses

As previously stated, the desaturation in the cell walls tends to reduce the speed of deferred deformations. To estimate the sensitivity of dimensioning to this phenomenon, the effect of a reduction of 25%[74] in deferred deformation speed was analysed. This analysis shows that the lining as it was dimensioned would be less loaded by 0.5 MPa over the period extending from 100 to 300 years after construction. This load reduction on the lining at a century could allow a reduction in lining thickness of some ten centimetres to be considered.

For cells containing weakly exothermic waste, temperature plays a part in the dimensioning, both due to the effect of thermal expansion of the concrete and the rock, and due to the acceleration of deferred deformations of the argillites. According to the thermal power of the packages and the duration of the ventilation phase of the cell before its closure, it could be necessary to increase the lining's thickness from 20 to 40%.

5.1.3.6 Materials making up the cell and the access drift, plus impact on argilite and packages

The material constituting most of the cell and the access drift is concrete. It was chosen for its durability and for the favourable physical-chemical environment it offers to the disposal packages. Other materials are required but in smaller quantities, such as steel, or alternatively fibreglass and resin composites.

● Concrete

The concrete envisaged is HPC (high-performance concrete), a type that is now commonly used in civil engineering infrastructures. The mechanical performance of this type of concrete stems from the type of cement used and the high cement content (on average 400 kg/m^3). An admixture (limestone filler) is introduced into the concrete composition in order to reduce the relatively high release of heat from this type of cement during setting, and thus reduce cracking of thermal origin.

It should be recalled that the concrete is not designed to act as a hydraulic barrier within the cell. HPC has two major advantages for type B waste cells: thanks to its high mechanical properties, it enables the thickness to be reduced, thereby minimising the volume excavated per given useful volume, and its low porosity ensures long-term strength by minimising interaction with the water from the rock. The construction joints and possible cracking of the concrete will not compromise the durability and strength of the facility, which is subject solely to compressive stresses.

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[74] Which means dividing the Arrhenius coefficient by 3 in Lemaître's law

Furthermore, for cells containing bituminous waste (type B2 packages), the composition of the concrete will be adapted to keep the pH in the cell at below 12.5.

The phenomena involved in the interaction between the argilites and the concrete lining liable to degrade the retention properties of the argilites primarily concerns the fractured rock zone (extension estimated at a few decimetres) [48]. The extension of chemical disturbances is therefore slight and has no impact on the properties of the argilites in the undisturbed thickness of the layer above and below the repository.

- **The other materials**

We attempt to limit the quantity of steel left inside the cell when it is closed, in order to avoid the mechanical problems related to corrosion and swelling of corrosion products, and to minimise the long-term production of hydrogen by corrosion. The handling equipment and the access chamber in particular comprise large quantities of steel and are recovered before closure of the cell.

The concrete lining structural ring works in compression and thus contains no reinforcement. The use of steel in the ground support and lining is thus limited to the protection mesh laid at the face of the worksite, at the same time as the rockbolts and hangers for attaching the filler concrete to the structural ring.

It should be noted that stainless steels may be chosen in order to delay and reduce the effects of corrosion. Alternatively, materials such as fibreglass - resin composites could conceivably be used in place of certain steels.

5.1.3.7 Criticality-safety

A criticality-safety analysis was conducted in two stages. A preliminary risk analysis for the array of B type waste packages (i) demonstrated that criticality was not a determining factor for most disposal packages and B cells and (ii) identified the envelope packages requiring a more detailed criticality risk study (B5 packages in particular). A more extensive analysis then confirmed that the criticality aspect was not determining for cells containing this kind of package [55].

5.1.3.8 Gas management and cell ventilation

The vast majority of B packages give off small quantities of hydrogen (a few litres or tens of litres per year and per package) and gaseous radionuclide traces. Cell ventilation enables these gases to be evacuated during operation, without affecting the personnel, who always work upstream of cell ventilation. It should be noted that the production of hydrogen is so low that it would be possible for the ventilation to be shut down for several weeks with no risk.

The studies conducted to date show that with the envisaged spacing between packages, an airflow of about 3 m^3/s would be sufficient to ensure good ventilation of a cell during filling or when filled. The fresh air supply is in the full section of the drifts from the air inlet shaft to the cell. At the top of the cell, the air passes through the chamber by orifices with baffles (to protect the personnel from the irradiation risk).

The air returns through the end of the cell and then through reservations made in the concrete and finally through a duct which joins the general air return system. The airflow is controlled by the perforated wall at the bottom of the cell and by adjustable valves in the ventilation ducts.

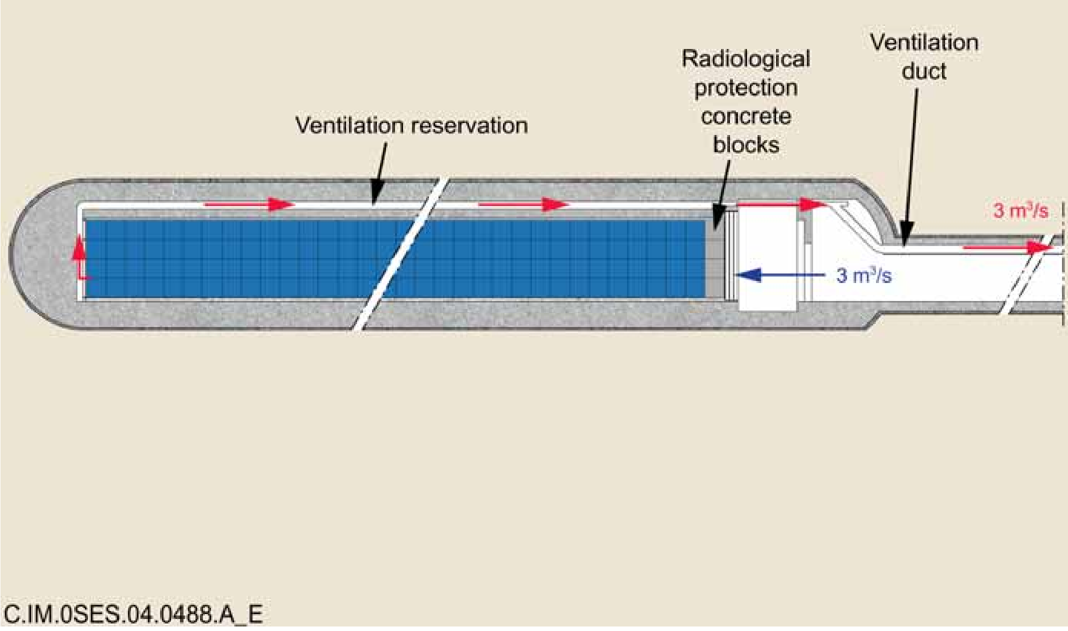

Figure 5.1.20 Ventilation of the B cell pending sealing

The ventilation creates little mechanical or chemical disturbance within the cells (see chapter 10.2). Desaturation of the rock wall by relatively dry air in fact tends to increase the mechanical strength of the cell, without extending the damaged rock zone in the vicinity [57], oxidization of the argilites by the air infeed remains extremely limited to a heavily desaturated zone about a decimetre thick. furthermore, the disruptions linked to oxidisation of the metal materials present in the cell are considerably limited by the small quantity of metals introduced into the cell (apart from the package) and the degradation of concrete by atmospheric carbonation only concerns a maximum thickness of about a centimetre, in particular because of the low porosity of HPC concrete.

5.1.3.9 Compatibility of the design with the disposal package emplacement method

The design of the cell is inseparable from that of the package handling and emplacement system. In this respect, two elements are of considerable significance: the compatibility between the functional clearances and the performance of the handling equipment, and the approach to personnel radiological protection during disposal operations.

With regard to functional clearances, minimising the residual spaces within the cell requires that the packages be positioned and stacked with considerable precision (about a few centimetres). The positioning principle envisaged for the transporter (described in chapter 9 covering operational systems) is based on the use of coders and sensors, possibly backed up by a laser system. Equipment such as this, which is commonly used in industry, guarantees that the goal of minimising clearance will be consistent with the performance of the envisaged handling system.

With regard to radiological protection during package transfer from the surface installations to the cells, the personnel are protected initially by transport transfer casks and then by the cell head chamber. The cell transporter is remote-controlled and the personnel do not enter the chamber during package emplacement operations. The transporter extracts the package from its transfer cask, transfers it to the disposal chamber and positions it.

5.1.4 Layout of different types of B waste cells

Standardisation of the disposal packages presented in chapter 4 enables several different package types to be grouped in the same cell (co-disposal). Given what we currently know, certain groupings are nonetheless avoided in order to limit potentially harmful interactions in terms of release of radionuclides [61].

To illustrate the possibilities in this area, one possible co-disposal scenario was defined, on the basis of the package inventory presented in chapter 3, complying on the one hand with the separation constraints for certain package types and on the other with the geometrical constraints of standardised packages. This scenario therefore separates packages containing organic materials liable to release complexing chemical species from the other packages. It keeps the bituminous waste (type B2 packages) cells far enough away from the other cells to protect this waste from possible heating. Finally, it allows differentiated management of packages producing gases.

This scenario is such that the height and the width[75] of all the disposal packages intended for co-disposal in the same cell are identical, in order to minimise the volume of residual space around the disposal packages, to avoid disrupting the longitudinal ventilation flow through the disposal chamber and to standardise handling. For the same reasons, the height and width of the disposal chamber are constant over the entire length of the cell, as a result of standardisation of the disposal packages (see chapter 4).

These considerations led to identification of 10 different types of cells. For example, Figure 5.1.21 is a schematic representation of 4 cell cross-sections of different dimensions, with the corresponding packages.

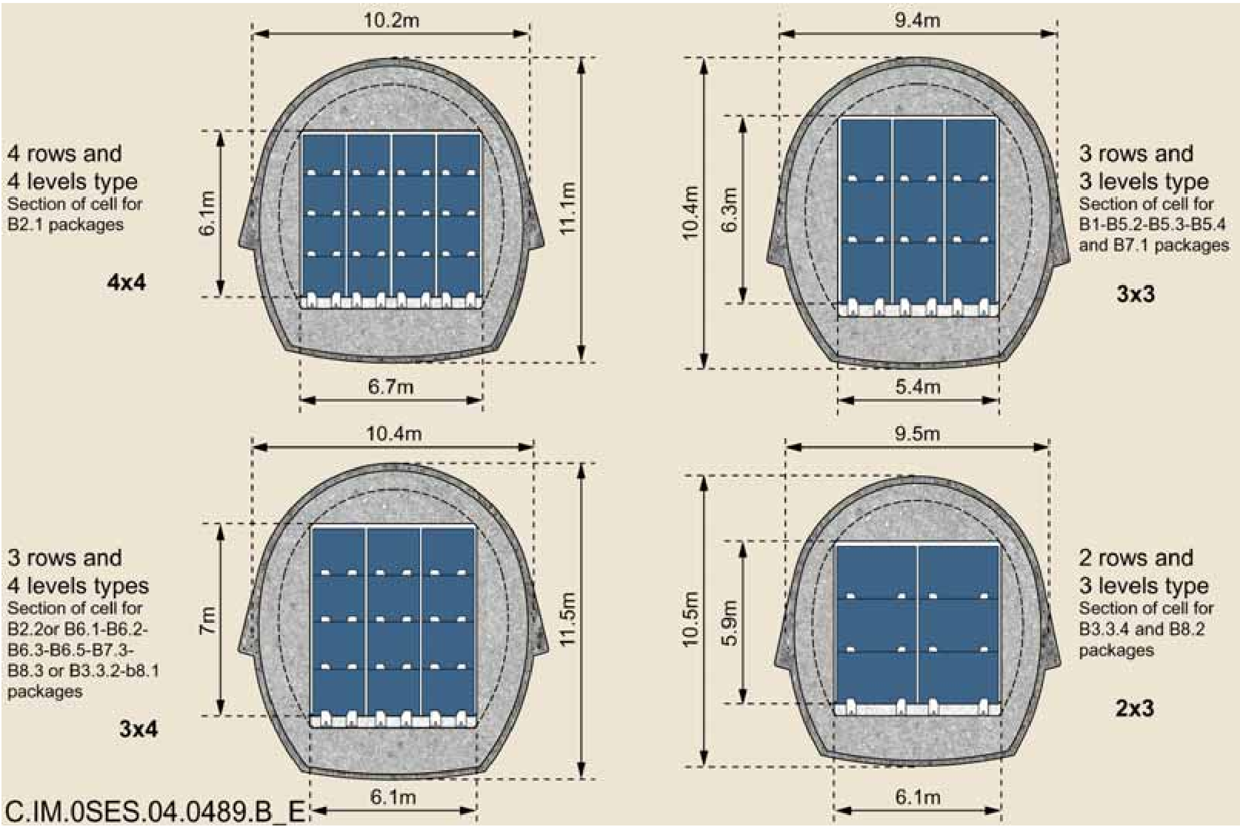

Figure 5.1.21 Cell cross-sections

Finally, the distances between the cells prevents interaction in the very long term. This in particular concerns packages containing organic materials, for which the disposal cells are isolated from the other cells at this stage of the study. In the particular case of type B2 packages, this distance is enough to maintain the temperature within the cell at below 30 °C (see chapter 6).

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[75] In the transverse direction of the cell

5.1.5 Construction of the B cells

The construction process can be sub-divided into three basic processes:

- excavation,
- installation of the ground support to ensure that the site is safe,
- installation of the lining ensuring the stability of the structure throughout the operation and monitoring periods.

Underground work has been carried out for each of these processes. At this stage in the studies, only the use of standard equipment has been taken into account and proven operating methods have been favoured.

5.1.5.1 Excavation method

Several options can be envisaged for excavation of the cell: borehole drilling and blasting, roadheader and full-face tunnelling machine.

At this point in the studies, the roadheader machine (Figure 5.1.22) is the preferred option for excavating the access drift and the cell. This technique is well suited to the characteristics of the argilite and the geometry of the cell. By comparison, the full-face tunnelling machine is cumbersome and less suited to the configuration of the cell owing to its reduced length (about 250 m) and the dimensional restriction imposed by the cell entrance chamber. Given the mechanical properties of the rock and the diameter of the cell, it may be necessary to excavate the cell in two passes, whereas the entrance drift could be excavated in a single pass. The development of a specific roadheader would mean the section of the cell could be excavated in a single pass.

5.1.5.2 Installation of the support and lining

- **The cell**

Installation of the ground support in the cell, consisting of short rock bolts, a welded mesh and shotcrete, as described in the previous sections, is done with a bolting jumbo (Figure 5.1.22) and an elevator platform. The shotcrete is installed with a projection jumbo.

The choice of method for installing the lining is linked to the support method. It may consist of concrete poured in-situ or of prefabricated concrete segments. For a bolted support (or one using arches), the first option should be preferred. It should be noted that if segments are used, the support function will be provided by a shield integral with the excavation machine.

Figure 5.1.22 Examples of roadheader and bolting jumbo

- **The access drift**

For the access drift, we have opted for a ground support using arches and shotcrete, with a subsequent lining with poured concrete. This technique avoids having to use rock bolts and thus preserves the ground opposite the sealing zone as much as possible.

5.1.5.3 Construction sequence

This description mainly concerns the construction of the actual cell proper. It gives a possible sequence of the operations to be carried out.

Construction can thus be broken down into several phases; each phase consists of a series of working cycles carried out over the entire length of the cell, before moving onto the next phase.

- **1st phase: excavation and support of the upper part of the drift**

During the first phase, illustrated in Figure 5.1.23, the work is organised into excavation - support cycles. Each cycle corresponds to an advance of about 1.50 m depending on the rock support requirements. The roadheader excavates to a depth of 1.50 m (see top of figure) and immediately afterwards, a row of anchor bolts is installed. If necessary, horizontal bolts made from glass fibre are put in place to ensure the stability of the face.

The shotcrete (bottom of the figure) is installed about ten metres behind the cutting face, in passes of about 3 m. If necessary, a thin layer of concrete can be sprayed right up to the face.

- **2nd phase: excavation and support of the lower part of the drift**

Once the upper part of the cell has been excavated and its entire length supported, the next phase is to excavate and support the lower part of the cell. This phase, illustrated in Figure 5.1.23 is comparable to the first phase.

- **3rd and 4th phases: pouring the concrete slab and then the cell and abutments**

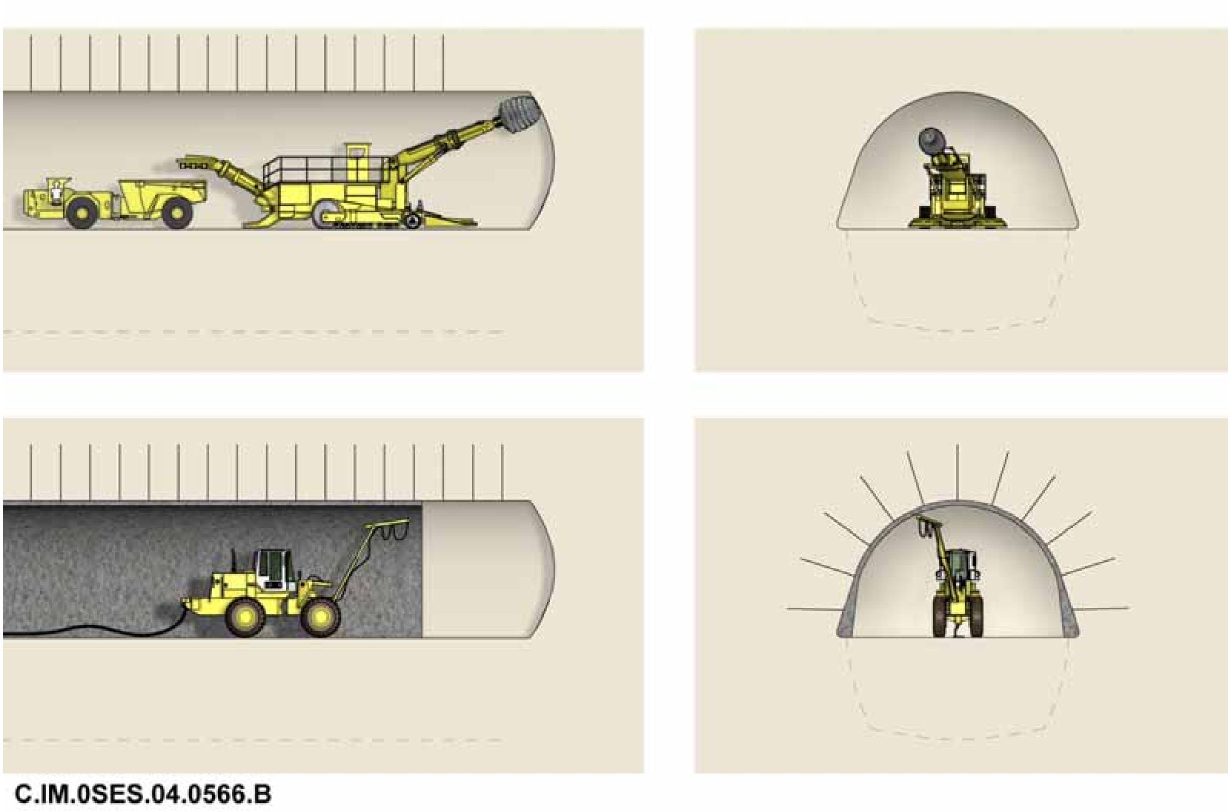
Once the cell has been excavated and supported over its entire length, we move onto the final concreting phase, first of all the slab, then the vault and the sidewalls.

The slab is poured in sections about 12 m long. The sections can be separated by dry seals to reduce concrete cracking.

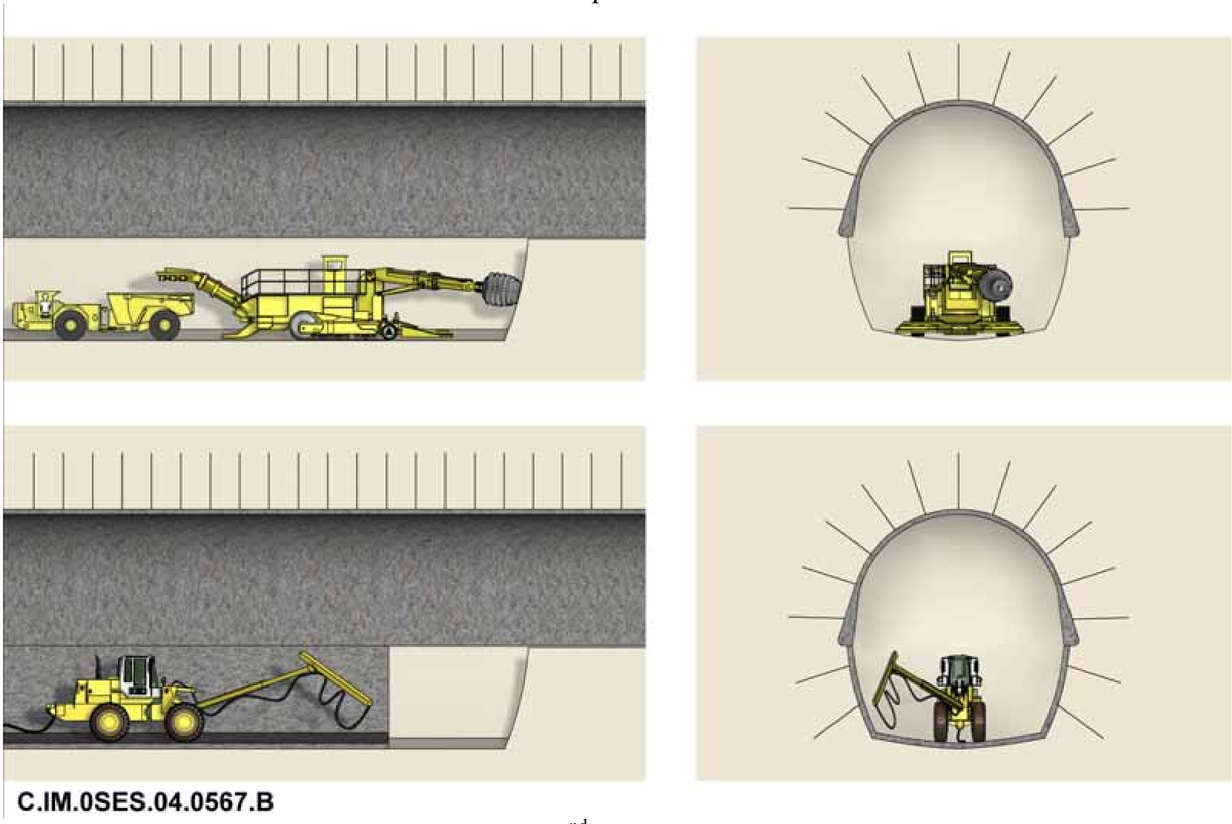
Once the slab has been poured over the entire length of the cell, the vault and the sidewalls are poured. To do this, we use a mobile formwork (Figure 5.1.24) with the dimensions of the disposal chamber. Pouring is in sections of about 6 m. As with the slab, these sections can be separated by a dry joint.

- **5th phase: equipping the cell**

After finishing lining of the cell, it then has to be equipped: construction of a perforated wall at the end of the cell to regulate the airflow, installation of the finishing slab with handling grooves and rails, construction of the access chamber and installation of mechanical elements (door and handling equipment).



1st phase



2nd phase

Figure 5.1.23 Excavation and support of a B cell in two phases

Figure 5.1.24 Mobile formwork for tunnel

5.1.6 Closing the cell

Sealing of the B cells is very similar to sealing of the connecting drifts, which is described in more detail in section 7.6. Special arrangements must however be made to protect the personnel from irradiation when removing the cell head equipment. This section briefly describes the design principle of the B cells closure, paying particular attention to the aspects specific to these cells [61].

5.1.6.1 Brief description of cell closure

As illustrated in Figure 5.1.25, the cell closure structure comprises the following, from upstream to downstream:

- a radiological protection shield consisting of concrete blocks,
- cell head filler which constitutes the mechanical support for the core of swelling clay,
- a core of swelling clay, which is the essential component in ensuring the tightness of the seal,
- grooves filled with swelling clay associated with the core,
- a concrete retaining plug, which could itself subsequently sit on the connecting drift backfill.

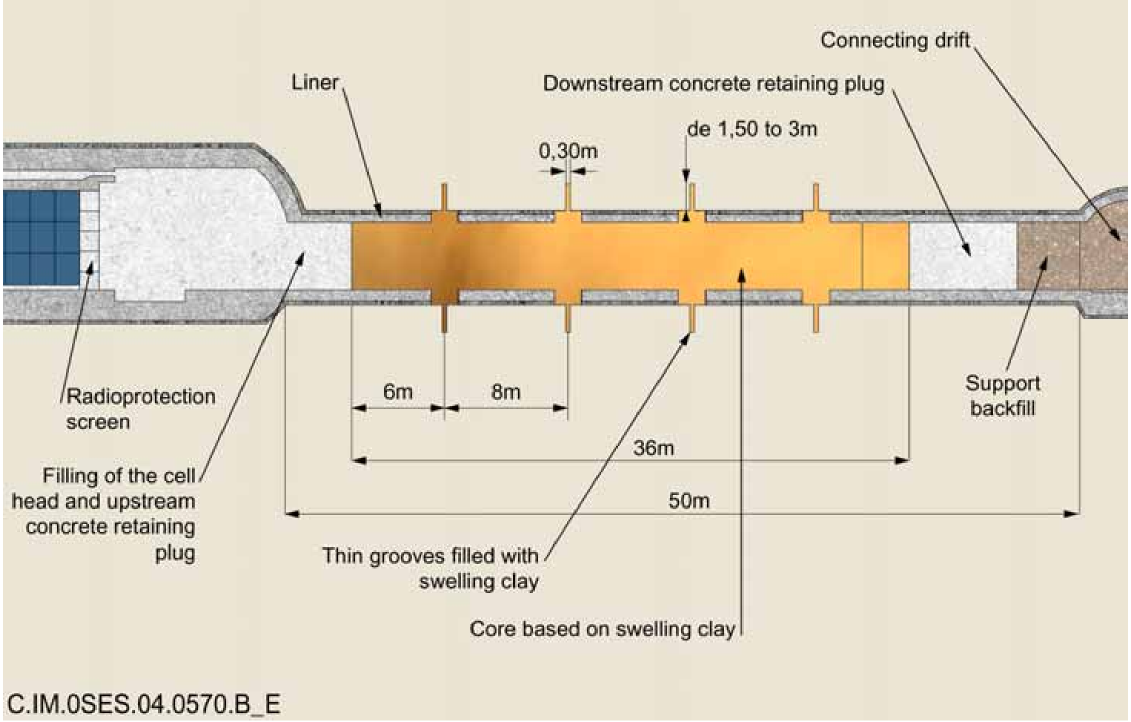


Figure 5.1.25 Schematic diagram of cell closure

5.1.6.2 Installation of cell closure

Closure of the cell consists in gradually installing the various sealing components, from upstream to downstream. The steps specific to closure of the cells are installation of the radiological protection shield, removal of the equipment and filling of the cell head.

The radiological protection shield consists of a double row of concrete blocks, arranged in a staggered pattern in order to prevent diffused radiation. A step in the cell filler concrete avoids radiation diffused along the cell walls. This shield could be installed a number of years before the cell is closed and is perforated with angled holes to allow passage of the ventilation while providing radiological protection. Figure 5.1.26 gives the principle of this radiological protection shield. The thickness of concrete needed is up to 120 cm for the packages giving off the highest levels of radiation.

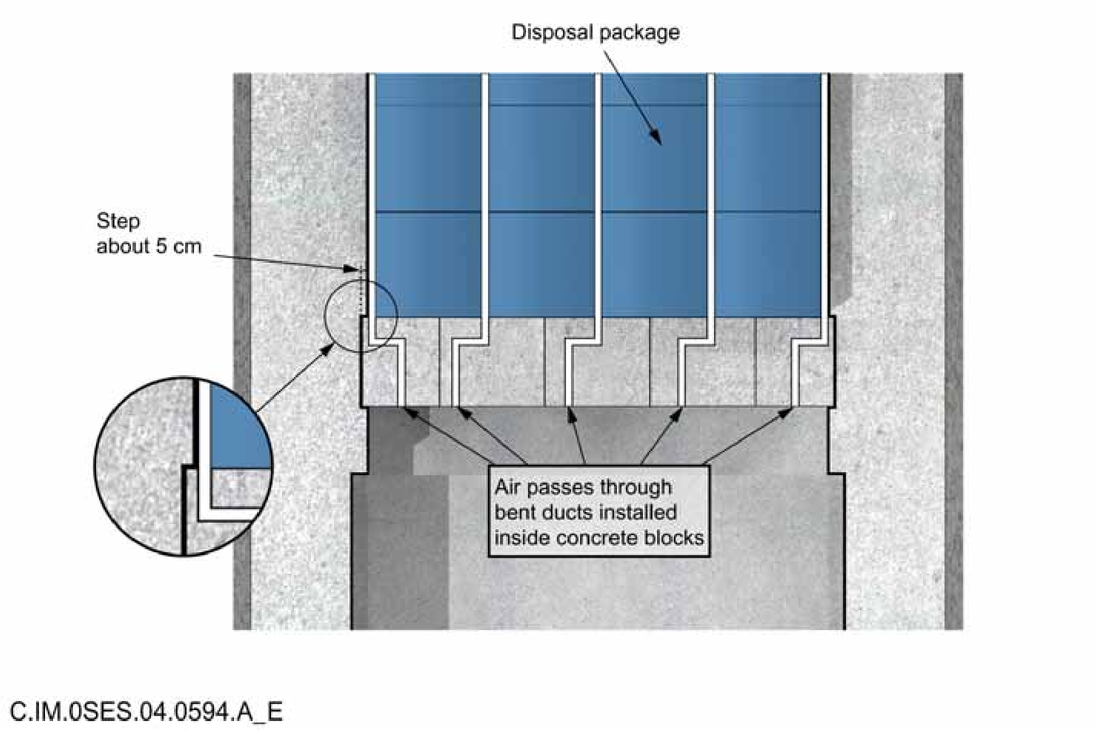


Figure 5.1.26 Radiological protection shield (plan view)

During and after installation of this shield, the cell can continue to be normally ventilated. Once the radiological protection shield is in place, removal of the equipment on the cell head can begin, while retaining the benefits of cell ventilation.

Before filling the cell head, the ventilation ducts locating in the cell lining are filled with concrete slurry. The concrete is then poured in bulk into the cell head and thus constitutes the retaining plug for the clay core. Absorptive formwork on the upstream side is used to separate the radiological protection shield from the filler concrete, so that the latter can be removed in the event of the package being retrieved.

The subsequent steps are identical to those for sealing the drift, as described in section 7.6.

5.2 C waste repository modules

This section first of all describes the objectives pursued in the design of the C waste disposal cells. It presents the various solutions envisaged, the general principles currently adopted and, for comparison, the concepts being examined abroad.

It then presents a description of the cell, the access drift and their equipment. The layout of the cells within a module is also described. The design values are justified according to the functions to be performed: safety functions, operational functions concerning package emplacement and reversibility. The safety functions in particular consist in limiting the mechanical damage to and heating of the argilite and minimising the circulation of water.

The construction processes are then described. In the feasibility study, the design of a component is in effect inseparable from its construction processes. However, in many cases, a number of processes can be envisaged: the description concentrates on whichever of them appeared to be most appropriate at this stage in the studies.

5.2.1 Presentation of the main issues

The factors which supported the design choices for the C waste repository modules are primarily linked to managing the heat given off by the waste, creating a favourable physical and chemical environment and controlling hydraulic phenomena.

It is of particular importance to be able to dissipate the heat given off by the waste to minimise damage to the argilite and remain within a range of operating parameters in which the phenomena are known and can be modelled.

To these considerations can be added the requirements linked to module separation and reversible management of the repository.

5.2.1.1 Managing the heat given off by the waste

The heat given off by the waste is due to radioactive decay. It drops off with time, depending on the radioactive half-life of the isotopes that cause it.

An initial criteria is linked to controlling the phenomena involved in the repository. This entails limiting the temperature in the cell and the argilite to less than 100°C. Above this temperature, the phenomena and their interactions are more complex. They are not fully understood today. In particular, it would be impossible to demonstrate that there would be no short-term damage to the argilite. For thermal design calculations, we have opted for a maximum cell wall temperature of 90°C (in contact with the argilite).

A second criterion is to avoid mineralogical transformation of the argilites under the effect of the thermal load applied over the longer term. Knowledge acquired on the basis of experiments shows that the most important mineralogical transformation processes with respect to the hydrodynamic, hydromechanical and retention properties, concern the smectites [37]. The experiments carried out on this subject show that the smectites are only transformed when large amounts of energy are transmitted to them (combination of both the heating period and the temperature reached). Furthermore, experimentation with potassium smectites (more reactive than those associated with the Callovo-Oxfordian argilites) indicates that less than 50% of the smectites would be transformed when subjected to a temperature of 80°C for a period of 10,000 years. These experiments show that a thermal loading of 70°C for 10,000 years would lead to only extremely limited irreversible transformation of the Callovo-Oxfordian argilites. We therefore aim to dip below the value of 70°C well before 10,000 years. It was conservatively checked that the temperature falls below the 70°C threshold after 1,000 years.

5.2.1.2 Control of release of radionuclides, through a physical and chemical environment favourable to the packages

C waste repository packages comprise an over-pack which protects the primary package; it prevents water contacting the glass until its temperature has fallen below about 50°C. No release of radionuclides occurs as long as the over-pack remains watertight.
After deterioration of the over-pack, release of radionuclides is limited by restricting the speed of dissolution of the glass. This is achieved by favourable environmental conditions.

- **Contribution to controlling corrosion of the over-pack**

First of all, we must limit the risks of local or galvanic corrosion of the over-pack at the interface with the cell.

- **Limiting aqueous alteration of the glass**

After the over-pack deteriorates, environmental conditions must be such as to ensure a slow rate of glass dissolution. The pH must therefore preferably remain between 7 and 9 (which determines the choice of materials in the cell). The glass must be kept in chemical equilibrium with the water in contact with it and dissolution of vitrified silica is minimal if the water in contact with the glass is silica saturated [9].

When the water reaches the glass it is not silica saturated and the glass therefore dissolves at an initial[2] rate, V_0. This leads to silica saturation of the water in contact with the glass. The dissolution rate then gradually drops, $V(t)$, settling at a residual rate, Vr. This rate, determined experimentally, is several orders of magnitude lower than V_0.

These conditions require that the design ensures no flow and convective transport in the cell (this point is examined below) and ensures that in the immediate vicinity of the packages, there is a medium in which transport is itself limited. In this respect, the argilite must be protected from damage as much as possible.

The need to control damage applies as of the cell construction phase and continues into the later phases. Convergent deformation of the argilite may occur, owing to creep, in combination with resorption of the cell's internal spaces: minimising the internal spaces is a way of limiting these deformations. It should be noted that the expansion of corrosion products can lead to deformation in the opposite direction [13] [53].

5.2.1.3 Controlling water circulation and the transport of radionuclides

Water circulation is a factor in deterioration of the materials, in particular the packages. It then encourages migration of the species released.

Flows through the cell occur differently, depending on whether the rest of the repository is resaturating or whether resaturation is completed. These two periods therefore have to be examined.

Steel corrosion in anoxic conditions produces hydrogen. This process influences the resaturation phase. The fate of the gases in the cell and their evacuation outside are also dealt with.

- **Limiting water circulation in the cells and modules; general aspects**

The modules must help limit water circulation in the cells. An arrangement in which the cells are in a dead end is in this respect beneficial. In a configuration such as this, no difference in the hydraulic head occurs in the cell. Consequently, the only phenomenon affecting the disposal cells is the result of these cells intercepting the vertical flows passing through the Callovo-Oxfordian formation (as a result of the head differences between the Dogger and the Oxfordian). This natural flow, designated by the term "leakage flow" is also limited by the low permeability of the formation.

After resaturation, shaft sealing completes the arrangement by limiting the part of the intercepted flow that then travels towards the access drifts. The leakage flow thus remains at its natural level. This limits the possibility of transport of released substances in the drifts.

This limitation must be maintained as far as is possible in the various potentially altered situations (failure of shaft sealing, intrusion, etc.). Hydraulic closure of the modules and cells is therefore required: this consists in seals with hydraulic conductivity that is as low as possible.

- **Particular case of the resaturation period**

During resaturation of a structure, flows in the argilite converge towards this structure. If the resaturation periods of adjacent structures are different, they can lead to transfer of water from one structure to the next. If the cells reach saturation first, flows can occur towards the as yet unsaturated access drift and are liable to transport any radionuclides released by the packages.

The disposal concept presented here comprises a number of factors which contribute to limiting the possibility of convective transport in the cell: hydraulic closure of the cell, cell dimensions limiting the intercepted water flow, elongation limiting the axial rate of the water for a given intercepted flow.

- **Production and fate of gases (corrosion hydrogen) in the C cells**

When decided on as part of reversible management, closure of the structures leads to them being gradually resaturated by the water from the argilites and that of the surrounding rock, if there was desaturation during the operating phase. Given the low permeability of argilites, this is a slow process. It is accompanied by the production of hydrogen as a result of corrosion of the metal components, which delays the return to complete saturation.

The very slow corrosion rates (a few microns/year, or probably even a few tenths of a micron/year) lead to a period of several thousand years (about 5,000 years) for the main hydrogen production phase. The modelling conducted on the basis of experimental work with samples and a borehole led to an assessment of the properties of hydrogen transfer in the argilites. It shows that hydrogen transfer takes place first of all by dissolution, and then by diffusion through the Callovo-Oxfordian. When the water is saturated with hydrogen, this then follows two-phase migration, principally through areas with the lowest gas inlet pressures (close to 2 to 3 MPa for the initial ruptured/damaged zone, as compared with 5 to 7 MPa for sound argilites). If hydrogen production is faster than its migration, this is expressed in gaseous form and the gas pressure can reach the porosity threshold of the argilites (micro-fissures) or of the swelling clay engineered components (cell plugs). Opening up of micro-fissures enables the gas to escape and the pressure may drop. It was found on the samples and during a borehole test that the micro-fissures close up after the gas passes, without altering the properties of the rock (the water permeability of the argilite remains unchanged) ([62] and [6] - Tome 2). Finally, when the pressure has dropped enough for the hydrogen to be no longer able to enter the porosity of the various components, it slowly evacuates in dissolved form.

5.2.1.4 Module separation

The design of the C waste disposal zones involves division into about ten subassemblies, in order to minimise the consequences of an altered situation (failure or intrusion). These subassemblies are isolated from each other by seals in their access drifts.

The sealing of each cell also contributes to limiting the impact of any such altered situation.

5.2.1.5 Reversibility

Reversibility is designed to maintain flexible management of the repository packages, cells and modules. At the beginning of the disposal process, this flexibility is comparable to storage; the packages can be simply retrieved over a period of from one to a few centuries.

The option of retrieving the packages depends on the durability of the packages, cells and access drifts. This covers the integrity of the disposal packages, the components of the cell containing them, as well as ensuring that a minimum functional clearance is maintained around the packages to enable them to be retrieved over this same period of centuries. The integrity of the various elements for a period of at least a century implies a mechanical design taking account of the evolution of the materials and, in particular in the case of C cells, of corrosion of the metal parts. Similarly, maintaining the access drifts implies mechanical sizing of the concrete lining for an identical period.

Finally, the modularity of the C waste repository zone provides it with overall management flexibility.

5.2.2 Design principles adopted

5.2.2.1 Several solutions envisaged

The options envisaged start from a certain number of common characteristics or principles. They differ in the size or layout of the repository cavities, the materials employed and the emplacement methods.

- **Common principles**

The importance of controlling heat release with respect to damage to the argilite was underlined in the presentation of the main issues. One general principle of repository design is to build its long-term security on passive evolution (with no human intervention). After closure, the heat produced by the packages dissipates by conduction through the geological medium. Ventilation is not used to dissipate heat during the operating phase. This basic choice means that the closure decisions can be dissociated from the thermal phase management arrangements.

All the cell solutions considered are of the dead-end type. This arrangement minimises water circulation after closure, even in altered situations.

Limiting the migration of released substances requires the preservation of undisturbed argilite thickness around the repository. This goal leads to the cells and their access drifts being placed in the middle of the argilite formation. The geometry of the formation entails a primarily horizontal footprint of little thickness. On this basis, vertical (shaft) and horizontal (tunnel) cell solutions were examined.

Finally, immobilisation of the radionuclides in the repository requires control of the flow and transport conditions in the immediate vicinity of the packages. This goal implies limiting damage to the immediately surrounding argilite.

- **Horizontal or vertical cells**

Horizontal cell have less impact on the geological formation in terms of excavated volume and repository footprint. Tunnel-based architectures require significantly less excavated volume than shaft architectures. The gain is due to the length of the access drifts, as one access drift can serve two rows of horizontal cells located on either side of it, whereas it could only serve one row of vertical cells. The same length of access drift thus serves twice as many horizontal cells as a vertical shaft. Figure 5.2.1 illustrates this aspect. The horizontal arrangement also maximises the thickness of the undisturbed argilite.

Using horizontal cells offers optimisation possibilities, as for a constant total cumulative cell length (i.e. for the same disposal capacity), increasing the unit length of the cells enables their number to be reduced, consequently reducing the length of access drift required. In the clay formation studied, this type of optimisation would only be possible in a horizontal configuration as preservation of the argilite buffer zones limits vertical extension of the cells and consequently rules out deep shafts.

Package handling would at first glance appear more complex with a horizontal configuration than with a vertical one. However, section 9, which deals with operating systems, demonstrates the feasibility of package disposal using a horizontal configuration. This relative drawback does not outweigh the advantages with respect to the other criteria, in particular those concerning repository confinement.

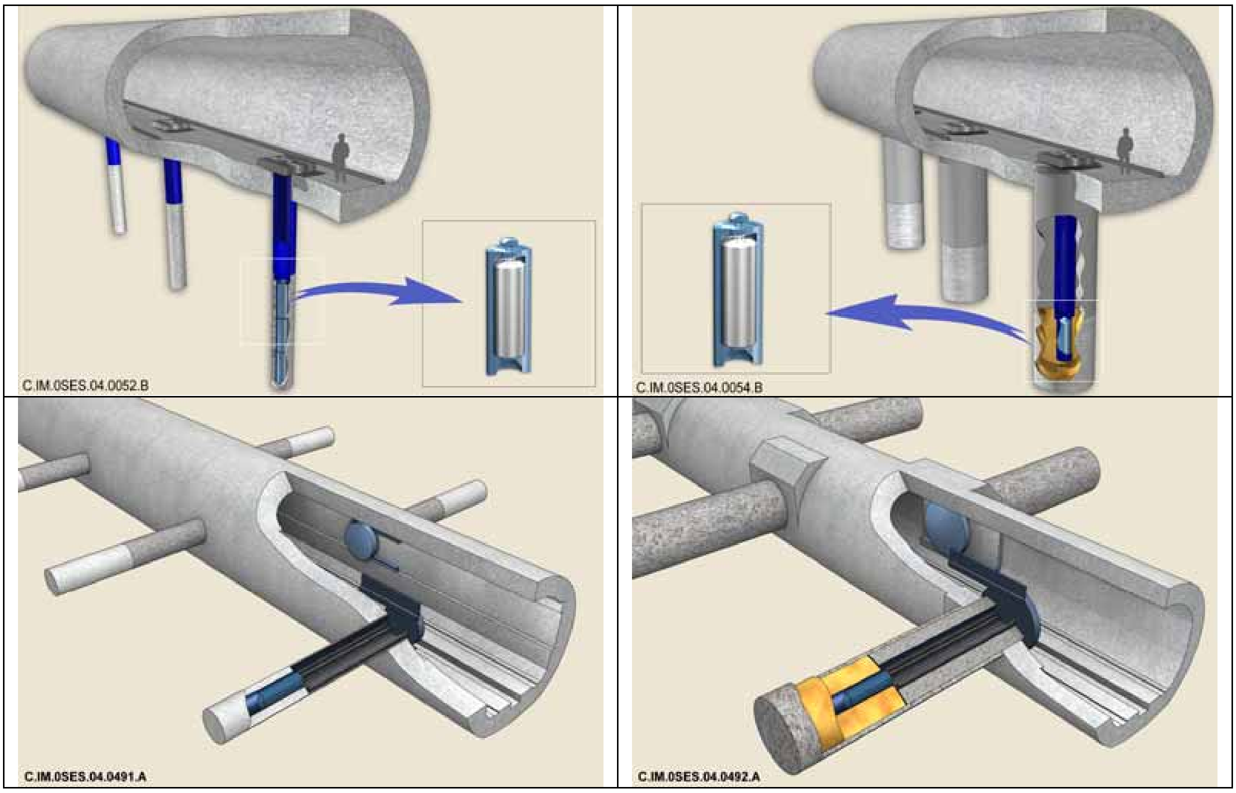


Figure 5.2.1 C waste cell concepts (shaft or tunnel, with or without engineered clay barrier)

- **Disposal drift or disposal cell**

The term "disposal drift" designates a structure in which the useful diameter is significantly higher than that of the disposal package; the remaining space can be used for handling equipment traffic and for ventilation of the structure. The disposal cell is on the contrary characterised by a diameter closely tailored to that of the disposal package. The concept of disposal cell is illustrated in Figure 5.2.1. The disposal drift concept is illustrated in Figure 5.3.2, which is used for spent fuel.

The disposal drift allows direct access to each package during both the operating and monitoring phases; it has no particular advantage after closure. It is penalised by the very large excavated volume of these cavities. Ventilation of these drifts could allow an increase in disposal density. However it would not make up for the increased volume excavated. On the contrary the more complex ventilation network would require additional access drifts. Furthermore, the use of ventilation for this purpose does not comply with the principle of purely passive dissipation of the thermal energy of the packages (by conduction alone).

Consequently, only the "disposal cell" configuration is envisaged in the feasibility studies.

- **Cell with or without swelling clay buffer**

A concept with a swelling clay engineered structure offers low permeability around the packages, favourable to controlling the environmental conditions of the glass in terms of its dissolution kinetics. This low permeability is maintained for the long-term life of the structure, owing to the deformability of the swelling clay and its ability to swell.

A concept without an swelling clay buffer has considerable advantages in terms of the simplicity and compactness of the repository. The absence of swelling clay buffer limits the diameter of the excavation and facilitates construction, thereby disturbing the rock less. A cell without a swelling clay buffer, of a more simple design than a cell with a swelling clay buffer, would also limit the number of interfaces between the packages and the ground; the quantity of steel is reduced; the cross-section of the cell seal retaining plug is smaller thus limiting the amount of concrete used. As the space between the cells is above all dictated by thermal considerations, using an swelling clay buffer would be such as to increase the distance between the cells owing to the introduction of additional clearances or materials which conduct heat less (swelling clay buffer partially saturated at installation). This leads to a larger footprint for the repository.

Analysis of these two options led Andra to prefer a solution without swelling clay buffer for the C waste cells. This type of configuration is made possible by the compactness of the damaged zone expected around the cells, owing to their small diameter, the geotechnical properties of the rock and the envisaged excavation method. The studies have shown:

- the absence of any fractured zone around the cell at a depth of 500 m at construction of the cell,
- the creation of a small micro-fissure area, the permeability of which does not modify the diffusion transport conditions in the near field around the cell,
- long-term evolution tending to close the micro-fissures around the cell (phenomena of creep on the support and clogging),

The uncertainties concerning the geotechnical characteristics, rheological models, or even the long-term evolution prior to seating, may lead to a fractured zone around the cell. However, this would in any case be limited to a very small thickness of argilite (a few centimetres) and would not warrant adopting an swelling clay buffer. A cell variant with swelling clay buffer would in principle be similar to the spent fuel disposal cell (see section 5.2.3.5).

5.2.2.2 The chosen solution

The reference concept considered at this stage for the C waste is a dead-end horizontal tunnel without swelling clay buffer. This tunnel is about 700 mm in diameter and has a metal sleeve. At this stage in the studies, the length of cells was limited to make the technological feasibility demonstration easier.

The design work primarily concerned the following aspects: defining the spacing between packages and cells, for thermal reasons; control of damage to the argilite by minimising empty spaces in the cell; sealing of the cell and the resulting provisions for the cell head.

The cell comprises a "useful part" intended for disposal of the packages, and a cell head designed to seal the cell. The heat produced by the waste is evacuated solely by passive conduction in the geological formation; no ventilation is required for this process. To adhere to the temperature criteria mentioned earlier, some packages could only be placed side by side after a very long storage period. These packages could be placed in the repository earlier provided that they are spaced in order to reduce the mean heat flux. One solution would be to place inert spacers between the packages, the length of which is adjusted according to the heat rating of the packages concerned.

After the packages are emplaced, the cell head is sealed by a swelling clay core. This swelling core is mechanically confined by a concrete plug.

The disposal cells are arranged on either side of an access drift. They are spaced between 8 and 13 metres apart, depending on the heat given off by the waste.

The diagrams in Figure 5.2.2 illustrate this design.

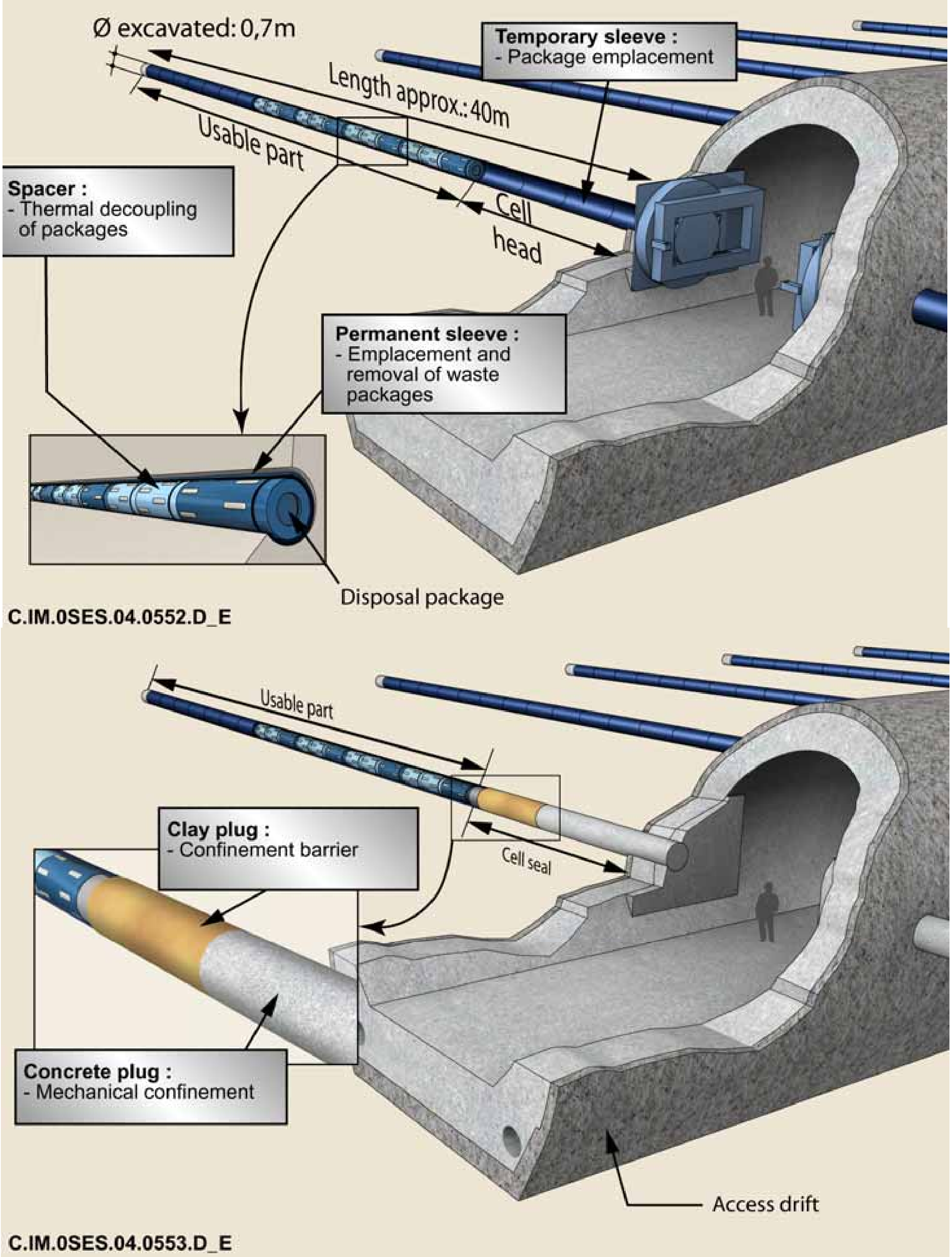


Figure 5.2.2 *C waste disposal cell: main components and associated functions (at top, cell in operation, at bottom, sealed cell)*

- **Orientation of cells and architecture of the disposal zone**

The cells are oriented parallel to the major horizontal stress. This configuration leads to an isotropic stress field in a plane perpendicular to the main axis of the cell and thus helps minimise mechanical disturbance of the rock around the cell (no fractured zone created around the cell at a depth of 500 m).

The disposal cells are grouped into modules. A disposal module consists of several tens to several hundreds of cells (depending on the type of waste) served by three interconnected and parallel access drifts (see Figure 5.2.17).

- **The sleeve**

The cell contains a low-alloy steel metal sleeve. This solution was considered to meet three main requirements: the sleeve mechanically supports the cell for emplacement of the packages; it mitigates in favour of reversibility by ensuring long-term preservation of the internal functional clearances for up to several centuries; in chemical terms, it is compatible with the disposal packages.

The sleeve comprises two parts: a permanent sleeve is placed in the useful part in which the packages are to be emplaced, and a temporary sleeve is placed on the cell head and is then removed when the cell is sealed.

- **The plug**

The cells are sealed by a swelling clay plug installed in the cell head. This plug, together with the argilite, constitutes a low-permeability continuous medium: it thus provides hydraulic and physical-chemical closure of the cell.

The clay plug is located outside the damaged zone of the access drift. It is mechanically confined by a concrete retaining plug which limits volumetric expansion of the clay while it is resaturating. A length of 3 m was considered for the swelling clay plug. This length was chosen for reasons of robustness: aspect ratio higher than one and relaxation compatible with maintaining a minimum swelling pressure (this point is examined in detail in § 5.2.6.2). This is sufficient given the extension of the alkaline disturbance caused by the neighbouring concrete (in the retaining plug and the drift sleeve): the study of alkaline disturbance propagation led to an estimate of this extension in the clay plug of about 0.6 m after 100,000 years and 1.8 m after one million years.

- **The spacers**

Inside the cell, C1 to C4 disposal packages are separated by spacers. A spacer consists of a metal envelope containing a material chemically compatible with the vitrified waste (glass frit, silica, etc.).

The presence of spacers creates thermal separation between the packages. It reduces the mean thermal flux density applied to the sleeve and avoids temperature peaks at the packages by ensuring greater thermal uniformity. This arrangement enables the number of packages per cell to be increased without increasing the thermal peak value. It thus enables the number of disposal cells to be reduced by making them longer (in relation to a configuration in which the packages are placed end to end in short cells). It thus makes the repository more compact.

In the case of type C0 waste, spacers are not needed owing to the moderate heat rating.

- **Summary of requirements and solutions adopted**

The various cell components described above, and their associated functions, are summarised in Table 5.2.1 [7] [22].

Table 5.2.1 Functions and main components of the C waste cell and module

Functions	**Period**	**Metal sleeve**	**Plug and metal shielded trap door**	**Cell plug**	**Spacers**	**Module sealing**	**Access drift backfill**
Transfer the packages to their disposal location	Operations	**X**					
Mechanically support the structures	Operation and observation	**X**					
Protect persons against irradiation	Operation and observation		**X**	x			
Enable the disposal packages to be retrieved	Operation and observation	**X**	x				
Prevent circulation of water	After closure			x		**X**	
Limit release of radionuclides and immobilise them in the repository	After closure	x		**X**			
Delay and attenuate migration of radionuclides	After closure			x			
Limit mechanical deformation in the Callovo-Oxfordian argilites	After closure	x		x	x	x	**X**
Dissipate heat	All	x			**X**		
Divide the repository	After closure					**X**	

Captions: **X** component essential to performance of a function

x component contributing to a function

* Module separation of the repository does not constitute, strictly speaking, a safety function, but is a device adopted with safett objectives in mind

5.2.2.3 Solutions adopted abroad

A number of countries are examining underground repositories for waste similar to French category C waste.

In Belgium, the ONDRAF is looking at concepts for disposal in plastic clay (Boom clay) at a depth of about 200 m.

The SAFIR 2 (2001) file [63] presents a concept in which the disposal packages are placed in a stainless steel sleeve centred in the cell. The cell is a circular drift 2.4 m in diameter (see Figure 5.2.3). The packages are surrounded by a swelling clay barrier about 80 cm thick consisting of prefabricated blocks of swelling clay mixed with sand and graphite. A concrete lining about 25 cm thick supports the ground. The drifts housing the packages are either through-passages or dead-ends (see Figure 5.2.4). At emplacement, the packages have to be translated over about 200 m through the stainless steel tube.

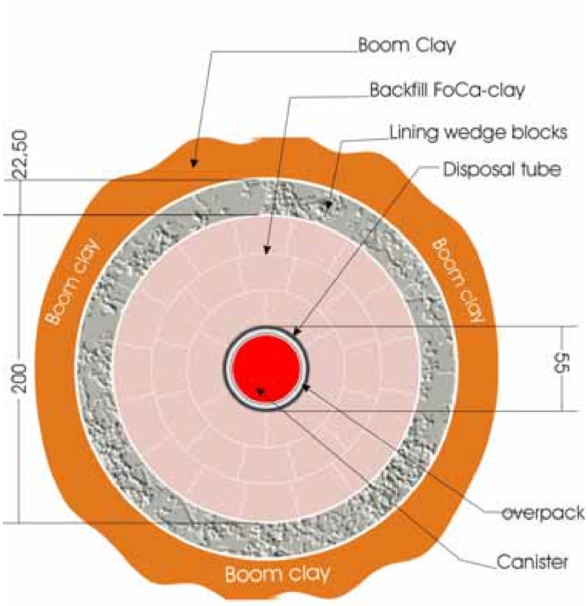


Figure 5.2.3 *ONDRAF concept for disposal of C packages, transverse section according to SAFIR 2*

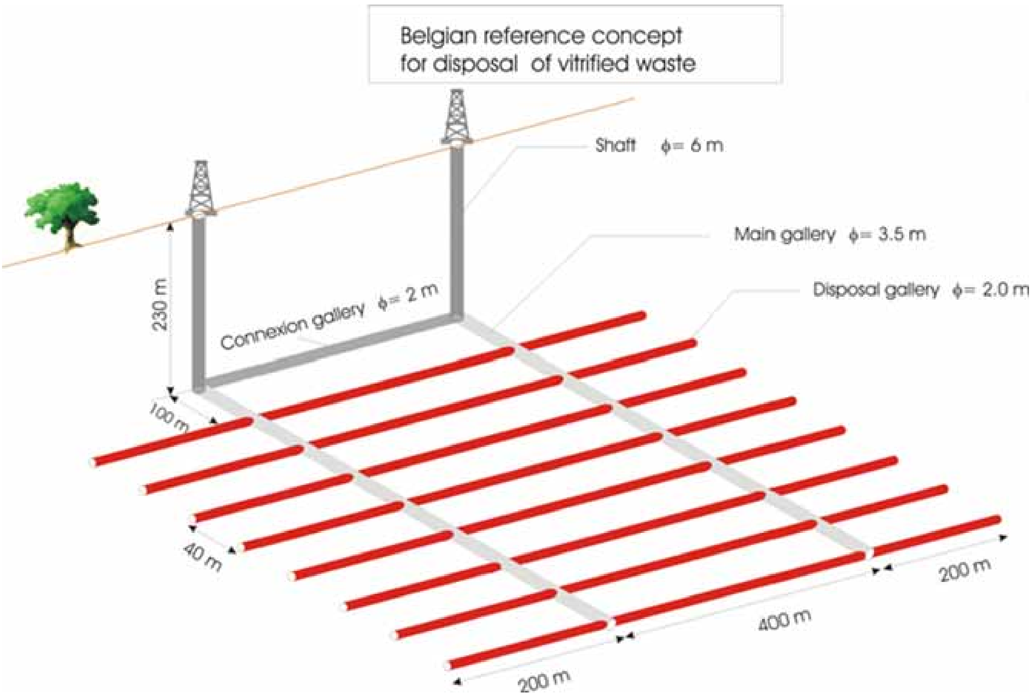


Figure 5.2.4 *ONDRAF concept for disposal of C packages, general architecture according to SAFIR 2*

Alternative concepts were recently envisaged by the ONDRAF [64]. In these concepts, two primary packages are paired in the same supercontainer and placed in horizontal cells or vertical shafts with or without an swelling clay buffer.

In Japan, two generic geological media are considered: granite and clay. Report H12 (1999) [51] presents a concept in which the primary package (CSD-V) is protected by a low-alloy steel over-pack. The over-packs are placed in horizontal or vertical cells about 2.20 m in diameter. A buffer of prefabricated blocks of swelling clay (with 30% sand) is placed between the disposal package and the terrain (see Figure 5.2.5). The thickness of the swelling clay buffer varies according to the geology considered and the specified strength of the over-pack. This thickness is in any case somewhere between 30 and 70 cm.

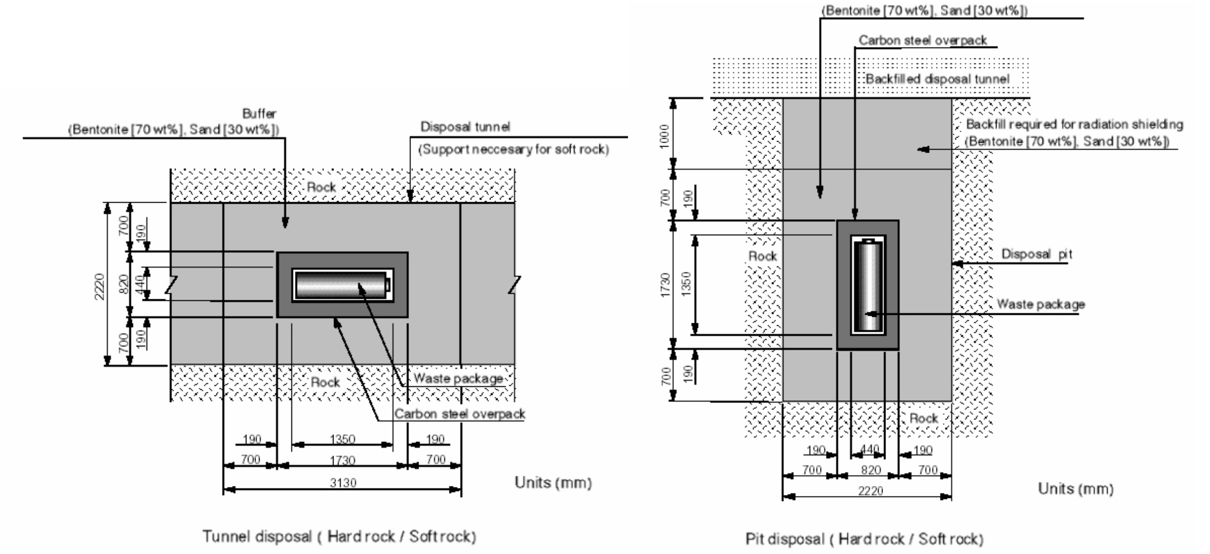


Figure 5.2.5 JNC (Japan) concepts for disposal of C packages, according to the H12 report

In Switzerland, the Nagra's "Project Opalinus Clay" report [44], presents concepts for disposal in relatively stiff clay located at a depth of less than 600 m.

The disposal packages are placed on compacted swelling clay bases in a lined repository drift (see Figure 5.2.6). The distance between two adjacent packages is about 3 m. The spaces between and around the packages are then filled in with pulverulent swelling clay, lightly compacted in-situ.

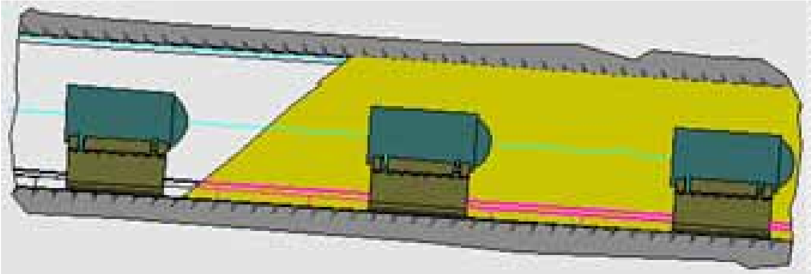


Figure 5.2.6 Nagra (Switzerland) concept for disposal of C packages

The three examples presented above highlight the similarities with the Andra concept. The foreign concepts generally adopt the principle of over-packs and the cells are usually horizontal. Furthermore, in nearly all cases, the packages are spaced a distance apart for thermal reasons.

5.2.3 Description and sizing of the cell and access drift during the operating period

This section is devoted to a description of the structures in the operating configuration. A description of the "sealed cell" configuration is given in section5.2.6. The main characteristics of the cell and its associated access drift are presented in Figure 5.2.7. Figure 5.2.8 gives a more detailed presentation of the various components described below [65].

5.2.3.1 Description of the cell in operating configuration

- **Description of the equipment in the useful part of the cell**

The useful part of the cell consists of a permanent steel sleeve. The choice of steel is justified by its mechanical strength and the ease it offers for package handling in the cell. The sleeve is in contact with the ground. The choice of steel grade at this stage in the feasibility study aims to minimise galvanic corrosion effects and studies were therefore conducted on a low-alloy steel of grade identical or similar to that of the over-pack.

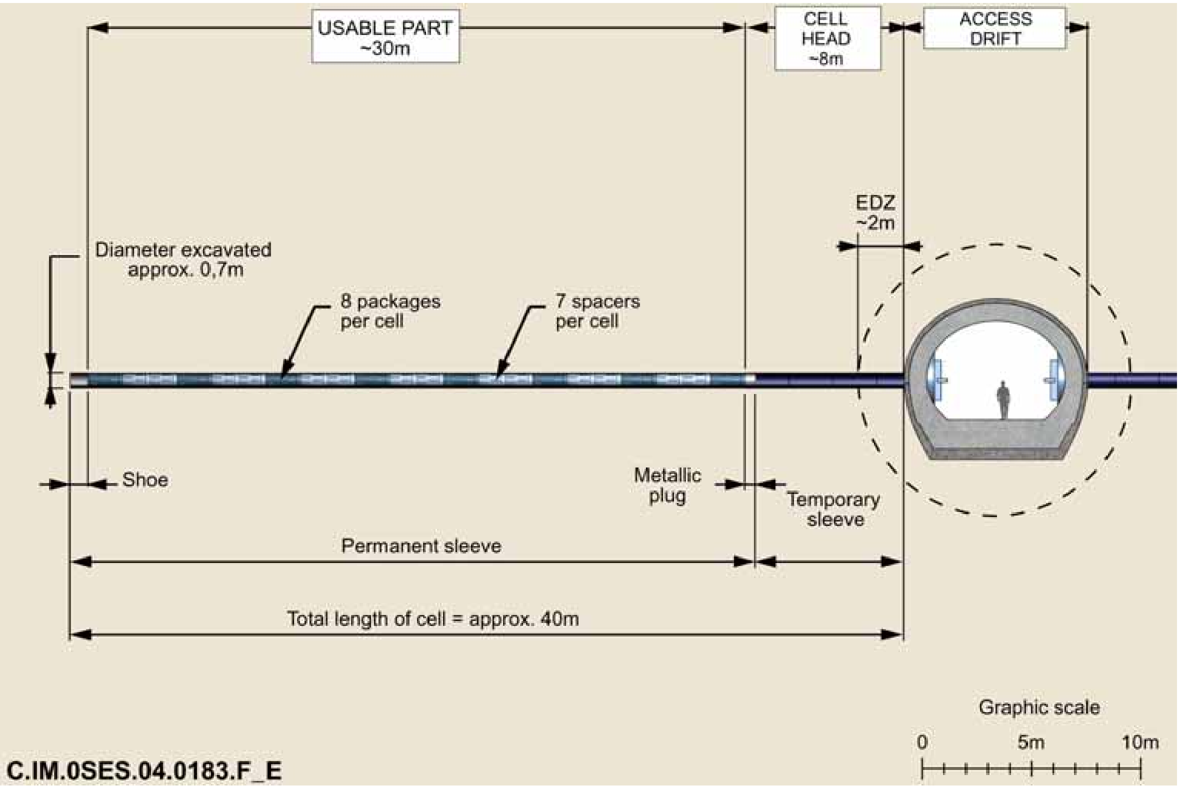


Figure 5.2.7 General longitudinal section of the C cell

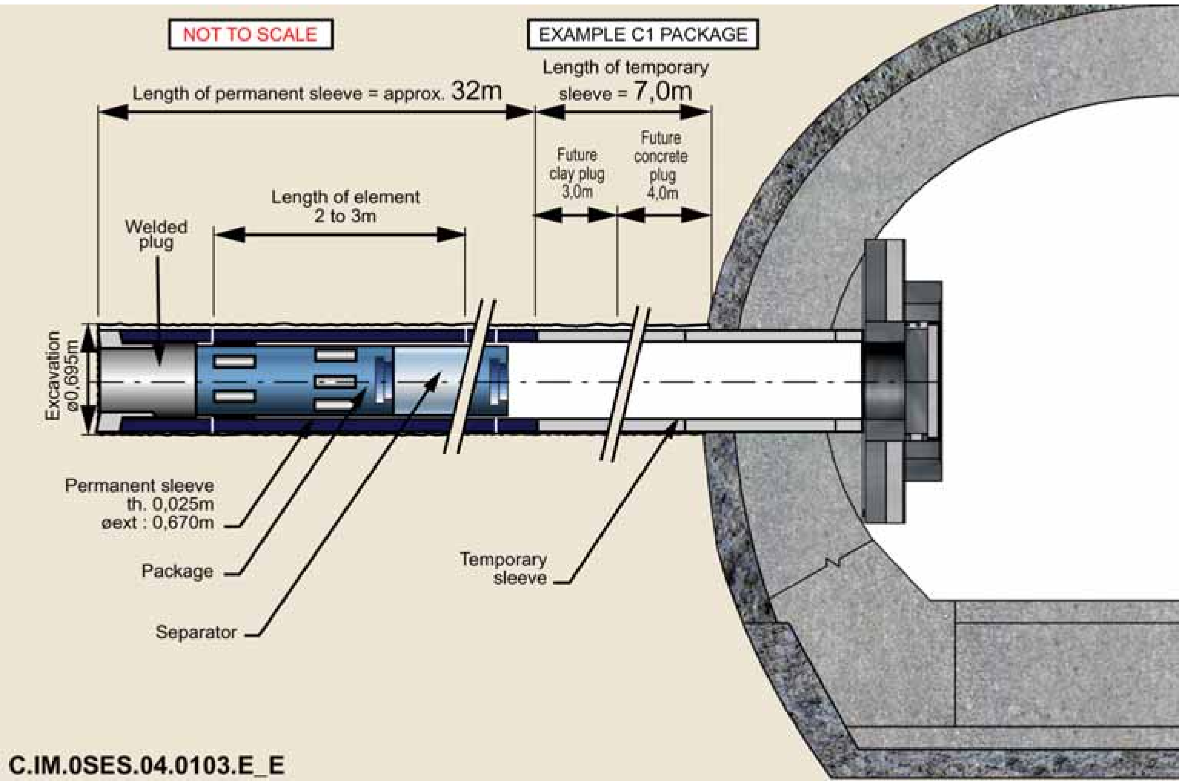


Figure 5.2.8 Detailed longitudinal section of the C cell (distorted proportions)

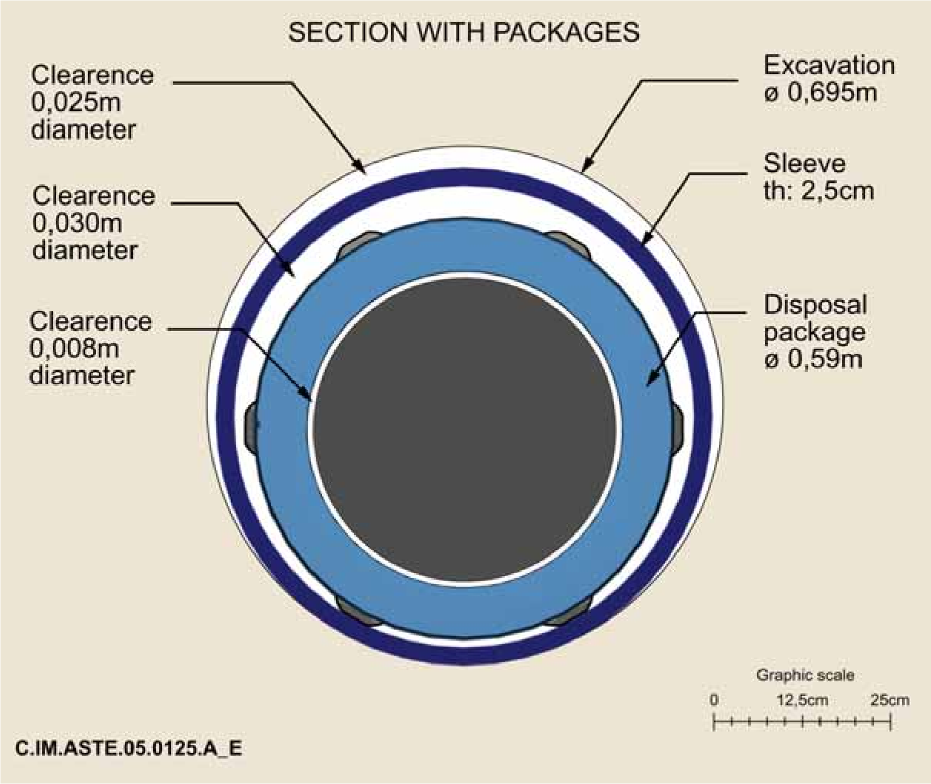


Figure 5.2.9 Cross-section of a cell for C1 to C4 type packages

The thickness of the sleeve must guarantee the mechanical strength of the cell and support the tool thrust during excavation (see § 5.2.5). The strength calculations led to a pre-sizing thickness of 25 mm.

A minimum annular space is required between the sleeve and the ground. The maximum value, of about one centimetre at the radius, corresponds to a conservative recommendation from civil engineering and mining companies and includes a margin to prevent jamming at excavation. This annular space will have to be adjusted to the conditions observed (on-site tests will be necessary). Whatever its initial value, this annular space will eventually close up owing to subsequent deformation (or creep) of the ground.

Functional clearance between package and sleeve allows handling to take place. A clearance of a few centimetres (3 cm at the diameter) is currently adopted by the studies. This is compatible with handling of the packages by pushing on sliding runners.

The sleeve could be inserted into the cell in sections[76], about 2.5 to 3.0 metres in length. The length of these sections must be as great as possible in order to minimise the number of connections. A 3 m length is today considered to be the maximum allowable given the dimensions of the access drift.

The joins between sections must not generate any excess thickness either on the exterior of the sleeves (so that the sleeve can be more easily pushed in) nor on the interior (so that the packages can be more easily inserted into the sleeve). Screwed, clamped and welded joins are the techniques currently available and that comply with this requirement.

Spacers are placed between the packages when the heat rating so demands. A spacer consists of a metal envelope fitted with handling devices identical to those of the packages, and an internal matrix. The nature of this internal matrix has not yet been defined and will have to offer a compromise between good thermal conductivity, chemical compatibility and mechanical strength.

- **Description of the cell head equipment (before sealing)**

The diameter and thickness of the temporary sleeve are identical to those of the permanent sleeve. The join between the permanent and temporary sleeves could be an unwelded force-fit to facilitate dismantling.

The function of the metal plug is to act as a shield against the β, γ and neutron radiation produced by the packages. It is installed in the permanent sleeve after the last package has been emplaced in the repository (see section 5.2.6).

At the head of the cell, a shielded trap door consisting of a metal frame sealed into the access drift liner and a vertical sliding gate, provides radiological protection when closed as well as docking of the handling devices for package emplacement. The shielded trap door is designed to be partly recovered and reused on other cells. It is then replaced by a leaktight cover isolating the cell before it is closed, in order to limit gaseous exchanges and create conditions favourable to controlling corrosion within the cell.

5.2.3.2 Description of the access drift

The access drift is first of all determined by the package handling needs during their emplacement in the cell.

On this basis, we used pessimistic design scenarios based on the available knowledge of the site. Once more detailed knowledge is acquired from actual sites, more favourable scenarios could be adopted.

The exercise carried out shows that these drifts are technically feasible, even with the pessimistic scenarios considered. It results in a useful access drift width of about 6.40 m at mid-height, 4.50 m at slab level and a useful height of 4.50 m. The roof support laid at excavation of the drift comprises rock bolts 4 m long[77] and a 20 cm thickness of shotcrete. The lining, laid 6 months to one year after excavation of the drift, consists of concrete (B60) about one metre thick.

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[76] The section in the dead-end (the first one inserted) could be equipped with a drive shoe. This shoe would be used for excavation and left in-situ. See section 5.2.6.

[77] The bolting diagram could be modified at the cell locaitons. In any case, the size of the anchor bolts would be less than the length of the concrete plug in the sealing zone.

Reservations are made in the slab for running cables. The slab is equipped with a concrete roadway for transporters running on tyres. Depending on the type of transporter chosen, the slab could also be fitted with rails.

The concrete lining does not need to be reinforced in the standard section.

5.2.3.3 Thermal design of the repository modules

The thermal design of the module consists, for a given package heat rating, in determining the geometries which meet the thermal criteria (defined in section 5.2.1.1).

- **Objectives of the thermal design**

The first objective of the thermal design is to identify the foreseeable preliminary storage period prior to placing the waste in the repository, for the proposed concepts.

For this preliminary storage period, the second objective is to identify the geometrical configuration of the repository modules corresponding to the smallest possible total excavated volume and meeting the temperature limit value. This temperature limit is relative to a specific phenomenon called the "thermal peak". The arrangement of the packages in the cells and of the cells in the repository modules is chiefly dependent on this phenomenon. It is recalled that the temperature limit used in the calculations is 90°C in contact with the rock.

- **Thermal modelling**

The thermal design is conducted by finite-elements 3D modelling [10].This modelling is also used to evaluate the duration of the thermal phase, in other words the time for which the temperature of the packages exceeds a pre-defined threshold value. This latter aspect justifies the design of the packaging (see chapter 4). Thermal modelling gives the main time and space scales. The thermal effects linked to the general architecture (general footprint of the modules and layout of the modules in relation to each other, verification of thermal independence of the repository zones) are presented in chapter 6.

Modelling data and hypotheses

C1 to C4 disposal packages are highly exothermic. Their heat rating drops from 2600 watts to 300 watts in 100 years (see chapter 3). For their part, C0 disposal packages are significantly less exothermic. Their heat rating at the time they are packaged is about 10 times lower than that of a C1 package.

In the model, the heat transfer modes are conduction and radiation. Conduction is modelled for all the materials making up the cell. Radiation is taken into account between all the components of the model separated by a film of air (functional clearance, cell ends, etc.).

To simplify matters, it was also considered that all the cells in the repository zone concerned were simultaneously loaded on the same date and that all the access drifts were backfilled after 30 years. This is a conservative approach, which ignores evacuation of some of the heat through drift ventilation during the operating phase.

Finally, the value chosen for the initial temperature of the Callovo-Oxfordian formation at the time of disposal was 22 °C.

Modelling principle

The main problem with thermal modelling of the repository lies in the considerable disparity between space and time scales.

In terms of space, there is a significant contrast between the dimensions of cell components (for example just a few centimetres for the functional clearance between packages and sleeve) and the dimensions of the repository as a whole.

In terms of time, the conditions which in the short term govern evacuation of the heat produced by the packages are different from those characterising the thermal behaviour of the repository in the longer term. In the short term, the cells are in fact thermally independent of each other, while in the longer term (more than three centuries), the "overall" heating of the repository zone leads to thermal coupling between the various units.

To deal with this problem, a 3D finite-elements model was produced on the basis of three "nested" models (see Figure 5.1.10). Each of the three models is characterised by its own validity range:

- the overall model on the scale of the site,
- the median model on the scale of the repository module,
- the local module on the scale of the disposal cell.

The *overall model* (kilometre scale) represents the geological medium from the surface down to a depth of 3,500 m. The thermo-physical properties of the various geological layers are taken into account. This general model can be used to calculate temperature evolutions over a period of 10,000 years at numerous points located more than 50 m from the disposal packages. Over a period such as this, the heat given off by the packages has an influence over a distance of a kilometre and the various repository modules interact thermally with each other. This general model thus represents all the repository modules and covers a lateral distance of 2,000 m around the repository.

The *median model* is on the scale of the repository module (metre scale). Its geometrical representation is less detailed than the local model but it does include the structures surrounding the cell (access drifts, seals, etc). The calculation is made by applying to the edges the limit conditions obtained on the overall model.

The *local model* allows a detailed representation of the various cell components with a high degree of geometrical precision (centimetre scale). It enables the temperature evolution to be evaluated for the immediate environment of the cell for all types of packages in the repository. There are as many local models as there are exothermic type packages. This model is used by applying to the edges the limit conditions obtained on the previous median model. It represents all the cell components, the functional clearances, the spacers and the access structures.

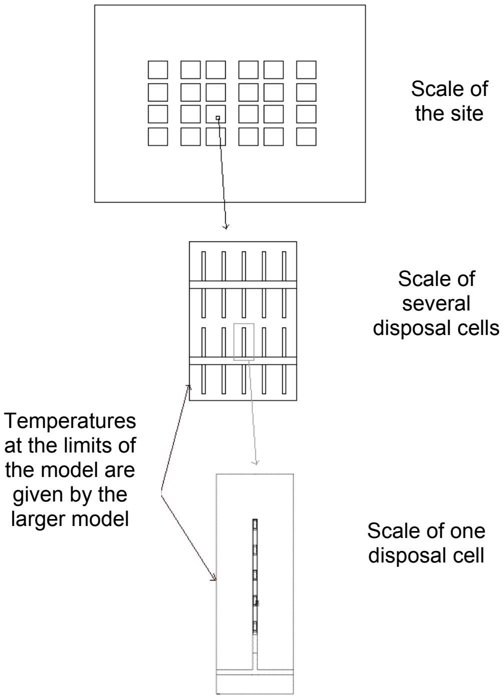

Figure 5.2.10 "Nested" modelling principle used

The local scale model is illustrated in Figure 5.2.11 giving the temperature isotherms during the thermal peak for a C1 type cell.

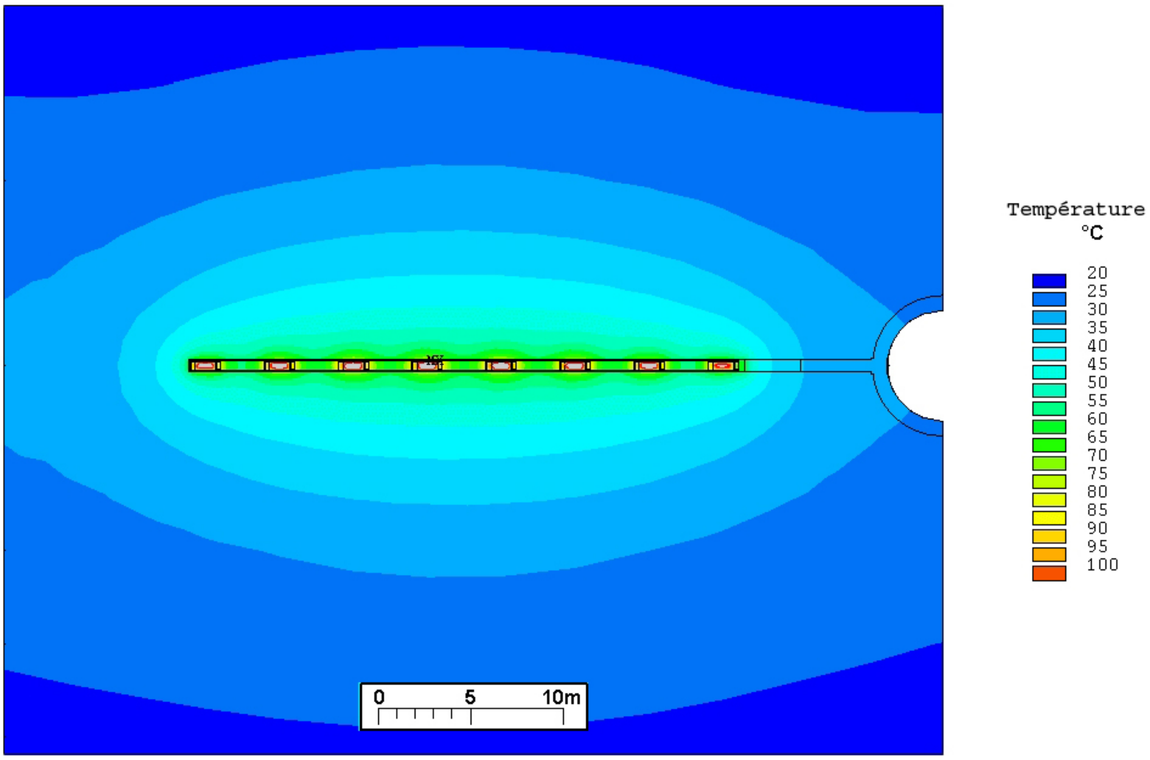

Figure 5.2.11 Temperature isotherms around a C1 cell at the time of the thermal peak

- **The significant parameters in thermal design**

For the thermal design, it is essential to identify important parameters, any variation of which is likely to have a significant impact on the scale of the underground repository installations (in terms of footprint and excavated volume). In this respect, the impact of the various operational and construction provisions was examined.

In terms of operation, the first important parameter is the residual heating power of the waste at the time of disposal, which depends on the duration of its preliminary storage.

In design terms, several aspects were explored. For example, adaptation of the loading phasing was envisaged. However, this strategy offers no gains in terms of compactness. Construction measures consisting in increasing the exchange surface area between the packages and the geological medium (for example using finned sleeves) were also explored. These measures, which help reduce the flux density are of limited interest because the gains achieved in terms of compactness are offset to varying degrees by the increased cost of cell construction. Cell ventilation was also envisaged, although at this stage of the studies it was ruled out because a passive evacuation solution requiring no human maintenance was preferred. Finally, various geometrical configurations were studied with regard to cell spacing and spacing of C type waste inside a given cell. A parametric study highlighted the importance of these parameters, in particular the spacing between packages, which plays a primordial role as it enables the length of the horizontal cell to be increased up to a value that is reasonable in terms of feasibility (40 metres).

To conclude, the important thermal design parameters so far defined are:

- the preliminary storage time for highly exothermic packages,
- the spacing between packages inside the same cell and the inter-axial distance between cells.

Storage period

The evolution over time of the residual heat rating of the packages has a determining influence on the choice of preliminary storage of the primary packages. There is a duration below which it is impossible to comply with the temperature criteria, even for an isolated package (the temperature on the cell wall exceeds 90°C). Above this period, the footprint and excavated volume needed for package disposal (comprising the volumes linked to the cell and to the access drift) diminish in line with the age of the package. Figure 5.2.12 for example shows the influence of the cooling period on the excavated volume for disposal of a C1 package, identifying 3 domains. Domain (A) corresponds to storage periods incompatible with the thermal criteria, even for an isolated package. Domain A covers the 0 - 45 year range approximately. In domain (B), at between about 45 and 60 years, the excavated volume is highly sensitive to a slight variation in the age of the package. In domain (C) which begins as of about 60 years, the architecture is less sensitive to a variation in the age of the package at the time it is placed in the repository. At the end of domain (C), after about a hundred years, it becomes virtually impossible to reduce the excavated volume (and footprint) of the repository by increasing the preliminary storage period.

Domain C was therefore chosen as the design domain for the repository architectures. The beginning of the domain is called "earliest possible" disposal and constitutes the reference for the proposed concepts.

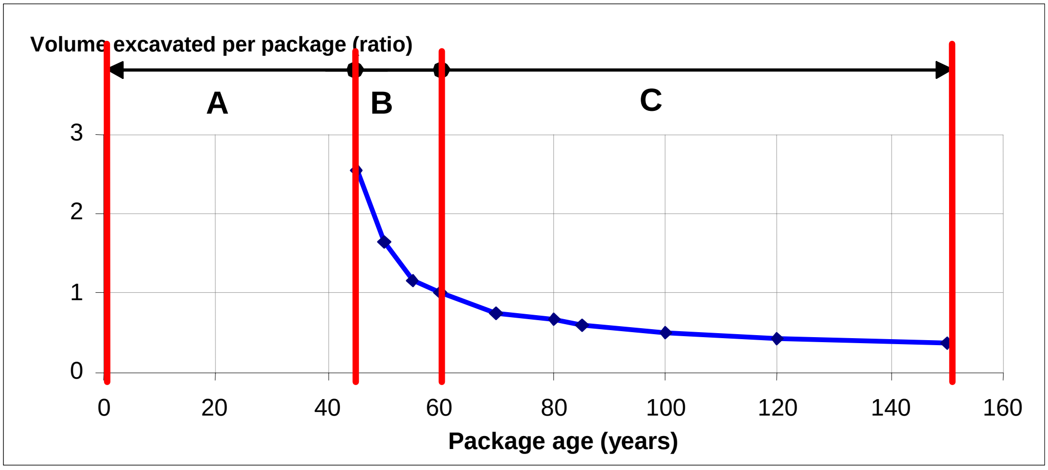

Figure 5.2.12 *Influence of the preliminary storage period on the excavated volume per C1 package (standardised volume in relation to the volume for a preliminary storage period of 60 years)*

Spacing between C waste packages inside a cell

The spacing between packages is an important parameter in limiting the excavated volume needed for disposal of a package. It is linked to the notion of thermal decoupling. To understand the reasons this parameter is important, we must differentiate between the useful volume (corresponding to the part in which the packages are emplaced) and the non-useful volume (corresponding to all the other underground infrastructures in the repository zone, such as cell heads and access drifts).

The intuitive configuration which would be to have abutting packages leads to a considerable increase in the non-useful part because when the packages are juxtaposed, the heat given off by the packages in the event of earliest possible disposal is such that only a few packages can be emplaced in each cell (1 to 2 depending on the type of package). This entails a considerable imbalance between the useful and non-useful parts of the same cell. The total number of cells thus increases as the number of packages per cell decreases, which leads to extremely long access drifts.

If the packages are further away from each other, there is a spacing distance (thermal decoupling value) as of which the thermal load per linear metre in the useful part is such that it is possible to place an infinite number of packages in a cell of length presumed to be infinite. It then becomes possible to adopt the longest possible cell length, given technological, construction and handling considerations. This length was set at a reasonable value of 40 metres (including 30 metres useful length) for all type C packages.

The role of the spacers is to achieve a situation in which there is "thermal decoupling" of the packages. As long as the packages are "thermally coupled" their number and the length of the cell are limited in order to meet thermal criteria. "Thermal decoupling" corresponds to a package spacing configuration for which it is thermally possible to adopt the maximum cell length (defined by technological criteria).

Inter-axial distance between C waste cells

The inter-axial distance between cells has a major influence on the scale of the repository installations in that it enables the number of packages contained in the cell to be optimised. The number of packages that can be arranged in a cell in compliance with the thermal criteria rises as the space between cells increases. The studies show that when this spacing increases from the minimum value (which for geotechnical reasons is about five times the diameter of the cell), the footprint of the installations drops, reaches a minimum and then increases again. The inter-axial distance between cells is therefore a parameter to be optimised.

● Results of thermal design and sensitivity to important parameters

The results of the thermal design can be expressed in terms of variations in the geometrical characteristics of the installations as a function of the preliminary storage period. The repository module architectures presented here are calculated for a preliminary storage period of 60 years for C1 and C2 packages and 70 years for C3 and C4 packages. This corresponds to "earliest possible" disposal: the packages are separated by thermal decoupling spacers.

For C0 packages (which are stored for at least 20 years), the architecture corresponds to the "most compact" repository: the number of packages contained in the cell is maximum (18 or 22 juxtaposed packages) and the inter-axial distance between two cells is close to the minimum determined by the geotechnical considerations.

For these preliminary storage periods, the thermal design enables the following geometrical parameters to be determined (see Figure 5.2.13):

- inter-axial distance between two adjacent cells (or the pitch Px),
- the number (N) and spacing of the packages they contain (linked to the useful length of the cell, Lua, and the number N of packages),
- the distance between cell ends (the pitch Dy).
- The footprint per emplaced package can then be easily deduced.

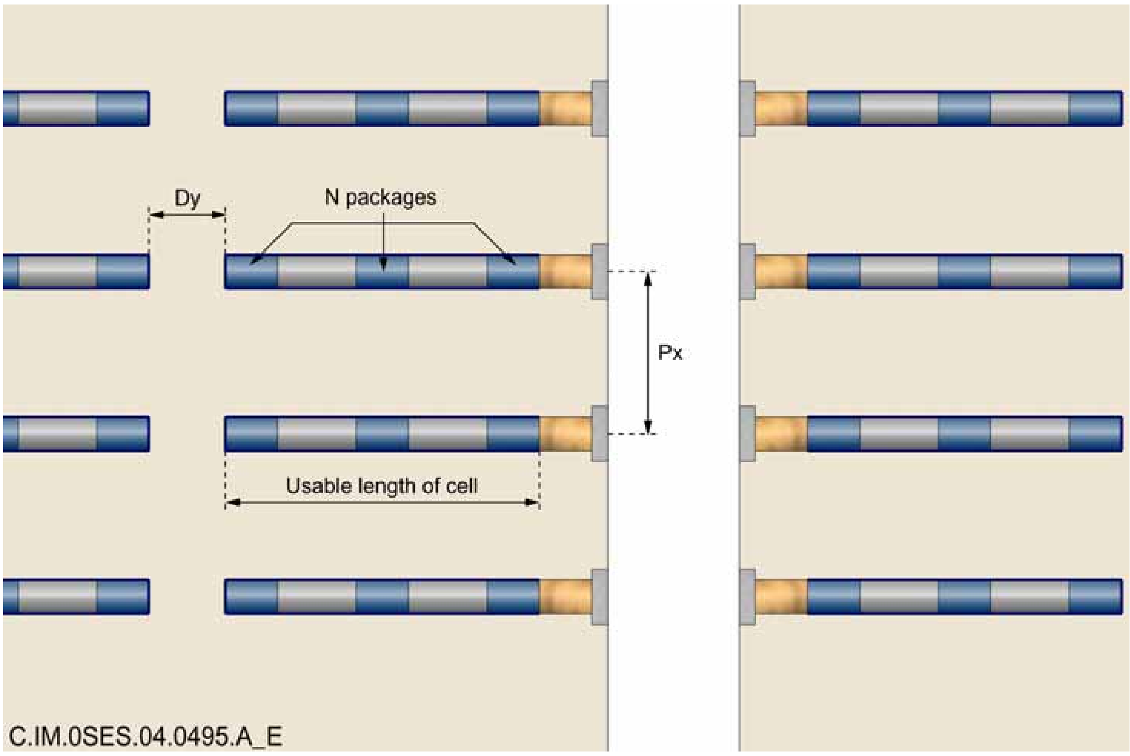

Figure 5.2.13 Thermal design geometrical parameters

The results are given in Table 5.2.2.

Table 5.2.2 C waste package footprint

Type of waste package	**C0 (AVM)**	**C0 (R 7/T7)**	**C1**	**C2**	**C3**	**C4**
Age (years): preliminary storage period	20	20	60	60	70	70
Horizontal footprint (m^2/package)	20	25	80	85	103	115
N: number of packages per cell	22	18	8	7	7	6
Px (m): inter-axial distance between cells	8.5	8.5	12	11	13.5	13
Dy (m): distance between cell ends	20	20	20	20	20	20
Lua (m): useful length of cell	30	30	30	30	30	30
Pc (m): pitch between packages	0	0	2.4	3.1	3.1	4.0

Figure 5.2.14 illustrates the different package spacings in the cells according to their heat rating.

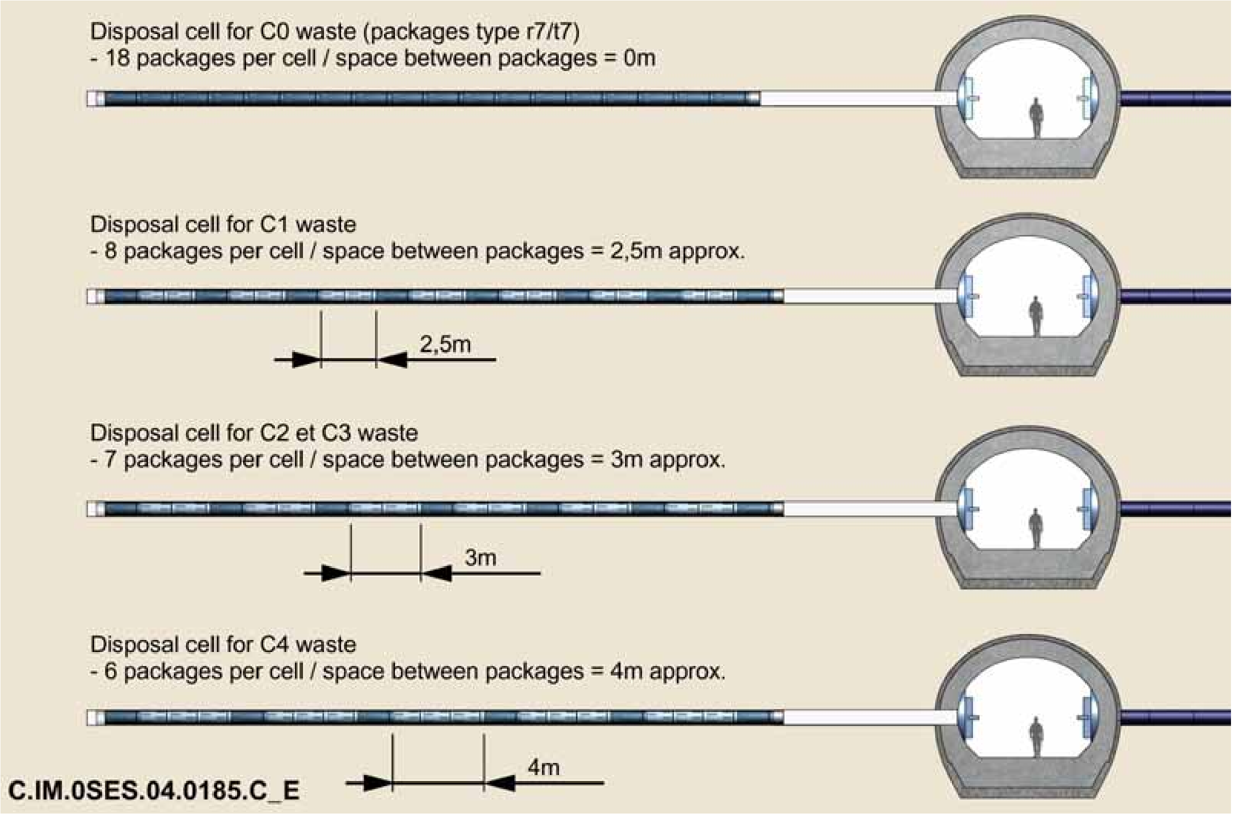

Figure 5.2.14 C cell longitudinal cross-sections

It should be noted that the temperature evolution on the cell wall between 0 and 600 years, at the hottest point in the argilite (Figure 5.2.15), shows a dip below the 70°C threshold well before 1,000 years, thus ruling out any risk of mineralogical transformation of the argilite.

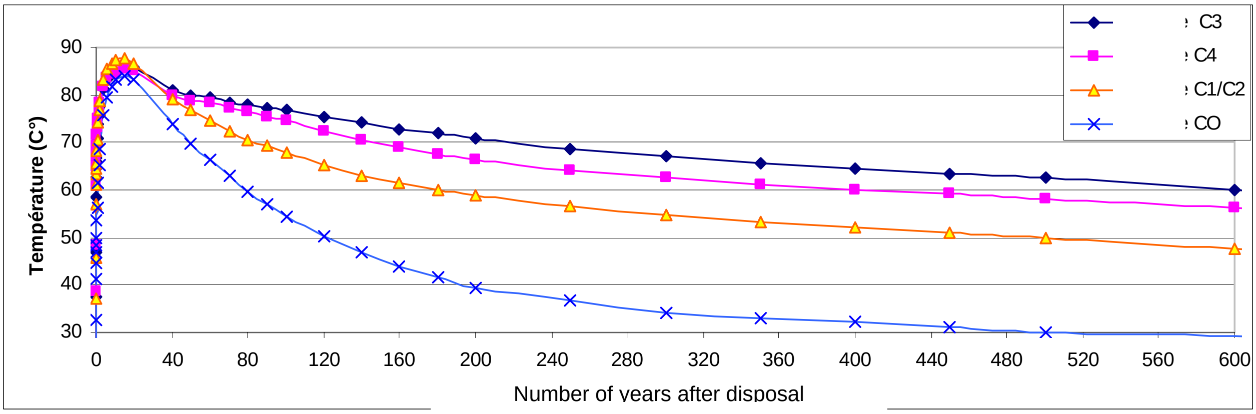

Figure 5.2.15 Cell wall temperature for C waste (hottest point in the argilite)

Sensitivity to uncertainties in the input data.

Apart from the design elements aimed at helping dissipate heat (package and steel sleeve), the following main parameters influence the temperature peak:

- the thermal properties of the geological medium (Callovo-Oxfordian argilites),
- the presence or absence of a functional clearance between the sleeve and the geological medium[78].

Uncertainties regarding these parameters were approximated through various sensitivity calculations. These show an increase or reduction in the temperature peak of about +/- 10°C. Adopting 90°C dimensionning ensures that the rock temperature does not exceed 100°C taking the uncertainties into account.

The consequences of these deviations can be assessed in terms of the impact on the package preliminary storage period. The resulting storage period variation for "earliest possible" disposal is about +/- 10 years.

- **Conclusion concerning thermal design**

The dimensions of the C waste repository modules are primarily the result of the thermal design. This determines the number of packages per cell and the inter-axial distance between cells. However, there is room for optimisation if the feasibility of longer cells can be demonstrated, both in terms of their construction and from the package handling viewpoint. This avenue of optimisation has yet to be explored at this stage in the studies.

5.2.3.4 Mechanical and thermomechanical design of the access drift - disposal cell system

The mechanical and thermomechanical design is intended to ensure the integrity of the access drift – disposal cell system structure and functional clearances during a minimum secular period. It concerns the thickness of the disposal cell sleeve and the characteristics of the access drift concrete lining.

- **Disposal cell sleeve calculations**

The following phenomena may affect the sleeve's integrity in the long term:

- Argillite creep filling the annular cavity on the sleeve extrados and producing radial compression stress around the sleeve. The radial compression stress value at a given data depends on the argillite creep rate and the initial dimensions of the annular space. The creep rate is itself dependent on the argillite temperature.
- Terrain expansion (due to the exothermicity of the packages), producing a supplementary radial compression stress in the absence of clearance. This stress increases during the first decades and then decreases once the temperature peak has been passed.
- Expansion differential between steel and argillite (due to the exothermicity of the waste) which, combined with the lateral friction stresses due to argillite creep, induces an axial compression stress in the sleeve. This phenomenon undergoes a time evolution similar to terrain expansion.

Sleeve steel corrosion (its thickness includes a 5 mm corrosion allowance).

Quantification of radial load stresses

Given the uncertainties concerning the initial dimensions of the annular space and the kinetics of the various phenomena involved, it has been decided to dimension the sleeve thickness for a 12 MPa load, corresponding to the initial geostatic stress of the geological medium.

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[78] The thickness of the functional clearances is not as important as the number of clearances located between the package and the geological medium. The difference in temperature caused by the air gap between two cylinders is hardly affected by the thickness of this gap between one and several cms

Sleeve thickness calculation

Based on knowledge of the load applied on the sleeve, it is possible to calculate the thickness required to not exceed a given stress level in the steel. It amounts to 20 mm (not including corrosion allowance) for S235 grade steel [65], chosen for its compatibility with the over-pack but showing low thermal characteristics.

This design includes safety margins, since the sleeve thickness required varies significantly with the radial load considered and the 12 MPa load taken into account is particularly high. Moreover, it must be noted that a lower thickness could be considered in the case of a more resistant steel grade.

Design verification with respect to axial load thermal stresses and risk of buckling

When the temperature increases, the sleeve tends to expand radially and axially.

Its thermal expansion (free displacement) is centimetric[79]. This increase in length will be theoretically absorbed at the two ends of the sleeve, which are left free. If the terrain quickly closes in on the sleeve, the tube deformation could be negatively affected, leading to an axial stress inside the tube close to the elastic limit of S235 steel at 100°C. Given the capacity of argillites to accompany the sleeve deformation, the appearance of plastic deformations in the sleeve is not foreseen.

The risk of buckling[80] has been analysed according to the above factors, in terms of both radial stress (risk of tube collapse) and axial stress. The buckling resistance of the sleeve has been verified for a thickness of 20 mm (not including corrosion allowance)[81].

- **Access drift concrete lining design**

The access drift lining is designed to withstand the effects of the heat released by the waste (radial expansion of concrete and argillite) and of argillite creep (itself accelerated by the thermal release). Argillite desaturation that rigidifies the argillite and reduces its creep rate has been taken into account for drifts ventilated in the operating phase.

The concrete lining is placed in contact with the rock (no annular cavity) after a deconfinement phase allowing a certain degree of stress relaxation. A period of 9 months to lay the lining has been hypothetically considered. The radial compression stress due to the weight of the soil on the lining is in the order of 6 MPa[82] after one century[83]. This value integrates creep acceleration due to increased temperature and takes into account the moderative effect of desaturation.

The thermomechanical stress in the concrete can be assimilated with a radial load of approximately 2 MPa at peak temperature.

The total equivalent radial load applied on the concrete lining is in the order of 8 MPa (not including ponderation coefficients), to be compared with the 12 MPa of isostatic stress theoretically applied after an infinite time period.

The calculation performed yields a lining thickness of approximately one metre[84] for B60 type concrete. The thermal component amounts to approximately 40% of this thickness.

The acquisition of better knowledge of creep rates in unsaturated conditions could reduce the concrete thicknesses.

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[79] For the S235 steel considered and a lining length of approximately 40 m, a maximum temperature increase of 78°C induces a lining length increase of 4 cm.

[80] Buckling is the rupture (and significant deformation) of a part under compressive stress. It occurs when a critical stress level is exceeded.

[81] The presence of the terrain around the lining limits lateral deformations, thereby significantly increasing the critical stress level. This effect has been taken into account in the verification performed.

[82] Average value based on access drift orientation (anisotropic stress).

[83] In case of extended use of the drift, reinforcement work remains a possibility.

[84] The anisotropic stress regime and the shape of the drift lead to higher thicknesses in the cell (1.20 m) and raft (1.40 m)

It must be noted that this drift lining is thicker than that of the B waste disposal cells, despite their higher effective cross-section. The difference is mainly due to the thermal effect. The higher thickness of the C-module access drift lining results from the integration of creep acceleration due to thermal release from C waste.

5.2.3.5 Assessment of impact on argillite in the immediate environment of the disposal cell

The need to minimise damage to the geological formation in the immediate environment of the disposal cells leads to verifying the low impact of their construction on the argillite.

- **Short-term impact**

The design is intended to minimise short-term impact, on the one hand by orienting the disposal cells parallel to the major horizontal stress (to reduce the extent of the fractured zone around the cells) and, on the other hand, by sufficiently spacing the cells (to reduce mechanical interactions among them). For this purpose, a minimum centre-to-centre distance corresponding to 5 cell diameters has been adopted.

The extent of the fractured zones[85] and microfissured zones[86] surrounding the structures when opened is first evaluated assuming that the rock is not supported, and ignoring the effects of the neighbouring access drift. The results of the purely mechanical calculations [66] are shown in Table 5.2.1 below. They indicate that the construction of C waste disposal cells at a depth of 500 m does not induce a fractured zone.

Table 5.2.1 Extent of fractured and microfissured zones in the short term (depth: 500 m)

Geological horizon C (circular structures assumed isolated)	**Extent measured from structure wall (ratio with respect to radius R)**	
	Fractured zone	**Microfissured zone**
Disposal cell (oriented parallel to major stress)	None	0.5 R
Access drift (oriented perpendicular to major stress)	0 to 0.1 R (vertical aspect ratio ellipsoid)	0.3 to 0.7 R (vertical aspect ratio ellipsoid)

In order to prevent the interaction with the access drift from increasing the damage facing the useful part of the disposal cell and its sealing plug, the latter are located outside the fractured zone of the drift. Due to their orientation perpendicular to the major horizontal stress, the access drifts are surrounded by an ellipsoidal microfissured zone whose main axis is vertical and whose smaller axis (horizontal) amounts to 0.3 times the drift radius R [66]. Considerations regarding the operation of the concrete plug have led to prescribing a length of 4 m for the latter. The swelling clay plug is therefore located 4 m from the access drift, in a zone unaffected by the damage induced by the latter.

- **Long-term impact**

In the longer term, the argillite creeps freely until reaching the disposal cell sleeve, and then the packages when the sleeve ruptures (after corrosion). The various annular cavities must therefore be minimised so as to limit argillite deformation. Given the various mechanisms involved and the small diameter of the C waste disposal cell, the appearance of a fractured zone of significant thickness is considered highly unlikely.

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[85] Fractured zone: Geomechanical zone above the works, where the rupture threshold may be exceeded. It is characterised by the appearance of **fractures** possibly connected, leading to a significant increase in rock **permeability** (5.10^{-9} m/s, as opposed to 5.10^{-14} - 5.10^{-13} m/s for unaltered rock).

[86] Microfissured zone: Zone appearing either near the works (if no **fractured zone** has been produced) or behind the **fractured zone** (if present). It is characterised by diffuse, scarcely connected microfracturing leading to only a limited increase in **permeability** (5.10^{-11} m/s).

In addition, the sealing zone undergoes specific processing to preserve the characteristics of the argillite (see section 5.2.6).

The long-term evolution of the drifts is covered in section 7.6.

5.2.3.6 Seismic behaviour of disposal cell

The seismic stresses to be considered below the surface have been evaluated [36]. They do not affect the design of the structures or the long-term behaviour of the argillites. Seismic is very limited under the surface as compared to on the surface (due to amplification of seismic movements on surface, low dynamic amplification undergone by buried structures, and small dimensions of structures with respect to wavelength of seismic movement). An analysis of the various possible dynamic effects (seismic wave interaction with isolated cavity, diffraction for all repository cavities) applied to the various types of disposal systems in a repository shows that such effects are negligible.

5.2.3.7 Durability of disposal cell

Here we consider the sleeve function with regard to maintaining favourable conditions for waste package removal during a pluri-secular period (reversibility). This durability essentially depends on the corrosion taking place and the mechanical resistance of the sleeve. The corrosion has been estimated. The sleeve design adopted takes into account a corrosion thickness and a mechanical resistance thickness.

The sleeve described is made of the same type of steel as the over-pack. The properties involved are of the same type (mechanical, physical and chemical) and the similarity of materials prevents the effects of galvanic corrosion.

The corrosion regimes and rates are identical to those described in chapter 4 for the over-pack (section 4.2.3.2). They are divided into three successive periods: an initial period without corrosion, a transitory period of oxidising corrosion and a period of anoxic corrosion during which the corrosion rate becomes very low (ranging from a few tenths of micrometre to a few micrometres per year [53]). Risks of localised corrosion (pitting or crevice corrosion) or specific corrosion (stress corrosion, fragilisation by hydrogen) have been taken into account and their consequences evaluated. Based on the results of the analysis conducted, generalised corrosion is considered the dominant corrosion mechanism in the medium and long term.

Under these conditions, the corrosion allowance of 5 mm for the sleeve will only be consumed after several centuries [87]. This durability forecast is consistent with observations performed on similar archaeological sites.

It must also be noted that the sleeve connections can offer a certain degree of impermeability that contributes to durability, even though this impermeability has not been defined as a sleeve function and has not been taken into account in the repository safety assessments.

5.2.3.8 Compatibility with disposal package installation method

The disposal cell and access drift design takes into account operating constraints, particularly the package installation method.

In this respect, the disposal cell must first and foremost enable packages to be transferred via sliding runners on the sleeve. As for the access drift, it must be sufficiently wide to allow the vehicle carrying the transfer cask to manoeuvre and place itself in docking position.

Section 9 provides a description of the various systems for transferring packages in access drifts, docking the transfer cask, and positioning packages in a disposal cell (pusher robot). A few important details with regard to the disposal cell and access drift design are indicated below.

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[87] The design hypotheses adopted for the corrosion allowance of the lining are reasonable. However, they are less conservative than for the C waste package over-pack. This is explained by the absence of a long-term safety function associated with the lining.

- **Disposal cell design and construction**

A functional clearance of 30 mm in diameter has been included in the disposal cell design to enable package and pusher robot displacement. This functional clearance is understood with respect to the outside dimensions of the packages including sliding runners. It has been minimised as far as possible at this stage so as to limit the mechanical degradation of the argillite on a very long-term basis in case of sleeve collapse. It is intended to enable the transfer of packages without risk of jamming (for example, due to sleeve section alignment defects or the presence of rough or jagged edges in connections). In order to minimise these risks, several technical measures can be considered:

- Controlling the alignment of the sleeve sections. Misalignments may result from angular defects, or from lateral displacements of correctly oriented sections. A preliminary inspection with an optical sighting device prior to welding the tube components can prevent angular alignment defects during the installation of the sleeve. Likewise, misalignments due to lateral displacements can be controlled using optical sighting and centring devices.
- Obtaining a good running surface. This mainly depends on the quality of the connections. The above-mentioned connections without internal sleeves satisfy this requirement.

In addition, the radiological protection calculations show that a cylindrical plug without shoulder is enough to ensure radiological protection. The absence of shoulders on the metal plug (and therefore on the sleeve) simplifies the installation of the packages.

All of these design factors facilitating package installation also favour reversibility. The passage of packages during a possible removal operation does not entail specific difficulties with respect to installation. The removal operation even provides additional advantages associated with the possibility of exerting significant tensile forces on the packages.

- **Access drift design**

The effective cross-section of the access drift is dimensioned based on transfer cask displacement and docking. The transfer cask travels in transverse position inside the drift (without rotation for docking). The figure below shows the docking of the transfer cask in front of a disposal cell.

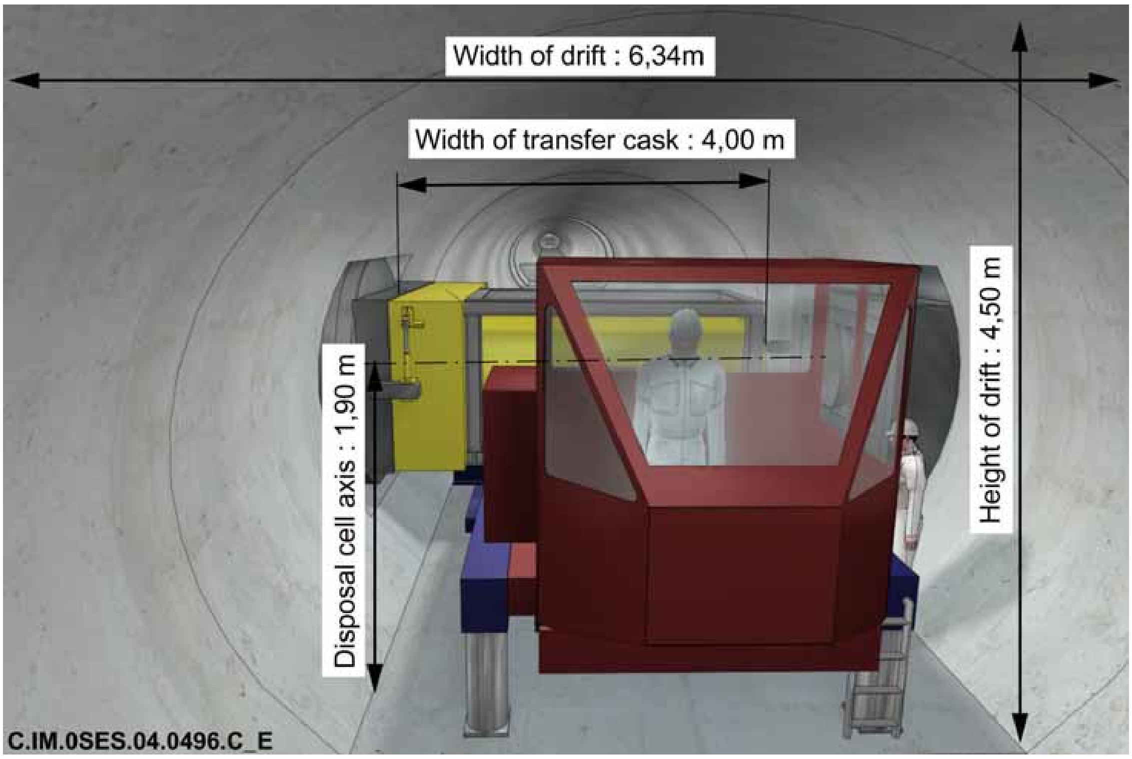

Figure 5.2.16 Docking of C waste transfer cask in front of disposal cell

5.2.4 Arrangement of disposal cells and access drifts in the repository module

5.2.4.1 Module structure

An operating unit is made up of 3 access drifts, perpendicular branch tunnels (called interconnecting drifts) and from 150 to 200 disposal cells (Figure 5.2.17).

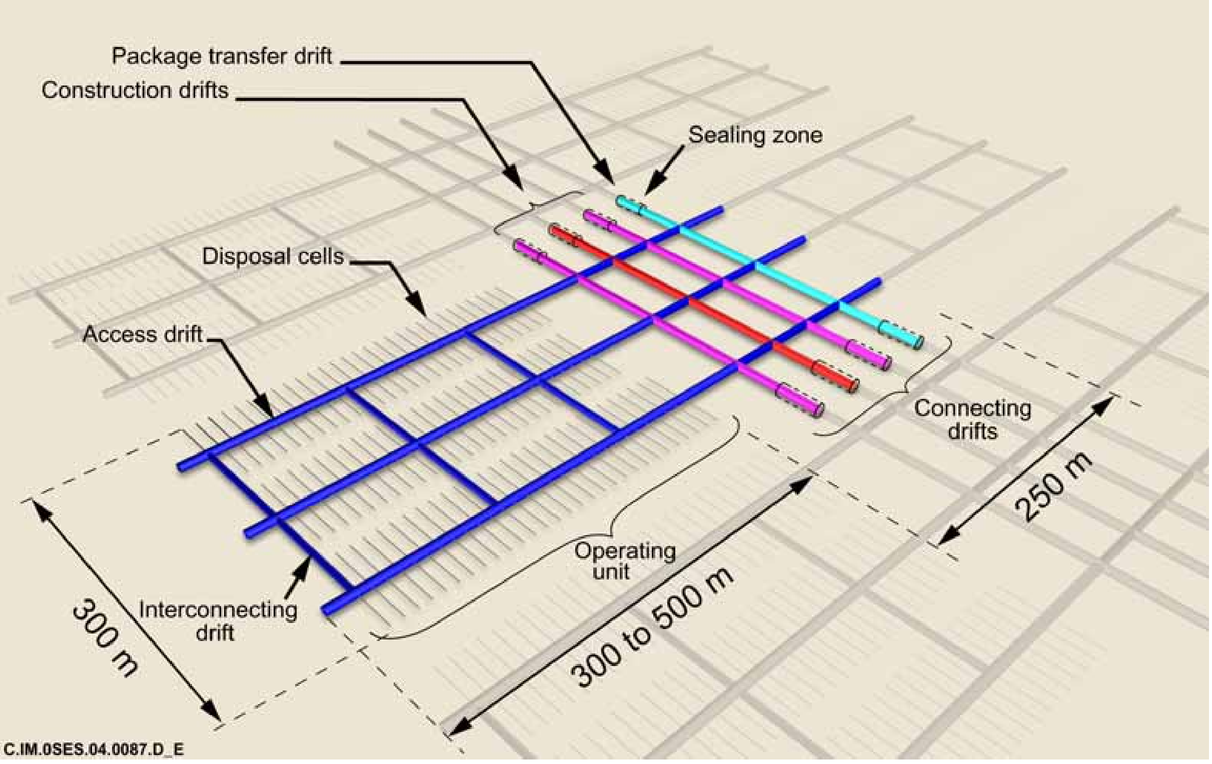

Figure 5.2.17 General layout of a C waste repository module operating unit

The disposal cells are arranged perpendicularly to the access drifts. The length of the access drifts has been limited to approximately 600 m due to operating requirements.

The operating units are distributed on both sides of a network of 4 parallel secondary access drifts (see chapter 7). Upon closure, each module comprising two operating units facing one another is separated from the others by seals so as to divide up the repository zone.

This arrangement allows a favourable orientation of the disposal cells and seals with respect to natural stresses.

The length of the disposal cells is constant. The distance between dead ends is also constant. The centre-to-centre distance between disposal cells and the spacing of packages within a disposal cell vary according to the packages (heat rating). As indicated earlier, the centre-to-centre distance varies from 8.5 to 13.5 m, the spacing between packages varies from 0 to 4 m, and the distance between disposal cell ends is 20 m.

5.2.4.2 Ventilation constraints taken into account.

In the operating phase, in order to eliminate the need for ventilation ducts (and thereby minimise the diameter of the drifts), two access drifts ensure the supply of fresh air in full cross-section whereas the third access drift ensures air return, also in full section (see Figure 5.2.18)

Activity zones are strictly restricted to the two air supply drifts and the interconnecting drifts between them. This arrangement therefore ensures the constant availability of two fresh air inlets. In case of fire, at least one of these two drifts is accessible as an emergency exit and entrance.

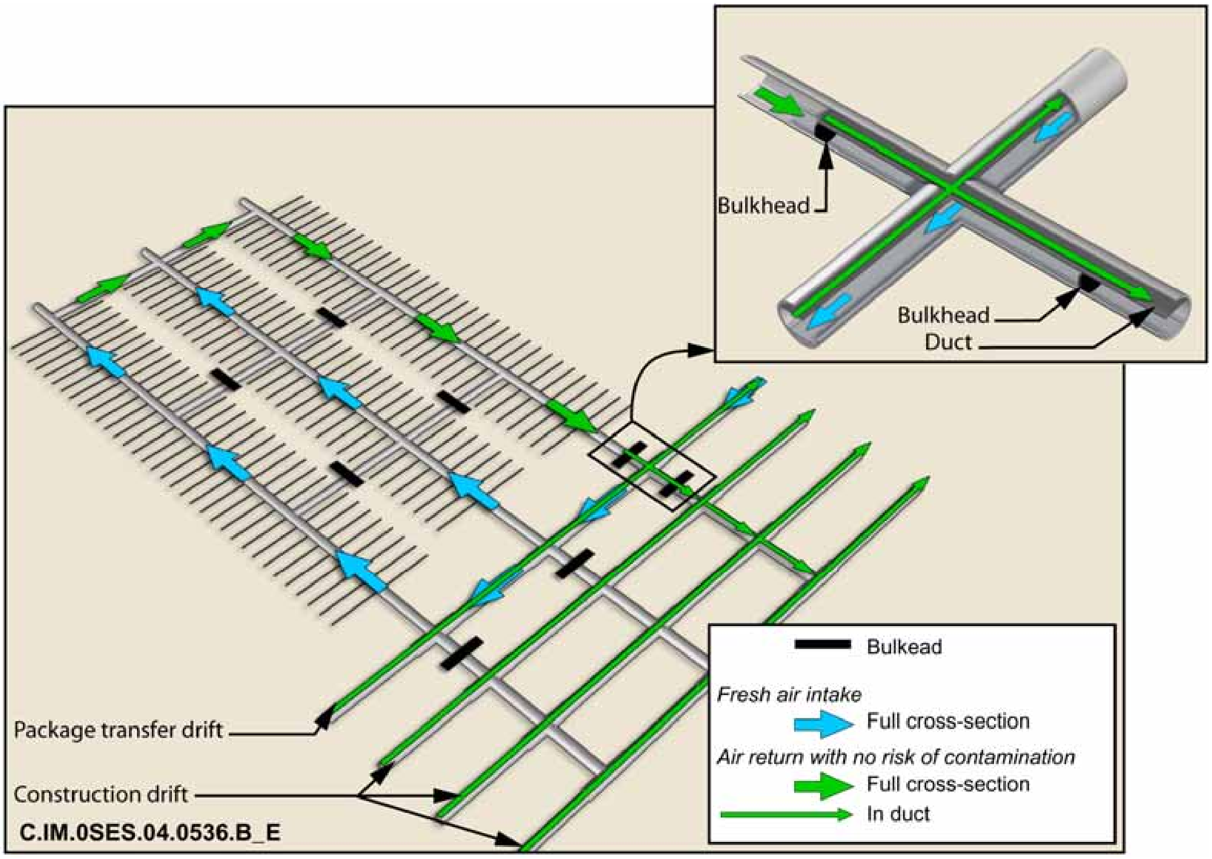

Figure 5.2.18 Ventilation of C waste repository unit in operation

5.2.5 Disposal cell construction

Various proven methods and industrial processes can be considered for disposal cell construction. This section briefly discusses them, with their respective advantages and disadvantages. It then describes one of them in particular, indicating the reasons for it being privileged at this stage of the studies.

5.2.5.1 Various processes considered, each associated with several applicable techniques

The construction of disposal cells is performed in three elementary process steps:

- Excavation
- Installation of the sleeve
- Assembly of sleeve sections

There are numerous industrial references for these processes both in civil engineering (laying of piping or ducting) and the oil industry (drilling and laying pipelines) which use such techniques frequently.

The sequencing of these elementary processes is more or less dependent on or dissociable from the method chosen. For example, the sleeve can be installed during the excavation work or after its completion.

- **Excavation methods (drilling or microtunneling)**

Two methods used in civil engineering, particularly to excavate underground pipelines, can be considered for excavating a horizontal tunnel with a 700 mm diameter:

- Horizontal drilling
- Microtunneling

The term 'drilling' is used here to refer to any technique where the rotation of the boring tool is ensured by a motor remaining in the access drift (on the drill) and where a central drill string transmits the rotation and thrust to the boring tool. Inversely, the microtunneller rotation motor penetrates the excavation and follows the bore path. The thrust is transmitted to the boring tool by a tube generally left in place as a lining.

Drilling techniques seem to offer higher excavation rates than microtunneling (industrial excavation rates, not including tube connection - in the order of 5 m/h, as opposed to 2 m/h for microtunneling).

The microtunneling technique allows better control of trajectory deviations. However, that criterion is not relevant here since the position of the dead end is not very important (one-metre accuracy).

The two methods are considered equivalent in terms of annular space created at the start. They offer the same possibilities for adopting a drive shoe (left in place) or a retractable tool (removed after excavation). The equipment dimensions are comparable.

The drilling method is privileged at this stage due to its greater speed of execution. Microtunneling is nevertheless a completely valid alternative.

- **Sleeve installation (during or after excavation)**

The sleeve can be installed inside the disposal cell and advanced as the excavation progresses. It is also possible to first excavate the entire disposal cell and only install the sleeve afterwards.

The perturbations induced in an excavated terrain generally tend to increase with the length of time during which it is left without support. In this respect, installing the sleeve at the same time as the excavation work will contribute to minimising the instantaneous convergence of the terrain if the initial annular space is sufficiently low.

In addition, this method can only reduce the possible risks of losing the structure due to destabilisation of non-supported walls.

On the other hand, it induces the following constraints:

- technology allowing the boring tool to be withdrawn after completion of the drilling by retracting it into the tube left in place
- a posteriori closure of the tube end
- cleaning the sleeve after installation

Technical solutions are available to satisfy these three requirements.

The insertion of the sleeve during excavation is therefore privileged in the description that follows. However, the solution consisting of installing the sleeve after the drilling work remains a possible alternative.

- **Drilling technique (in-the-hole drill, or rotary drill with carbide teeth)**

Two air drilling techniques allow the boring tool to be retracted into the tube left in place:

- In-the-hole drill with retractable bits [88],
- Rotary drill with carbide teeth and pivotal bits

These two techniques offer similar industrial excavation rates (in the order of 5 m/h, not including tube connection). The in-the-hole drill technique seems to be slightly faster (in situ tests are required to improve the estimates). However, it requires the use of powerful compressors (70 m^3/minute for 1 MPa) and imposes handling the dust at the head of the cell.

This analysis leads to the conclusion that both solutions can be considered for C waste disposal cell construction.

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[88] Disposable drill bit tools are also available, but they are excluded for reasons of cost in favor of pivotal drills, which offer the advantage of complete recovery.

- **Assembly method for sleeve tube components**

The sleeve components can be connected using various techniques:

- Automatic welding of tubes with similar dimensions. This technique is well proven (pipeline laying) but it is the longest to implement in the case of C waste disposal cells.
- Threaded connections enable quick implementation. However, fewer references are available for this technique and its cost is higher.
- Connections via mechanical locking are particularly adapted to site conditions (fast implementation, rotation equipment of no use).

At this stage, the automatic welding solution seems interesting since it benefits from a very large amount of experience feedback.

5.2.5.2 Description of complete construction solution

Taking into account the preceding sections, the following is a construction solution [65] (See Figure 5.2.19) :

- The disposal cell is drilled using a tool followed by a tube that supports the terrain and is left in place to constitute the sleeve.
- The sleeve components are pushed by a tube pusher installed on the drill. They are progressively welded together upon their insertion. The drill – tube pusher assembly rests on the thrust frame secured in the access drift. The sleeve is pushed without rotating inside the terrain.
- The peripheral bits are retractable. Set in spaced position for the drilling, they give the excavation a diameter slightly exceeding that of the sleeve. They are retracted at the end of the drilling so as to withdraw the tool inside the sleeve.
- The bottom of the sleeve is then sealed by welding a plate on it.

These various phases and the associated equipment are described below.

Upon completion of these operations, the head of the disposal cell is fitted with the equipment required for its operation (shielded trap door).

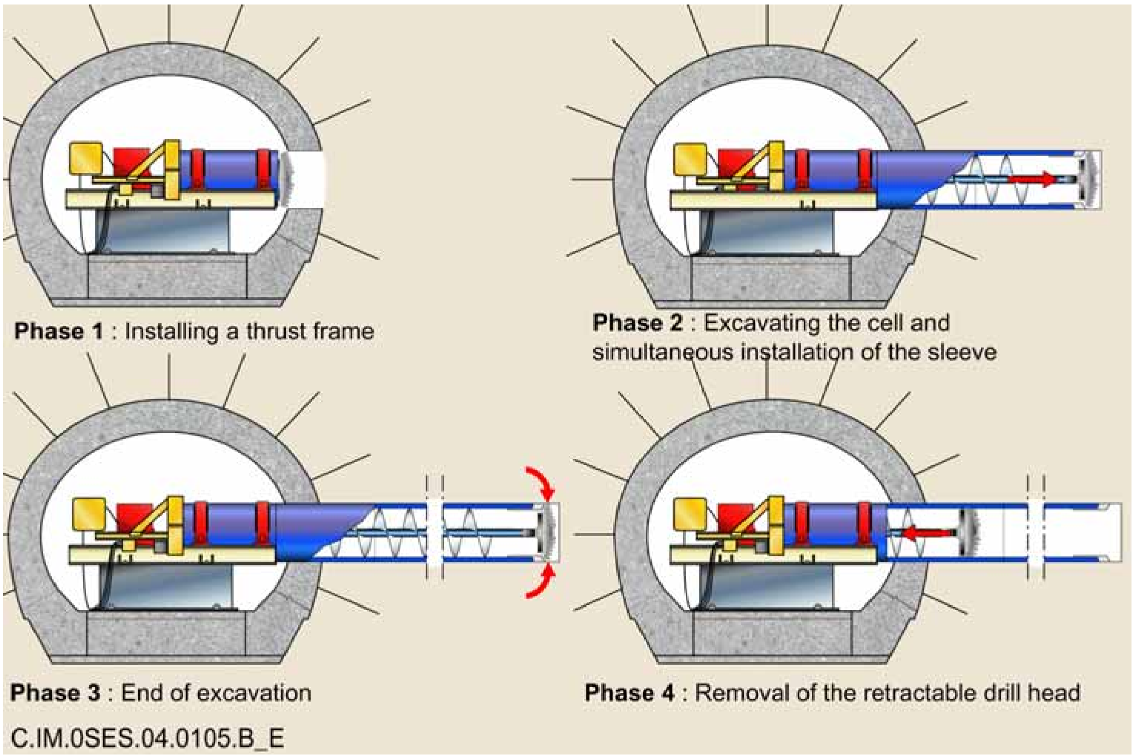

Figure 5.2.19 C waste disposal cell excavation sequence

- **Thrust frame**

The thrust frame is anchored to the drift lining. Its length inside the drift is approximately 5 m (compatible with 2.5 m long sleeve components).

- **Boring tool and drill string**

The boring tool proposed is equipped with carbide teeth.The three peripheral bits are pivotal and can be retracted at the end of the drilling (see Figure 5.2.20)

The thrust and rotation of the boring tool are transmitted by a drill string. It seems preferable to equip the drill string with a helicoidal screw ensuring centring and broken rocks removal. Other broken rocks removal solution can also be considered. A drive shoe installed at the end of the sleeve and left in place enables allows for bore finishing operations.

The head excavation diameter is adjustable and can be set according to the penetrability of the sleeve and the quality of the boring. The manufacturers recommend accommodating a centimetric radius annular space between the sleeve and the terrain. This annular space can be obtained with the drive shoe or through adjustment of the drill bits (to be optimised via in situ tests).

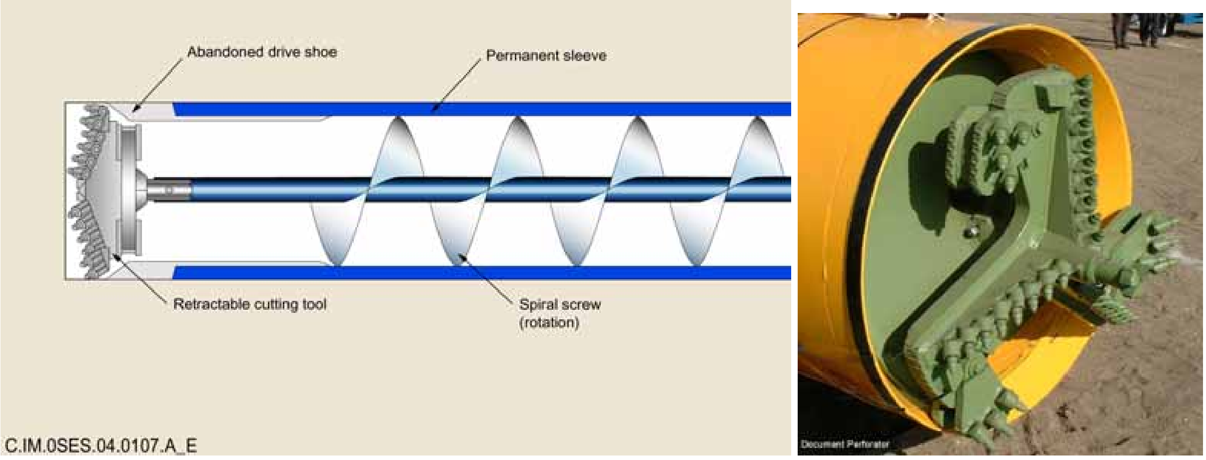

Figure 5.2.20 Tool used for C waste disposal cell excavation

- **Installation of sleeve tubes (permanent and temporary parts)**

The standard sleeve components are positioned at the end of the tube already engaged, and they are welded immediately before their insertion in the disposal cell (MIG or MAG welding, for example).

The temporary sleeve tube components can be connected via mechanical locking, allowing faster installation and subsequent recovery upon closure of the disposal cell.

The temporary sleeve is connected to the permanent sleeve via a remotely removable shank (simple shrink-on or bayonet fixing).

- **Welding of the sleeve bottom sealing plate and cleaning**

After withdrawing the boring tool, a metal plate is welded on the bottom of the sleeve. This operation is performed with a welding robot of similar design to those used in the petroleum industry (see Figure 5.2.21).

Figure 5.2.21 Welding robot used for welding inside the sleeve (photograph courtesy of Air Liquide)

- **Assessment of basic solution**

The total execution time for the disposal cell using the drilling method is estimated at seven 8-hour shifts (total of 56 hours) broken down as follows:

- thrust bench installation and removal: 5 shifts
- disposal cell excavation, not including tube connection: 1 shift (40 m at 5 m/h)
- miscellaneous (tube connection, cleaning, etc.): 1 shift

5.2.5.3 Alternative solution: Microtunneling and thrust tubes left in place

In this alternative solution, the head of the hydraulic motor driven microtunneller is pushed using the sleeve. Specific characteristics:

- The tool is a retractable full-face boring wheel. Rotation is ensured by a hydraulic motor anchored to the front end of the sleeve via lateral cylinders.Figure 5.2.22 shows industrial equipment used in civil engineering;
- The pivoting wheel solution is preferred to the solution consisting of abandoning the boring wheel periphery in the terrain (cleaner and more economic).
- Broken rocks removal preferably performed using an endless screw.

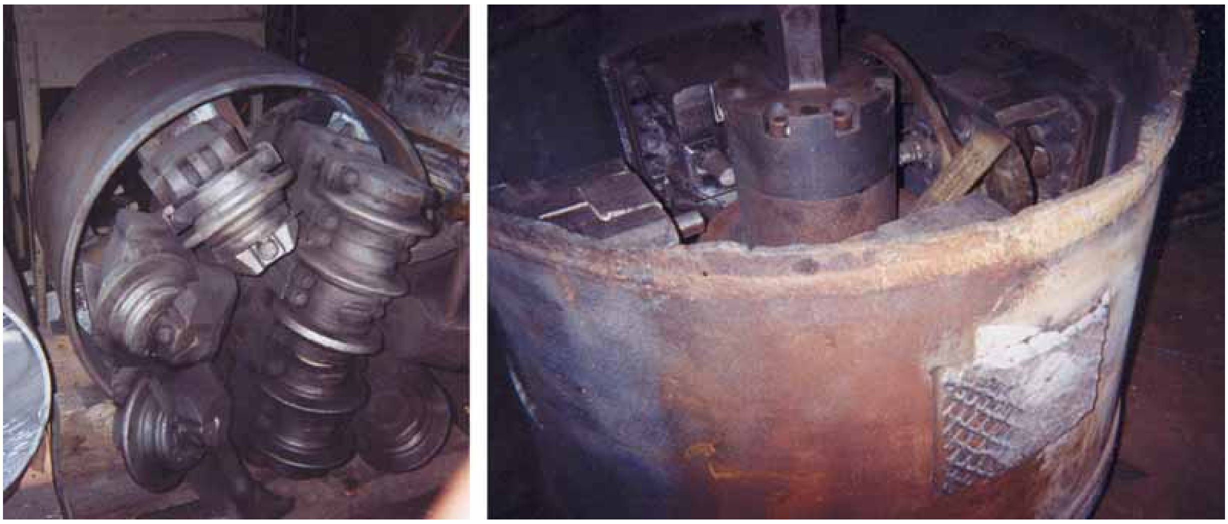

Figure 5.2.22 Microtunneller head (photographs courtesy of CREATIV ALLIANCE and ROBBINS Equipment)

The total execution time for the disposal cell using the microtunneling method is estimated at nine 8-hour shifts (total of 72 hours) broken down as follows:

- Thrust bench installation and removal: 5 shifts
- Disposal cell excavation, not including tube connection: 3 shifts (40 m at 2 m/h)
- Miscellaneous (tube connection, cleaning, etc.): 1 shift

5.2.6 Disposal cell closure

The disposal cell is closed by a plug that ensures a hydraulic barrier function. A system is also implemented to ensure the radiological protection of personnel in the access drift.

This section first discusses the various components intended to perform these functions and then describes each of them in particular, indicating their respective design and implementation.

5.2.6.1 Principles of C waste disposal cell closure design

In order to minimise the transport of dissolved components, a low-permeability continuum must be reconstituted around the packages. This continuum is materialised by the geological argillite formation and the swelling clay-based plug.

To achieve optimal hydraulic closure of the disposal cell, the plug must have the lowest possible permeability value. Three components are involved: the argillite contact aureole (potentially damaged) facing the plug, the swelling clay-based plug, and the interface between the plug and the argillite. The design is intended to obtain the optimal hydraulic properties of each of these three components.

In order to preserve the low permeability of the argillite around the disposal cells, damage must be minimised and fracturing avoided. Several design measures have been defined for this purpose, as indicated above (orientation, excavation and support methods, plug location outside the damaged zone of the access drift). The damage expected under these conditions has been indicated in section 5.2.3.5. The permeability of the microfissured argillite aureole around the structures is estimated at approximately $5\ 10^{-11}$ m/s [13]. If the argillite rests on a body that limits its displacement, the creep phenomenon can further contribute to microfissuring, thereby reducing permeability.

The permeability that can be obtained for the plug is lower than or at most equal to that of the microfissured argillite. A low transmissivity is obtained for the interface due to plug material deformation and the swelling pressure developed on the excavation wall. These factors have been confirmed in real scale by the TSX test [67]. This test has shown an equivalent permeability of 10^{11} m/s with a material consisting of Kunigel swelling clay and sand (20%). Andra is considering MX80 type clay with lower permeability (see section 7.6). In the argillite, the swelling pressure exerted by the plug after resaturation is susceptible of closing the possible fractures.

The measures previously indicated allow for obtaining an equivalent permeability lower than that of the microfissured argillite. In the current state of knowledge, this corresponds to approximately 10^{-11} m/s. An evolution towards a lower value (close to 10^{-12} m/s) is probable with the creep phenomenon, bringing the equivalent permeability of the disposal cell seal to a value approaching 10^{-12} m/s.

5.2.6.2 Description of closed disposal cell

The description that follows covers the following three components (in order of installation): metal plug, clay plug and support structure. It specifies their design with respect to the functions to be ensured.

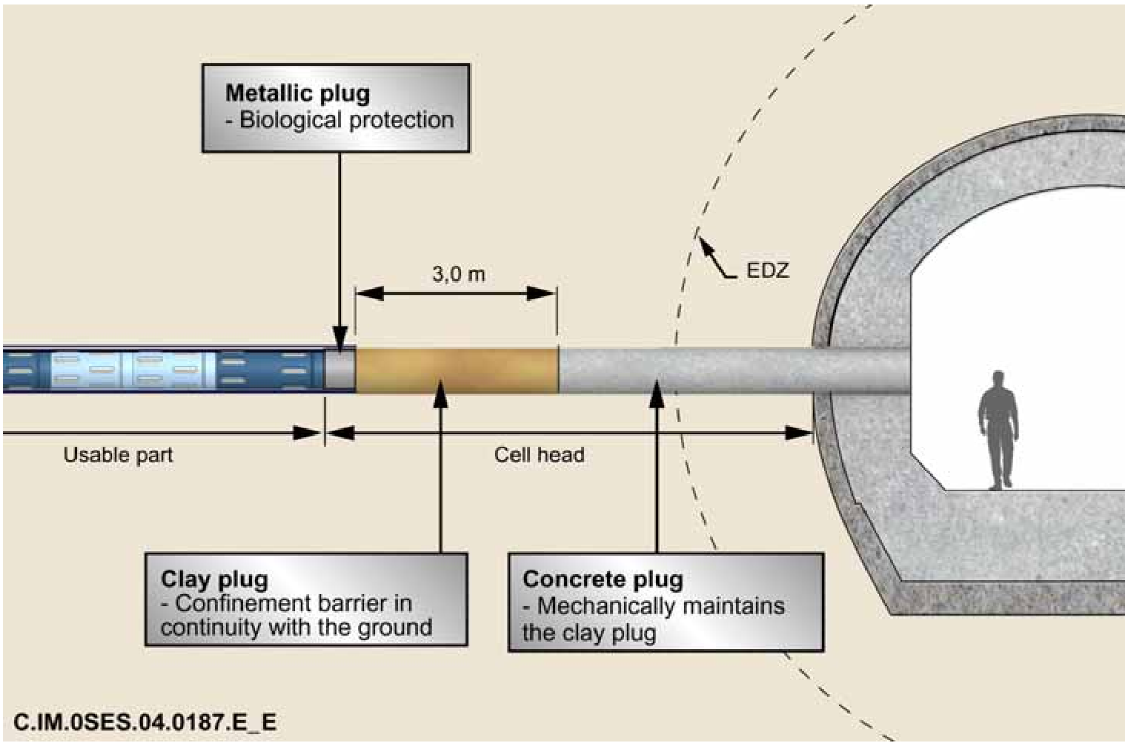

Figure 5.2.23 Design principle for C waste disposal cell plugs

- **Metal plug**

The metal plug is intended to ensure radiological protection during disposal cell sealing operations, thereby eliminating the need to use the protection transfer cask during the installation of the swelling clay (hence possible with simple and reliable non-nuclear methods).

Predesign calculations have been performed to limit the dose rate in the access drift to less than 3 µSv/h. The metal plug (see Figure 5.2.24) can consist of a steel cylinder approximately 50 cm long (two thirds devoted to radiological protection and one third adapted for gripping by handling tools), possibly covered with ceramic to prevent adhesion to the sleeve (under the effect of corrosion).

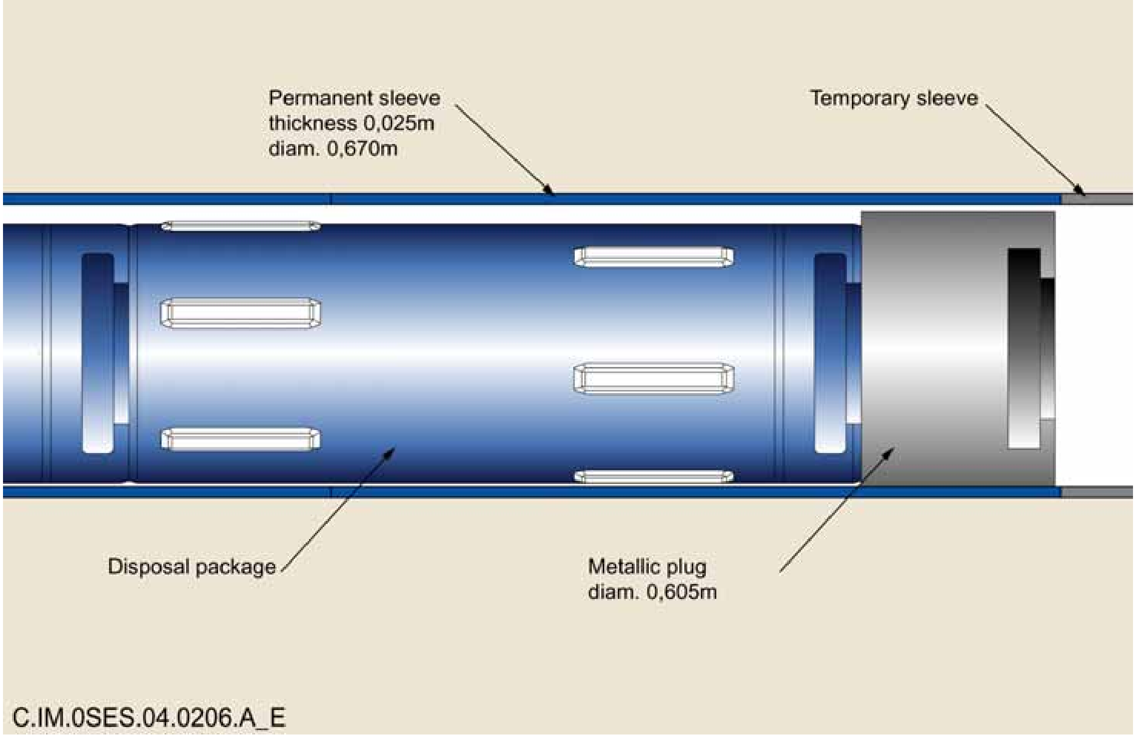

Figure 5.2.24 Metal plug for C waste disposal cell

- **Swelling clay plug**

In order to ensure its hydraulic function, the material must have low permeability and good deformability. These properties do not require high swelling pressures. Moderate pressures are sought (a few MPa) to limit the mechanical load applied on the supports.

The various design choices made with respect to swelling pressure, swelling clay type, mixture composition and associated dimensioning are specified below.

- **Swelling pressure**

Swelling pressure refers to the effective pressure exerted by the hydrated clay laminations[89].

The swelling pressure must be comprised between 1 and 13 MPa (or lower, if possible, for the reasons explained below).

The low value (1 MPa) provides a reserve of swelling capacity ensuring impermeability to contact with the argillite. It covers the uncertainties regarding the relaxation of the clay (following the degradation of the retaining plug) and the at least partial transfer of mechanical confinement stresses from the clay plug to the access drift backfill.

The high value (13 MPa) corresponds to the tensile rupture of the argillite on the excavation wall (cancellation of its effective tangential stress). It is therefore an imperative limit. A value below 7 MPa is looked for, as this will be the ultimate value obtained in equilibrium with the site’s radial geostatic stresses at a depth of 500 m (a total stress of 12 MPa due to the weight of the soils, minus 5 MPa of interstitial pressure, resulting in an effective stress of 7 MPa); it is therefore pointless to attempt to develop higher swelling pressures, as they will only produce unnecessary stress on the supports before returning to 7 MPa. An even lower pressure is in fact preferable, provided that the minimum pressure of 1 MPa after relaxation is guaranteed.

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[89] The effective pressure is the total pressure less the pressure exerted by free water

The evolution of the swelling pressure with time may be summarised as follows (Figure 5.2.25): The clay (or mixture) is installed with its retaining plug. The resaturation of the clay plug by the interstitial waters of the surrounding argillite induces a swelling pressure attaining a first maximum level. Eventually, a degradation of the support materials may induce a certain relaxation. The most penalising scenario has been considered in this respect: a piston-like displacement of the retaining plug on the liner intrados, which occurs because the force of the swelling clay exceeds the reaction of the backfill. The swelling pressure then decreases due to expansion and the reaction of the backfill increases until a state of equilibrium corresponding to a minimum pressure is reached. Finally, the argillite creep sets the entire system at a second maximum level equal to the effective geostatic stress (7 MPa).

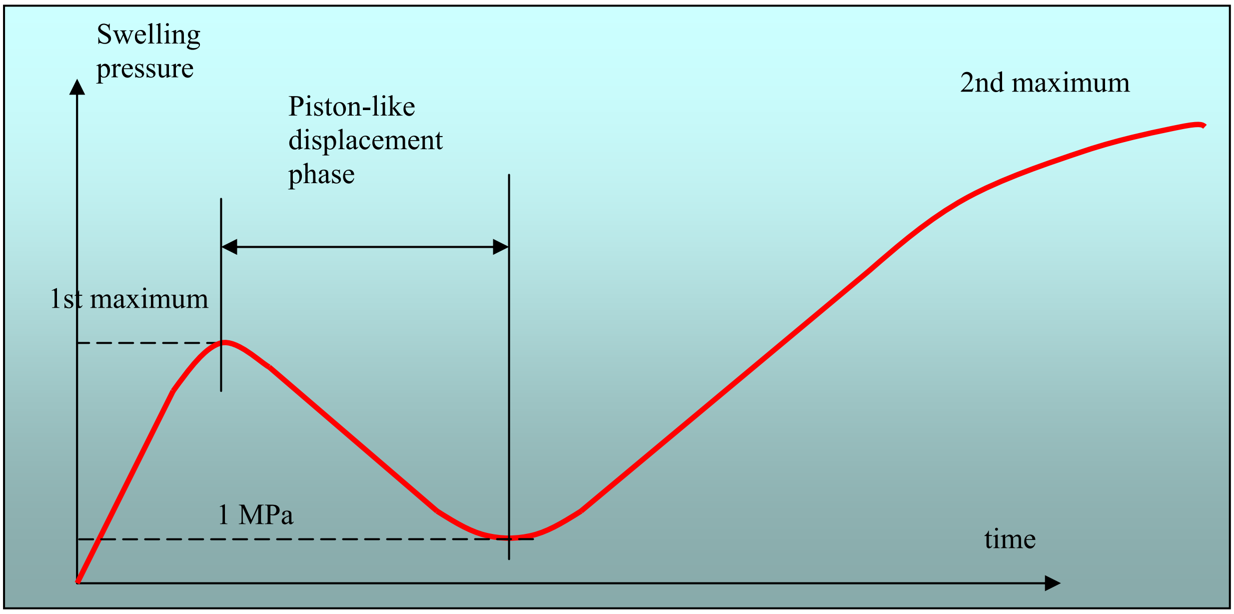


Figure 5.2.25 Evolution of the swelling pressure in the swelling clay plug

- **Choice of clay type and mixture composition**

The deformability of the swelling clays available is high from an industrial point of view and remains high for clay and sand mixtures as long as the sand does not form a continuous skeleton (which limits its proportion to approximately 50%).

The swelling pressure of a swelling clay-based material depends on the type of clay chosen, the composition of the mixture (proportion of non-swelling granular material), the dry density of the clay and its water content.

The swelling clay currently selected is of MX80 type or equivalent (low hydraulic conductivity at low dry density).

The relationship between dry density, water content and swelling pressure constitutes the design basis for the swelling pressure of the clay plug described below.

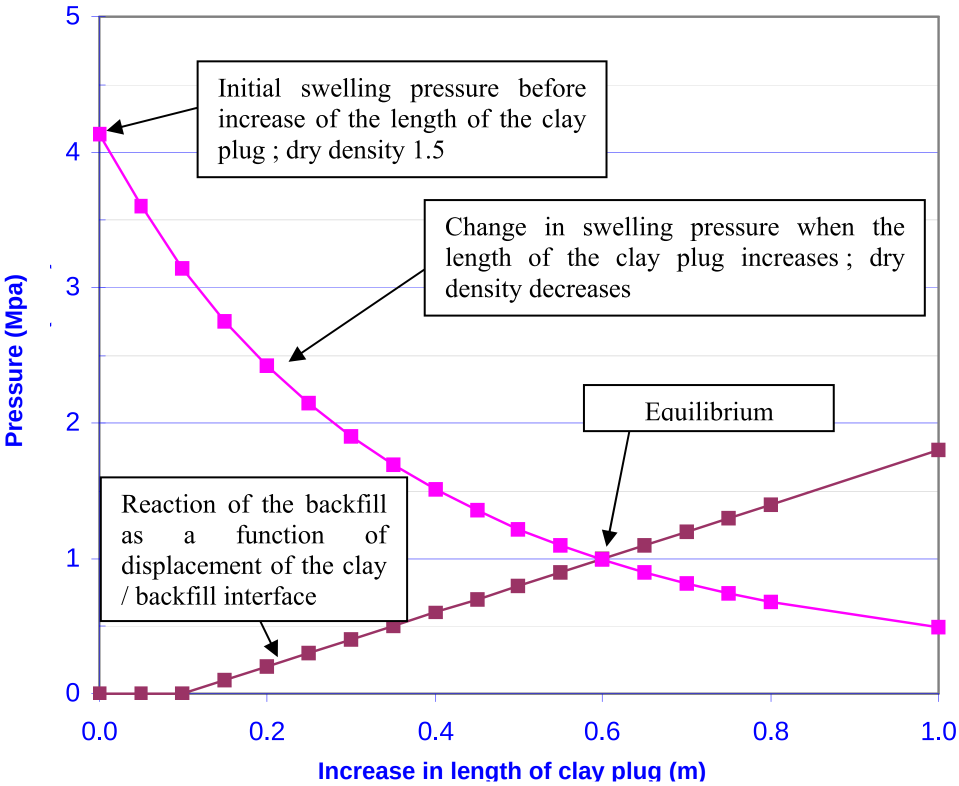
- **Mechanical dimensioning of clay plug**

A length of approximately 3 m for the clay plug ensures the protection of the disposal cell with respect to alkaline perturbation (Ph). The dimensioning calculations described below confirm that this length is sufficient with respect to the possible relaxation of the swelling pressure and the possible long-term effects of alkaline perturbation.

As indicated earlier, the swelling pressure sought lies between a minimum value of 1 MPa and a maximum (initial) value of 7 MPa. For the permeability of the clay plug (or core), the range of values sought is in the order of 10^{-12} to 10^{-11} m/s.

The calculation method is illustrated based on the example of MX80 swelling clay, without taking into account the effect of the sand (simplified approach).

The maximum swelling pressure is determined in Figure5.2.26. One of the curves shows the evolution of the clay swelling pressure during degradation of the retaining plug (as the clay core swells, it increases its length by pushing the degraded concrete and backfill constituting the support). The other curve shows the reaction of the backfill, which increases as the backfill settles. Mechanical equilibrium is attained where the two curves intersect. The curve representing the swelling pressure is adjusted based on the initial dry density so as to obtain an equilibrium point at 1 MPa. Pessimistic hypotheses have been taken into account regarding the deformability of the degraded concrete and the access drift backfill. Equilibrium with the backfill is obtained for an initial swelling pressure (prior to concrete degradation) in the order of 4.5 MPa (4.1 MPa in the figure), corresponding to an initial dry density of approximately 1.5.



Equilibrium between swelling pressure of the clay plug and reaction of backfill (degraded concrete), assuming a 0.1 m displacement before reaction of backfill and a stiffness of 0.5 m/Mpa (MX80 type clay, sand not taken into account)

Figure5.2.26 *Equilibrium between the swelling force of the clay plug and the reaction of the backfill*

A similar calculation for a mixture with a sand content of 30% yields an initial dry density [90] of approximately 1.7 [65].

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[90] Initial dry density target values for swelling clay compacted in situ (according the hypothesis currently considered for plug construction). If prefabricated swelling clay components are used, the initial dry density will need to be higher so as to compensate the presence of the cavities installed.

The lowest dry density attained during the evolution of the materials is approximately 1.4. The experimental results available confirm that MX80 clay has a permeability of less than 10^{-12} m/s for such a density, even when mixed with 30% sand. This preliminary design of the swelling clay plug therefore satisfies those requirements.

- **Concrete retaining plug**

The function of the concrete retaining plug is to oppose the deformation of the swelling clay core. During the development of swelling pressure (core resaturation), the concrete plug offers the core a simple geometry favouring homogeneous evolution (deformation and permeability). During this transitory phase, the concrete plug also slows down possible water ingress susceptible of creating gutters in the swelling clay prior to swelling. During this phase, it rests on the terrain (friction contact) and on the access drift lining [91]

In the long term, the material could be subject to chemical degradation, which will decrease its mechanical properties. The retaining plug will nevertheless remain a link between the swelling clay plug and the access drift backfill, still contributing to the mechanical confinement of the swelling clay and to the preservation of low hydraulic conductivities.

5.2.6.3 Constructive provisions for closing a repository module

Closing a type C waste repository module involves five stages: (i) fitting of the metal radiological protection plug in each cell, (ii) removing of the temporary sleeve, (iii) fitting of the swelling clay plug, (iv) fitting of the retaining plug and (v) back-filling of the access drifts. These various stages are described below.

- **Fitting of the metal radiological protection plug**

The metal plug is fitted using the same equipment as that used to place the disposal package in the cell (see Chapter 9). This operation may be carried out after putting the last package in place.

- **Removing the temporary sleeve**

When the decision to close the cell has been taken, the removal of the temporary sleeve makes it possible to obtain direct contact between the swelling clay plug and the rock[92]. A certain number of precautions have to be taken in order to avoid damaging the argilite in the sealing zone.

In particular, in principle it is preferable not to leave the ground physically unsupported during this operation: it is therefore envisaged that the swelling clay core will be placed in position as the sleeve is being withdrawn, or very soon afterwards. Additionally, in order to give immediate support, the swelling clay must be placed in contact with the ground: the in-situ compacting of clay pellets or a mixture of pellets and powder is therefore now preferred to the fitting of prefabricated blocks which require clearances.

As far as radiological protection is concerned, the metal plug provides it in the cell axis and as for oblique radiation, it is stopped by the argilite in the future sealing zone.

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[91] The preliminary design of the concrete plug neglects friction on the terrain, with the entire load transferred by the drift lining. This predesign is based on a swelling clay pressure of approximately 4 MPa. In order to integrate the friction in the argillite within the scope of more complete design calculations for higher loads, the length of the concrete plug has been temporarily fixed at 1 access drift radius. It is recalled that the swelling clay plug must be positioned outside the damaged zone, i.e., at a minimum distance corresponding to half the access drift radius.

[92] The temporary sleeve may be removed a long time after the metal plug is fitted. If that is the case, a sealing cap is fitted to prevent oxygen renewal inside the cell.

- **Fitting of the swelling clay plug**

As indicated above, the preferred method is compacting in situ in order to provide immediate contact between the ground and the swelling clay core.

The clay is produced by mixing pellets of various sizes which improves compacting. Initial positioning is carried out, for example, by pneumatic means or using an Archimedes screw. Dry densities greater than 1.4 can be achieved by such methods without compacting. A piston can complete the compacting process if greater densities are required (see Figure 5.2.27).

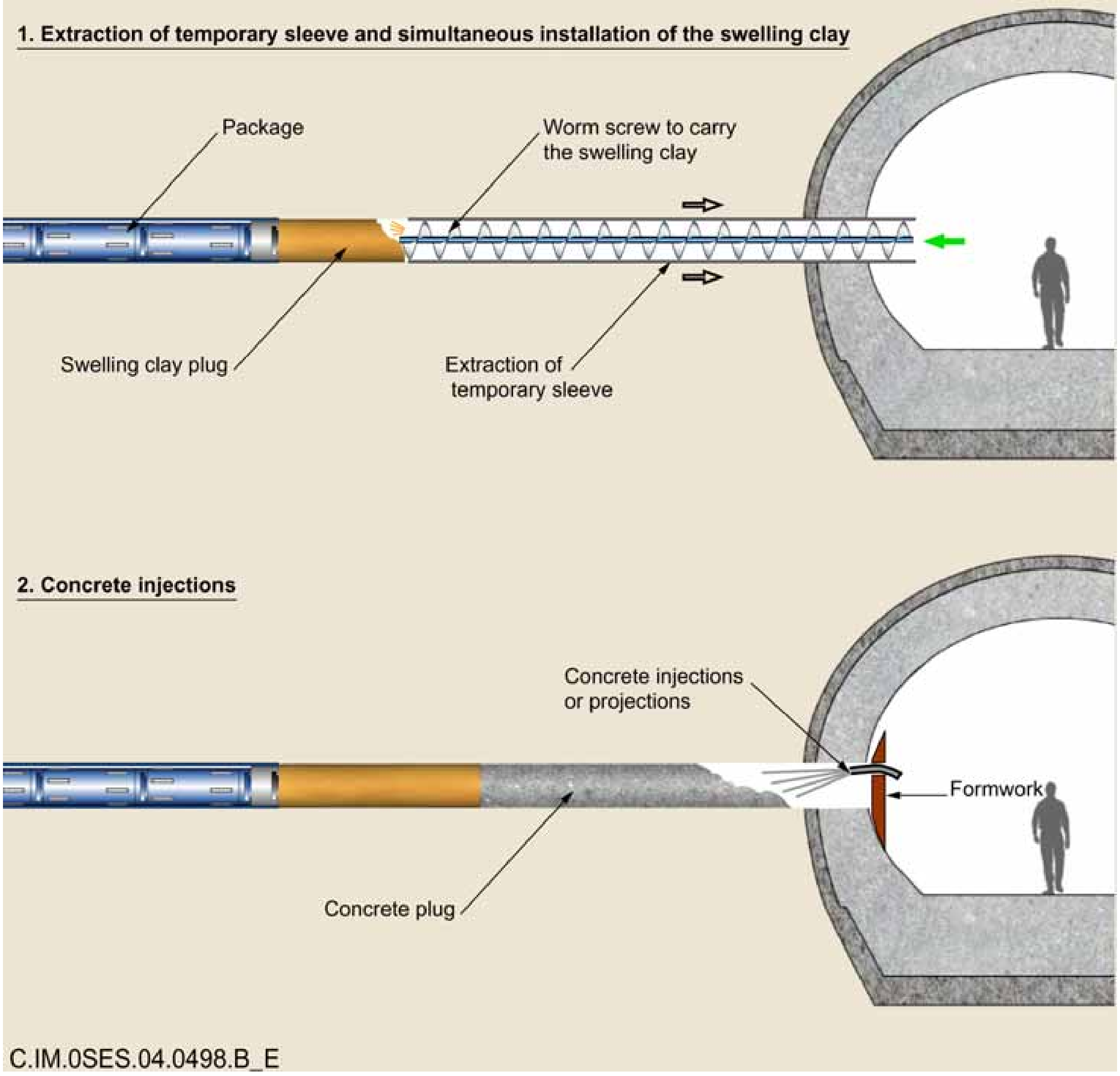

Figure 5.2.27 Procedure for removing the sleeve and simultaneously fitting the swelling clay plug (type C cell)

- **Fitting the retaining plug**

The final stage of closing a cell, the fitting of the concrete plug, can be carried out by pouring behind vertical workform fitted with a vent. It can also be carried out using shotcrete; this second solution is currently the subject of a demonstration programme as part of the European ESDRED (Engineering Studies and Demonstration of Repository Design) project.

- **Back-filling the access drift**

When all the cells of a repository module have been closed, the decision may be taken to back-fill the access drifts (see Chapter 10). Back-filling the drifts fulfils the same basic function of all back-filling: to limit in the long term the extent of the damaged argilite zone around the drift. As previously indicated, it must also be able to fulfil a support back-fill role at the cell location, i.e. resist the movement of cell retaining plug in the event of their deterioration.

This latter function justifies carrying out this back-filling in the same way as drift sealing support back-fills (see section 7.6). The back-fill can consist of a mixture of prepared excavated argilite (re-ground and screened to approximately 20 mm) and sand, in similar proportions. At the bottom of the drift it can be placed in compacted horizontal layers (20 to 30 cm thick); at the top it is placed in sloping layers; for the latter, it is intended to compact the mixture using a pneumatic tamper. Pneumatic injection of powdered bentonite can be used in order to improve the concreting joints. Using these methods, it is possible to obtain a mean dry density in-situ of around 1.7; this figure is compatible with the target characteristics (deformation modulus of 20 MPa and an internal friction angle of 40°).

Initially, the entire access drift could be back-filled in this way. Back-filling demonstration trials currently in progress may open the way to improvements: alternating several metres of support back-filling at the cell location and standard back-filling (without sand).

5.3 Spent fuel repository modules

Spent fuel is not currently considered as waste. The possibility of one day placing it in a repository in a deep geological formation has nevertheless been examined. The feasibility of such disposal is thus assessed with respect to various scenarios considered for downstream management of the electro-nuclear cycle.

This chapter describes spent fuel disposal cells, their equipment and their layout with respect to each other. The main design options are examined by comparison with those of type C waste cells. For type CU1 and CU2 spent fuels, whose heat rating is high, and for which the temperature decrease is slow, the reference solution is a cell with a swelling clay-based engineered barrier; the description below concentrates on this solution. Type CU3 spent fuels have a lower heat rating. Separate management of these fuels allows more freedom for finding the best individual solutions. Given their low heat rating, it would be possible to dispose type CU3 spent fuels in cells similar to those described above for type C0 waste.

5.3.1 Presentation of main questions

Spent fuel modules must accommodate various types of package in distinct zones. This type of separation makes it possible to take account of their individual thermal behaviours.

The dimensioning requirements are generally similar to those of type C waste. In particular, they concern the management of heat given off and the limiting of transport possibilities in the immediate vicinity of the fuel. This latter point is aimed at reducing the dissolving of fuel pellets by checking the solubility of their components.

For type CU1 and CU2 packages, another question is the particularly large weight and dimensions of the packages (which impose handling constraints).

Finally, the spent fuel poses a problem of criticality control due to the fissile material content. Sub-critical conditions are ensured by the design of the disposal packages (see Chapter 4).

5.3.1.1 Heat release management

Fission products and actinides are the sources of the heat released from spent fuel packages. This release decreases as a function of the half-life of the radioactive nuclides. The presence of a large quantity of actinides may induce a slower temperature decrease than for type C waste (as in the case of type CU1 and CU2 packages). On the other hand, type CU3 spent fuels have a level more akin to that of medium heat generating type C0s. Such considerations lead to the disposal of the different types of spent fuel in separate zones.

Two thermal criteria must be observed, as for type C waste:

- the first criterion consists of maintaining a temperature of under 100°C in the cell (the cell thus remains in a domain in which the combined thermal, hydro, mechanical and chemical phenomena are known and understood). As for type C cells, and for the same reasons concerning the management of modelling uncertainties, this criterion results in the requirement to ensure that the clay wall temperature does not exceed 90 C. This criterion, localised to argilite walls in the case of type C waste cells, applies to the interior wall of the clay engineered barrier in the case of spent fuel cells.
- the second criterion is aimed at preventing significant mineralogical changes in the argilite and, in particular, in the swelling clay of the engineered barrier, which would reduce its ability to swell (transformation of the swelling smectites into non-swelling illites). As for type C waste cells, a check is made to ensure that the temperature drops back below 70°C after around a thousand years.

5.3.1.2 A favourable physico-chemical environment for the packages

The immediate environment of the packages should form a diffusive hydraulic barrier (homogeneous materials with low permeability and with a diffusion coefficient that is as low as possible), so that the cell functions as a closed chemical system. This situation provides a chemical balance between the package's components (envelopes and ceramic pellets forming the fuel) and the water in contact with them. It makes it possible to limit the alteration of the packages and assemblies.

The pH must be maintained in the range 6-9, the range in which the pellet dissolution model is valid.

These properties are provided jointly by the swelling clay engineered barrier and the surrounding argilite (reference solution for type CU1 and CU2 cells) or by the argilite protected from damage, for cells without a clay engineered barrier (CU3).

5.3.2 Design principles used

The key parameters used are the same as for type C waste. The cells in a dead end configuration (to control water circulation), with a single row of packages in each section (to dissipate the heat released by the packages); they are placed in a middle section of the formation (to preserve undisturbed argilite thickness).

The main design questions concern the orientation of the cells (horizontal or vertical), the presence or otherwise of an swelling clay buffer, its fitting (integrated into the package or separate from it), the choice of cross-section (as near as possible to the package or providing handling room or ventilation space) and the choice of materials (concrete or steel for linings; concrete or swelling clay for the engineered barrier).

5.3.2.1 Several possible solutions

The various solutions envisaged are summarized in the illustrations below (Figure 5.3.1 to Figure 5.3.3).

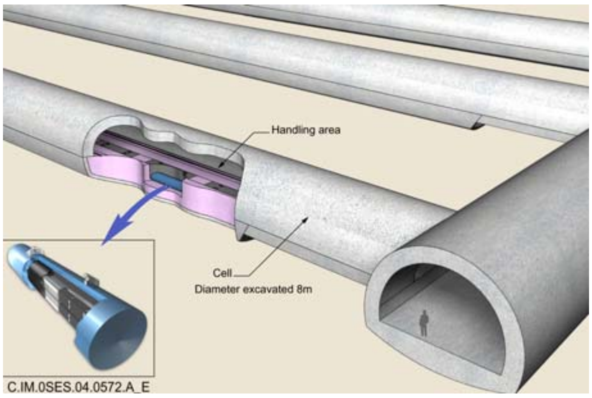

Figure 5.3.1 “Repository drift” concept

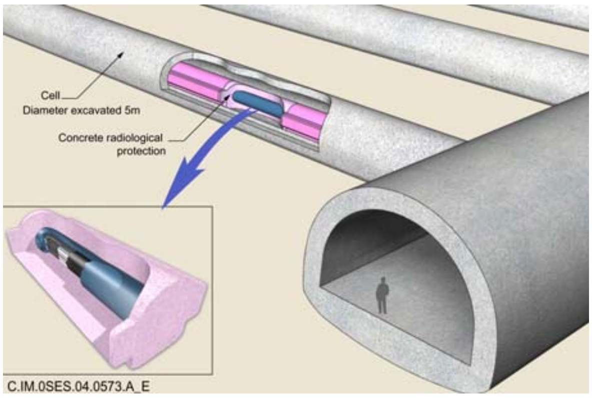

Figure 5.3.2 “Drift over-pack”concept

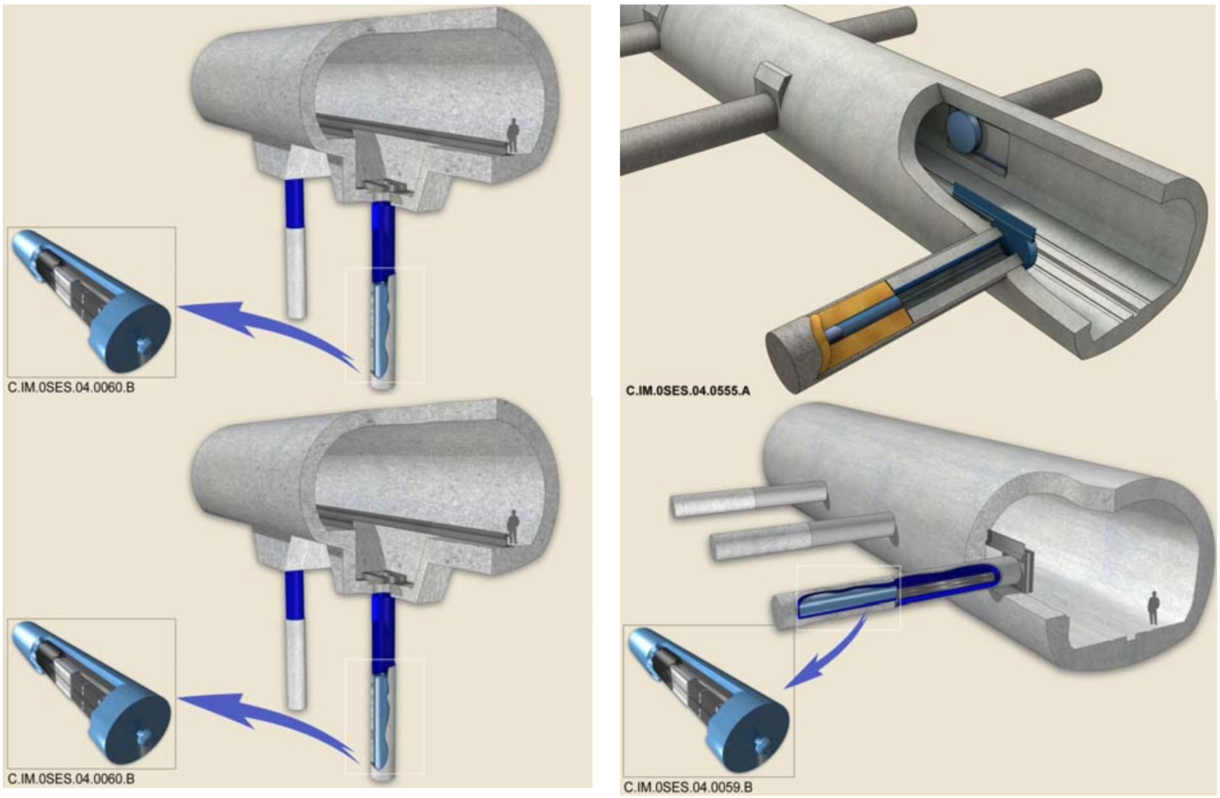

Figure 5.3.3 Shaft and short tunnel concepts for spent fuels

5.3.2.2 Comparison of possible solutions and justification of choice

- **Comparison with or without swelling clay buffer**

Following the deterioration of the spent fuel container, the control of the release of radioactive nuclides essentially depends on the existence of a diffusive barrier around the package and on the physico-chemical characteristics of the components of the spent fuel (uranium oxide pellets and structures). Furthermore, when compared with type C waste, the decrease in thermal activity of spent fuel is slower due to actinides present in large quantities. In order to guard against thermo-hydro-mechanical (THM) effects on the argilites over periods in excess of 1 000 years, it has been considered preferable to resort to the use of a clay engineered barrier[93]. This provides resistance to possible damage associated with these long-term THM effects Its plasticity allows it to repair its own fissuring. Studies have in fact shown that, after a thermal phase, it regains its plasticity, swelling properties and low permeability.

- **Comparison between "horizontal" and "vertical" cells**

As for type C waste, a comparison between the horizontal and vertical configurations has led to preference being given to the horizontal configuration. It offers the possibility of optimising thermal dimensioning and reducing the excavated volume.

- **Comparison between "disposal cells" and "disposal drifts"**

The "disposal cell" option consists of selecting a diameter appropriate to that of the disposal package; the "disposal drift" option has additional space for handling and ventilation. As for type C waste, the disposal cell is the preferred option. The disposal drift is in fact penalised by the requirement for a significantly larger excavated volume. Furthermore, the capability to ventilate that it offers is valid only during the operational phase but not for the post-closing phase (the package heat dissipation therein is purely passive in nature). Finally, it should be noted that the use of concrete in the vicinity of spent fuels does not appear favourable at this stage (alkaline pH, risk of increasing the long-term permeability).

5.3.2.3 The solution adopted

The spent fuel disposal cell has a number of similar features to that of the type C waste cell. The main difference is the presence of an swelling clay buffer which leads to its diameter being increased (to approximately 3.3 m for type CU1 waste and to approximately 2.6 m for type CU2).

As for waste cells, spacers are used to space the packages for improved heat distribution within the rock.

The various components of the spent fuel cell and their associated functions are illustrated in the diagram at Figure 5.3.4 and Table 5.3.1.

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[93] It has been decided not to use concrete as the engineered barrier material for two reasons: its permeability and the alkaline pH that it induces Its permeability cannot be reduced to that of swelling clay and cannot be maintained at its initial level due to the deterioration of the material (of chemical or thermal origin). The concrete gives its immediate vicinity an alkaline pH; it would be outside the validity range of the spent fuel dissolving model currently available (pH 6 to 12).

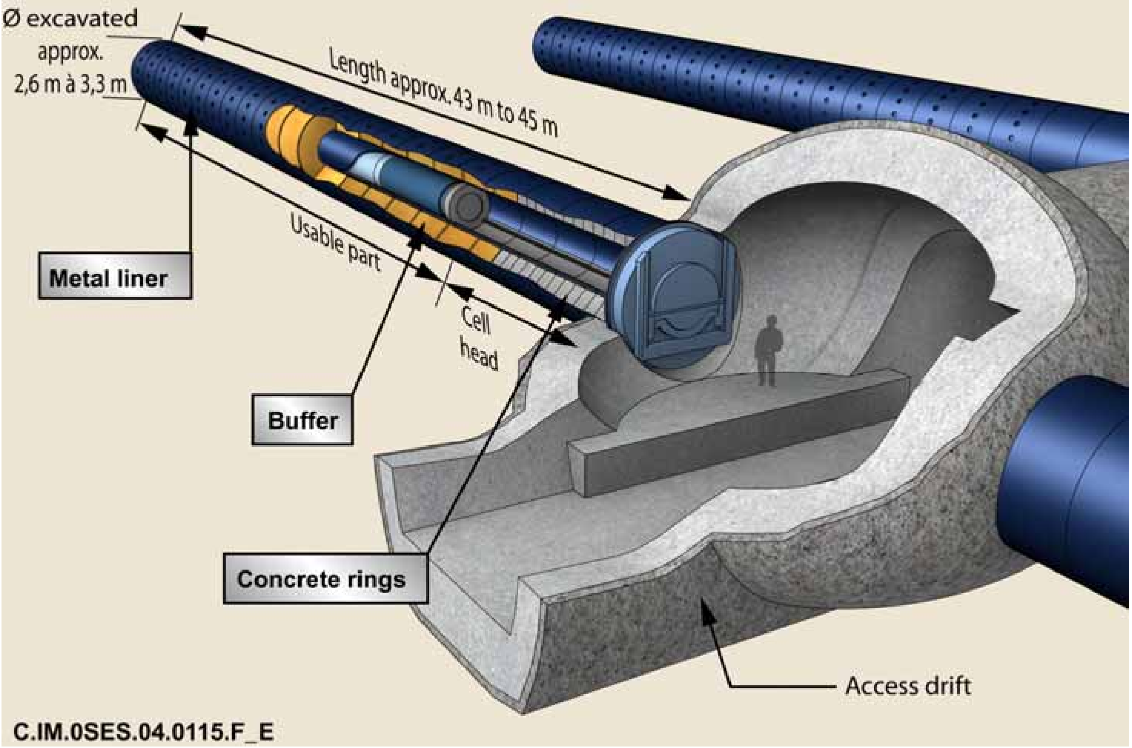


Figure 5.3.4 Spent fuel cell : principal components

Table 5.3.1 Functions and principal components of the spent fuel cell

Function	Period	Metal sleeve	Swelling clay engineered barrier	Metal plug and shielded trap door	Cell plug	Spacers	Module sealing	Access drift back-filling
To transfer the packages to their disposal location;	Operations	**X**						
To mechanically support the structures	Operations and monitoring	**X**						
To protect personnel from radiation	Operations and monitoring		x	**X**	x			
To enable packages to be retrieved from disposal	Operations and monitoring	**X**		x				
To stop water from circulating	After closing		x		x		**X**	
To limit the release of radioactive nuclides and hold them within the repository	After closing	x	**X**		**X**			
To retard and reduce the migration of radioactive nuclides	After closing		x		x			
To limit mechanical deformation in the argilites of the Callovo-Oxfordian clay	After closing	x	x		x	x	x	**X**
To dissipate the heat	All	x	x			**X**		
To divide up the repository	After closing						**X**	

Key : **X** essential component in the fulfilment of a function

x contribution made by a component to a function

* Strictly speaking, module separation of the repository does not constitute a safety function, but it is a design principle adopted with safety objectives in mind.

5.3.2.4 Solutions adopted or being studied in other countries

The direct disposal of spent fuels in clay formations is under study in Belgium and Switzerland. The American (Yucca Mountain), Swedish and Finnish concepts should also be mentioned although they correspond to different geological contexts.

- **Belgium**

The concept of direct disposal of spent fuels studied by the ONDRAF is presented, in the SAFIR2 (2001) report, as an adaptation of that used for vitrified waste. Since that date, the concept has evolved.

The disposal package consists of a stainless steel container (AISI 316) holding in cladding, for criticality reasons, a single assembly.

The cells are 2.7 m diameter, 600-800 m long circular horizontal tunnels. They have a 25cm thick concrete lining and are fitted with 4 longitudinal pipes separated by swelling clay, in the case of UOX packages, or a single central tube, in the case of MOX packages. The dimensioning thermal criteria are a container wall temperature of under 100°C, and temperature increase in the overlying water-bearing geological formation of under 6°C. The longer duration of the thermal phase for spent fuels requires the inter-axial spacing of the cells to be increased to 110 m (instead of 40 m for the Belgian vitrified waste concept).

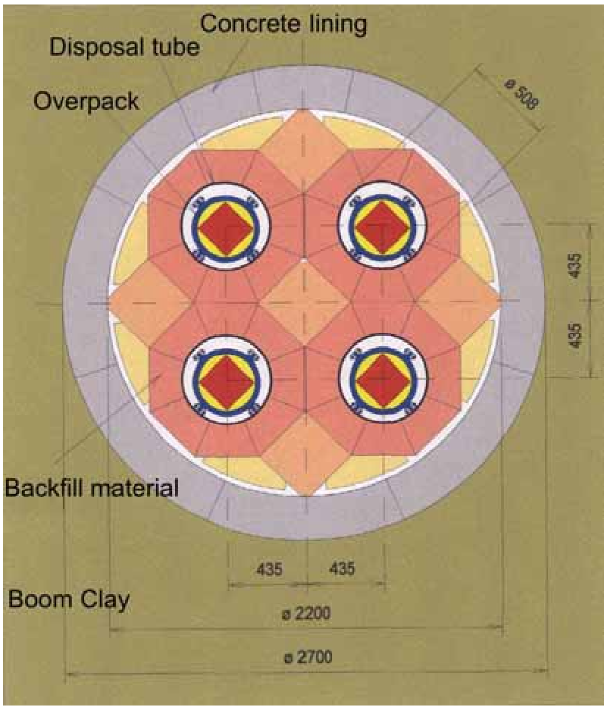
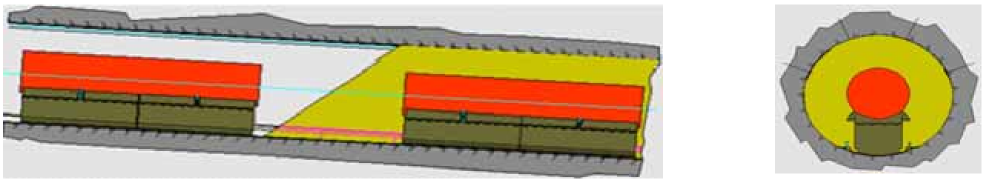


Figure 5.3.5 *ONDRAF concept for the disposal of spent fuels, transverse section in accordance with SAFIR 2*

● Switzerland

For spent fuels, NAGRA envisages a similar concept to that for vitrified waste, a brief description of which is given at § 5.2.2.3. The detailed description of the NAGRA concept is available in its Technical Report [44]. The disposal package is a steel or copper container, described at § 4.3.2.4.

The cells are orientated according to the major stress. The mechanical characteristics of the formation considered (Opalinus clay) take for granted under these conditions that the excavations will be self-supporting: they are not lined; only a ground support by mesh and bolts is planned for safety reasons. The cells are "through" cells. They are 2.5 m in diameter and several hundred metres long. The disposal packages are placed on compacted swelling clay bases. The annular space between the package and the cell walls is filled by spraying-in a mixture of loosely compacted pellets and powder (target dry density 1.5). The cell is filled in cycles alternating the emplacement of a package and the filling in of the swelling clay buffer.



Longitudinal section

Transverse section

Figure 5.3.6 *Swiss NAGRA concept for the disposal of spent fuel packages*

- **Sweden and Finland**

The Swedish (SKB) and Finnish (Posiva) concepts are designed for granite rocks. The full description of the Swedish KBS-3V concept is given in [68], pp 63-66. The Finnish concept refers to the Swedish concept.

The assemblies are placed in groups of 4 or 12 in a 1.05 m diameter, 50 mm thick copper container, fitted with a cast iron insert. The cells are 1.75 m diameter vertical shafts, holding a single container surrounded and covered by MX80 swelling clay.

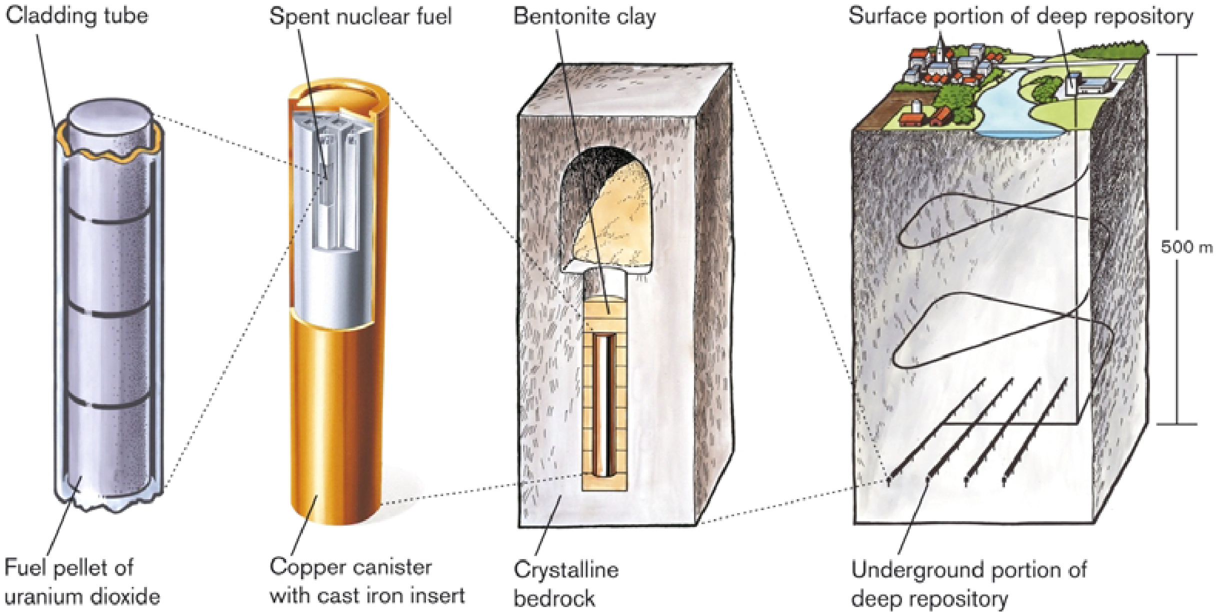


Figure 5.3.7 Swedish and Finnish concepts with vertical cells (KBS-3V)

SKB and Posiva are currently studying a horizontal variant (KBS-3H) the basic principle of which is the use of a supercontainer consisting of a copper container surrounded by an engineered barrier made from prefabricated swelling clay. These over-packs are placed in repository drifts several hundred metres long. The aim of this variant is to reduce significantly the length of access drifts.

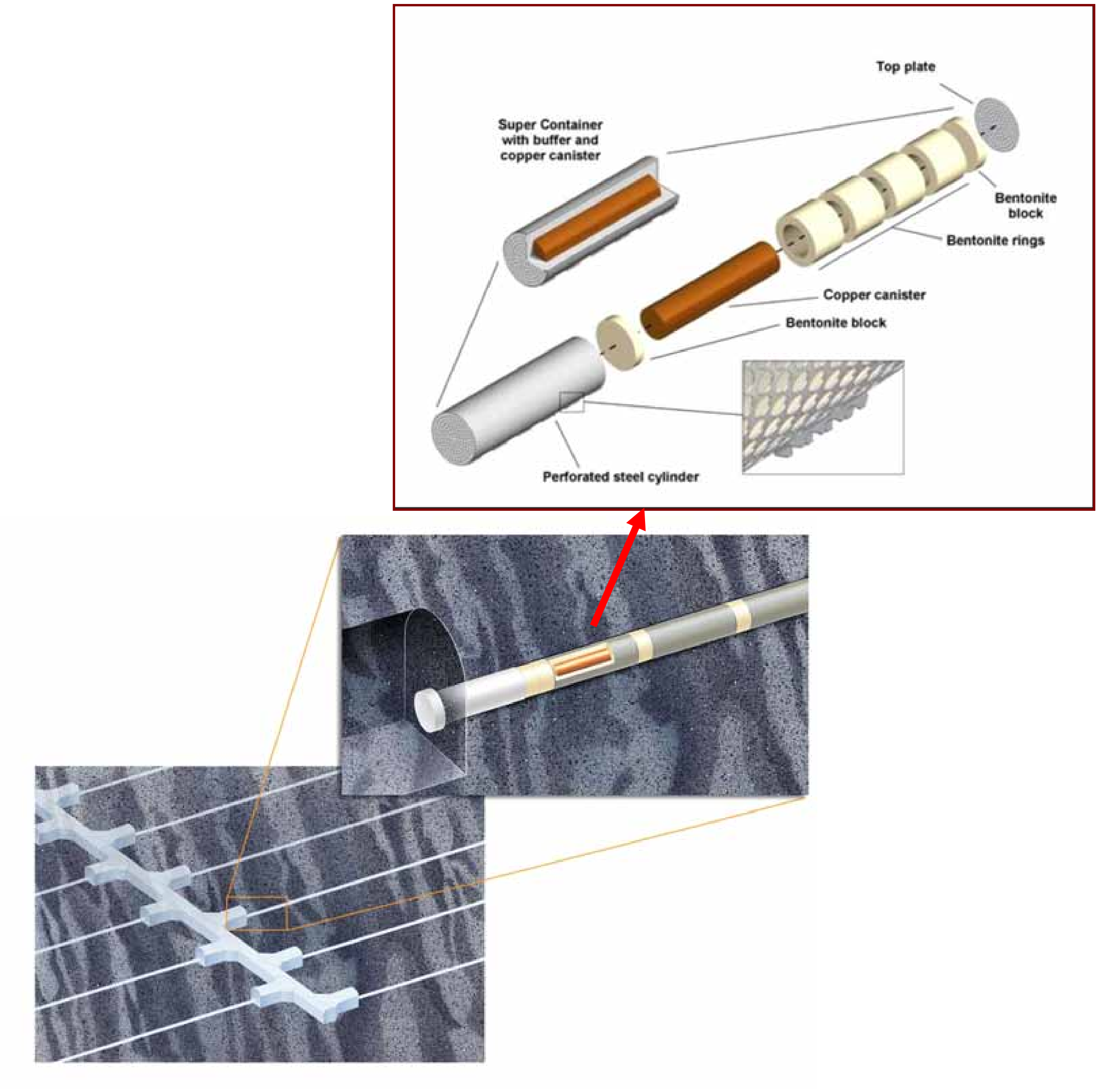


Figure 5.3.8 KBS3-H horizontal concept with over-pack (SKB, Sweden) : top, over-pack ; bottom, horizontal cells.

- **USA**

The American Yucca Mountain project is dedicated to civil and military spent fuels. The geological formation is a volcanic tuff. The disposal cells are 5.5 m diameter, 970 m long horizontal “through” drifts [69]. The packages are placed in them in line, without buffer, but in a raised position and under a titanium drip shield, so as to protect them from local percolation (meteoric water) and localised induced corrosion.

The difference between this concept and all the other projects lies in the fact that the heat produced by the packages is evacuated by forced ventilation which ventilates the entire line of the repository drifts for a period of 69 years. Once the packages have been placed in the drifts, no back-filling is carried out. The structures are sealed after a period of approximately 100 years.

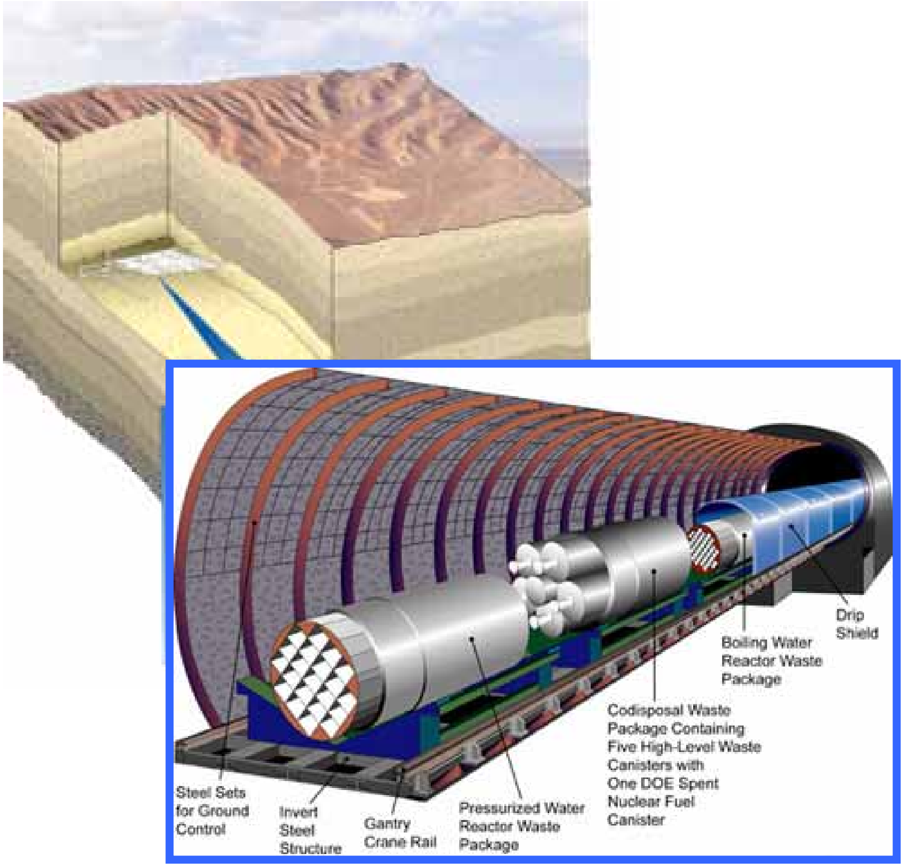


Figure 5.3.9 Yucca Mountain project disposal concept (USA)

- **Comparison of spent fuel disposal concepts**

The ANDRA concept chosen for this feasibility study has a point in common with all the foreign projects, at least in a saturated medium: the presence of a swelling clay engineered barrier. The only project which does not use an engineered barrier of this type, the Yucca Mountain project, is in a de-saturated formation.

Under the Belgian (SAFIR 2) and Swedish and Finish (KB3-V) concepts, the swelling clay buffer is positioned at the time that the cell is constructed. The package is only placed in the repository on completion of this operation, similarly to the ANDRA concept described.

However, the Swiss concept is based on the principle of a construction operation combined with the placing of the package in the repository: the swelling clay buffer is positioned after each package has been placed in the repository; when the packages are completely surrounded by bentonite, a new package is put in place. This concept has the advantage, compared with the ANDRA concept, of avoiding the use of a metal sleeve. However, it has the disadvantage of requiring simultaneous “civil engineering” type operations and radioactive nuclear material handling operations At this stage of the studies, ANDRA preferred to dissociate the construction operations from those involving the handling of radioactive materials.

The new Swedish/Finnish concept currently under study (KBS3-H) is an supercontainer type concept. It has the advantage of being able to prefabricate in surface facilities an engineered barrier continuum around each package but makes retrieving the packages more complex. In fact, unlike the ANDRA concept in which, during the first stage (before sealing of the cell), the packages can be retrieved in the same way that they were positioned, the “supercontainer” concept involves the development of special procedures for retrieving packages.

Finally, it should be noted that the Yucca Mountain concept, due to the forced ventilation running through the drifts in which the packages are disposed, has limited similarity with the other concepts. Furthermore, the environmental conditions in which the packages are disposed are different, as the host geological formation is not saturated.

5.3.3 Description and dimensioning of CU1 and CU2 modules

This section describes the CU1 and CU2 modules. CU3 modules do not have clay engineered barriers and are in principle identical to those described for type C waste in section 5.2.

5.3.3.1 Description of the cell and access drift

The description below emphasises the specific features of the spent fuel cell. The features in common with the type C waste cell are described in brief.

- **Description of the cell**

The cell, as designed at this stage of the studies, is a tunnel closed at one end, around 3.3 m in diameter in the case of the CU1 cell and around 2.6 m in diameter for the CU2 cell.

In the usable part destined to receive the packages, the cell consists of three components: a steel lining, a swelling clay-based engineered barrier with a radial thickness of 800 mm, and a permanent metal sleeve (maintained after closing). The sleeve facilitates the positioning or withdrawal of packages.

The top of the cell is designed to receive a seal. The latter consists of a clay plug and a concrete retaining plug. The peripheral parts of the retaining plug (clay and concrete) are positioned after the swelling clay buffer, before the packages. The central space allows the packages to pass and to this end receives a temporary sleeve, removed in order to close the cell.

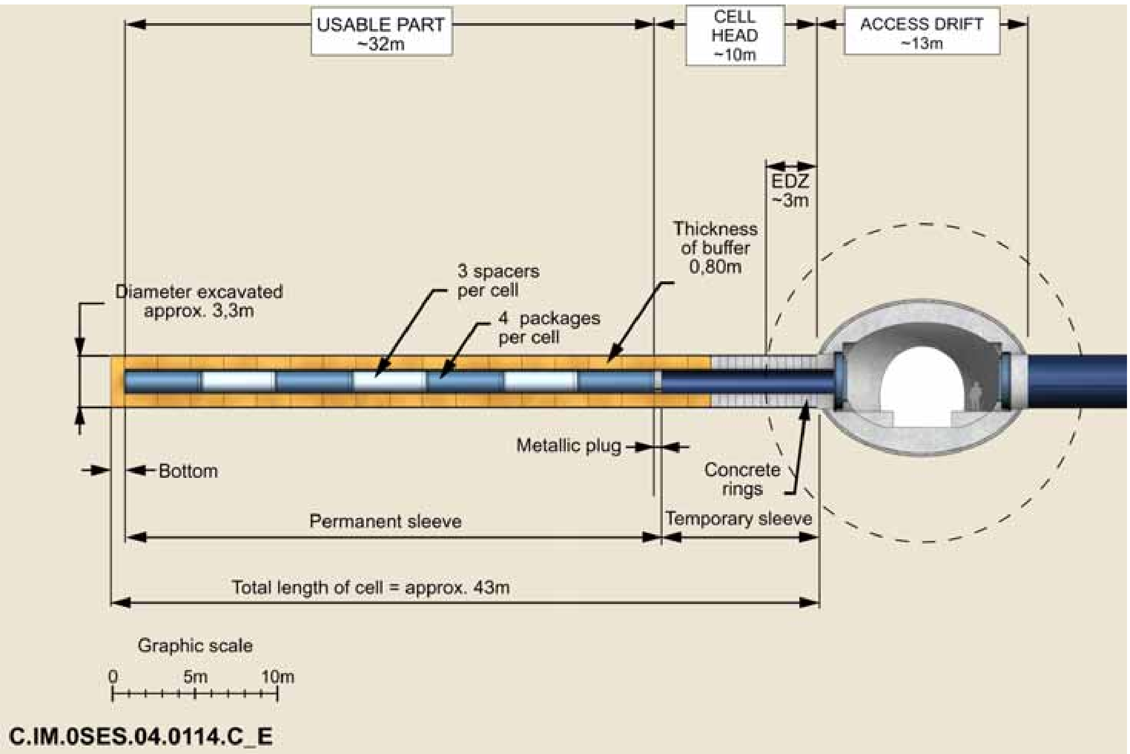


Figure 5.3.10 Longitudinal section through CU 1 cell

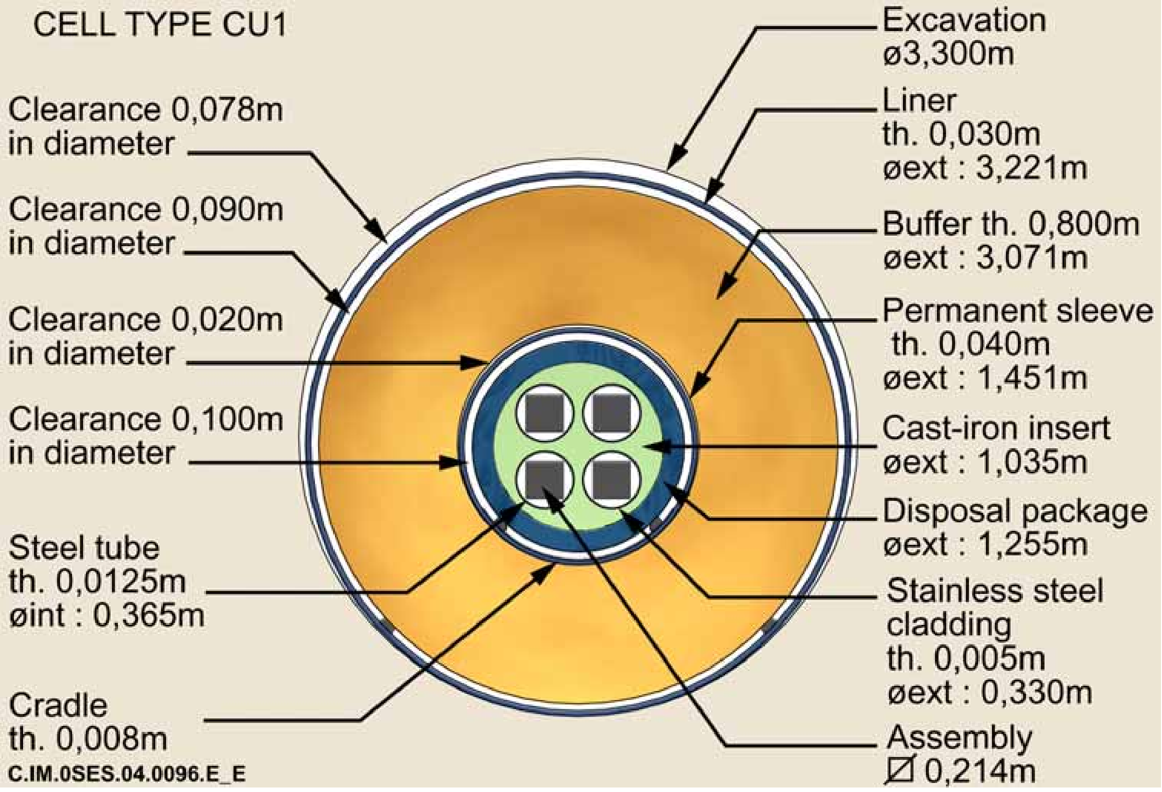


Figure5.3.11 Transverse sections through CU1 spent fuel cells

- **Components and functions of the usable part of the cell**

The metal lining has the following three functions : to physically support the argilite, protect personnel and, during excavation, act as a thrust tube. The larger diameter of CU1 cells leads to their thickness being increased to 30 mm, as against 25 mm for CU2 cells. The metal lining is perforated to allow water to pass through it and re-saturate the swelling clay buffer

The clay engineered barrier consists of swelling clay (approximately 70%) and sand (approximately 30%) in the form of prefabricated rings.

Three major phases can be identified and analysed in the light of the functions fulfilled by the clay buffer or to which it contributes. These functions are the constitution of a diffusive barrier (protecting the packages from aqueous alteration) and the dissipation of the heat released by the packages (and its transfer to the argilite) [13].

In **phase 1**, during the first decades, the unsaturated clay buffer does not need to fulfill its role as a diffusive barrier (the container prevents the water from coming into contact with the fuel). However, the clay buffer must allow the still very high heat flow from the packages to be evacuated (the temperature peak occurs a few decades after placing the packages).

In **phase 2** (up to approximately 10 000 years), the container still protects the fuel (by preventing water from coming into contact with them). The clay buffer, by being re-saturated, is able to fulfil its role as a diffusive barrier. The buffer continues to dissipate the heat produced by the waste to the argilite. However, the heat flow rate is gradually reduced as the heat rating of the packages decreases.

In the longer term, in **phase 3**, (beyond 10 000 years), the container loses its watertight integrity and the water can come into contact with the spent fuel assemblies. The clay buffer (re-saturated to over 95%) then fulfils its function as a diffusive barrier, limiting the possibility of transport around the spent fuels. The buffer's thermal role gradually diminishes.

The internal sleeve of the spent fuel cells is of the same type as that of type C cells. Its thickness is adapted to the diameter of the packages. It would be possible to install fittings to make it easier to guide and retrieve packages (for example rails or shims or ceramic linings).

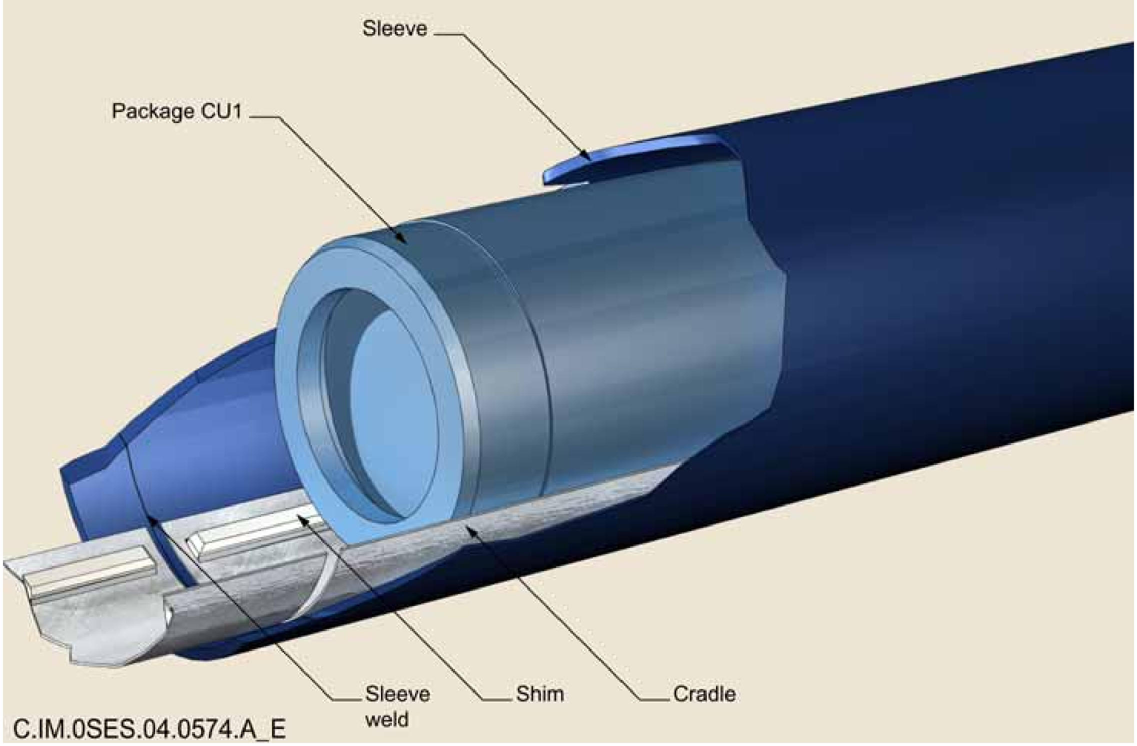


Figure 5.3.12 Internal equipment of the CU1 sleeve

- **Components and functions of the cell head in the operating configuration**

The metal lining is identical to that described on the inside of the cell, except that there are no perforations in the head of the cell.

The swelling clay buffer rings in the future sealing zone are identical to the rings around the permanent sleeve.

The prefabricated concrete rings are the same size as the swelling clay rings. These rings support the temporary sleeve during package insertion. They participate in radiological protection. They confine the clay during its re-saturation and transfer the clay swelling thrust to the access drift.

- **Description of the access drift**

The size of the access drift depends on the spent fuel package handling requirements. Due to their length, the packages are transported lengthwise in the drift. Consequently, they have to be turned or pivoted in order to insert them in the cell.

For the current section, the size of the passage for the package transporter is approximately 4 m by 4 m. Its inclusion in a roughly circular section requires an internal diameter of approximately 6 m. This figure is close to that of the drift for type C modules; the support and lining can thus be the same[94] : support by 4 m rock bolts and shotcrete, metre thick B60 concrete lining poured in-situ.

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[94] The excavated section should be optimised: the useable section given, elliptical in shape, minimises stresses and, therefore, the thicknesses of the coating; however, a shape more akin to the transporter's square cross section would allow a smaller useable section.

There are several possible solutions to the problem of positioning the container for insertion in the cell. The various figures shown illustrate the solution using pivoting. The operation is carried out in a "positioning chamber", broadening the access drift at the cell location. The dimensions of the packages require chambers approximately 10 m in diameter. Studies have confirmed the feasibility of this solution: the inter-axial distance between cells (between 22.5 m and 24 m as indicated in section 5.3.3.2) is sufficient. The chamber is approximately 7 m high; its mechanical stability is provided by 5 m bolts and lining thicknesses of 1.40 m. Another solution would consist of gradually turning the container at the same time as it engages in the head of the cell. This solution would reduce the size of the civil engineering structures. An initial study has enabled the feasibility of this second solution to be established.

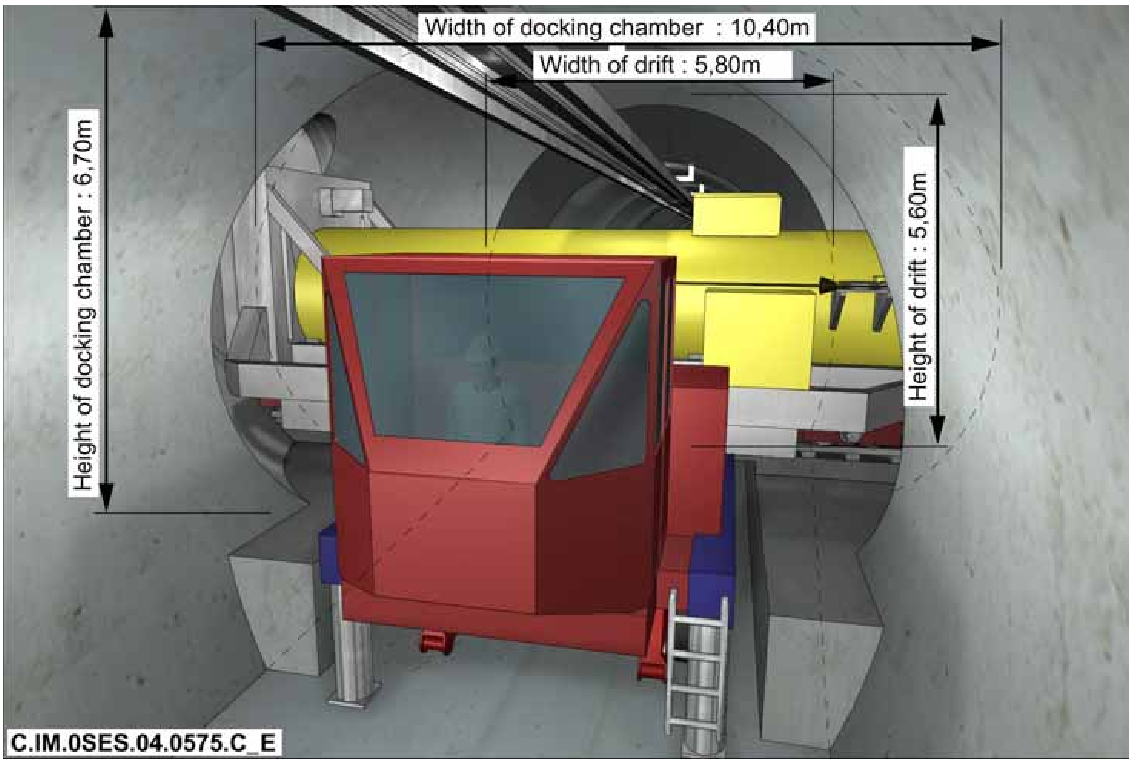

Figure 5.3.13 Access drift for type CU1 or CU2 spent fuel

As for access drifts to type C cells, the geotechnical dimensions have been calculated for a minimum lifetime of a hundred years and take into consideration thermal effects which represent approximately 40% of the stresses on the lining. The lining is dimensioned and constructed so as to minimise its thickness. In its current section it is not reinforced [65].

5.3.3.2 Dimensioning of cells

The dimensioning of the cells takes the following into account: choice of materials and characteristics of the clay buffer, dimensional stability of the sleeve and metal lining. The cell's thermal dimensioning governs the spacing between packages and between cells.

The specific characteristics of the spent fuel cell that influence the thermal and mechanical dimensioning are as follows :

- the heat transfer of spent fuels reduces more slowly than that of type C waste,
- the presence of the buffer changes the near-field thermal behaviour (see below),
- the presence of the buffer leads to the insertion of a large diameter metal lining,
- finally type CU1 spent fuels have a greater diameter, which has repercussions for all radial dimensions of the cell's components; it leads to greater sleeve and lining thicknesses.

- **Description of and justification for the dimensioning of swelling clay rings**

The expected properties of the clay buffer are as low a permeability and high a thermal conductivity as possible.

The aim of the low permeability is to create a diffusive medium around the packages; this is the first property to be achieved. Studies have shown that a permeability of around 10^{-13} m/s is achievable on a small scale, in the knowledge that the full scale permeability objective of 10^{-11} m/s would suffice.

A high thermal conductivity makes it possible to dissipate the heat released by the waste. Studies have shown that it is possible to achieve a long-term thermal conductivity in excess of 1.5 W/m/°C (re-saturated material) and in excess of 1.2 W/m/°C during the thermal peak (unsaturated material).

In order to achieve the aforementioned properties, the following characteristics are envisaged [65], [70]:

- mixture of swelling clay (approximately 70%) and sand (approximately 30%), the latter enabling the thermal conductivity to be improved;
- choice of an "MX80" type clay or equivalent (low permeability even at low density);
- swelling pressure: between 1 MPa (or even 0.5 MPa) and 7 Mpa, effective stress;
- dry density at time of placing (prefabricated block: approximately 1.8 for the clay/sand mixture: approximately 1.6 for clay alone (it can change to a figure of 1.5 as the cell evolves) ;
- degree of clay saturation at the time of placing: approximately 80%;
- water content: approximately 15% for the clay/sand mixture; approximately 20% for clay alone;
- mechanical strength of blocks: approximately 10 MPa under compressive stress, approximately 1 MPa under tensile stress.

The target maximum swelling pressure is 7Mpa : this is the final value which will establish itself in the long term, in equilibrium with the argilite; refer to section 5.2.6.1 for a discussion of this point.

The addition of swelling clay enables the thermal conductivity to be improved and the swelling ability to be reduced if necessary. A sand content of 30% makes it possible to considerably improve the mixture's thermal characteristics without adversely affecting the permeability.The thermal performance of the core of the buffer is of considerable importance here: it affects the package disposal compactness and earliest disposal age.

The dry density indicated enables the swelling pressure to be maintained later in the desired range: it takes into account the clearances established.

The figures indicated for the degree of saturation and water content at the time of placing the packages in the repository are a compromise between the following characteristics: dry density at the time of placing, compactability and mechanical strength of the parts.

It should be noted that the clay materials envisaged have good resistance properties with respect to the disturbances resulting from interactions with the other materials. On the one hand, these interactions are disturbances due to iron and, on the other, alkaline disturbance.

- The corrosion of steels (package, sleeve, lining) frees iron, liable to interact with swelling clay and argilite: smectites (swelling) are transformed into chlorites (non-swelling). This transformation spreads radially in the clay buffer from its internal and external faces. The studies assess the possible extension from a surface in contact with the steel to a distance of 30 to 50 cm; it can affect the entire buffer. However, other than in the area in contact, it is limited in intensity (beyond 5 cm from the interface, the percentage of smectites transformed is less than 10% and less than 1% beyond 30 cm). The buffer thus retains most of its swelling ability (Figure 3.3.3).

- The alkaline disturbance transforms smectites (swelling) into illites (non-swelling). It is associated with the presence of concrete (retaining plug and access drift lining). It develops axially, from the bearing face of the clay plug. The studies assess its extension as being 0.60 m after 100 000 years and under 2 m after a million years95. The disturbance can affect part of the plug but it does not reach the clay buffer of the inside part of the cell [71], [58].

- **Specific thermal dimensioning characteristics of spent fuel cells and modules**

The short-term thermal dimensioning criterion and calculation procedure remain identical to those used for type C waste (see section 5.2.3.3). Like type C cells, the thermal dimensioning of spent fuel cells depends on (i) the age (or the heat rating) of the packages on the date of placing in the repository, (ii) the distance between adjacent cells (inter-axial distance or Px pitch), (iii) the distance between the disposal cell ends (Dy pitch), (iv) the number of packages per cell (N).

However, spent fuels differ from type C waste by their initial high thermal rating, which reduces from 7 000 watts to 1 000 watts in 100 years, and by their slow temperature decrease (see figure 3.2-21 chapter 3). Furthermore, the concept using buffers introduces the following additional thermal data:

- an 800 mm thick buffer whose thermal conductivity is lower than that of the geological medium;
- two additional functional clearances around the buffer;
- an increase in the minimum pitch between cells which, for geotechnical reasons, is approximately 13 meters for type CU2 cells and 16.5 meters for type CU1 cells.

As a result, the horizontal footprint and excavated volume of spent fuel modules are larger than those of type C waste modules.

Results of the thermal dimensioning for the various spent fuel packages

The repository module architectures described here have been defined for a pre-disposal storage time corresponding to an earliest package disposal age for the concepts proposed, namely 60 years for type CU1 packages and 90 years for type CU2 packages. For these pre-disposal storage times, the horizontal footprints occupied by the type of package disposed in a module are summarised in Table 5.3.2. The corresponding cells are shown in Figure 5.3.14.

Table 5.3.2 Footprint areas required for the disposal of spent fuels

Disposal package modules	Long CU 1 [96]	Short CU 1 [97]	CU2
Age (years) : pre-disposal storage time	60	60	90
Horizontal footprint (m^2/package disposed)	385	301	346
No. Number of packages per cell	3	4	3
Px (m) inter-axial distance between cells	22.5	22.5	24
Dy (m) : DistBetween disposal cell ends	20	20	20
Lua (m) : Inside length of the cell.	32	32	34.5
Pc (m) : Pitch between packages[98].	7.5	4.2	10.3

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[95] This extension varies by a few decimetres depending on the heat rating released by the packages.

[96] Long CU1 = type AFA-2L2 package from 1300/1450 Mwe reactors; length = 5 390 mm

[97] Short CU1 = type AFA-2G2 package from 900 Mwe reactors; length = 4,640 mm

[98] The actual pitch between packages will be adjusted according to the effective length of the buffers (constraints associated with handling equipment, notably the transfer cask)

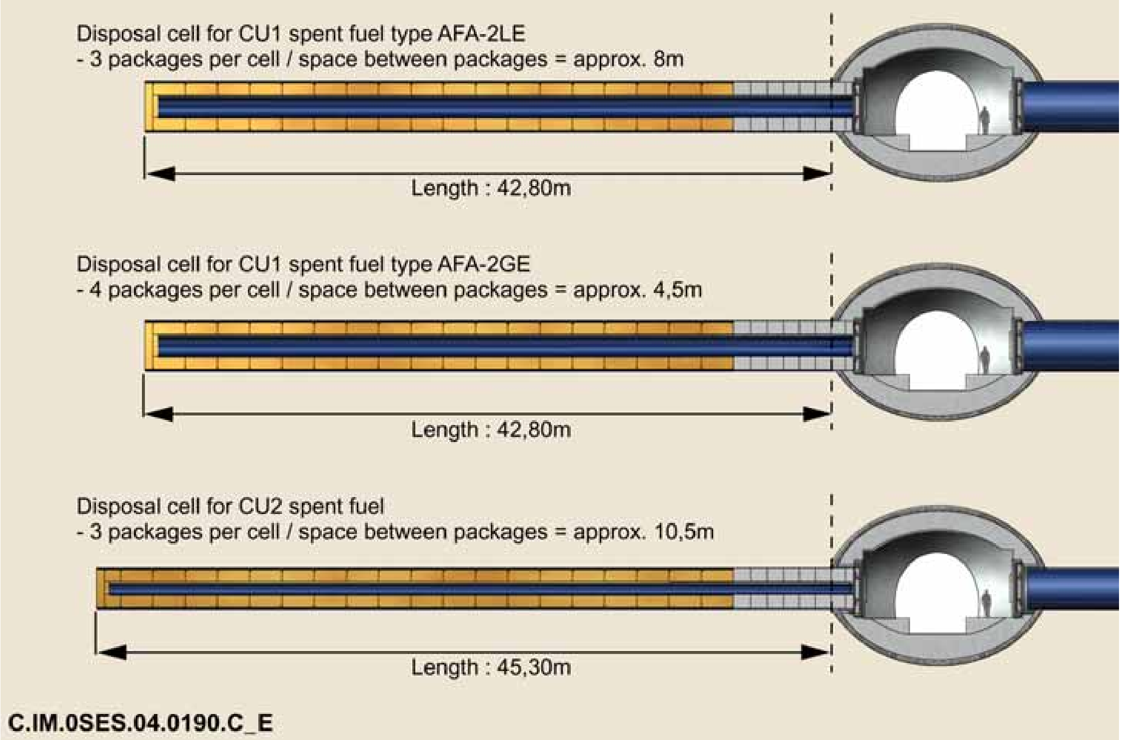

Figure 5.3.14 Longitudinal section through type CU1 and CU2 cells

The temperature change of the wall of the clay buffer between 0 and 600 years (see Figure 5.3.15) shows that, for the dimensioning indicated in the table above, the temperature returns below the 70°C threshold well before 1 000 years, which meets the long-term thermal criterion.

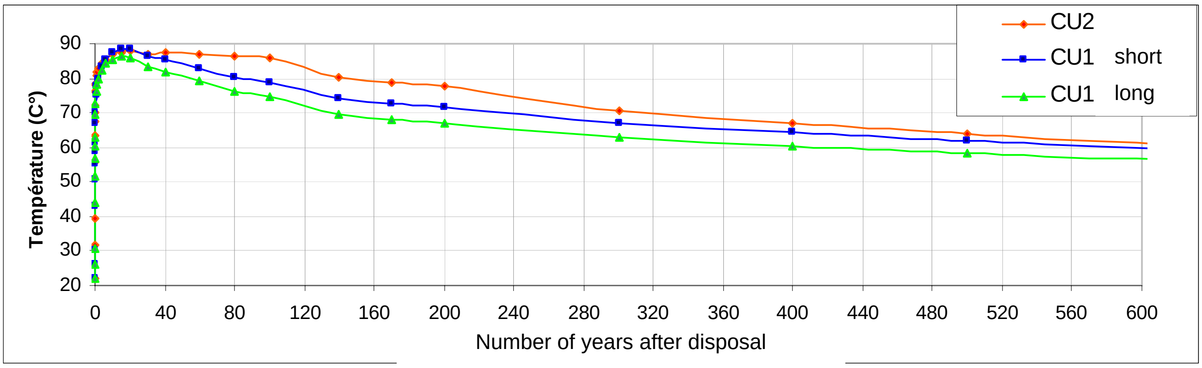

Figure 5.3.15 Clay buffer wall temperature for spent fuels

The dimensioning shown leads to a more rapid decrease in the temperature inside the argilite than in type C waste. This result may appear paradoxical, given the slower decrease in the heat rating of spent fuels; it is due to the large distances between packages imposed by the short-term thermal criterion.

- **Specific mechanical and thermo-mechanical dimensioning characteristics of spent fuel cells**

The sleeves of cells must maintain functional clearances that retain the capability to withdraw the packages, for a period in the order of a few centuries. The dimensioning calculation is identical to that for type C waste, in both its purpose and assumptions. The only difference is the larger diameter of the cells.

The result is a sleeve thickness (which takes account of the mechanical dimensioning and a corrosion allowance of a few millimetres) of 40 mm for type CU1 cells and 25 mm for type CU2. These dimensions are based on the same loading case as for type C cells (12 MPa).

The excavation of cells with a clay buffer, followed by the fitting of buffer rings, requires the use of a metal securing support. As indicated above, the pre-dimensioning calculations lead to the use of a ring approximately 30 mm thick for type CU1 packages and approximately 25 mm thick for type CU2 packages [65].

5.3.3.3 Constructing the cell

This section describes the procedures and resources required to excavate and coat the cell, then prepare and position the components of the buffer and, finally fit the other cell equipment.

- **Excavating and lining the cell**

Several methods can be used for excavating the cell. The micro-tunnelling technique appears to be the best-suited, the thrust tubes remaining in place and forming the metal lining. This technique is industrially proven in the field of civil engineering for tunnels with small diameters compared with the cross section of the cells for spent fuel. The cutting tool is a solid-faced wheel type cutter, a technique which, thanks to the homogeneous nature of the cutting face, minimises induced terrain damage[99]. On completion of excavation, the micro-tunnelling head is extracted from the cell.

This excavation/lining method enables the work to be carried out at all times sheltered by the metal lining.

Cutting tool and shield

The cutting tool is a solid-faced wheel with retractable cutting wheels.his arrangement allows the micro-tunnelling head to be retracted inside the metal lining left in place (Figure 5.3.16).

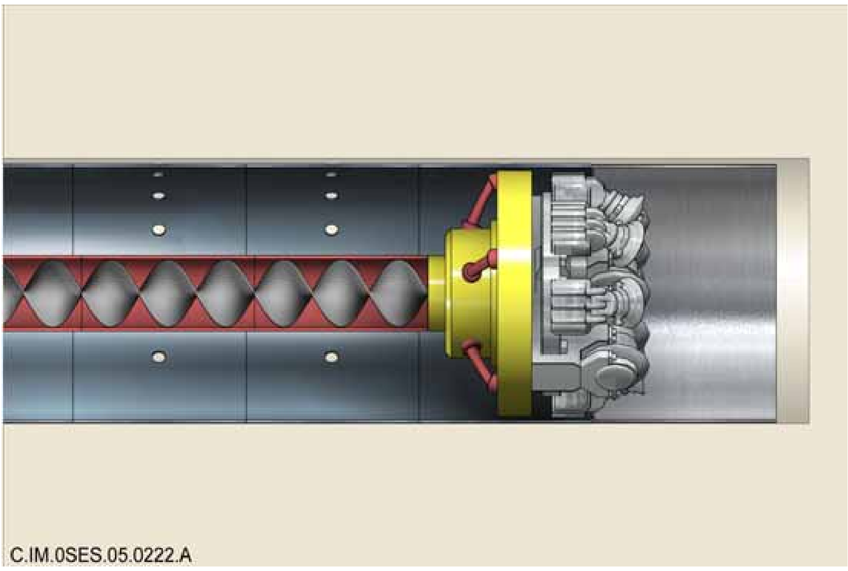

Figure 5.3.16 Cutting wheel (cutters pivoted) being retracted inside the lining

The cutting tool can work ahead of a shield, i.e. a metal ring protecting the micro-tunneller rotation motor-drive. The shield is then lost on completion of excavation: after dismantling its internal components, it is abandoned in-situ and forms the end section of the metal lining.

The thrust on the cutting wheel can be exerted by rams fitted to a thrust frame; it is transmitted via thrust tubes which, left in place, form the cell lining.

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[99] The solid faced wheel could be replaced by a point cutting type machine if in-situ trials demonstrated that it gives an identical quality of cut to that obtained using the solid-faced wheel type cutter.

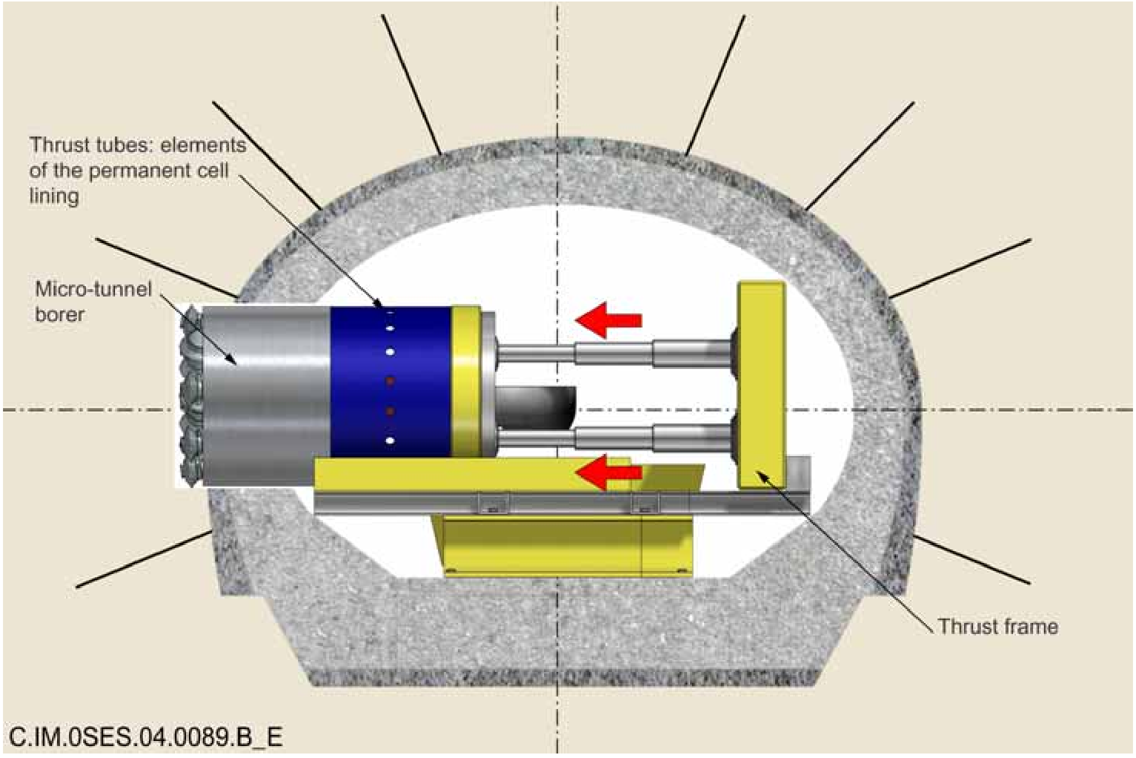

Figure 5.3.17 *Thrust frame in the access drift (difficult case of an access drift without a positioning chamber)*

Fitting the thrust tubes (future lining)

The thrust tubes are fitted in approximately 2 m long sections, or longer if the dimensions of the access drift allow. They are welded together after adjustment by a system of jacks connected to the drift’s face.

- **Fitting the clay buffer and sleeve**

The clay buffer described above is formed by complete rings in a single piece. The external diameter of the rings is approximately 2 meters and their thickness (along the cell axis) is 0.5 m. These dimensions are due to manufacturing constraints. Each ring pre-fabricated in this way will weigh approximately 5 tonnes.

There are two compacting techniques for parts of this size : uniaxial pressing and isostatic pressing. The former is used, for example, in Sweden [72], [73]; the latter has been tested in Japan, on 1.3 m diameter 1.7 m high cylinders [74]. The advantages of the isostatic process is its speed and the homogeneous nature of the material; it can be used to compact large blocks. However, uniaxial pressing currently has more references.

A high-capacity uniaxial press (for example : 30 000 tonnes) makes it possible to achieve the pressures in excess of 50 MPa required to obtain dry densities of around 1.9.

Inserting pre-assembled buffer rings

In order simplify the positioning operations, the rings can be assembled in the workshop in groups of four. This assembly method is currently under study as part of the European ESDRED project.

There are various possible techniques for fitting these rings into the cell. For reasons of size and the availability of experience feedback, the air cushion technique appears to be particularly suitable. The pre-assembled rings are placed on a cradle fitted with air cushions (see Figure 5.1.17). After the air cushions have been inflated, a trolley rolling on guide rails pushes the cradle to the required position in the cell. The air cushions are then deflated. The rings then sit on the rails, thus freeing the cradle.

The carrying capacity of a 380 mm diameter air cushion is around 2 500 kg. Each cushion is inflated to 0.3 MPa and slightly raises the ring to be moved by lifting it.

The procedure for putting heavy loads with large diameters in place is the subject of technological testing in the framework of the ESDRED project.

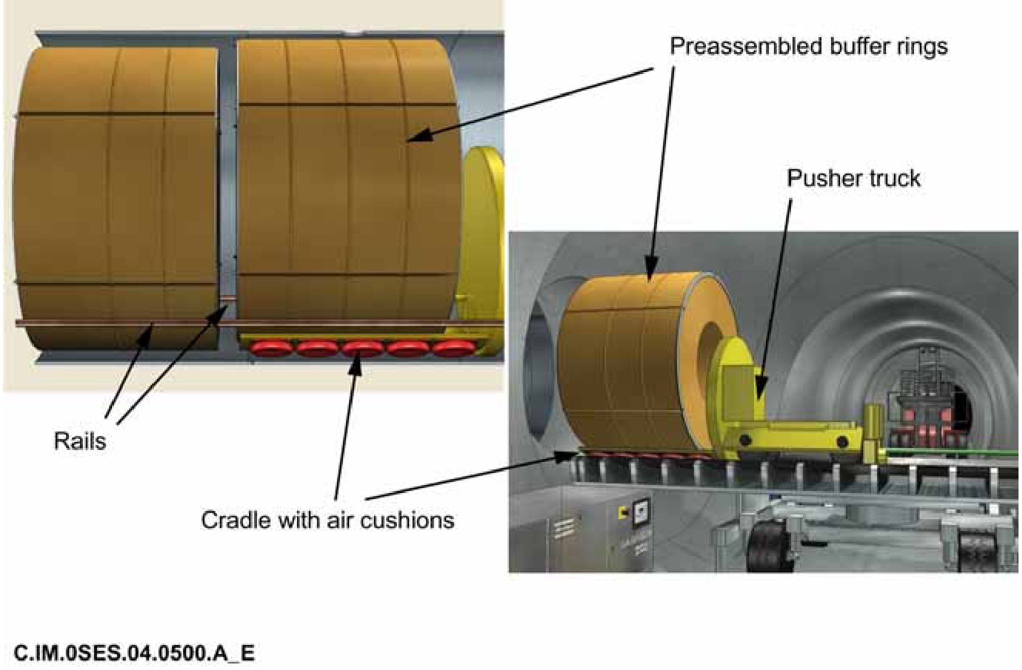

Figure 5.3.18 Fitting buffer rings using an air cushion

Inserting concrete rings at the head of the cell and connecting to the access drift lining.

The concrete rings forming the future swelling clay plug bearing support are inserted after the swelling clay buffer rings. They contribute to the protection of the swelling clay against hygrometric variations during the construction and operating phases.

A mechanical stop is then made with the drift lining in order to absorb any clay swelling thrust.

Inserting the sleeve

The sleeve is inserted after the last concrete ring. The preferred method of tube assembly, as for the type C cell, is welding and for the same reasons.

As far as fitting out the cell is concerned, special provisions are envisaged to make it easier to handle the packages, given their size : a cradle with shims, if necessary ceramic coated, is a possible solution.(see figure 5.3.11). The shims can be fitted to the elements of the cradle in the workshop, in order to facilitate their installation inside the sleeve.

5.3.3.4 Closing the disposal cell

The spent fuel disposal cell closing process begins as for that of the type C cell, with the fitting the metal radiological protection plug.

Once the choice has been made, there follows the fitting of the swelling clay core, in addition to the rings already installed. There are at least two possible processes:

- one consists of inserting pre-fabricated cylinders in the central space, probably at the same time as the temporary sleeve is withdrawn; this process, however, leads to the creation of an initial round space between the prefabricated cylinders and the rings already in place (thickness of the temporary sleeve increased by the handling clearance), a space which will in time close up as the clay swells;

- another possible process would consist of compacting clay pellets or powder in-situ; it would be done in the same way as the solution described for the type C disposal cell.

At this stage, the prefabricated component solution appears to be the simplest.

The next phase consists of producing the retaining plug. Unlike for the type C disposal cell, part of the retaining plug is already in place before closing the cell (prefabricated concrete rings). Closing therefore consists of pouring an additional concrete plug in the central space and, if necessary, injecting the concrete/concrete and concrete/lining contacts.

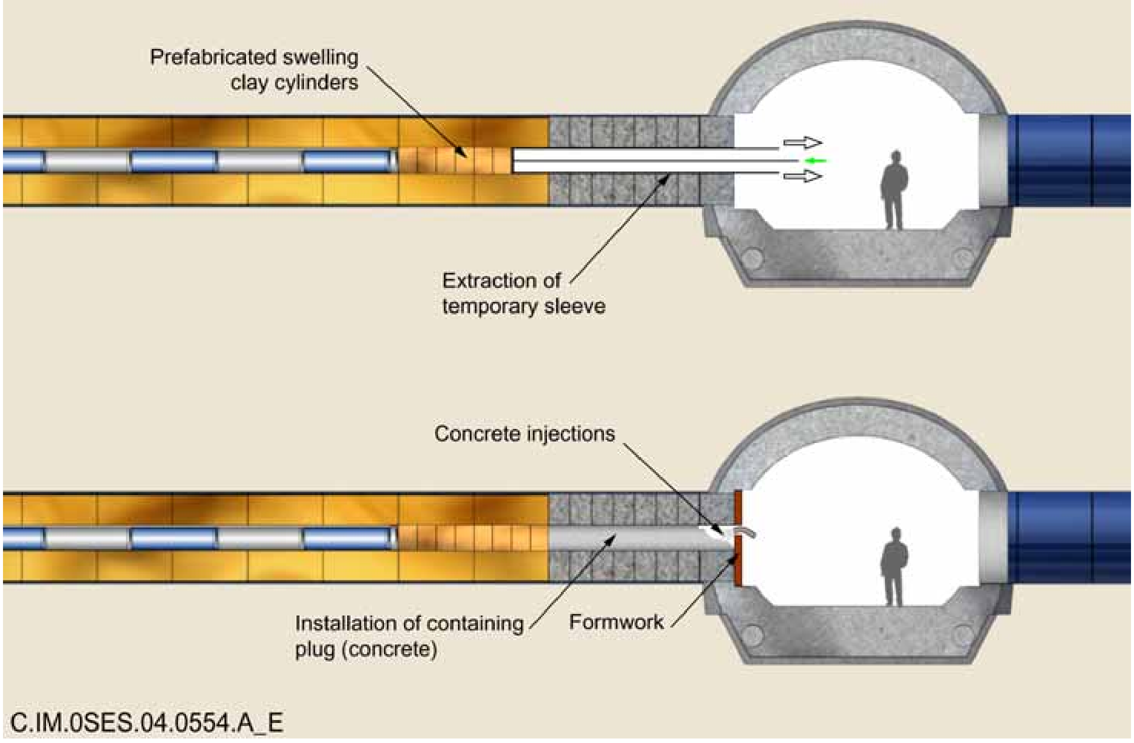

Figure 5.3.19 *Procedure for removing the sleeve and simultaneously fitting the swelling clay plug*

5.3.4 Layout of the type CU1 and CU2 cells in the repository module

The layout of type CU1 and CU2 repository modules, as presently proposed, is very similar to that of type C modules. Each module consists of two work units, each work unit grouping together three access drifts. The only difference is the number of cells and the details of the secondary infrastructure drifts.

Type CU1 and CU2 modules contain 80 to 130 disposal cells.

In order to take flow hypotheses into consideration it is proposed that five secondary infrastructure drifts be excavated in type CU1 repository zones and four in type CU2 zones. The additional drift in type CU1 zones is an air return drift, justified by operational requirements[100].

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[100] An increase in the internal diameter of 1 m would allow the number of secondary infrastructure drifts to be reduced from five to four in type CU1 zones.

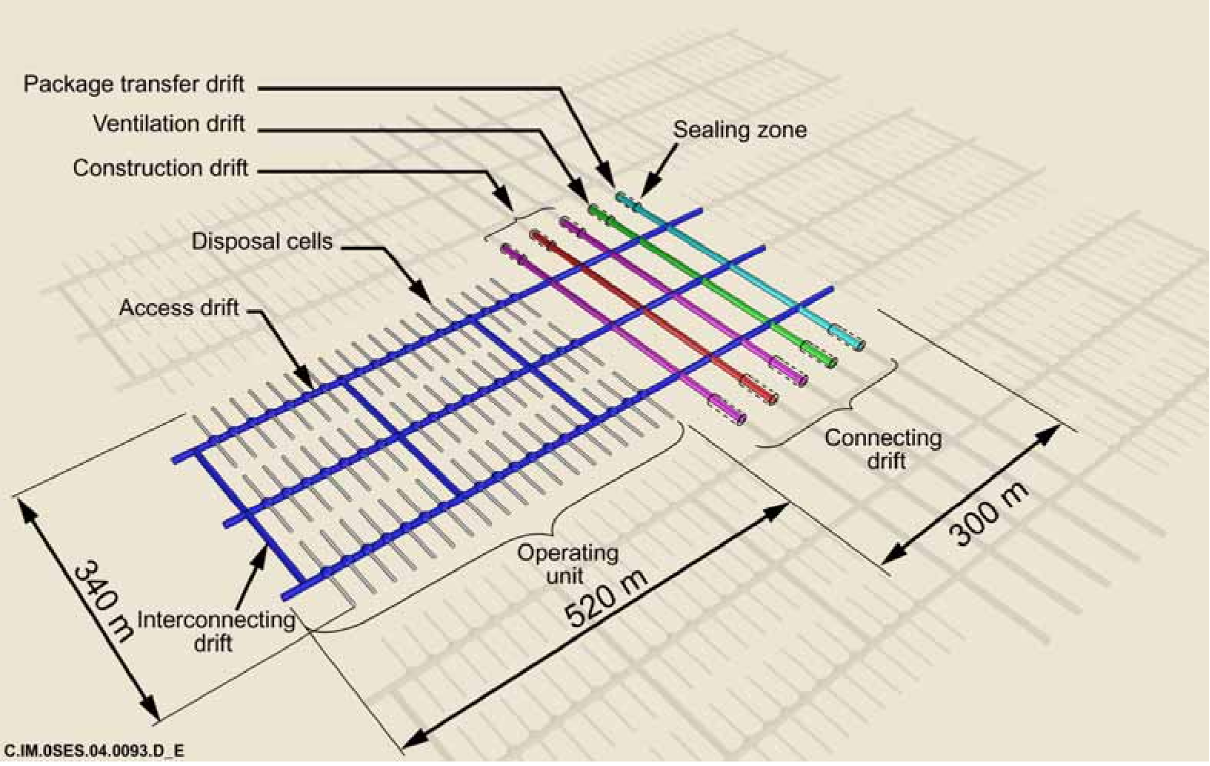

Figure 5.3.20 General layout of type CU1 working unit

Unlike the case of type C packages, for which differences in thermal dimensioning have been noted between one type of package and the other, the thermal dimensioning of type CU1 and CU2 packages is roughly the same.

5.3.5 The CU3 module

The thermal and dimensional characteristics of type CU3 and C0 packages are similar. At this stage of the studies, this allows the design of a CU3 module to be based on that of a C0 module.

In the reference solution, the cell does not have a buffer. Thanks to their low heat load, the packages are disposed in them without spacers. The inter-axial distance between cells is 8.5 meters (identical to that of type C0 cells)

The access drift for type CU3 packages is similar to that of type C0 packages, except for its width, which needs to be increased by approximately 40 cm to allow the type CU3 transfer cask to pass through.

6

Overall underground architecture

The purpose of this chapter is to describe the logic behind the layout of the repository module in the clay formation studied and that of the shafts and drifts giving access to it.

The introduction recaps the main questions to be taken into consideration in the overall architecture concerning long-term safety, reversibility and operational aspects.

It then describes the design principles adopted to meet these requirements. In particular, these principles include a modular tree-structure for the repository zones, both for long-term safety reasons and to provide management flexibility. It is also shown how the architecture allows the orientation of the structures to be adapted to the distribution of the natural mechanical stresses in the formation.

This chapter then goes on to detail the main dimensioning factors of the overall architecture. The geo-mechanical stability defines the distances to be observed between excavations The thermal criteria affect the area of the footprint of heat-generating waste repository zones; in particular, the thermal independence of repository zones is checked. Finally, this chapter details why, at this stage, the grouping of surface/bottom connecting structures and a principle of dead-end elements increase the effectiveness of the control over long-term water circulation.

The procedure for progressively constructing repository modules, as part of a phased approach, is described. Material, waste package and ventilation flows determine the number and dimensions of connecting drifts making it possible to construct then use the repository modules

Finally, this chapter outlines a few orders of magnitude concerning the underground footprint of a repository corresponding to the package production scenarios introduced in Chapter 3. It also describes the sensitivity of the footprint to the pre-disposal storage time of high-level waste.

6.1 Presentation of main questions

6.1.1 Long-term safety

Chapter 2 introduced the long-term safety functions of a repository. The architecture described here incorporates provisions that favour the fulfilment of these functions. A first point concerns the limitation of the ability of water to circulate within the repository; in fact, the architecture conditions the expected overall hydraulic behaviour. The layout of the structures in the clay formation also affects the ability of the repository to delay or reduce the migration of the radioactive nuclides released by the waste packages. Finally, the overall architecture must contribute to the limitation of mechanical, thermal and chemical disturbance of the host medium and repository modules.

6.1.1.1 Control of the repository hydraulic behaviour

The search to limit the water circulation concerns several spatial scales within the repository: the immediate vicinity of waste packages, disposal cells and the entire repository

At disposal cell level, limiting the renewal of water makes it possible to reduce the alteration of waste packages and the release of the radioactive nuclides they contain; Chapter 5 indicated that a very slow water circulation rate, making transport by convection negligible, particularly favours the durability of the glass which forms type C waste and of the spent fuel ceramic pellets. At repository level, limiting flows in drifts and shafts delays the migration of radioactive nuclides that have been released.

The characteristics of the formation studied (low permeability, small gradients) naturally limit water flows liable to be drained in the argilite. However, the possibility of reducing these flows even further in each type of structure, by means of the repository architecture, was investigated, notably by minimising the differences in hydraulic head within it. As far as this function is concerned, the architecture and seals of the drifts and shafts can play complementary roles, strengthening the concept.

6.1.1.2 A structure layout that helps to delay and reduce the migration of radioactive nuclides

In order to delay and reduce the migration of radioactive nuclides released by the packages, the clay formation forms the essential retention barrier. The transport of species in solution occurs principally by diffusion in the water present in the pores of the argilite : physically, molecular agitation displaces the solutes very slowly from the zones in which the concentration in the water is the highest (the disposal cells) to the low concentration zones. For most species, this displacement is delayed by chemical sorption phenomena on the surface of minerals.

Another objective of placing structures in the clay formation is to maximise the transit and diffusion times. That makes it possible (i) by favouring dispersion, to limit the flow of solutes reaching the boundaries of the clay formation and, consequently, to reduce the concentrations there and (ii) to benefit from the radioactive decay of the radioactive nuclides.

At this stage of the design of an architecture, only the Callovo-Oxfordian clay formation has been considered as a retention barrier, without taking into account the additional contributions of the over and underlying formations.

6.1.1.3 Limiting mechanical disturbances in the geological environment

Mechanical disturbances induced in the adjacent argilite during excavation work must be limited. That will prevent any damage in the argilite from increasing the water flows in the repository or significantly reducing the migration time of radioactive nuclides released by the waste packages.

The first point concerns, in particular, the seals for which it is best to prepare against a risk of hydraulic short-circuit by the damaged argilite zone. In order to do that, at this stage, we are looking to install structures that can be sealed as well as possible taking into account the argilite's mechanical response. As a reminder, Chapter 5 indicated how such provisions can be integrated into the design of each disposal module.

More generally, around repository structures, the thickness of the argilite potentially damaged by the construction work must remain small when compared with the overall thickness of the formation studied. This point has already been raised in Chapter 5.

6.1.1.4 Limiting thermal disturbances

Vitrified type C waste and, it applicable, spent fuels, are characterised by the large amount of heat that they give off. In Chapter 5, an explanation was given of the temperature criteria used for the design of a repository, in order to remain within a field currently understood concerning (i) changes to materials and (ii) a knowledge and modelling of phenomena: as a reminder, we are seeking to maintain a disposal temperature of under 100°C; in concrete terms, we have adopted a criterion of 90 °C in the argilite wall (or, where applicable, in the clay buffer). Chapter 5 also described the dimensioning elements for disposal modules enabling these criteria to be met.

The maximum temperatures in the exothermic waste disposal modules are rapidly reached after insertion of the packages, when the heat flows are still confined to the inside of the same module. Thus in practice, these maxima depend solely on the design of each module. In the longer term, the temperature in the cells reduces as the waste's radioactivity decays.

However, the volume which is thermally influenced by each structure gradually extends with time, with the heat being diffused in the geological environment. Thus, the relative layout of the various modules within the overall architecture affects the repository's long-term thermal behaviour and the temperature distribution over a large spatial scale.

The link should also be noted between the duration of a repository's thermal phase and the design of the disposal package, explained in Chapter 4.

It is also reiterated within this context that type B2 package (bituminised sludge) repository modules must, as far as possible, be maintained at a temperature of under 30°C, in order to preserve the integrity of the bitumen and its containment capacity. The architecture must therefore protect them against a thermal flow coming, in the long term, from other heat generating waste packages.

6.1.1.5 Limiting physico-chemical disturbances, independence of the various categories of waste package

We consider the disposal of various categories of package in physically distinct repository zones. This separation prevents having to consider interactions between these various categories, in the study of long-term behaviour of the repository.

In addition to the thermal interactions mentioned above, it also concerns potential physico-chemical interactions.

Within the type B waste category, this same problem led, in Chapter 5, to considering specific repository modules according to the chemical content of the waste; in the overall architecture, it is therefore advisable to separate these different modules.

6.1.1.6 Compartmentalization

In order to limit as much as possible the impact of an altered situation to only a fraction of the repository, and thus reduce its potential radiological consequences, the repository can be sub-divided into sub-assemblies separated from each other by seals.

6.1.2 Taking account of reversibility

Reversibility is associated with disposed waste package management flexibility. It refers to the capability to retrieve waste packages and intervene in the disposal process. As indicated in Chapter 5, the capability to retrieve the waste package has an essential influence on the design of the disposal cells.

6.1.2.1 Intervention capability

The capability to intervene in the disposal process involves, in particular, the ability to take decisions concerning part of the repository without affecting decisions taken or to be taken concerning other parts of the repository. In other words, in order to be exercised effectively, intervention capability requires a modular repository design. The repository is therefore sub-divided into sub-assemblies which can be managed individually with a flexibility similar to that found in a storage facility.

Modularity thus defined ties in with the advantage of sub-division for long-term safety reasons.

6.1.2.2 Progressive construction of the repository

The period of time during which packages are placed in the repository, which may extend over several decades, calls for a progressive approach to repository construction. As experience feedback is accumulated in repository operation, scientific knowledge improves and technology evolves, it is possible to envisage that disposal procedures will evolve with time.

Modular repository design, combined with progressive construction allows these changes to be taken into account: by constructing these repository sub-assemblies progressively, as they are needed, we retain the ability to alter their design.

6.1.3 Taking account of operational safety and the diverse nature of the activities

The design of the repository's architecture must include the capability to construct repository sub-assemblies at the same time as other sub-assemblies are in use or being closed. This leads to the co-existence of nuclear operation activities (transfer and placing of packages) and civil engineering activities (construction and closing of repository structures). These activities are characterised by different safety and security requirements and different physical flows. Safety and efficiency require installations to be designed so as to separate these activities in either space or time.

6.1.3.1 Construction activities

Construction activities include the excavation, support, lining and fitting out of underground structures. They fall within the scope of a conventional underground work site or mining operation.

6.1.3.2 Repository placement or "nuclear operational" activities

Repository placement or "nuclear operation" activities concern the receipt of primary packages and the preparation of disposal packages in surface installations, the transfer of these disposal packages to underground installations and their placement in the disposal cells.

They also concern the observation of the installations for a period during which they are accessible, within the context of reversible repository management.

These nuclear activities are characterized by constraints similar to those of conventional nuclear installations.

The repository's siting underground entails additional constraints and particular attention must be given to the management of ventilation and the mechanical stability of underground structures (adaptation of their dimensions to the geomechanical characteristics of the ground, surveillance of underground structures).

6.1.3.3 Closing activities

These activities concern the sealing of the cells, the sealing and back-filling of the drifts and the sealing and backfilling of the shafts.

The sealing of the cells requires civil engineering techniques in the immediate vicinity of a "nuclear" structure; it will therefore be subjected to constraints similar to those of nuclear operations.

The sealing and back-filling of the drifts are possible using civil engineering techniques outside the "nuclear" context as they are located at a significant distance from the disposal cells.

6.1.3.4 Ventilation of underground installations

Ventilation is an essential element of the hygiene and safety of all underground structures. As such, it is an dimensioning element which must be considered from the structure's design stage. It enables personnel to work in constantly renewed fresh air and makes it possible to evacuate personnel and control smoke in the event of a fire.

6.1.4 Quantities and flows of packages and materials to be transferred into underground installations

As far as quantities are concerned (number of cells, excavated volumes, repository footprint areas), the repository architecture is determined directly by the number of waste packages to be disposed.

The architecture is also determined by the progress of the disposal process, which is involved at two levels. On the one hand, the duration of the pre-disposal storage of highly exothermic packages influences the number of packages disposed per cell and the spacing between cells. On the other hand, with a progressive approach to repository construction, the rate at which packages are placed in the repository affects that of the construction work and, therefore, the dimensioning of the infrastructures required to carry out the work.

The quantitative data on which the architectures described in this chapter are based, refer to the various study scenarios and package receipt flow assumptions described in Chapter 3. The volumes of disposal packages are those of the packages described in Chapter 4. The number and layout of the cells correspond to the descriptions in Chapter 5.

From a thermal point of view, the figures given in this section correspond to “at the earliest reasonable disposal” of highly exothermic packages, with the options described in Chapter 5. The influence of any extension of the duration of the pre-disposal storage and a change in the placement rate will be discussed in section 6.6.

6.1.4.1 Summary of the number of packages taken into account and the number of cells

Table 6.1.1 summarizes the number of primary packages of waste and spent fuel to be taken into account in the event of a decision to treat them also as waste. The corresponding numbers of the disposal packages and disposal cells are shown.

From a thermal point of view, three levels can be considered:

- Non-exothermic or slightly exothermic packages (B packages),
- Moderately exothermic packages (C0 packages), that can be disposed of without prior storage,
- Highly exothermic packages (C1 to C4 packages and, where applicable, CU1 and CU2), which require prior storage for several decades, the duration of which affects the dimensioning of the repository zones.

Table 6.1.1 Number of packages taken into account and number of cells

		Scenario S1a	**Scenario S1b**	**Scenario S1c**	**Scenario S2**
Non-exothermic or slightly exothermic packages					
B waste	Number of primary packages	199,815	197,115	197,115	168,265
	Number of disposal packages	54,700	54,000	54,000	46 200
	Volume of disposal packages m^3	321,000	317,000	317,000	273,000
	Number of cells	38	37	37	32
Moderately exothermic packages					
C0 Waste	Number of primary packages	4,120			
	Number of disposal packages	4,120			
	Volume of disposal packages m^3	1,600			
	Number of cells	200			
Highly exothermic packages					
C1 C2 C3 C4 Waste	Number of primary packages	32,200	32,100	38,350	10,560
	Number of disposal packages	32,200	32,100	38,350	10,560
	Volume of disposal packages m^3	12,900	12,800	15,300	4,200
	Number of cells	4,800	4,500	4,800	1,400
SF1 spent fuel	Number of assemblies				54,000
	Number of disposal packages				13,500
	Volume of disposal packages m^3				82,000
	Number of cells				3,900
SF2 spent fuel	Number of assemblies		5,400	5,400	4,000
	Number of disposal packages		5,400	5,400	4,000
	Volume of disposal packages m^3		7,500	7,500	5,500
	Number of cells		1 800	1 800	1,300

With respect to CU3 type packages, which for investigative purposes are taken into account alongside the inventory model scenarios (and are moderately exothermic), their disposal would represent in total 120 cells for 2,170 disposal packages, all families combined.

6.1.4.2 Package flows

As indicated in Chapter 3, for highly exothermic packages, the emplacement flow hypotheses are close to the waste production flows. In the case of slightly or moderately exothermic packages, at this stage in the studies, flows have been taken into account that are considered "reasonable" from the point of view of the construction and operation of the repository.

The annual flows of different types of packages are summarized in Table 6.1.2, which also shows the orders of magnitude of the duration of emplacement in repository (assuming continuous operation with regular flows).

Table 6.1.2 Annual package flows

	Number of primary packages processed per annum[101]	number of primary packages produced per annum	Duration of operation
Not very or slightly exothermic packages			
B waste	5,000	1,400	40 years (scenario S1) 30 years (scenario S2)
Moderately exothermic packages			
C0 Waste	400	400	10 years
SF3 spent fuel	400	150	15 years
Highly exothermic packages			
C1 C2 C3 C4 Waste	600 to 700	600 to 700	55 years (scenario S1) 15 years (scenario S2)
SF1 spent fuel	1,500	350	35 years
SF2 spent fuel	150	150	35 years (scenario S1) 25 years (scenario S2)

6.1.4.3 Other flows

Because of the concomitance of the operation of the repository and construction work, the main flows produced by these activities are an essential factor in the dimensioning of the architecture, in particular the flows of broken rock resulting from excavation work and the flows of concrete related with the installation of the lining in the drifts. Closure work also produces major flows of backfill.

Flows related to construction are determined on the one hand by the construction of the repository modules described in Chapter 5, that is to say, the cells and access drifts from which they are excavated, and on the other, by the construction of the drifts that provide the connections between the shafts and repository modules. The latter represent a significant part of the construction flows. At this stage in the project, only orders of magnitude can be given.

On the basis of the conventional rates used above, the "typical values" of the annual excavated volumes vary depending on the package types. In the case of B packages, this figure is in the region of 50,000 m^3 per year[102]. These volumes are significantly higher in the case of very exothermic packages: of the order of 80,000 m^3 per year for C packages, 120,000 m^3 per year for CU2 packages and up to 300,000 m^3 per year for CU1 packages although they are not significant for moderately exothermic C0 (and CU3) packages, the number of which is low. These figures constitute orders of magnitude around which the actual values may vary greatly[103] in accordance with decisions taken on repository management.

On the basis of the conservative hypotheses currently used for the lining of the drifts, the flows of concrete amount to approximately 50% of the excavation flows. With regard to backfill, backfill rates in the region of 200,000 m^3 of drift backfilled per year are foreseeable. However, this is not a value defined for the repository, but a possible order of magnitude.

Infrastructure must also be designed to allow the passage of other flows that circulate in the repository such as building materials (steel for support, clay buffer) and consumables required for mobile equipment operation.

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[101] Or number of spent fuel assemblies or cladding.

[102] Volume excavated. Because of the “swell factor” of the broken rock, the actual volume to be transported is approximately 50% greater.

[103] With a range in the region of ± 50 %

Ventilation flows, largely determined by operation and above all construction requirements, may reach or even exceed 500 m^3/s and are an essential factor in the dimensioning of the underground installations.

6.2 Overall design

6.2.1 General organization of the repository

Packages are isolated in different zones (B, C0, C waste and, if applicable, spent fuel) through concern, stated in Section 6.1.1.5, to ensure that different package categories are kept independent of each other [37].

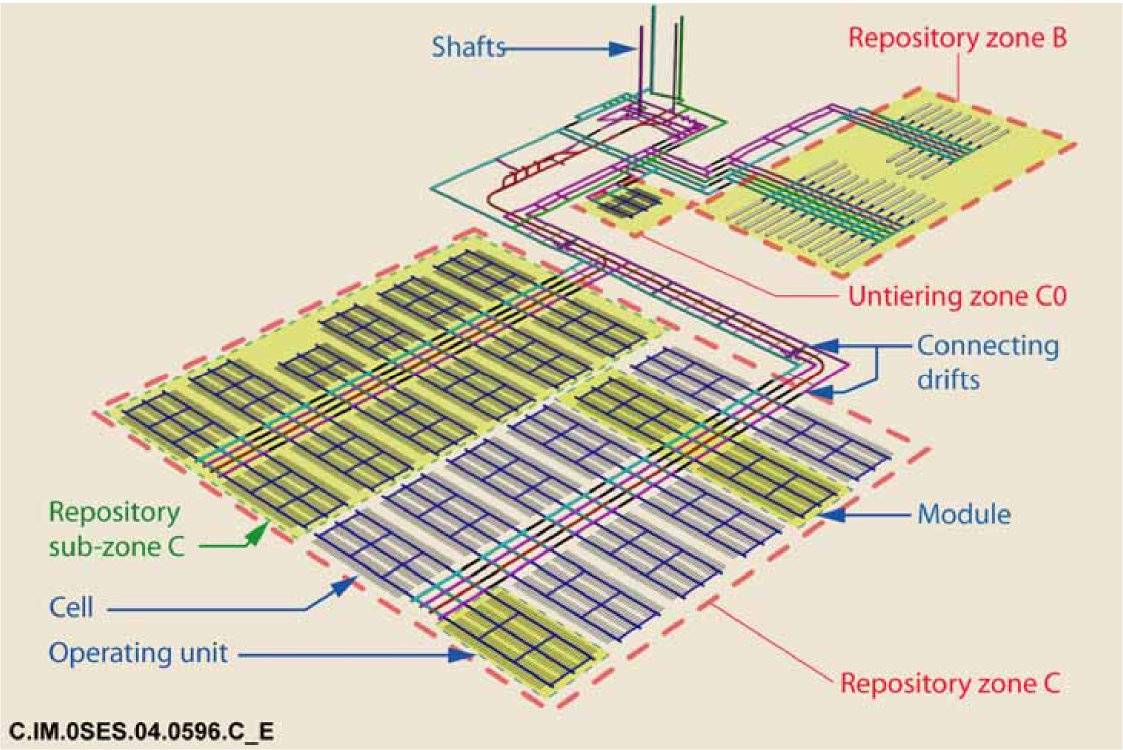

Figure 6.2.1 General organization of the repository

6.2.2 Modularity of the repository zones

In response to the need for compartmentization to ensure long-term safety and the need for modularity in the interests of flexibility and a progressive approach to the construction and operation of the repository, the repository zones are subdivided into a tree structure comprising *sub-zones*, *modules, operating units and cells*.

The need for a flexible approach to construction and operation has led to the division, depending on the magnitude of the inventories of C packages and, where applicable, spent fuel, of each corresponding repository zone, into 2 to 4 *sub-zones*, each of which comprises several *modules*.

The *modules* form the basic elements of repository compartmentization justified by long-term safety. Each zone is thus divided into at least ten modules.[104].

Where operational organization is concerned, the modules can be subdivided into *operating units*, in which only one type of activity is carried out (construction, operation or closure) for a period of several months or years.

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[104] In the case of zones with a small inventory, the number of modules may be less than 10.

In the B waste zone, each module comprises one *cell* and one *drift* that provides access to it and corresponds to an *operating unit*. In C waste (or spent fuel) repository zones, each module comprises several dozens of *cells*. In the architecture presented here, one module is subdivided into two *operating units*.

Operating units are constructed and operated as repository space is required at a rate of one unit every 1 to 2 years depending on the zone. When the construction or operating periods exceed this periodicity, several operating units can be under construction or in operation simultaneously in the same zone.

Details of the layout of the various repository zones is given in Sections 6.2.5 and 6.2.6 below.

In order to ensure compartmentization, each module is isolated from the rest of the underground installations by one or more seals at the time of closure.

6.2.3 Access to repository zones

6.2.3.1 Repository access shafts

The surface installations are connected to the underground installations by means of a group of shafts common to all repository zones. The layout used facilitates control of the long-term hydraulic functioning of the repository:

- The shafts are all located together in the same zone, which has a radius of approximately 200 meters and is offset from the repository zones;
- The shaft zone is connected to the repository connecting infrastructures by a group of drifts that run parallel to the main geotechnical stress. These parallel drifts shall be sealed when the repository is closed.

A detailed description of the shafts is given in Section 7.3.

6.2.3.2 Connecting drifts

The repository modules are connected to the shafts by *connection infrastructure* made up of clusters of *parallel connection drifts* that vary in number depending on the size of the flow to be managed. These are all hierarchised into *main connection drifts*, which connect the shaft zone to the various repository sub-zones, and *secondary connection drifts*, inside each sub-zone. This hierarchisation makes the construction and operation of the repository more flexible and means that the various sub-zones are independent from each other. Distinguishing between dedicated *package transfer drifts, construction drifts* and, depending on requirements, *air exhaust drifts* facilitates the management of coactivity between nuclear activities and civil engineering activities.

A detailed description and design of the connection drifts can be found in Section 7.4.

6.2.4 General repository layout

6.2.4.1 Positioning in the clay formation

At this point, Andra used the layout of all the repository modules in the median part of the Callovo-Oxfordian formation. This option ensures the same undisturbed argillite thickness between the repository and the over- and underlying carbonate formations[105]. There is no significant vertical variation in the parameters that govern the retention and solubility of the radionuclides between the different lithofacies of the formation; the Callovo-Oxfordian conceptual model therefore adopts identical values to these parameters for different lithological horizons [75] and [76] – Chapter 6).

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[105] From an optimisation viewpoint, this option could be reviewed taking into account (i) the geomechanical behaviour of the different lithofacies of the formation, and (ii) the migration times of toxic elements into the surrounding formations.

The mechanical properties of the median part are weaker than those of other parts of the Callovo-Oxfordian formation. This ensures the study takes a conservative approach as regards the geotechnical feasibility of the repository.

As the maximum dip of the layer is 3%, the direction of this dip is not a determining factor in the overall architectural design.

6.2.4.2 Repository component topology

The topology taken into account favours the long-term hydraulic functioning of the repository. The repository has a dead end type tree architecture from the cells to the shafts. On all levels of the tree structure, access to each element of the repository is via a small number of clustered access ways.

At this stage in the studies, the incorporation of this architectural topology shows its feasibility despite the inherent constraints from the point of view of ventilation in particular.

6.2.4.3 Drift arrangement

The drifts and cells are arranged over a rectangular grid. Thus, all the drifts and cells to be sealed can be oriented parallel to the main horizontal stress to limit damage to the argillite in the vicinity of the seals.

6.2.5 Description of the B waste repository zone

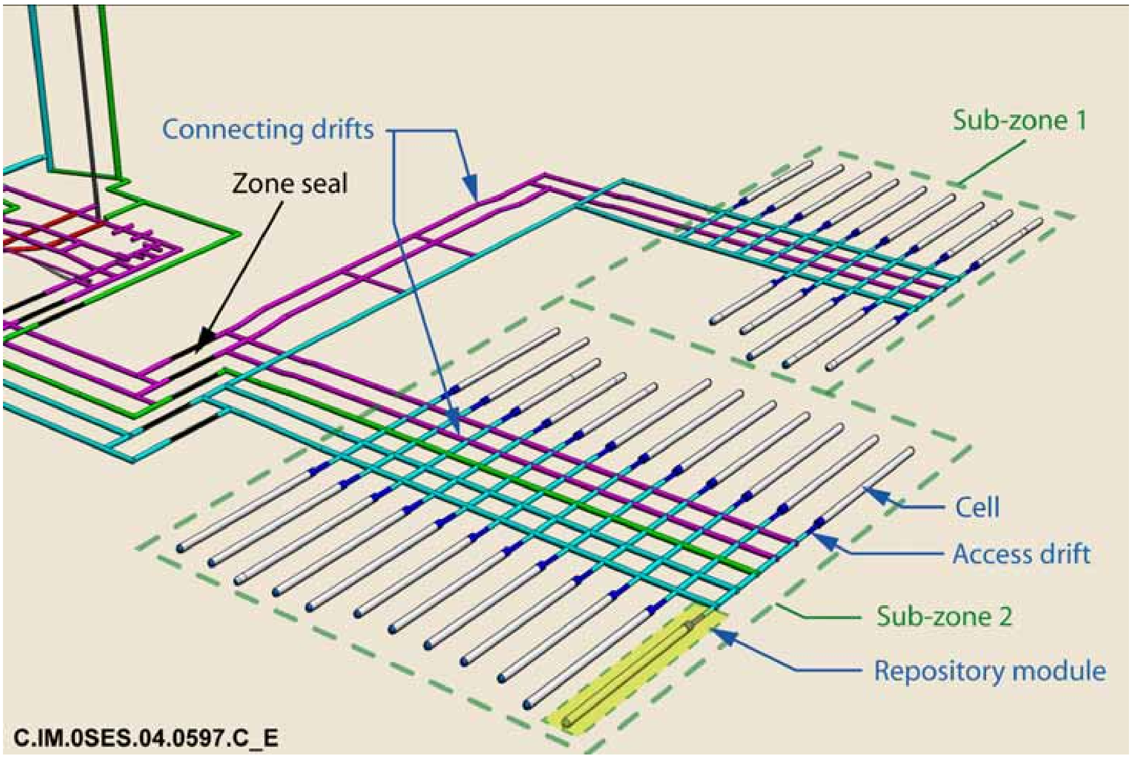

Figure 6.2.2 Layout of B repository zone

B packages whose physical and chemical properties differ are disposed in different modules (see Chapter 5). In Figure 6.2.2, packages containing no organic matter have been grouped together in sub-zone 1.

The space between the cells is defined by geotechnical dimensioning. The centre-to-centre distance between the cells used here is 72 meters which leaves a pillar of at least 5 times the diameter of the cells between two cells whose excavated diameter is 12 meters in order to ensure good stability.

Segments of zone B drifts that run parallel to the main horizontal stress are sealed with argillite plugs. The seals situated in the cell access drifts ensure the zone is compartimentized into one-cell modules. Seals situated in connection drifts separate B zone from other repository installations.

6.2.6 Description of the C waste and spent fuel repository zones

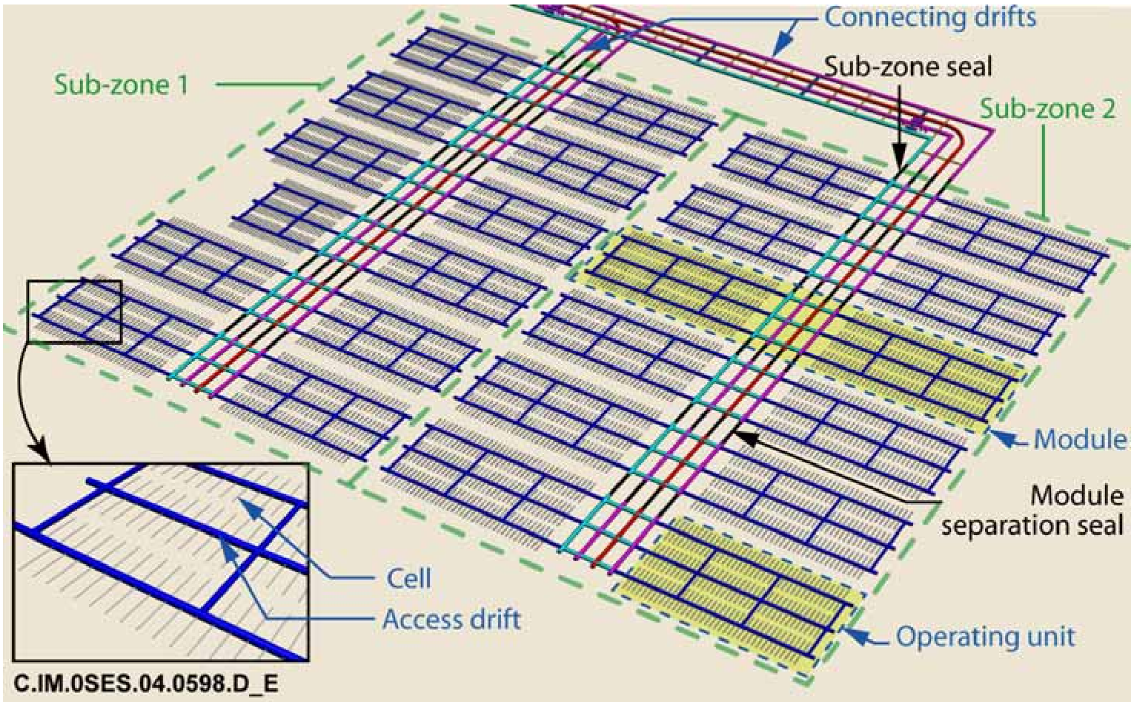

Figure 6.2.3 Layout of a C (or spent fuel) repository zone

The layout of C Waste (and, where applicable, spent fuel) repository zones is similar. Their design and dimensioning are greatly conditioned by thermal considerations.

In order to facilitate the organization of their construction, operation and closure, these zones are split into sub-zones, each of which is then subdivided into 8 to 12 operating units.

Each operating unit comprises 80 to 220 cells. The space between the cells is defined by thermal dimensioning (see Chapter 5).

The operating units comprise 3 parallel drifts, the *cell access drifts*, connected to the connecting drifts. These access drifts are connected to each other by perpendicular *interconnecting drifts*. This layout of drifts in threes ensures a high degree of ventilation operational safety even in the event of fire.

Zone C is sealed with argillite plugs located in structures that run parallel to the main horizontal.

- **Special case of C0 (and CU3) packages**

C0 type C packages, which are significantly less exothermic than other C packages, are assigned to a specific sub-zone with only one module. This would also be the case for CU3 type fuels, if applicable.

6.2.7 Capacity to adapt to the possible discontinuity of the geological environment

No fault was detected during surveys of the Callovo-Oxfordian formation. Geological modelling gives grounds for considering that this situation can be extrapolated to the whole transposition zone introduced in [6] - Tome 1. This is conducive to the description of a regular architecture. However, it is clear that the modular nature of the architecture could be adapted for a scenario (deemed unlikely, as knowledge about the site increases) in which the repository would intercept a secondary fracture with a greater hydraulic transmissivity than that of sound argillite. Such a fracture would, in any event, be detected at the latest during surveys carried out before or during the construction of connection drifts. The architecture could then be adapted accordingly: an undisturbed argillite thickness over a distance of a few hundred meters would be maintained between this fault and the nearest repository modules; in addition to this, connection drifts nearing or passing through the fracture could be sealed when the repository is closed.

6.2.8 International comparison factors

In the United States of America, the Department of Energy has been operating an underground radioactive waste repository, the WIPP (Waste Isolation Pilot Plant), situated in a salt bed at a depth of 650 m since 1999. It is the only underground long-lived radioactive waste repository facility currently operating in the world. Figure 6.2.4 gives a perspective view of these facilities [77].

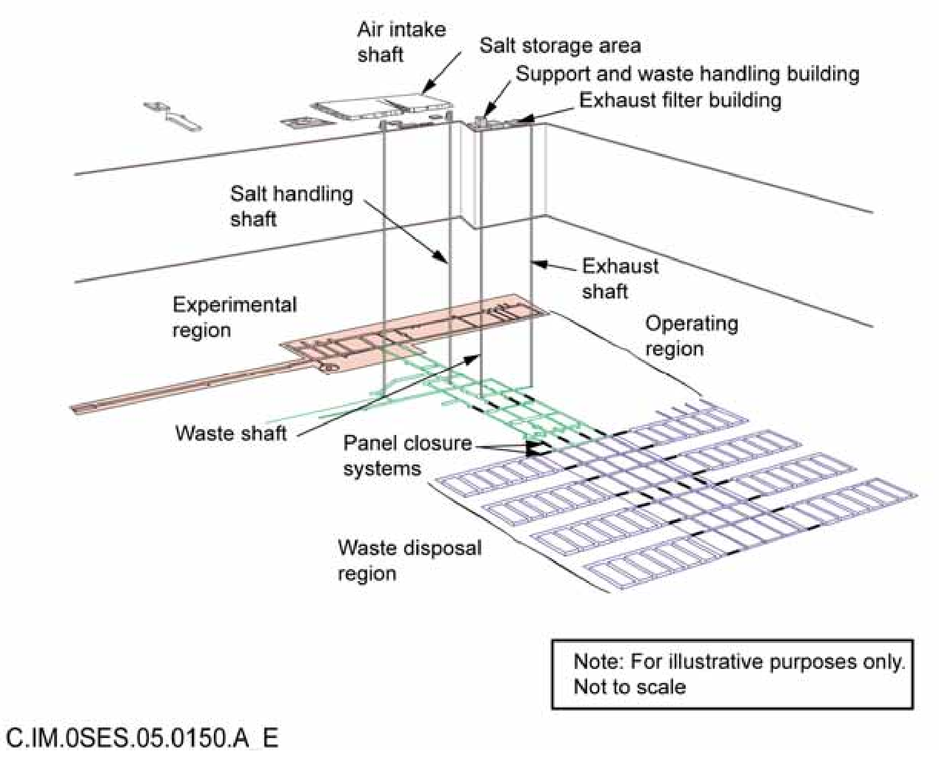

Figure 6.2.4 Perspective view of the WIPP underground repository

This architecture and the underlying organisation of the work have several points in common with those set forth in this chapter:

- Modular repository zone, constructed progressively according to disposal needs
- Network of a number of dedicated connection drifts facilitating coactivity between nuclear and civil engineering activities.
- Clusters of shafts connecting surface and underground installations.

6.3 Architectural dimensioning factors

The dimensioning factors of repository architecture include, notably, (i) geotechnical factors that result in constraints on the dimensions and spacing of the cells and drifts, (ii) thermal factors that also affect distance, (iii) hydraulic factors that affect the geometric and topological layout of some architectural elements [37].

6.3.1 Geotechnical aspects

From the point of view of repository architecture, geotechnical dimensioning, beyond the dimensioning of the ground support and the lining of each structure (drift, cell), is a factor in the definition of the minimum distance between engineered structures. Given that the impact of an isolated drift on the terrain is not detected further than a distance of two diameters over the course of several centuries, we have used a distance between parallel drifts or cells that is equal to at least five times their diameter to ensure the mechanical independence of the structures. The stability of each structure on an individual basis then makes it possible to ensure the stability of the whole zone. At this point in the studies, account has not been taken of the effect of the "firm band" which tends to transfer the weight of overlying ground to bands of ground left untouched around edges of the excavation areas thus reducing the stress exerted on the drifts or cells.

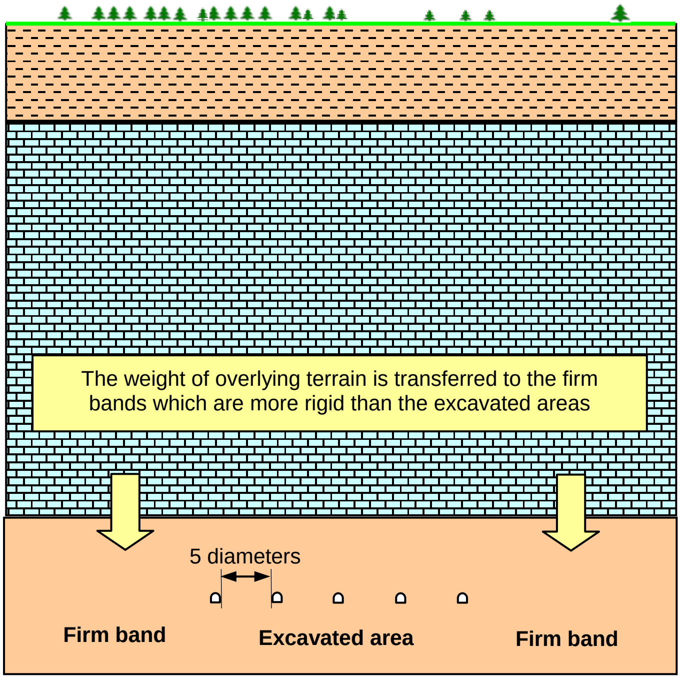

Figure 6.3.1 Distance between structures, "firm band" effect

This minimum distance between structures applies to all cells and drifts. It is notable that in the case of cells containing moderately or highly exothermic packages, the distance between cells is above all determined by thermal considerations.

In the very long term, if the liners deteriorate, the limitation of residual empty space left in the disposal cells and backfilled drifts would counter the propagation of damage to the argillite [78].

6.3.2 Thermal behaviour of the repository

Limiting the temperature in the repository is dependent on the dimensioning of the repository modules presented in Chapter 5. The interaction between repository modules, however, leads to diffusion of heat into the geological formations. This section evaluates the impact of this interaction and confirms that it is compatible with the above-mentioned objective of keeping different categories of waste independent.

6.3.2.1 Evolution of Temperatures in and around high level waste repository modules

For an initial period of some decades after emplacement in the repository, the temperature of a waste package solely results from the heat it releases and that released by packages in immediate proximity to it; this is due to the slow diffusion of heat into the geological formation. In the longer term, the area of thermal influence of each package gradually increases. The evolution of the temperature in the repository modules therefore becomes sensitive to the relative layout of the modules.

Thus, the further a module is extended and the closer it is to neighbouring modules, the longer packages situated at the centre take to cool. Similarly, the temperature of modules situated at the core of the repository zone will take longer to drop than that of the modules situated around the perimeter.

The following figures show the evolution of the temperatures on the scale of the C waste repository zone. This evolution has been calculated by projecting in time the thermal simulations produced by three-dimensional finite elements presented in Chapter 5.

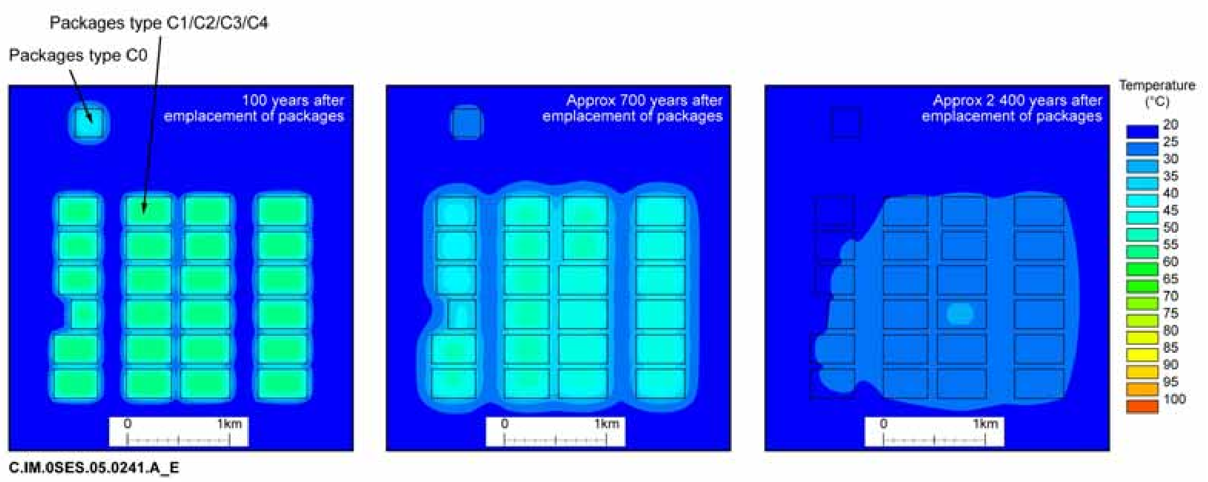

Figure 6.3.2 Horizontal evolution of the temperatures in the c waste repository zone, (scenario s1a, disposal of the waste after 60 to 70 years of temporary storage)

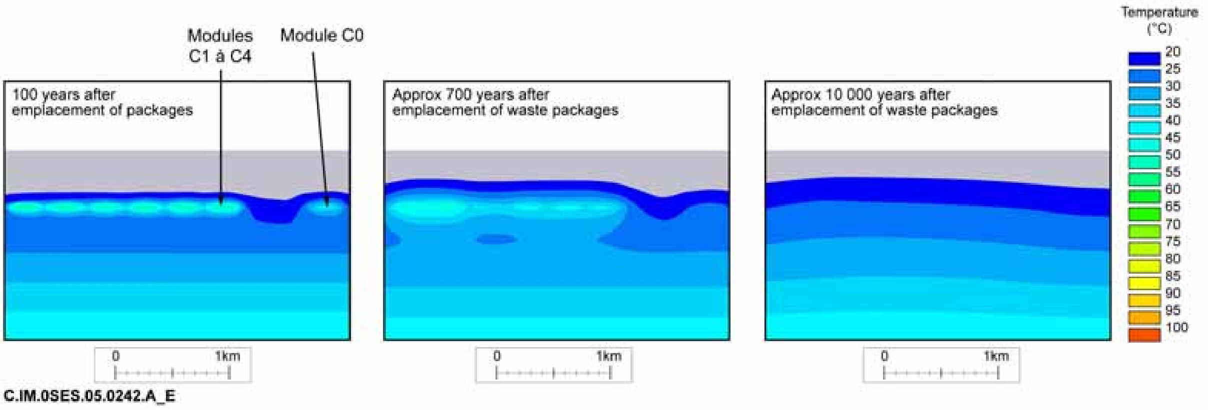

Figure 6.3.3 Vertical evolution of temperatures around the c waste repository modules

Over the scale of a century, there is little interaction between the modules. On the other hand, after several centuries, the temperature tends to become progressively homogenous in the repository zone, with a slight gradient from the core of the zone towards its perimeter. On a scale of tens of thousands of years, the distribution of temperature in and around the C waste repository zone returns close to the initial natural geothermal gradient (Figure 6.3.2 and Figure 6.3.3).

Because of the interactions between modules that occur over time, the thermal period, defined by a temperature at the core of the packages that is higher than approximately 50 °C, depends on the density of the placement of the packages in the repository on the scale of the repository zone. This density brings the distances between modules into play.

A more rapid drop in temperature will be observed in the part of the repository where C0 type packages are placed (see Chapter 3) due to the lower exothermicity of these packages; the distance between this part of the repository and other modules taken into account ensures thermal independence.

6.3.2.2 Thermal independence of different repository zones

The thermal independence of the B waste repository zone from the C waste and, where applicable, the spent fuel repository zones has also been verified. The influence of such a zone situated 250 meters from a B waste disposal cell is less than 4 °C. The corresponding thermal peak is reached several thousand years after placement in the repository.

Within B waste, while B2 type packages (bituminised waste) are very slightly exothermic, they are very sensitive to temperature. Thus it has been verified that the distance between cells containing B2 packages and cells containing other packages will keep the temperature of B2 packages below 30°C.

Figure 6.3.4, for example, shows the increase in temperature above the initial temperature of the rock (equal to 22°C) in a cell of B2.1 packages the end of which would be situated 100 meters from a cell of slightly exothermic B packages (here a B3 reference package has been adopted, the heat rating of which decreases more slowly over time compared to that of the other reference packages, and, as a result, it is more likely to have greater influence of the neighbouring cells).

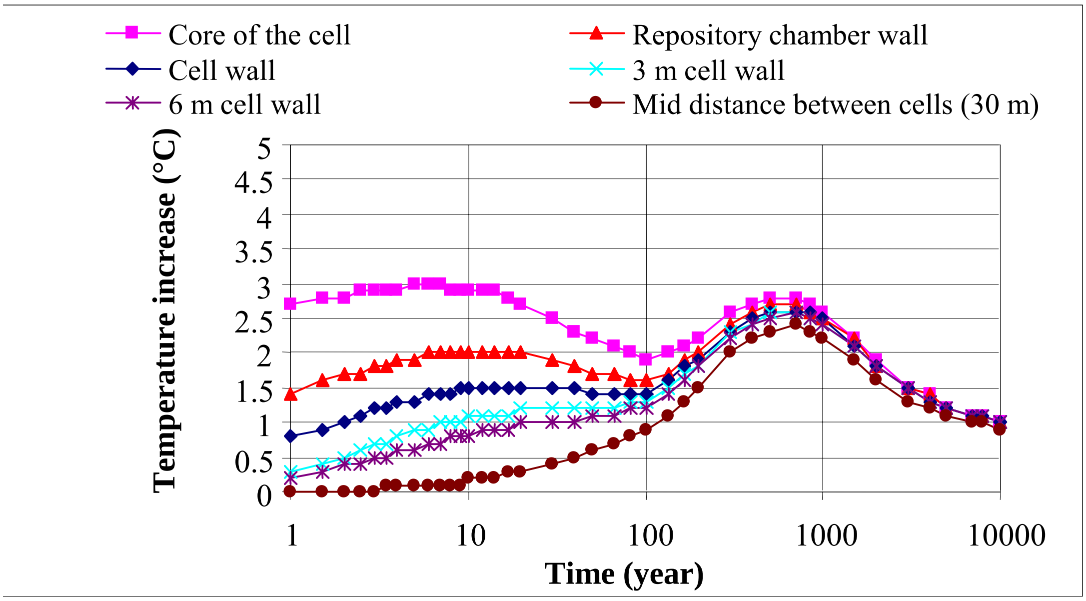

Figure 6.3.4 Increase in temperature in a cell of B2.1-type waste as a function of time

In this configuration, an initial temperature peak occurs less than ten years after the packages are placed in the repository. This peak is caused by the thermal power emitted by the B2.1 packages and is very low. After several centuries, a second peak can be caused by the heat flux emitted by neighbouring slightly exothermic packages [10].

6.3.3 Hydraulic behaviour of the repository

The limitation of water flows in the repository depends above all on the characteristics of the site (low permeability of the argillite, gentle gradients). As indicated above, the architecture studied contributes to this in a complementary way through the general topology and the seals; it can, therefore, reinforce the robustness of the hydraulic functioning of the repository.

This section presents the simple principles of the hydraulic functioning of the repository and illustrates the contribution of the architecture to the robustness of this functioning.

After hydraulic balance is re-established, the following should be distinguished: (i) water flows drained by the repository into the argillite (ii) those that could be trapped by the shafts passing through overlying formations.

Darcy's law, which constitutes an envelope model for argillite formation, has been used here to describe these flows [106].

6.3.3.1 The hydraulic situation upon closure of the repository and resaturation

In its natural state, the Callovo-Oxfordian layer is saturated with water. The water can move there vertically under the effect of the head difference between the over- and underlying geological formations (Oxfordian and Dogger). Its rate of displacement is very slow on account of the very low permeability of the formation. For a medium hydraulic head gradient in the Callovo-Oxfordian layer of the order of 0.2 meter per meter, natural vertical displacement of the water takes place[107] at a rate of a few centimeters per hundred thousand years. The corresponding flows are some hundred litres per square kilometer of horizontal footprint.

During the repository operation and observation phase, the excavation of the structures and their ventilation bring about a drop in hydraulic head that is accompanied by a desaturation of the argillite around the structures. When the repository is closed, the drifts are progressively backfilled, seals are constructed all the way through and ventilation is stopped.

A repository resaturation phase follows, controlled by the low permeability of the argillite formation: this is what determines the flow of water entering the repository. The influence of gas produced by the anoxic corrosion of the metals present in the repository structures after closure which tends to slow resaturation should also be noted. This reaction between the iron and the water may, in fact, begin before the structures are completely resaturated from the moment there is no more gaseous oxygen.

The differences between structures in terms of the volume of the empty spaces to be filled with water (cells filled with packages, backfill of drifts, etc.), the different kinetics of gas production and differences in the hydrological properties of porous materials (bentonite, concrete, backfill) result in differences in the resaturation time of the various structures by the argillites [8] [62]. The seals planned in the design slow down the hydraulic circulations in the repository (cell plugs and connection drift seals); others hydraulically isolate overlying formations (shaft and drift seals in the shaft zone). In this way, these seals limit the water flows inside the underground installations. Having taken account of these factors, resaturation periods can vary from a few decades to several tens of thousands of years depending on the structures.

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[106] This model tends to overestimate the flows for very low permeabilities.

[107] This drainage rate is lower than the rate of diffusion of the solutes in the water

6.3.3.2 Water flows drained into the argillite after return to hydraulic equilibrium

When resaturation is almost complete, the potential water movement in the argillite occurs again unidirectionally, from the surrounding formation with the strongest hydraulic head towards the formation with the lowest hydraulic head.

Water flows that circulate in this way in the argillites are liable to be intercepted by the disposal cells and by the access and connection drifts. On the scale of the repository, the total flow intercepted is proportional to the accumulated surface area (drifts and cells). It is evaluated[108] at several cubic meters per year.

If the overall permeability of the repository is low, close to that of the argillites, the water flow intercepted by each structure (cell containing packages or drift) is restored to the argillite without circulating through the drifts and shafts.

The design of the repository aims to come close to this situation. In order to do this, the installation of seals in the shafts and in the drifts provides considerable hydraulic resistance to the circulation of the water. Thanks to these seals, the presence of the repository does not significantly modify the hydraulic regime of the geological formation. In the case of an upward gradient, only a small fraction of the flows intercepted by the repository is removed via the drifts and shafts; it is evaluated for a shaft seal permeability of 10^{-11} m/s at several hundred litres per year for the entire repository. This low flow rate renders the rate of the water in the structures negligible. The migration of radionuclides released by the packages therefore takes place essentially by diffusion and not by advection within the water flow. So these radionuclides will migrate preferentially into the Callovo-Oxfordian layer rather than via the drifts towards the shafts.

In a situation in which the role of the drift and shaft seals is not taken into account (this would correspond to a situation of total or partial seal failure), the repository would no longer provide resistance (or would provide reduced resistance) to the circulation of the water.

In the case of an upward hydraulic head gradient, such a situation would result in an increase in the water flows that would be evacuated via the drifts and connection shafts rather than via the argillite. Thus, for an upwards gradient of the order of 0.2 and in the absence of seals, the flow evacuated via the drifts would represent 2 to 3 m^3/year.

Although independently of any other considerations this flow rate remains low, Andra has adopted an architectural topology whereby its impact on the release and migration of radionuclides can be reduced: it is a matter of locally limiting the proportion of flow circulating in and near to each disposal cell.

The topology adopted is a dead end type tree layout, the principle of which is illustrated by the following figure. The dead ends on different levels of the tree structure are shown in red from the individual cell to the repository zone. On all levels of the tree structure, access to each repository element is via clusters of a small number of access ways.

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[108] For a vertical hydraulic gradient of 0.2.

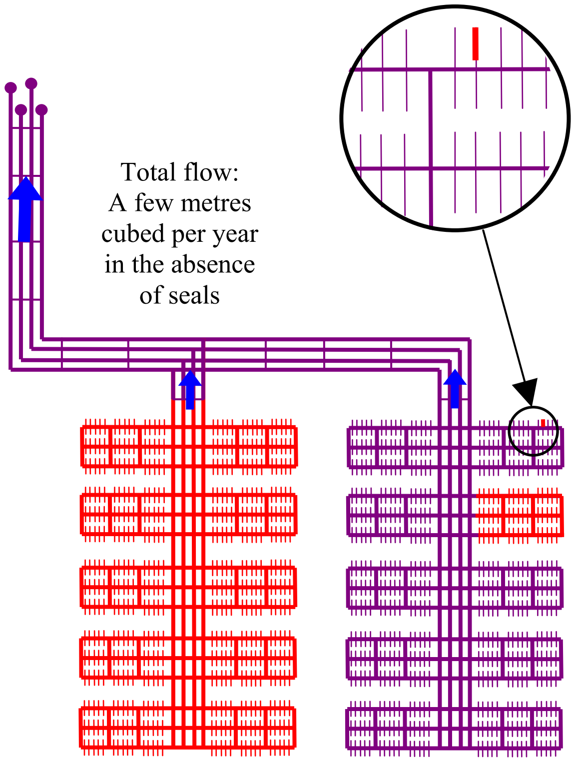


Figure 6.3.5 Dead end type tree architecture

The flow of water drained into each dead end is limited to the flow that this element can exchange with the argillite. As the elements of the same tree structure level run parallel to the trajectory of the water, inflow from other elements is avoided in each case. Thus, the flows circulating in the structures and, consequently, the rates of advection are low closest to the cells. The flows drained are only combined progressively towards the main connecting drifts and the shafts.

It should be noted that, this principle allows a certain degree of flexibility in the detailed configuration of the structures compared with the architecture presented.

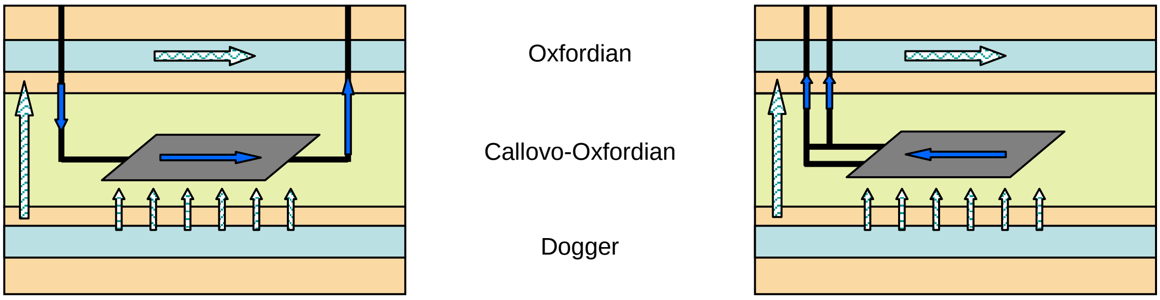
6.3.3.3 Water flows trapped by the shafts in overlying formations

Depending on the direction of the hydraulic head gradient between the Oxfordian and the Dogger, connecting shafts could capture the water flows in geological formations passed through and carry them into the repository. These flows would then be added to those drained into the argillite. The seals planned for these shafts, and present also in the drifts, prevent this process by the hydraulic resistance that they provide against the circulation of the water.

If the role of these seals is not taken into account (failure situation), the grouped arrangement of the shafts and their location away from repository zones would, however, make it possible to limit the flow of water that would be trapped in the overlying formations and which could flow into the drifts [80].

This option can be compared with that of distant shafts as illustrated in the diagram in Figure 6.3.6. A difference in hydraulic head between the distant shafts could induce a U-shaped flow passing through the repository and would bring it into contact with the overlying formations. In this situation, the flows of water trapped by the shafts would not be limited by the low permeability of the argillite.

On the contrary, a short distance between the shafts eliminates the possibility of a U-shaped flow. In the case of an upwards gradient in the shaft zone (Diagram b), no water flow would be trapped in the overlying formations. In the case of a downwards gradient, the flow trapped by a poorly or un-sealed shaft would be limited by the low permeability of the formation studied and would remain of the same order as the flow intercepted in the argillite so there would be no significant impact on the release of radionuclides by the packages and this flow would not constitute a migration vector of these elements.



a) U-shaped flow situation between distant shafts under the effect of hydraulic head gradients within the Oxfordian and between the Dogger and Oxfordian formations

b) Offset shafts in clusters

Figure 6.3.6 Shaft layout and flow limitation

6.4 Logic governing the overall construction and operation of the repository

Section 6.3 showed that the architecture presented was designed to meet long-term safety requirements. This section describes an overall layout that ensures the progressive construction of the repository at the same time as the physical separation of different activities. One point in particular concerns ventilation which is an essential factor in the dimensioning of the repository infrastructure.

6.4.1 Separation of activities

The principle of separating construction work and "nuclear" operation has led to certain infrastructures being dedicated to one or other of these activities.

The infrastructures dedicated to *nuclear operation* activities (waste package transfer) comprise the *waste package transfer shafts, waste package transfer drifts* which connect the shafts and the operating units, and *access drifts* leading to the cells located inside the operating units.

The infrastructures dedicated to *construction work* (and closure) comprise the *construction shafts* and *construction drifts*.

Figure 6.4.1 shows a possible example of work and operation activities being carried out simultaneously.

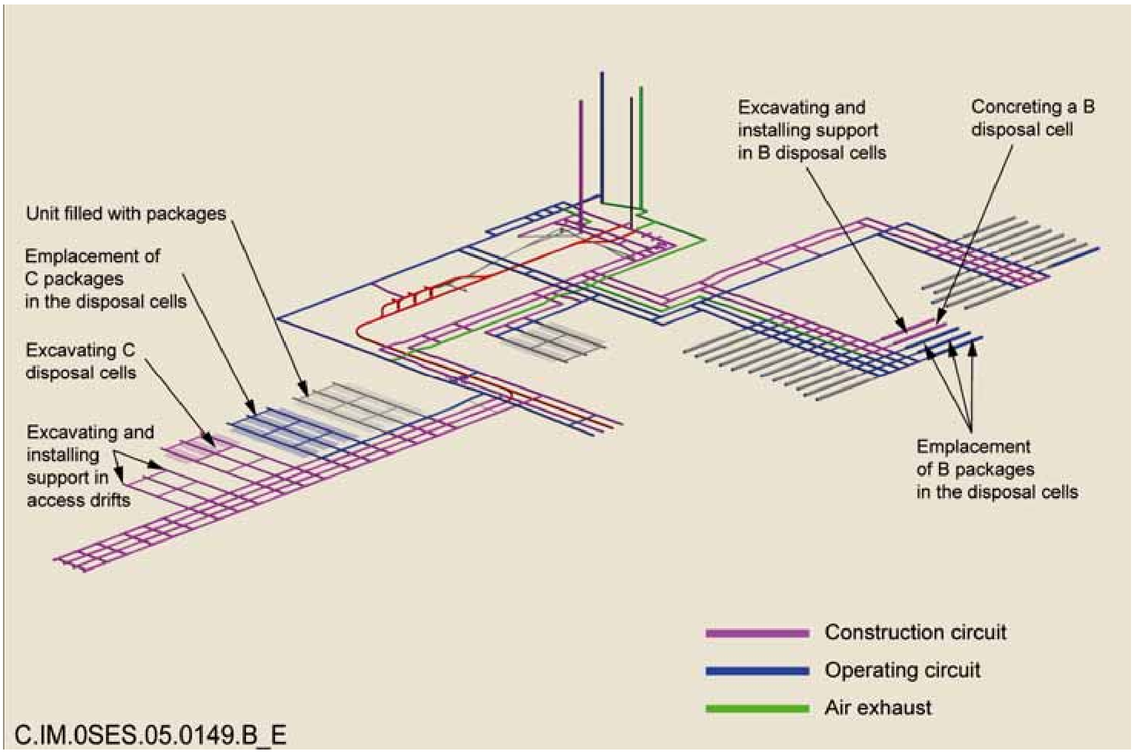


Figure 6.4.1 Separation of operation and construction circuits

6.4.2 Progressive nature of the construction and operation of a repository zone

This section presents a possible organisation of construction and operation activities.

- **Role of the operating unit**

The organization of activities centres on the division of the repository zone into operating units. In the B waste repository zone, each operating unit comprises a single cell with an access drift. In the C waste repository zone (and, if applicable, the spent fuel repository zone),an operating unit comprises several dozens cells served by three access drifts.

Only one type of activity is carried out in one operating unit at a time: construction or nuclear operation.

- **Sequential organization of work**

Thus, an operating unit passes consecutively through a construction phase then an operation phase.

In the space, several operating units can be active simultaneously at different phases. In order to synchronise phases with different durations, the number of operating units in each phase can be altered. For example, if the construction phase takes twice as long as the package emplacement phase, there can be two operating units under construction while one unit is in operation.

By way of illustration,

Figure 6.4.1 shows, in the foreground, the situation in a C repository zone in which two operating units are under construction, one unit is in a nuclear operation phase and one unit is full of packages.

- **Progression of work**

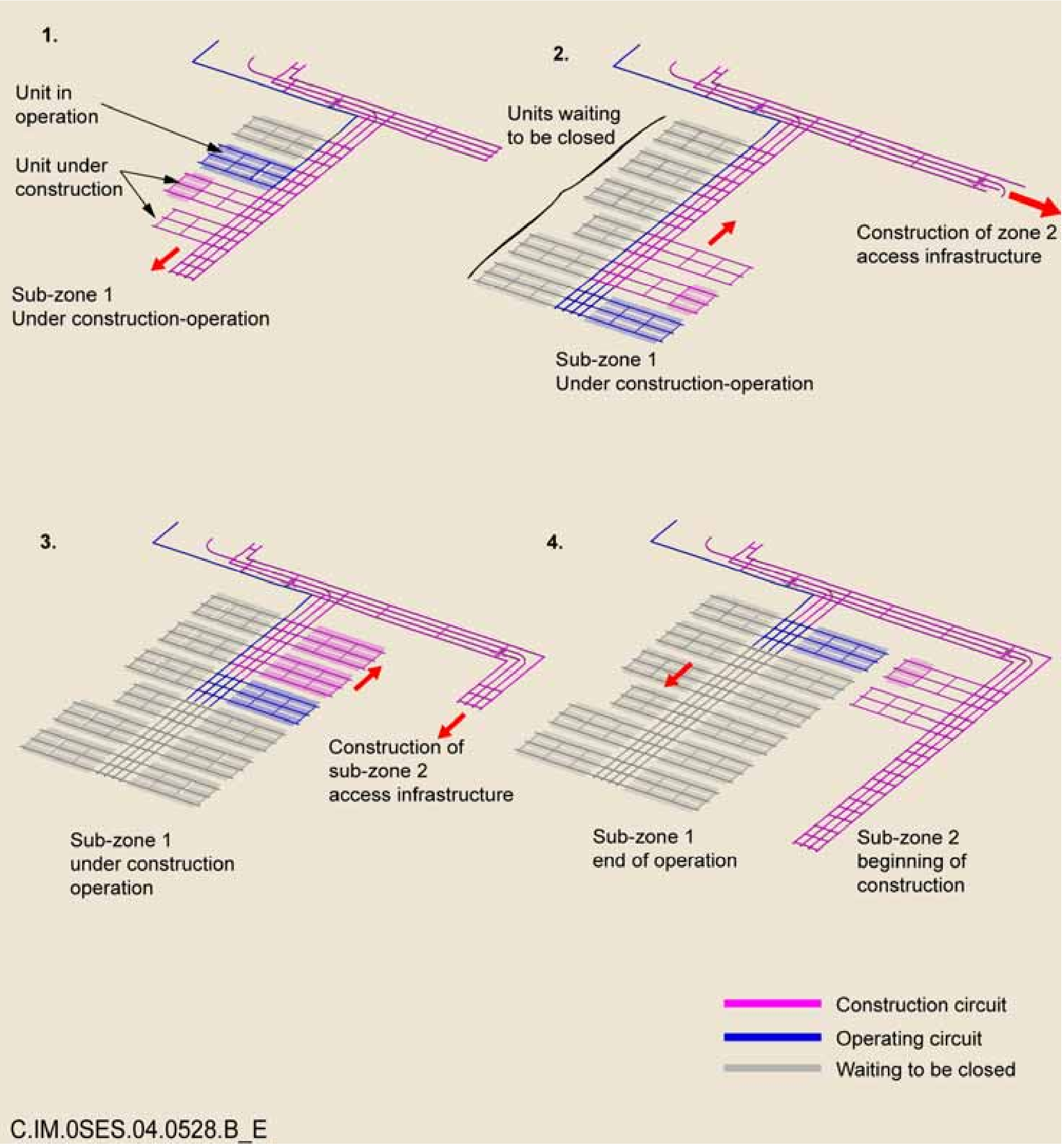


Figure 6.4.2 Construction and operation phases of a c waste repository

Starting at the the entrance to a zone, operating unit work progresses from one side only of the connecting infrastructure, moving away from the shafts ("advancing" in mining terminology). Once the end of the connecting infrastructure is reached, work continues on the other side back towards the shafts ("retreating" in mining terminology). This approach is illustrated in Diagrams 1 and 2 of Figure 6.4.2. The combination of advancing and retreating methods inside the same sub-zone simplifies the management of simultaneous construction and operation activities as it prevents the flows of construction and operation from interfering with one another. This method is currently used in an industrial situation in the WIPP (United States)[109].

The connecting infrastructures are also constructed progressively before the construction of work units. This progression is illustrated in Diagrams 2 and 4 of Figure 6.4.2 and may vary depending on the organisation of work.

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[109] If the intensity of work and operation is relatively low, as in sub-zone 1 of zone B, an entirely "advancing" strategy is foreseeable.

6.4.3 Organisation of construction activities

In addition to the actual construction sites, construction work involves the transportation of large amounts of broken rock, concrete and other materials. Transportation is via the access drifts and the shafts. Concrete and other materials are prepared at the surface installations. Broken rock are stored in a storage dump (see Chapter 8).

The transportation of broken rock and concrete (as well as the transportation of backfill during closure work) is carried out in bulk by truck or railway. At this point in the studies, the use of trucks is preferred for short distances and moderate flows and rail transport is used for long distances and major flows.

Other transportation requirements can be met by vehicles with pneumatic tyres with the advantage of the flexibility of this method of transport.

Depending on the distances concerned, vehicle types and available space in the drifts, the method of propulsion may be diesel or electric with catenary, batteries or cable.

Figure 6.4.3 shows an example of the organization of broken rock transport. Bins and silos provide the interface between different modes of transport such as railways and shafts.

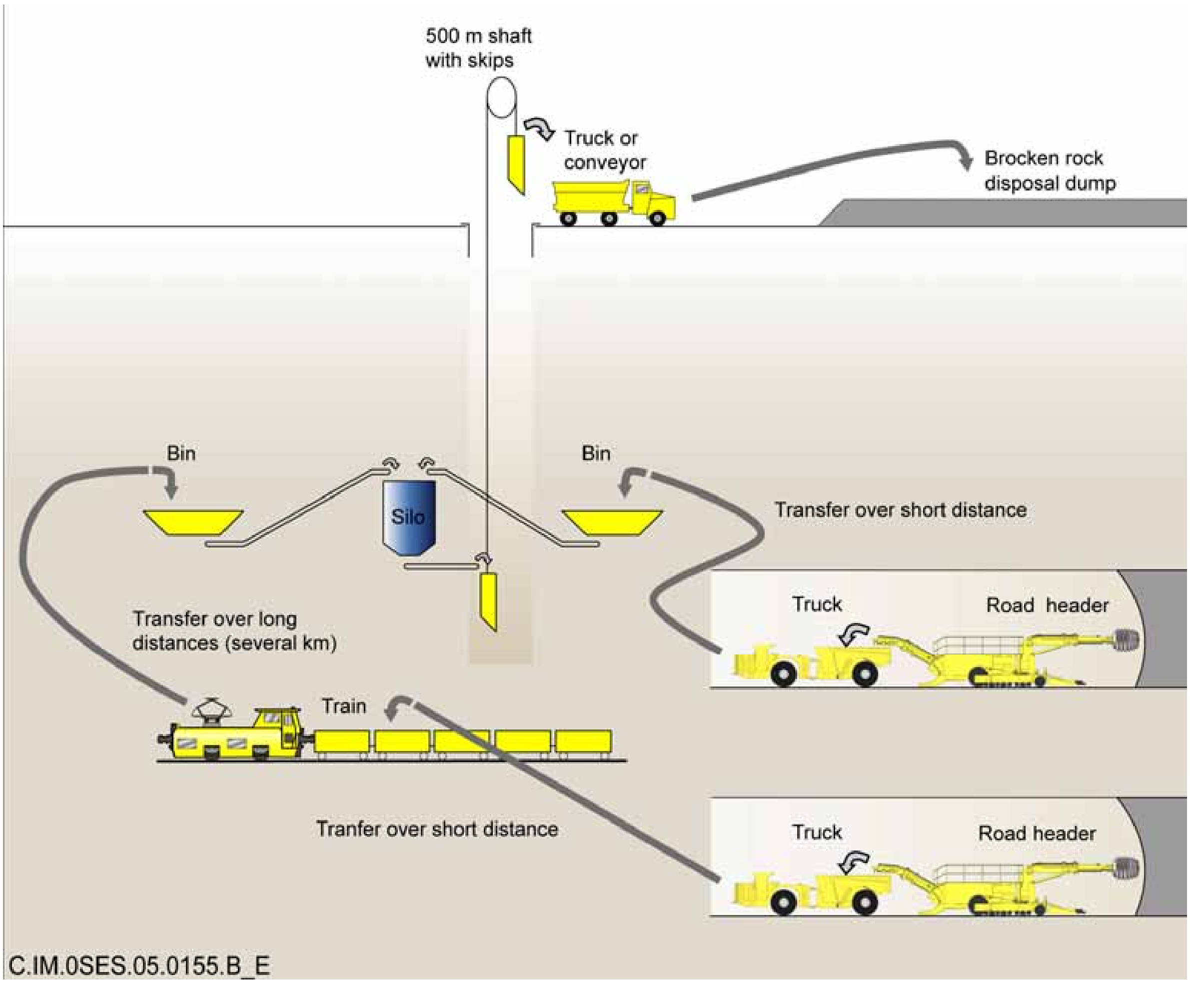

Figure 6.4.3 Block diagram of broken rock transportation

Concrete can be manufactured on the surface. It is then conveyed by the force of gravity to the bottom of the shaft via piping (technique used in the construction of mine shafts, in particular) or mixing drums lowered in the shaft cage. In the drifts, concrete can be transported by mixing drums on a truck (distances of up to 1 to 2 km) or by train (distances of over 2 km) and is pumped into place once it is near the site.

6.4.4 Ventilation

This section presents a possible organisation of ventilation that would provide health, safety and fire functions.

The tree structured architecture involves the construction of long dead ends (up to several kilometers). This geometry entails very significant aerolic head loss which is taken into account in the design of the ventilation system.

6.4.4.1 Design principles

- **General design of the ventilation of the underground installations**

Three main design principles for the ventilation of the underground installations were retained :

A primary ventilation circuit using blowers located on the surface

Air is circulated in the underground installations mainly by fans located on the surface: fans blowing air at the head of the personnel transfer and service shafts and exhaust fans sucking air at the head of the air exhaust shaft. This arrangement ensures that the fresh air entries are always overpressurised with respect to the air returns or the smoke removal shaft.

A full section air intake and an air exhaust in a duct or in a dedicated air drift

The incoming fresh air sweeps over the entire section of the underground drifts without a dedicated duct. This applies to both the drifts connected to the nuclear operation and the drifts dedicated to the construction activities.

Air exhaust and smoke removal are accomplished through ducts located in the crown of the drifts or, when the size of the vehicles circulating in the drifts is incompatible with the presence of ducts, in ventilation drifts exclusively dedicated to these functions.

Figure 6.4.4 and Figure 6.4.5 show these principles of ventilation. In normal operation, the fresh air circulates up to the end of the drifts to be ventilated and then the air is returned from the end. In case of a fire, the smoke can be sucked up by several traps ensuring a redundancy for the smoke removal system.

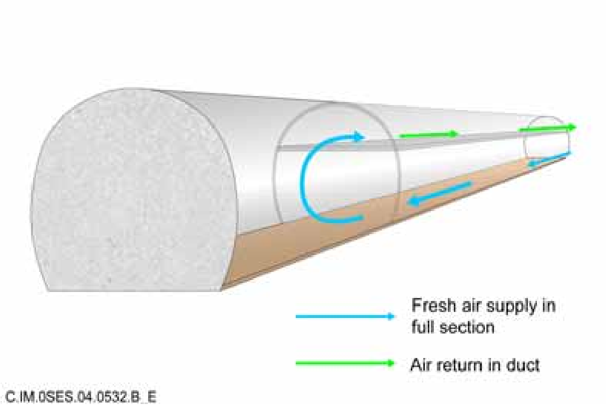

Figure 6.4.4 Operating principle of ventilation with air exhaust in a duct

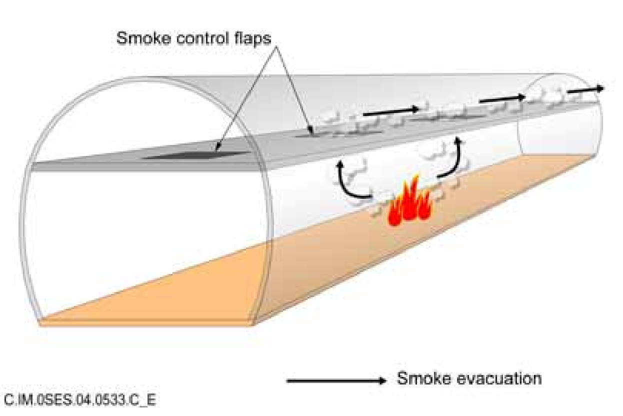

Figure 6.4.5 Operating principle of a smoke removal duct

A separation of the air ventilation circuits

The nuclear operation drifts have a fresh air supply independent from that of the construction drifts in order to prevent the dusts and smoke generated by the construction activity from entering. On the other hand, the air return and smoke removal circuits can be common to both types of drifts because there is no risk of radioactive substances being spread by the nuclear operation processes implemented in the repository installations (transfer of the waste packages into the drifts and emplacing in the cells).

However, the ventilation circuit of the package transfer shaft makes up a separate circuit independent from the other ventilation circuits in order to guard against the consequences from a package falling in a shaft (see chapter 11).

- **Ventilation model**

The ventilation model (Figure 6.4.6) consists of several branches between the pressurised air intake shafts and the depressurised air exhaust shaft.

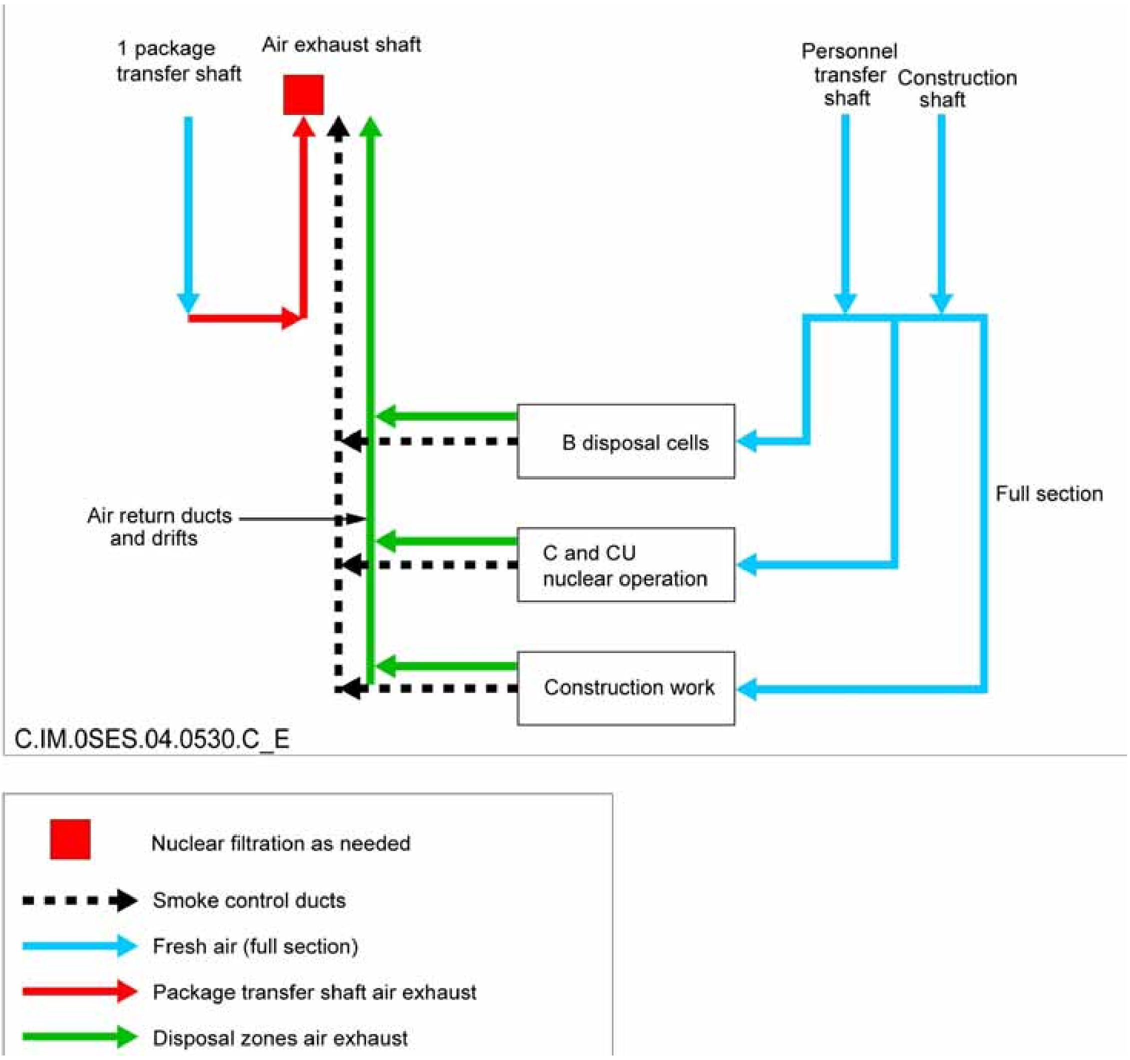

Figure 6.4.6 Ventilation principle

The geographical layout of the air ventilation circuit branches (see Figure 6.4.7 for an example) consists of networks of parallel drifts for the air intakes. Air exhausts and smoke removal are accomplished through networks of air exhaust ductings or air exhaust drifts depending on the space available in the construction and waste package transfer drifts.

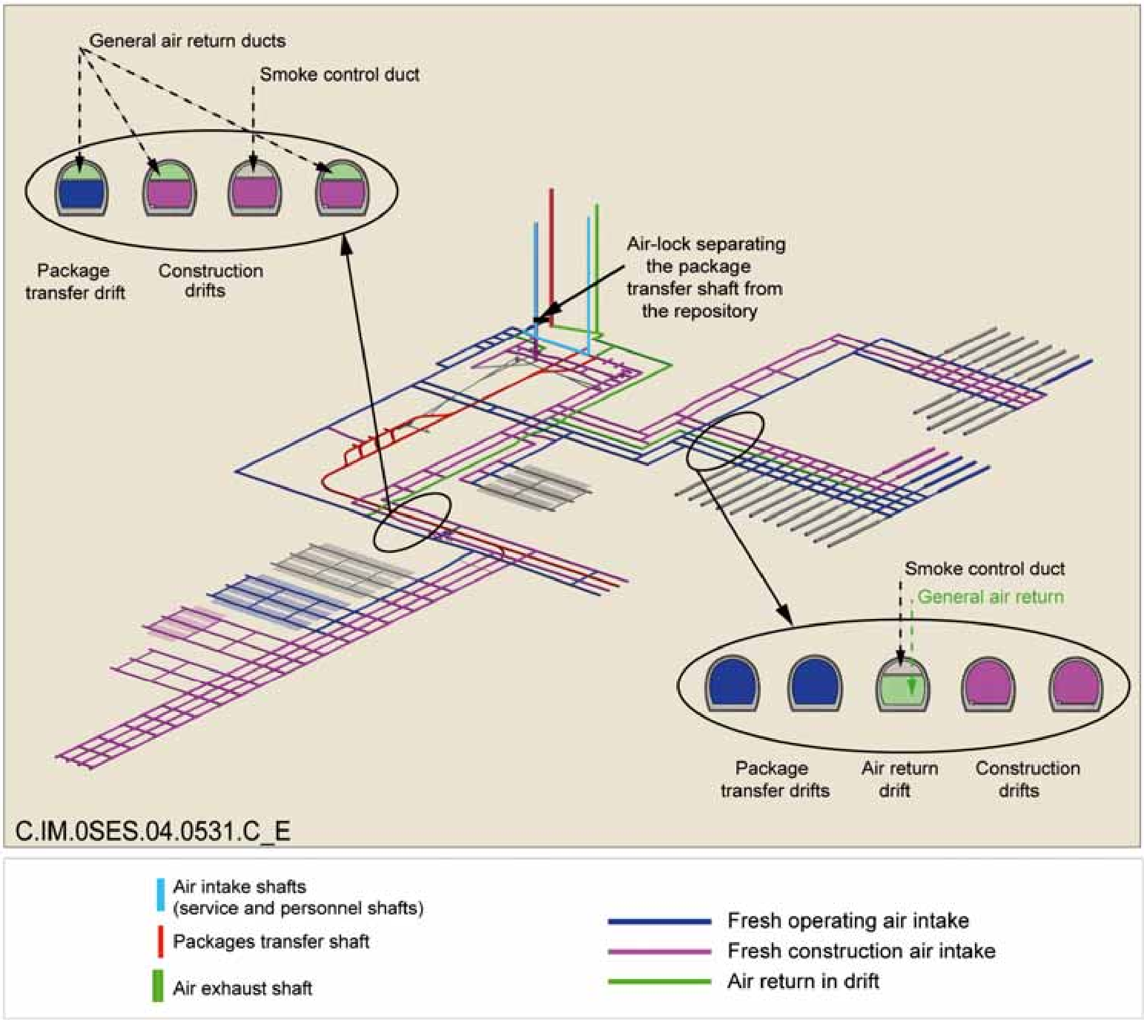

Figure 6.4.7 Ventilation organisation (Example of scenario)

A preliminary estimation of the ventilation needs give an overall flow rate of 500 m^3/s, requiring an electrical rating on the order of 3 MW for the situation represented in Figure 6.4.7[110].

6.4.4.2 Ventilation of the B waste repository zone

The figures below show the B waste repository zone ventilation system.

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[110] In the case of scenario S2, because of a much greater intensity of work and a linear system of upper drifts, these values may be increased to 650 m^3/s and 6 MW, respectively.

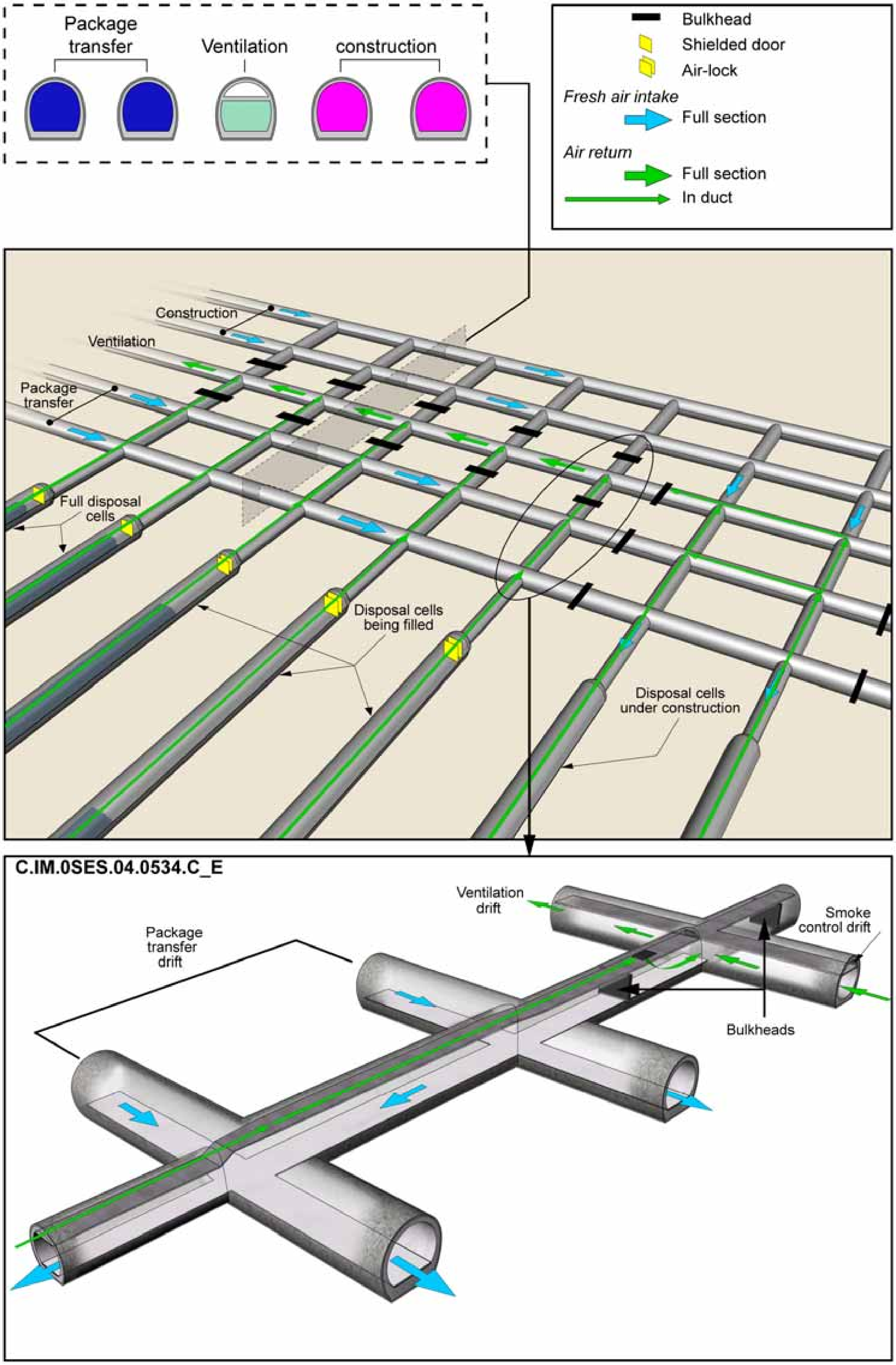

Figure 6.4.8 Ventilation of the B waste repository zone

This drawing represents a situation where two cells are being constructed, three cells are being filled, and two cells are already filled. Ventilation barriers separate three sectors :

- The construction sector,
- The operation sector, which contains the cells being filled and those already filled,
- The air exhaust drift sector, which includes two compartments : general air exhaust and smoke removal.

The pressurised fresh air arrives in full section through the construction drifts and the package transfer drifts to supply their respective sectors. The air of the cells is evacuated through the depressurised air exhaust drift.

6.4.4.3 Ventilation of the C waste repository zones (or spent fuel repository zones)

The drawing below shows the ventilation principle of a C waste repository sub-zone, where the operating units are drift triplets.

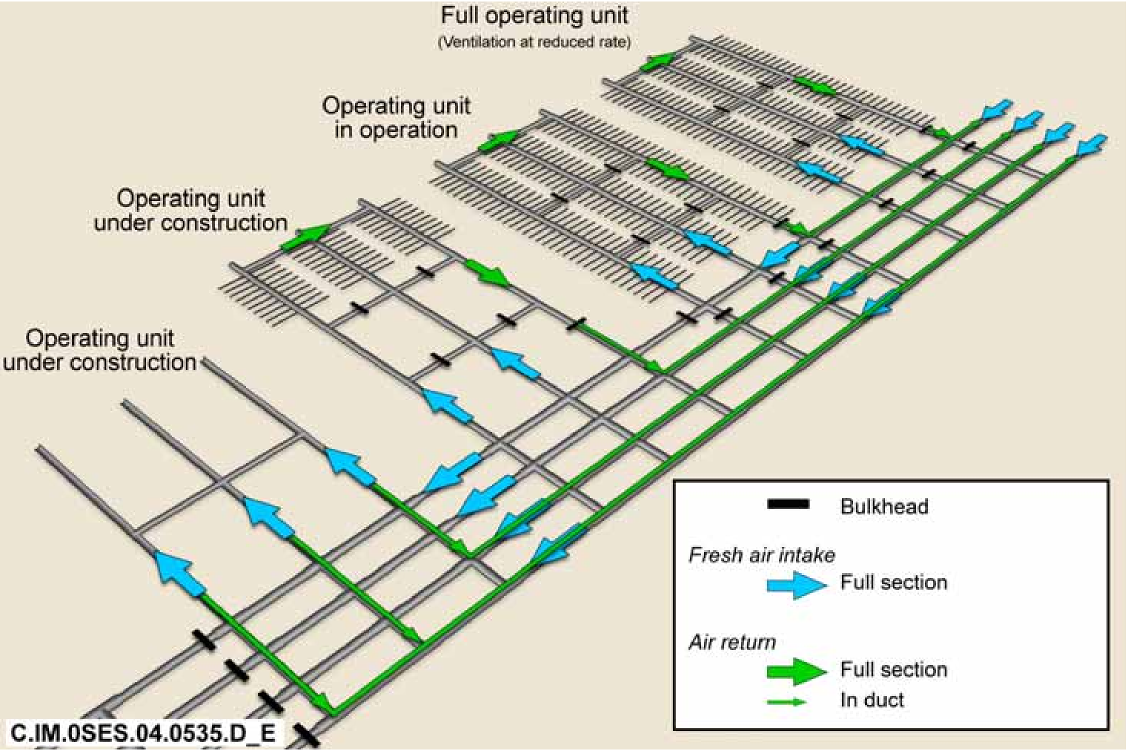

Figure 6.4.9 Ventilation of the C waste repository zone

This drawing represents a situation where two working units are in construction and one unit is in operation. There are thus two sectors of activity, a construction sector and an operation sector. These two sectors are separated by a series of light bulkheads, some of which are equipped with an air lock which the operating personnel can go through[111].

The first working unit is in the excavating phase. Temporaryair ducts ensure the exhaust of air from the excavating worksites. The second operation unit is in the cell excavating phase; it is ventilated in full section according to the same principle as that of the units in operation described in section 5.2.4.

The air exhaust of the various working units are connected to the air exhaust ducts of the connecting drifts (construction drifts or package transfer drifts). Within the sub-zone, these ducts ensure the air return and smoke removal functions and are interconnected.

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[111] The air pressure difference is small between these two sectors and, therefore, compatible with the air lock installation.

The already filled operation units can continue to be traversed by a low-rate ventilation (approximately 2 m^3/s). This allows the already filled units to be slightly depressurised with respect to the worksites in activity.

The ventilation of spent fuel repository zones would be organised in a similar manner. Because of the size constraints which make it impossible to install large section ducts, air would be returned through an additional dedicated drift, with smoke being removed through small section ducts.

6.5 Sizing the connecting infrastructures

The size of the drifts is determined by the size of the vehicles circulating in these drifts and, in particular, the package transfer vehicles equipped with their transfer cask and the cosntruction machines.

In addition, the total section of a group of parallel drifts is amply determined by ventilation needs: air speed is limited to approximately 3 m/s maximum in the air entry drifts where the personnel move and work and approximately 8 to 10 m/s in the air return drifts and ducts in order to limit ventilation circuit load losses.

6.5.1 Access drift diameter and number of drifts

In order to respond to the same flow requirement, a choice can be made between a smaller number of large sized drifts or a larger number of small sized drifts. At this stage, the second option was retained.

A usable diameter of 5.7 m in a current drift is sufficient for all the flows to go through. This corresponds to an excavated diameter of approximately 7 m (see chapter 7).

With these drift diameters, and according to the number and type of zones to be served, the main connecting infrastructures will normally consist of 4 to 5 drifts. This number may be increased by one or two units for the scenarios including the disposal of highly exothermal spent fuels. Similarly, the secondary infrastructures within a sub-zone will include 4 or 5 drifts.

6.5.2 Distance between connecting drifts

The minimum distances between drifts of the same group will be determined by geotechnical factors: the pillar separating two drifts must have a width at least equal to five times the excavated diameter of the drifts.

6.5.3 Connections between connecting drifts

In the main infrastructures, 2 m dia. crosscuts [112] connecting the connecting drifts spaced approximately every 100 metres apart allow the smoke removal ducts to pass; 4 m dia. crosscuts spaced approximately every 400 metres apart allow the personnel to be evacuated and emergency vehicles to pass, if necessary.

In the secondary infrastructures, the crosscuts are located opposite to the access drifts to the cells.

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[112] Drifts interconnecting parallel drifts. They are normally perpendicular to the connected drifts.

6.5.4 Examples of the preliminary sizing of the connecting infrastructures

The preliminary sizing of the connecting infrastructures is illustrated by a few characteristic examples in order to show the feasibility of the proposed principles.

6.5.4.1 Infrastructure of the repository zone of the B waste packages

In the B waste repository zone, the construction flows are moderate, while the package transfer flows are more important. The disposal packages are relatively bulky and do not allow installing large section air return ducts. The infrastructure consists of five drifts, comprising one reserved for air return and smoke removal, two for construction and two for package transfers.

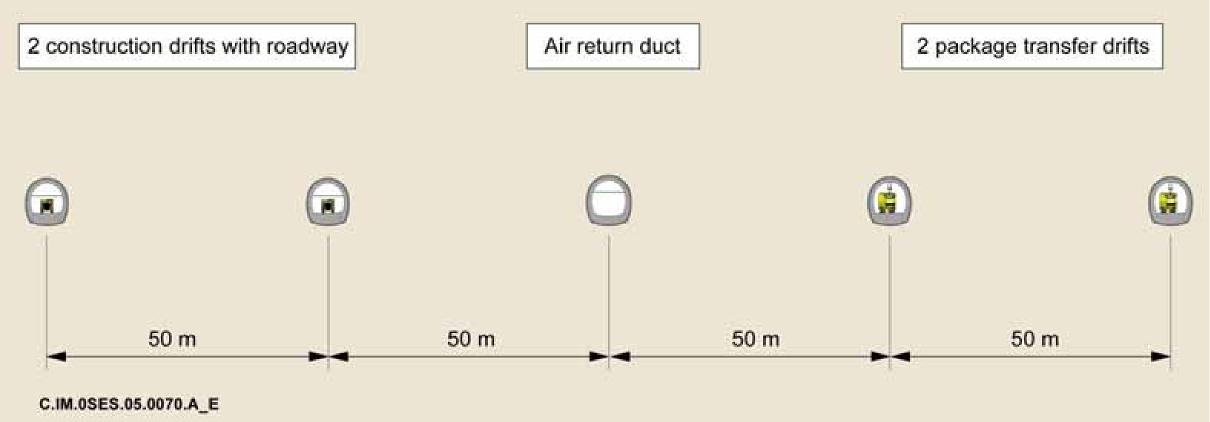

Figure 6.5.1 Main infrastructure of a B waste repository zone

6.5.4.2 Secondary infrastructure of the repository zone of the C waste packages

In the C waste repository zone, the construction flows are important, while the package transfer flows are less important. The size of the packages and their transfer cask is relatively small, and all the drifts can be equipped with air return and/or smoke removal ducts. An air return drift is not necessary. The infrastructure consists of four drifts, comprising three reserved for construction and one for package transfers.

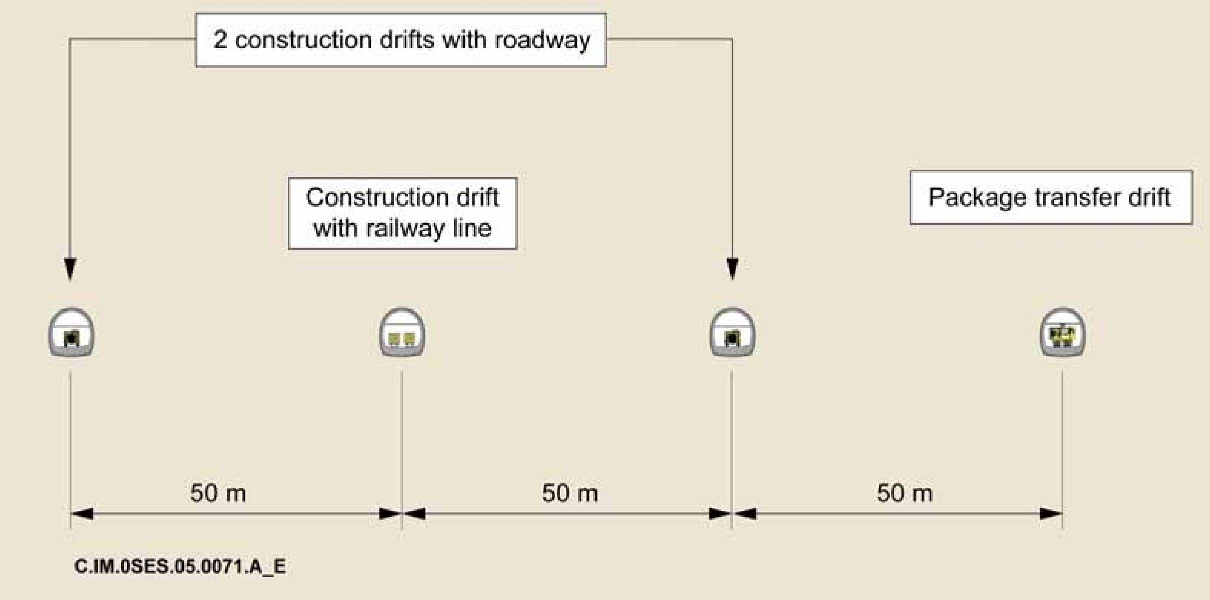

Figure 6.5.2 Secondary infrastructure of a C waste repository zone

6.5.4.3 Secondary infrastructure of a repository zone of spent fuel packages (CU1)

In the case of a repository zone of spent fuels (CU1 types), the construction flows are more important and the package transfer flows less important than for the repository zone of C waste packages. The transport vehicles used for the construction [113] and the package transfer vehicles would have larger sizees which would be incompatible with the presence of large section ducts. The infrastructure consists of five drifts, comprising one reserved for ventilation, three for construction and one for package transfers.

6.6 Adaptation of the underground architecture to the various scenarios

This section focuses on the architecture's flexibility with respect to the inventory assumptions made evident by the scenarios described in chapter 3. For the same scenario, the architecture can also be adapted according to how long it takes to receive the various package categories.

6.6.1 General

A distinction is made between the repository zones according to the exothermal or non exothermal character of the packages to be disposed :

- The B and C0 wastes are hardly or only moderately exothermal and can be disposed without a pre-disposal storage time. The package repository zones represent footprints and relatively small construction work volumes. The sizing of these zones and the connecting drifts which allow them to be served seems hardly sensitive either to the start date of the disposal or the construction and operation rates.
- The C wastes other than the C0 waste and possibly the spent fuels CU1 and CU2 are characterised by a high exothermicity, which implies within the studied concepts a pre-disposal. The corresponding repository zones represent larger footprints and construction work volumes. The sizing of these repository zones and their connecting drifts is sensitive to the disposal dates and the construction and operation rates. Finally, the package inventories corresponding to these zones may be highly different from one scenario to another (see chapter 3).
- After the initial construction phase, which includes the shafts, a portion of the infrastructures of the shaft zone and of the connecting infrastructures, as well as the initial waste respository cells, the construction of the repository underground structures can be progressively pursued. Thus, for each repository zone, an additional infrastructure needed for the construction of the said zone can be constructed. The design of the infrastructures must therefore be a trade-off between flexibility, which tends to favour connecting infrastructures specific to each zone and minimisation of excavations, which tends to favour common infrastructures.

6.6.2 Presentation of the overall architecture of a repository for the scenario S1a

An example of an architecture corresponding to the scenario S1a is shown in Figure 6.6.1 below. The pre-disposal storage time of the highly exothermal packages corresponds to a disposal ″as reasonably early as possible″ with the proposed concepts, such as indicated in chapter 5 (that is, 60 and 70 years, respectively, for the reference packages C1/C2 and C3/C4).

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[113] In particular, the transports of engineered barrier (EB) elements

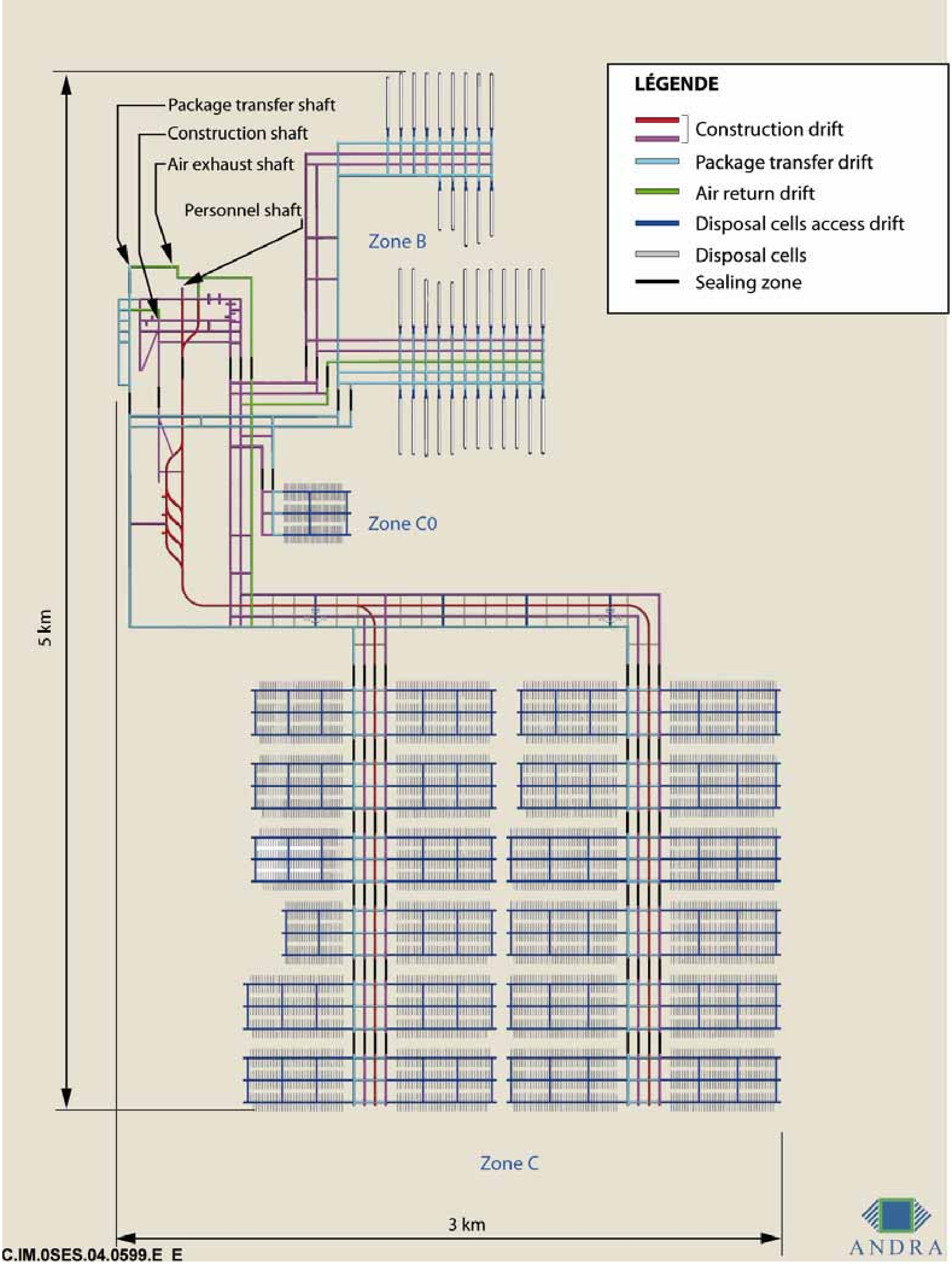

Figure 6.6.1 Architecture principle for the scenario S1a

The total excavated volume is approximately 7.6 million m^3. This volume is split into 1.9 million m^3 (that is, 25 % of the total) for the common installations, 1.8 million m^3 (that is, 23 % of the total) for the B wastes, 0.1 million m^3 (that is, 3 % of the total) for the C0 wastes and 3.8 million m^3 (that is, 49 % of the total) for the C wastes. This breakdown is shown in Figure 6.6.2.

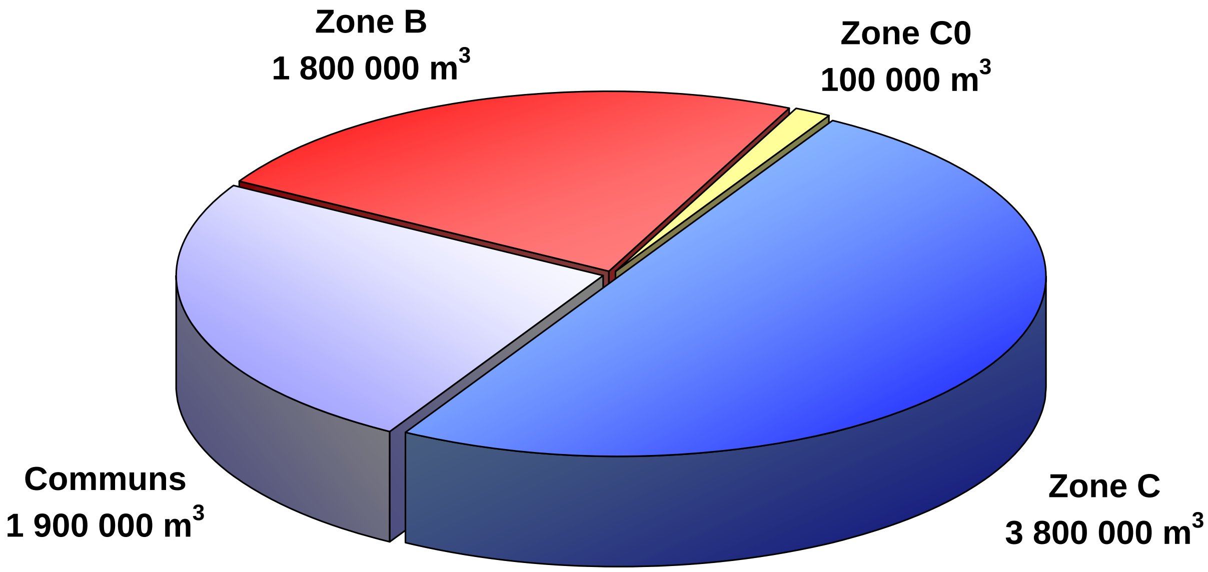

Figure 6.6.2 Breakdown of the excavated volumes in the scenario S1a

Approximately 40 % of the excavated rock may be reused for the backfilling of the drifts. The difference compared to 100 % is based on the volumes occupied by the disposal packages and the structure liners and by the backfill “swell factor” effect[114].

The volumes of excavated and backfilled materials can be compared to the volumes excavated in large sedimentary underground mines of coal, potash, bauxite or iron. These volumes can represent several tens of millions of cubic metres exploited over several decades.

6.6.3 Adaptation of the architecture to the scenarios S1b, S1c, S2

The architecture presented above can be adapted to the other scenarios considered in the study (see chapter 3). Figure 6.6.3 shows the adaptation of the architecture to the scenarios S1a, S1b and S2. It should be noted that the scenarios S1b and S1c lead to very similar architecture plans[115].

---

[114] A backfill made up of crushed and compacted rock has a density less than the density of the rock in place

[115] In fact, if the number of C waste packages is less in the S1b scenario, then the considered packages are more exothermal and imply a lower storage density.

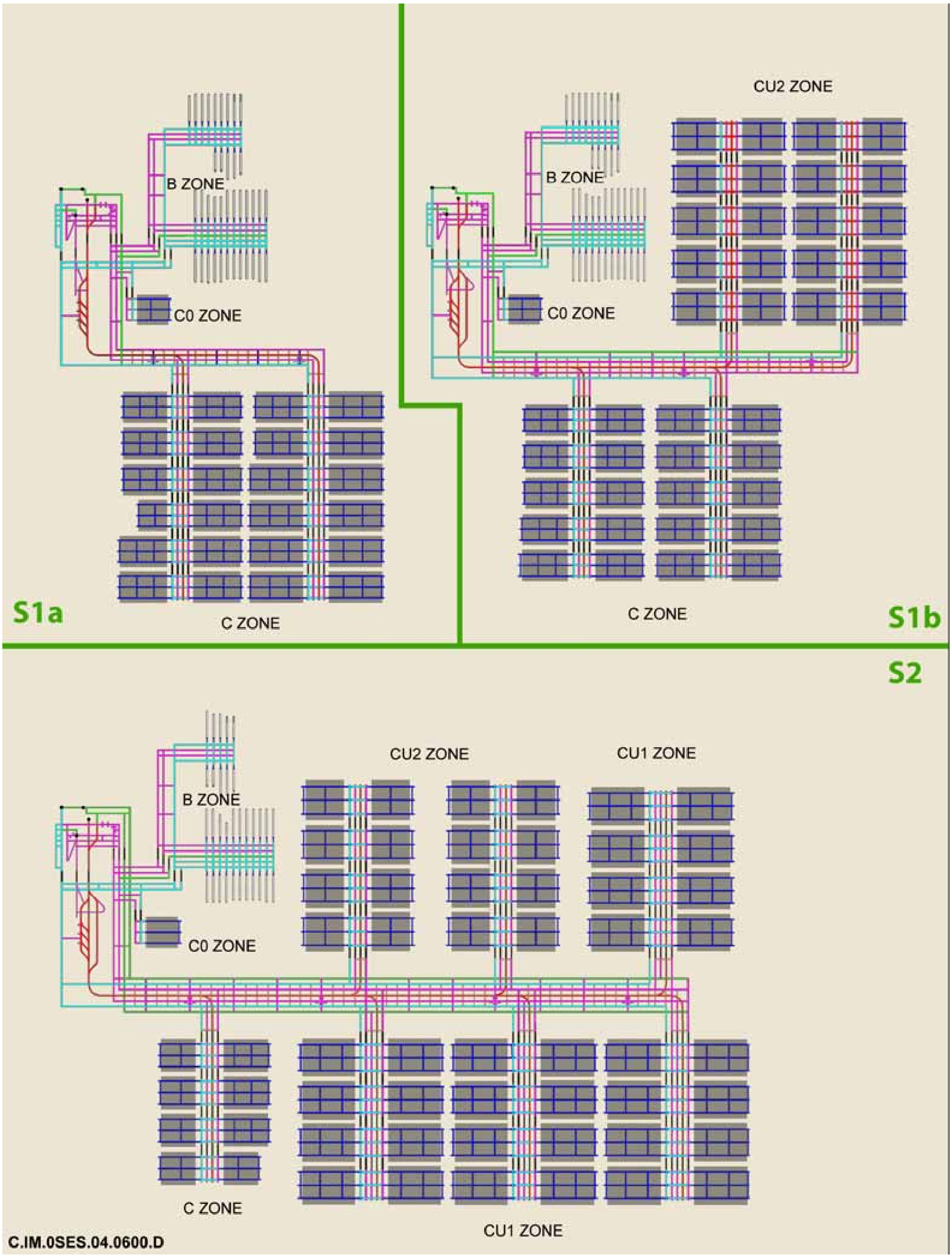

Figure 6.6.3 Possible adaptation of the architectures to the various study scenarios

6.6.4 Architecture's flexibility with respect to the waste inventory and waste management

- **Effect of the waste quantity**

The architectures presented can be adapted without any problems to more (or less) important waste inventories, since the number of modules to be created can be easily adjusted without jeopardising the general organisation.

- **Effect of operation rates**

Recall that the operation reports retained under the study are only to be considered as assumptions. They cannot constitute forecasts or prefigure any industrial reality. They offer, however, a reasonable and conventional framework for a feasibility estimation.

A variation in the operating rate of the repository or the simultaneous operation of several repository zones of exothermal packages would have a minimum effect on the general footprint, but could impact on the sizing of the drifts of infrastructures: with all other things equal, higher operating rates would lead to higher construction working rates and, therefore, could necessitate higher capacity infrastructures, that is, a larger number of drifts or drifts with larger diameters.

Architectures of different shapes might also have to be designed if simultaneous disposal of C waste packages and spent fuel packages is desired by doubling the infrastructures.

- **Taking into consideration the repository of spent fuels CU3**

The architecture can be easily adapted to take into consideration the repository of spent fuels CU3 in case they would not be recycled. The corresponding repository zone would represent approximately 5 ha (Figure 6.6.4).

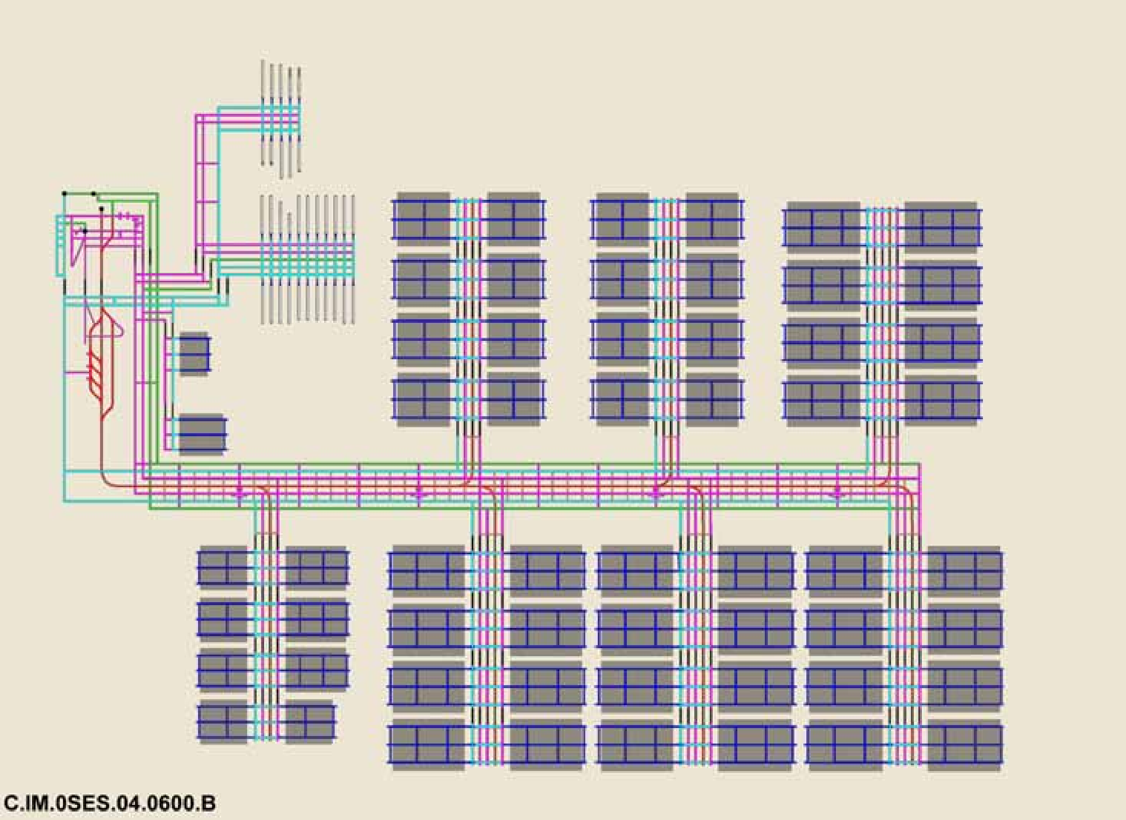

Figure 6.6.4 Adaptation of the architecture to spent fuels CU3

6.6.5 Sensitivity of the footprint of the repository to the pre-disposal storage duration.

The footprint of the B waste and C0 waste repository zones does not depend on the pre-disposal storage duration. For highly exothermal packages, the total footprint of the repository zones results from that of the repository modules, sensitive to the pre-disposal storage duration, and the distances between these modules. The C waste repository zone for the scenario S1a has an footprint of approximately 500 hectares for a previous surface storage from 60 years (for the reference packages C1/C2) to 70 years (for the reference packages C3/C4). Above a certain storage duration, the sensitivity of this footprint is attenuated: it becomes 300 hectares for a surface storage duration of 150 years (Figure 6.6.5) and is reduced by half for a duration of 200 years. Under the assumption of a repository with spent fuels (scenario S2), a similar sensitivity is observed for the footprint to the pre-disposal surface storage duration (Figure 6.6.6). This sensitivity varies with the speeds of thermal decrease of the different types of packages.

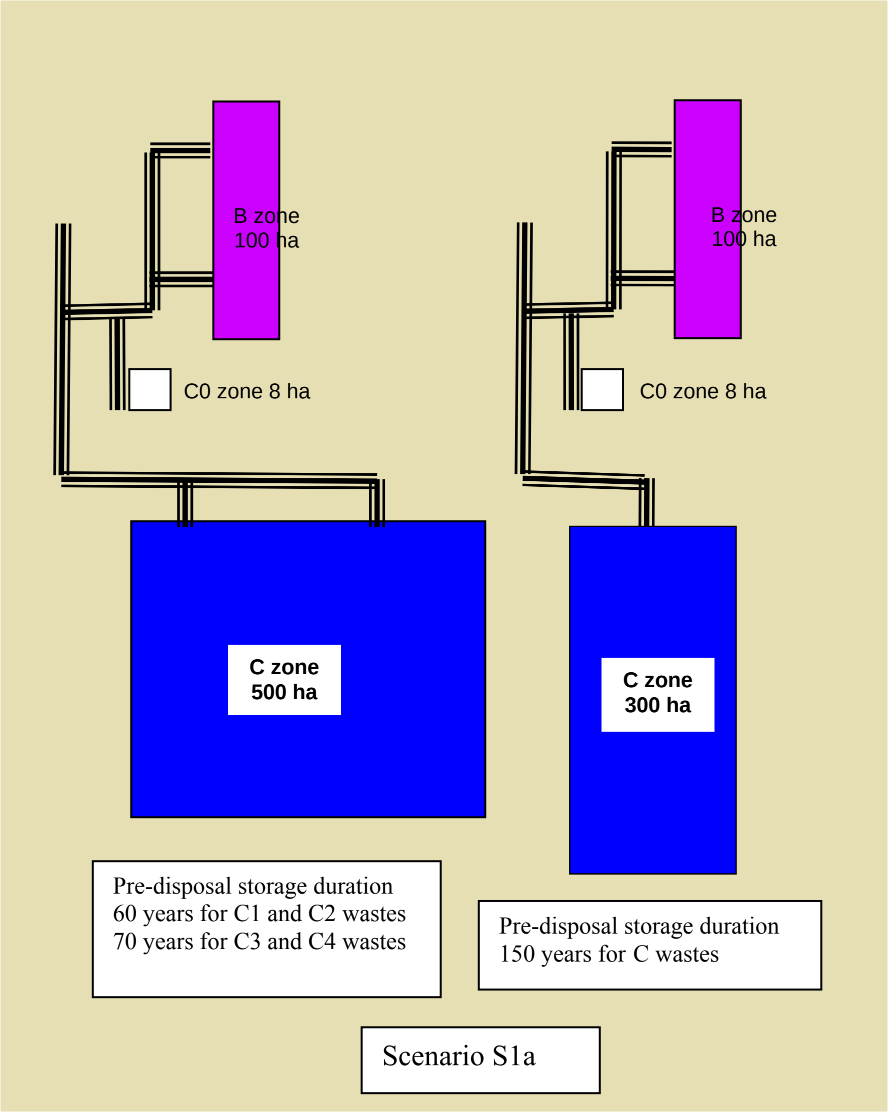

Figure 6.6.5 Sensitivity of the footprint of a repository to the previous surface storage duration of highly exothermal packages - scenario S1a

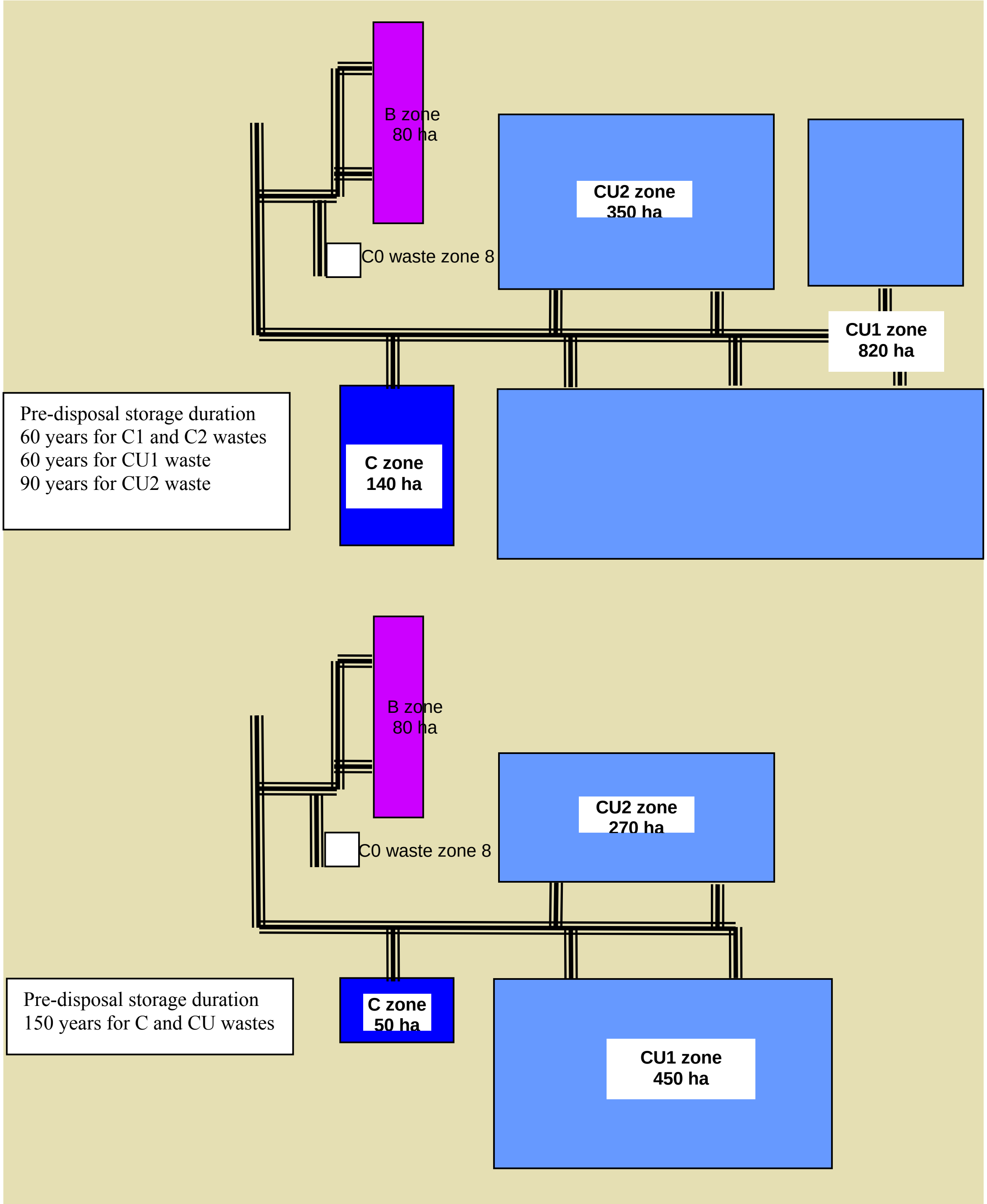

Figure 6.6.6 *Sensitivity of the footprint of a repository to the previous surface storage duration of highly exothermal packages - scenario S2*

7

The shafts and the drifts

The connecting and access structures to the repository modules are made up of shafts and drifts. The purpose of this chapter is to present the design of these structures, their sizing, and their mode of construction, management and closure.

To begin with, this chapter reviews the functions of these structures and the retained design principles regarding the operational needs and the long-term safety objectives.

Then, it describes the shafts and drifts. It shows, in particular, the logic underlying the determination of the number of shafts. It also mentions the possibility of using a ramp. Regarding the drifts, it describes the principles of sizing.

This chapter next describes the construction mode of the shafts and drifts. It shows the constructibility of the access structures in the argillites of the formation studied, as well as when the overlying geological formations are crossed through.

It indicates how reversibility is taken into account in the sizing and maintenance of the structures.

Finally, it gives a description of the way the structures are closed. It explains the backfilling techniques with a material prepared from the excavating mucks, as well as their sealing by plugs made of swelling clay of low permeability. It also mentions the demonstration tests on the backfilling and sealing of drifts.

7.1 Presentation of the main questions

The function of the connecting and access structures is to allow the transfer of the flows generated by the activities of construction, the disposal of the packages and the closure of the underground installations. Their design is based mainly on the operational needs of these activities. It also integrates the considerations on reversibility and long-term safety [37].

7.1.1 Operational needs

The connecting and access structures to the cells must allow the construction, operation and closure of the repository according to the principles defined in chapter 6, that is, progressive construction and separation of the flows. Chapter 6 also gave the orders of magnitude of the flows generated by these various activities and indicated that the sizing of the drifts was mainly determined by the size constraints of the circulating vehicles and by the ventilation needs.

These same factors, as well as the mass of the packages and transfer casks to be transferred, determine the sizing of the shafts. At this stage in the studies, the maximum weight of the transfer cask and package combination is estimated at approximately 100 tons (case of some B waste packages and possibly spent fuel containers with four type CU1 assemblies).

7.1.2 Reversibility and long-term safety

The repository structures (shafts and drifts) must be able to remain open over a minimum 100-year duration for reversibility. They must be capable of resisting the pressure of the grounds which may be applied over this time scale.

But these structures must also be able to be closed if desired. They can be closed in successive steps in order to take advantage of the managerial flexibility which is related to reversibility.

Once closed, the structures must contribute to the following safety functions : i) limit the mechanical deformations of the argillite over the long term, ii) limit the circulation of water and iii) separate the modules of the repository.

The ground pressure on the structures progressively increases over time with the creeping and relaxation of the argillite. In parallel, a decrease in the mechanical resistance of the liners with chemical alterations must be taken into account. These two phenomena are such that they lead to a breakage of the liners a long time after the closure. The result is that deformations resume in the argillite, which may cause or reactivate damaged zones (fractured and microfissured) around the structures.

In order to limit these deformations, Andra has decided to carry out a systematic backfilling of the drifts during the closure.

With respect to water circulation limitations, chapter 6 shows how they are based, first of all, on the argillite's characteristics. Installing seals in the shafts and drifts allows reducing even more over the long term the flow of water percolating in the repository and the flow rate of this water.

The drift seals are also aimed at compartimentalizing the repository. The principle of compartimentalization consists of limiting an altered situation to a fraction of the repository. The compartimentalization must limit as much as possible the effects of such a situation on the surrounding modules of the directly implicated module.

7.2 Retained design principles

The disposal cells are accessed by two types of structures :

- The connecting structures between the surface installations and the underground installations (shafts, ramps) ;
- The connecting and access underground drifts.

7.2.1 Shaft or ramp

In order to access the underground installations of the repository, two types of structures can be imagined, shafts and ramps :

- Shafts are vertical structures. They are normally equipped with a machinery allowing loads to be lowered and raised by cages suspended on steel cables ;
- Ramps are inclined drifts, normally at a slope less than 15 % ; they can be used by tyred vehicles[116].

These two types of structures are currently in widespread use in the mining industry : shafts have been used for more than a century and ramps for several decades.

The reference solution retained for the underground repository uses only shafts. This solution has the advantage of simplicity (only one type of structure) ; the shafts can be adapted to large flows to be transported.

The possibility of using a mixed shaft – ramp solution will be discussed below in section 7.3.4.

Among the existing underground repositories or those in project, the WIPP (United States) and the Gorleben project (Germany) use only shafts ; these are sunk to respective depths of 650 m and 900 m in sedimentary soils down to the base salt formation. In Sweden and Finland, mixed solutions combining shaft and ramp are planned to depths of approximately 500 m in granite.

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[116] There are also inclined shafts whose slope is between 20% and the vertical. This type of structure is only used under special conditions (inclined layers, mountainous topography, etc.).

7.2.2 Number and assignments of the shafts

At the current stage in the studies, a set of four shafts is planned to control all the flows to be transferred :

- a shaft exclusively reserved for package transfers ;
- a shaft exclusively reserved for air exhaust, to ensure all the air exhausts and smoke removals ;
- a personnel transfer shaft and a construction shaft to ensure all the other flows, including the fresh air supply.

- **Discussion and comparison with the WIPP**

The thus-defined set of four shafts offers great flexibility for adapting to the various scenarios described in chapter 3, while limiting interferences between flows.

This set can be compared to the WIPP (see chapter 6), which for a comparable depth (650 m instead of 500 m), but less important flows (annual excavation volume of a few tens of thousands of cubic metres, no concrete, less bulky packages), includes also four shafts :

- A waste package shaft ;
- A construction shaft for muck handling, equipment and personnel ;
- A shaft reserved for air intake (+ auxiliary personnel) ;
- A shaft reserved for air exhaust.

7.2.3 Design principles of the access and connnecting drifts

These principles were defined in chapter 6 :

- hierarchising the drifts into main connecting drifts common to several zones, secondary connecting drifts specific to each zone, and access drifts specific to each module ;
- specialising the drifts by function (construction with railway or path for tyred vehicles, operation, air exhaust).

In addition, remember that the design presented in the current stage allows minimising the drifts' diameter.

7.3 Description of the shafts

7.3.1 Package transfer shaft

This shaft is exclusively assigned to the transfer of packages in their protection transfer cask (and for the transfer of empty transfer casks). There are two reasons for this exclusive assignment : i) the special character of the transfers (high load, specific prevention and protection arrangements against the risk of packages falling in a shaft), ii) the number of packages to be transferred, which may be close to a shaft's maximum capacity.

The shaft's usable diameter is 11.50 m. This diameter is completely determined by the equipment : that is, the equipment necessary to transfer the waste disposal packages between the surface and the bottom, as well as the auxiliary equipment (emergency cage for the maintenance and inspection personnel).

The shaft's ground support is adapted to the various grounds encountered.

- Near the surface, a 60 cm thick moulded wall may be necessary to cross the potentially aquiferous grounds (Barrois limestones, whose thickness can attain twenty metres).
- Above the Callovo-Oxfordian layer, the ground support consists of 3 m long rockbolts and shotcrete ; the concrete thickness varies from 20 to 30 cm according to the ground and the depth.

- In the Callovo-Oxfordian layer, two types of ground supports are planned. In the future shaft sealing zone (see below in section 7.7.3), steelsets arches and shotcrete will be used; this zone extends fifty metres above the top of the formation. Outside of the sealing zone, the ground support consists of 4 m long rockbolts and shotcrete.

At the current stage in the studies, the concrete liner thickness is 45 to 50 cm in the earths located above the Callovo-Oxfordian layer and 1.35 m in the Callovo-Oxfordian layer, except for the local reinforcement at the shaft station.

The ground support and shaft liner were sized using conventional geotechnique analytical methods (″convergence confinement method″[117], associated with a ″beam element calculation″[118] in order to take into account the anisotropy of the horizontal stresses). The sizing parameter is the pressure applied by the surrounding ground and, in particular, the pressure exerted by the argillite because of its creep. Studies show that the chemical degradation phenomena of the liners only take place over very significantly longer durations. This ensures a multiple 100-year service life for the structure.

The ground support and the liner of the other shafts are similar and adapted according to the shafts' respective diameters.

The distance between the shaft bottom and the wall of the Callovo-Oxfordian formation is approximately thirty metres based on the assumption of a 130 metre thick formation.

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[117] The convergence confinement method uses the stress – deformation curves of the liner (or the ground support) and the ground. The equilibrium of the liner – ground system is located at the intersection of these two curves.

[118] In the beam element calculation, the liner is schematically represented by a set of beam elements and the ground's action is schematically represented by springs. This calculation combined with the convergence – confinement method allows processing the cases of anisotropic stresses.

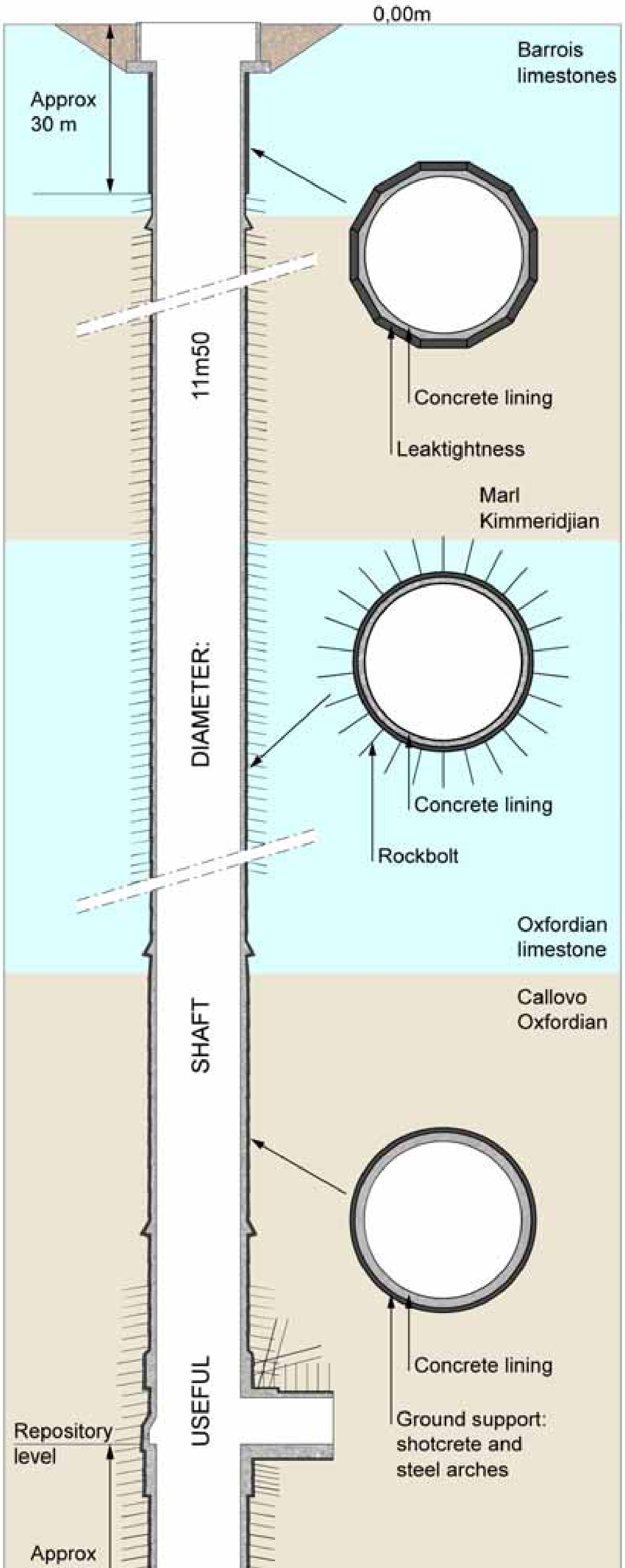

Figure 7.3.1 Axial section of the package transfer shaft

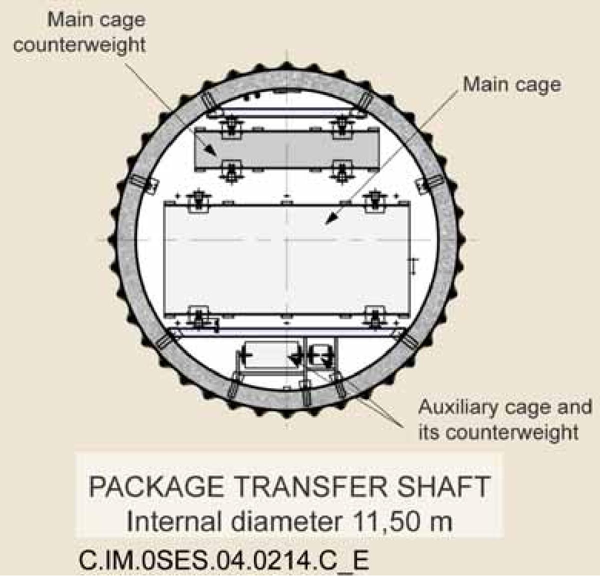

Figure 7.3.2 Section of the package transfer shaft

The shaft's special equipment is detailed in chapter 9. The shaft machinery can transport a payload of 110 tons at a rate of 1 m/s. The cage weight is balanced by a counter-weight. The cage is guided by steel profile guiding systems. A small independent emergency cage ensures the safety of the personnel assigned to the maintenance operations.

7.3.2 Air exhaust shaft

The purpose of the air exhaust shaft is to ensure the general air exhaust from the repository (construction and operation), the evacuation of smoke in case of fire and, if neessary, the return of possibly contaminated air in case of an accident (air coming from the package transfer shaft).

The need for a dedicated air exhaust shaft can be explained by the very high air flow rates (several hundred cubic metres per second) and by the necessity of avoiding the placing of large-scale equipment in stale air (diesel fumes, dust, other possible fumes) to the detriment of their resistance over time.

The shaft diameter is determined by ventilation requirements. The usable diameter is 10 m. It would allow a possible increase in ventilation capacity and limit energy expenses related to ventilation. The structure is divided into 3 compartments, one for each air exhaust. It is only equipped with equipment for inspections and maintenance.

7.3.3 Personnel transfer shaft and construction shaft

This set of two shafts ensures the transfer of the other flows necessary for the construction, operation and closing of the repository. These shafts are also used for the entry of air for all the underground installations except for the package transfer shaft.

In the architecture presented, one shaft is exclusively reserved for the transport of personnel and small equipment. The other shaft, the construction shaft, ensures the extraction of broken rocks, the lowering of backfills in bulk, the descent of a surface-prepared concrete, the transfer of large-scale equipment, parts and building materials.

The construction shaft can also serve as an emergency exit in case the personnel transfer shaft is unavailable.

The equipment of these shafts is conventional equipment such as used in the mining industry. Cables and pipelines are also installed in these shafts.

7.3.3.1 Personnel transfer shaft

The personnel transfer shaft has a usable diameter of 6.50 m. Its sizing depends mainly on the equipment's size and ventilation needs.

It is equipped with a main cage which can carry simultaneously several tens of persons. A secondary cage is used to evacuate, if necessary, the personnel from the main cage.

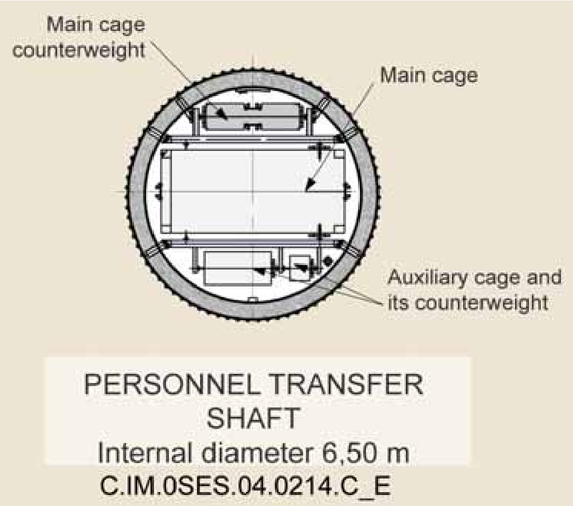

Figure 7.3.3 *Section of the personnel transfer shaft*

7.3.3.2 Construction shaft

The construction shaft has a diameter of 11.50 m, exactly like that of the package transfer shaft.

The shaft is divided into two compartments :

- a compartment equipped with two skips (movable hoppers for transporting bulky materials) for raising broken rocks and lowering backfills[119] ;
- a compartment equipped with a large cage, for raising and lowering vehicles and large equipment. The cage has a usable capacity of 40 tons. It is designed to evacuate the personnel from the underground installations in case the personnel transfer shaft is unavailable.

In each compartment, an emergency cage allows evacuating the personnel from the shaft.

According to ther characteristics, the concretes can be lowered by pipelines or by mixing drums using the cage.

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[119] Depending on the shaft design, these two operations can be simultaneously performed

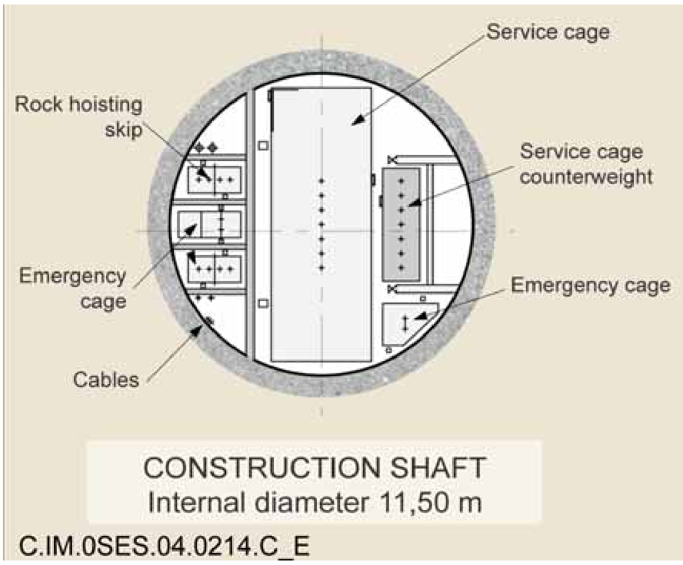

Figure 7.3.4 Section of the construction shaft

7.3.4 The advantages of a ramp

A ramp is an inclined drift, normally at a slope less than 15 %, allowing access to the underground installations. This type of structure has been in widespread use in the mining industry since the second half of the last century, together with the development of diesel mining machines and vehicles and conveyor belts. The comparison between shafts and ramps has become a permanent debate within the mining industry. A large number of mines are equipped with both types of structures.

The ramp is more flexible to work with than a shaft because it can be used without causing load interruptions by a wide variety of vehicles. It does not depend like a shaft on a single piece of equipment, which even though highly reliable does require heavy-duty maintenance. However, the flows possible on a ramp are more limited than in a shaft and experience has shown that the risks of incidents are higher.

It should be noted among the factors which would lead by analogy to the mining industry favouring an access by ramp that :

- The overlaying grounds are hardly aquiferous and have normally good mechanical characteristics ;
- The package flows are limited in terms of the number of movements and consist of bulky and heavy loads ;
- The material flows generated by construction remain small as long as construction is restricted to zones receiving B and C0 waste packages.

On the contrary, the depth of 500 m is rather high for a ramp, but not without precedence. The layer’s geometry and topography are simple, which would tend to favour the shaft solution.

Aside from the air exhaust function, where the ramp has no interest here, the above list of factors does not allow a very sharp comparison between the two types of accesses. A ramp can be used for the lowering of packages, on the one hand, and for construction functions, on the other hand. At this stage in the studies, the use of ramps is only considered as a variant.

The paragraphs below show two examples of possible ramps. The first example is an example of a “construction oriented” ramp designed to facilitate the flow of vehicles. It is very similar to a mining ramp. The second example is an example of a “package transfer oriented″ ramp designed to limit the impact velocity in case a vehicle transporting packages goes out of control.

7.3.4.1 Construction ramp

This type of ramp can be imagined as a replaccment for the service shaft for the construction and operation of the B and C0 waste zones.

In the example given, the ramp consists of 8 straight sections 340 m long sloped 15 %; they are interconnected by half-circle sections sloped 10 % with a radius of 30 m. The ramp has a usable diameter of approximately 6 to 8 m. The straight sections are oriented (to within the indicated slope) according to the major horizontal constraint in order to ensure the best possible conditions for the ramp's future sealings.

A small diameter ventilation shaft[120] facilitates the ventilation of and the removal of smoke from the structure while under construction and in use. Laybys allow the vehicles to pass by.

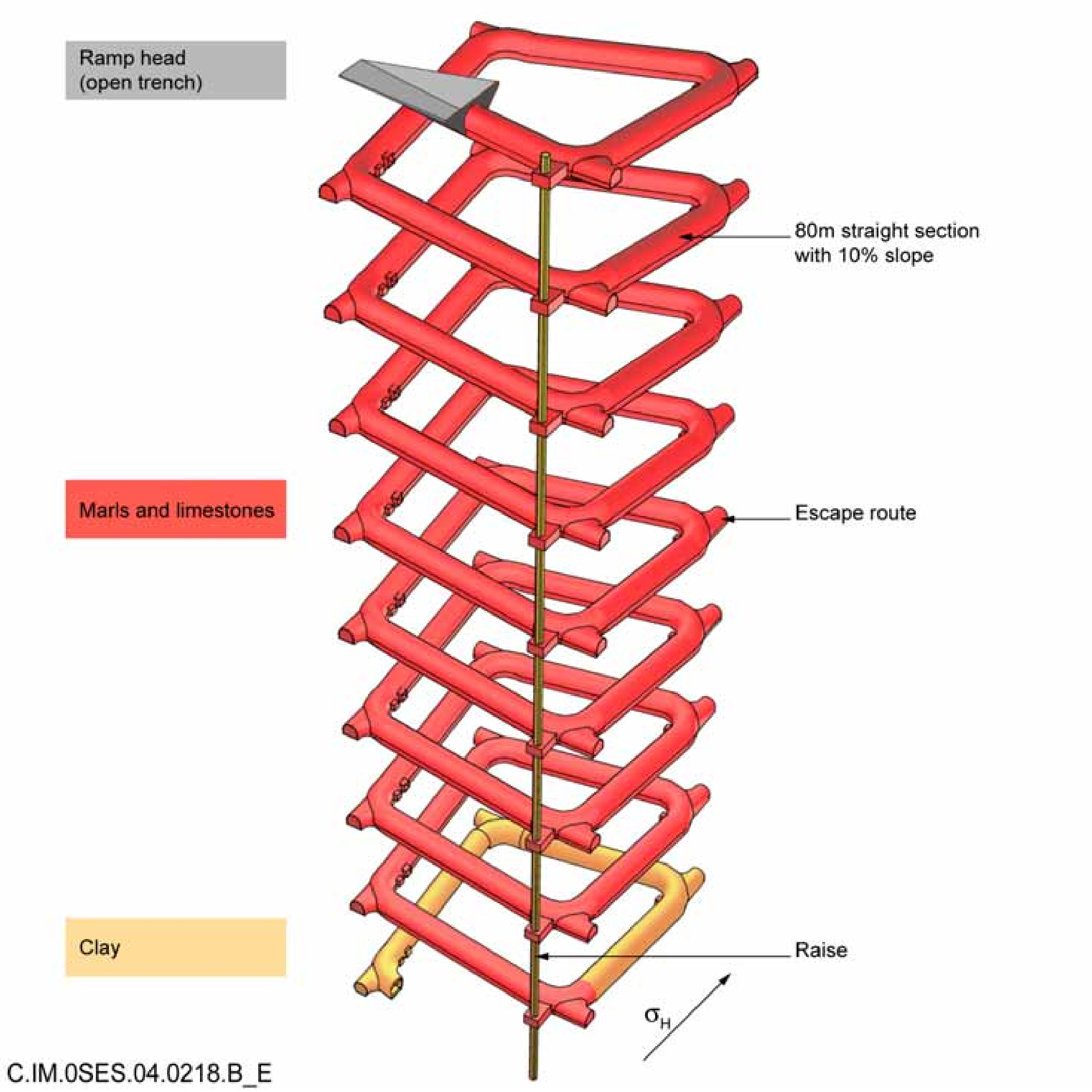

Figure 7.3.5 Construction ramp

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[120] For information, this shaft would be sealed during the closing of the repository in the same way as the other shafts.

7.3.4.2 Package transfer ramp

Packages are lowered and transfer casks raised by means of a ramp with electric vehicles similar to that used for the horizontal transfer of packages in the repository (see chapter 9). Such a structure would allow eliminating the risks of falling from a great height. In the example given, the drift is sloped 10%. It general shape is helical. Each spiral is square shaped and consists of straight sections 80 m long and curves having an inner radius of approximately 10 m. The section length was limited in this example in order to reduce the potential speed (50 km/h at most) of a package transfer vehicle in case its braking system should fail. At each turn an escape way would allow stopping the vehicle in case it misses the turn. The drift has a usable diameter of approximately 7 m. A 3 m dia. vertical air shaft interconnects the various spirals and ensures an air circuit specific to the ramp independent from the repository's ventilation.

During closure, the assembly is also sealed in a way similar to that of the construction ramp.

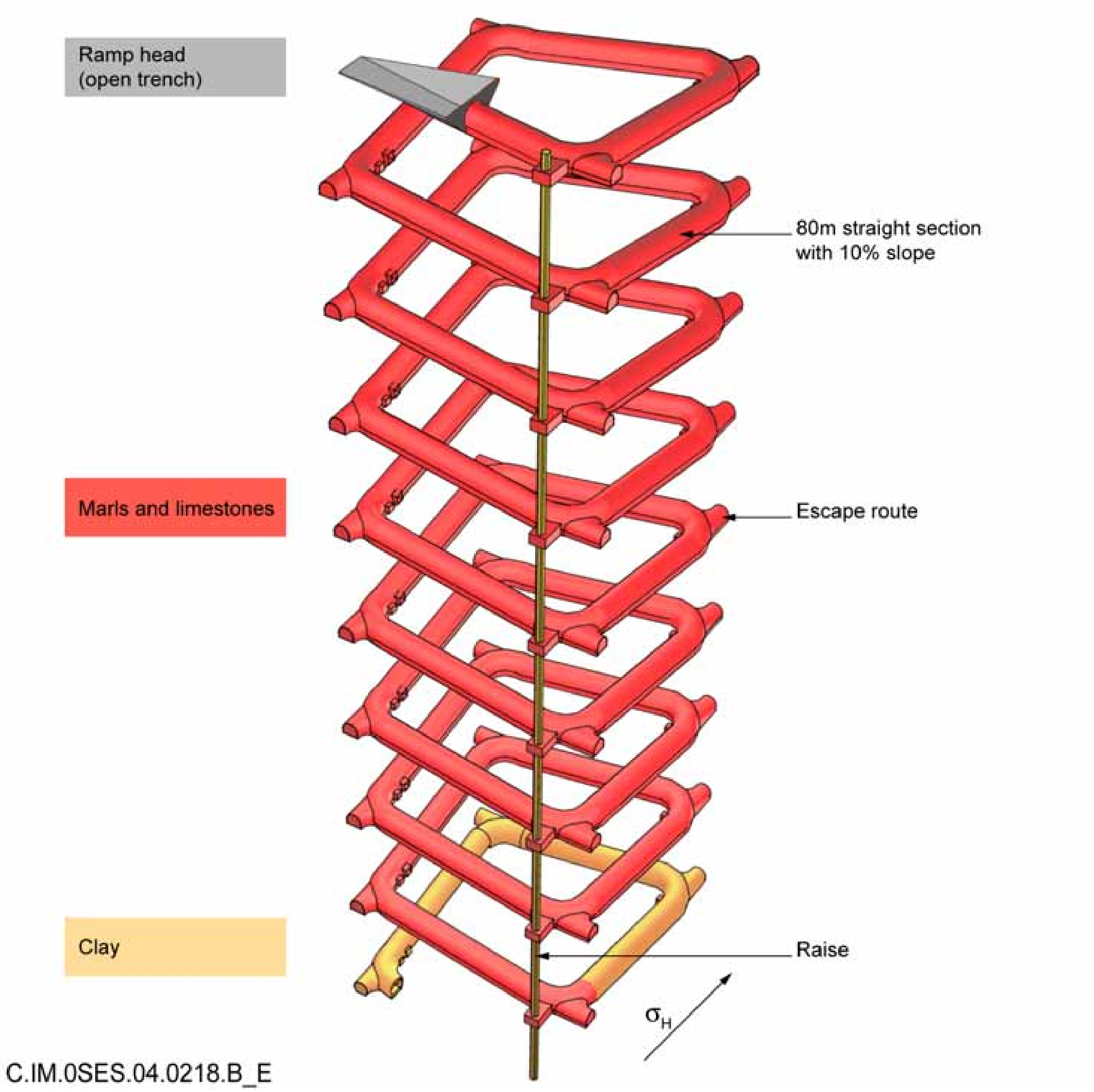

Figure 7.3.6 Ramp for the transfer of packages

7.4 Description of the connecting infrastructures

These infrastructures comprise, on the one hand, the infrastructures of the shaft zone described in section 7.4.1, and, on the other hand, the connecting drifts described in section 7.4.2, and connecting this zone to the access drifts to the cells.

7.4.1 The infrastructures of the shaft zone

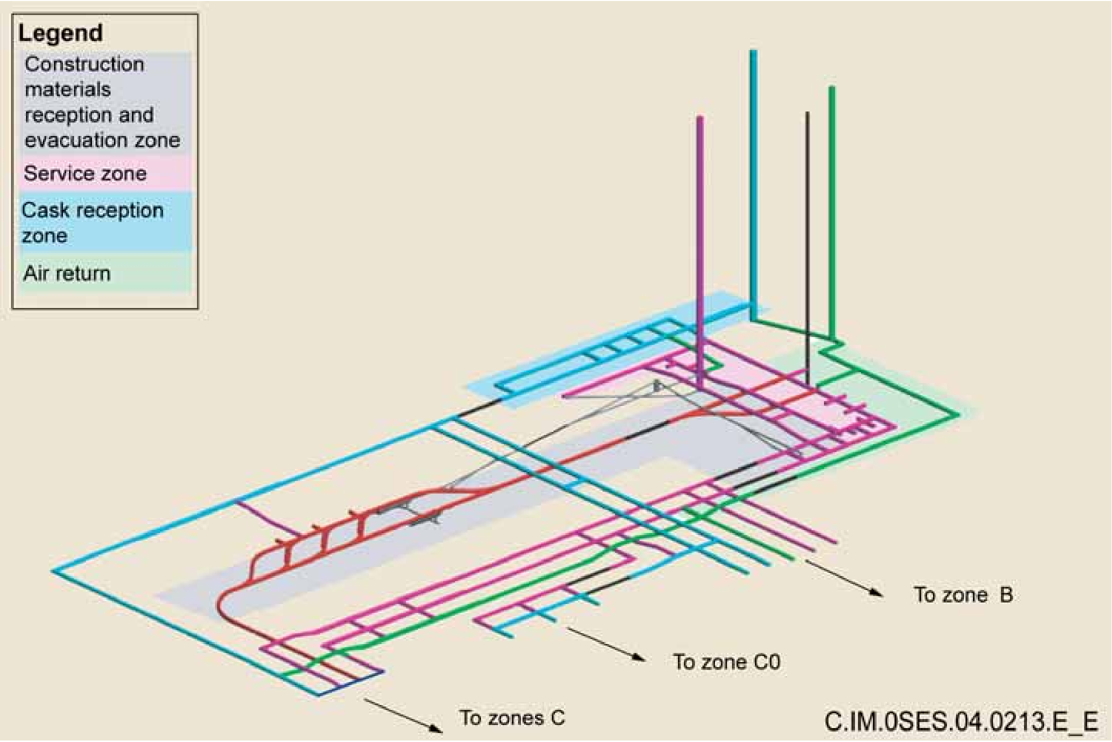

Figure 7.4.1 Shaft zone

The infrastructures of the shaft zone make up the interface between the shafts and connecting drifts and the repository zones. They are organised around the following four functionalities :

- Receipt and evacuation of the building materials (mucks, concrete, backfills, miscellaneous materials and equipment) ;
- Receipt of the transfer transfer casks of the full and empty packages ;
- Support for the operation of the underground installations ;
- Air exhaust.

Because of the diversity of the functions to be satisfied and the flows to be controlled, the shaft zone is a complex zone whose design must be studied in depth. Described here is a possible preliminary design capable of being adapted and optimised according to the study scenarios. This design is comparable to that of an underground mine, but rendered more complex by the presence of waste packages and large concrete flows.

Figure 7.4.2 gives as an example the shaft zone of the Gorleben repository project in Germany.

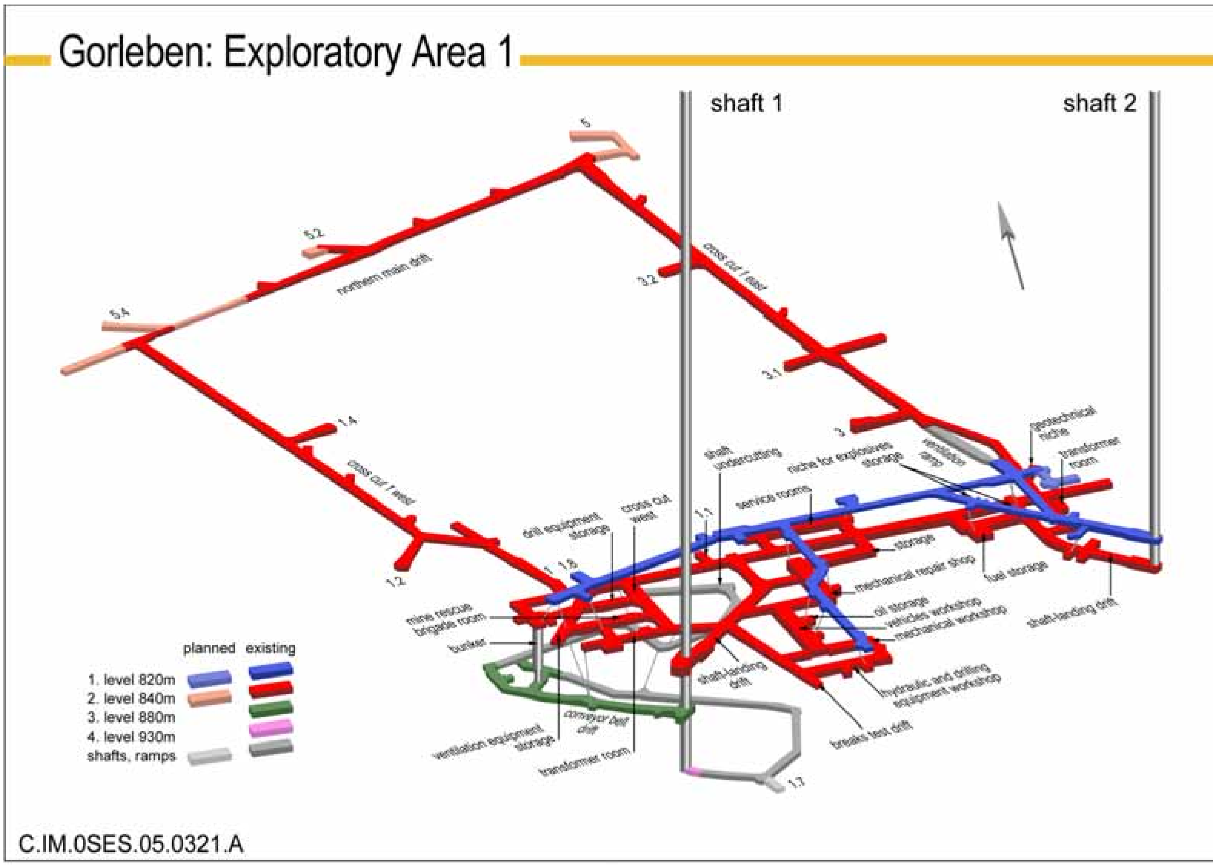

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Figure 7.4.2 Gorleben shaft zone

7.4.2 The connecting drifts

The general organisation of the connecting drifts and the drift layout examples were presented in chapter 6. This section is limited to individual drifts. For information, the access drifts to the cells are described in chapter 5.

7.4.2.1 Geometry of the connecting drifts, ground support and liner

At this stage in the studies, the diameter of the drifts was deliberately limited to a section as small as possible, taking into account the flows passing through these drifts. Except for a few cases, the usable diameter of the connecting drifts is 5.7 metres. The section is "horse shoe" shaped. The shape of the drifts is adjusted according to the drift's direction with respect to the horizontal stress.

The ground support of the drifts consists of 3 m long bolts and 20 cm thick shotcrete.

In the resemblance of civil engineering tunnels, the liner is sized to ensure the drifts a 100-year service life.

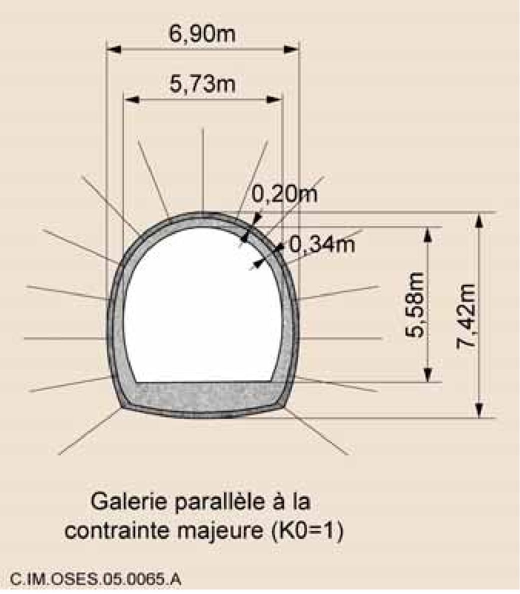

Figure 7.4.3 Standard drift sections having an average usable diameter of 5.7 m

At the intersection of drifts of the same size, specific constructive requirements must be taken into account to ensure mechanical stability. In the solution proposed at this stage in the studies, the diameter of one of the drifts is increased so that the ratio of the usable heights is approximately 1.3 in order to give a more advantageous form to the drift intersections (the intersection of two drifts of the same diameter would generate "flat domes")[121]. Reinforcment pillars made of reinforced concrete having a section of approximately 5 m^2 can also be constructed at the four corners of the drift intersection.

Special arrangements can be planned for the drift sections designated to receive a seal when the repository is closed. They aim at minimising the damage or the extension of the damaged zone in order to enhance the seal's effectiveness. In order to prevent potentially damageable effects from the rockbolts on the argillite's integrity, the use of rockbolts will be avoided and replaced by a ground support using steelsets and 30 cm thick shotcrete. The drift shape can be made to resemble a circular form by locally reducing the usable diameter (5.2 metres).

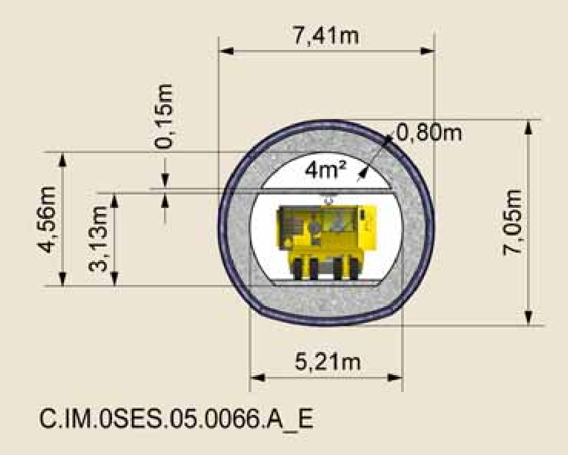

Figure 7.4.4 Possible drift section in a seal zone

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[121] This arrangement also facilitates the turning of more bulky vehicles (B and CU package transfer vehicles).

7.4.2.2 Connecting drift functions and equipment

This section shows the examples of the various types of connecting drifts indicated in chapter 6.

- **Package transfer drifts**

The main function of these drifts is the transfer of the packages between the package transfer shaft and the access drifts to the cells.

In addition, these drifts ensure the supply of fresh air to the modules in operation for all the zones (see chapter 6).

It should be noted that these drifts are not sized to allow the passing of a package transfer vehicle by walking personnel or another vehicle. This can be planned due to low traffic (ten trips a day), slow package transfer vehicle speeds (5 to 10 km/h) and a strictly limited flow of personnel in these drifts. Service personnel or vehicle access can be accomplished from the cosntruction drifts by the interconnecting drifts joining together the various drifts of the group.

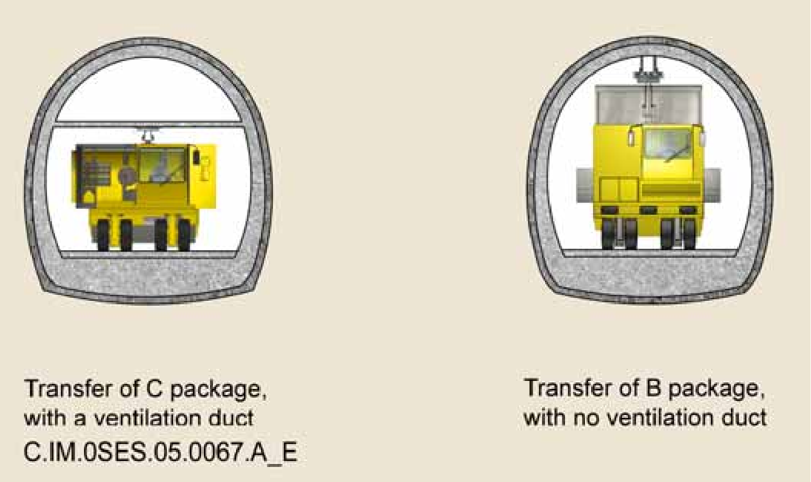

Figure 7.4.5 B and C waste package transfer drifts

- **The construction drifts for tyred vehicles**

The main function of these drifts is to allow the circulation of the auxiliary construction and transport vehicles (such as personnel, ground support, liner, emergency vehicles). For the B and C0 waste zones, the muck, concrete and backfill are transported by trucks and use these drifts.

In addition, these drifts allow the passage of networks and the supply of fresh air in the construction zones.

These drifts have a concrete or a tar covered roadway installed in them for the circulation of tyred vehicles. A sidewalk is provided for walking personnel. This sidewalk can be driven over to allow emergency vehicles to pass by other vehicles, but the drift width is not sufficient for two-way traffic flow.

In the drifts travelled through by vehicles without overhead electric lines (low power electric vehicles and low or high power diesel vehicles), an air exhaust / smoke removal duct with a large section (8 to 9 m^2) can be installed.

The drifts travelled through by high power electric vehicles are equipped with overhead electric lines. The size constraint of this overhead electric line system, which must allow a radial clearance for the trucks to pass by other vehicles, such as emergency vehicles, does not allow the installing of large section ventilation ducts[122].

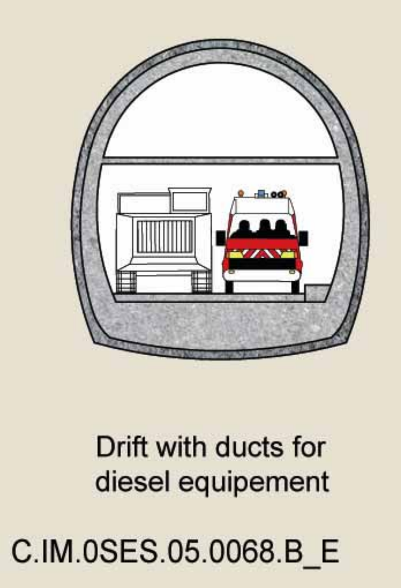

Figure 7.4.6 Construction drift with track

- **Construction drifts equipped with railways**

The main function of these drifts is to ensure the transport of broken rocks, concrete and backfills between the shafts and the repository working units in operation for the C waste repository zone and possibly the spent fuel repository zones.

They are equipped with two metric-gauged railways connected by crossings – junctions, overhead electric lines, large section ventilation ducts (approximately 7 m^2) and network installations.

- **Air exhaust drifts**

The main function of these drifts is to ensure under normal conditions the exhaust of air from the constuction and operation worksites to the air exhaust shaft. According to needs, they can also be equipped with smoke removal ducts.

These drifts do not have equipment other than that required by ventilation or smoke removal needs. The presence of personnel in these drifts is strictly limited to maintenance requirements and assumes the suspension of upstream construction or operation.

7.5 Construction of shafts and connecting drifts

7.5.1 Construction of shafts

This section briefly reviews the various shaft sinking techniques in industrial use and then describes the favoured method by indicating, if necessary, the possible variants of this method.

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[122] On the other hand, the electric power systems of the package transfer vehicles and the railways require hardly any or no axial clearance and are much less bulky.

7.5.1.1 The shaft construction methods

For the construction of large diameter shafts, the conventional method consists of sinking the shafts from the surface by blasting the rock with explosives or drilling the rock with a roadheader and installing as the sinking operation progresses the ground support and the liner of the shaft. This method is well adapted to the planned usable diameters between 6.50 m and 11.50 m.

Fully mechanised sinking methods have been developed in the mining industry. The “shaft drilling" method consists of drilling shafts with a kind of vertical tunnel drilling machine equipped with cutting wheels. In the “raise boring” method, a "pilot hole" approximately 30 cm in diameter is drilled from the surface down to a pre-existing drift. From the drift, a boring tool is raised in the drilled section up to the surface. These technologies offer the advantage of not requiring personnel in the shafts during the sinking operations, but the disadvantage of not allowing the ground support and liner of the shaft to be progressively installed during the sinking operations. Moreover, in the current state of technology, these methods are not applicable to the diameters considered.

7.5.1.2 The main phases in the construction of a shaft by a conventional method

In order to construct a shaft, a foreshaft is sunk a few tens of metres into the ground and then the shaft sinking equipment is installed. Then the main sinking operations take place. After the sinking operations are completed, the shaft equipment is installed and then the final machinery.

- **Foreshaft**

Foreshaft construction details can vary according to the exact location of the shafts and the characteristics of the ground close to the surface. According to the consistency of the surface ground, the first few metres can be excavated with a dredger. The foreshaft is sunk a few tens of metres by successive sinking phases with drilling and blasting and ground support by rockbolts and grillage (and shotcrete, if necessary). As soon as there is no longer any risk of damaging it with blasting, a reinforced concrete slab is poured to serve as a base for the construction of the shaft.

- **Shaft sinking equipment**

The shaft sinking equipment is generally made up of two sub-assemblies : on the one hand, the movable equipment circulating in the shaft and, on the other hand, the fixed equipment located on the surface.

The movable equipment consists of a movable planking and a platform from which the work in the shaft is performed. The planking and platform are suspended on cables and are progressively lowered as the worksites progress.

Figure 7.5.1 Shaft sinking platform (salt mine of Konradsberg – Heilbronn – Germany)

The fixed equipment consists of a head frame and a set of winches which are used to move the movable equipment. This fixed equipment installed to construct the shaft will be totally or partially replaced by final equipment at the end of the shaft's construction.

- **Shaft sinking**

The largest part of the shaft sinking operations are performed with the platform. This platform is used, on the one hand, for the sinking – ground support operations and, on the other hand, for the liner installing operations.

Mine holes are drilled using drilling jumbos supported by the work platform.

After the mine holes have been loaded with explosives, a blasting volley is fired corresponding to a depth of approximately 2 to 3 m according to the shaft's diameter.

After the blast fumes have been evacuated thanks to forced ventilation, the broken rocks are evacuated. A cactus grab loads a kibble[123], which is raised to the surface by a winch.

A ground support (rockbolts or steels sets) is gradually installed as the broken rocks pile diminishes.

The concrete liner is then poured by segments from the work platform, with the concrete lowered into the shaft by specially equipped pipelines.

- **Final shaft equipment**

Installing the final shaft equipment consists of, first, installing the fixed installations located inside the shaft : equipment of the sump and the bottom station, installation of the cage guiding rail supports and the rails themselves, and, if necessary, construction of walls between the various compartments of the shafts. This assembly is normally accomplished by using the equipment used to sink the shafts.

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[123] Cyllindrical buckets specifically designed for shaft sinking.

Then, the head frame, the extraction machines and the electric equipment are installed. Finally, the cables and the shaft cages are installed.

7.5.2 Construction of the drifts

The drift construction techniques are similar to those used for the construction of the B waste repository's cells and are described in section 5.1. However, since the connecting drift sections are smaller, the drifts can be sunk in full section and not in a divided section.

7.5.2.1 Current drifts

The connecting drifts and the access drifts of the C waste modules (and spent fuel modules) are constructed in four phases by sections of several hundred metres :

- Excavation by a roadheader[124] and ground support by rockbolts and shotcrete of the drift (steel arches and shotcrete in the sealing zones) ;
- Pouring of the concrete slab ;
- Pouring of the concrete liner ;
- Drift equipment (utilities, rails or roadway, ventilation duct, etc.).

7.5.2.2 Drift intersections

Drift intersections are built in a number of stages:

- Excavation and support of the larger diameter drift;
- Excavation of vertical grooves at the four corners of the future intersection, followed by filling of these grooves with reinforced concrete so as to form four pillars with a cross-section of approximately 5 sq. meters in order to reinforce intersection roof support;
- Excavation and support of the smaller diameter drift;
- Pouring of concrete slab for both drifts;
- Pouring of concrete lining into both drifts. This lining is integral with the pillars.

7.6 Durability of structures

Reversible disposal implies that shafts and drifts must last for as long a time as is decided to keep underground installations open.

Industry experience in terms of civil engineering tunnels and mining installations shows that suitably designed and built structures can be kept in service for more than a century. Keeping these structures in service generally implies that they will need to undergo maintenance. Indeed, requirements for the use of a structure are more stringent than requirements governing its overall stability. In fact, localised problems may prevent safe operation of the structure, without however jeopardising its overall stability[125].

The scale of maintenance operations on underground structures depends on support and lining design. At the current stage of study, preference has been given to a civil-engineering type approach: installation of a thick lining in order to be able to operate drifts and shafts with less maintenance for at least one hundred years. Beyond that point, the stability of these structures could be maintained for several hundreds of years through monitoring and increased maintenance if needed.

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[124] For constrcution work taking palce away from nuclear operations and outside sealing areas, drill and bast could be considered.

[125] It is this overall stability, and not operational safety requirements, that is taken into consideration regarding long-term behaviour of structures following storage closure.

7.7 Closure of underground facilities

Closure operations may be carried out over a number of stages that take into account the rationale of reversibility and in particular, the possibility of going backwards. See chapter 10.

For the purpose of repository closure operations, structures are designed so as to minimise long-term mechanical argillite deformation, limit water flow and compartmentalize the repository (see section 7.1) [38].

These functions are assigned to various types of structure. Minimising mechanical argillite deformations essentially relies on backfilling of all drifts. Limiting water flow relies on localised impermeable structures known as seals. Various seals are installed at points that enhance their effectiveness and redundancy, thereby compartmentalize the repository.

The building of these structures forms part of a stage-based approach to disposal process management, with each type of structure marking a stage of the process.

Indeed, it is planned for cell sealing operations to be followed by backfilling of the drifts that serve them: connecting drifts inside a B-waste disposal area, access drifts to C-waste cells within each module.

The decision could then be taken to close a disposal area. This would require the sealing of connecting drifts providing access to this area: seals at the entrance to a B-waste disposal area, separation seals for a C-waste disposal area.

The last stage would entail backfilling of connecting drifts linking disposal areas to shafts, as well as the sealing of shafts. Seals built inside drifts located close to the shafts would reinforce seals built inside the shafts.

Mining experience shows that backfilled (or sealed) drifts can be reopened as long as precautions are taken to restore support and lining integrity, as the drift is gradually cleared out.

7.7.1 Typical drift backfill

7.7.1.1 Design principles

Typical backfills must be able to support argillite pressure, considering the possible rupture of drift lining long after closure. This entails minimising long-term rock deformation in order to prevent or curtail spreading of the damaged area around the structures.

Lining rupture results in argillite convergence. After vacuums left by backfill operations are filled in, the backfill subsides and offers increasing resistance (its deformation module increases together with stress) until equilibrium is once again reached between the argillite and the backfill.

Potential argillite damage during this process depends on two factors: the magnitude of total deformation and argillite loading rate. In this case, the latter is the decisive factor: instantaneous relaxation could result in significant damage in the case of minor deformations; very slow changes might not damage the rock, even in the case of major deformations.

Two criteria are therefore necessary for backfill operations: (i) vacuums must be kept to a minimum; (ii) Backfill material must have sufficient load-bearing capacity from the time it is put in. Its hardness then increases as it becomes more tightly packed through the effects of the argillite. Research shows that an initial deformation module of 10 MPa is sufficient in this respect.

The amount of backfill is considerable (several million cubic meters). Research was therefore conducted into possible reuse of excavated argillite as a basic backfill material. This option would be economically beneficial, while also reducing the need for filler materials.

In close proximity to the seals, the backfill also fulfils a mechanical containment function. This aspect is dealt with in section 7.7.2 on drift seals.

7.7.1.2 Description

Backfill is composed of excavated argillite which, following storage at the surface, is reconditioned by being crushed to a thickness of 20 millimeters. Its water content is close to that of the normal Proctor optimum (NPO)[126], i.e. 10 to 15%. The aim is to have a dry backfill density of at least 1.6 at the time of installation, with a swelling potential of one percent or slightly more.

7.7.1.3 Installation procedures

Backfill is initially prepared at the surface before being taken to the backfill site. It can be installed by horizontal compacting in the lower section of the drift, with inclined sloped layers in the upper part of the drift. Horizontal tamping is done using standard roadwork equipment. For oblique layers, it would be possible to use a rammer placed at the end of the articulated arm of an earth mover; oblique compacting is undergoing a demonstration test.

A hydraulic ram was therefore tested on backfill made up of pure argillite or argillite-sand mix in a concrete structure simulating a drift (see Figure 7.7.1). Dry densities in excess of 1.7 were obtained.

Figure 7.7.1 Hydraulic ram in action in the backfill demonstration model

7.7.2 Drift seals

Each connecting drift seal consists of a core of swelling clay, which gives the engineered structure its very low permeability, and the concrete retaining plugs which give the core its mechanical containment (see Figure 7.7.1). The mechanical properties of the drift backfill are reinforced compared with the standard backfill over twenty to thirty metres approximately on both sides, to contribute to the mechanical containment of the engineered structure.

This principle has to be adapted to the special configuration of the B waste disposal cells when sealing the drifts giving access to these cells.

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[126] The NPO, or normal Proctor optimum, is a standard test used to determine a material's most favourable water content for compaction purposes. Backfill mechanical resistance is favoured by slightly higher water content than NPO.

7.7.2.1 Design principles

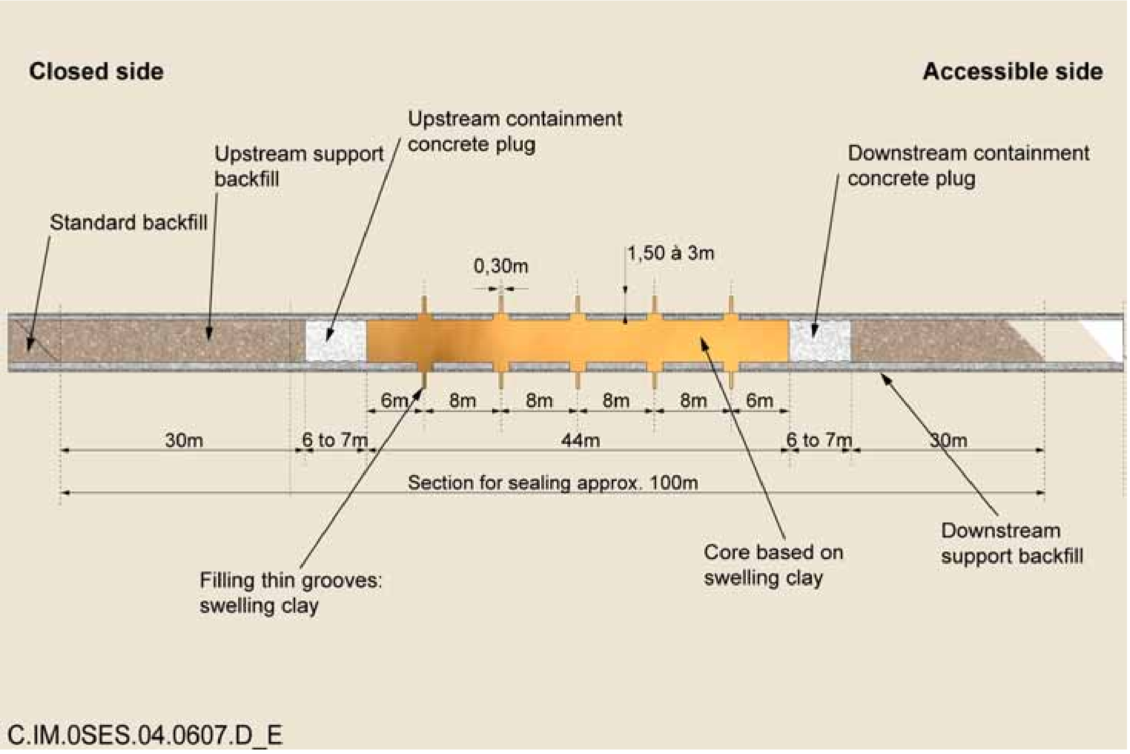

Figure 7.7.2 Drift seal diagram (with hydraulic cut-offs of the fractured zone)

Swelling clay is adopted as the base material for the seal core given its favourable properties. Its very low permeability satisfies the objective of not allowing water to circulate in the drifts. Its swelling and deformation capability when water is present means that it fills the clearances left during the construction of the core and provides a good contact with the drift wall; once the clay is swollen, the water has no possible flow path through the core. Its natural character and chemical compatibility with argillite guarantee a high durability.

The core hydro-mechanical properties can be adjusted by varying the method of implementation and the formulation of the material. The potential swelling pressure of the clay increases with its average dry density in the engineered structure. This density depends on the compaction rate of the clay, itself a function of the implementation method. In terms of formulation, adding sand, for example, may encourage compaction and improve the mechanical properties of the material without significant increase in permeability.

For the clay in the core to develop and maintain a swelling pressure in the presence of water in the long term, it must be located in a contained volume. Thus the role of the concrete retaining plugs is to limit the core expanding in volume; to achieve this, they must resist the pressure developed by the clay mechanically, particularly during the transient phase of core hydration and swelling. A very long-term chemical alteration of the concrete cannot be excluded, which would reduce its properties; to prevent such an alteration reducing the core performance, support backfilling will then take over the role of the concrete retaining plugs.

Note that these design principles for the drift seals are similar to the plugs for the C waste disposal cell presented in Chapter 5.

7.7.2.2 Design and production technique for a swelling clay core

- **Design and justification**

The length of about 40 metres adopted for the swelling clay core guarantees performance with little hydraulic transmissivity; several hydraulic cut-offs can be created in the aureole of the argillite damaged by the excavation. The motivations for these cut-offs and their definition are discussed further on, in § 7.7.2.5.

To ensure sufficient, long-term swelling pressure under all circumstances, the clay is given an initial swelling pressure of 3 MPa.

The swelling clay being considered is MS80[127] or equivalent. This industrially-used clay has a particularly low permeability of less than 10^{-13} m/s at the scale of the material. In addition, this permeability seems less dependent on the dry density than most other industrial clays (it remains low even at low densities). This is a clear advantage in this situation, where restricted swelling pressure is important.

To avoid fracturing the argillite on the excavation wall, the core swelling pressure must not exceed 13 MPa, as for the C waste cell plugs (see Chapter 5). In addition, the support engineered structures (retaining plug and bakfill) will be less under stress the lower the swelling pressure. Nevertheless, there must be sufficient pressure to ensure leaktightness in contact with the drift wall: to have a swelling reserve, the intention is that the core swelling pressure is always higher than or equal to 1MPa during the evolution of the engineered structure.

The principle of this evolution is similar to the C waste cell plugs (Chapter 5). The core swelling pressure starts with a first maximum after resaturation; this initial swelling pressure depends entirely on the formulation and installation conditions of the clay (dry density, water content, clearances left for installation). A relief period may follow, reducing the swelling pressure, if an alteration in the retaining plugs causes the core to expand laterally: in this pessimistic situation, it is important to maintain the swelling pressure above 1MPa. Ultimately, the pressure will increase to a state of equilibrium with the rock, corresponding to the effective geostatic stress (7 MPa at the depth of the underground research laboratory).

For the pessimistic situation adopted for the dimensioning, the following figure illustrates (i) the progressive reduction in the core swelling pressure, with its volume expansion, and (ii) the increase in the mechanical containment capability of the support backfill as it is compacted by the core deformation. It shows that based on an initial swelling pressure of around 3 MPA, the backfill can block the core deformation whilst it shows a residual swelling pressure of 1MPa.

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[127] It is a natural, sodium smectite mined in Wyoming (United States)

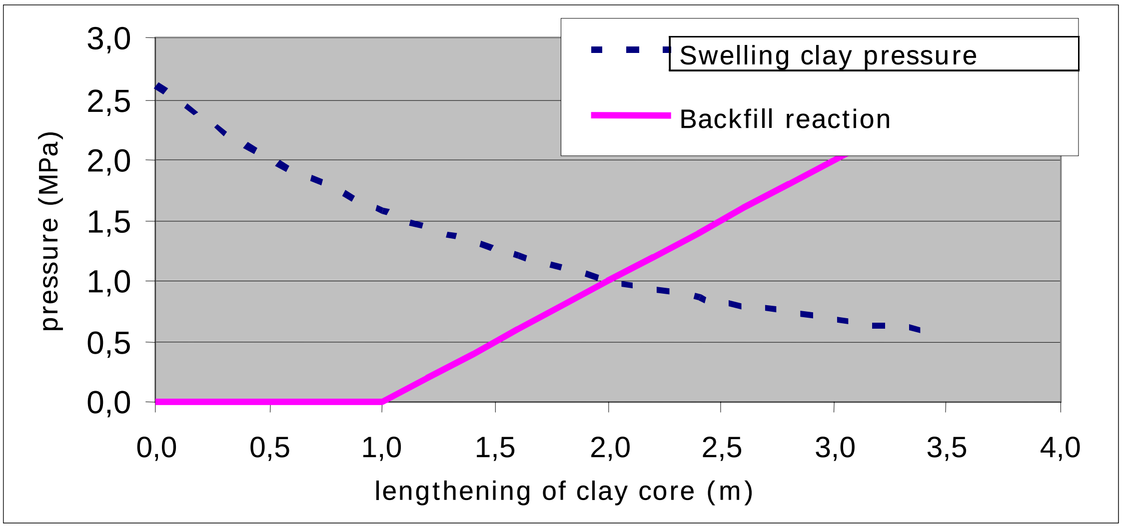

Figure 7.7.3 *Equilibruim between the pushing of the core swelling and the reaction of the backfill (initial move of 1 m before placing the backfill under stress and backfill stiffness of 1 m/MPa)*

Note that for the C waste cell plugs, a greater initial swelling pressure is sought (see Chapter 4), given the restricted length of these plugs.

- **Constructing, shaping and installing the core material**

To achieve an initial swelling pressure of 3 MPA, the knowledge acquired on swelling clay MX80 [47] shows that the dry clay density should be 1.4 to 1.5 approximately (in a mix, this is the density of clay in the mix[128]). This is an average value on the engineered structure given the voids at installation [38].

Two implementation techniques are possible to achieve this. The first involves the factory pre-fabrication of pressed, compacted blocks, then their dry assembly in the drift being sealed. To adjust the swelling pressure, the blocks consist of a mix of clay and sand (with 20 to 30% sand). The second technique is to spray high-density aggregate (or pellets), possibly mixed with pulverulent clay. For example, the average dry density sought can be achieved with compacted clay pellets with a density of 1.8 and a void coefficient between pellets of 20%, representative of traditional spraying techniques.

The use of pre-compacted blocks has been full-scale tested in the Tunnel Sealing Experiment (TSX) in the Canadian Underground Research Laboratory (Figure 7.7.4). To improve filling of the drift and obtain a more homogenous core, the peripheral voids, particularly in the cell, were filled with clay powder (or a mix of pellets and powder).

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[128] Clay mass/water mass occupying the same volume as the mix

Figure 7.7.4 Experimental seal made up of bentonite blocks - Tunnel Sealing Experiment in Canada (these blocks would be larger at industrial scale).

For reference, before the core is constructed, the drift equipment such as rails, pipes, cables and the roadway will be removed to prevent them creating a favoured path for water.

7.7.2.3 Retaining plugs

The retaining plugs planned to contain the core mechanically must resist the initial swelling pressure applied (3 MPa). They assist therefore in controlling the core resaturation phase: simple geometry for the core and support face encourage homogeneity of resaturation and predictability of the swelling pressure.

These plugs are designed in high-performance, non-reinforced concrete, choices dictated basically by durability. High-performance concrete is more compact, water percolates through it less and its alteration is delayed accordingly. The lack of reinforcement prevents fissuring from corrosion products expanding. It does however create a design constraint: these plugs must work by compression only. This may be achieved by a conical shape.

The low permeability of the bases is thus a guarantee of robustness: it contributes to restricting the water flow reaching the clay core in the event of abrupt hydraulic head and thus protects it from the risk of mechanical erosion.

7.7.2.4 Description and creation technique for support backfill

Like the drift liner, the retaining plugs may ultimately be altered chemically. As indicated above, the support backfill will take over the role of mechanical containment of the swelling core.

The principle adopted is to restrict the seal from moving by backfill friction on the drift wall. The support backfill must therefore be given rigidity and friction. A 20 MPa modulus of deformation is therefore considered together with an angle of friction (internal or on concrete) of 40°. These properties can be obtained with a mix, in near proportions, of excavated argillite and sand, with the excavated argillite being ground and screened to 20 mm as for the standard backfill.

The length of the support backfill allows the friction between the backfill and the drift wall to balance the swelling pressure of the core. This length is about four times the excavated diameter[129].

The same basic techniques are used to install this support backfill as for the standard backfill. The grouting (filling) of the drift crown can be improved by clay powder injections.

7.7.2.5 Treatment of the argillite zone damaged by the drift excavation

The argillite damaged zone around the seal engineered structure may limit its overall performance, if this zone shows inferior hydraulic properties to the rock or the swelling clay core. Andra has considered two design options, based on the presence or otherwise of a more permeable damaged zone (particularly a fractured zone).

- **Design options considered**

The first option involves removing the liner the entire length of the argillite core and ensuring direct contact between the swelling clay in the seal and the argillite. This solution is appropriate if the damaged zone is of limited extent and its evolution results in it recovering low permeability. The pressure applied by the swelling of the core, the creep or relaxation of the argillite may restore properties close to the undamaged rock, by reclosing the fissuring. This type of process has been observed in the clay in the Mont Terri underground laboratory in Switzerland. This can also be caused by the fissures being healed or clogged chemically.

The second option can deal with the appearance of a far more extended fractured zone, for which uncertainties exist on its ability to recover a permeability close to that of the undamaged rock. It involves interrupting the fractured zone by thin grooves, filled subsequently with swelling clay. These hydraulic cut-offs are effective when the potentially fractured argillite is replaced by a less permeable material. The technique envisaged to create these grooves limits the appearance of new damaged zones. Nevertheless, should a damaged zone be created, particularly at their extremity, checks have been made that the hydraulic cut-offs retain their effectiveness, as these new damaged zones do not connect with each other or with those already existing. The drift liner could also be maintained either side of the grooves.

On the site studied, the appearance of a fractured zone is considered possible around the drifts. As a precaution at the current state of knowledge, Andra is taking the second option as the reference for drift seals: hydraulic cut-offs, with localised liner removal.

- **Description**

The grooves in question are around 30 cm thick and 1.5 to 3.0 metres deep. This is deeper than the liner thickness and any argillite fractured zone. The groove can therefore anchor itself in an argillite zone that has not been microfissured during creation of the drift.

It is planned to space the grooves around 8 m apart; this could be modified in the light of the extent of the induced damaged zones, to optimise the hydraulic effectiveness of the cut-offs.

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[129] The excavated diameter, not the useful diameter, is considered here: when the backfill is applied as support, the surrounding liner can also become degraded; it can then be considered an integral part of the support backfill and resist by its friction on the argillite on the excavation wall.

The grooves are filled with swelling clay (type MX80, like the core). The aim is to have a swelling pressure at installation in the order of 3 MPa on the groove faces. The density of the clay and the installation voids are adjusted to this purpose.

The liner is removed over around 1.30 m perpendicular to each groove, leaving 0.5 m either side; the distance thus separating the concrete and the clay from the grooves limits a potential alkaline disturbance in the clay, which thus retains sufficient swelling capability.

- **Construction of hydraulic cut-offs**

The liner is removed locally. The grooves are excavated using a saw fitted with picks, with a cutting tool similar to the cutters used in salt and coal mines to create grooves in the rock massifs.

The technological feasibility of creating a groove has been tested in the Mont Terri laboratory (EZ-A test) and in the Meuse/Haute Marne laboratory (KEY test). These tests have confirmed that it is possible to create such grooves and has checked their effectiveness in interrupting the fractured zone in the rock.

The grooves may be filled by assembling pre-compacted bentonite blocks. These blocks are set in place mechanically using erectors: they can weigh individually a few hundred kilograms to several tonnes depending on methods implemented. Injections of bentonite powder fill the interstices.

Figure 7.7.5 Groove excavation for the KEY test at the Meuse/Haute Marne laboratory

7.7.2.6 Special case of B waste disposal cell seals

The seal design presented for the connecting drift is adapted slightly to close a B waste disposal cell (Figure 7.7.6).

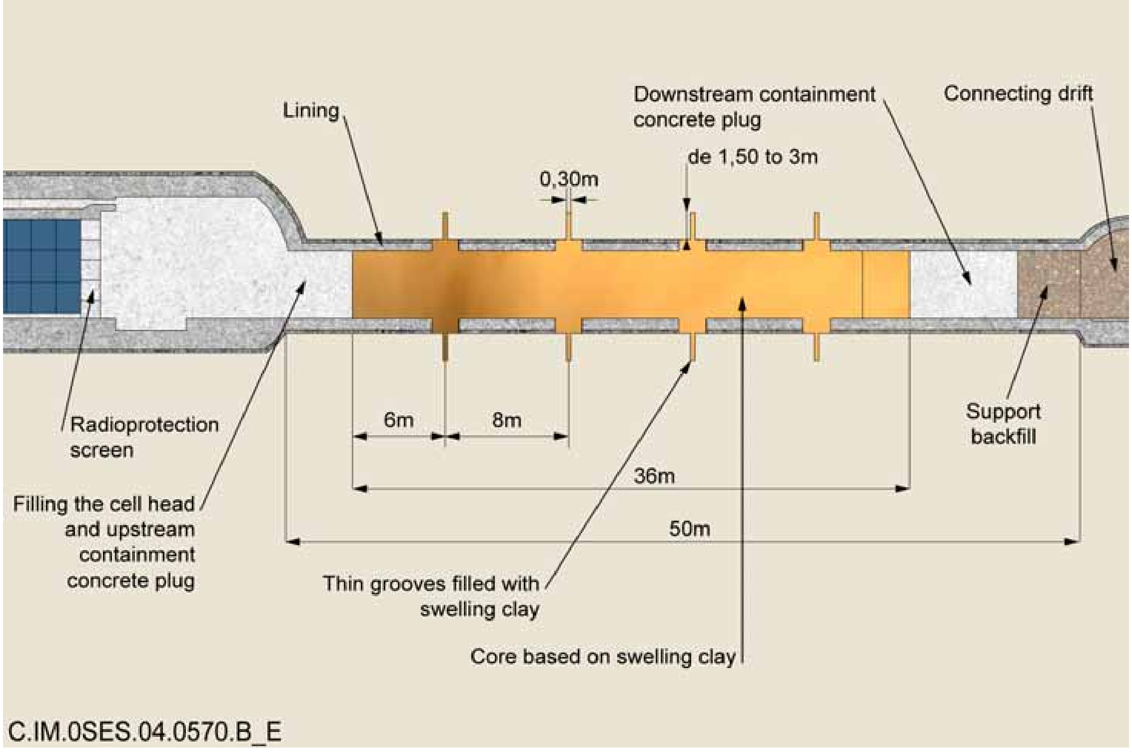

Figure 7.7.6 Diagram of a B waste disposal cell seal

At the front end of the seal, on the cell side, the geometry of the retaining plug is adapted to that of the cell head (see Section 5.1). In addition, the dimensions of the drift giving access to the cell allows the seal core to be installed away from the influence of the damaged zone in the connecting drift.

7.7.3 Shaft seals

7.7.3.1 Design principles

A shaft is closed with two seals and backfill (Figure 7.7.7).

A first seal in the upper part of the argillite formation being studied, isolates the repository from the overlying geological formations. The aim is for its permeability to be as low as possible. Its core is based on swelling clay, like the drifts. This core lies on a concrete retaining plug set at the bottom of the shaft, the station and extending several tens of metres along the drifts that are linked to it. The mechanical robustness of this plug ensures the stability of all the closing engineered structures superposed in the shaft. The weight of the overlying materials may ultimately contribute to the containment of the swelling clay; a retaining plug is nevertheless built above the core to play a mechanical role during the resaturation phase.

The first seal is covered by backfill up to the top of the Oxfordian limestone, using identical material as for the drift backfill.

A second seal is built above the backfill separating the most permeable layers of the overlying strata formations. These levels consist of three hydraulically independent assemblies: the Oxfordian limestone, the Kimmeridgian (two limestone beds) and the Tithonian. They are not really aquifers on the site in question; the hydraulic conditions have to be restored nevertheless close to this initial state. The separation seal could be located in the lower Kimmeridgian marls, 10 to 15 metres high. Its make up is similar to the repository isolation seal, detailed later.

Backfilling continues in the upper part of the shaft right up to the surface.

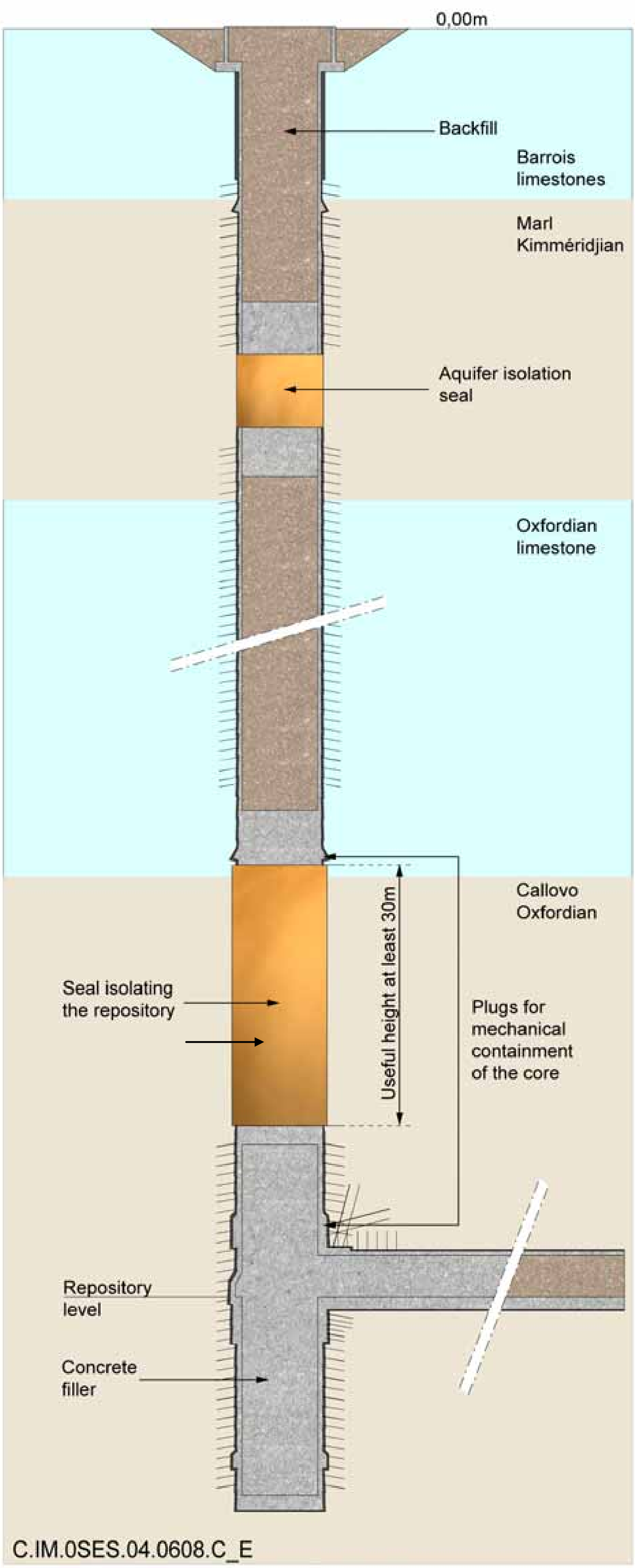

Figure 7.7.7 *Shaft seal diagram - general view*

7.7.3.2 Description and design of the repository isolation seal

- **Installation and height**

The seal is installed as high as possible in the upper Callovo-Oxfordian. The argillites are stronger mechanically here than in the middle of the formation. These stronger levels are at least about thirty metres thick (38 m perpendicular to the underground laboratory [6] - Volume 1). Acquired knowledge suggests that the creation of the shaft does not cause a fractured zone to appear [38]. The intention is to remove the liner when the seal is created over the entire core height. The swelling material thus comes into direct contact with the argillite.

- **Swelling core**

The core is based on MX80 swelling clay or its equivalent. This choice is dictated by the same considerations as for the drift seals. The swelling pressure targeted at installation (after closure of installation voids) is 7 MPa. This value corresponds to the main minor stress (effective). This high level is compatible with mechanical robustness of the containment engineered structures (retaining plug and backfill).

The pressure sought may be obtained with a dry material density[130] of 1.8 and 10% installation voids.

As for the drift seals, two implementation methods are possible: pellets (or mix of pellets and powder) and pre-compacted blocks. Spraying of pellets and powders leads firstly to densities in the order of 1.4 to 1.5; mechanical compacting is then possible to obtain the targeted densities (dry densities of 1.70 were obtained by tipping in bulk and compacting into place during full scale tests such as the one carried out in the shaft of the Salzdetfurth mine in Germany). The targeted densities are obtained directly, however, if pre-compacted blocks are used. Figure 7.7.8 illustrates a possible layout of huge, pre-compacted blocks, each one weighing nearly 4,500 kg.

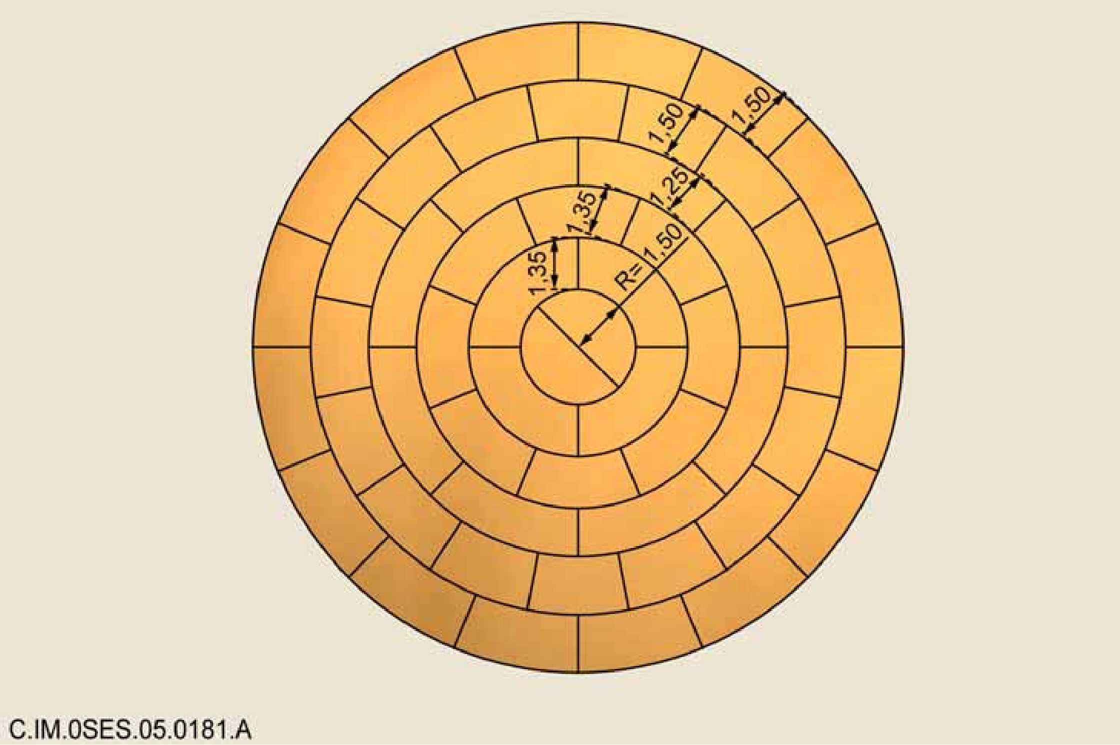

Figure 7.7.8 System of swelling clay bricks for a shaft seal

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[130] For a clay-sand mix, this value relates to the density of the clay fraction in the mix; thus, for a mix of 70% type MX80 clay and 30% sand, the corresponding density of the mix will be 1.95.

- **Upper retaining plug**

A concreted containment plug covers the core. It is anchored in the rock, on which it relies to resist the push by the swelling clay. Its effectiveness is therefore independent from the state of the shaft liner.

The geometry of this plug is two opposing cone frustums at 35°, so that it works by compression and thus has no need of reinforcements.

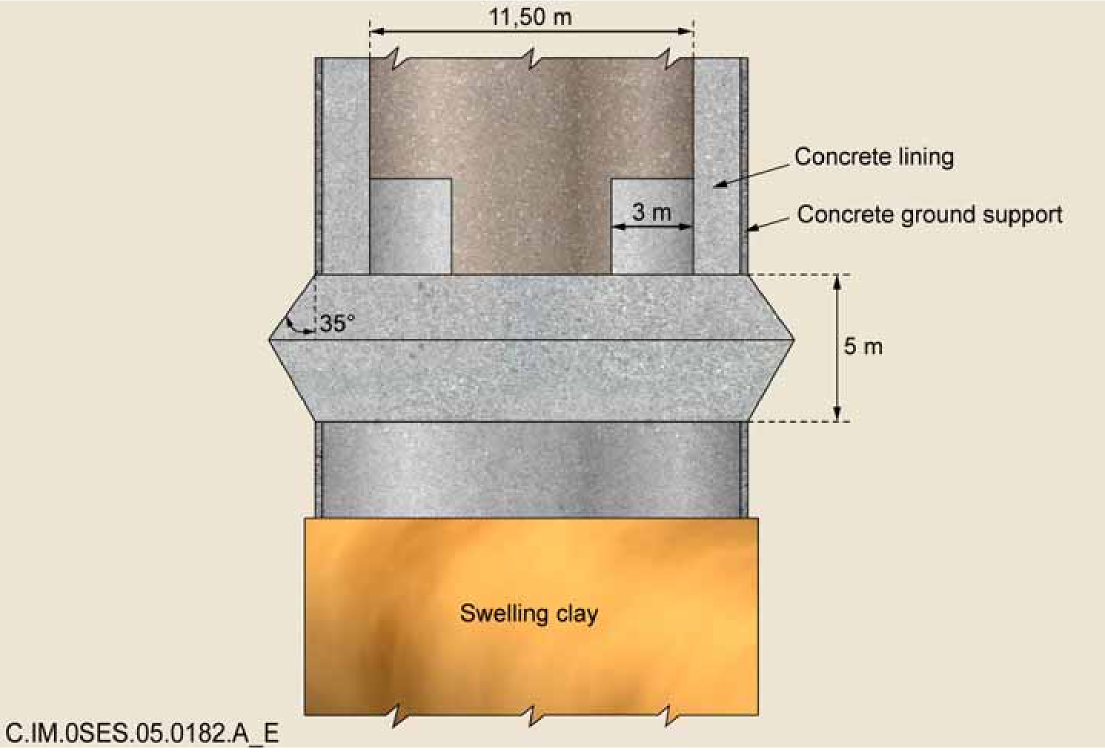

Figure 7.7.9 Containment plug for a shaft seal

7.7.3.3 Construction techniques

All equipment is removed from the shaft before it is closed. The closing operations use equipment similar to that used for sinking.

For the construction of the clay cores, the liner is removed and the clay installed are the same time: several successive passes take place, to limit the unsupported height and ensure site safety. The liner is removed therefore in two metre-high sections approximately. The shaft wall may be surfaced using a small road header machine. Wire mesh and steel arches are installed if needed to support the uncovered facing. The swelling clay is then set in place over the height of the section, by gradually raising the temporary ground support structure

A variant has been studied to take into account uncertainties over the long-term behaviour of the argillite with respect to the mechanical stability of the shaft wall. This consists of leaving mechanically-reinforced liner rings in place. The shaft wall is therefore only exposed in 7-metre sections approximately, separated by 3.5 m-long rings. The ring reinforcement consists of radial, concrete anchoring studs in the argillite.

The concrete is simply poured in place to construct the containment plugs.

Lastly, backfill may be used for traditional compacting, in horizontal layers a few tens of metres thick.

8

Surface installations

Repository construction, operating and closing operations require support installations at the surface. This chapter presents their main characteristics.

It specifies firstly the general organisation principles for the surface installations grouped on a single site.

It then describes the design of the "nuclear zone", consisting basically of a building for receiving the primary packages and preparing the disposal packages. The hypothesis that these operations will be performed at the repository site underlies this design. Analogies between the planned installations and other existing nuclear installations are highlighted. These installations pose no new technical problem in terms of feasibility. Their design is based in particular on proven arrangements in similar installations in terms of safety and environmental protection.

This chapter also describes the industrial and administrative zone for non-nuclear activities in the installations.

Lastly, special attention is given to the storage zone for the broken rock produced by underground excavation, known by the mining term "dump". Its environmental impact is analysed briefly. It is assumed here that all rock extracted is stored on the site, temporarily for those volumes that will be re-used subsequently as backfill material.

Possible surface installation diagrams are given for information only. No option has been fixed and everything is at a very preliminary stage. Note, in particular, that these diagrams cannot take into account constraints relating to the installation location, such as topography or the vicinity. They nevertheless give an overall assessment of the surface installation dimensions, particularly their footprint, and an overall estimation of the sensitivity to the study scenarios described in Chapter 3.

8.1 General organisation of surface installations

The surface installations are divided into four main zones:

- the nuclear zone, with a surface area of around 25 ha, where the primary waste packages are received and the disposal packages are prepared,
- the industrial zone, with a surface area of around 35 ha, grouping the workshops and facilities required in support of the work underground,
- the administrative zone, with a surface area of around 20 h, consisting of offices, car parks and personnel buildings,
- the broken rock storage dump, with a surface area of between 120 and 300 ha depending on the scenarios.

Note that the surface area allocated to the industrial and administrative zones (55 ha) is around the same size as the area occupied by the surface installations for a major underground works site, such as the Channel Tunnel.

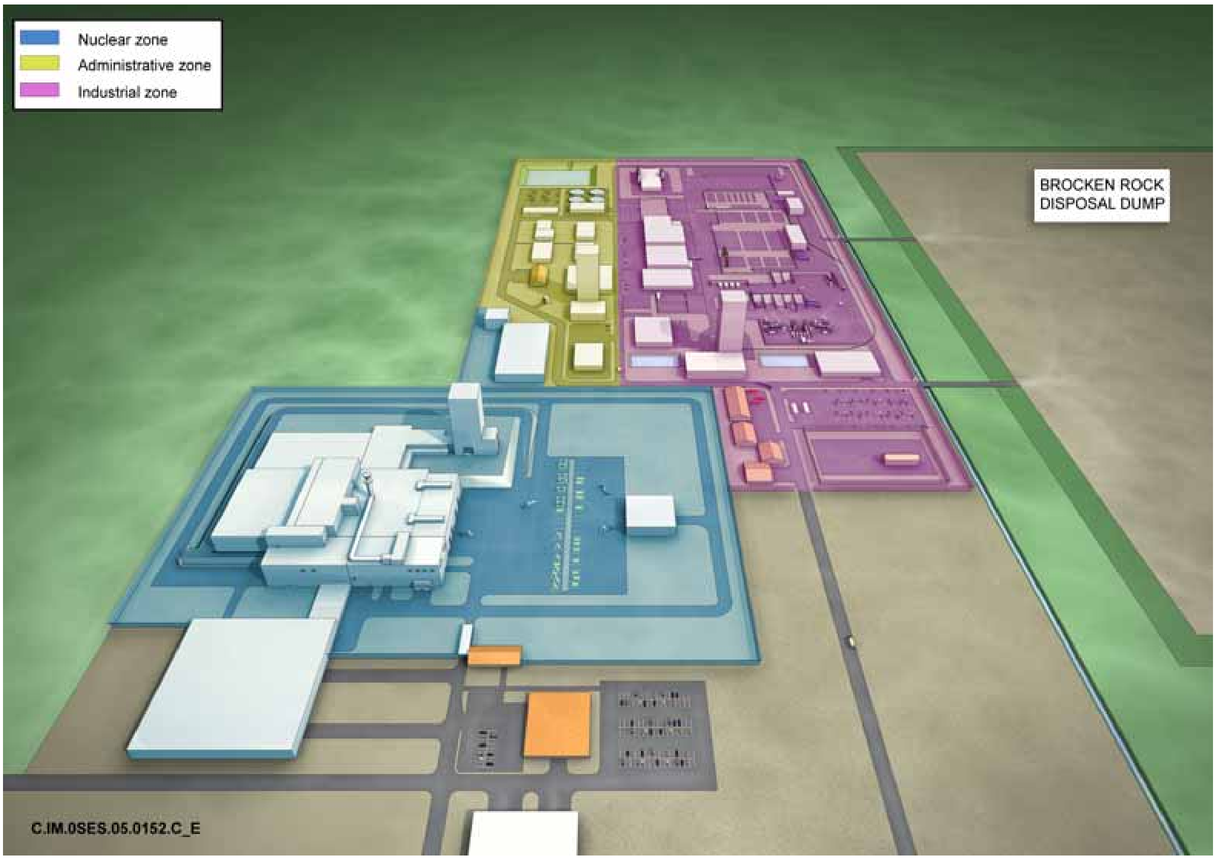

Figure 8.1.1 General view of surface installations

8.2 Nuclear zone

8.2.1 Overall logic for the nuclear zone

The "nuclear" activities zone within the surface installations is a specific industrial zone, with controlled access. It includes:

- a traditional controlled zone (without specific risk linked to the nuclear activity), comprising the support installations (fire service building, equipment warehouses, etc.). The manufacture and procurement of the components needed to produce the disposal packages must at least have a warehouse in which to store these components,
- a "sensitive" zone, corresponding to nuclear facilities governed by special Nuclear Facility regulations. This zone is fully protected by a physical fence and a second level of access control. It includes the unloading and temporary storage facilities for the transport transfer casks, the buildings where the waste is received and the disposal packages are prepared, the package transfer shaft to the underground installations and the air exhaust shaft.

The functional features of the nuclear "sensitive" zone in terms of the type of waste to be handled depends on the study scenario considered. It includes B and C waste-specific buildings. In the study scenarios including the hypothesis of spent fuel disposal, a dedicated building would be added.

8.2.2 Building for receiving B and C waste and for preparing disposal packages

The building for receiving the B and C waste and for preparing disposal packages has three schematic sections:

- a zone for unloading the primary waste transport transfer casks,
- a zone for manufacturing and storing the disposal packages,
- a zone for transferring the disposal packages to the transfer shaft.

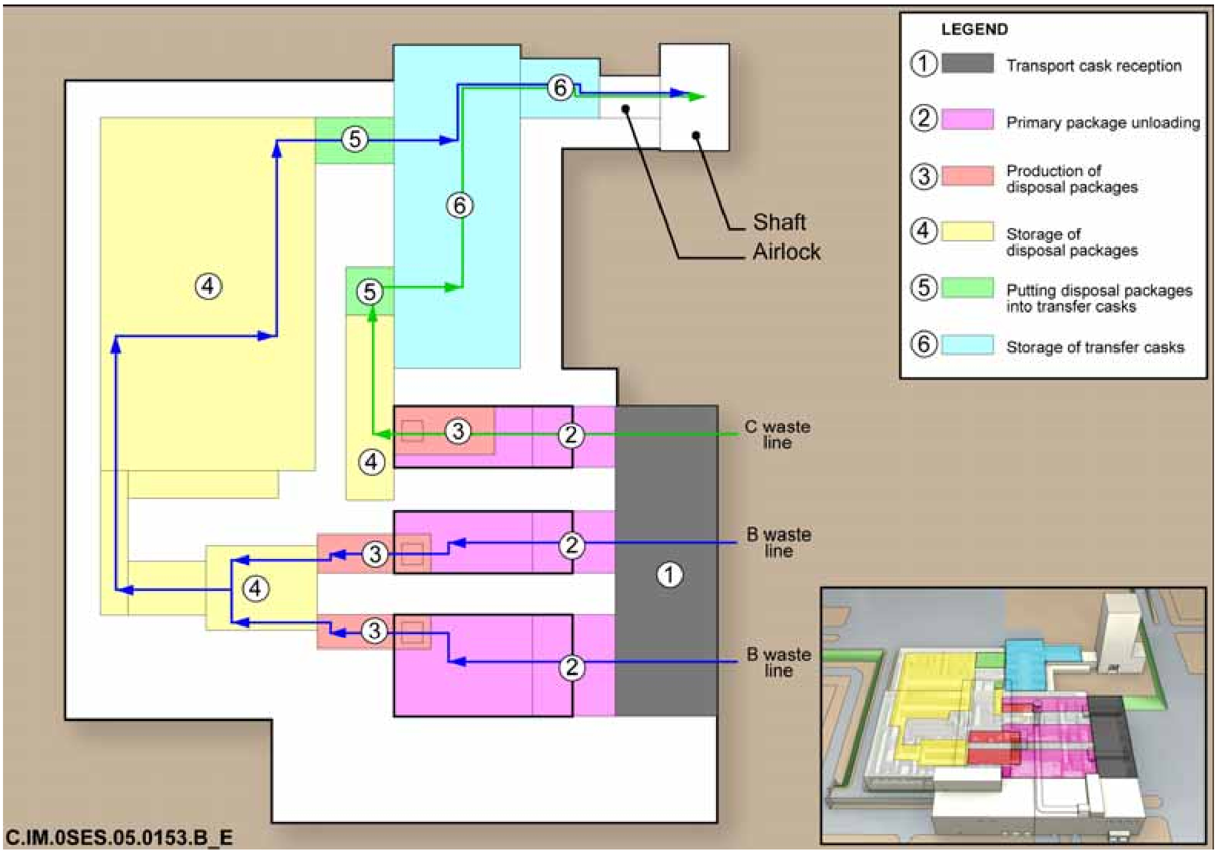

Figure 8.2.1 B and C waste building

The transport transfer cask unloading zone has a travelling crane and shielded cells. The primary packages are extracted from the transfer casks and placed in buffer storage before being recovered and placed in disposal packages.

The zone for manufacturing and storing the disposal packages consists of several manufacturing lines. Each line is made up of a succession of shielded cells. Two manufacturing lines are considered for the B disposal packages and one line for the C disposal packages.

A concreting facility is in particular part of the B waste lines so that the concrete containers may be closed. The full containers are stored temporarily in a curing room until sufficient mechanical properties are obtained before transfer to the bottom of the shaft (around 28 days).

The C waste line has facilities for demagnetisation and electron beam welding, so that the lid can be welded to the over-pack body. The disposal packages are placed in temporary buffer storage.

In the shaft transfer zone, the disposal packages are taken to the transfer transfer cask loading station. The transfer transfer cask is then conveyed to the shaft which transfers it to the bottom.

All types of activities planned for the building are already implemented in similar industrial nuclear facilities.

Such a building would operate permanently twenty-four hours a day for 225 days a year. For reference, the throughputs considered in the study are:

- 5,000 primary B packages per year,
- 400 C0 primary packages per year, then 600 or 700 C1 to C4 primary packages per year (according to the scenarios),
- production capacity for 1,400 B disposal packages on average per year,
- production capacity of 600 to 700 C disposal packages per year.

8.2.3 Surface building for receiving spent fuel and placing it in containers

Should spent fuel disposal be considered (UOX and MOX), the processing building will have to be extended to receive and condition it before transfer to the underground installations. The building could be an extension linked to the previous one.

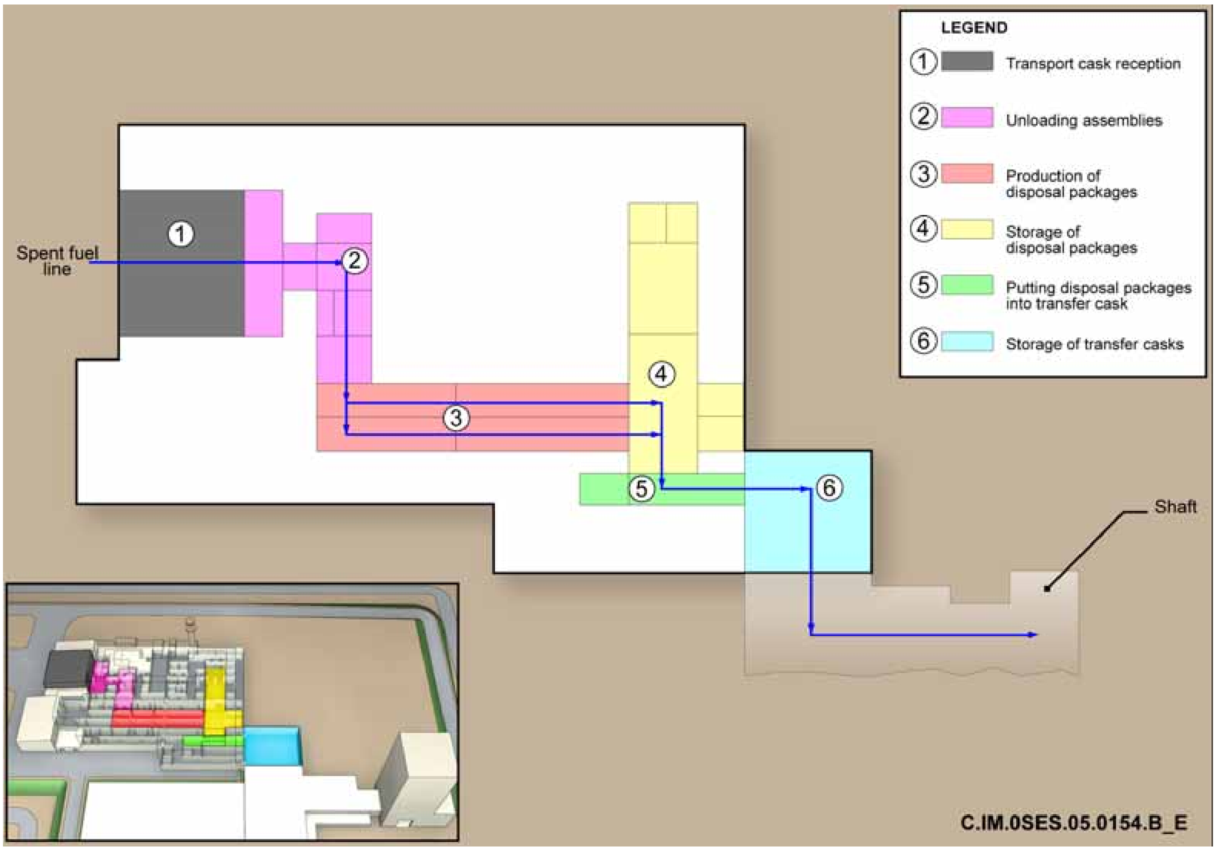

Figure 8.2.2 Building for spent fuel

8.3 Industrial and administrative zones

The industrial zone covers a surface area of around 35 ha. It is organised around the construction shaft. These installations group in particular:

- the construction shaft operating buildings;
- the workshops for preparing the construction materials (drift liners, etc.);
- equipment maintenance and repair shops (electrical, hydraulic, mechanical, electro-mechanical, welding, wiring, etc.);
- service buildings (warehouses, stores, core library, concrete laboratory, etc.).

This industrial zone is developed progressively based on the changing needs of the underground work. For example, the backfill preparation installations may only be built once the decision to close has been taken.

The surface installations for site management and administration are grouped around the personnel transfer shaft. These are basically office buildings, a central emergency building and a "living" space for the personnel working on the site (cloakrooms, showers, canteens, etc.).

8.4 Broken rock storage dump

Broken rocks from the excavation sites are stored in a dump built at the edge of the working zone. These broken rocks are re-used as much as possible to make up the repository closing backfill, to a height of around 40%. The remainder of the broken rocks stays on the surface[131].

- **Brief assessment of the surface area**

The broken rock storage dump represents a volume of several million cubic metres; this volume (and even more) is frequently found in open-cast mines. As the date for backfilling is not fixed in advance, the surface area for a dump capable of holding all the broken rock has been estimated.

As there is no defined dump site, only the general dump management principles can be given, that will subsequently be adapted to the site topography. A compromise will have to be found between the dump height and its surface area, as a dump can be more flexible to manage if it’s height is lower. At this stage in the studies, a low-lying dump has been considered, around ten metres high. The dump surface area could therefore be in the region of between 100 and 300 hectares.

- **General dump design and operation principles**

The dump project should be studied for its greatest integration with the landscape and the hydrographic network.

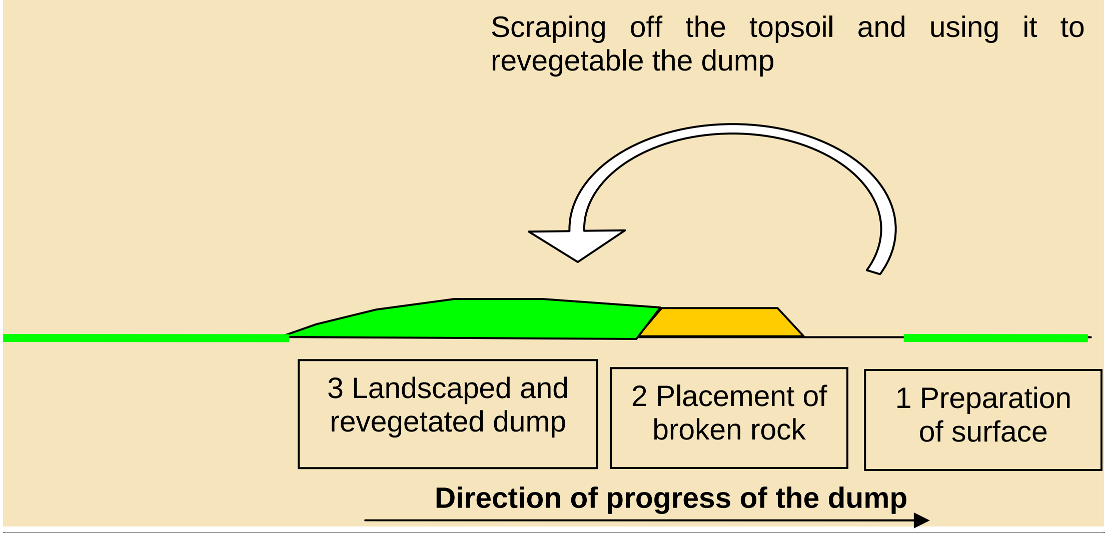

Figure 8.4.1 Dump operating principle per section

A dump is generally operated in sections. The scraping and surfacing operations, constructing the drainage network, placing the broken rock and covering the soils follow on from each other and progress with the development of the dump.

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[131] The difference compared with 100% is explained by the volume occupied by the disposal packages and the engineered structure liners, and by the "swell factor" effect of the backfill

Apart from the geometric aspects, the dump is mainly designed to ensure the stability of the broken rock and prevent rainwater from percolating into the stored materials.

Preparatory earthworks, scraping off the topsoil, creating subgrade and building ditches, slopes and collection and settlement basins are necessary. A specific site organisation has to be implemented to limit the exposure time of the active part of the dump to weathering.

Lastly, the topsoil from the scraping of the various zones where the surface installations and dump are built is assembled and stored near the dump. It is used as and when necessary to cover the dump before revegetating.

- **Recovering broken rocks from the dump for backfilling operations**

Broken rocks can also be recovered for backfilling operations by section, similar to the way in which the dump was first organised.

The backfill materials recovered from a dump must be conditioned before their re-use. This conditioning covers in particular regularisation of the granulometry and humidity of the backfill materials.

9

Nuclear operating resources in the repository

The purpose of this chapter is to explain how nuclear-related operational activities could be organized and to describe their main characteristics and related processes.

These activities involve receiving the primary packages and preparing the disposal packages, the transfer of these packages into the underground installations and their emplacement in the disposal cells. This chapter attempts to show for all these processes that the equipments and procedures studied at this stage of the studies are simple, robust and safe. This is partly the result of industrial feedback from existing nuclear and mining facilities and partly the result of choices based on a comparative analysis of the various possible solutions.

In terms of nuclear processes, it highlights how safety considerations (particularly of radiological protection) and the reliability of mechanical systems have been taken into account in the design.

Solutions adopted internationally and the results from technological tests concerning package emplacement are mentioned.

9.1 Receiving primary packages and preparing disposal packages

This section explains the equipments and procedures for receiving the transport casks containing the primary waste packages, then describes those relating to the manufacture of the disposal packages.

The surface nuclear installations, where these activities are carried out, have many similarities with certain existing nuclear facilities such as the COGEMA reprocessing centre at La Hague or the Dutch COVRA storage facility. The operating principles and related resources presented in the sections below are thus largely the result of transposing industrial feedback and adapting to the specific features of the waste packages to be processed.

9.1.1 Receiving the transport casks, unloading the primary waste packages and storing them temporarily

The primary waste packages are brought to the repository site from the production sites in identical or similar transport casks as the existing ones. These transport casks may be transported by road or rail convoy then, in common with nuclear practices, be stored temporarily in an area dedicated to the surface installations.

When they leave this storage, the transport casks are transferred to a building called "reception and conditioning", containing a succession of shielded cells where operations are carried out by remote control. The packages are docked to an unloading cell and the primary packages are extracted by a handling crane equipped with a grab specific to each type of package. The primary packages are then transferred to a zone of the building dedicated exclusively to storing them.

The operations described above (identical for all types of waste) are illustrated by the diagram in Figure 9.1.1

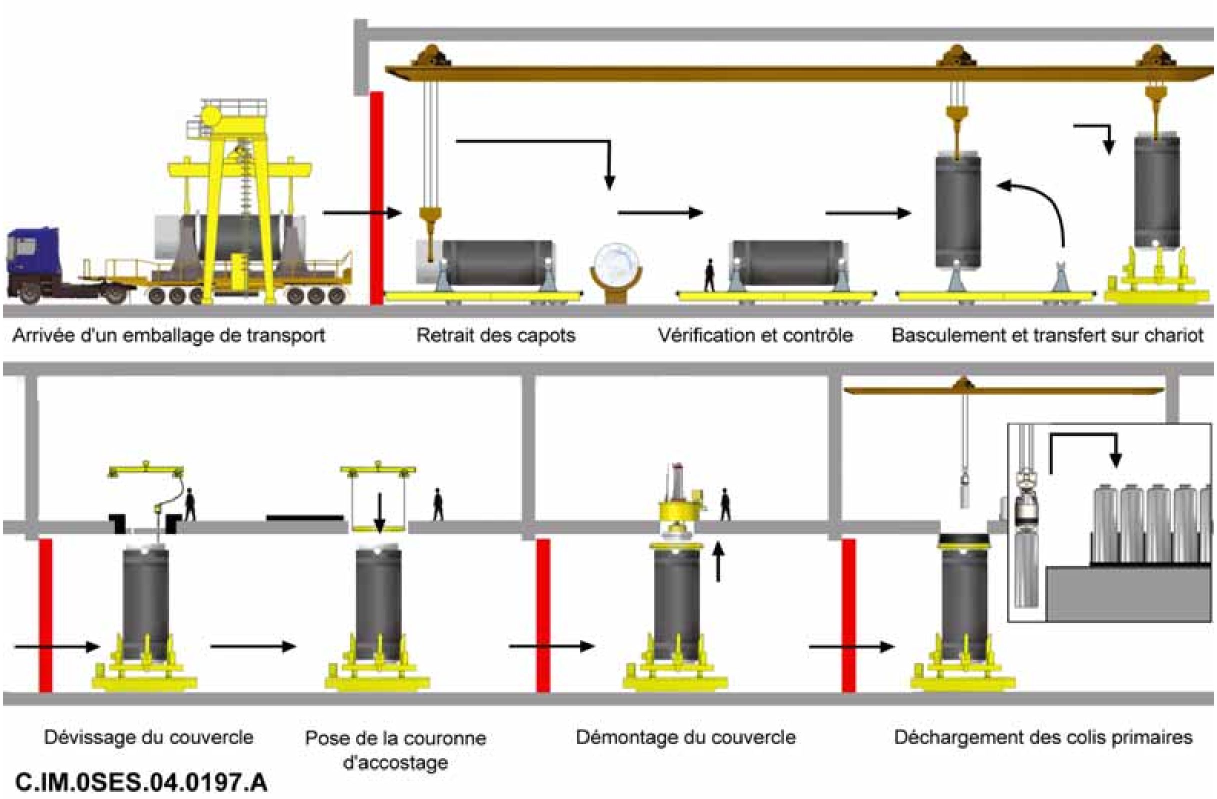

Figure 9.1.1 Block diagram of primary package reception operations

Operations of this type are carried out traditionally at the COGEMA centre at La Hague (Figures 9.1.2 to Figure 9.1.4).

Figure 9.1.2 Transport casks being stored on dollies (Cogema doc.)

Figure 9.1.3 Package being docked under an unloading cell (Cogema doc.)

Figure 9.1.4 Primary package unloading and storage cell (Cogema doc.)

9.1.2 Preparing B waste disposal packages

Preparing the B waste disposal packages takes place over the following stages:

- The pre-fabricated container is taken from the storage warehouse to the conditioning line in a primary package loading station. The primary packages are placed in the container using a gripping system specific to each primary package.
- Once the lid has been positioned, the container is then closed by pouring mortar under the control of a robot. The mortar is transferred from the production unit and the volume of mortar deposited is controlled by technical systems.
- The packages are stored temporarily for the mortar to dry up (24 hours). The containers are then checked (non-contamination control, then dimensional and weight control). The packages declared non-conforming with the respect to the acceptability criteria, as yet to be defined, are transferred to a specific processing cell to recover the primary packages, so that they can be returned to the cell to be reconditioned.
- Conforming packages are stored in a temporary storage room for at least 28 days to cure the sealing mortar. After this period, the containers may be transferred to the transfer cask loading station for transport into the underground installations.

These operations are performed in a series of shielded cells illustrated by the diagram in Figure 9.1.5.

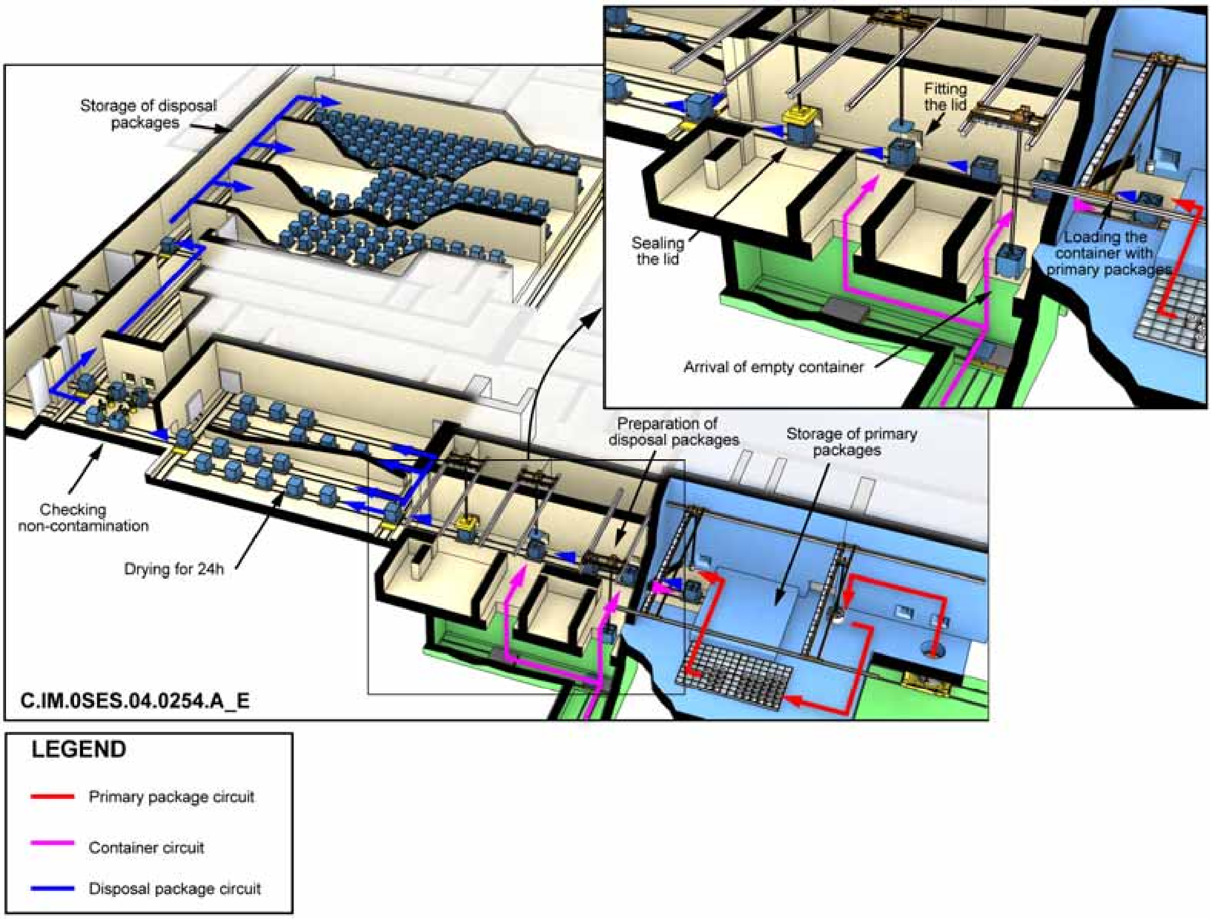

Figure 9.1.5 Preparation cycle for B waste disposal packages

The average time to manufacture a waste B disposal package under the operations listed above is estimated at around 2½ hours. On this basis, two conditioning lines operating continuously will be necessary to produce an average six disposal packages per day, with a maximum of nine packages per day depending on the type of package to be manufactured.

9.1.3 Preparing C waste disposal packages

Preparing the C waste disposal packages takes place over the following stages:

- The empty over-pack is taken from the storage warehouse to the conditioning line. Before entering the packaging cell, the over-pack and its lid are demagnetised as required for the electronic beam welding.
- The primary packages are then placed in the over-pack in a loading station, using a specific gripping system. The lid is positioned and the whole is transferred to the welding chamber.
- The lid is welded. The process adopted for closing the C packages is electron beam welding. This technology requires the elements being welded to be placed in a vacuum. This process was described in the chapter relating to C waste disposal packages (see Section 4.2). The welding machine consists of a chamber, a pumping unit and a welding gun. The lower section of the package reception chamber, about 3 m3 in total, is fitted with a turntable on which the package starts to rotate. The chamber head has a door fitted with seals so that the container can be introduced by the top and the chamber closed and made leaktight. The welding gun, with an estimated power of 45 kW and a travel speed of 10 to 15 centimetres per minute, carries out the welding operation in a single pass of around 20 minutes.
- Checks are then carried out on the weld and for non-contamination (described in Section 4.2). As for the B packages, the C packages declared non-conforming are transferred to a specific processing cell to retrieve the primary packages so that they can be returned to the cell to be reconditioned.
- The conforming packages are stored in a temporary storage room before being transferred to the underground installations.

These operations are performed in a series of shielded cells illustrated by the diagram in Figure 9.1.6.

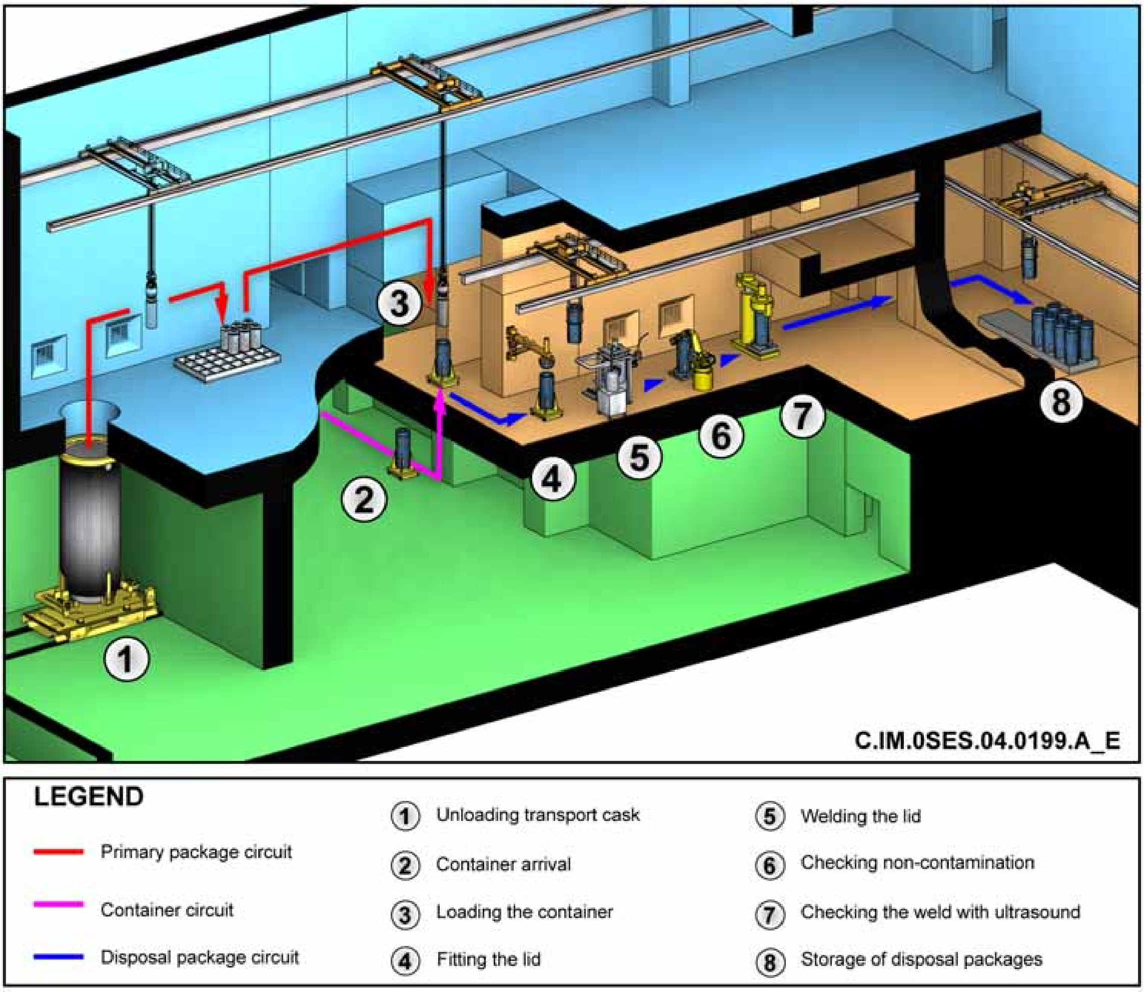

Figure 9.1.6 Preparation cycle for C waste disposal packages

It takes three hours on average to manufacture a C waste disposal package. On this basis, a single conditioning line operating continuously would be necessary to produce an average five disposal packages per day, with a maximum of eight packages.

9.1.4 Preparing spent fuel disposal packages

Preparing the spent fuel (UOX, MOX) disposal packages takes place over the following stages:

- bringing up empty containers and demagnetisation,
- loading containers with spent fuel assemblies and placing the lid,
- welding the closing tape,
- welding the lid,
- non-contamination check (described in Section 4.3),
- weld check (described in Section 4.3),
- temporary storage of disposal packages before transfer into the underground installations.

These operations are performed in a series of shielded cells illustrated by the diagram in Figure 9.1.7.

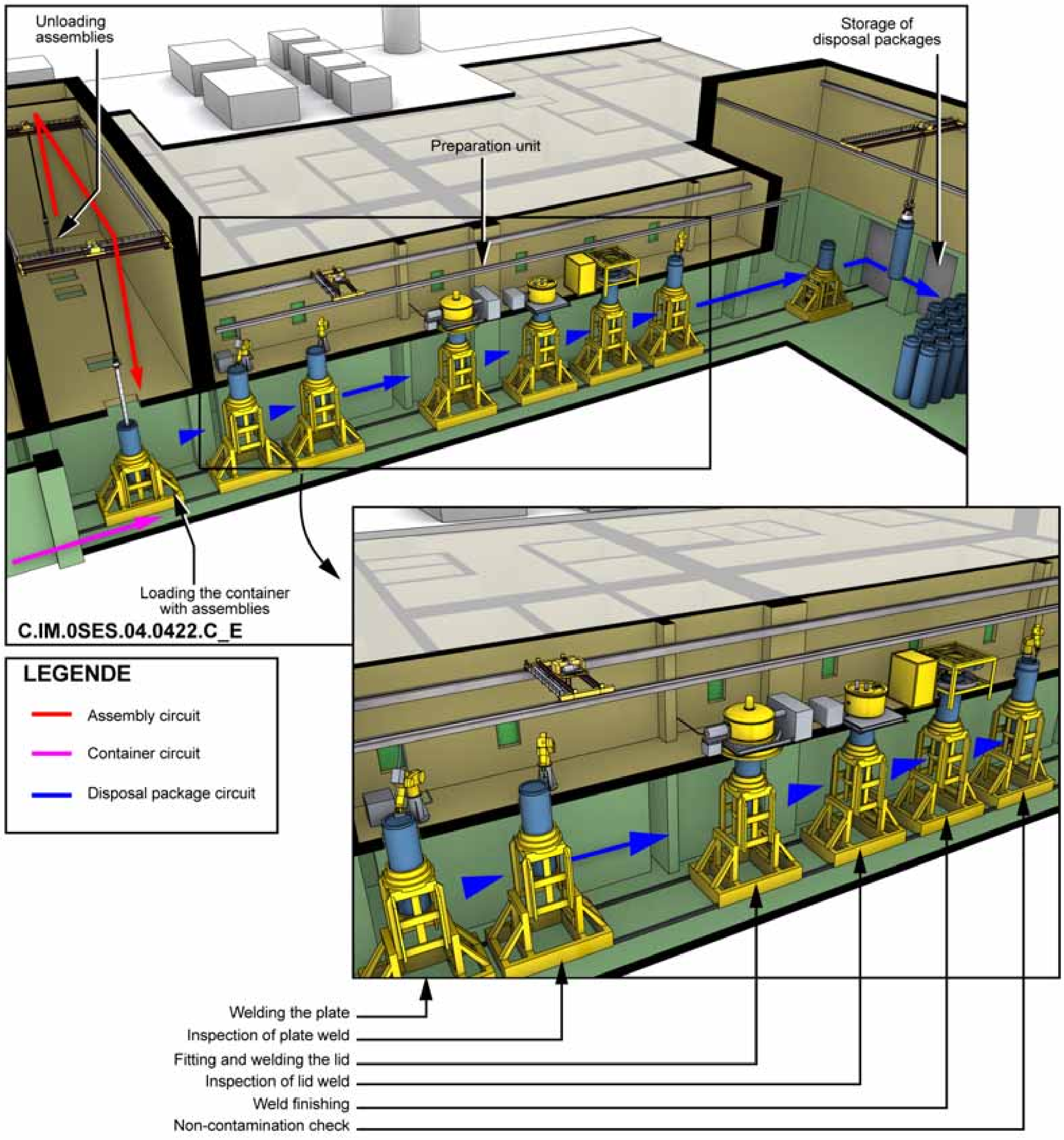

Figure 9.1.7 Preparation cycle for spent fuel disposal packages

The main operations for preparing the spent fuel disposal packages are similar to the C waste disposal packages.

Some additional operations are, however, necessary. The need for vacuum in the lid welding environment means that a plate has to be welded beforehand to the top of the spent fuel emplacements, to limit the volume that will be depressurised.

In addition, there is a difference between the electron beam welding station and that planned for the C packages. In fact the huge size of the spent fuel disposal package means that only the head and the lid are placed inside the vacuum chamber. This constraint forces loading from above (see Figure 9.1.8).

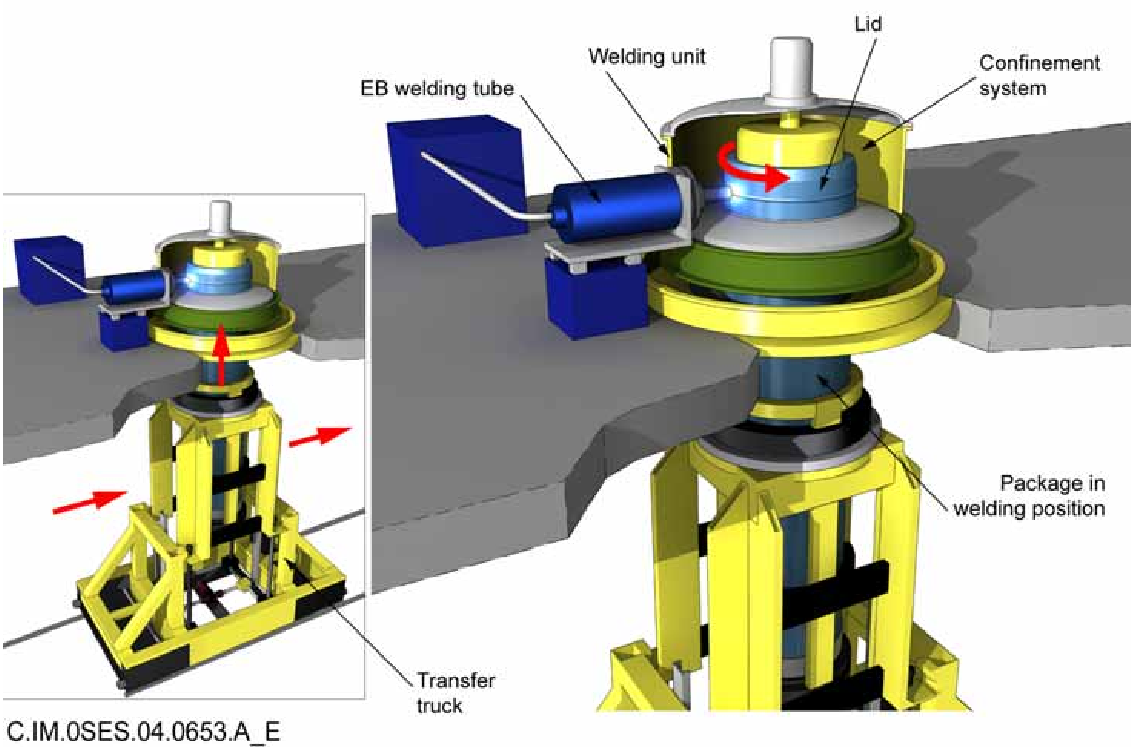

Figure 9.1.8 Lid welding station for a spent fuel package

The container starts rotating driven by a mechanism underneath the welding cell. A specific rotating joint ensures leaktightness between the rotating container and the welding chamber.

The welding gun, with an estimated power of 50 kW and a travel speed of 10 to 20 centimetres per minute, carries out the welding operation in a single pass and in less than one hour.

It takes ten hours on average to manufacture a spent fuel package. On this basis, two conditioning lines operating continuously will be necessary to produce an average two disposal packages per day, with a maximum of three packages.

9.2 Process for transferring the disposal packages from the surface to the disposal cells

The present section describes the equipment and the processes used for transferring the disposal packages from the surface installations to the disposal cells [81]. All the operations described can be reversed, in order to bring back to surface packages retrieved from the repository, if necessary.

9.2.1 General principles for transferring the disposal packages

The principle for transferring the disposal packages between the surface installations and the disposal cells depends mainly on radiological protection considerations. The residual rate of equivalent dose around the disposal packages (all categories combined: B, C, and CU) makes it impossible to handle them without radiological protection for the personnel. The principle adopted therefore consists of putting the packages into a shielded so-called "radiological protection" transfer cask within the surface installations. This transfer cask is then transferred to the entrance of the disposal cells where the disposal packages are extracted and are placed in their final position in the cell.

The cycle of transferring the protective transfer casks containing the disposal packages from the surface installations to the disposal cells consists of the four following stages:

- loading the transfer cask at the surface,
- transferring the transfer cask into the shaft,
- transferring the transfer cask through the drifts,
- docking the transfer cask at the head of the cell.

The diagram in Figure 9.2.1 illustrates the main operations needed for conducting this cycle.

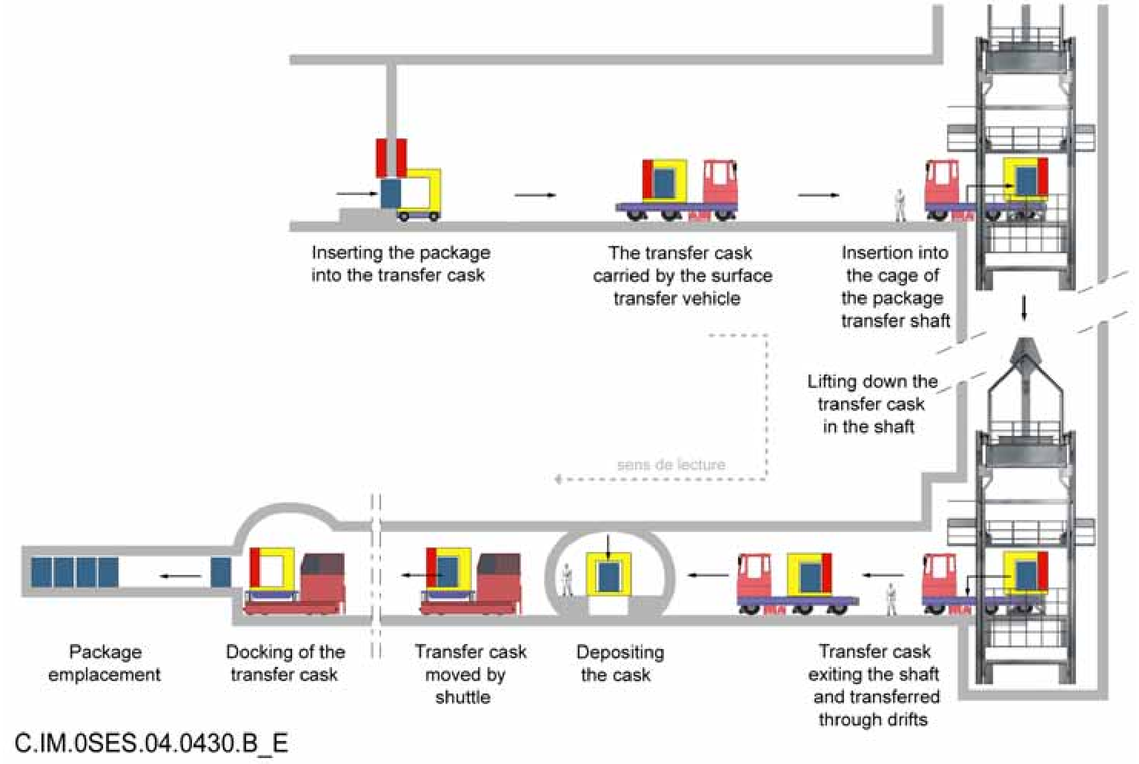

Figure 9.2.1 General diagram of the transfer of disposal packages to the cell

9.2.2 The radiological protection transfer casks

9.2.2.1 Functions of and definition of radiological protection transfer casks

The radiological protection transfer casks used for transferring the disposal packages are designed so as to only contain a single disposal package. They are dimensioned to meet two requirements.

- The transfer transfer casks for B, C and CU packages have a radiological protection function of limiting the exposure of personnel to below the limits of the annual dose fixed by Andra (5 mSv/year).
- The transfer cask must also contribute to maintaining the confinement of the radionuclides if the transfer cask is dropped in the descent shaft. The dynamic simulation of such a scenario has shown that the degree of deceleration that the transfer cask is subjected to can be limited (see chapter 11).

A transfer cask consists of a handling frame with a shielded container on top. The container itself is equipped with a shielded door for loading and unloading the packages from the side. The dimensions of the frames of the three types of transfer cask are similar so as to standardise their handling from below.

However, differences in the geometry of the three types of disposal package (B, C and CU) have led to the adoption of specific transfer casks for each type. The diagrams in Figure 9.2.2 illustrate these three types of transfer cask.

The use of protective casks is common in the nuclear industry. For example, Figure 9.2.3 illustrates a similar transfer cask envisaged for the disposal of highly radioactive transuranium "RH" (Remote handled) type wastes in WIPP installations (Waste Isolation Pilot Plant – USA).

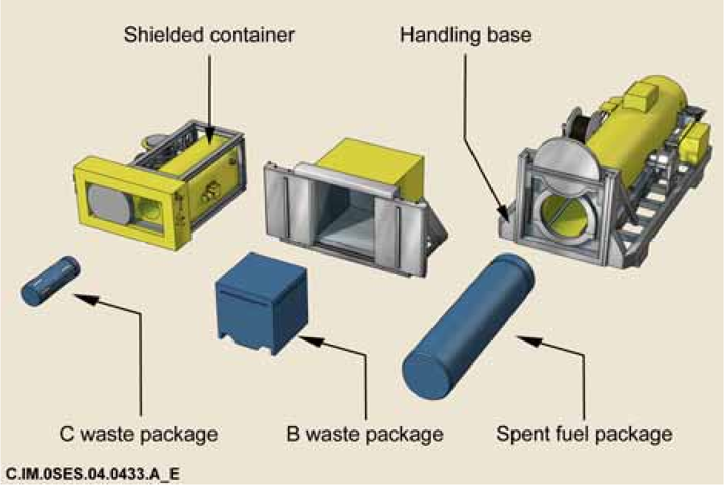

Figure 9.2.2 Transfer transfer casks for B, C and spent fuel packages

Figure 9.2.3 Transfer transfer cask for disposal packages (photo from WIPP)

9.2.2.2 Description of the three types of transfer cask

- **The transfer cask for B wastes**

The radiological protection transfer cask for the disposal package of B wastes, consists of a base, a shielded parallelepiped-shaped container and a two-flap door system. It has no on-board mechanical components because the loading and unloading operations are conducted by separate equipment. The walls of the transfer casks are made of materials suited to the types of radiation emitted by the waste packages transported (lead or steel for γ radiation, neutron-absorbing material for neutrons), and if necessary a heat shield for protection against fire risks.

The existence of several types of disposal package for B wastes, in terms of dimensions, weight and dose equivalent rates has led to the definition of several categories of transfer casks. Their full weights vary from 40 to 100 tonnes for packages of 7 to 25 tonnes. Their radiological protection thicknesses vary from 50 to 300 mm of steel or composite material depending on the equivalent dose rate of the packages transported.

- **The transfer casks for C wastes and spent fuels**

In the case of C wastes and spent fuels, the shielded container is cylindrical and the door is a "sliding" type. In both cases, the transfer cask is fitted with an on-board mechanical unit consisting of a robot situated inside the shielded container. This is a hydraulic jack-actuated push robot in the case of C wastes and an air-cushion transporter robot in the case of the spent fuels. These robots are used to extract the packages and place them in the cell.

The shielded container has walls made of steel/PPB/steel sandwich panels. The PPB (Plaster/Polyethylene with Boron addition), a neutron-absorbing material, has been chosen because of the type of radiation emitted by vitrified C wastes and spent fuels. The total thickness of the side walls, bottom and the door is of the order of 400 mm for the C transfer cask and of the order of 200 mm for the spent fuel transfer cask.

The loaded weight of the C transfer cask is about 41 tonnes for a disposal package of 2 tonnes.

The loaded weight of the transfer cask for spent fuels is about 105 tonnes for a disposal package of 43 tonnes.

9.2.3 The transfer of the packages in the transfer shaft

After loading a package into a transfer cask, it is then is transferred to the underground installations by the packages transfer shaft. The process described here is largely the result of a transposition of the industrial practices used in the mining industry, but also of experience drawn from the operation of WIPP underground disposal facility (USA) that has been working from 1999.

The transfer casks are transferred in the shaft by means of a cage pulled by a cable system. The whole of the shaft and its associated equipment consists of a space confined by two airlocks: one situated in the upper part in the surface station and the other situated in the bottom station. During the transfer of a transfer cask, the airlocks are closed. This space thereby confined is maintained at an underpressure. It communicates by a special drift to the nuclear filtration system which could if necessary be installed at the head of the air exhaust shaft, so as to reduce the possible radiological consequences of a "transfer cask fall in the shaft" type accident (see chapter 11).

9.2.3.1 Description of the shaft equipment

● Justification of the equipment considered

The main technically envisageable solutions for lowering the transfer cask whose laden weight can reach 110 tonnes are:

- a 10% ramp on which a vehicle travels on pneumatic tyres;
- a shaft equipped with a multirope winch system[132];
- a shaft equipped with a Koepe pulley type friction system.

All three principles are possible. However the "Koepe pulley type friction system" solution, illustrated in, is considered at this stage of the studies to be the reference solution, because this system, that has been very widely proven in a mining context for over a century and throughout the world, is a reliable technology.

The table below gives some reference figures comparable to the present study.

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[132] The mobile hoist reduces the effort exerted by the winch

Table 9.2.1 References to shafts equipped with a "Koepe Pulley" system

Location	**Use**	**depth (m)**	**suspended load (tonnes)***	**No. of cables**	**load suspended per cable (tonnes)**	**speed (m/s)**
Sweden	Ore hoisting, Kiruna mine	802	192	6	32	17
Poland	Ore hoisting, Pniowek	1 160	229	4	57	18
USA	WIPP nuclear waste repository	698	120	6	20	2,5
Switzerland	Access to the St. Gothard tunnel, Sedrun	796	117	4	29	18
Germany	Radioactive waste repository project in Gorleben	870	214	8	27	5
France	Study presented by Andra	500	300	10	30	1

* The suspended load is the sum of the rated load of the cage, the mass of the cage and the mass of its cables.

- **Description of the equipment and the safety systems**

The "Koepe" friction system consists of a motorised pulley, around which are suspended two mobile units (the cage transporting the payload and the counterweight) by means of suspension ropes. For the envisaged configuration, 10 cables of 70 mm diameter would be needed. Tail ropes, connected to the bottom of the cage and to the bottom of the counterweight, complete the arrangement. A small independent safety cage ensures the safety of personnel conducting maintenance operations. The diagram in illustrates this principle.

The Koepe pulley is installed at the top of a tower about fifty metres high. It is driven by variable speed electric motors and equipped with a system of disc brakes.

The system is dimensioned to allow the transfer of a load of 110 tonnes at a speed of 1 m/s.

The shaft also has an independent ventilation system. It is connected to the surface and bottom installations by airlocks.

Figure 9.2.5 shows the Koepe pulley that equips the packages descent shaft of the WIPP installation (USA).

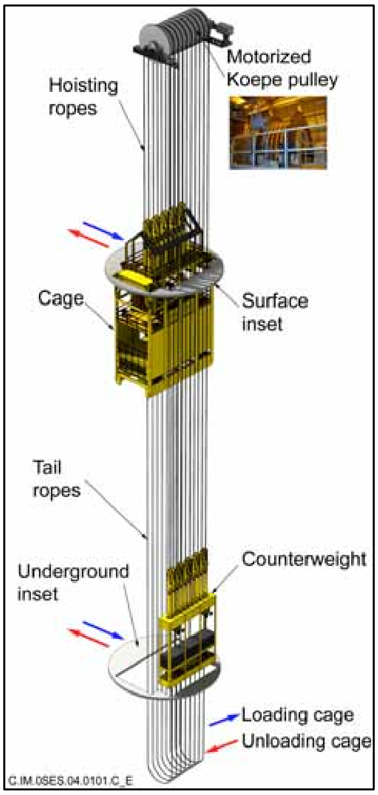

Figure 9.2-4 Principle of the "Koepe pulley" friction system

Figure 9.2.5 Koepe pulley of the WIPP packages descent shaft (USA)

The safety of the equipment described above is ensured by four independent devices:

- A disc brake braking system acting directly on the Koepe pulley. These brakes are activated by two independent circuits, one to ensure the role of static service brake and the other the function of dynamic safety brake.
- An anti-fall system, independent of the previous system, which can bring the cage to a halt on specific cables suspended from the surface superstructure to the bottom of the shaft.
- Two arrestor systems installed in the tower and under the bottom station can stop the cage if it exceeds its normal course. They work by deforming metal sections that thereby absorb the cage's kinetic energy.
- Finally a passive fall shock absorbing system, installed in lower part of the shaft (see section 11.7), could complete these arrangements. Such a system could be justified in the very unlikely case when none of the first three systems were capable of stopping the cage's course.

The first three systems have been proven to be reliable systems in mining installations over many years. Moreover the fall shock absorbing system has been used in many industrial applications from vehicle crashes, high-speed trains and missile impacts. However the anti-fall and fall buffering systems require further studies because of the weight that is transported.

9.2.3.2 Principle of the surface/bottom transfer

The shaft equipment operates entirely automatically. When a transfer cask descends no one is present in the cage, nor in the surface and bottom airlocks.

The introduction of a transfer cask in the shaft cage at the surface and its extraction at the underground installations level is conducted by similar vehicles. These vehicles, running on tyres, are like a fork-lift truck (Figure 9.2.6)

The vehicle lifts up the transfer cask, then transfers it from the storage building towards the shaft through an airlock, and places it in the cage on the lateral supports.

The transfer cask is then sent down in the cage at a nominal speed of 1m/s. The time taken to descend to the bottom is about 10 minutes taking into account the acceleration, deceleration and stopping times.

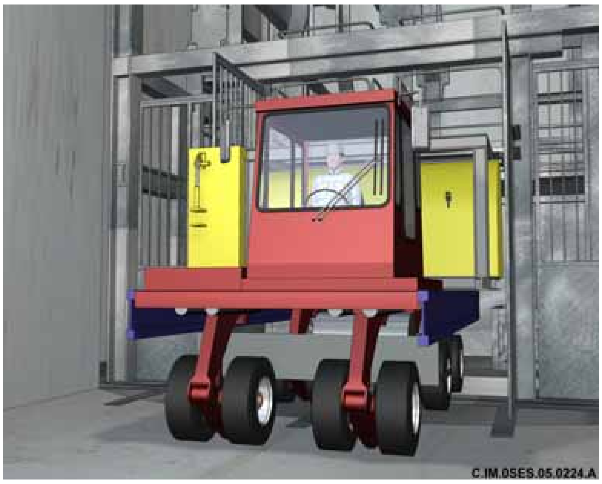

Figure 9.2.6 Principal of loading and unloading the casks in the cage

The transfer cask is removed at the bottom using the reverse procedure to its introduction at the surface by means of a self elevating vehicle on tyres of the same type. This vehicle picks up the transfer cask and transfers it in the drifts to the vicinity of the disposal cells.

9.2.4 The transfer of the transfer casks in the underground installations

This section describes the procedure for transferring the protective transfer casks in the underground installations. The process described here is based mainly on a transposition of the industrial practices used in the mining industry. It aims at minimising the dimensions of the drifts and crossing structures and separating the process of long-distance transport from that of docking the transfer cask at the head of the cell (which requires more specific equipment).

9.2.4.1 Principle of the cask transfer operations

The operations of transferring a transfer cask from the bottom station of the packages descent shaft until it is docked at the head of the cell is the most specific part of the transfer cycle of the disposal packages between the surface and the underground installations. At this stage of the studies, we favour a cycle consisting of two stages.

The first stage involves transferring the transfer cask from the cage in the descent shaft to the immediate proximity of the disposal cells through a network of drifts. This transfer is conducted using a machine called the "*transfer vehicle"* that is capable of transporting heavy loads over long distances. This vehicle is similar to that used at the surface for putting the transfer cask into the cage.

The second stage is the docking of the transfer cask at the head of the cell. This operation is conducted using specific equipment working over short distances. This is called the "*docking shuttle"*.

The transition from the first stage to the second therefore requires the load to be transferred from the "transfer vehicle" to the "docking shuttle". The separation of the two processes described above and the use of two different vehicles has several advantages: the specialisation of each vehicle means that the cross sectional area of the docking shuttle and the length of the transfer vehicle can be reduced and also the mechanical systems needed for docking are not unnecessarily included in the transfer vehicle and transported over long distances. Finally, the transfer vehicle does not stand idle during the stage of docking and unloading the transfer cask.

It should however be pointed out that the principle described above is not the only solution to the problem posed. The relevance of shifting the load that is required by use of two vehicles could eventually be re-examined.

9.2.4.2 Transfer of the transfer casks in drifts

The diagram in Figure 9.2.7 illustrates the design of the transfer casks transfer vehicle.

The feasibility studies have led us to propose a few principles for this low-slung vehicle resembling an electric fork-lift truck on pneumatic tyres.

The "low-slung" character enables the outside dimensions of the combination of vehicle and transfer cask to be reduced and thereby also reduces the rotating radius and the cross-section of the drifts. The load-bearing platform can be raised or lowered for the loading and unloading operations. It is equipped with independently motorised wheels that can turn in all directions to have a very small turning circle.

Figure 9.2.7 Transport vehicle of a cask of B waste

Electrical energy is preferred to a diesel motor because of the fire hazards inherent in the latter type of motor.

Finally, the principle of pneumatic tyres was preferred to a vehicle on rails. The use of vehicles on tyres avoids the construction and maintenance of a rail network. Using vehicles on pneumatic tyres also enables the drifts to have tighter bends than with vehicles on rail.

It should be noted that this type of vehicle is a technique that widely exists and has been proven in the nuclear context. Such vehicles are produced by several European manufacturors.

Figure 9.2.8 shows an example of this technology used for several years at the Cogema site at La Hague.

Figure 9.2.8 The transfer vehicle used on the La Hague site (doc from Cogema)

9.2.4.3 Docking of the transfer casks in the cell heads

The docking of the transfer casks at the cell heads is conducted by a specific vehicle: the "docking shuttle". There is a specific shuttle for each type of transfer cask (B, C and CU). The special features of these three shuttles are related to the docking process of the three types of transfer cask and to the associated docking mechanisms. They have similar design principles to those of the transfer vehicle described above.

The docking of B transfer casks is conducted in the same direction as the shuttle's axis of motion. After being deposited by the transfer vehicle, the transfer cask is picked up by the shuttle, then travels along the drift giving access to the disposal cell and docks on a window equipped with metal doors, fitted into the wall of the radiological protection airlocks at the head of the cell.

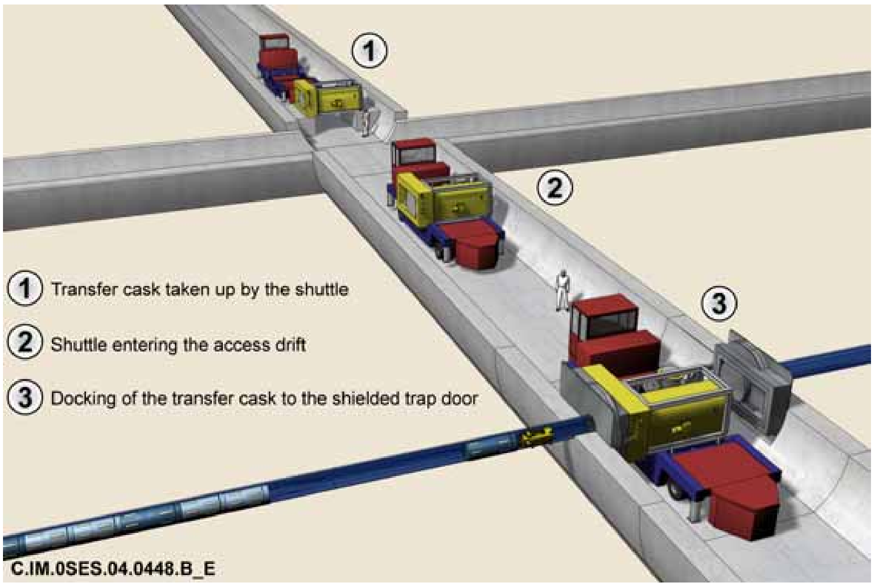

Figure 9.2.9 Docking of C casks by the shuttle at the head of the cell

The docking of C transfer casks is conducted at right angles to the shuttle's axis of motion. As in the previous case, the transfer cask is picked up by the shuttle after being deposited by the transfer vehicle. The shuttle travels in the access drift serving several disposal cells. After stopping at the head of the cell, the transfer cask is moved sideways and then docked to the shielded trap door of the cell (see Figure 9.2.9).

The docking of spent fuels transfer casks is conducted after a rotation by a quarter turn, as the length of the transfer cask does not allow it to be transported at right angles to the axis of the drift, in contrast to the case of C wastes.

The shuttle is equipped with a turning platform and a travel drive. Once the shuttle is positioned opposite a cell, the turning platform rotates the transfer cask through 90° and it is then moved sideways, to be docked in the cell shielded trap door.

9.3 Process of installing the packages in the disposal cells

The present section describes the equipment and procedures used for installing the packages in the disposal cells [81]. The process can be reversed in order to retrieve the packages from disposal cells, if needed.

The various technical solutions that could be used for each of the configurations studied (B wastes, C wastes and spent fuels) are presented and compared. The choice of the preferred solution at this stage of the studies results from considerations of sturdiness, of minimising the height of the vehicles entering the cells and of reducing the size of empty spaces after installing the packages.

9.3.1 General principles of the installation of packages in disposal cells

The design principles chosen for the procedure and the equipment for installing disposal packages in cells have to fulfil two essential functions: the function of transferring the disposal package from the protective transfer cask to its disposal position in the cell and the function of radiological protection for personnel.

In the three configurations studied (B wastes, C wastes and spent fuels), the function of transferring the packages requires that the transfer cask containing the disposal package be first docked at the head of the cell. A single type of machine then extracts the package and installs it in the cell.

In the case of C wastes and of spent fuels, the geometrical configuration of the cell (a cylinder whose diameter is adjusted to the size of the disposal package) must allow this machine to be included in the shielded container of the transfer transfer cask. It consists of a robot connected to the transfer cask by an umbilical cable. It is brought back into the transfer cask after the installation of each package. For C wastes, the system chosen is a self-propelled push robot with step-by-step type jacks. For spent fuels the system chosen is a transporter working on an air-cushion principle.

In the case of B wastes, the size of the cell and the choice of piling the packages one on top of the other requires a large-sized machine that cannot be included in the transfer cask. The machine chosen is a fork-lift type truck stationed at the head of the cell.

In all three cases, the function of radiological protection for personnel during the whole process (in both normal and malfunction conditions) is ensured by the protective transfer cask and the fixed equipment at the head of the cell onto which the transfer cask is docked.

9.3.2 Description of the equipment and process of installing packages of B wastes

9.3.2.1 Design principles

● Required functions

Disposal package of B wastes are characterised by a weight varying from 6 to 25 tonnes, a volume of about 4 to 10 m^3 and a contact dose rate that can reach 5 600 mSv/h for the most radioactive of them.

The handling of heavy, radioactive packages piled in several vertical and horizontal layers in a large-sized cell (250 metres long) requires a remote-controlled mobile machine capable of moving the load in the cell's three dimensions, i.e. longitudinally, laterally and vertically. This machine must also be capable, when depositing the packages, of a precision compatible with the functional clearance between the packages and the cell wall that is of the order of 10 cm. This machine must be able to turn through 180° to change from the position of "facing the transfer cask" to the position of "facing the cell".

Furthermore, the existence of a mobile machine operating in an irradiated environment requires a radiological protection airlock to ensure the radiological protection of personnel when the machine has to come out for maintenance or other operations. This airlock also allows it to be recovered when the cell is full.

A first feasibility study has led to the identification of three essential components to fulfil the functions described above:

- mobile handling equipment responsible for the function of transferring the packages from the transfer cask to its final position in the cell,
- radiological protection airlocks to ensure the function of radiological protection for personnel,
- fixed equipment situated in the radiological protection airlocks to facilitate the machine's movements when transferring the packages.

- **Choice of package handling equipment**

Three options were investigated during the study. They are illustrated in

Figure 9.3.1.

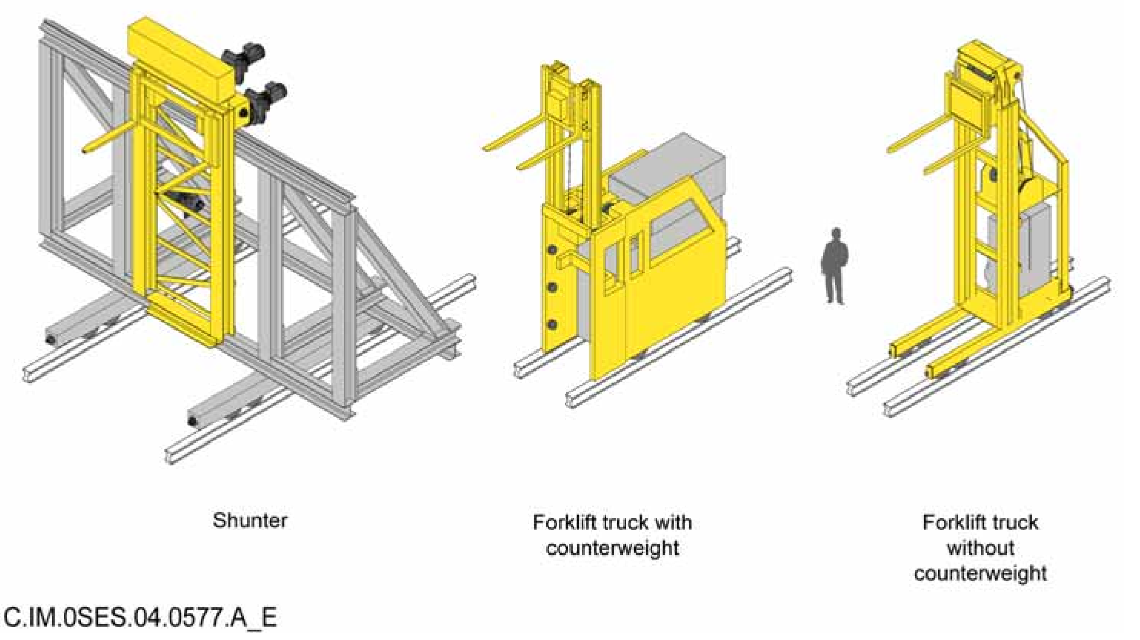

Figure 9.3.1 Types of handling equipment envisaged for B packages

The first option envisaged is a ”shunter”. This machine consists of a vertical framework mounted on rails occupying the entire width of the cell. An on-board system allows lateral and vertical movements. Such equipment would require large-sized airlocks and an opening of full cross-sectional area for the airlock doors.

The second option envisaged is a traditional fork-lift truck. This machine has a counterweight to balance the load held by forks and jutting out in front. This counterweight would take up a large amount of space especially in terms of length. In the case of the load in question (25 tonnes), the length of a traditional fork-lift truck would be about 6 m. This length would require large-sized airlocks to allow the truck to turn through 180° in the cell. The weight of such a machine would be about three times the load to be lifted, i.e. about 75 tonnes for the heaviest packages.

The third and final option studied is a fork-lift truck without a counterweight. This equipment is characterised by the fact that the centre of gravity of the load remains within the supporting polygon formed by the wheels. The counterweight is not needed and therefore the length is shorter. In the case of the loads in question, the length of such a truck would be about 4 m. Its weight would be of the same order of magnitude as that of the load to be lifted, i.e. about 25 tonnes.

The comparison of these three options led us to prefer the truck without a counterweight that is called the "disposal truck" in the following paragraphs. This machine is characterised by a significantly reduced size compared to the other solutions. It allows unused volume of the cell head to be reduced. It allows for easier movements during the operations of extracting the packages from the transfer cask and of preparing for installing in the cell. Its lower weight also makes it easier to recover it by emergency means in the event of a breakdown.

- **Choice of the radiological protection equipment**

The radiological protection airlock consists of two door systems enclosing an area sufficient to house the disposal truck. A first option consists of placing the doors at the two ends of the access drift. Another option consists of placing these doors at the head of the disposal cell.

The comparison of these two options led us to prefer airlocks situated at the head of the cell, as this solution provides greater safety and working flexibility. In particular it allows for easier maintenance and breakdown operations on the fixed and mobile equipment. Finally, in terms of the volume excavated it is equivalent to the other alternative, because in both cases, a volume that is not used for disposal is required at the head of the cell for manoeuvring the disposal truck.

The outside door is equipped with a transfer cask-docking window. The inner door consisting of sliding panels covers the entire width of the cell. Between the two doors, fixed equipment is used to rotate and move the disposal truck sideways.

9.3.2.2 Description of the disposal truck

- **General description**

A first feasibility study of the disposal truck enabled us to assess the order of magnitude of its dimensions, which are about 2 metres in width, 4 metres in length and 6 metres in height. It weighs about 25 to 30 tonnes. Its power supply could come from on-board batteries.

The principle of this disposal truck is illustrated by Figure 9.3.2.

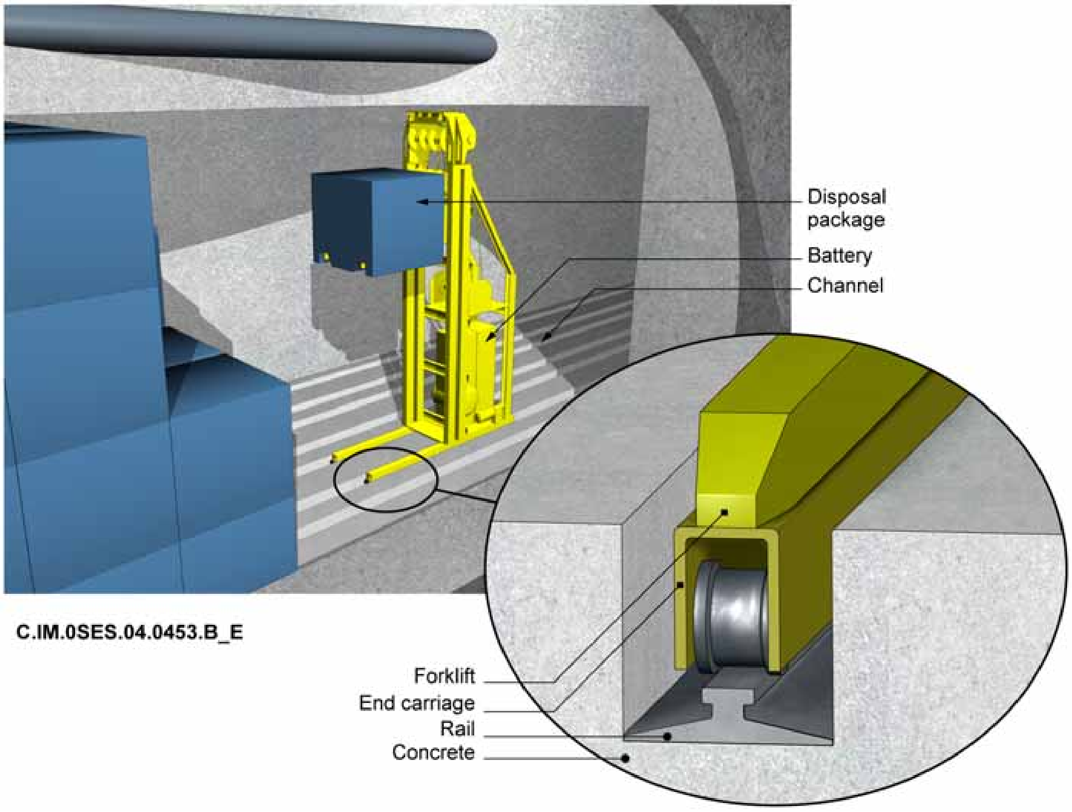

Figure 9.3.2 Disposal truck without counterweight

The main structure of the disposal truck consists of two metal beams equipped with wheels. These two beams are connected to one another by a mast on which the two lifting forks slide vertically. The mast is positioned so that the forks are directly above the beams, so that during the handling of a package, the centre of gravity of the package lies within the supporting polygon formed by the wheels, thus ensuring the stability of the whole.

This truck can move backwards and forwards in the cell and also has a lifting movement for handling the packages. The disposal truck is mounted on rails placed in grooves made in the foundation throughout the length of the cell.

- **Working performances**

An important technological question for the functioning of the disposal truck is that of its performance in terms of positioning the packages. Reducing the clearance within the cell implies placing and piling the packages with great precision (of the order of a few centimetres).

There are several technologies that could meet this requirement. For example it is possible to measure the distance covered by the disposal truck by a laser distance meter that is commonly used in industry for measuring distances of up to 500 metres with a precision of a few millimetres.

The development of such a procedure is compatible with of the functional clearances between the packages and cell walls and between the packages themselves, of the order of 10 cm.

Finally, faced with the risk of dropping packages, this disposal truck must be equipped with safety devices corresponding to the practices used in the design of nuclear equipment. For example, it is envisaged to include a device for slowing the speed of descent of the load in the event of malfunction or a breakage of one of the components of the lifting gear.

Figure 9.3.3 shows a similar handling truck working under remote control in an irradiated environment on the COVRA site in the Netherlands.

9.3.2.3 Description of the fixed equipment in the cell

The fixed equipment is installed in the airlocks at the head of the cell (see Figure 9.3.4). It consists of:

- the shielded doors of the airlocks,
- a moveable floor equipped with a turntable,
- rails in grooves forming the running tracks,
- various utilities facilitating the maintenance of the equipment.

Figure 9.3.3 Handling truck (photo COVRA)

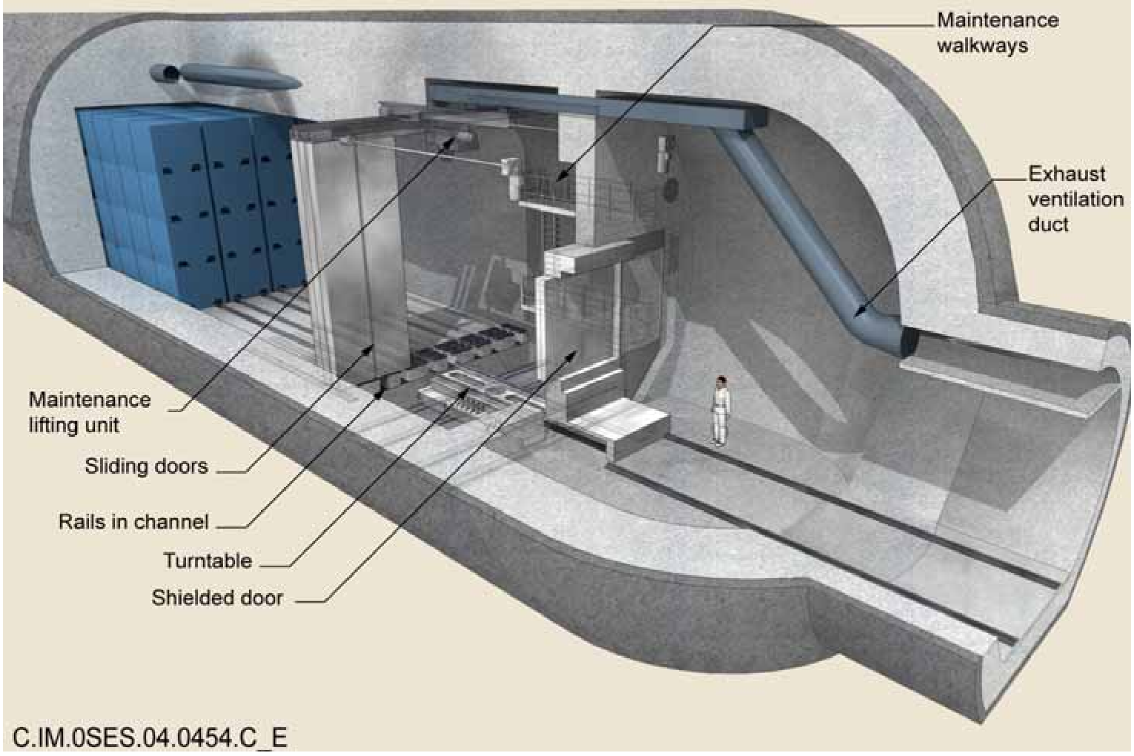

Figure 9.3.4 Cell equipment

- **The shielded doors of the airlocks**

The airlock is equipped with a "docking door" onto which the transfer transfer cask docks and "sliding doors " separating off the irradiated part of the cell containing the packages.

The "docking door" consists of two motorised sliding steel sections about 300 mm thick. The "sliding doors " consist of sliding panels (steel plates about 300 mm thick) over the entire height of the cell. These panels are also responsible for allowing air through for ventilating the disposal chamber. At this stage of the studies, there has been no detailed design work on these doors. However, large-sized doors (about 6 to 7 metres high and weighing about 30 tonnes) existent in the COGEMA installations on the La Hague site.

- **Moveable floor with turntable**

The moveable floor supports the disposal truck. By means of its turning and sideways movement it enables the disposal truck to be positioned facing the transfer cask for extracting packages or facing a row of packages for the operation of transferring into the disposal chamber. It moves at right angles to the disposal chamber on rails fixed to the floor.

- **The running tracks**

The running tracks consist of metal rails. This system was preferred to a system on tyres because it takes up little space that fits well with the dimensions of the grooves.

9.3.2.4 Description of the process of installation in the cell

The disposal cycle of B packages (illustrated by the diagram in Figure 9.3.5) takes place in four stages.

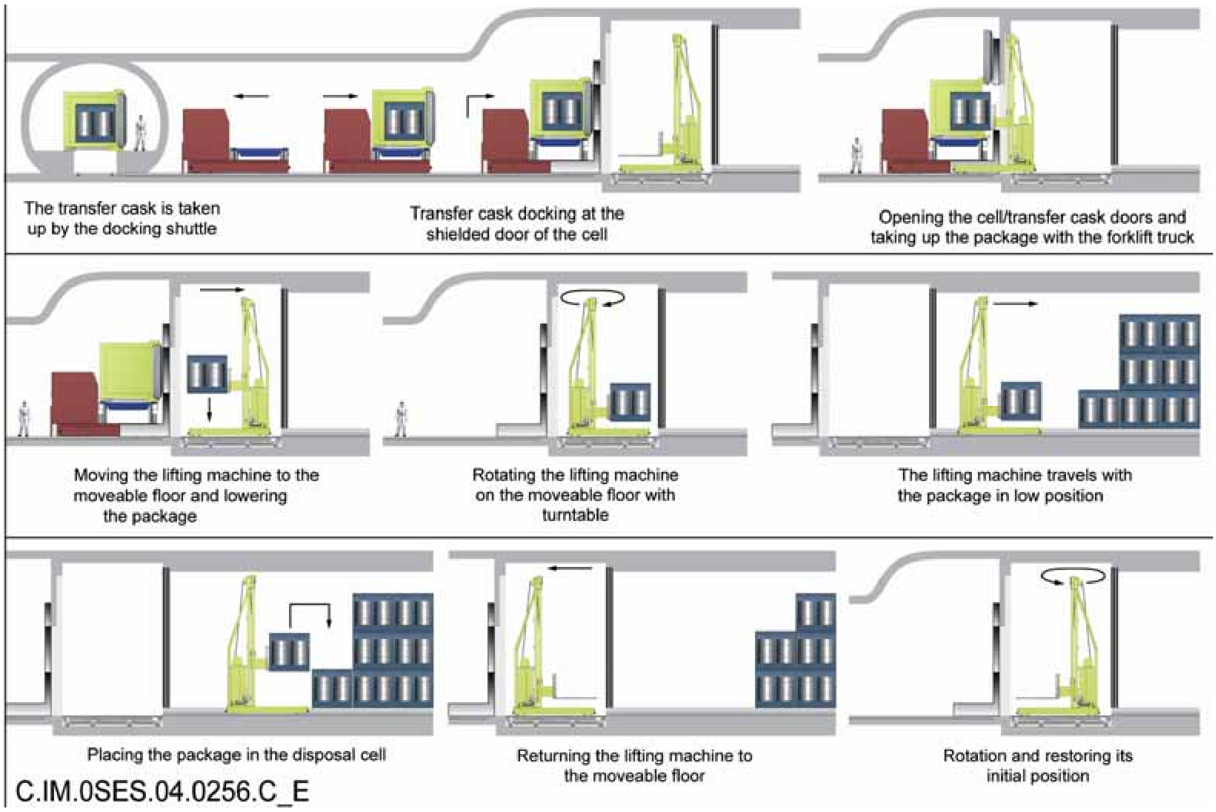

Figure 9.3.5 Diagram of the installation of B packages in the cell

As a first stage, the transfer cask is docked by the shuttle at the docking gate of the cell chamber. The disposal truck can then extract the disposal package.

As a second stage, after closure of the docking door, the moveable floor rotates the disposal truck through 180° and moves it to face the selected disposal row.

As a third stage, the sliding doors are opened and the disposal truck then enters the cell. During the travel in the disposal chamber, the package is in the low position to prevent any risk of falling and to make the moving truck and package stable. When it arrives next to the front of the packages already disposed, the disposal truck gradually slows so that the operations of placing the package can begin. The package is lifted to the height at which it is to be deposited which can be as high as 4.50 m. The disposal truck advances very slowly and positions the package just above the disposal level constituted by the package below. The package is then deposited very slowly. The operations of installing the packages is illustrated by Figure 9.3.6 and

Figure 9.3.7. Finally as a last stage, the disposal truck reverses and returns to the airlock whose sliding doors are shut again.

The time taken to complete a whole cycle of installing a package over a distance of about 120 metres is estimated to be about 2 hours from the extraction of the package from the transfer cask to the return of the empty disposal truck to the airlock.

The design of equipment related to the emplacement of the packages is based on the principle of the redundancy of motorisations and their associated commands. In case of breakdown, the disposal truck is designed to set down its load passively. A winch system would be used to return it to the airlock.

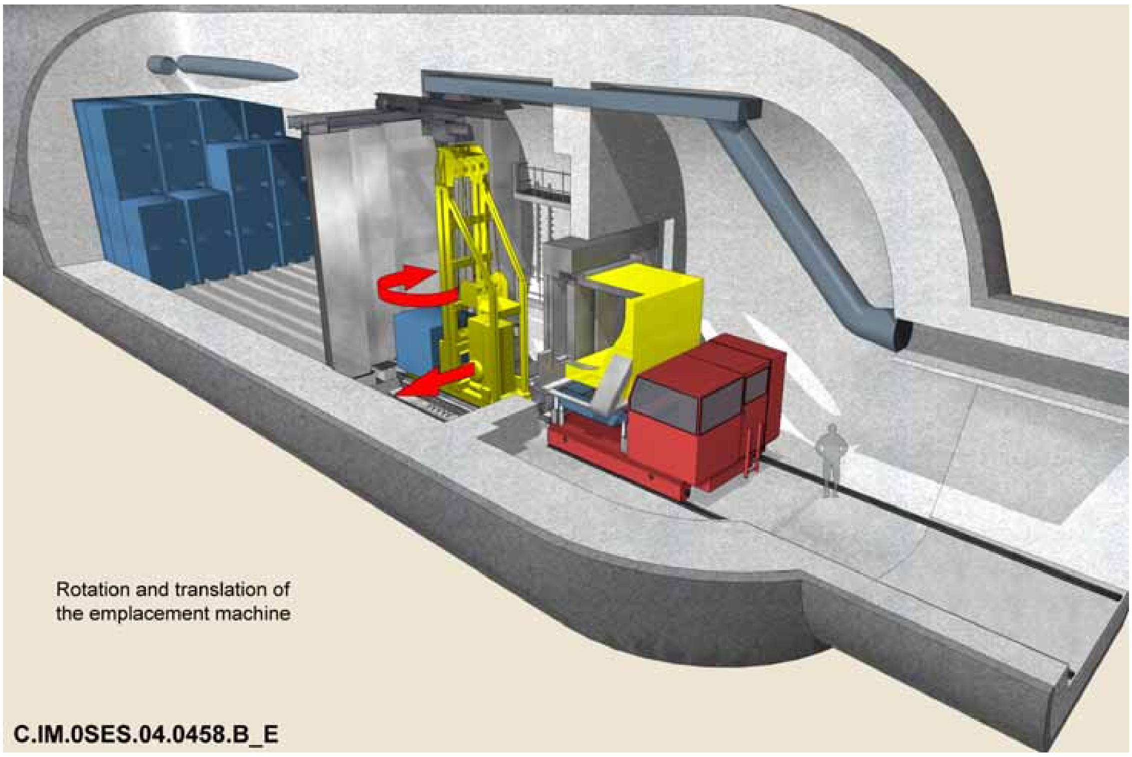

Figure 9.3.6 Rotation and movement of disposal truck in the airlock

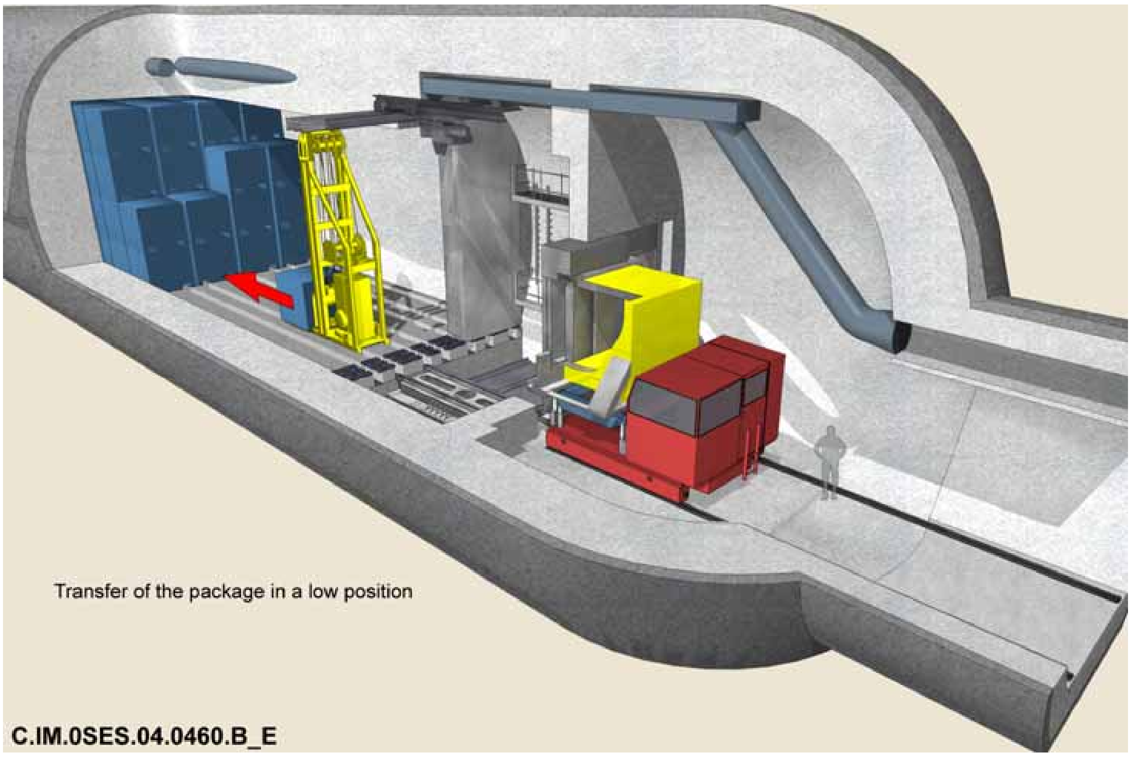

Figure 9.3.7 Transport of the package in low position

9.3.2.5 A similar solution studied in Germany

The photo in Figure 9.3.8 illustrates the solution adopted in Germany in the future "Konrad" installations for the disposal of type B low-level wastes [81]. The machine is a fork-lift truck with a counterweight with a capacity of about 20 tonnes, that is articulated for taking tight corners. It has a shielded cabin to provide radiological protection for the on-board operator.

Figure 9.3.8 A fork-lift with counterweight (photo DBE)

9.3.3 Description of the equipment and process of installing packages of C wastes

9.3.3.1 Design principles

- **Required functions**

The disposal packages of C wastes weigh about 2 tonnes. Type C1 to C4 packages are about 0.60 m in diameter and about 1.60 m long. Type C0 packages are 0.65 m in diameter and about 1.30 m long.

The placing of cylindrical radioactive packages in a horizontal cell of circular section requires a remote-controlled machine capable of being contained in the shielded transfer cask and of transferring the packages to their final position with a functional clearance between the packages and the cell as small as possible.

- **Choice of the principle for handling the packages**

Three principles, illustrated by Figure 9.3.9, have been identified for the transfer of the disposal package:

- a air transport robot using the air cushion principle,
- a self-propelled transporter robot,
- a self-propelled pusher robot.

The "air cushion" principle on a circular support has been the subject of two conclusive feasibility tests. One was conducted by Andra (case of type CU1 spent fuels) and the other by the Swedish agency SKB (case of a super-container). However, these tests were conducted on a load with a much greater diameter (1.80 m and 1.25 m) than that of type C disposal packages (0.60 m) so that they cannot be considered to be readily transposable. The diameter of C packages is in fact too small to be able to use standard air cushion cells. The thickness of the structure bearing the air cushions (about 5 cm) imposes a relatively large functional clearance compared to the diameter of the cell (0.60 m).

The principle of the transporter robot consists of lifting the disposal package in a position jutting out in front, by a self-propelled robot. This robot has a counterweight to balance the weight of the package. The combined package and robot therefore constitutes a rigid block whose length requires a large clearance between the packages and the sleeve.

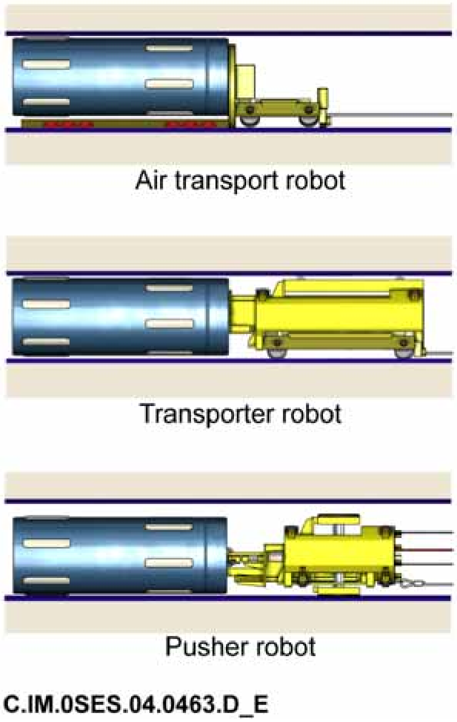

Figure 9.3.9 Illustration of the envisaged handling principles

The principle of lifting in an offset position requires compensation by the weight of the robot, leading to a rather long machine. This factor therefore leads to an increase in the size and weight of the protective transfer cask.

The principle of the pusher robot with step-by-step jacks consists of pushing the package by simple sliding on the cell sleeve. The push is exerted by an axial hydraulic jack. The robot buttresses itself using radial jacks that push on the sleeve. The robot advances by retracting the push jack.

At this stage of the studies, the push option by a jack was preferred to the other options. This principle of pushing by sliding, benefits from the experience gained in two trials conducted, one by ONDRAF and the other by Andra. These tests showed that the key factor is the nature of the contact between the packages and the sleeve. In particular, contacts of the "metal on metal" type are not allowed. The use of stainless steel is a factor that would be liable to seize the system as shown by the test conducted by ONDRAF.

Taking into account this difficulty has led us to envisage using ceramic sliding runners included on the packages.

9.3.3.2 Description of the equipment used for installing C waste disposal packages

The equipment studied, complying with the principle described above, consists of three parts: a mobile robot, fixed equipment mounted on the chassis of the protective transfer cask and fixed equipment installed at head of the cell.

The robot is connected to the fixed equipment of the transfer cask by means of an umbilical cable. The fixed equipment at the head of the cell contributes with the transfer cask to the radiological protection of personnel.

- **The pusher robot**

The pusher robot is a small but powerful piece of equipment adapted for the dimensions of the C waste disposal cell.

It consists of a frame equipped with rollers and a series of hydraulic jacks. A preliminary study provided an assessment of the order of magnitude of its dimensions, which are about 1.30 m long and 0.55 m in diameter.

The robot fulfils two functions that are conducted one after the other: pushing the package and moving the robot body. These two functions are ensured by two main mechanisms: an axial pusher and two systems used to apply pressure to the sleeve. The first system immobilises the body of the robot and the other immobilises the axial pusher. The role of the longitudinal jack is to push the packages. When pushing, the body of the robot is kept in a fixed position thanks to the support system which is immobilised on the wall sleeve.

This system is unblocked and the pusher jack system is blocked so as to move the robot body by retracting the longitudinal jack.

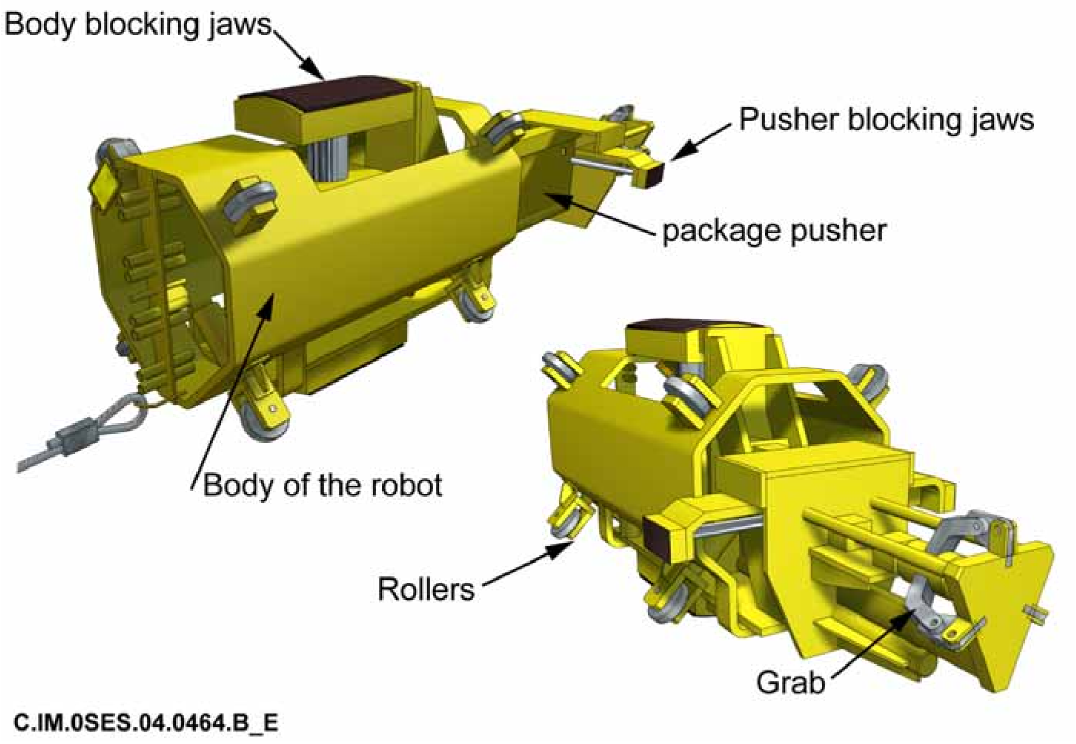

Figure 9.3.10 Pusher robot for C packages

Two technical solutions for provision of support have been studied. The first is based on hydraulically powered jaws and is depicted in Figure 9.3-10 and Figure 9.3-11. The second uses pneumatically inflatable ring-shaped chambers. It is the subject of studies presented in Section 9.3.3.4.

The kinetics of the pusher robot are illustrated by Figure Figure 9.3.11.

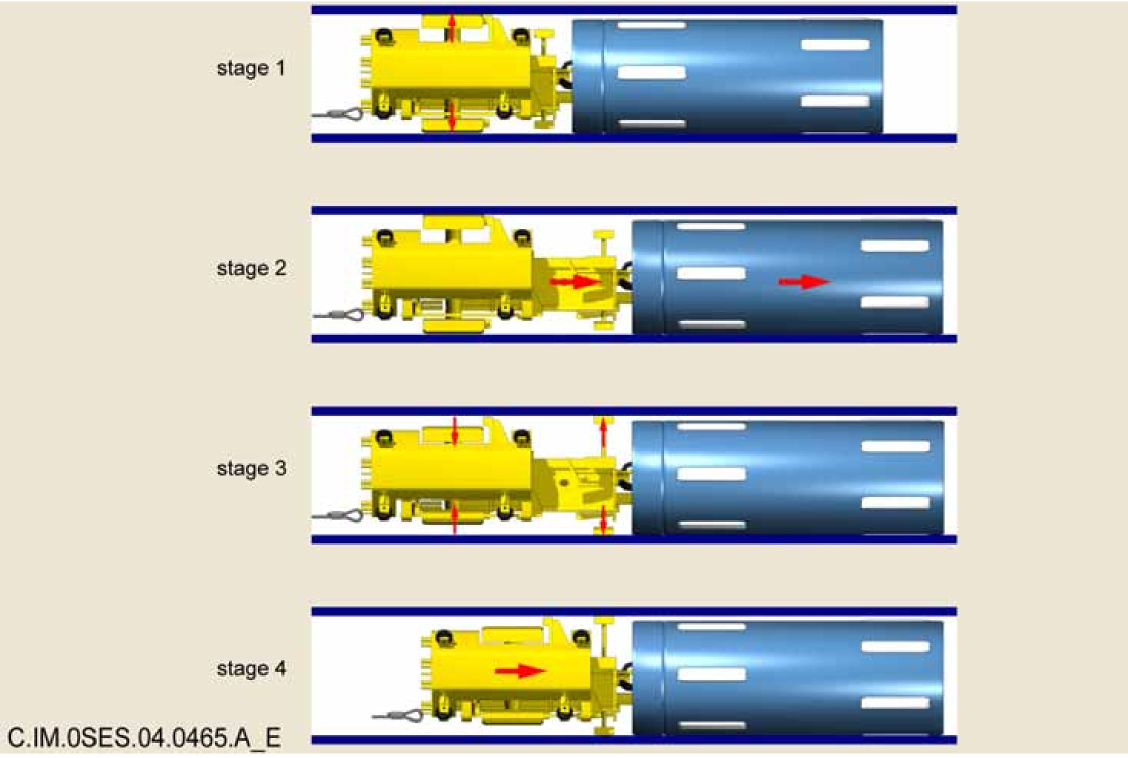

Figure 9.3.11 Illustration of the pusher robot operation principle

A gripper situated at the head of the robot allows the packages to be withdrawn if necessary.

- **The fixed equipment attached to the transfer cask**

The fixed equipment attached to the transfer cask consists of a return winch and a hydraulic unit that powers the jacks of the robot. The return winch allows the robot to be brought back in the event of a breakdown. This equipment is connected to the robot by a cable and flexible hydraulic pipes.

The shielded container is equipped with a moveable sleeve containing the packages and the pusher. This sleeve can move over about 80 cm to ensure a physical continuity with the cell sleeve which is itself connected to the shielded trap door installed at the head of the disposal cell.

- **The fixed equipment attached to the head of the cell**

The head of a disposal cell consists of a shielded trap door itself composed of a fixed part connected to the cell sleeve and a sliding door operated by the door of the transfer cask when this is docked. This shielded trap door provides the cell's radiological protection, plus supplementary protection when the transfer cask is docked. This protection is similar to that of the transfer cask walls.

9.3.3.3 Description of the process of installation in the cell

A cycle of placing C packages is divided into three stages.

In the first stage, the transfer cask is docked on the shielded trap door at the head of the cell (see Figure 9.3.12). The doors of the transfer cask and shielded trap door are then mechanically coupled. The door of the transfer cask is the motor that drives that of the shielded trap door.

In the second stage, the robot activates the transfer of the disposal package to its final position in the cell according to a "step-by-step" advance process (see Figure 9.3.13).

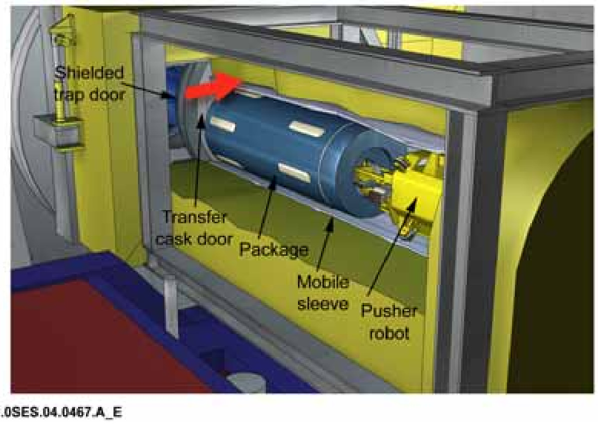

Figure 9.3.12 Transfer cask docked on the cell head

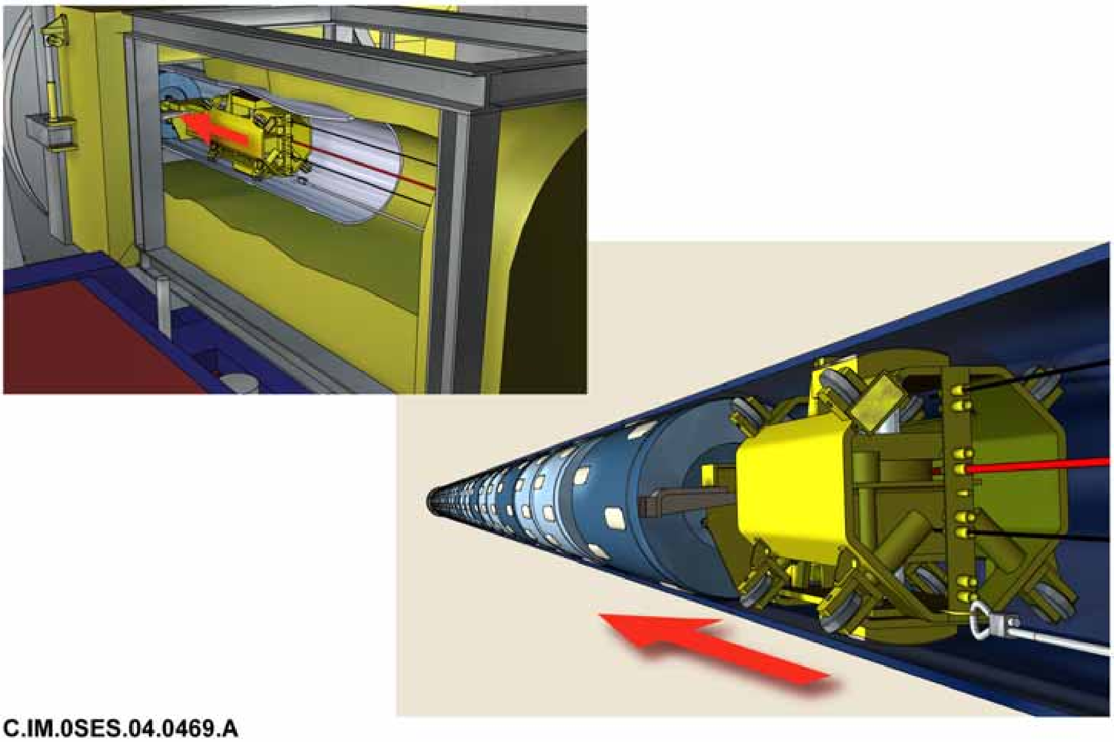

Figure 9.3.13 Extraction of the transfer cask and putting the package in place in the cell

Finally, in the last stage, the robot is brought back into the transfer cask using a return winch installed on the the transfer cask outside frame. The doors of the shielded trap door and the transfer cask are then shut.

The time taken to complete a full cycle of putting a package in place over a distance of about 20 metres is estimated to be about 2 hours.

In the event of robot failure or immobilization of the package during transfer, the principle envisaged consists of setting the package down in the cell and returning the pusher robot to the cask by means of the robot return winch.

9.3.3.4 Demonstration of the validity of the principle chosen by a workshop test

The process of putting C packages in place described above is the subject of two full-scale validation tests.

The first test validated the principle of ceramic sliding runners

Figure 9.3.14). The tests confirmed that these runners would reduce the friction coefficient between the disposal package and the cell sleeve and made it possible to define their shapes and dimensions. (cf. § 4.2.4.2)

Figure 9.3.14 Mock-up C Waste Disposal Package Used for Demonstration Models

The purpose of the second test is to validate the principle of emplacement in a cell by a pusher robot. This test is conducted as part of the ESDRED European project coordinated by Andra.

A demonstration model was developed comprising a tube of about fifteen metres long simulating the cell sleeve, a mock-up package equipped with ceramic sliding runners (of the same weight and dimensions as a real disposal package) and a prototype pusher robot. The systems that support the robot on the wall of the sleeve are made up of two ring-shaped chambers that can be inflated with air. This solution makes it possible to obtain a homogeneous distribution of the immobilisation effort over the entire periphery of the sleeve wall and reduces the length of the robot by approximately 30 cm compared with the solution of an entirely hydraulic robot with hydraulically powered jaws). Figure 9.3.15 shows the prototype robot in its retracted and deployed configurations.

Tests carried out to date have demonstrated the robustness of the runners in the event of faults in the assembly of sections of the sleeve as well as the efficiency of the robot and its support system.

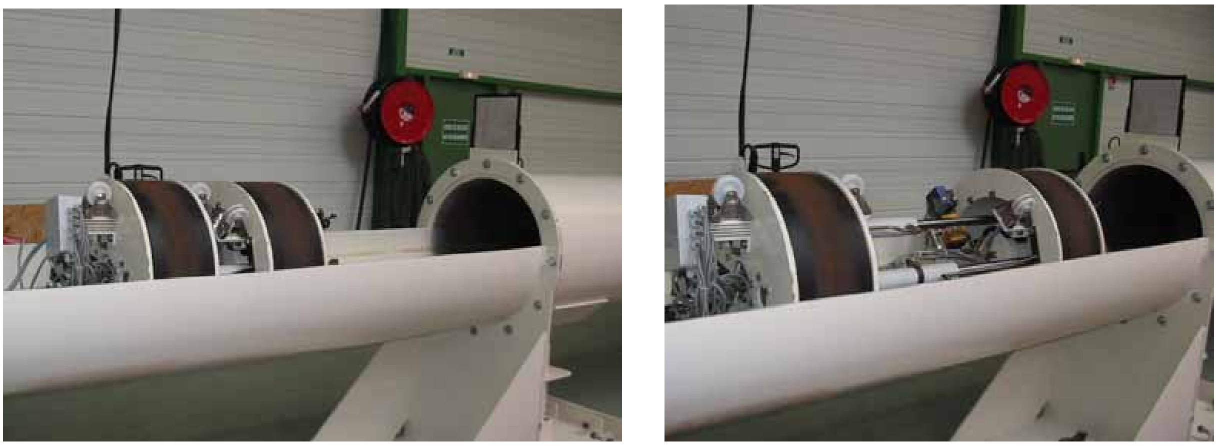

Figure 9.3.15 *Pusher robot in retracted position (left) and in the deployed position (right)*

9.3.3.5 A similar solution developed abroad

At the WIPP (Waste Isolation Pilot Plant - USA) disposal facility it is envisaged that "remote handled" (RH) type high-level wastes are disposed in a similar configuration to that envisaged by Andra. The disposal packages of these wastes are in fact similar in terms of size and have a level of radioactivity requiring a protective transfer cask. Furthermore the disposal cell is a short horizontal tunnel of small diameter. The equipment envisaged by US DOE, responsible for this facility, consists of a transfer cask docked at the head of the cell and a hydraulic pusher installed in the axis of the transfer cask.

Figure 9.3.16 *Transfer cask equipped with a hydraulic pusher for installing type RH wastes in horizontal cells at the WIPP disposal facility.*

9.3.4 Description of the equipment and the process of installing spent fuel disposal packages

This section describes the justification of the choice of two different principles for installing packages of four assemblies (type CU1; diameter about 1.25m) and packages of one assembly (type CU2; diameter about 0.60 m). The principle favoured for the type CU2 packages is similar to that described for C packages. A simple reminder will therefore be given and there will be no specific description. The principle chosen for type CU3 spent fuels is also identical to that adopted for C packages.

9.3.4.1 Justification for principle chosen

- **Required functions**

There are two types of disposal package. CU1 packages are characterised by a weight of about 43 tonnes and a length of about 5.40 metres. CU2 packages are characterised by a weight of about 10 tonnes and a length of about 4.60 metres.

The installation of these heavy and large-sized disposal packages in a horizontal cell of circular section requires, as for C packages, a remote-controlled machine capable of being contained in the shielded transfer cask and of transferring the package to its final position with a functional clearance between the package and the cell as small as possible.

- **Choice of the package handling principle**

In the same way as for the installation of C waste packages, three principles have been identified for the transfer of the disposal package (SeeFigure 9.3.17):

- transfer by a self-propelled pusher robot with jacks with sliding of the package (principle similar to that chosen for C packages),
- transfer by a self-propelled robot with rolling of the package requiring the incorporation of wheels into the container structure,
- transfer of the package by a robot using the air cushion principle.

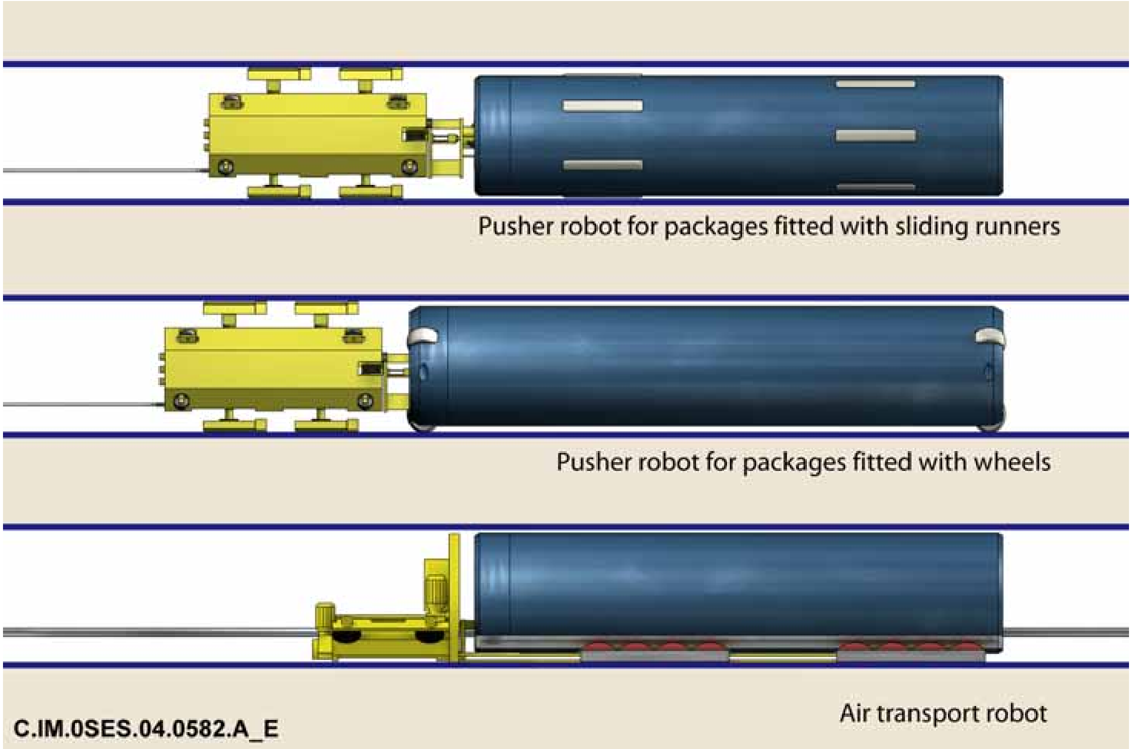

Figure 9.3.17 The handling principles envisaged for spent fuels

In the case of CU1 packages, the air cushion principle was preferred to the other two alternatives envisaged. The weight of CU1 packages (43 t) is in fact almost incompatible with the principle of pushing by sliding which would require the production of a very high thrust force. The option consisting of including wheels in the container structure would complicate its manufacturing process and would significantly increase the length of the package and its weight.

The air cushion principle has been the subject of a representative test by the Swedish agency SKB using a demonstration model of similar dimensions to the packages in question. [81]. More recently, Andra has conducted another test using a full-scale prototype in terms of the diameter as part of the ESDRED European project.

On the other hand, in the case of the CU2 package, the weight is compatible with the technique of pushing by sliding. The diameter of the CU2 package is at the lower limit for using air cushion cells. Finally, as in the case of the CU1 packages, the incorporation of wheels would complicate the manufacturing process and increase the length of the package.

Consequently, the comparison of the three options presented above led to us favouring the air cushion technique for type CU1 packages and the technique of pushing by a robot with jacks for type CU2 packages. This latter principle being similar to that adopted for C packages, it will not be described in the sections below.

9.3.4.2 Description of the equipment for installing type CU1 packages

The equipment studied using the chosen air cushion technique consists of three parts: a mobile robot called "air cushion transporter", fixed equipment mounted on the chassis of the transfer transfer cask and fixed equipment installed at the head of the cell. The air cushion transporter is connected to the fixed equipment on the transfer cask by means of an umbilical cable. The fixed equipment at the head of the cell contributes with the transfer cask to the radiological protection of personnel.

- **The air cushion transporter**

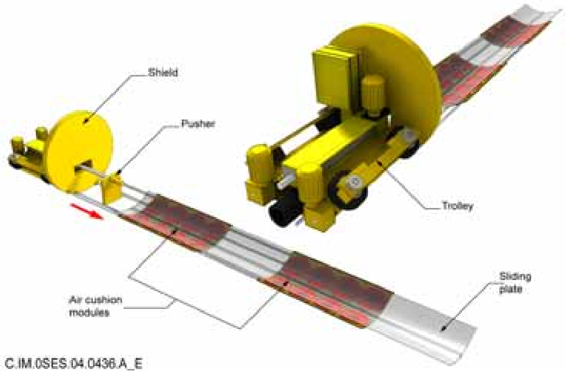

Figure 9.3.18 Air cushion transporter

The air cushion transporter illustrated by Figure 9.3.18 consists of two components connected to one another by a coupling system: an electric trolley and a cradle bearing the air cushion modules.

The air cushion transporter fulfils three functions: keeping the package floating, pushing the floating package and moving the empty air cushion transporter.

The first function (keeping the package floating on an air cushion) is ensured by a structure bearing the air cushions called the "cradle". This cradle is positioned under the disposal package in the space bounded by rails of 50 mm thick fixed to the cell sleeve. It comprises a dozen standard air cushion modules operating at a pressure of about 4 bars. These air cushions create an air layer that keeps the package floating.

Each air cushion module consists of a ring-shaped, inflatable rubber apron curved to the diameter of the disposal package. The air blown in first inflates the rubber apron that expands to a height of about 20 mm then lifts the load of its supports[133]. The air then escapes to form a very thin air mattress that raises the load by a few tenths of a millimetre. The package is then in a state of suspension and can be moved with very little effort. This principle is illustrated by Figure 9.3.19.

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[133] An intermediate sliding plate is placed between the packages and the air cushion. This stainless steel “plate” has a very smooth surface to obtain maximum effectiveness from the air cushion..

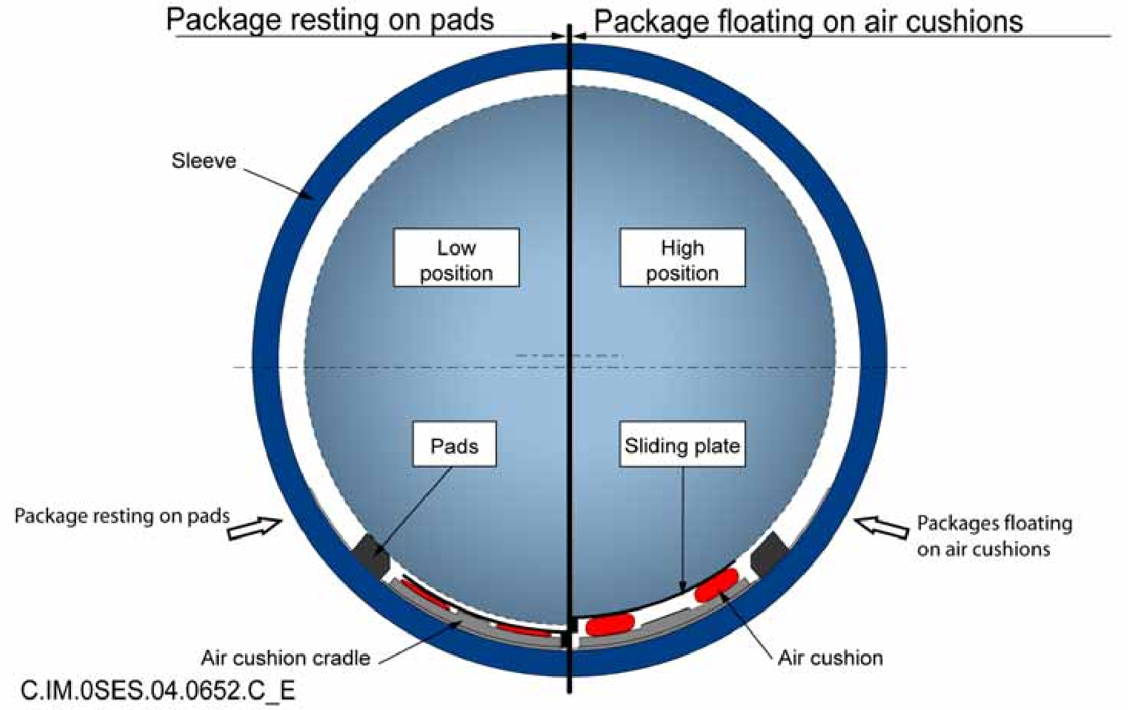

Figure 9.3.19 Principle of the function of the air cushions blowing upwards

The two other functions (pushing the package and moving the empty air cushion transporter) are carried out by an electric truck. This truck consists of a wheeled structure that moves the empty air cushion transporter. It is connected by an umbilical cable to the equipment fixed to the transfer cask that supplies it with air and electricity. It is also connected by a cable to a return winch.

The truck moves by means of small electrically motorised wheels. The packages are pushed by means of a mechanical jack with a course of 1 m that moves the packages when they are in a state of floatation.

The force needed for the movement is estimated to be less than 1 tonne to overcome resistance forces caused by any defects that could occur along the path. The weight of the truck and the adherence of its wheels on the cell sleeve should overcome the reaction of the thrust when the jack is working.

A first preliminary study has assessed the order of magnitude of the truck dimensions which are about 7 metres long, of which 5.50 metres is used for the cradle equipped with air cushions and 1.50 metres for the electric truck connected at the front.

The time needed to complete a cycle over a path length of 1 metre is about 5 minutes.

- **The fixed equipment**

As in the case of C packages, the head of the cell is equipped with a shielded trap door activated by the transfer cask doors.

The fixed equipment specific to the working of the air cushion transporter consists of a return winch, an air compressor, a pneumatic pipe reel and an electric cables reel. This equipment can in part be fixed to the transfer cask (winch and reels) and partly fixed to the docking shuttle (compressor).

9.3.4.3 Description of the process of installation in the cell

A cycle installing a type CU1 package consists of three stages following the same logical sequence as that previously described for the vitrified wastes transfer cask.

In the first stage, during the docking of the transfer cask, the doors of the shielded trap door and the transfer cask are mechanically coupled. The transfer cask door drives the shielded trap door.

In the second stage, the air cushion transporter, acting in a step-by-step mode, transfers the disposal package to its final position in the cell.

Finally in the last stage, the air cushion transporter is brought back into the transfer cask using the return winch situated on the transfer cask outside frame.

The time needed to complete an entire cycle (See Figure Figure 9.3.20 of putting a package in place over a distance of about 20 metres is estimated to be 3 hours.

The failure recovery system envisaged is similar to the one that would be used for C packages (cf. § 9.3.3).

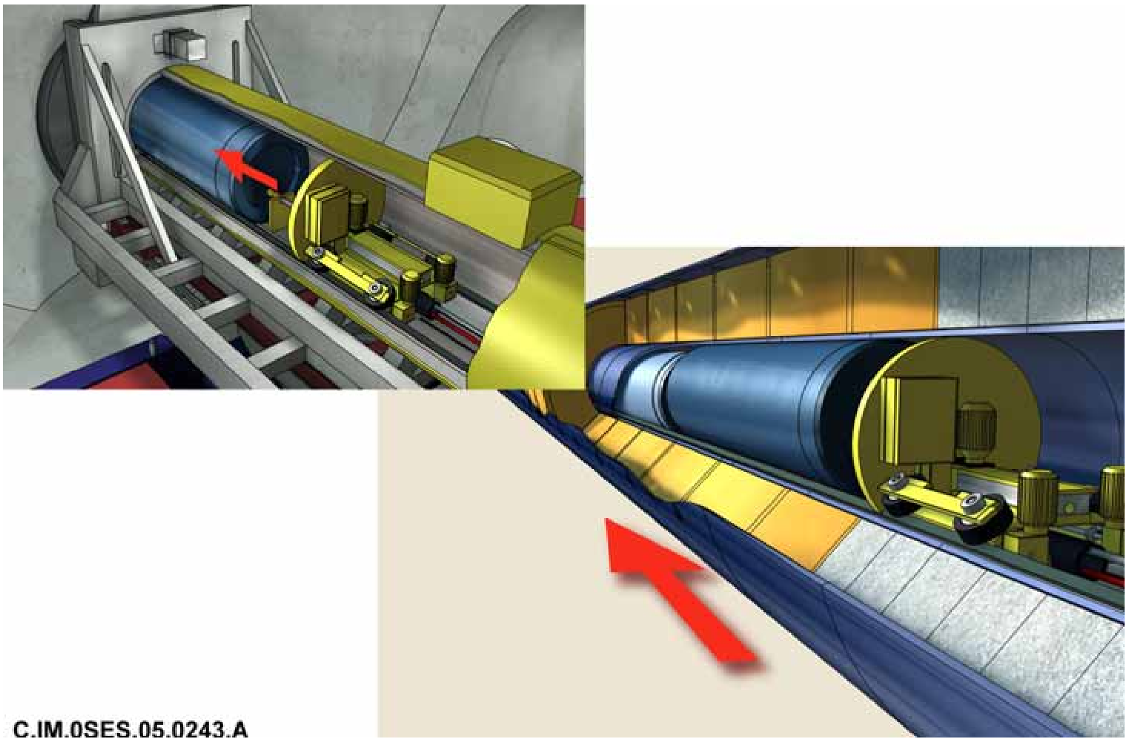

Figure 9.3.20 Transfer of the package into the cell

9.3.4.4 Demonstration of the validity of the principle chosen by a workshop test

The principles described above for putting type CU1 packages of spent fuels into the cell (transfer by air cushion transporter) are the subject of full-scale validation tests as part of the ESDRED European project coordinated by Andra. Since the principle of transferring the CU2 package is similar to that of the C vitrified waste packages, the demonstration of its validity is conducted at the same time as that of the C packages described in section 9.2.

- **Validation test on the transfer of CU1 type packages by air cushion transporter**

The first part of the test consists of validating the "air cushion" principle. To do this a prototype structure bearing air cushions was manufactured (See Figure 9.3.21). A load simulating the weight of the package was then placed on a steel sheet of full-scale diameter (1255 mm). The whole was then suspended by the air cushions and moved over a distance of about 1 metre. This test showed that the air cushions worked correctly and confirmed the slight effort needed to move the load sideways by pushing. Figure 9.3.22 illustrates this test.

Figure 9.3.21 Prototype air cushion cradle

Figure 9.3.22 Tests of moving a load simulating the shape and weight of a type CU1 spent fuel disposal package using air cushions

The second part of the test consists of producing a full-scale demonstration model. It uses a tube twenty metres long simulating the cell sleeve, a dummy package of the same weight and dimensions as a real package and a prototype robot. Geometric faults and obstacles on the tube will be created to validate the correct working of the process.

9.3.4.5 A similar solution studied in Sweden

The Swedish agency SKB has studied a horizontal disposal concept called KBS-3H, whose principle consists of depositing a super-container (diameter 1.80 m – weight 45 tonnes), consisting of a copper spent fuels container surrounded by rings of bentonite, in a horizontal tunnel (

Figure 9.3.23). As part of this concept, the use of air cushion technology is envisaged by SKB. This principle is similar to that envisaged by Andra. However, as the irregularities in the tunnel walls excavated in granite are likely to require the use of very high air flow rates to keep the load suspended by the air cushion, SKB therefore envisaged replacing the air by water. This project will also be the subject of a full-scale technological demonstration model carried out as part of ESDRED project coordinated by Andra. A first successful test was conducted with the same test bench as that used by Andra and mentioned previously. [81].

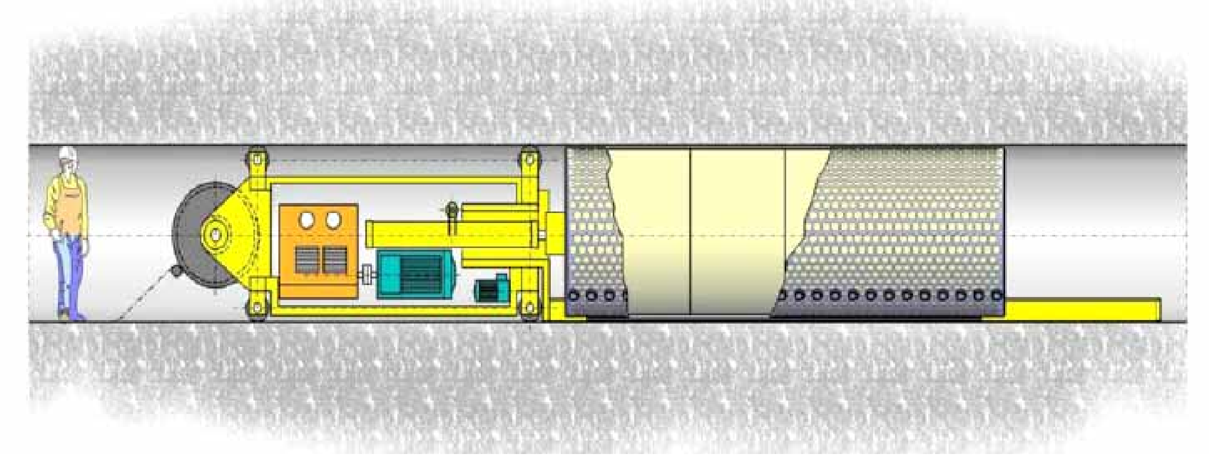

Figure 9.3.23 Diagram of the principle adopted by SKB

10

Reversible repository management

The purpose of this chapter is to describe the disposal management principles with the aim of ensuring reversibility. As indicated in Chapter 2, reversibility is not dependent on purely technical factors. It aims to meet the social expectations of retaining freedom of choice. This chapter illustrates the technical provisions that make it possible to offer this possibility. These provisions must thus allow changes to be made, when desired, in waste management.

The chapter starts by describing the paradigm of a progressive waste disposal process, which consists of constructing, operating and closing the repository by means of a succession of stages, the duration of which is not pre-determined. The fact is underlined that this progressivity makes it possible, over a period of several centuries, to manage the disposal process with a flexibility similar to that offered by a storage facility, i.e. so as to be able to retrieve waste packages from disposal if necessary or desired. This progressivity also allows the closing of the repository to be controlled in an adaptable, flexible manner whilst retaining the option of reversing the process. It is also stressed that this progressivity offers the ability of changing the design of the repository and allows to baskfill from experience gained during the initial construction.

The chapter then goes on to describe the principal phenomena that characterise the various key stages of the process. It analyses their impact on the condition of the packages and the argilite from the point of view of reversibility and the possible options available in terms of process management. It also underlines the ability to take action on the disposal process.

It provides a description of the resources available for monitoring phenomena throughout the disposal process. It stresses the extent to which advantage can be taken of monitoring experience feedback from operators of major public works. It shows that at each stage, reliable, durable measuring techniques can thus enrich knowledge and provide additional elements, particularly in decision-making when moving from one stage to the next.

Finally, this chapter proposes an outline of the technological resources that could be brought into play if it was decided to reverse the previous stages of the disposal process and retrieve the waste packages. It demonstrates the technical feasibility of such an eventuality.

10.1 Stepwise managment of the disposal process

This section identifies the various stages of the disposal process, from receipt of the first packages through to closing of the entire repository.

10.1.1 Progressive operation of the repository

The industrial commissioning of the installation begins with the on-site receipt of the first waste packages and their placing in the repository in the first disposal cells constructed. At the same time as these cells are being brought into use, the construction of new modules could progressively begin. Thanks to the design of the infrastructures, using separate shafts and drifts for construction and disposal activities, it is possible for both types of activity to co-exist and for them to progress independently of each other.

All type B cells could be progressively constructed and operated over a period of 40 years at a rate of one new module annually. All type C modules could be built and operated over a period of approximately 50 years at a rate of one new operating unit initiated every two years.

If spent fuel were to be placed in the repository, the rate of progress could be one operating unit approximately every two years for type CU2 spent fuel and one per year for type CU1. The overall construction and operating periods would then be approximately 35 years for type CU1 spent fuel and approximately 30 years for type CU2.

Thus, in order to resorbe all the waste packages under reasonable technical and economic conditions, the disposal period would be at least several decades and could last on the other of a century. This estimate, based on the inventory of French waste packages, is of the same order of magnitude in other European countries.

During the operational phase, the disposal process is thus progressive. Once the waste packages have been placed in the disposal cells, the latter could be managed with a flexibility reminiscent of a storage facility, characterised by total reversibility.

Unlike a storage facility, a repository is also designed to be closed, in order to create a system that is safe over the long-term, without requiring any human intervention. This closing is carried out in successive stages. The level of reversibility gradually reduces as each stage is passed. The configuration in which all the installations are closed constitutes the lowest level of reversibility.

10.1.2 Progressive closing of the repository

On completion of a monitoring period, the duration of which is, in principle, undefined, in the event of a formal decision which thus marks the desire to pass a milestone and initiate the closing process, the filled disposal cells are closed.

The closing process thus begins with the sealing of cells. On completion of sealing, the drift giving access to the cells remains accessible. A new monitoring phase can then begin.

The next decision concerns the back-filling of the access drifts to the cells (drifts inside the module). This operation lasts from 2 to 4 years depending on the size of the repository module. On completion of this work, the connecting drifts giving access to the back-filled module remain accessible. A new monitoring phase can again then begin.

Depending on the decisions taken, the closing work on certain modules already full within the repository zone can be carried out at the same time as packages are being placed in other modules.

The subsequent decisions concern the closing of the connecting drifts. This begins, in a first repository zone, by back-filling drift sections giving access to the most remote repository modules, and by sealing them. On completion of this work, the main connecting drifts giving access to the closed repository zones will remain accessible.

It should be noted that the modular design of the repository makes it possible to envisage closing some structures whilst others are still in operation.

After closing repository zones, the next stage of the process involves the back-filling and sealing of the main connecting drifts. Finally, the last stage concerns the sealing of the access shafts to the geological formation.

On completion of this final stage, which ends the closing process, the entire repository is in the so-called “post-closure” configuration. The repository then requires no further maintenance or additional work. It gradually becomes passive and safe in the very long term.

Thus, the progressive nature of the repository closing process offers the possibility of implementing a decision-making process consisting of several successive stages, with the ability to introduce a period of monitoring and to decide to maintain the installation in its present condition, move on to the next stage, or reverse the process. The decision to move on to the next stage is facilitated by data provided by monitoring the behaviour of the structures. This logic forms a favourable element in the reversibility of the disposal process, given that allows, at any moment, to reverse to the previous stage.

10.1.3 Key stages of the disposal process

This section describes the key stages that enable the disposal process to be managed in an adaptable, flexible manner [83]. These stages form the basis of the description of the reversible disposal management process given in the following sections (cf. Figure 10.1.1).

- **“Post package-emplacement” stage**

The “Post package emplacement” stage corresponds to the period in which one or more cells are filled with packages but not sealed. During this stage, the cell is made safe from a radiological point of view by a totally reversible shielded physical barrier, which protects the operators present in the access drifts. The network of connecting and access drifts and shafts remains fully accessible. At this stage, the only difference between a type B waste cell and a type C waste or spent fuel cell is that the former is ventilated whereas, in the latter, aire removal is strongly limited by a sealing closure device.

Certain structures are monitored. The drifts are ventilated, thus allowing easy access to the entire network. At all times, the physical disposal cell closing device can be opened so that the packages can be retrieveed without further delay. This stage is comparable with a storage configuration.

- **“Post cell-sealing” stage**

The “Post cell-sealing” stage starts once the cells have been sealed by a swelling clay plug. This plug limits the physico-chemical exchanges between the cell and the access drift. At this stage, the cell access drifts are ventilated and the sealed cell heads are thus accessible. The monitoring of certain structures continues. During this stage, it is technically possible to retrieve the packages. It requires preparatory work consisting of removing the clay plug and restoring the head of the cell.

- **“Post module-closing” stage**

The “Post module-closing” stage starts once all the components of a module have been sealed and back-filled. In the case of type B cells, this stage is no different from the previous stage since a module consists of only one cell. However, in the case of type C waste or spent fuel modules, the closing of the module includes back-filling of its connecting access drifts. The module’s connecting drifts remain ventilated and accessible.

At this stage, it is also technically possible to retrieve the packages. The preparatory work for this operation is longer than that in the previous case. It consists of removing the back-filling from the drifts using excavation techniques similar to those used during construction the, as during the previous stage, renewing the tops of the cells.

The following stages concern the entire repository and no longer just individual modules.

- **“Post repository zone-closing” stage**

The “Post repository zone-closing” stage starts when the repository zone’s internal connecting drifts are back-filled and sealed. At this stage, the main connecting drifts giving access to the repository zone in question remain ventilated and accessible. The transition to this stage has little phenomenological impact on the evolution of the repository modules and only increases the lengths of the drifts to be re-excavated in order to gain access to the packages in the event of their retrieval.

- **“Post-closure” stage**

The "post-closure" stage starts after sealing and back-filling the shafts. It corresponds to the end of the disposal process. The repository is then in the “Post-closing” configuration. However, it is possible to envisage an monitoring period for the repository and its environment. Although more complex, it remains technically possible to retrieve the packages in this configuration [20], [16].

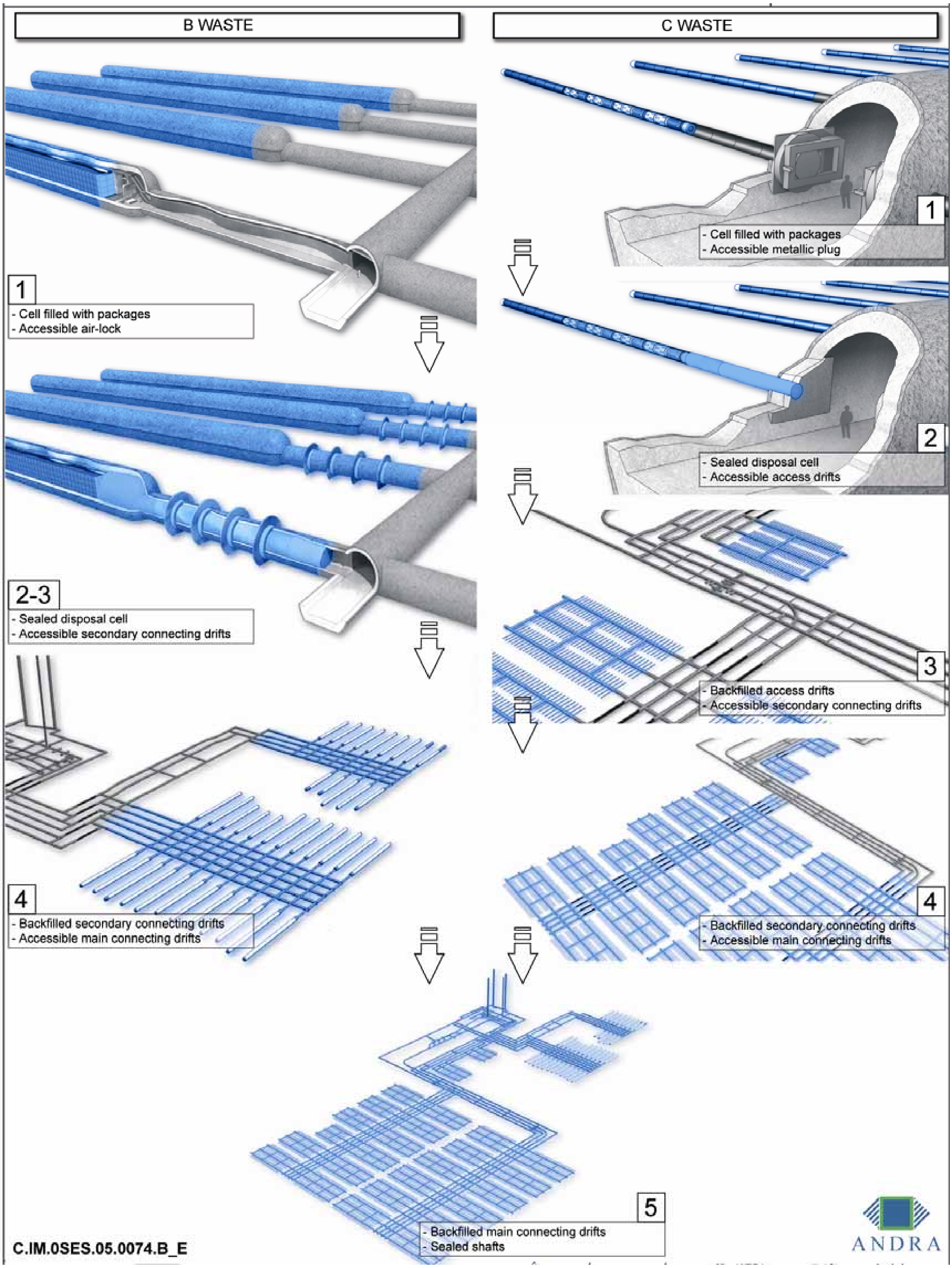

Figure 10.1.1 Key repository operating and closing stages

10.2 Mastery of the repository behaviour and ability take action [82]

This section describes the changes to the condition of the structures and packages that gradually occur as the disposal process proceeds. For each key stage defined above, it underlines the principal phenomena and explains to what extent they are liable to affect the ability to take actions affecting the process and any operation that may be undertaken to retrieve the packages [83]. In each case, it details the time constants particular to each stage, given that they correspond to changes that occur without any modifications to or major operations being carried out in the repository management process. It also underlines the potential effect, in the longer term, of changes to the repository with respect to safety functions.

10.2.1 Behaviour of type B waste disposal cells

For type B waste cells, only two stages have a significant impact on their behaviour during operation of the repository. They are the "Post package-placement" stage, during which the cell is ventilated, and the "Post cell-sealing" stage (which is the same as the "Post module-sealing" stage) during which the cell is no longer ventilated. The subsequent "Post repository zone-closing" and "Post-closing" stages have no notable impact on the physical or chemical evolution of type B waste cells.

10.2.1.1 "Post package placement" stage

During this stage, the tops of the cells filled with packages are accessible under the same conditions as at the time the packages are placed in position (see Figure 10.2.1). The disposal chamber ventilation is maintained and the heads of the cells are still fitted with their radiological protection airlocks and associated mechanical devices used to place the packages in position. The access drifts are ventilated, maintained and accessible. Part of the structures, notably the cells, are monitored using various devices described in paragraph 10.3.7.

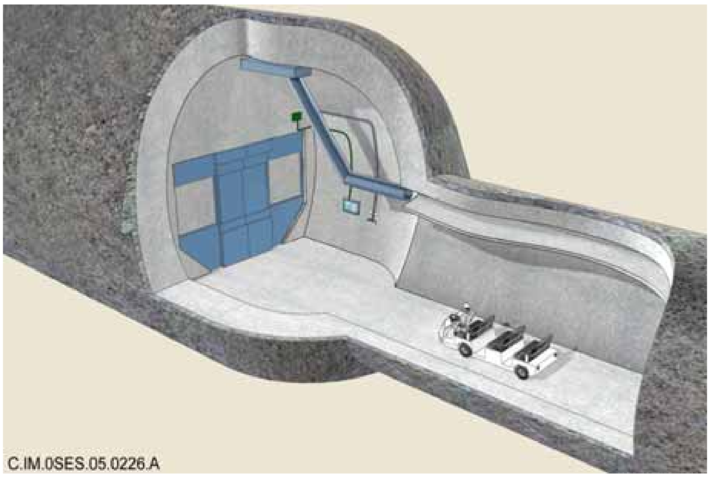

Figure 10.2.1 Accessibility of B cell heads

- **Evolution of the cell**

The chemical alteration of the concrete liner is very slow, due notably to the low relative humidity of the ventilation air (estimated at 50%).

The liner is gradually loaded by the thrust of the rock. However, the de-saturated state of the rock on the wall tends to reduce the speed of these delayed deformations and slow the increase in thrust on the lining. The thickness of the liner used enables it to resist the thrust of the rock without any loss in rigidity for at least a century and it has been shown in Chapter 5.1 that it can provide the cell with geotechnical stability for at least two or three hundred years and probably longer. Thus, the handling clearances left free around the disposal packages do not change significantly during this timescale.

As for the liner concrete, the low relative humidity of the air in the cell has little impact on the concrete forming the disposal packages, which is initially highly de-saturated, and the physico-chemical evolution of the concrete of the packages (atmospheric carbonation, reinforcement corrosion) is extremely slow [48]. The slowness of the alteration of the disposal packages and their mechanical strength keeps them intact for at least a century without any intervention. The slow corrosion rate of the metals also concerns the waste primary containers placed inside the disposal packages.

The radioactive elements can thus be confined within the packages on a long-term basis (except for gaseous radioactive nuclides as mentioned above).

Additionally, from a phenomenological point of view, the insertion of certain packages induces the production of gas or heat.

Packages containing bituminous coated materials (type B2 packages) and radioactive packages containing organic materials (type B5.1 packages for example) emit gases by radiolysis of the constituent materials, principally hydrogen, but also carbon dioxide or methane. The quantities of gas emitted outside the disposal packages are of the order of several litres to several tens of litres of gas per package per year. In addition, certain packages (type B5.1 packages for example) may also emit traces of radioactive gases in very small quantities [62]. The architecture described in Chapter 5 shows that it is possible to place the packages emitting gases within dedicated cells. The small quantities of gas (radioactive or otherwise) are evacuated by ventilation. They are sufficiently small for it to be possible to stop the ventilation for a few weeks if necessary.

Only certain packages give off heat, principally type B5.1, B5.2 and B1 packages. The amounts are modest compared with those given off by type C waste but cannot be ignored. However, the ventilation inside cells allows approximately 80 to 90% of the heat given off to be evacuated, even with a relatively small air flow of 3 m^3/s. The impact of this heat emission on the cell is thus limited: the air at the end of the cell, having passed through the entire cell, thus has a maximum temperature of slightly under 40°C and the maximum disposal package temperature remains under 40 °C [10].

It should be noted that maintaining the cell in this state and, in particular, ventilating for several decades or centuries does not noticeably increase the disturbances induced by excavation. In fact, even if the de-saturation front can reach the un-fissured rock, the latter de-saturates very little and the extent of the micro-fissured rock zone does not vary [8], [57]. In addition, the oxidation of the pyrites and organic material present in the rock, by the oxygen in the air, and the associated chemical disturbances are small and remain limited to the fractured rock zone that may be created by excavation [84]. Thus the chemical and hydro-mechanical disturbances induced by maintaining the ventilation remain limited to the excavation damaged zone (EDZ), whose extent does not increase as long as the lining remains intact[134].

- **Possibilities available for taking action and possible duration of the stage**

The package disposal conditions at this stage are similar to those during pre-disposal storage. The deformations of the lining are sufficiently small that they do not modify the geometry of the disposal chamber. It would therefore be possible to retrieve the packages, simply by reversing the placement process (see §10.4). The ventilation evacuates any radiolysis gases and heat given off by the packages. Maintaining the ventilation in the cells requires only a small additional air flow at the entrance to the repository zone. It should be noted that the conditions in the repository are less sensitive to seasonal variations than in a surface installation. In fact at the entrance to the cells, the air temperature is always at the temperature of the rock at the disposal position (22°C) and the relative humidity varies around 50% (30 to 80% of the relative humidity variation amplitude) [8].

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[134] More precisely, the delayed deformation of the argilites tends to close and recompress the fissures in the rock in the presence of a rigid coating [66].

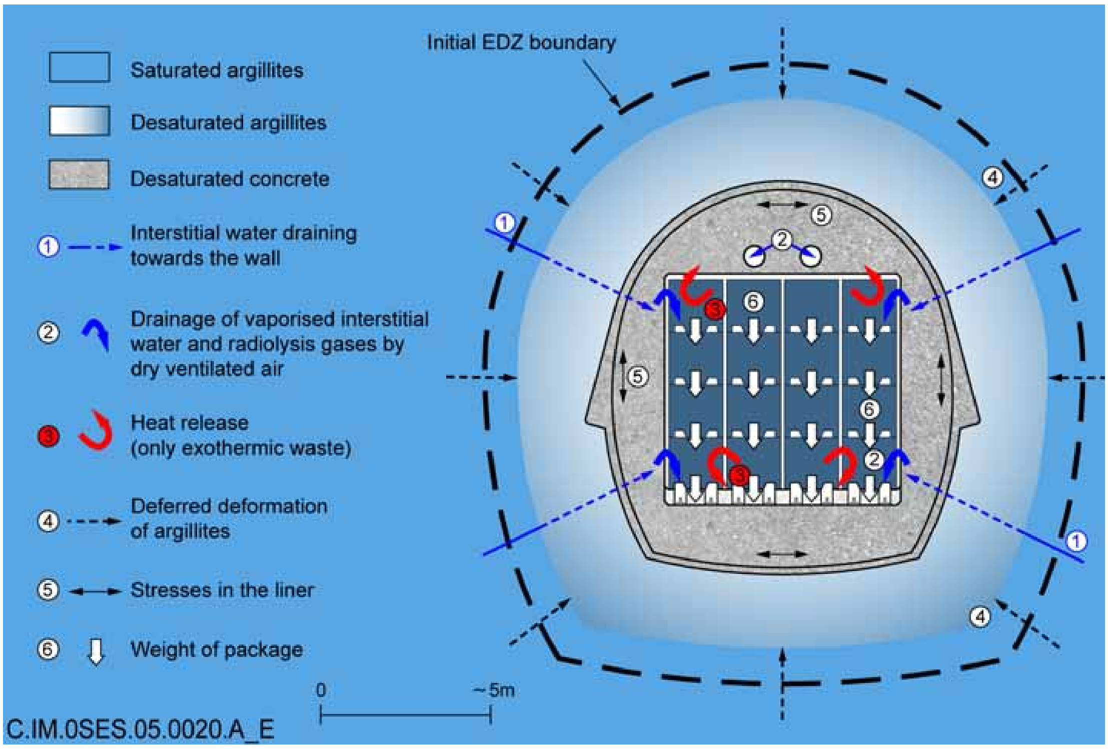

Figure 10.2.2 Diagrammatic representation of the principal phenomena with a type B waste disposal cell after inserting the disposal packages

Technically this stage may last for several centuries, which represents the time during which the liner remains intact.

Monitoring of the increase in the stresses in the liner using the observation devices fitted during construction (see § 10.3.) is a means of regularly reassessing and more accurately predicting the lifetime. If it were required to prolong this stage over longer timescales, human intervention would be necessary, particularly in order to retrieve the packages and adapt the installations.

10.2.1.2 "Post cell sealing" stage

Closing the cell consists of stopping the ventilation and sealing the cell's access drift. Stopping the ventilation has an impact on the cell's evolution; whereas sealing the drift essentially only concerns the evolution of the access drift and the seal itself.

This closing action is an important stage in the disposal process, as it reduces the accessibility of the waste packages (see Figure 10.2.3) and makes it more difficult to continue to monitor the cell. However, technical solutions exist to continue monitoring the cell's evolution (see section 10.3).

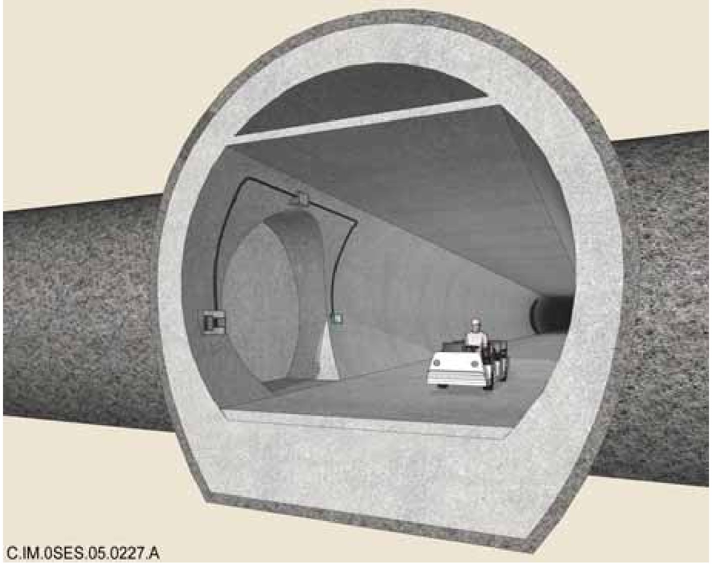

Figure 10.2.3 Accessibility to the entrance of sealed access drifts

Furthermore, equipment and liner maintenance operations in the accessible connecting drifts can be carried out depending on the regular visual inspections and results of the dedicated monitoring of these structures.

In addition, in the event that the packages are retrieveed, it is technically possible to dismantle the seal and restore the access drift, as indicated in Section 10.4.

- **Evolution of the cell**

Stopping the ventilation fairly quickly induces a change in the physical conditions within the cells: consumption of the oxygen in the air and, for certain cells, heating of the packages and cell or accumulation of radiolysis gases. In addition, it stops the de-saturation kinetics in the rock and thus triggers the cell and seal re-saturation process.

This re-saturation process represents an important phase in the evolution of the cell, even if this evolution is very slow due to the very low permeability of argilite. The rock and liner re-saturation process is accompanied by an increase in the relative humidity of the air in the cell, which is thus always in equilibrium with the moisture conditions of the cell wall concrete. The increase in the relative humidity contributes simultaneously to the increase by capillary action of the degree of saturation of the concrete in the disposal packages. However, due to the slow re-saturation of the cells[135][8], over a period of several centuries, there will be no liquid water in the spaces between the packages and liner concrete. The concrete of the disposal packages remains unsaturated.

In the cells containing slightly exothermic packages (essentially type B1 and B5 packages) the heat is no longer evacuated by ventilation. The temperature of the packages, then of the liner and the rock increases. The maximum temperature of the packages remains below 60 °C [10]. It is reached a little under ten years after the ventilation is stopped. The temperature of the packages then slowly decreases, initially by approximately 1°C per decade, then more and more slowly. The temperature in a cell containing non-exothermic waste always remains below 30°C. Monitoring of the temperature makes it possible to check that the temperatures reached fully meet the laid down criteria (see chapter 5) and to establish its condition at the time of a potential waste package retrieval.

In cells in which packages emit gases through radiolysis, closing the cell and, in particular, stopping the ventilation, lead to the trapping and gradual accumulation of these gases. In view of the very slow decrease in their production [62], the duration of the ventilation before sealing only slightly modifies the gas accumulation kinetics in the cell. When they accumulate in a cell, these gases become slightly pressurised. As long as the connecting drift is open and ventilated, the gas pressure difference between the two ends of the access drift to the cell promotes the transfer of these gases through the unsaturated cell. These small quantities of gas can be diluted in the ventilation air in the connecting drifts or, if necessary, collected. In addition, this accumulation of gas contributes to the slowing down of the already very slow process of cell re-saturation.

The absence of water from the cell for several centuries considerably limits the chemical degradation of the liner, of both disposal packages and primary packages (by carbonation, hydrolysis, oxidation and corrosion). Changes to the cell therefore result above all from the very slow and gradual increase of the thrust of the argilites on the liner during their re-saturation. This thrust, which is very small or even stopped so long as the rock was de-saturated, nevertheless remains sufficiently moderate for the liner and filling concrete to remain intact for several centuries (see chapter 5) [57]. The durability of the lining and the maintaining of the functional clearances between the packages and the wall do not therefore deteriorate after closing the cell. Similarly, as long as the lining remains intact, the functional clearances between the packages should not have changed very much or at all.

Under these conditions, the disposal packages remain intact, as they have no loading applied to them other than the weight of subjacent packages. The absence of any notable damage to the disposal packages and primary packages thus prevents any dissemination of radioactive materials within the cell.

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[135] It is estimated that the cell will take thousands if not tens of thousands of years to be re-saturated

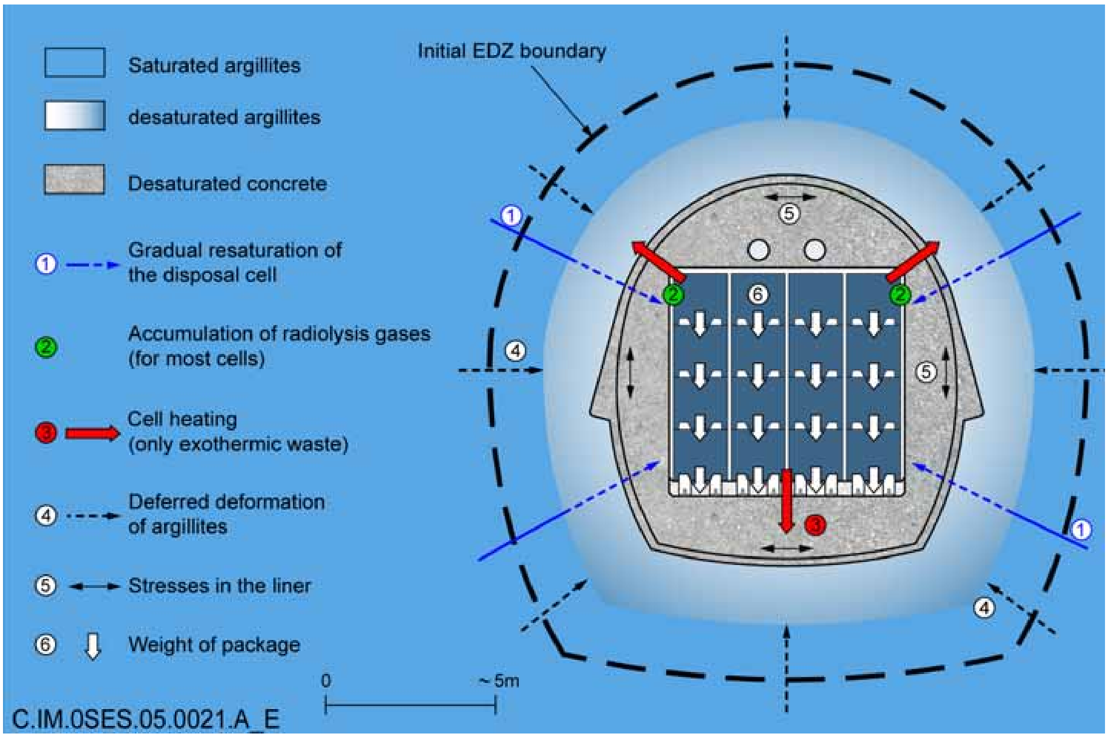

Figure 10.2.4 *Diagrammatic representation of the principal phenomena within a type B waste disposal cell after closing.*

- **Evolution of the access drift and seal**

In the access drift, stopping the ventilation, as in the cell, causes very slow re-saturation of the rock. Over several centuries, the wall rock and liner concrete are again significantly de-saturated, as is the sealing clay [8], [66]. The swelling of the sealing clay caused by re-saturation thus remains very limited, or even non-existent, during the operation of the repository.

In the access drifts to cells containing only slightly exothermic waste, sealing considerably slows down heat propagation; the temperature at the downstream end of the seal in the accessible zone increases by only a few degrees. Furthermore, as with the cell liner concrete, the concrete either side of the clay seal remain intact for several centuries or much longer.

The small change to the seal over a period of several centuries [85] facilitates its eventual dismantling in the event of reversing the disposal process in order to retrieve the packages or simply to return to operating conditions close to those of a storage facility.

- **Possibilities available for taking action and possible duration of the stage**

At this stage, it remains technically possible to retrieve the packages using means similar to those used when inserting the packages, thanks to having maintained the functional clearances in the cell, as long as the latter is mechanically stable, i.e. for several centuries after its construction. It would however require preparatory work whose technical content, as described in section 10.4, could be adapted according to the condition of the cell, established by analysing the results of observation.

The observation of the liner and the terrain thrust on the liner, associated with temperature measurements within the cell, can be carried out for as long as possible in order to establish sound knowledge of the effective condition of the cell.

Monitoring of the quantities of gas actually emitted in the cell and evacuated by ventilation during the previous stage, make it possible to detail the precise gas production kinetics and, thus, more accurately predict the quantities of gas trapped in the cell after closing.

The condition of the access drifts and shafts can be maintained over very long periods (several centuries or more) by the durability of their liners and the ability to conduct maintenance. This has little impact on the evolution of the cells.

10.2.2 The behaviour of type C waste (or spent fuel) disposal cells

There are three main stages in the evolution of type C waste or spent fuel disposal cells during repository operation: “Post package-placement”, “Post cell-sealing” and “Post module back-filling”. In fact the latter stage has very little impact on the evolution of the cells but is important to mention as it notably reduces cell accessibility and, thus, disposal package accessibility.

10.2.2.1 “Post package placement” stage

The heads of cells are accessible under the same conditions as at the time of placing the packages in the disposal cells. As in the case of type B waste seen previously, the access drifts are ventilated, maintained and accessible (cf. Figure 10.2.5). Part of the structures, notably the cells, are monitoring using physical measurements, supplemented by visual checks.

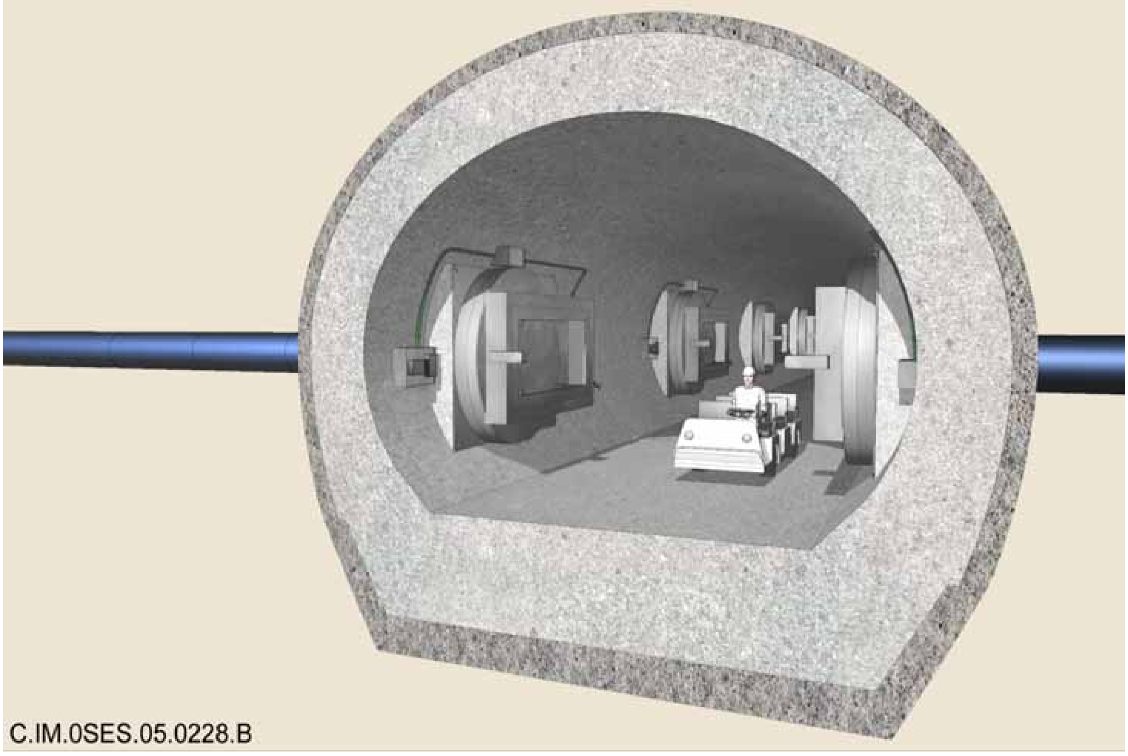

Figure 10.2.5 Accessibility of the heads of type C cells

- **Evolution of the cell**

The evolution of the cell, not only during this stage but also during subsequent stages, is essentially linked to heat generation caused by the waste [13], [10].

Due to the high thermal conductivity of the metal components, the temperature very quickly reaches the same level within the sleeve over the entire length of the cell. It increases almost simultaneously within the rock: after a year in disposal, the temperature of the rock wall reaches almost 40°C for type C0 packages and over 50°C[136] for type C1 to C4 packages. Thermal interaction between adjacent cells is already marked by a 5°C increase at the mid-distance between type C waste cells. In spent fuel disposal cells, the heat transfer is slowed down by the swelling clay as it has a lower thermal conductivity than that of argilites. Thus the heating of the wall rock is slowed and reduced by the clay ring that maintains a temperature difference of around 30°C between its internal and external faces during the temperature rise.

The maximum temperature on the surface of the packages, of between 90°C and 100°C, is due to the dimensioning of the architecture of each repository zone for a given package age (see § 5.2 and 5.3). This maximum temperature is reached after 10 to 20 years for all type C or spent fuel waste packages. At the same time, the argilites or swelling clay in contact with the sleeve reach a temperature of between 80°C and 90°C.

This temperature rise within the cells would not be significantly changed by sealing them immediately after they have been filled. Given that the temperature rise is relatively rapid (from 10 to 20 years), maintaining the cell unsealed during this transitional evolutionary phase could be considered in order to allow the fullest possible monitoring to be carried out without placing major constraints on the transmission of measurement data (see 10.3.8.3). Furthermore, a sound knowledge of the temperature of the packages and the cell is needed in order to check that the cell behaves as expected and, in particular, in order to establish the actual conditions inside the cell in case it is decided to retrieve the packages.

Propagation of heat from the cells leads to heating in the access drifts within the module. The temperature of the wall rock remains below 60°C in the vicinity of the cells. Ventilation is maintained constantly in the drifts with reduced flow. In the event of intervention by personnel, this flow can be increased in order to keep the air temperature at a value below regulation limits. The thermo-mechanical effects on the sleeve induced by this heating are taken into consideration when dimensioning and do not reduce the durability of the structures (see sections 5.2, 5.3 and [13]).

One of the principal effects induced by the heating of the cell is the expansion of the packages, the sleeve, the swelling clay for spent fuel disposal cells and of the rock. Thanks to the functional clearances between the packages on the one hand and between the packages and the sleeve on the other[137], the thermal expansion of the packages, spacers and sleeve do not create notable thermo-mechanical stresses within the packages[138] and the deformations induced are sufficiently small so as not to block the packages or the spacers, at the same time as they reach their maximum amplitude. It is therefore possible to retrieve packages at any time, whatever the amplitude of the expansion deformation, in the cell.

The heating of the rock also accelerates the delayed deformation of the argilites (by a factor of 2 to 3). For type C waste cells, this acceleration encourages the closing of the functional clearance for fitting the sleeve and accentuates the terrain pressure on the sleeve after closing of this functional clearance. However, the dimensioning of the sleeve makes it possible, as soon as the functional clearance has closed, to ensure the durability of the sleeve and the maintenance of the geometry within the sleeve for at least two or three hundred years, and probably longer.

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[136] The temperatures and durations indicated in this section correspond to the reference dimensioning used for the studies (see chapters 5 and 6)

[137] The low level of corrosion during the heating phase does not significantly change the width of these clearances.

[138] Constructive provisions having been taken in order to limit these stresses locally in the area in which the package touches the sleeve, for example by placing friction pads between the packages and the sleeve.

The sleeve's durability is improved by the environmental conditions, which considerably limit corrosion of the sleeve [53]. Corrosion is limited firstly by the absence of oxygen renewal inside the cell thanks to the fitting of a shielded trap door at the time the cell is constructed. After the packages have been inserted in the cell, the shielded trap door can, if required, be replaced by a leaktight cover throughout the remainder of the stage. This oxidising then anoxic corrosion is also greatly limited by the very small quantities of water vapour trapped inside the sleeve. Corrosion therefore has no significant affect on the durability of the sleeve.

The external face of the sleeve, in contact with a rock which always remains saturated, only corrodes under anoxic conditions, i.e. very slowly (a few microns per year), except at the head of the cell in the area of rock de-saturated by the access drift ventilation. In this area, oxidising corrosion (a few tens of microns per year) can occur but it is significantly slowed by the transfer of oxygen in the low porosity of the rock and concrete [53].

In the case of spent fuel disposal cells, the temperature of the swelling clay buffer, which is higher at the intrados than at the extrados, initially causes a low level of migration of the interstitial water that it contains towards the outside. After this transitional phase of around ten years, the re-saturation of the swelling clay can continue until reaching a state of near saturation after approximately 70 years[8]. The swelling of the clay which accompanies this re-saturation process leads to the gradual re-closing of the clearances either side of the clay ring. As for type C waste, the sleeve resists a gradual loading.

- **Possibilities available for taking action and possible duration of the stage**

The design of the sleeve and the limiting of the corrosion in the cell, thanks to it being blanked off by the shielded trap door or a leaktight cover, offer great flexibility in managing disposed packages.

Thus the sleeve remains intact for at least two or three centuries and probably much longer, without any maintenance being carried out inside the cell and with the possibility of carrying out maintenance at the head of the cell, where the corrosion is slightly more marked[139].

As for type B waste disposal cells, it is possible to retrieve the packages using means comparable with those used to place them in the cell, as long as the sleeve remains intact. The cell's stability can be assessed accurately thanks to the observation of the terrain thrust on the sleeve, or the swelling of the clay in the case of spent fuel disposal cells, associated with the measurement of the sleeve deformation and the temperature in the core and at the head of the cell. The possible maintenance of the access drifts and connecting structures when combined with their observation ensures accessibility of the cells over a period of several centuries.

The gradual loading of the temporary sleeve at the top of the cell could have an impact on the technically possible duration of this stage before fitting the cell plug. In fact when sealing the cell, according to the current design, it is intended to extract this section of temporary sleeve in order to ensure that there is direct contact between the argilites and the swelling clay of the plug. Mechanical tightening could make the section more difficult to extract. As current knowledge stands, this phenomena, which could be monitored, should not have any impact for a hundred years or more given the minimum thickness of the technically feasible clearances (of around 10 mm) (see chapter 5.2).

If it were required to prolong this stage, specific actions would be necessary, notably the retrieval of the packages in order to work on the cells.

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[139] Only in the area of de-saturated rock in the vicinity of the ventilated access drift.

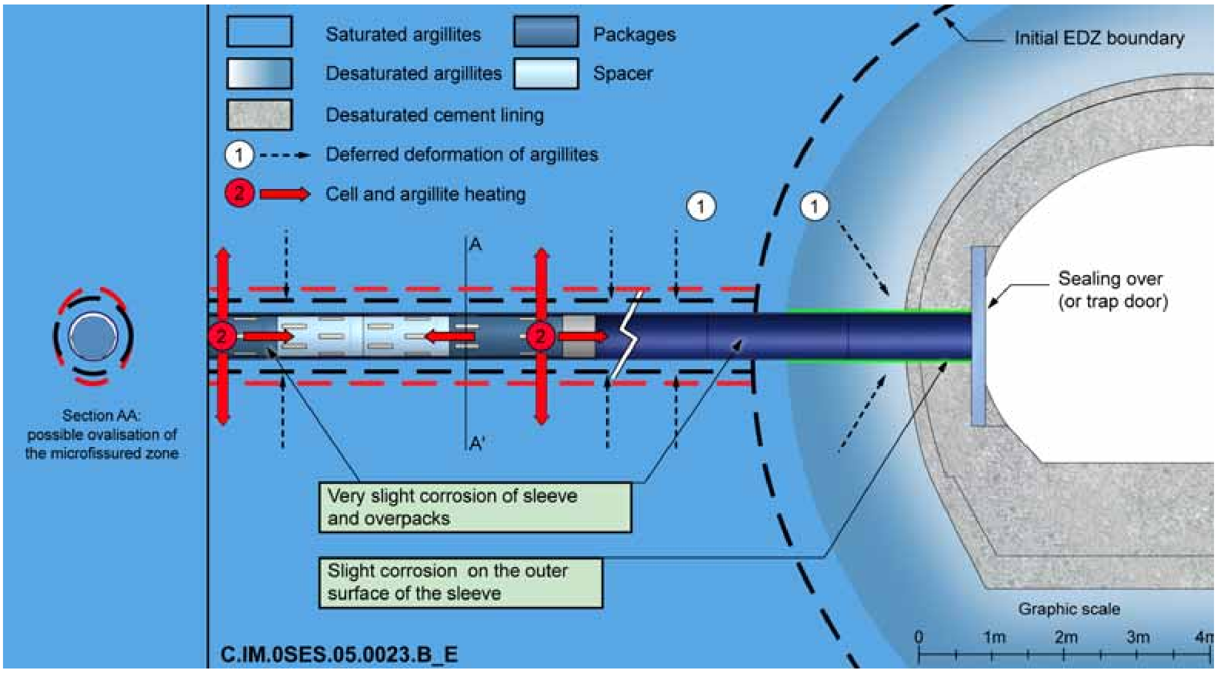

Figure 10.2.6 *Schematic representation of the principal phenomena within a type C waste disposal cell after package placement*

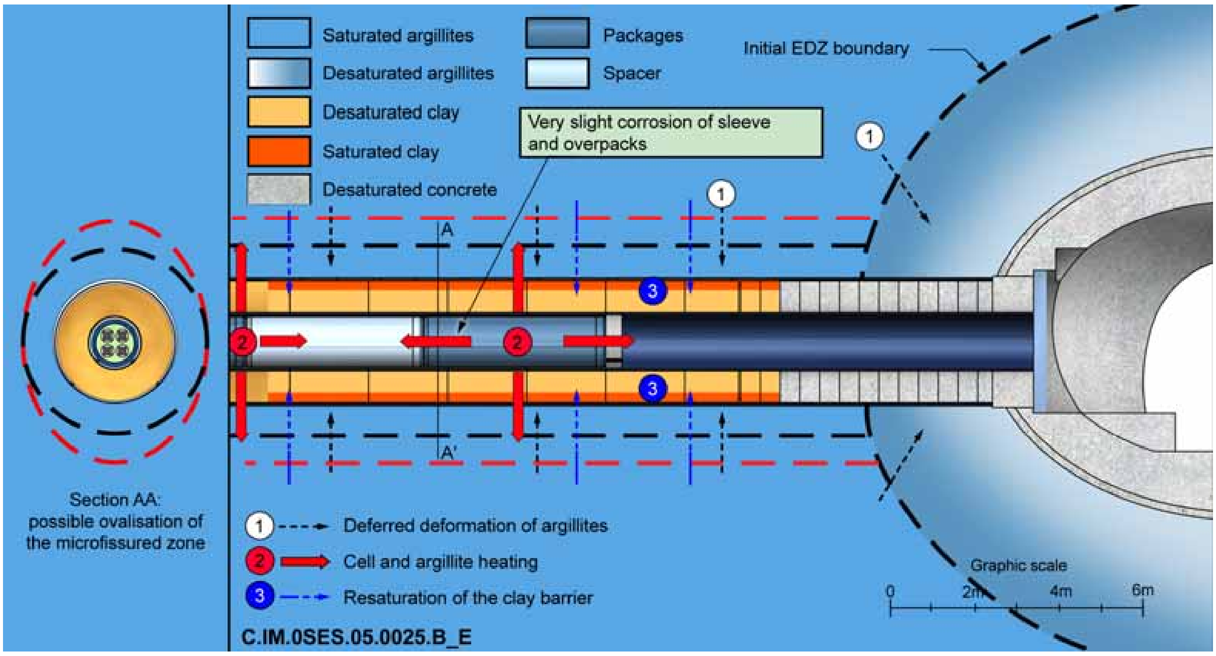

Figure 10.2.7 *Schematic representation of the principal phenomena within a spent fuel disposal cell after package placement.*

10.2.2.2 “Post cell-sealing” stage

Closing the cell consists of extracting the temporary sleeve and fitting a clay plug confined by a concrete plug. The ventilation in the access drifts is maintained and the sealed cell ends are still accessible under the same conditions as in the previous stage (see section 10.2.2.1).

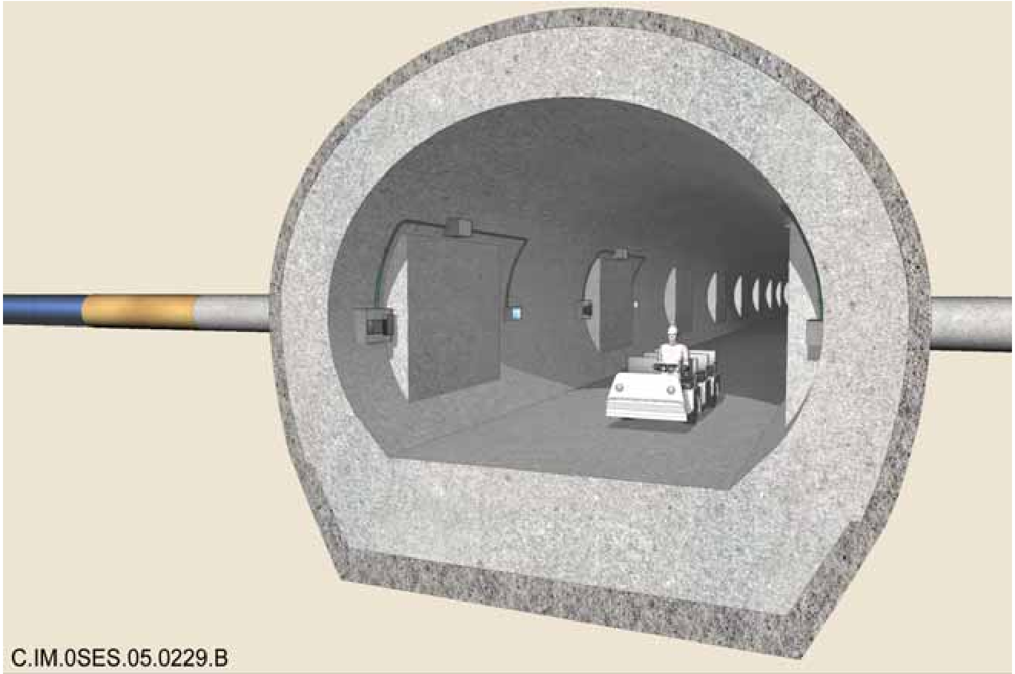

Figure 10.2.8 Accessibility of type C cell ends after fitting the seal

As in the case of type B cells, fitting the seal makes cell monitoring more difficult. However, techniques exist (notably wireless transmission technology) making it possible to continue to monitor their evolution (see section 10.3). The access and connecting drifts are monitored and, if necessary, are the subject of maintenance (see §10.3.). Moreover, it remains technically possible to dismantle the seal and retrieve the packages. (see §10.4.).

- **Evolution of the cell**

The fitting of a cell’s seal requires the cell to be left open throughout the operations (a few days). However, the quantity of oxygen provided by the partial or total renewal of the air in the cell is sufficiently small not to induce notable corrosion inside the sleeve.

As far as air renewal is concerned, after the cell has been sealed, the plug plays the same role as the operational shielded trap door or leaktight cover. The core of the cell and the packages it contains thus continue to evolve to the next stage, without significant variations due to the presence of the clay plug. The durability of the sleeve and the corrosion-limiting conditions inside the cell continue to provide flexibility in the management of the packages in the cell. Furthermore, the thickness of the over-packs ensures that the radioactive nuclides are confined for at least four thousand years in the case of type C waste and for over ten thousand years in the case of spent fuel (see chapter 4).

At the top of the cell, extracting the temporary sleeve allows the argilites to deform and gradually close the clearances left at the time of fitting the cell seal. Then, as soon as the seal has been fitted, it is subjected to heating by the waste: its internal face quickly comes into thermal equilibrium with the nearest package, whilst the external face is in thermal equilibrium with the rock of the access drift wall, which is ventilated [10], [13].

The swelling clay plug and concrete retaining plug, which close the cell, cause a slight, transient de-saturation of the wall rock and are then very slowly resatured, over several decades, from the periphery to the core of the clay plug [8]. For spent fuel disposal cells the clay plug, which is placed inside the partially saturated swelling clay rings, re-saturates even more slowly than in type C waste cells, where it is placed in direct contact with the saturated rock. As the clay gradually re-saturates, it swells and fills the residual spaces, then exerts mechanical pressure on the surrounding materials (rock, metal plug and concrete retaining plug) with which it comes into mechanical equilibrium.

As long as the access drift is ventilated, the concrete retaining plug at the entrance to the cell (type C waste or spent fuel) remains de-saturated throughout the thickness of rock already de-saturated on the drift wall, without having any significant impact on the clay plug re-saturation kinetics or the temperature in the cells.

As during the previous stage, inside the cell the evolution of the sleeve and packages is very slow. The sleeve remains intact and the functional clearances remain in place.

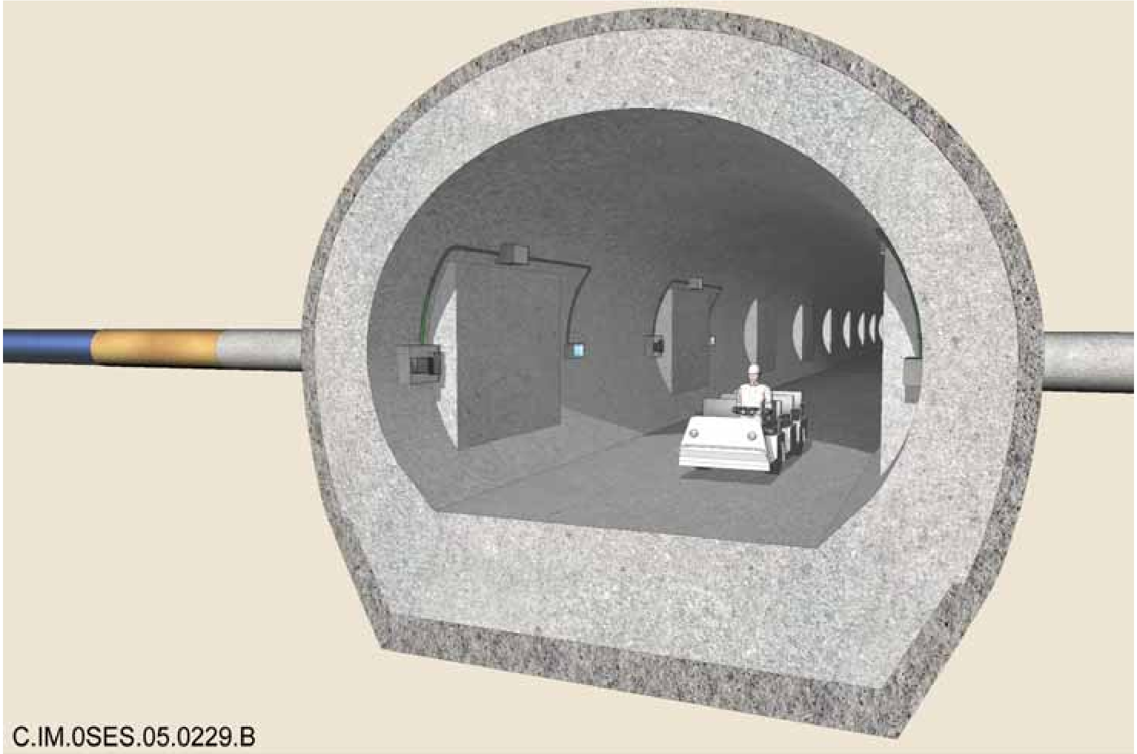

Figure 10.2.9 Schematic representation of the principal phenomena within type C waste disposal cells after sealing

- **Possibilities available for taking action and possible duration of the stage**

At this stage, the packages can still be extracted relatively easily as long as the sleeve has remained geometrically intact (with no significant deformation); i.e. at least 200 to 300 years after it has been put in place. Continued monitoring of the thrust exerted by the terrain on the sleeve and, as far as possible, of the deformation of the sleeves of a few reference cells, makes it possible to reassess the sleeve's lifetime, whether or not these cells have been closed.

However, the level of reversibility has reduced at this stage because the sealing of the cells makes the retrieval operations more complex. Retrieving the packages requires the head of the cell to be re-equipped. The technical feasibility of this process is described in section 10.4. The volume to be cleared in order to remove the clay plug and its concrete retaining plug is only a few cubic metres of material per cell.

As far as long-term safety is concerned, maintaining the ventilation in the access drifts has little notable impact on the evolution of the cells and their plug, nor on the undisturbed argilite thickness above and below the repository. The technically possible duration of maintaining the cell at this stage, before back-filling the access drifts, then depends on the durability of the liner of the drifts and the ability to maintain them, which is expected to be several centuries (see section 10.2.3).

Finally, given the large number of cells in each repository module, not all the cells within a single module are necessarily closed at the same time; thus, closing of the first cells helps to increase the industrial experience feedback data base concerning fitting seals.

10.2.2.3 "Post module-closing" stage

Closing a module consists of back-filling the cell access drifts. The ventilation in connecting drifts is maintained.

- **Evolution of cells and access drifts**

The closing of a module's drifts has no notable impact on the behaviour of the cells. This stage is principally characterised by an evolution of the back-filled drifts and concrete retaining plugs at the heads of cells, due to stopping the ventilation and putting the filling materials in place.

This evolution is reflected firstly in the heating of the back-fill material in contact with the liner and by the gradual homogenisation of the temperature in the repository module. After a few centuries, the temperature reaches approximately 50°C for highly exothermic type C waste [10].

The drift takes a long time to re-saturate. A transitional phase of a few decades, which slows down the re-saturation process by the same amount, is needed in order to bring the back-fill to a state of hydric equilibrium with the liner and the wall rock. Although the heating accelerates the flows of interstitial water, the re-saturation of the back-fill requires at least several tens of thousands of years [8].

The liner of the back-filled drifts, which can no longer be maintained, deteriorates very slowly, due to the small quantities of water coming from the rock. Thus, during the century following back-filling, the drift back-fill and liner change very little.

- **Possibilities available for taking action and possible duration of the stage**

This stage is more characterised by the reduction in the accessibility of packages due to the back-filling of the drifts than by phenomenological changes to the modules. It is still possible to retrieve the packages with relative ease as long as the cell sleeve remains intact (at least 200 to 300 years after placement). The level of reversibility has been reduced by the extent of the work to be carried out to gain access to the packages: the volume to be cleared is approximately one hundred times greater than during the previous stage.

Over periods longer than the lifetime of the sleeve, the packages can still be retrieveed using special means (given that disposal containers have a lifetime of several thousand years).

Observation of the evolution of the back-filled drifts concentrates principally on the saturation state of the back-fill and seals, any deformation or swelling of them, the stresses within the linings and the terrain thrust. This information makes it possible, before any package retrieval decision is taken, to establish the conditions under which the back-fill will be cleared and, thus, the resources actually required to restore the drifts.

The technically possible duration of this stage depends on the durability and maintainability of the connecting drifts and shafts (several centuries).

10.2.3 Behaviour of access structures during the “Post repository zone-closing” phase

The closing of secondary connecting drifts (inside the repository zones) reduces the level of reversibility. In fact, access to packages becomes more and more difficult, even if technical solutions exist for clearing the back-fill from the drifts (see section 10.4). In type B waste repository zones, clearing the back-fill from secondary connecting drifts only slightly reduces accessibility since the volume to be cleared is around 20,000 to 30,000 m^3. However, closing type C waste (or spent fuel) repository zones considerably reduces the accessibility of the packages. The volume to be cleared to gain access to the cells increases by a factor of 3 to 5 when compared to the previous stage.

The evolution of the cells and repository modules is influenced very little by closing a repository zone. The evolution of back-filled and sealed connecting drifts in these zones is very slow, as previously described for access drifts to type C waste (or spent fuel) cells, or even slower as they are subjected to less heating. The seals placed in drifts behave like type B waste cell seals. They are not re-saturated, even around the periphery, for over a thousand years. Any re-saturation of the rock in contact with these seals and clay grooves is also very slow and all the more slow (one to several thousand years) if the ventilation has been maintained over a long period [8]. This slow re-saturation also limits the chemical breakdown of the lining, particularly by corrosion or hydrolysis. The absence of any notable change to the structures after having been closed for several decades, or even centuries, thus facilitates any reversal to dismantle a seal or retrieve packages.

The main connecting drifts still accessible can be left as they are for an unlimited period, thanks to the design of their liner, maintaining the ventilation and, in particular, thanks to being able to maintain these installations. This maintenance does not significantly increase the disturbances induced in the rock at the location of the future seals. In fact, the area of micro-fissured or potentially fractured rock near the disposal cell wall due to excavation does not extend. On the contrary, the fissures tend to be compressed by delayed deformation of the argilites blocked by the liner [66]. The rock is de-saturated notably by the dry ventilated air in the micro-fissured or fractured areas. Maintaining the ventilation for a century or more only induces a very low level of de-saturation beyond that in the non-fissured rock (saturation rate over 95%), without any impact on the state of the rock, but contributies to slowing the later re-saturation (Figure 10.2.10).

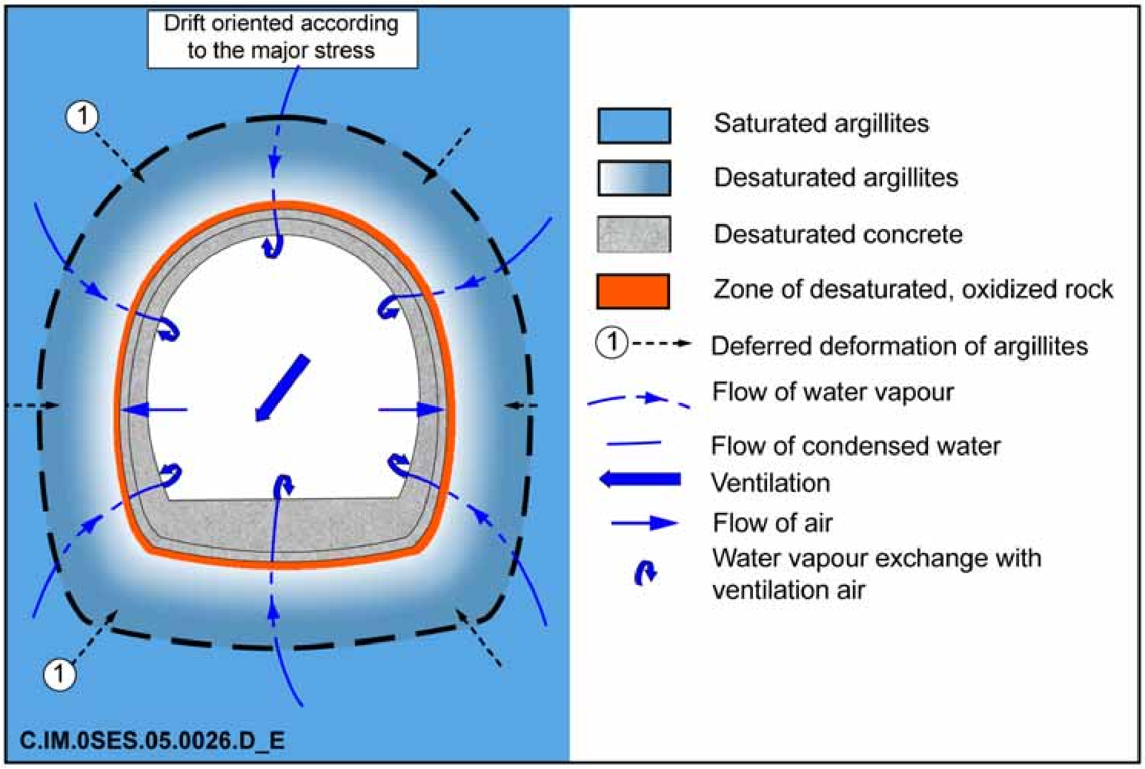

Figure 10.2.10 *Diagrammatic representation of the principal phenomena around a connecting drift, depending on its orientation over a century*

As for access drifts to disposal cells, maintaining the ventilation in the shafts does not increase the extent of the micro-fissured zone which appears on the wall during their construction, nor the area of significantly de-saturated argilites (under 90% saturation) by several decades of ventilation. This aspect is particularly important at the location of the future shaft seals.

The liner of shafts, designed like the other repository structures to remain stable for at least a century [86], and maintenance associated with their monitoring, makes it possible to maintain the stability of the shafts throughout the period in which they are open, even if they are open for several centuries.

In order to do this, the observation of connecting drifts and shafts concentrates on monitoring the evolution of the delayed deformation of the wall clays, the extension of the de-saturated zone and the stresses within the liner.

The shafts drain the surrounding rock from the time they are constructed. The impact of this draining is marked, above all, in the Oxfordian limestones where it rapidly extends, over a few years, to the entire shaft area, and eventually extends on a kilometre scale after a century. This depression in the Oxfordian limestone can cause a slight drop in interstitial pressure (around a metre) in the clays after one or several centuries, without modifying the properties of the argilites. Maintaining the ventilation in the shafts over several centuries does not notably accentuate the induced hydraulic disturbances for several decades, or even a century.

10.2.4 Conclusion concerning the minimum duration of reversible management of the disposal process

Throughout the disposal process, the mechanical stability of disposal cells affects, to a greater or lesser extent, the difficulty of any package retrieval operations.

The design of the liner of type B waste cells and the sleeve of type C waste (or spent fuel) cells gives them mechanical stability for 200 to 300 years without special maintenance, and practically independently of going through the closing stages. Given the dimensioning margins, the cells should in fact be stable for an even longer period. Monitoring of these structures would enable their lifetime to be regularly re-assessed. In order to extend the period during which it would be possible to retrieve the packages, special work (for example additional maintenance) would be required, that may include temporary recovery of the packages disposed therein. The complexity of this work increases as each closing stage is completed, as gaining access to the cells then involves re-opening sealed sections.

As for the stability of the access structure liner (drifts and shafts), it can be increased by maintenance work as long as the structures are accessible. As for the cells, this is at least several centuries. The in-situ measurements made while they remain open and, where applicable, after they were closed, would enable this period to be more accurately predicted.

It is considered that the ultimate end of reversible management of the disposal process will be the mechanical failure of the cell lining. In fact, beyond this milestone, retrieving packages blocked by the geological formation would require the simultaneous use of mining and nuclear resources. Although technically possible (based on experience feedback from certain uranium-rich deposits), their use represents a low level of reversibility.

A period of two or three centuries therefore represents the minimum period during which reversible management by stages can be implemented without requiring technically complex operations. In concrete terms, that means that, whatever the level of repository closing, it would be possible to retrieve packages from a cell once access to the cell has been regained, using handling facilities similar to those used at the time of package placement. In order to extend this period, from a technical point of view, it would be necessary to adopt specific measures (increased maintenance, strengthening of the structure, reconstruction etc.).

10.3 Observation and surveillance

This section firstly describes the main motivations for observing and surveilling a repository, and gives a brief overview of thinking on the subject at international level. It underlines the contribution that observation makes to reversible management. It then identifies the main constraints specific to the repository. It also sets out the industrial experience feedback from the monitoring of major structures and available technologies. Finally, it proposes monitoring systems adapted to the disposal of radioactive waste, which will be enriched at a later date by knowledge acquired from the Meuse/Haute-Marne underground laboratory [87].

10.3.1 Why carry out observation and surveillance?

The main reason for conducting observation and surveillance is to provide tools for controlling the disposal process. In fact, monitoring the evolution of the structures and host rock will, in the long-term, improve our knowledge and strengthen confidence in the mastering of the process.

Under no circumstances is this monitoring aimed at replacing the preliminary knowledge acquisition stages, notably by conducting experiments in the underground laboratory. On the contrary, implementing monitoring inside the repository could benefit from the feedback of experience acquired in the underground laboratory. Nor can the existence of an observation and surveillance programme during repository operation be used to compensate for a lack of any data concerning the safety assessments that would precede any disposal authorisation.

10.3.1.1 Overview of the principal motivations

There are three main reasons for conducting observation and surveillance of the repository: (i) to assist in reversible repository management, (ii) to contribute to the mastering of operational and long-term safety (iii) to supply additional information through geological reconnaissance.

The term "observation" corresponds to the first objective (to assist in reversible management). The term "surveillance" corresponds to the second objective (contributing to the mastering of safety). It should be noted that the measurements made for suveillance are essentially the same as those that assist in the reversible management of the repository. The reason for this distinction is purely to do with the manner in which the measurements are used.

10.3.1.2 Assist in reversible repository management

Observing the repository makes it possible to monitor the principal phenomena associated with each successive stage of the disposal process, strengthen our understanding of the disposal process and thus contribute to its reversible management. It in fact enables the evolution of the structure and geological formation to be characterised during the operating phase, based on a known initial state. The information that it provides represents an important element in decision-making. As an example, observation informs the operator of the temperature reached in the cells, the state of corrosion of metal components or the level of stresses placed on the linings by the geological formation. These elements contribute to (i) the assessment of the relevance of moving on to the next stage, (ii) the assessment of the feasibility of retrieving the packages, (iii) preparing any changes to the design of the next structures to be built, particularly in terms of geotechnical dimensioning.

10.3.1.3 Contributing to operational and long-term safety

Repository surveillance is aimed at detecting changes that might affect operational safety or long-term functions. It makes it possible to increase knowledge of models and parameters involved in the assessment of long-term performance.

For operational safety, it aims to prevent the development of dangerous situations in order to provide personnel and environmental protection. As an example, it provides information about the ambient conditions in the structures (gas, dust, temperature), control of non-dissemination of radioactivity as well as mechanical integrity and dimensional stability of the structures. However, this conventional aspect of the operation of nuclear installations will not be discussed in detail in this chapter.

For long-term safety, Basic Safety Rule N° III.2.f ([2] - Annexe 1) recommends that the repository be instrumented[140]. Generally speaking, it is a question of confirming the existence of conditions conducive to long-term safety. In order to do this, the measurements made are aimed at ensuring that any short or long-term changes to the structures and adjacent argilite remain within a range compatible with subsequent long-term changes, as predicted in the models. Monitoring thus provides information about the respect of temperature limits, the short-term state of the damaged argilite zone around the structures and its medium term evolution, the corrosion of type C (or spent fuel) waste disposal packages and the detection of any chemical interactions between materials (concretes, argilite, seal swelling clays). The data thus acquired makes it possible to confirm the initial data used in the long-term evolution simulations.

Under no circumstances is it intended here to base the assessment of a repository's safety on its monitoring. However, in accordance with the practices in existing nuclear installations, the information gleaned from monitoring would make it possible to update the safety reference base, introducing the possibility of carrying out periodic reassessments.

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[140] "In view of the extended period covered by the operation of the repository and the disturbances induced during this period, it appears essential to provide appropriate instrumentation for monitoring changes in the parameters associated with the site and structures. This instrumentation should be installed as soon as possible, so as to provide monitoring of the structures and site, not only during but also before the repository operating period." (Excerpt)

10.3.1.4 Supply of additional geological information

Prior reconnaissance of the rock (i.e. throughout the construction phase) represents the third objective of observation and surveillance. This supplements the detailed knowledge already acquired before the start of the repository construction, that made it possible to establish the characteristics of the Callovo-Oxfordian formation on the site of the underground research laboratory and of the sector under study (see section 2.2).

However, despite this acquired knowledge, any additional reconnaissance yields more detailed knowledge of the initial state and properties of the rock at the site of future construction. This initial state forms a reference for future evolutions, to be monitored and modeled during operation of the structures.

Moreover, this prior reconnaissance allows confirmation of the absence of heterogeneity or any irregularities. In fact, the dimensioning of the structures and the safety assessment are based on the homogeneity of the host rock's properties, i.e. on a relatively low and known level of variability of its properties. If the preliminary reconnaissance detects greater variations than those already known, they must be taken into consideration in the models and, if necessary, make local adjustments to the design of the structures. If necessary, the distribution of monitoring resources mightness have to be adapted to such variations (see section 10.3.6).

Prior reconnaissance at the site of the structures is thus an essential tool in correct implementation of repository monitoring.

10.3.2 Parameters to be monitored during repository operation

The parameters to be monitored during the various stages of the disposal process are those which make it possible to track and quantify the various phenomena to which any later retrieval operation would be subject and to maintain the installation in good condition (see section 10.2). Monitoring the evolution of these phenomena provides the operator with the data required to better manage the repository in a reversible context and contributes to operational and long-term safety.

10.3.2.1 Monitoring of type B waste disposal cells

It has been shown previously that the level of reversibility of type B waste disposal cells basically depends on the mechanical stability of the cell's structure. The primary objective of monitoring these structures is therefore associated with the assessment of the parameters which indicate this stability and which enable its durability to be assessed. To this end, monitoring must concern the level of stress exerted on the liner by the geological structure and any deformation which could affect the liner. Furthermore, given that the level of stress exerted by the geological formation is associated with the level of saturation in the immediate environment, this latter parameter must also be monitored.

The second objective is associated with the production of gas since any subsequent parcel retrieval requires knowledge of the composition of the cell's atmosphere. To this end, the monitoring programme must include an analysis of the gases contained in the disposal cell (particularly hydrogen).

Finally, the third objective of monitoring of type B cells is associated with the exothermicity, though slight, of certain type B wastes. In fact, knowledge of the temperature is important, not only in order to understand the evolution of the various phenomena but also to assess the conditions of any subsequent package retrieval operation. Changes in the temperature in the various cell components are therefore also an element of the monitoring programme for type B waste cells.

10.3.2.2 Monitoring of type C waste and spent fuel disposal cells

The level of reversibility of type C waste and spent fuel disposal cells depends on the mechanical stability of the metal sleeve which contains the disposal packages and on its state of corrosion. Consequently, the observation programme for these cells is essentially oriented towards those parameters that indicate the condition of the sleeve, but also towards those that make it possible to explain and predict its evolution.

These parameters correspond to joint and coupled phenomena that determine the physical conditions of the cell’s sleeve, namely:

- the thermal behaviour of the cell and its environment,
- changes in the level of stresses exerted on the sleeve by the geological formation and any subsequent deformation that it might cause.
- changes in the composition of the atmosphere inside the cell (notably oxygen content) and its relative humidity.
- changes in the level of saturation of the cell’s near field.

10.3.2.3 Observation of shafts and drifts

In the case of access structures (shafts and drifts) the purpose of observation is firstly oriented towards the mechanical stability of the linings. Consequently, as in the case of type B waste cells, the observation programme for these structures applies to the parameters that indicate this stability. These parameters are associated with the initial relaxation of the host rock, with changes to the near-field saturation state, to the level of the stresses exerted by the geological formation on the lining and to the deformations which can result from it.

Additionally, particular interest is paid to the positions of the future seals. To this end, the observation aims to assess the formation of and changes to a possible damaged zone in the geological formation.

10.3.3 Situation at the international level

Studies into the observation and surveillance of a repository have been carried out internationally, sponsored respectively by the International Atomic Energy Agency (IAEA) [88], the Nuclear Energy Agency (NEA) of the Organisation for Economic Cooperation and Development (OECD) [89], and by the Commission of the European Union [90]. They show that the principal motivations described above are shared to a great extent by the bodies concerned in various countries.

However the technical interpretation of these motivations remains specific to each body, as it has to be adapted to the national context and, in particular, to the strategy adopted on the subject [90]. Notably, the link between reversibility and the observation of a repository and, more generally, the question of reversibility, are approached under different angles from one country to another.

- **Reflection within international bodies**

In its definition of "monitoring[141]" (i.e. “periodic or continuous observations and measurements of engineering, environmental or radiological parameters"), the IAEA defines its purpose as being: "to assist in assessing the behaviour of the components of a repository system or the impact of the presence or operation of the repository on the environment" [88].

Monitoring is justified then as a decision-making aid. The accumulation of data acquired, from the time of construction and during the operation of the repository, would make it possible to check, refine or, if necessary, modify the design of the repository. These data would also enable a check to be made of the feasibility of retrieving the packages. Finally, the IAEA indicates that monitoring will contribute to increasing knowledge used for long-term safety assessment.

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[141] English term corresponding to the French term “Auscultation”

A European Commission working group [90] has used the definition proposed by the IAEA. In particular, it has developed the place of monitoring in the staged operation of a repository.

More recently, the IAEA has also introduced staged development of the repository in its approach to observation [91].

Finally, the NEA [16] also considers that monitoring of the various repository parameters and of the site provides data related to safety assessment. It suggests that the safety reference base be periodically re-examined in the light of these data. The latter may concern confirmation of the properties of the site, the site's response to the presence of the repository and the beginning of changes to the repository structures.

- **Situation in Canada**

In 1997, AECL[142] examined monitoring methods in a spent fuel repository[143][92]. The field covered is vast; it ranges from monitoring confinement structures and the environment to the monitoring of the socio-economic fall-out.

In order to minimise any interference between monitoring and operation of the repository, and to avoid any impact on the functions of the engineered barriers, AECL proposes that an experimental zone be established within the repository, in addition to the direct monitoring of the repository's evolution during construction and operation and, if necessary, for an indeterminate period prior to closing the repository. This zone would enable experiments to be conducted in situ over an extended period, for instance experiments associated with the long-term behaviour of materials (for example corrosion) and with the performance of hydraulic barriers.

AECL mainly uses existing technical means or those that appear to be able to be inferred from existing techniques.

- **Situation in the USA**

The development of a staged disposal approach ("adaptive staging") proposed by the National Research Council (NRC) [21] is similar to the reversibility approach presented by ANDRA, in which a range of options is proposed for managing each stage of the process (see section 10.2). However, it differs from it in that its purpose is more technical, rather than meeting any social or political demands.

The approach proposed by the NRC is accompanied by a monitoring programme covering both manufactured and natural barriers. Various motivations are mentioned, similar to those presented in earlier paragraphs: characterisation of the initial state, analysis of the actual performance of the system and structures, aid to decision-making, notably those concerning improvements to the system, check on the meeting of requirements, personnel protection and nuclear safeguards. The NRC stresses that the approach proposed has to be seen in a context of responsible management in order to increase stakeholder confidence.

The Yucca Mountain project (dedicated to civil and military spent fuels) is a good illustration of this paradigm. The project involves monitoring adapted to the specific features of the concept. Indeed, this project can be described as a ventilated underground storage facility that can be transformed into a repository. During an initial 70-year phase, it has to be managed like a storage facility. The observations made during this period constitute essential elements on which the decision-makers will base their future choices [69].

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[142] Atomic Energy of Canada Limited

[143] As a reminder, spent fuel to be managed in Canada comes from the CANDU reactor national subsidiary, which use natural uranium. They have a low combustion rate and, consequently, give off far less heat than French CU1 and CU2 type fuels. However, the volumes considered are large.

The project's monitoring programme is considered to be an important element of the repository's performance confirmation programme. Its objective is to check that the data used to demonstrate safety were adequate and to demonstrate that the structures are behaving in accordance with the predictions [89]. It could also assist in increasing confidence or optimising the disposal process.

- **Situation in Sweden**

The Swedish body responsible for radioactive waste management (SKB) is studying the integration of observation and surveillance activities in the phasing of the development of a spent fuel repository [93].

SKB has identified the following phases: a site characterisation phase from the surface, a construction phase of the central structures and of the first structures for waste package disposal, a waste emplacement phase of an initial fraction (about 5 to 10%) of the inventory, followed by a so-called industrial phase (dedicated to the overall inventory), and then a closing phase.

SKB states that at the end of each phase, the data acquired by monitoring could contribute to the updating of the long-term safety assessment. The detection of changes other than those predicted would first trigger an analysis of the differences, then an update of the models and finally, if required, a change in the design.

It should be noted that the study is based, amongst other things, on experience feedback from the monitoring of the Swedish low and medium level waste underground repository (SFR), the underground spent fuel disposal facility (CLAB) and experiments conducted in the Äspö underground research laboratory.

- **Situation in Switzerland**

The expert group on radioactive waste management models (EKRA), created by the Federal Council, has proposed a concept of a "monitored durable geological repository" [94]. This model "associates three repositories forming a system: a test repository, a main repository and a pilot repository", and includes a "monitoring, control and possible retrieval" period. The test repository serves as an underground laboratory specific to the site, the operation of which can continue after the main repository is commissioned. The main repository is designed to hold most of the waste. Its infrastructures (shafts and drifts) remain accessible throughout the monitoring phase.

The pilot repository is designed to hold a small fraction of the waste and enables the behaviour of the technical barriers to be monitored, and the theoretical models to be confirmed, for a period which can extend beyond the closing of the main repository. "Based on the observations made in the pilot repository" it may be decided to intervene in the main repository, including retrieving the waste.

This concept of a monitored repository has been adopted by NAGRA, the Swiss waste management body [44]. This approach aims to involve a high level of interaction with the stakeholders based, notably, on the presentation of a safety demonstration at each milestone of the process. This approach also offers flexibility in taking into consideration knowledge acquired during the process. For example, it enables the design to be adapted or earlier decisions to be revoked and, if necessary, packages to be retrieved.

10.3.4 Constraints specific to monitoring a repository

The constraints specific to observation and surveillance of a geological repository for radioactive waste, compared with those applicable to major civil engineering structures, are essentially associated with the long lifetime required of monitoring equipment and its "discretion", i.e. this equipments non-interference with the monitored phenomena and with safety functions.

In particular, it should be noted that at this stage of the studies, due to the constraints described below, it is not intended to instrument the disposal packages, so as to avoid impeding handling due to the possible presence of cables or protruding sensors.

10.3.4.1 Lifetime of monitoring equipment and environmental conditions

The equipment used to monitor the structures must therefore be able to operate reliably over long periods of time (at the century scale).

Moreover, as soon as the package emplacement phase begins, the disposal cells will no longer be accessible. Consequently, it must be possible to take remote measurements and it will be difficult to replace a defective sensor during or after the filling of the cells. The same applies to back-filling or sealing of drifts. The distribution and number of measuring instruments in these structures must therefore make allowance for certain sensor failure rates, so as to be able to have sufficient data available for as long as possible in order to monitor the evolution of the structures.

For the most part, the cells represent harsh environmental conditions, in terms of radioactivity and temperature, under which the monitoring equipment will have to operate correctly. The sensors must therefore be able to operate correctly at a temperature approaching 100 °C in type C (and spent fuel CU) cells, and up to 60 °C in the liners of cells containing low exothermic type B waste.

The operation of the sensors, particularly their electronic components may also be disturbed by the effects of radiation. Depending on the equipment available, the sensors selected will be as invulnerable as possible to the effects of radiation and placed in the cell in a manner that minimises these effects.

Other environmental conditions are not specific to radioactive waste disposal but related more to the great depth of the structures and to the small quantities of water contained in the rock (such conditions can be encountered in deep road tunnels). In particular, precautions must be taken when fitting sensors designed to measure the high interstitial pressures around structures.

The conditions in the cells, however, limit losses of sensors due to corrosion, which are frequent in road or rail tunnels. In fact, the concrete liner and on rock walls of type B disposal cells are highly de-saturated and the ventilated air in them is relatively dry. In type C cells, corrosion occurs mainly under anoxic conditions and, thus, very slowly.

10.3.4.2 Discretion of monitoring equipment

The “discretion” of a monitoring device is its ability to limit any disturbance it might cause in the monitored object to an insignificant level. This discretion usually means that the measurement is not significantly influenced by the presence of the instruments. In the repository context, it also means that the use of monitoring equipment shall not have a significant impact on (i) the operating conditions, (ii) the mechanical strength of the structures, and (iii) long-term performance (particularly the hydraulic properties of the seals and rock). “Discretion” is therefore a major constraint to be considered in the development of a repository observation and surveillance programme.

- **Absence of significant impact on the operating conditions of the structures**

The implementation of monitoring shall not interfere with the operation of the repository. Thus, any transmission cables used must not impede the placement of packages in cells. In order to achieve this, they may be integrated into the liner or secured to the excavated wall of the drift or the cell. Moreover, care must be taken when using a monitoring system to avoid producing sparks, particularly in cells liable to produce hydrogen. Any power sources, for instance batteries fueling wireless transmission, are prone to this risk.

- **Absence of a significant impact on the mechanical strength of the structures**

Among other things, the use of monitoring instruments is motivated to supply data to support reversible management of the repository. This must not be achieved at the cost of a reduction in the reversibility. For example, the integration of monitoring devices into the structures must not lead to more rapid deterioration of their mechanical strength or their dimensional stability. Indeed, the integration of sensors into concrete, frequently practised in civil engineering, can be used with negligible impact on the structure, given the small size of the objects inserted.

- **Absence of a significant impact on the safety functions of structures and on the favourable properties of the geological medium**

The monitoring equipment used must not affect long-term safety. On the one hand, this concerns any irreversible changes caused by monitoring equipment during operation of the repository and, on the other, the consequences of abandoning some of the equipment in the structures after they have been closed.

First and foremost, the layer of undisturbed host rock between the repository and the adjacent layers must not be disturbed by the presence of instruments. The measurements made in the various Callovo-Oxfordian horizons shall thus either be non intrusive, or situated in the near field of the shafts and underground structures.

The risk of a chemical impact must also be taken into consideration. It shall be overcome by selecting measuring instruments made from appropriate materials: The materials inserted (metals, silicas etc.) and any of their corrosion products are similar to those also used in the construction of the structures. Special care shall be taken to ensure that no organic materials areintroduced into the repository, for example in the form of hydraulic fluids present in pressure cells. The risk of impact on the evolution of the excavation damaged zone on cell walls depends on any voids that monitoring equipment might cause in the long term after their complete degradation. However, the volumes occupied by measuring instruments are small compared to the structure construction and package emplacement clearances. For the same reasons, the presence of monitoring equipment inserted into a swelling clay buffer or a seal does not compromise the swelling and space-filling capacity of the clay they are made of.

Finally, and above all, the use of signal transmission equipment requires particular attention in order to avoid any downgrading of the hydraulic behaviour of the geological environment and seals. In fact, the presence of cables or fibre optics could create short-circuits for water flow and the transfer of radioactive nuclides. Three possible approaches are considered in this respect: not to pass cables once a seal is being constructed, tolerate cables through seals during a transitional period, then restore the seal, or by-pass the seal during a transitional period, then seal the lateral borehole used for this purpose.

Avoiding passing cables requires either that measurements upstream of the seal are abandoned as soon as it is constructed, or the use of wireless transmission through the geological medium or through the seal. The latter option represents an interesting option for development. It is based, in particular, on experience feedback from the oil industry and is used in the Meuse/Haute-Marne underground laboratory (EPG probe). Furthermore, the feasibility of wireless transmission in the specific environment of disposal cells is the subject of a research and development programme between ANDRA and the Japanese Radioactive Waste Management Funding and Research Centre (RWMC). In particular, the question of operational life expectancy must be examined.

The temporary passing of cables could also be envisaged when constructing seals consisting of pre-compacted swelling clay bricks. During final closing, the seals could be renewed by recovering the cables, for example by over-coring, followed by sealing the excavation thus made.

10.3.5 Industrial experience feedback concerning monitoring

Observation and surveillance are now a standard practice in many fields of activity such as major civil engineering projects, nuclear power stations and the mining and oil industries.

Repository structures are analogous to certain types of civil engineering structures, which already benefit from feedback of monitoring experience. The instrumentation of shafts, drifts and type B waste disposal cells benefits principally from feedback from experience gained in the construction of rail and road tunnels and that from concrete structures such as concrete hydraulic dams or the containment envelopes in nuclear power stations. For type C waste or spent fuel disposal cells, the feedback used is that from the instrumentation of pipelines, pipework networks and bearing piles. The monitoring of clay-cored barrages and clay repository covers and experimental data concerning seals and back-filling in underground laboratories, provide lessons concerning the monitoring of clay components (seals, back-fill and swelling clay buffers where applicable) within a repository.

10.3.5.1 Experience feedback from the monitoring of major civil engineering structures

Feedback from observation and surveillance demonstrates the benefits to be gained from monitoring during both the construction[95]and operational phases within installations[144]. It enables knowledge to be gained of how to design, build and operate a monitoring system [96], [97]. Finally, it has been possible to trial and test equipment under various environmental conditions and over periods of up to several decades.

In the field of tunnelling, monitoring has been a standard procedure for 10 to 20 years, both in old tunnels for maintenance purposes and in the design of new structures. This feedback can be of considerable interest in repositories given their similarity to such structures.

Monitoring combined with numerical modelling is a diagnostic tool for assessing the condition of old tunnels. It makes it possible to define the actions required to strengthen them or bring them up to current standards. As an example, this approach is used by “Réseau Ferré de France” for maintaining numerous rail tunnels, some over a hundred years old, that are still in service [98].

For more recent tunnels, monitoring has been gradually introduced, due to environmental constraints imposed on urban sites (excavation beneath existing constructions, often in loose soil) and in order to improve or optimise the designs of the structures. In both cases, it enables terrain deformation to be monitored and to adapt the excavation and support procedures where necessary. This was the case, for example, for the construction of the structures for the EOLE (and METEOR) railways under Paris and for the Tartaiguille tunnel, one of the largest underground structures for the French Mediterranean high-speed train (TGV) link, for crossing an area of marl. In the case of the Chamoise motorway tunnel, consisting of two independent tunnels commissioned ten years apart (in 1986 and 1996), instrumentation and monitoring of the first structure after its construction enabled the design of the slab of the second tunnel to be improved. Moreover, the monitoring of the behaviour and condition of such structures during their operation makes it possible to detect maintenance requirements at an early stage.

In the nuclear field, the monitoring of the pre-stressed concrete containment envelopes of nuclear power stations was designed into the construction of the first power station (first section of the Fessenheim reactor in 1971). The monitoring adopted mainly concerns the operating safety of the nuclear installation. But it also enables knowledge to be gained of the physical condition of the concrete during the structure’s lifetime. The data thus acquired can then contribute to the decision-making process concerning the management of the power station, for example an extension of its operational life.

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[144] A few decades ago, the monitoring of a structure was still often considered as a financial and technical burden which produced little benefit in return.

Dams are of particular interest when designing the monitoring of a repository. Their inspection and monitoring has indeed been mandatory for several decades. The improvement of knowledge of monitoring equipment, and the large increase in the number of dams in France between 1930 and 1970, led in 1970 and 1983 to a change to the 1927 circular. Regulations thus require continuous monitoring of the entire structure and its foundation during its filling, regular monitoring (on a weekly basis) by the operator, an annual inspection and a complete inspection every ten years by the government inspection department [99]. On certain dams, the sensors have thus been supplying measurements for several decades. Statistical analysis tools of measurement have also been developed over the last twenty years or so in order to assist the operator in detecting any slow changes liable to alter the behaviour of the structure [100] (for example swelling of the concrete or damage to the clay core’s seal). The implementation of similar monitoring policies in many countries has made it possible to reduce the worldwide rupture rate of 2.2 % for dams built before 1950 to 0.5 % for those built between 1951 and 1986 [101].

In addition, the problem of ensuring an operational life of at least a hundred years for major structures (tall buildings, bridges or viaducts) has led to the introduction of monitoring of the behaviour of these structures and their foundations. The purpose of this monitoring is to measure the gradual strains of the structure, detect any delayed settling of the foundations, that may be damaging to the structure, or to assess the impact of work carried out nearby (as, for example, in the case of the monitoring of the Ministry of Finance in Paris during the construction of the new “Metro” line N°14). In this respect, the metal foundation piles of certain of these structures are the subject of special monitoring.

As a reminder, the experiments conducted in underground research laboratories provide feedback that is somewhat different from that provided by civil engineering. These installations, dedicated to scientific research, have the advantage of using monitoring equipment that is specific to the rocks studied for deep disposal and specific to the particular phenomena associated with disposal. The knowledge base comes principally from laboratories on clay sites: at Mol in Belgium [102], Mont Terri in Switzerland and the Meuse/Haute-Marne in France. However, certain experiments conducted in laboratories on granite sites also provide interesting feedback like, for example, sealing experiments (named TSX) in Canada [67] or back-filling experiments at Äspö in Sweden [103]. As part of the experiments conducted in these laboratories, research was also carried out on measuring instruments, for example by comparing several redundant technologies or by exploring innovative approaches.

10.3.5.2 Lessons learnt from feedback for the design of a monitoring system

The “standard professional practices” that have developed based on feedback from observation and surveillance of numerous civil engineering structures make it possible to establish a series of good practices.

The first rule is redundancy of equipment. This redundancy enables a check to be made of the consistency of measurements made by different instruments. It also makes it possible to limit the loss of data when a sensor is defective and cannot be replaced. In inaccessible structures, several measurements of the same parameter can be made, either using different technologies or by doubling up the same type of sensor. In accessible structures, it is possible to combine a visual inspection with geometrical monitoring carried out using topographical equipment, and with measurements obtained using sensors buried in the structure. These methods are supplemented as required by taking and analysing solid or fluid samples. This procedure is used, notably, for dams, rail tunnels and nuclear power station containment envelopes. Another means of contributing to redundancy consists of supplementing a spread of point measurements with an overall measurement on a larger scale (for example local thermal expansion strain and overall deformation).

The choice of monitoring equipment and the quality of their implementation are also very important elements in developing an appropriate monitoring system, that is reliable over the long-term, and yields useable data [32]. The sensors must be specially selected according to the magnitude of the parameter to be measured and the required accuracy. Moreover, incorrect implementation of a sensor may lead either to its loss or to measurements with high interference levels.

The distribution of monitoring equipment must be selected with care. Preliminary numerical monitoring may help to determine the most suitable positions for sensors around structures. As an example, the position of the sensors placed around the shaft for monitoring of its excavation (REP experiment) was determined, in particular, using models of the rock's mechanical and hydraulic behaviour.

The monitoring equipment must make it possible to distinguish between phenomena in order to correct the raw data. Thus, in order to monitor strain (principally in the concrete or rock) using strain gauges buried in the structure, correct analysis of the measurements requires simultaneous monitoring of the temperature. In fact the amplitude of the strain (reversible) due to thermal expansion of the materials, particularly if they are only slightly deformable, may be of the same order of magnitude as the irreversible strain that it is hoped to monitor. The simultaneous measurement of the temperature also makes it possible to correct these thermo-mechanical effects[145]. Similarly, in the particular case of concrete, the use of instrumented samples, free to deform, makes it possible to assess the initial shrinking effect during the setting of the concrete, on strain measured by the sensor positioned before the concrete sets. It is also interesting to supplement these measurements, in the long term, by analysing core samples, in order to monitor the evolution of the concrete's intrinsic chemical and mechanical properties.

Finally, the study of monitoring equipment should also be conducted as early as the design phase of the structures to be observed. From this point of view, the monitoring working group of the Association Française des Travaux en Souterrain (French association of underground structures) [96] believes that "monitoring must be considered as a sub-project in its own right, which accompanies the structure from the design stage to completion". Amongst other things, this approach makes it possible to reduce to a minimum the implementation problems during construction and contributes considerably to making the sensors "discrete".

10.3.5.3 Survey of investigative monitoring equipment for repository purposes

The experience feedback relating to investigative monitoring provides interesting information regarding the type of sensors that would be best suited to repository observation, and also to the measurement transmission technology. These sensors have been selected to measure the dimensions referred to in section 10.3.2 (deformation and stresses in the linings, temperature, hygrometry, gas concentration and EDZ characterization) over long operating periods and, for some sensors, in extreme environmental conditions.

- **Strain, deformation and mechanical stress**

Local deformations in the concrete (of the order of one centimetre) are often measured by vibrating wire extensometers, whose typical operation is illustrated in Figure 10.3.1. They have been used in a large number of tunnels, dams and in all the confinement enclosures in nuclear power plants for several decades. They have been found to be highly reliable throughout their lifetime of over 50 years and there is no indication that they are nearing the end of their efficient operational lifetime. For example, this type of sensor is still operational in the Castillon arch dam (France), and has been since it was built shortly prior to 1950.

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[145] This correction must not be confused with the correction of the effect of temperature on the sensor, which is generally integrated into the measurement acquisition software.

The rate of operation of these sensors is very high even after several decades. Of the one thousand sensors that were embedded in the Daniel Johnson dam in Canada, 90% are still in service after 40 years of operation. The same rate of 90% has been achieved for the 630 sensors embedded in the linings and segments in the Channel tunnel for the last twenty years.

In rock or backfilling material, deformation is spread over greater distances. It is therefore measured by long base extensometers, fitted with several sensors and located in bore-holes or in backfill material.


Figure 10.3.1 Illustration of a vibrating wire extensometer, attached to a reinforcement and integrated in the concrete structure

These extensometers, whose measurement base can extend to about one hundred metres, provide, at several points throughout the bore-hole (in a given direction), the relative displacement of these points in relation to each other and in relation to the bottom of the bore-hole. A large number of tunnels and dams have been fitted with bore-hole or back-fill extensometers for over thirty years. Also, vibrating wire extensometers and long base extensometers of different types have been used in a future EPR feasibility demonstrator at the scale of 1/3 where they withstood pressure cycles of 0.4 Mpa and thermal cycles of from 5°C to approximately 100°C. Despite these difficult conditions, the rate of failure of the sensors remained limited and the measurements obtained in this way can be exploited without difficulty.

The overall displacement of a structure along three axes can be monitored by integrating vertical pendulums into the structure. Measurement is carried out on a measurement table located at one end of the pendulum (cf.Figure 10.3.2). The prestressed concrete confinement enclosures in nuclear power plants are thus monitored using vertical pendulums, capable of providing overall lateral and vertical deformation measurements, integrated along the length of the pendulum or in sections between two measurement tables. This principle is also used to monitor displacement in concrete dams (movements downstream, to the banks or swelling) and to monitor displacement in shafts (deformation in certain more deformable layers for example).

The displacement measurements only provide relative displacements in relation to a point that is rarely fixed (bottom of the extensometer bore-hole, or pendulum attachment point). This disadvantage can in certain cases be rectified by including a topographic survey as a complement to the system of sensor or pendulum monitoring. However, topographic measurements are often too imprecise compared with the displacement variations measured by sensors.


Figure 10.3.2 Measuring table for a vertical pendulum

There are few techniques available to measure stresses in an underground structure directly and continuously. Total pressure cells are sometimes used to measure the pressure of the ground on a tunnel lining directly, but they are not suitable for use in a repository situation, as they are not reliable over time and they are not easy to use. Often, the pressure of the ground is determined indirectly, from measurements of strain in the ground and possibly in the lining. In the same way, the stresses in the lining are determined from the local strain measured in the lining, assuming the lining concrete has a known elastic behaviour.

- **Variation of the EDZ**

The variation of the EDZ is coupled with the rate of deformation and the rock saturation value. It is monitored indirectly, by measuring the rock deformation near to the walls of the structure and by detecting any desaturated zone near to the walls.

Figure 10.3.3 Inductive extensometre for boreholes

This technique has the advantage of using reliable and proven monitoring equipment, and in particular multi-sensor inductive extensometers in bore-holes and on interstitial pressure cells. An example of an inductive core (copper rod) and a sensor (opaque coupling ring) is illustrated in Figure 10.3.3.

It is also possible to detect the presence and the variations in the EDZ by putting in place acoustic monitoring from the outer wall or microseismic measurement techniques. Several options are available, either listening directly for the sound produced when any fractures are created in the damaged zone, or transmitting a known wave and correlating its transmission properties with the damage to the rock on the outer wall. In all cases, listening is carried out using geophones or accelerometers. The microseismic wave propagation measurement technique has been used in the Meuse/Haute Marne laboratory and has proved effective.

- **Interstitial pressure**

The interstitial water pressure is usually measured in foundations, back-fill and in clay cores in all the large French dams, by vibrating wire interstitial pressure cells (Figure 10.3.4). There is no official data regarding their durability. The experience feedback in terms of reliability and longevity gives an 80% operating rate after several decades of operation, such as for example in the reservoir dam in Marne since 1971 or in the oued Mellegue dam in Tunisia since 1954. Moreover, this type of instrument can give a minimum indication of the saturation value of materials.

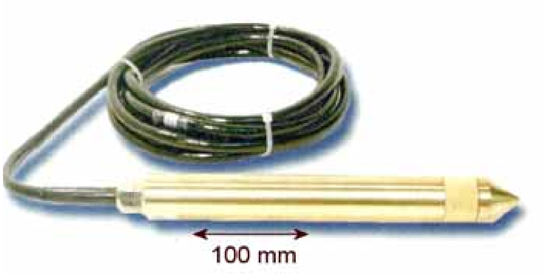

Figure 10.3.4 Vibrating wire interstitial pressure cells

- **Relative humidity**

The relative humidity of the air is measured regularly in a number of industrial installations where this parameter affects the manufacturing process (for example in the food processing industry) and in all meteorological stations. This measurement is most often carried out by dew-point hygrometers or capacitive hygrometers. These apparatuses rely upon the dielectric properties of the sensor and measure the variation in the relative permittivity as a function of the quantity of water absorbed. In view of the need for regular maintenance and calibration, their use is reserved for accessible zones.

- **Water content**

The water content of a material can be monitored locally by using a TDR probe (Time Domain Reflectometry or electromagnetic reflectometry). It exploits the difference in permittivity between rock and water, and allows the water content to be calculated from the permittivity of the porous medium. This type of probe must be calibrated specifically for the material concerned (back-fill, swelling clay) or the rock to be monitored. It is only used in accessible zones, in order to allow regular maintenance.

The distribution of water content, for example in the near-field of a drift, can also be monitored by electric tomography, by installing a set of electrodes in the walls and in bore-holes. Several experiments carried out by Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), especially in the underground laboratories of Äspö and Mont Terri, have demonstrated the technical performance of such a system. They demonstrated in particular the capacity to monitor the extent of the desaturated zone in the walls of the structure.

- **Temperature**

Temperature measurement is the most reliable and well-proven of all the different types of measurement. The temperature is monitored on all structures, either to contribute to the analysis of other types of measurements affected by thermal variations (in road tunnels depending on the season and the traffic for example), or to check the expected thermal variations or to monitor a dimensioning criterion. The most reliable means of measuring the temperature at a specific point is by using a vibrating wire sensor (Figure 10.3.5). This type of sensor is particularly robust and has the benefit of a large body of long-term experience feedback, in particular in tunnels (The Chamoise tunnel and the Channel tunnel).

Figure 10.3.5 Vibrating wire thermometre

Moreover, for around ten years, distributed temperature measurements on long profile sections have been carried out using fiber optic systems [104] (Figure 10.3.6). In view of the more recent use of fiber optic, it is recommended to combine the two techniques, operating redundantly. The point measurement sensors and the fiber optic sensors can be buried in concrete, placed in a bore-hole or in backfill, or left in the atmosphere inside the structures.

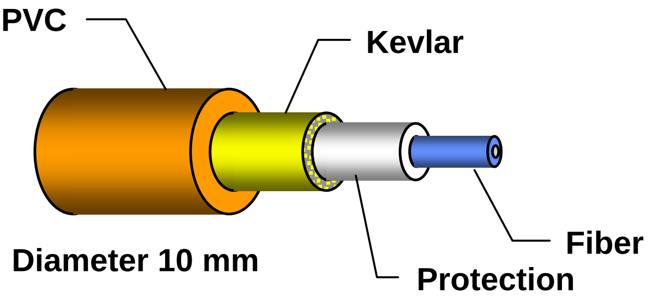

Figure 10.3.6 Fibre optic to take distributed temperature measurements

- **Concentrations of toxic gases, corrosion, contamination**

Physical and chemical sensors used to measure pH or concentrations of hydrogen or oxygen are fitted at a number of industrial sites. They nevertheless have a limited lifetime and require regular re-calibration. They can therefore only be used in accessible zones.

For example, hydrogen detectors based upon electrochemical or semi-conductor technology are currently available. Humidity, temperature, radiological atmospheres or even the length of the cable can all interfere with their operation and they require regular re-calibration.

To monitor the corrosion of metal components, visual inspection methods either employed directly or remotely using miniaturised cameras, followed by sampling or ultrasound measurement can be carried out as long as the object or the monitoring area is accessible or at a distance accessible by remote control. Corrosion indicators (sacrificial anodes, etc.) can be used, either to indicate an absence of significant corrosion, or to detect a high corrosion rate. This type of indicator is used in the monitoring of pipelines and reinforced concrete structures in marine environments.

In the nuclear industry, possible contamination is monitored regularly by mass spectrometry systems. They analyse samples obtained by suction from the atmosphere to be checked, through a filter, to identify the isotopes and to quantify their activity. This principle is used, for example, for the monitoring of α-β radioactive aerosols in the atmosphere in nuclear installations. The restrictions for use are similar to those for hydrogen detectors and they therefore require regular re-calibration.

- **Transmission and centralisation equipment**

More an more data acquisition and monitoring is centrally managed, due in particular to the rising number of measurements performed. Centralised management facilitates the acquisition and exploitation of measurements.

For around ten years, conventional electrical signal type measurement equipment have been complemented by fiber optic sensor technologies. This latter type of technology is easily integrated into a fiber optic type transmission system. Optical means have a number of advantages as compared with electrical cables. They are not sensitive to electromagnetic disturbance and the signals can be transmitted without amplification over several tens of kilometres.

It is also possible to use low or very low frequency electromagnetic transmission technology which obviates the need for physical connections between the sensor and the reception system. This wireless transmission technology has been used for around twenty years in the petrol refining industry for the control of directional boring and for the observation of oil accumulations. Just such a system is used on the Meuse/Haute Marne laboratory site for in-situ pressure and temperature monitoring (Figure 10.3.7). Piezometric probes installed 420 m under the ground transmit information to the surface without any wire connections. The lifetime of this equipment depends on the lifetime of the batteries that power the sensors and the frequency of measurements.

Their lifetime is approximately ten years for normal use [87]. One of the objectives of current developments is to increase this lifetime.

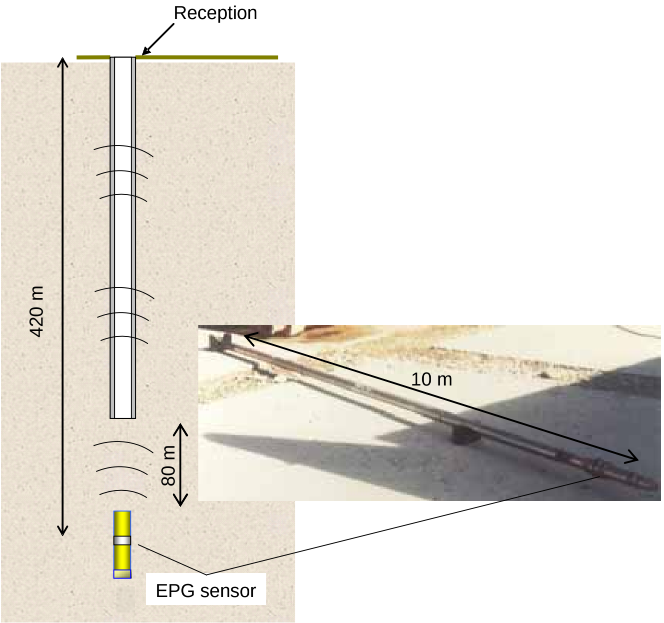

Figure 10.3.7 Wireless surface transmission to the Laboratory in the Meuse/Haute-Marne site

A similar wireless transmission technique from drift to drift has been successfully tested in Äspö's (Sweden) underground laboratory (Figure 10.3.8) by the Japanese agency RWMC (Radioactive Waste Management Funding and Research Center). It aims to increase the battery lifetime to several decades. Similar technology is also currently in use for the monitoring of settling of the Kansai international airport platform in Japan, which is located on an artificial island.

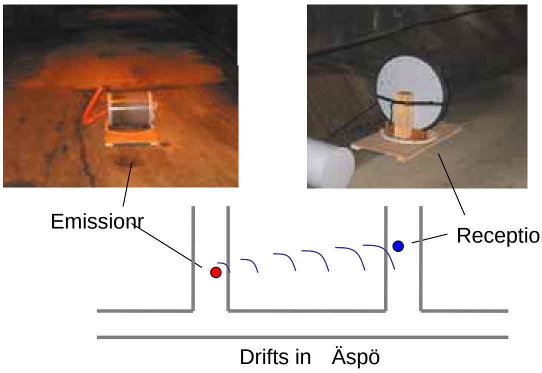

Figure 10.3.8 Experimental wireless transmission devise in the underground Äspö laboratory

As shown above, wireless transmission technology is currently the focus of a research and development programme carried out in partnership between RWMC and Andra aiming to study the feasibility of such a system in the specific case of constraints arising from waste disposal cells, especially in relation to temperature, radiation and interference with metal parts found in these structures.

10.3.5.4 Experience feedback regarding the exploitation of measurements

In respect of the exploitation of measurements, a statistical analysis method initially developed by EDF [100] has become internationally established in the monitoring of dams and nuclear power plants. This method is based on the measurements already obtained to describe the behaviour observed, to determine the amplitude of reversible variations brought about by known phenomena (such as thermal effects for example) and to calculate the extent of irreversible change. On the basis of an analysis of the past history of the structure, it is possible when taking a new measurement, to identify quickly (and automatically) whether the structure is evolving in a similar manner to past changes, or whether it has modified its behaviour. The establishment of correlations between measured values and the use of numerical models allows an assessment of the longer term evolution of structures.

This approach is now operational in the dams and nuclear power plant fields, as a considerable amount of long-term experience feedback has been accumulated, and this has allowed a good understanding of the behaviour of these structures and has therefore enabled an effective analysis method to be developed.

In respect of tunnels, and generally speaking of other types of civil engineering structure, measurement analysis beyond the construction phase is relatively recent, and the diversity of utilisation of tunnels has very often lead to customised measurement analysis solutions [32]. It is based upon correlations between measurement and upon the comparison between measurements and the predictions of numerical models. This comparison enables the models to be refined, then to improve the prediction of the future evolution of the structures. This process of iterative modelling, observation, comparison and improvement of models, can be pursued throughout the operating lifetime of structures [105].

10.3.6 Observation and surveillance strategy

This section summarises the strategy considered for the observation and surveillance of a reversible repository [87]. The essential elements involved reside in the selection of representative structures to be instrumented and the anticipation of monitoring requirements throughout the lifetime of these structures.

10.3.6.1 Selection of representative instrumented structures

In view of the homogeneity of the host rock and the repetitive character of the repository structures, it is envisaged to select structures considered as representative of different categories (disposal cells for B and C waste, and possibly for spent fuels; shafts and drifts; seals; backfill). The structures selected in this way will be monitored in a specific manner all through the repository process.

At this stage of the studies, the quantity and the distribution of monitored structures can only be given as a guide. They will be adapted in relation to the results obtained for the first instrumented structures, and management choices will be made at a later date. The knowledge gained will be put to use as the repository progresses and will enable us to specify the precise number of structures to be observed, and to optimise the distribution, and possibly to reduce the amount, of measuring equipment.

The disposal cells selected for thorough scrutiny are to be known as "control cells". Other cells, which will be greater in number and known as "standard cells", will be measured using lighter instrumentation equipment, to confirm the behaviour observed in the "control cells" and to transpose the results to the whole of the repository zone concerned.

In the B waste repository zone, containing approximately forty cells, several different types of cell can be identified depending on the packages they contain: bitumised waste packages, low-level exothermic packages and gas releasing packages. One cell of each type can be chosen as a control cell, and possibly a second cell to ensure redundancy.

The C waste or spent fuel repository zones however, are characterised by a very large number of identical cells. Certain control cells will naturally be selected from among the first modules built. Their number, which will necessarily be very low in relation to the total number of cells, can be set on a statistical basis, at less than 10% of cells in the selected module, and at less than 1% of all the cells needed for the disposal of all the packages. Within the "control module", the position of the cells will be adapted in relation to the real conditions foreseen (in particular in relation to the real thermal release of the package to be disposed of. Generally speaking, it may be worthwhile distributing the control cells firstly in the centre of the module and secondly on the periphery of the module, so as to be able to observe any differences in the corresponding behaviours (Figure 10.3.9).

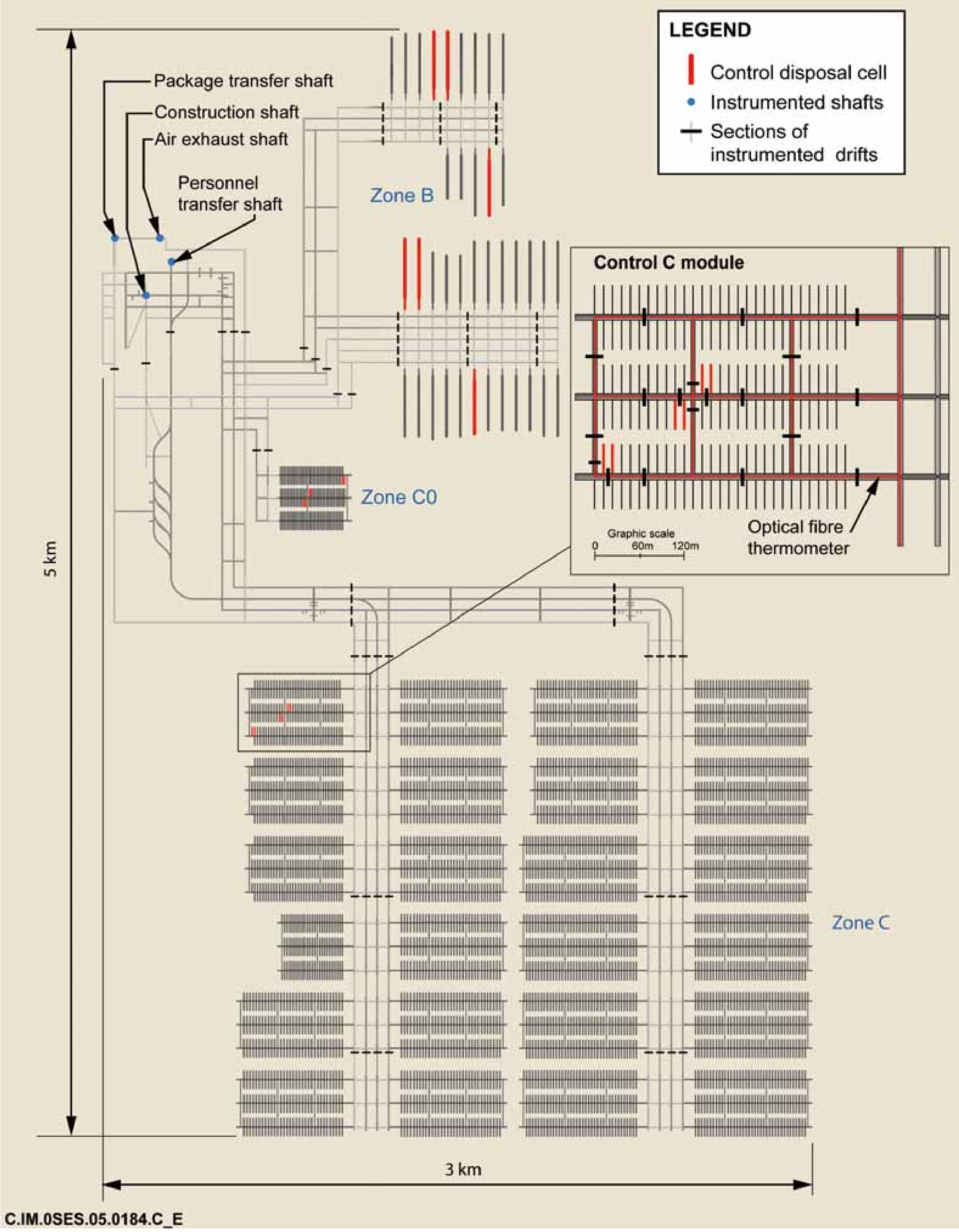

Figure 10.3.9 *Example of monitoring at the repository level, at a particular point in time in the repository process*

The monitoring of infrastructures requires us to select certain sections of drifts or shafts to be instrumented. These instrumented zones are spread throughout all the infrastructures. The distance between these zones is not specified in theory. The density of the instrumented zones in relation with operational safety, and in particular for the monitoring of the mechanical strength of the structures, will be based on the experience feedback built up in civil engineering and especially in the underground laboratory. In order to limit the number of instrumented zones, we will attempt to combine the measurements designed to observe the repository with those specifically for operational monitoring.

For the closure structures (backfill or seals), monitoring is designed to achieve objectives relating to long-term safety. However, the complete resaturation of these structures necessitates excessively long periods to permit comprehensive monitoring as part of a programme of observation and surveillance. The monitoring of these structures is thus limited to their short-term evolution after installation (settling and fluid exchange in the walls). The first seals of B cells and drifts and also sections of the first backfilled drifts will undergo thorough monitoring. The monitoring of the following structures will then be adapted according to the results obtained on the first structures.

The basis for the distribution of the control cells and the instrumented drift sections at the repository level, is illustrated in Figure 10.3.9. This distribution shows that a moderate number of structures observed allow monitoring at repository level. However, this illustration does not represent a frozen view of the monitoring programme in as far as the experience feedback from the first monitored structures will make it possible to adjust the choice and the distribution of the measurement equipment.

10.3.6.2 Anticipation of changes triggered by management stages.

The installation of monitoring equipment takes place at the construction phase of the structure concerned. This equipment must allow monitoring of the phenomena which will occur during the different repository stages, and in particular those which will occur after the packages are put in place, then again after the cells are sealed. The design of the monitoring system takes account of an expected sensor failure rate, according to the monitoring period envisaged. If the structure becomes inaccessible (for example after a cell is filled or after a drift is backfilled), these potential losses can be compensated by adapting sensor redundancy. Finally, when the use of transmission by cables or fiber optic becomes unfavourable (especially to avoid passing through a seal), it is possible to use a wireless transmission system.

10.3.7 Observation of B waste repository modules

The observation of B waste disposal cells is essentially focused on the phenomena which characterise these structures during the different stages of the repository process, i.e.: the evolution of stresses exerted by the geological formation on the lining, the evolution of the level of saturation of the structure's near environment and the production of gas by certain waste material. Moreover, for cells containing exothermic waste, the evolution of the temperature is also an important phenomenon.

10.3.7.1 The system of observation of a control module

The system enabling observation of a "B control cell" is made up of 6 instrumented sections providing measurements at certain specific points and of fiber optic systems providing measurements distributed axially along the whole length of the cell. This system is complemented by an instrumented bore-hole at the bottom of the cell and by the monitoring of the ventilation air (Figure 10.3.10). The entire system, conceived to provide physical measurements, is fitted during the construction of the structure.

In addition, a visual control system may be used in the usable part of the cell: for example by means of video camera, either fixed to a post or mobile and attached, for example, to a package handling truck or by a means of an adjustable, multidirectional robotic endoscopic arm to facilitate visual inspection of the clearance remaining between the packages once they have been put in place.

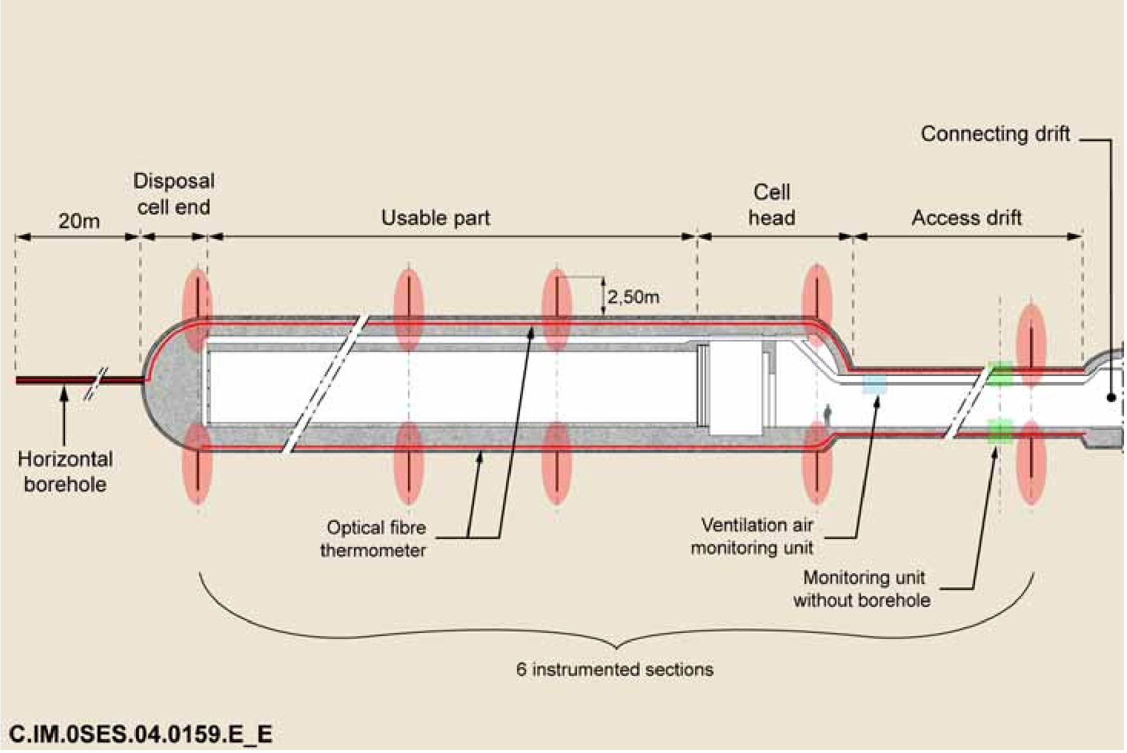

Figure 10.3.10 B control cell observation system

The instrumented sections are positioned at the end of the cell (one section), in the main part (two sections), at the head of the cell (one section) and in the access drift (two sections). Each instrumented section provide "two-dimensional" monitoring of the structure. The three-dimensional vision is achieved by collecting the information obtained in all the instrumented sections and by the distributed measurements provided by the fiber optic systems all along the structure.

- **The instrumented sections**

An instrumented section is made up of several monitoring units (see Figure 10.3.11). This distribution enables monitoring particularly of arch and slab deformations, and ensures that the filling concrete has only a slight impact on the behaviour of the compressed strength ring. The redundancy of the monitoring zones on the left and right sides make it possible to quantify any dissymmetry in the behaviour of the structure. Also, in the event of symmetrical alteration, this system offers redundant measurements.

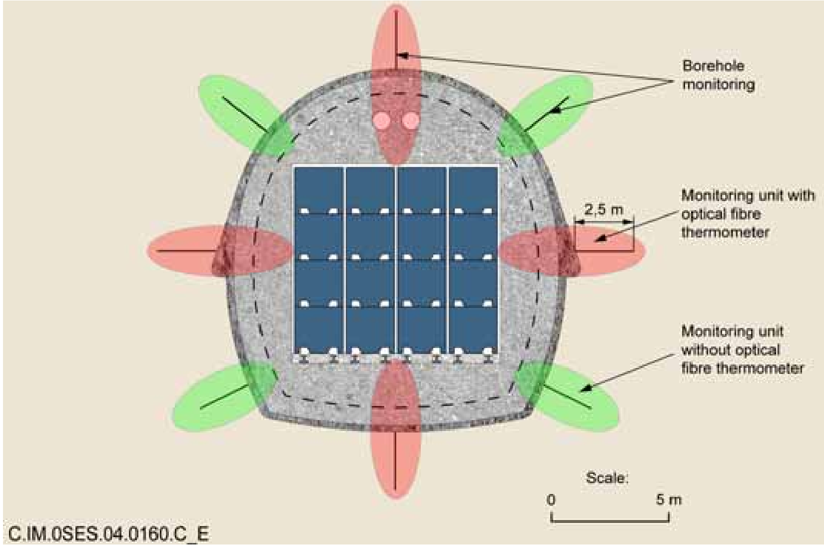

Figure 10.3.11 Composition of an instrumented section for a B control module

In the access drift, the instrumented sections are particularly worthwhile in that they provide information regarding the state of the rock and the lining before, during and after grooves are made and the clay core is put in place.

Each monitoring unit relates to the monitoring (i) of the atmosphere in the cell (ii) of the cell lining (iii) of the geological formation in the near field environment of the structure. All the sensors grouped in this type of unit are illustrated in Figure 10.3.12.

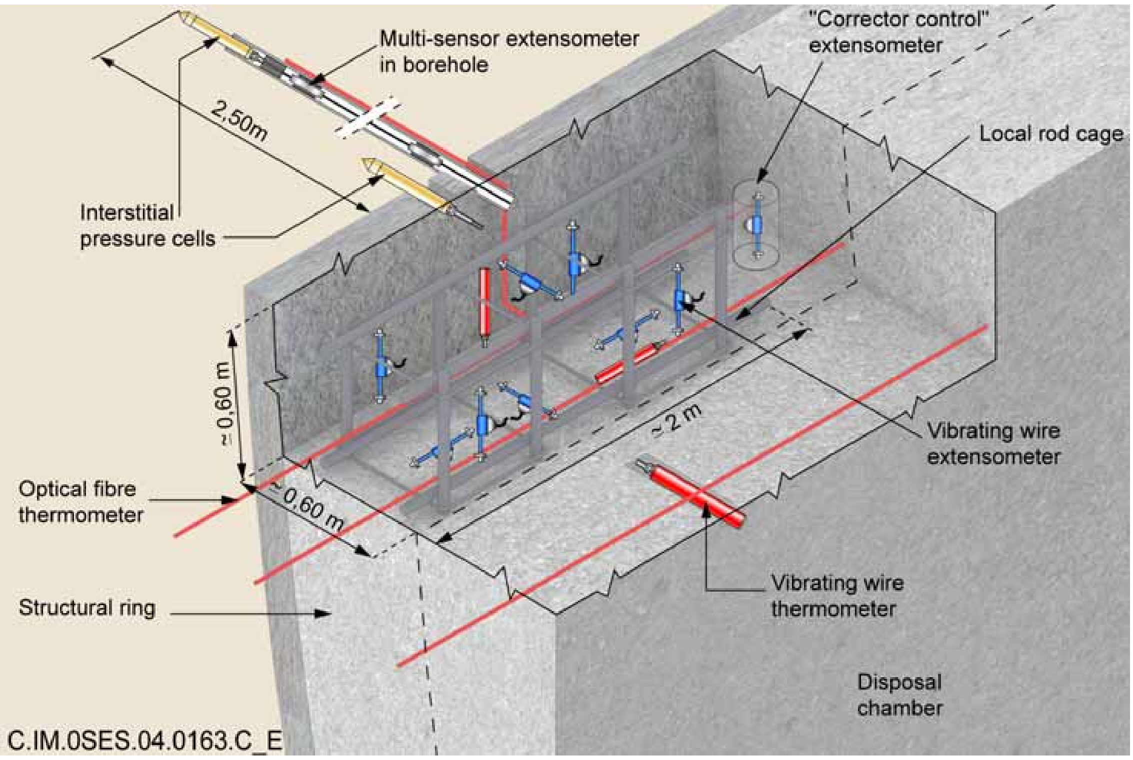

Figure 10.3.12 Monitoring unit in a B control cell

Cell atmosphere monitoring is limited to one temperature measurement near the liner. A vibrating wire sensor is embedded in the filling concrete, the sensitive part protrudes inside the repository chamber. Other characteristic data for this atmosphere, i.e. hygrometry and possible hydrogen concentration, are collected in the ventilation air leaving the cell. In fact, these parameters are difficult to measure in-situ without having access to the sensors to carry out maintenance on them (see below).

The monitoring of the lining can be carried out by a set of vibrating wire extensometers, a control compensating extensometer and two vibrating wire temperature sensors. All these sensors are installed in the lining compression ring, using a reinforcing cage (of approximately one metre in length), before concreting. They are therefore integral with the concrete once it has set.

The vibrating wire extensometers measure local deformations in all three directions. Deformation is measured in the center of the liner thickness, except for tangential deformation which is usually measured at the intrados and the extrados. In addition, redundant measurements will be made systematically. The control compensating extensometer, also set in the concrete, is dissociated from the strength ring so that it is not subject to stresses due to the pressure of the ground. It is therefore used for the precise measurement of deformation due to the contraction of the concrete during setting and to the temperature variations or saturation rates in the immediate vicinity of the other extensometers. It is then possible to calculate the deformation specific to the ground pressure in all three directions.

Each extensometer also provides a temperature measurement so that the acquisition system can correct the raw measurement of "parasite" deformation from the sensor due to temperature variations. These measurements are complemented by two temperature probes placed at the intrados and the extrados to determine the radial thermal gradient, and from there, to calculate the heat flow transferred to the rock from the package or to the ventilated air.

The monitoring of the near-field rock can be carried out by a set of sensors made up of (i) a multisensor inductive core extensometer fitted in a short bore-hole made perpendicular to the cell's axis, (ii) a fiber optic allowing distributed measurement of the temperature in the same bore-hole, and (iii) two interstitial pressure sensors

The multisensor extensometer provides the deferred displacement of the rock in the radial direction. These measurements can be correlated with the deformation in the lining caused by the ground pressure. The length of the bore-hole is limited to a length equivalent to that of the short rock bolts, so as to comply with the long-term safety functions. Consequently, the extensometer anchor point at the bottom of the bore-hole is not fixed, and the displacements measured are relative displacements of points in the rock distant to each other on the order of one metre.

Rock temperature monitoring complements the radial distribution measurement of the temperature field in the atmosphere and in the lining. Variations in the thermal gradient may make it possible to confirm the monitoring of the gradual desaturation of the rock in the walls, with which it is correlated.

The monitoring of the interstitial pressure allows us to monitor rock drainage in the walls and to detect a change in the desaturated state. The sensors are positioned near to the cell wall and at the end of the bore-hole, so as to detect the moment when the rock starts to desaturate, then the radial progression of the desaturation front in the microfissured zone.

- **Distributed measurement fiber optic systems**

Fiber optic systems embedded in concrete all along the structure (one at the intrados, one at the extrados and one in the filling concrete) can enable us to monitor the axial dimension of the thermal field. One of the fibers can be extended to the end of the bore-hole at the bottom of the cell so as to complement the thermal field monitoring in the near-field.

- **Monitoring the ventilation air**

Monitoring the air flow at the cell inlets and outlets enables us to complete the heat balance for the cell, to determine the hygrometry of the atmosphere and at a later date to detect any hydrogen or radioactive gases. The air flow can be easily measured in the return air ventilation duct, while the air temperatures are measured, at the inlet and outlet, with vibrating wire sensors. The humidity sensors (hygrometer), which require regular maintenance, can be installed in the drift and in the air exhaust duct to measure the relative humidity of the inlet and outlet air. Finally, additional measurements can be carried out by means of cell inlet and outlet air sampling systems.

10.3.7.2 The evolution of the module B monitoring system after the packages are put in place

The monitoring system described above is put in place during construction in order to monitor the evolution of the structure for as long as possible during the repository operation and mainly during and after the packages are put in place. The strength and the redundancy of the monitoring equipment envisaged provides a reasonable guarantee that this system will continue to provide reliable data for a sufficient period to allow us to assess the behaviour of the cell during the stage "after the packages are put in place".

The environmental constraints affecting the sensors are moderate. The temperature expected at the sensors should not exceed 50°C providing the cell is ventilated. The effect of radiation on the instruments is reliable as most of these instruments are protected by the concrete lining. No loss of equipment due to the environmental conditions is expected during this stage, except possibly the thermometers installed in the repository chamber wall.

Based on the experience feedback, it is probable that approximately 90% of the pinpoint sensors, will remain operational for at least fifty years. However, the environmental conditions of sensors evolve very little after twenty or thirty years and losses of this type of sensor occur mainly during the first few years of operation. A loss rate of less than 50% appears possible over a century and can be tolerated without causing a disturbance which would endanger the overall monitoring of the structure. It is true that fiber optics sensors have much shorter term experience feedback, (of the order of around ten years), but they do not have characteristics which appear likely to render them fragile in the long term.

The monitoring system, as it has been set up during the construction of the module can therefore be operated during this stage for several decades as regards systems which can not be maintained (especially those in cells). Systems that can be maintained can be operated without any time limitation.

10.3.7.3 The evolution of the module B monitoring system after the cell is sealed

The evolution of the environmental conditions brought about by the construction of the seal, has no significant consequences for the reliability of the sensors which have already operated without any possibility of maintenance since the packages were put in place.

However, the transmission of measurements carried out in the cell is rendered more complex by the presence of the clay core. The need to maintain the hydraulic efficiency of the seal requires a modification in the transmission system. It is important to be able to extend monitoring beyond this milestone in order to ascertain the conditions expected in the cell and the access drift if it is necessary to reverse the process, and dismantle the seal or retrieve the packages.

During a transitional period, the transmission of measurements through the seal is nevertheless a possibility, as long as it does not affect the long term mechanical and hydraulic efficiency of the seal. Several options are under study in this regard. They are founded on wireless transmission or on temporary transmission by cables followed by repairs to the seal.

Since it is not possible to monitor the resaturation, nor the swelling of the seal – which necessitates several thousand years – seal monitoring will focus on the evolution of the rock in the near-field, the possible evolution of the initial state (unsaturated) of the seal, and possibly the incipient resaturation in the vicinity of the grooves.

The monitoring of the seal can be carried out at the location of the two instrumented sections of the access drift, near to the interface between the clay core and the concrete retaining plug (Figure 10.3.13). The monitoring of the lining continues during this stage. It is complemented by several monitoring units integrated into the clay core and the concrete retaining plug.

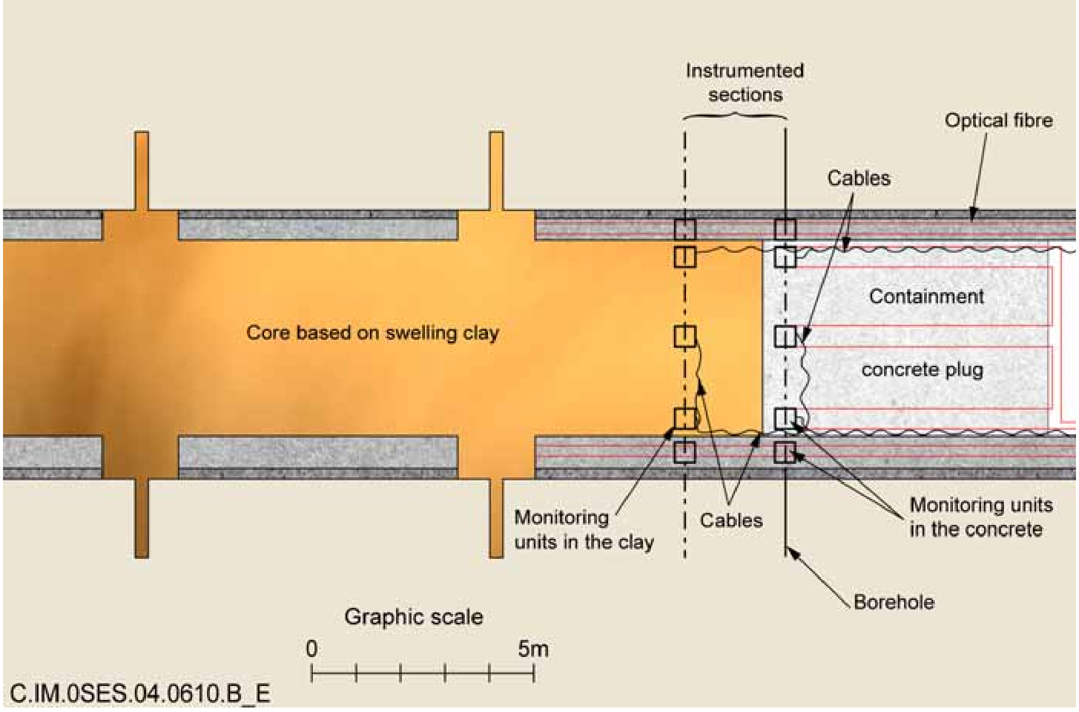

Figure 10.3.13 Monitoring procedures for the downstream part of a seal

The monitoring of the concrete retaining plug relies on monitoring equipment similar to those described for the lining (Figure 10.3.12). The monitoring of the swelling clay is based on the monitoring of the dam cores. It involves the use of groupings of monitoring equipment made up of several fiber optic extensometers, a vibrating wire thermometer, a humidity probe and an interstitial pressure cell.

10.3.7.4 The evolution of the module B monitoring system after the drift is closed

The closure of the internal connecting drifts in zone B necessitates the abandonment of wired transmission equipment leading out of the cell. If it were decided to pursue some of the measurements in the control cells, recourse to wireless transmission would be a suitable option. This wireless transmission through the sealing structures could be relayed by wired equipment in the backfilled connecting drifts.

The lifetime of wireless transmission equipment is limited by the frequency of measurement, the frequency of signal transmissions, by the number of sensors connected to the equipment and by the capacity of the system's batteries. By reducing the frequency and the number of measurements, it is conceivable for the lifetime to be extended to several decades. As an example, the RWMC research programme is aiming at a period of approximately fifty years.

10.3.8 Monotoring of C disposal cells

The observation of C waste disposal cells is essentially focussed on the phenomena which characterise these structures during the different stages of the repository process, i.e.: the evolution of the thermal field in and around the cell, the evolution of the mechanical constraints exerted by the geological formation on the sleeve and the evolution of the atmosphere in the cell which determines the level of corrosion of the metal components.

Different instrumentation options are proposed for C control cells and also for the clay plug which seal the cell. These options are also adapted where necessary to CU3 cells, whose reference design is similar to that of the C0 cells. At the current state of studies, it has been decided not to place any sensors inside the useful part of the cell.

10.3.8.1 The system of monitoring of a C control cell

C cells are different from B cells, drifts and shafts in that they are not accessible during construction as a result of their small diameter. Also, the rapid installation of the steel sleeve prevents the fitting of any monitoring equipment in the rock in the cell wall.

The instrumentation envisaged for a C control cell is made up of several instrumented sections providing specific measurements, fiber optics providing a temperature profile for the whole length of the cell, a cell atmosphere measurement system connected to its metal plug, and instrumented boreholes made in the access drift parallel to the cell's axis (cf. Figure 10.3.14) and, if necessary, in the interconnecting drift perpendicular to the cell's axis. A combination of these techniques offers flexibility and redundancy in the available means of investigative monitoring.

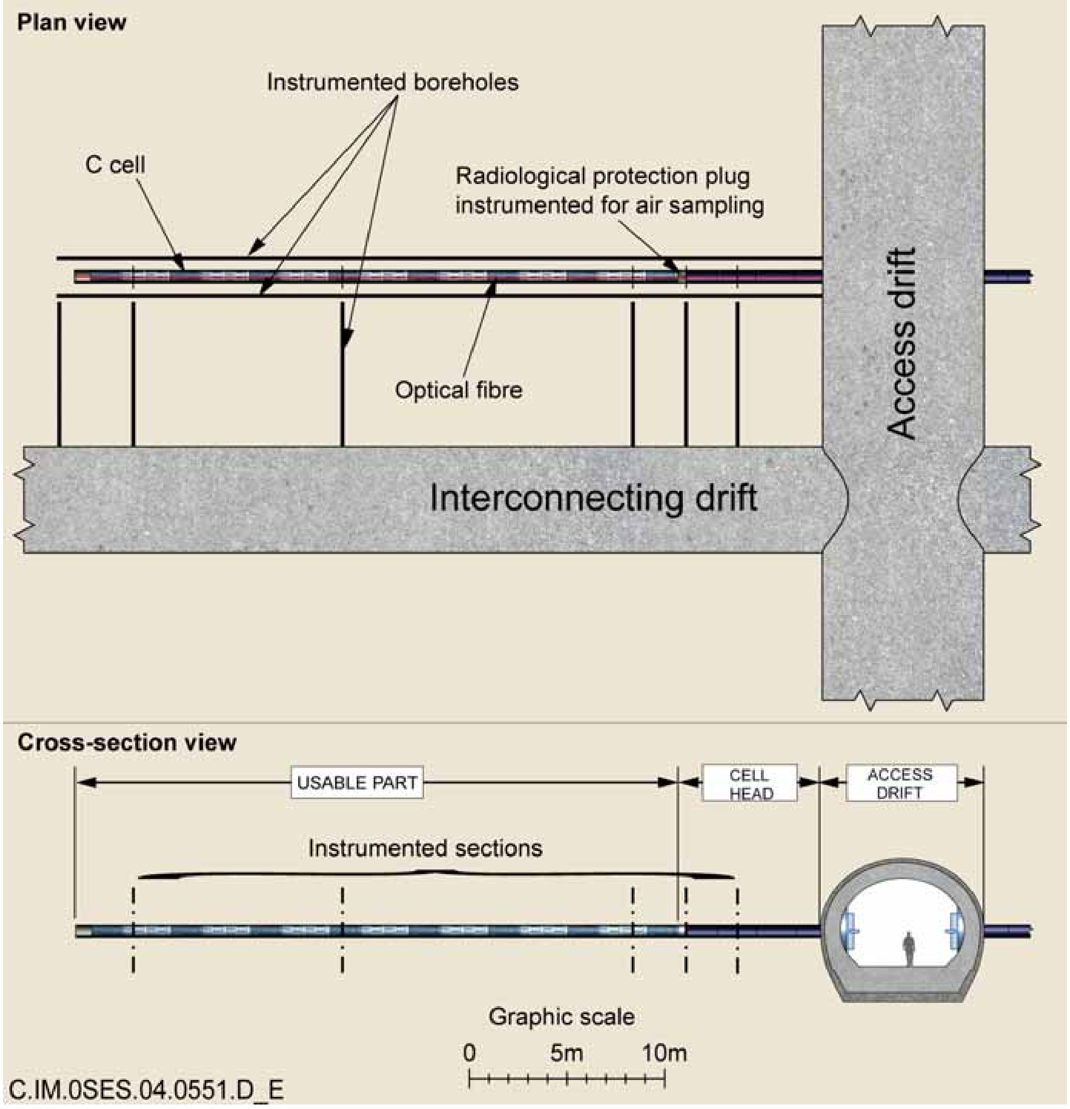

Figure 10.3.14 Monitoring equipment that can be used on a C control cell

- **The instrumented sections and the fiber optic cables**

The instrumented sections are positioned in the main part of the cell (three sections), at the location of the future metal plug (one section) and at the head of the cell at the location of the future clay plug (one section). Each section groups the sensors allowing the monitoring of the sleeve and of the rock around the cell.

The sensors and the transmission cables are attached to the external surface of the sleeve. Three sets of sensors are distributed in an instrumented section, as shown in diagrammatic form in Figure 10.3.15. Each set is made up of two extensometers and a vibrating wire temperature sensor to monitor the temperature and the axial and tangential deformation in the sleeve locally.

Moreover, these sensors are complemented by a fiber optic providing a continuous temperature profile over the whole length of the cell. These measurements also make it possible to assess the thermomechanical stresses to which the sleeve is subjected and also the temperature inside the cell.

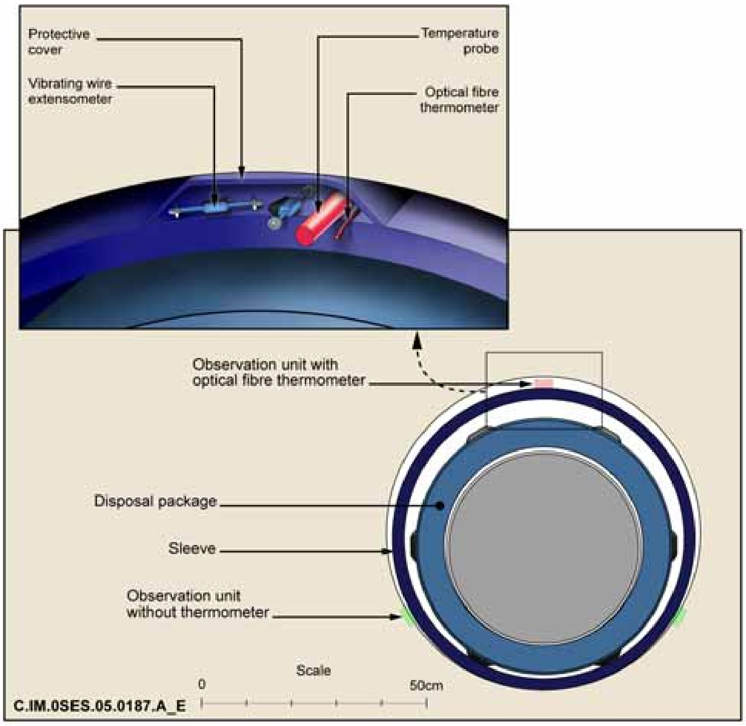

Figure 10.3.15 Example illustrating the surface auscultation of the cell C sleeve

As the sleeve is gradually pushed into place during the excavation of the cell, the sensors and the wired equipment are attached to each section of sleeve, before being inserted into the cell.

To protect the equipment when the tube is being pushed, it is covered with a protection cap welded to the sleeve, as is common practice for the instrumentation of the foundations of structures fitted with metal piles. This cap also enables the rock sensors to be isolated as long as the ground pressure remains at a low level, so that they only measure deformation of the sleeve, and not a combination of deformations of the sleeve and of the rock which would necessitate more complex interpretation.

- **Monitoring the atmosphere in the cell**

The atmosphere in the cell is monitored by a vibrating wire temperature sensor and a hygrometer attached to the internal surface of the metal plug. As the resistance of the sensors to irradiation is not known at this stage of the studies, it may be necessary to move these measurements to the external surface of the metal plug. These measurements are complemented by a laboratory analysis of samples of the atmosphere taken from the useful part of the cell, either by means of a branchpipe passing through the metal plug, or by leaving a capillary tube in the residual clearance between the plug and the sleeve available for use when required. This analysis is designed to ascertain the relative humidity rate and the oxygen rate in the cell, in order to calculate the corrosion rate, if applicable. A similar approach can be used in the sleeve at the head of the cell, from the access drift.

- **Instrumented bore-holes**

An option which is complementary to that of instrumentation of a cell consists in burying sensors in bore-holes parallel or lateral to the cell as illustrated in Figure 10.3.16.

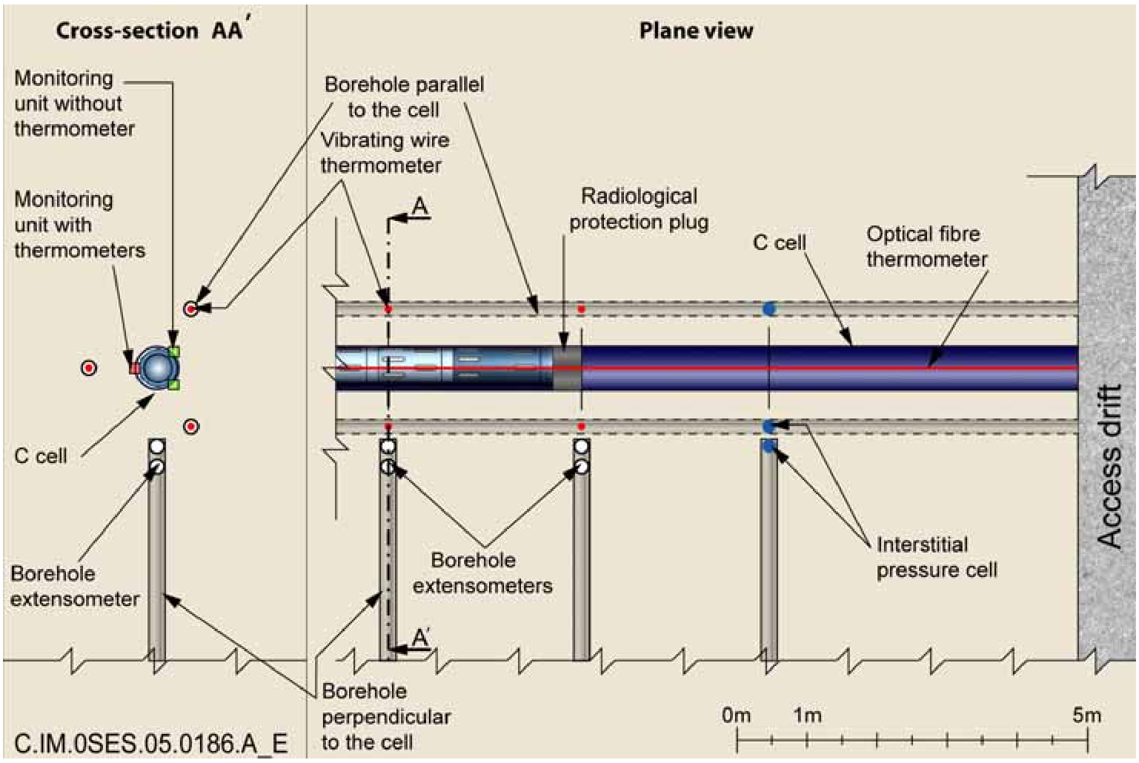

Figure 10.3.16 Monitoring of a C cell on the sleeve and in bore-holes

This type of system enables monitoring of the rock near to the cell. Bore-holes parallel to each control cell are distributed in the same way as the monitoring units on the sleeve. They are carried out from the access drift. The lateral bore-holes are distributed in the same way as the instrumented sections, with an additional bore-hole beyond the bottom of the cell. They are carried out from the interconnecting drift.

Several extensometers, thermometers and interstitial pressure cells can be incorporated into these bore-holes. They complement the deformation and temperature measurements carried out on the sleeve. In particular, they make it possible to determine the thermal field in the wall and near to the cell and the field of stresses in the rock and in the sleeve. Also, the monitoring of reductions in interstitial pressure near to the head of the cell provides a more accurate basis for developing models of prediction of any desaturation of the rock near the temporary sleeve.

Instrumentation in bore-holes has several advantages in relation to instrumentation in the sleeve. Firstly, the near-field of the control cell can be monitored, without being curtailed by the fitting of the cell plug. Moreover, the environmental conditions in the rock, and particularly the dose rate from the cell, do not constitute great limitations on the reliability or the lifetime of the monitoring equipment.

10.3.8.2 The evolution of the C control cell monitoring system after the packages are put in place

The mechanical and hydraulic evolutions and possible corrosion, initiated during the construction of the cell, continue after the packages are put in place. Moreover, this insertion of the packages causes heating in the structure and the near-field.

The deformation measurements carried out on the sleeve indicate the zones that are compressed, in response to loads due to a combination of ground pressure and thermal expansion of the sleeve. Temperature monitoring allows accurate interpretation of the data.

Also, the monitoring of temperatures on the sleeve allows us to check compliance with the thermal criteria ($T < 90$ °C in contact with the argilite).

The monitoring equipment installed on the upper part of the sleeve and at the head of the cell is subject to relatively high temperatures. It is also subject to a dose rate which may contribute to the deterioration of the electronic circuits. The dose rate is approximately 2 Sv/h on the side surface of a C2 disposal package (envelope for the other families of C package) [107]. The sensors tend to absorb the dose rate received, and this leads to a gradual loss of reliability. It will therefore be necessary to quantify the reliability of these sensors subjected to radiation in the long term.

However, the monitoring equipment fitted in the bore-holes are not subject to high level constraints after the packages are put in place. The temperatures remain relatively low for around ten years and the dose rates emanating from the cell are absorbed by the rock. The experience feedback shows that around 90% of sensors remain operational for a period of several decades. They provide redundancy as regards the losses expected in the sensors integral with the cell's components.

In an analogous manner to the B control cells, the monitoring system as set up during construction for a C control cell can therefore in theory be operated without maintenance for several decades during this stage. It should nevertheless be noted that after an indeterminate period, there is a risk of losses of the sensors integral with the sleeve, whilst sensors integral with the metal plug can be replaced as required.

10.3.8.3 The evolution of the C control cell monitoring system after the cell is sealed

Installing the closure plug does not modify the environmental conditions in the cell to a great extent, neither does it have implications for the operation of the bore-hole monitoring equipment.

It does however modify the measurement transmission conditions of sensors integral with the cell. Firstly, unless a customised system has been provided for during the installation, wired transmission on the outer surface of the sleeve is cut at the metal plug, as soon as the temporary sleeve is removed. Secondly, the transmission of measurements from the head of the cell (attached to the metal plug) must be adapted for the presence of the cell plug.

It is for example possible at the time of construction, to fit the control cell with a wired transmission system redirected through a lateral bore-hole near the metal plug. It would not be disturbed by the removal of the temporary sleeve, nor by the fitting of the cell plug. This option makes it possible in theory to extend the monitoring of the sleeve and the cell atmosphere up to the next stage, that is to say the closure of the operating unit. Before carrying out the closure, it is nevertheless necessary to cut the wired equipment and to seal the lateral bore-hole, in order to restore the hydraulic properties compatible with long term safety.

As in the case of B cells, it is also possible, during a transitional phase which may be as long as several decades, to install a wireless transmission system. A common RWMC/ANDRA research project focuses in particular on the transmission from the useful part of a cell, through a swelling clay plug supported by a concrete plug, to the drift. In the first stage, the transmission system could be integrated into the metal plug, as illustrated in Figure 10.3.17.

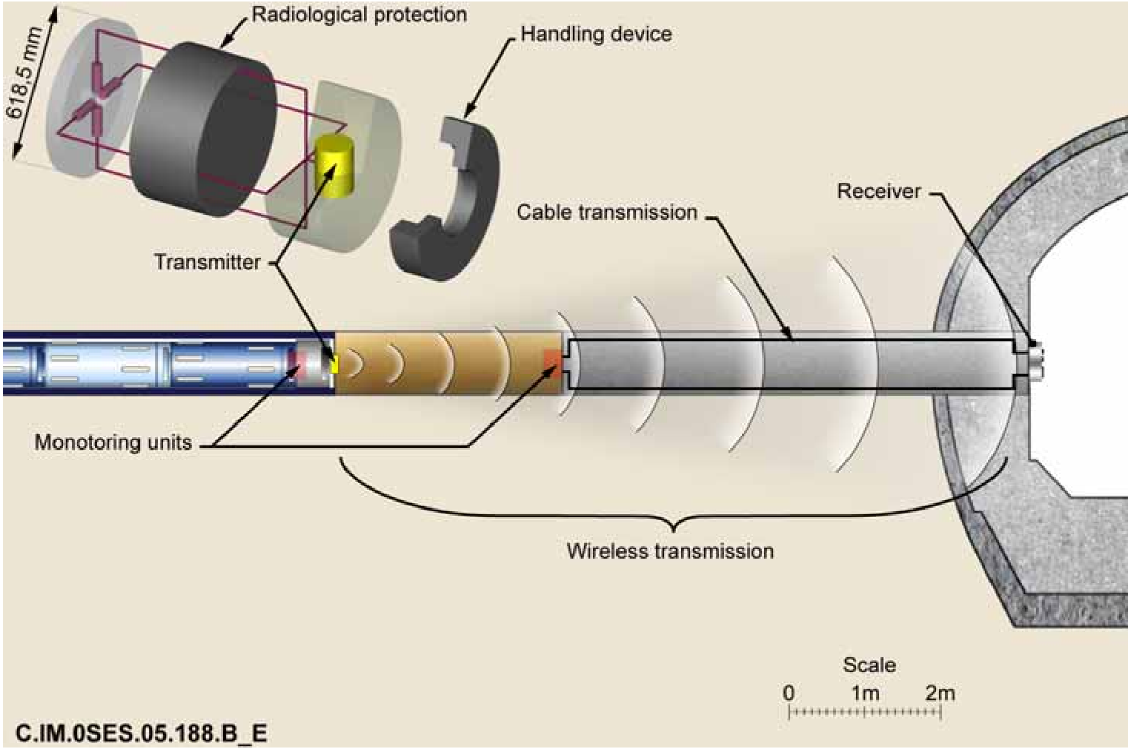

Figure 10.3.17 Wireless transmission system passing through a C cell plug, currently under study

Data transmission from the cell may be complemented by the monitoring of the swelling clay plug. It could be carried out by installing a set of sensors, similar to that described for the monitoring of the clay core of a B cell seal (cf. 10.3.7.3). So as not to diminish the long-term hydraulic efficiency of the cell plug, this monitoring equipment would be positioned in an instrumented section near to a concrete retaining plug. This equipment would make it possible to monitor resaturation and localised deformation of the plug due to the combined effect of settlement , rock deformation and the swelling of the clay. It would provide useful information if it were necessary to revert to the previous stage, and would enable us to confirm the evolution of the plug as regards the expected long-term hydraulic performance.

In summary, the monitoring of the evolution of the near-field in bore-holes is not affected by this stage. The lifetime and the reliability of the sensors embedded in the sleeve or in the cell are not degraded to a greater extent as a result of the fitting of the cell plug. Wired or wireless transmission options can be envisaged, which allows the acquisition of certain measurements to continue after cell closure.

10.3.8.4 The evolution of the C cell observation system after the drift is backfilled

The backfilling of the access drifts does not impose additional constraints on the reliability or the lifetime of the sensors. The only way of transmitting signals from the cells is to make use of wireless transmission to the drifts. As for the case of B modules, the concrete lining in the drifts and the backfill allow the presence of wired equipment. It can thus carry out transmissions from the entrance of a cell up to the accessible connecting drift.

In addition, the evolution of cells can be determined indirectly by the monitoring of the near-field of the operating unit. The measurements in instrumented section of the access drifts and the temperature measurements obtained via fiber optic distributed along the whole length of all the drifts can be continued without interruption, until the following stage when the connecting drifts are closed.

10.3.9 Observation of spent fuel disposal cells

This section describes the observation equipment which could be envisaged in the spent fuel control cells, if necessary. This equipment is similar to that described for C cells. The spent fuel cell differ from C waste cells in that they contain two additional components: the buffer and the metal lining of the cell. Accessibility during the construction phase allows instrumentation of the near-field through the perforated lining. Finally, it is possible to install the sensors in the prefabricated buffer rings before they are put in place.

The distribution of the instrumented section is comparable to that described for the C cells. An instrumented section of a control spent fuel cell (cf. Figure 10.3.18) is made up of three monitoring units, incorporating the monitoring of the sleeve, the buffer, the lining, and the rock.

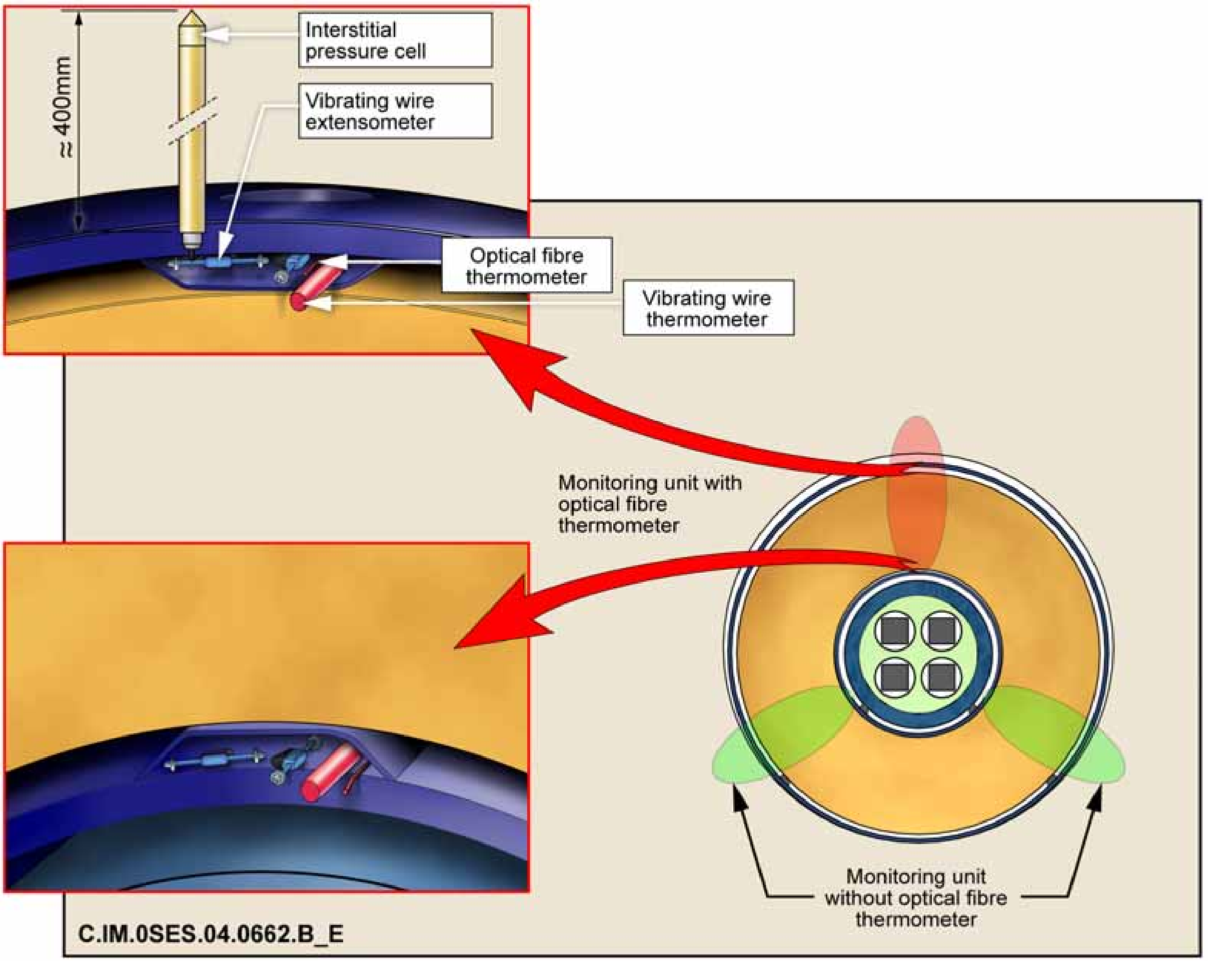

Figure 10.3.18 Instrumented section of a spent fuel cell

The sensors put in place on the extrados of the sleeve and on the intrados of the lining are identical to those described in section 10.3.8.1 (cf. Figure 10.3.15). The monitoring units in the swelling clay buffer are identical to those proposed for the clay core of B cell seals or C cell plugs. Also, an interstitial pressure cell is embedded in a radial bore-hole in the host rock.

Therefore, the monitoring equipment makes it possible to monitor thermal and mechanical evolutions of the structure and the hydraulic evolutions of the near-field. Their combination makes it possible to identify any thermomechanical effects.

When the packages are put in place this may reduce the cell monitoring capacity as the evolution of the condition of the thermal and radiological environment may gradually reduce the reliability of the sensors on the sleeve. These conditions are less restrictive outside the buffer, which attenuates the dose rate and imposes a radial thermal gradient. Thus, the lifetime of the monitoring equipment can be extended to several decades outside the buffer.

Cell sealing leads to gradual resaturation of the swelling clay in the cell plug and imposes the same transmission constraints as those set out above for B and C cells. In addition to the bore-hole transmission options or the use of a wireless system, the concept of a spent fuel cell offers the possibility of routing the cables through the metal lining.

As the drifts are gradually closed, the evolution of the monitoring system, which relates essentially to the measurement transmission equipment, is identical to that described for the C cells (§ 10.3.8.4).

10.3.10 The monitoring system of standard cells

The distribution of the monitoring equipment proposed in the above sections are appropriate for the monitoring of a selection of control cells. The monitoring of the standard cells relies upon a smaller amount of equipment. It is suggested that a standard B cell contains fiber optic cables and an instrumented section in the useful part of the cell. A standard (C or CU) cell contain the fiber optic and an instrumented section at the metal plug.

10.3.11 Observation of drifts

The monitoring of drifts focuses on the main phenomena which characterises these structures, in particular the initial deconfinement of the host rock, the formation of a damaged zone, a gradual desaturation of the near-field, the creep of the rock and the re-pressurising of the lining.

10.3.11.1 Drift observation system

The options for the use of monitoring equipment are comparable to those described for the B cells (cf. section 10.3.7.1). They are based on instrumented drift sections. One such section is illustrated in Figure 10.3.19. Only the depth of the bore-holes, which makes it possible to install a greater number of extensometers, differentiates it from an equivalent section of a B cell (cf. Figure 10.3.1).

The sensors distributed in eight monitoring units make it possible to monitor the mechanical strength and the dimensional stability of the structure, the hygrometric conditions in the drift, the mechanical and hydraulic evolutions in the near-field, the evolution in the thermal field, and possibly the chemical modification undergone during the operation period.

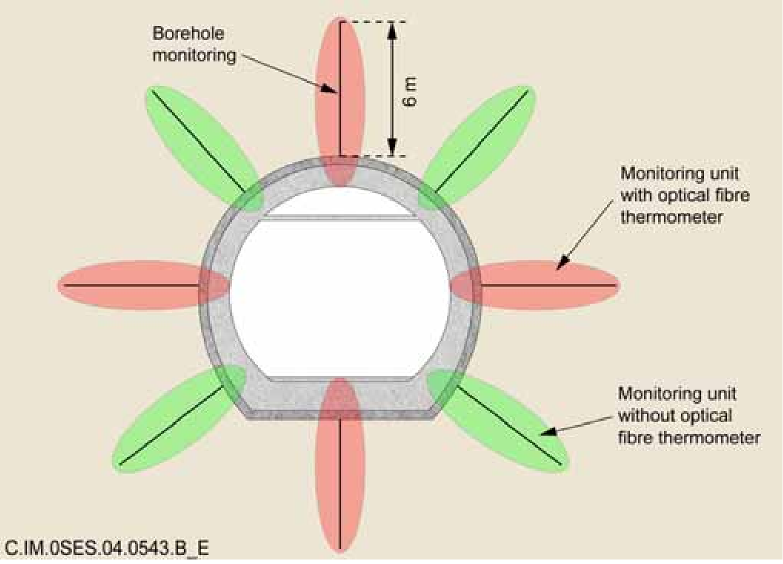

Figure 10.3.19 Illustration of the monitoring equipment distribution options in a drift section

These instrumented sections (cf. § 10.3.6.1)) are distributed along the length of the drifts. Also, they can be complemented by an overall visual inspection of the structures (or by optical means) and by measurements distributed by fiber optic cables integrated into the lining.

It must be pointed out that the connecting drifts also offer possibilities for the observation of the near-field, either of a cell, or of a module, without being restricted by their closure stages. Depending on the choice of sensors installed in the bore-holes made from these drifts, this allows monitoring of temperatures, interstitial pressures or deformations in the vicinity of the structure.

The monitoring of the drifts and specifically of their near-field, provides indications regarding the interaction between cells, which takes effect from the first years of repository for highly exothermic packages, and, after several decades, between modules. For example, the gradual homogenization of the thermal field and of the interstitial pressure could thus be monitored.

10.3.11.2 Evolution of the drift monitoring system after the packages are put in place then after the closure of the cells

Placing the packages in the cells and closing the cells causes the drifts to heat up over time. The extent of the heating is limited, even negligible when the drifts are ventilated, and this heating has no significant consequences on the reliability or the lifetime of the sensors. Their lifetime is comparable with that demonstrated by the experience feedback in other structures and varies in each case between several decades and approximately a hundred years.

Moreover, while the drifts are still accessible, their monitoring system can undergo maintenance. The fact that it is possible to install new sensors to replace faulty ones guarantees monitoring continuity for these structures with no time limit before their closure.

10.3.11.3 Evolution of the drift monitoring system after closure

The monitoring of drifts after they have been closed makes it possible amongst other things to ascertain the state of the lining and thus the condition if it should be necessary to reverse the process. It would also be possible to monitor any settling of the backfill and the seal, as illustrated for the sealing of a B cell (cf. 10.3.7.3).

The closure of a drift section causes very slow resaturation and, depending on its position, moderate and heating which takes place more or less slowly. In all cases, the evolutions expected during the operating-observation phase are not likely to affect the lifetime or the reliability of the monitoring equipment.

The installation of a drift seal restricts the transmission of signals from the upstream part (furthest away from the shaft) of a repository. As long as the seal remains accessible downstream, the different transmission options described for the sealed B cell remain available. When the seal is made inaccessible by backfilling of a further length of drift, wired transmission via the seal is no longer feasible. Monitoring of the part upstream from the seal, and of a section of the seal itself, can only be maintained by means of wireless transmission through the seal (see section 10.3.7).

10.3.12 Observation of shafts

The monitoring of shafts is directed to the main phenomena which characterise these structures, similar to those encountered with drifts, whilst taking account where necessary of the specificities of the geological layers passed through. All shafts are instrumented.

10.3.12.1 Shaft observation system

The equipment used in the shafts are divided into eight sections, located in different horizons of the geological environment (cf. Figure 10.3.20). Their vertical distribution depends on the presence of direct pendulums integrated into a duct in the lining, in order to monitor the overall dimensional stability of the shaft. The experience feedback relating to their use in dams and confinement enclosures suggests that the height of each pendulum should be limited to between approximately 60 and 80 metres.

In this way, all the sections (except for the section at the bottom of the shaft) are spaced out at approximately 80 metres. Three sections are proposed for the instrumentation in argilite: one at the bottom of the shaft, one at the repository horizon and another at the top of the Callovo-Oxfordian formation. Three sections are distributed in the upper and mid Oxfordian limestones. One section allows monitoring in the Barrois limestones and another in the Kimmerigian marl layer (located at approximately –100 metres for example).

Each section allows detailed monitoring of the shaft lining and the near-field. Four radial direction monitoring units seem to be sufficient to detect any asymmetry in mechanical evolution, as shown in Figure 10.3.21. The monitoring equipment installed in each unit resembles the equipment described for B cells (see section 10.3.7) and for the drifts (see section 10.3.11) with the exception of deeper radial bore-holes and the presence of the measurement table for a pendulum in one of the units.

The details of a monitoring unit, including the measurement table operating the vertical pendulum relating to the corresponding section, is illustrated in Figure 10.3.22.

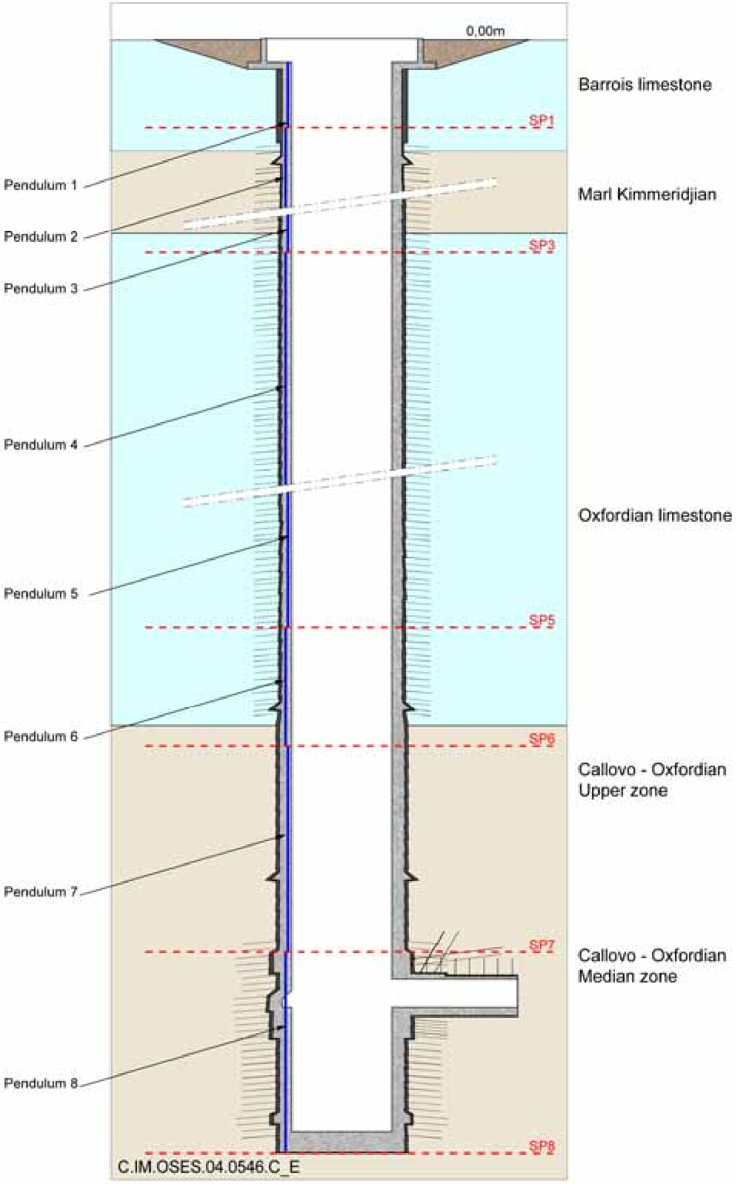

Figure 10.3.20 Distribution of the instrumented sections and the pendulums in a shaft

It makes it possible to monitor the mechanical strength and the dimensional stability of the structure and the mechanical and hydraulic evolutions of the near-field. It should be noted that the pendulum measurement table enables the measurement of relative displacement of the lining in three direction, for a height corresponding to that of the pendulum (separating two instrumented sections). The pendulum chain on a generator line enables the displacements to be cumulated in the three directions and allows calculation of the overall deformation over the whole depth of the shaft.

The monitoring equipment embedded in the structure and in the rock can be complemented by accessible equipment in the wall. In this way, it is possible to measure a seepage rate on the internal wall of the lining, an inlet air flow rate or the hygrometry and the temperature of this air.

As is the case for connecting drifts, the durability of the monitoring system before closure of the shaft is ensured by the possibility of maintenance, by replacing the faulty sensors or adding new sensors in the sections where the sensors which are buried in the lining no longer operate.

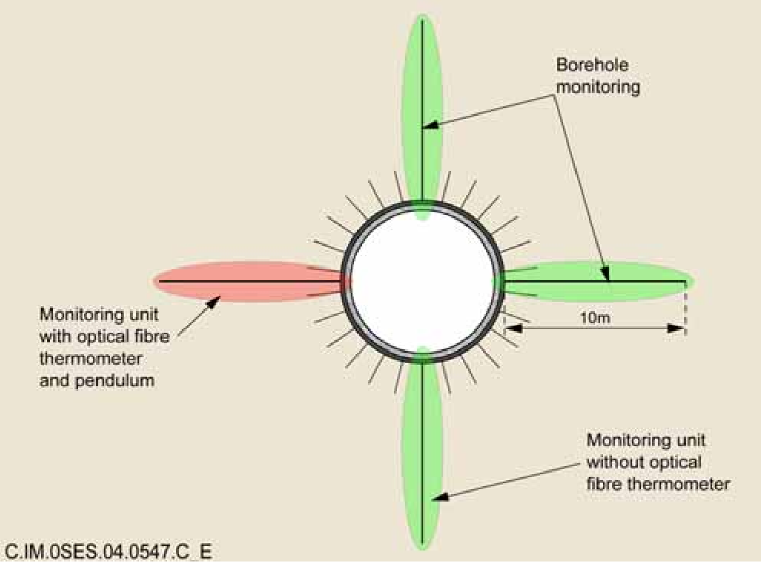

Figure 10.3.21 Instrumented section of a shaft

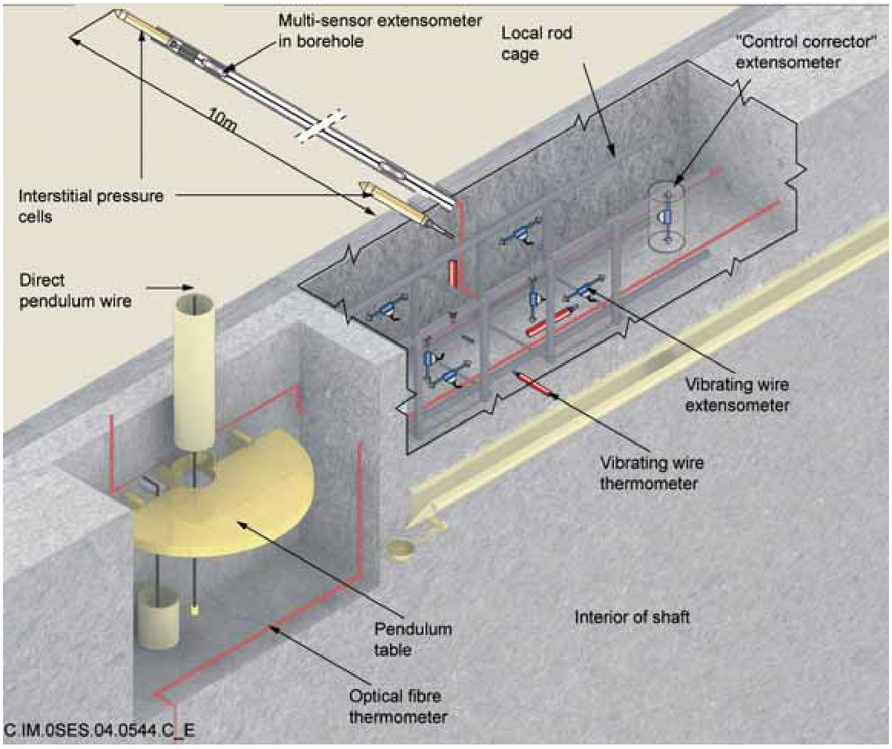

Figure 10.3.22 Equipment installed in a monitoring unit in a shaft wall

Figure 10.3.23 shows a cage with vibrating wire extensometers used in the shafts of the Meuse/Haute-Marne underground laboratory.

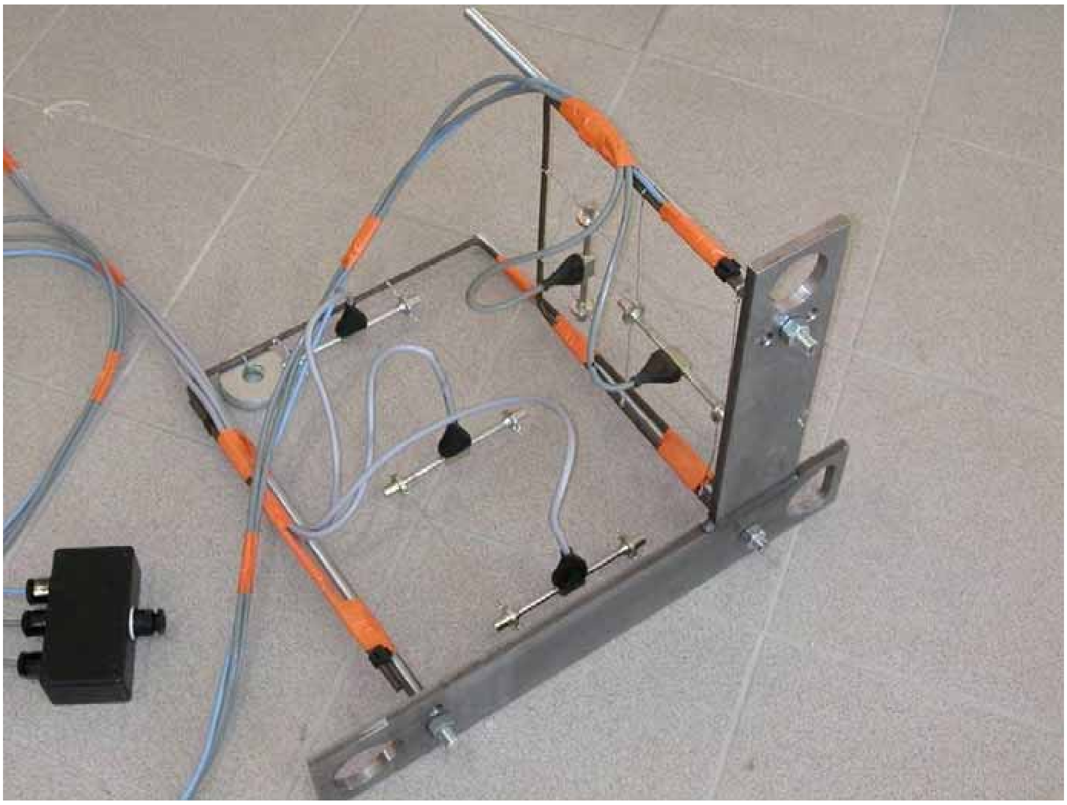

Figure 10.3.23 Cage with Vibrating Wire Extensometers

10.3.12.2 The evolution of the shaft observation system after the shaft is sealed

The structure sealing works include the removal of the lining at the location of the seal. The monitoring equipment is therefore also removed. The sealing operation does not affect the lifetime, nor the reliability of the monitoring equipment outside the sealing zone. The measurements made downstream (on the surface) can therefore be continued and transmitted to the surface. The upstream measurements (deep side) can, during a transitional period, be transmitted by wireless equipment (see paragraphs 10.3.5.3 and 10.3.7.4). If it were decided to seal one particular shaft before the others, these measurements could also be transmitted through one of the shafts that are still accessible. It should be noted that in all cases, it is possible to install monitoring equipment in two sections (upstream and downstream) of the seal, without significantly affecting its long-term hydraulic performance.

10.3.13 Conclusion regarding the contribution of observation to the reversible repository management process

The observation of the structures and in particular the cells enhances the phenomenological evolution of the repository process. It allows us to quantify the parameters which characterise each stage of the process, provides a reassessment of the lifetime of cells and specifies the information required to evaluate the conditions for possible retrieval of the disposal packages. All this information contributes to the underpinning of the decision to proceed from one stage of the repository process to the next with objective scientific and technical data. In the case of B cells, the observation enables us in particular to track the mechanical evolution of the lining upon which the lifetime of the cells depends. It also makes it possible to quantify the gases produced by the waste and to understand the conditions of a possible retrieval of the packages.

In the case of C waste or spent fuel disposal cells, the observation enables tracking of the thermal field created by the exothermicity of the packages and the verification of its mechanical incidence. It also permits tracking of phenomena such as the resaturation level or the composition of the atmosphere in the cell which conditions the evolution of the sleeve in terms of corrosion and stability and which therefore affects the conditions of possible retrieval of the packages.

In the case of access structures (shafts and drifts), the observation enables the tracking of the mechanical evolution of the linings and the identification of possible maintenance requirements allowing an extension of their lifetime. It also makes it possible to monitor the mechanical evolution of the near-field behind the lining at future seal emplacements and in particular the formation and evolution of a possible damaged zone.

The industrial experience feedback in the monitoring of large civil engineering structures shows that it is possible to observe the repository process for a period greater than 50 years thanks to the use of a measurement system made up of proven reliable sensors (vibrating wire sensors for example). Beyond this time scale, the observation system can be re-arranged in particular when passing from one stage to the next, by installing new sensors and a new data transmission technology. As an example, the installation of cell seals could give rise to the installation of wireless transmission technology (tested with success in the Meuse-Haute Marne laboratory) so as not to affect the integrity of the swelling clay plugs by cable penetration. Thus the use of durable sensors and the gradual adaptation of the monitoring system enables us to envisage the observation of structures throughout the entire repository process, on the considered time scales for reversibility (one or more centuries)

Finally, the principle of focusing the observation of the phenomenology of the repository process on judicially selected structures (control structures), as they are representative of the whole of the zone in question, constitutes an operationally realistic basis.

10.4 The capacity for package retrieval

The retrieval of the disposal packages is an operation that may be decided upon by future generations.

The aim of this section is to highlight the design factors that would facilitate the retrieval of packages and to assess the feasibility of this operation for the following three key stages:

- after the packages are put in place (cell not sealed),
- after cell closure (access drift accessible),
- after closure of the module drifts (connecting drifts accessible).

The analysis of the conditions and equipment required for retrieval is related to the phenomenological evolution described in section 10.2 and in particular to the evolution of the materials over time. This analysis is illustrated by a few examples of technical solutions [106].

The retrieval of C waste packages and spent fuel will be dealt with jointly as the two concepts have similarities in terms of cell geometry (moderately-sized drifts with metal sleeves), and of the package (cylindrical metal package), and in that there is no concrete in the structure or in the handling system (pushing robot or airborne carrier)

The retrieval of the B packages will be addressed separately. The B concept, unlike the previous concepts, is characterised by a large structure lined with concrete, concrete parallelepiped packages and a lifting truck handling system.

10.4.1 Retrieval of B packages

10.4.1.1 Design factors favourable to package retrieval

The design of the packages and B disposal cells is characterized particularly by the stability of the lining which helps sustain the functional clearances within the cell and by the durability of the waste packages. Both facilitate retrieval operations, where required.

- **Stability of the cell liner and durability of functional clearances**

The cell lining has two favourable characteristics for a retrieval operation.

Firstly, its dimensioning: the selected materials it is made up of (mass concrete) and its physical and chemical environment provide for the durability and stability of the structure which houses the packages for a period of at least a few centuries.

Moreover, the shape of the lining is designed to minimise residual clearances between the lining and the disposal packages to avoid filling work which would imprison the packages and render them integral with the structure. The repository chamber, which has a square cross-section, provides residual spaces between the stacks of packages and the lining with a width of the order of 10 cm along the whole length of the cell. These clearances, which are unfilled, remain unchanged for a period equal to that of the lining's lifetime. The packages remain free inside the cell. These conditions are the same as those prevailing during the phase in which they are implaced. (Figure 10.4.1).

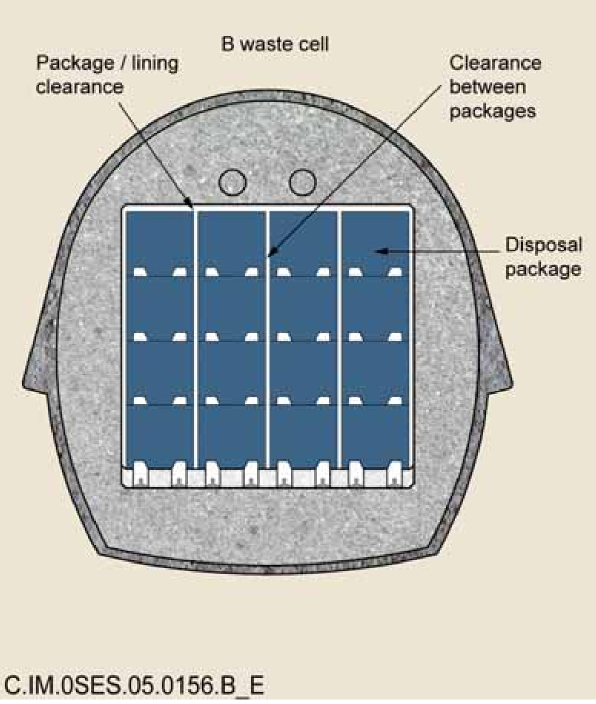

Figure 10.4.1 Functional clearances – Cross section of a B package disposal cell

- **Durability of disposal packages**

The choice of concrete for the composition of disposal packages will provide multi-century mechanical durability, especially in a weakly aggressive environment. Regarding the reinforced concrete solutions selected, the corrosion phenomenon of the reinforcement rods is prevented through the use of multi-century, non-porous compact concrete, an adequate thickness of concrete liner and the use of stainless steel for the frames.

Lastly, the strength of the disposal package also durably limits–over a period of several centuries–the risks of dispersal of radioactive elements within the cell.

10.4.1.2 Retrieval conditions at the “After package emplacement” stage

All of the equipment in the radiation chamber (port door and rotating table) is left in place. Ventilation of the cell is maintained.

When all the packages have been placed in the cell (Figure 10.4.2), a radiological protection wall consisting of concrete blocks may be erected between the last stacks of packages and the internal shielding door at the head of the cell, whereby making cell maintenance easier.

Packages may be withdrawn at any time, just like in a storage situation. However, a serviceability inspection of the cell head section shall be conducted prior to this operation.

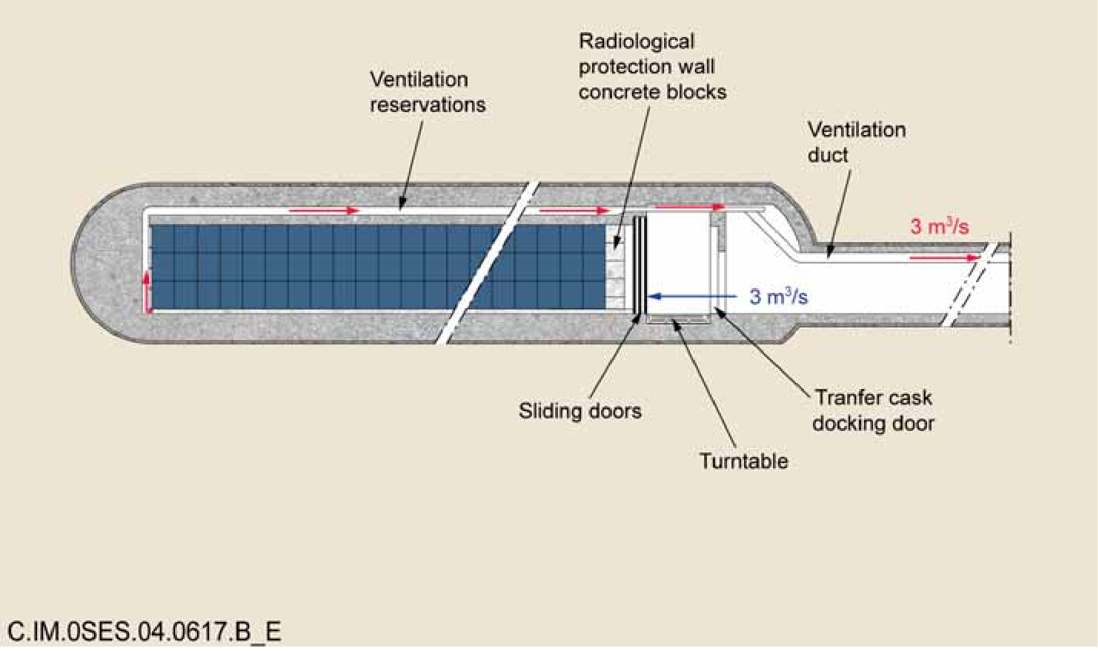

Figure 10.4.2 Cell filled with B packages at end of operation

- **Prior serviceability inspection process of the cell head section**

The restoration phase required prior to the retrieval operations is limited to routinely checking the chamber equipment if the packages were retrieved a few years after emplacement, and to replacing the same, possibly outdated, equipment if this operation were to be performed after several decades.

The only mechanical unit inside the cell is the steel track-mounted bearing system. The functionality of this unit during this phase is not compromised by the phenomenological evolution of the cell.

- **Package retrieval process**

The equipment and process used to retrieve the packages from the cell–after the radiation chamber has been restored–are strictly identical to the ones used for package emplacement. However, for safety purposes, a check for possible fragmental debris resulting from a damaged lining shall be conducted using a camera mounted on the forklift. A machine equipped with a manipulator arm may be used where such debris is found.

Management of the disposed packages may, at this stage, be performed as in a warehouse over 100-year to multi-century periods of time.

10.4.1.3 Retrieval conditions at the “After cell closure” stage

The "After cell closure" stage corresponds to the configuration in which the cell is sealed by a plug of swelling clay mechanically constricted by two concrete shells(Figure 10.4.3). At this stage, the connecting drift remains accessible and retrieval of the packages is still technically feasible, although this entails more complex operations than in the previous stage. Access to the packages requires prior dismantling of the seal and reconditioning of the cell access drift and of the radiation chamber.

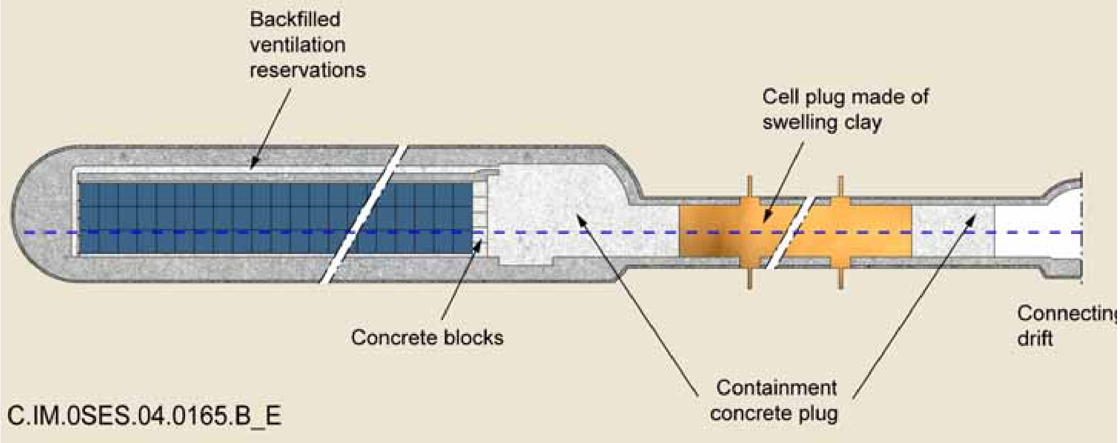

Figure 10.4.3 Cell filled with B packages after sealing

● Cell restoration to workable condition process

After closing the cell, the package retrieval operation proper is preceded by a phase for characterizing the condition of the cell and of the packages contained therein. The characterization results are then utilized to determine the prior work to be undertaken to restore the cell to its workable condition.

Checking the cell atmosphere

Checking the atmosphere in the cell may be performed by means of a horizontal drilling tube inserted into the drift entrance and run through the seal down to the internal side of the cell head section concrete fill (Figure 10.4.4). This drilling should be carried out in a neutral atmosphere maintained by an airlock.

Once drilling is complete, the cell may be subjected to atmospheric pressure and its atmosphere may be checked. This check consists in drawing and analysing a gaseous sample from the drilling operation performed in the seal. Its purpose is to verify the hydrogen and radioactive gas content of the sample. Should the hydrogen content of the cell atmosphere exceed the lower explosive limit (4% of hydrogen), the cell atmosphere shall be renewed. The atmospheric check shall be performed as close to the cell as practicable by means of a portable device including a vacuum pump, a safety filter, a pressure gauge and a hydrogen detector.

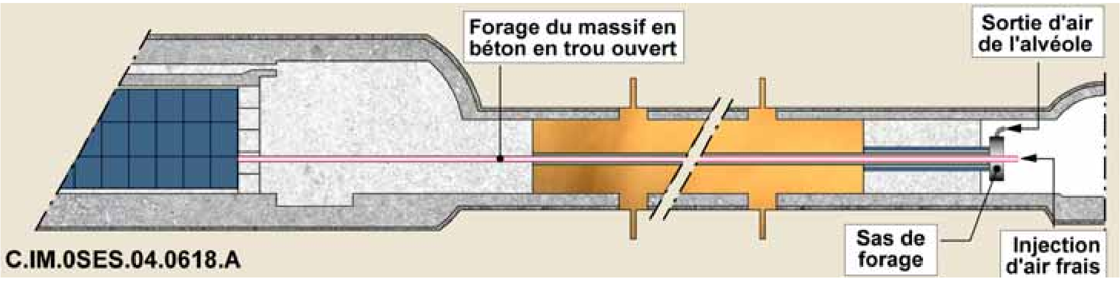

Figure 10.4.4 Checking the atmosphere of a B cell by drilling

Cell ventilation

When drilling is complete, it is recommended–for the purpose of the ensuing operations–to discharge the hydrogen from the cell (especially for cells containing B2/B3/B4/B6.4 type packages) as well as the gaseous radionuclides given off by the packages, if any. Ventilation also reduces the temperature on the access drift wall in the case of cells containing low exothermic packages (B1 and especially B5 type packages).

Ventilation of a 250-m long cell requires supplying fresh air at one end and retrieving exhaust air at the other end.

Several solutions may be considered to restore ventilation. One solution is to drill an air drift built specifically for package retrieval, thus removing the air through the bottom of the cells (Figure 10.4.5 and Figure 10.4.6).

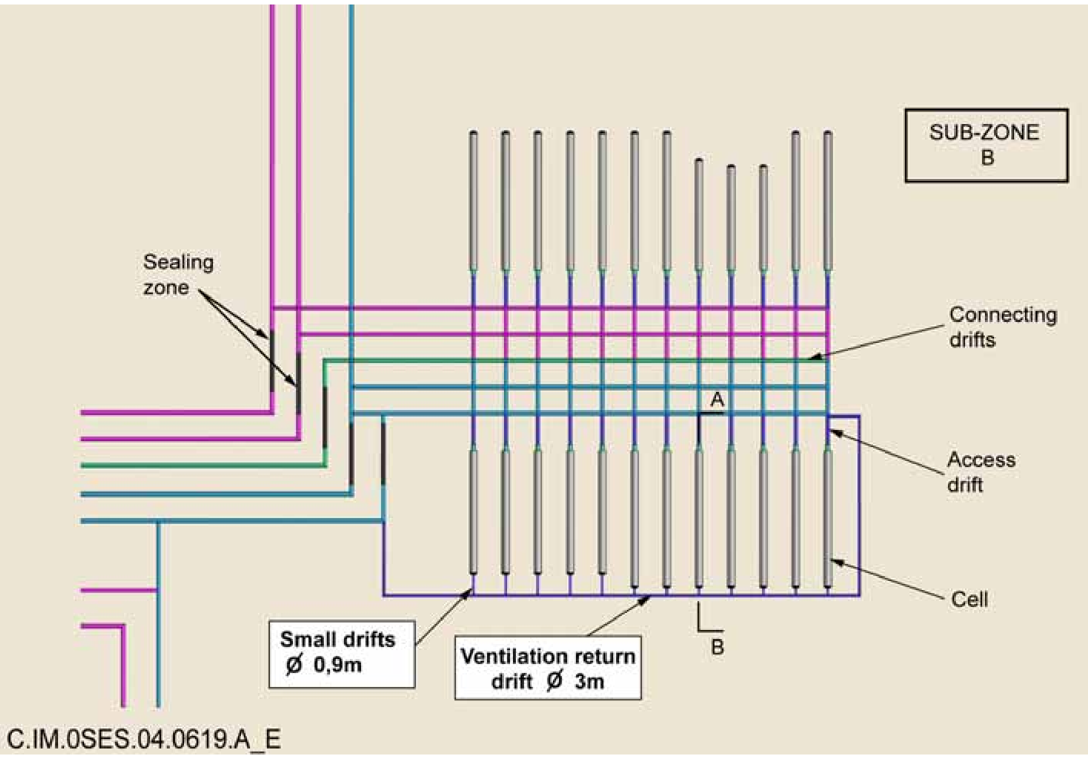

Figure 10.4.5 Top View of Airway with Antennas

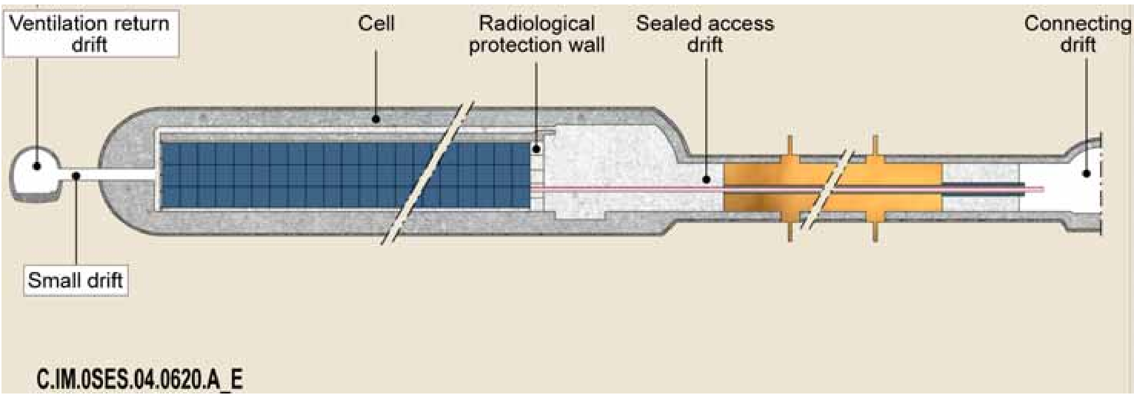

Figure 10.4.6 Construction of the Ventilation Airway

Deconstructing the Seal and Reconditioning the Access Drift

Restoring the access drift to its operating condition consists in clearing the seal down to the liner, then re-installing the same equipment as was used for waste package emplacement. A roadheader type machine is suitable for removing the materials from the seal (compacted clay and concrete) without adversely affecting the liner of the drift. The liner portions dismantled at the grooves are reconstructed using formed concrete. The areas of the liner with surface roughness after the boring operation can be repaired using standard civil engineering techniques.

Deconstruction work is complete when the radiological protection wall consisting of concrete blocks is reached.

Figure 10.4.7 describes the deconstruction process. It takes approximately the same amount of time to clear the seal and recondition the access drift as to build the drift.

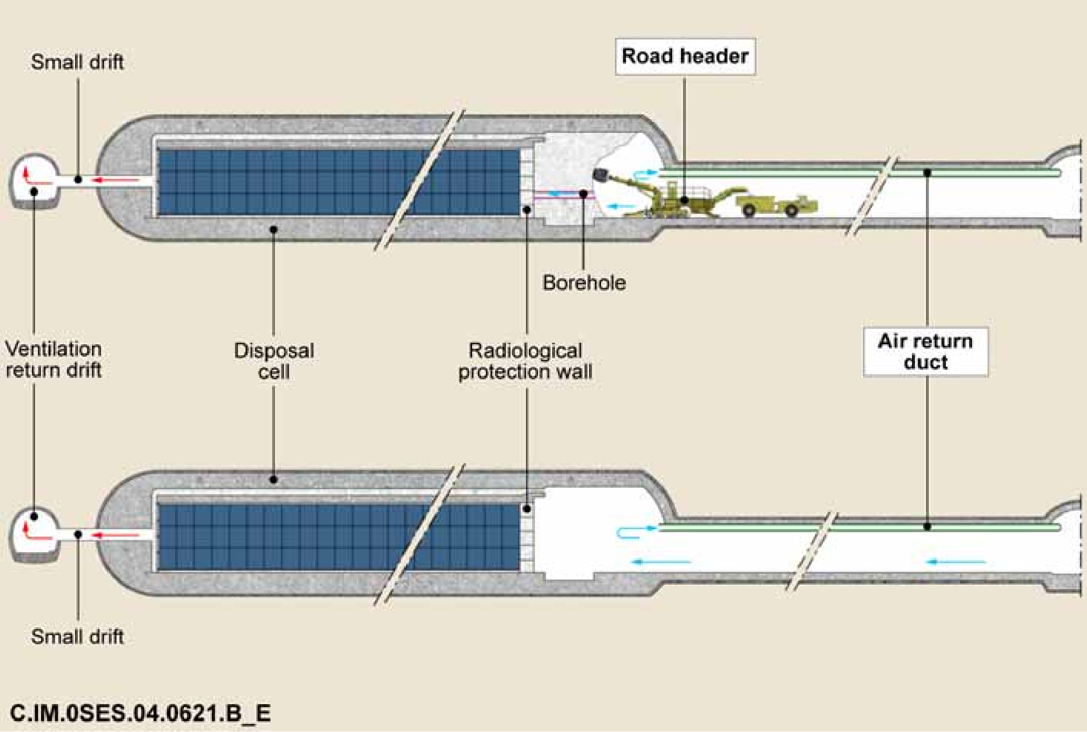

Figure 10.4.7 Seal deconstruction process

Re-equipping the cell head section (access drift)

Once the access drift is cleared, the cell head section may be re-equipped for the purpose of reconstructing the radiation chamber (Figure 10.4.8). The equipment is similar to the equipment initially used to install the packages. First, the shielding doors are re-installed sheltered by the concrete block radiological protection wall. Secondly, the other chamber equipment items are re-installed (moving floor equipped with a rotating table and port door) (see section 9.3).

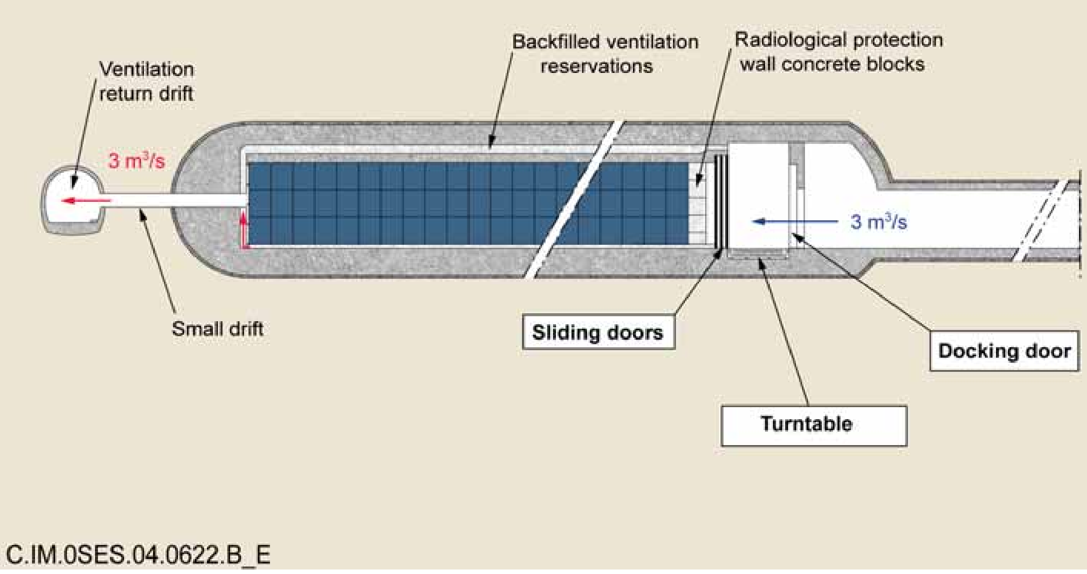

Figure 10.4.8 Reconstructed cell B

- **Package retrieval process**

Once the chamber is operational, the concrete blocks are removed through the same process used to install them and the packages are withdrawn following the same precautions as indicated in the previous stage. However, correct operation of the process and serviceability of the retrieval equipment described above are contingent upon the condition of the cell and packages. A number of phenomena may interfere with this operation. These phenomena are, for the most part, related to the risks induced by the changes in the packages and in the structures over a very long period of time. The major risks and risk-controlling measures are described in the following section.

10.4.1.4 Analyzing the situations likely to hinder the retrieval of the packages from the cell

- **Risks related to the changes in the cell liner**

The structure of the cell remains mechanically stable and undergoes minor changes for several centuries. The liner is still adequately rigid to prevent the cell walls from warping. However, some degree of scaling may occur on the surface of the filler concrete; this may require the use of a device equipped with a manipulator arm to remove the debris.

- **Risks related to the changes in primary packages**

For a major part of the inventory, primary packages give off hydrogen. The disposal packages are designed in such a way as to discharge the hydrogen produced even when moisture is present, which prevents the risks related to the pressurization of the disposal package.

The residual clearance between the primary packages and the internal waste recesses of the disposal package is sufficient (albeit small) to prevent all risk of bursting should corrosion affect the primary package and swelling of the formed products occur.

- **Risks related to the changes in the disposal package**

There are two types of risks to be analyzed: damage to the disposal package and mechanical adhesion of a package to another package or to the floor.

The selection of the concrete for the construction of the disposal packages provides for a multi-century mechanical durability, and for the absence of concrete-to-concrete binding phenomenons.

- **Risks related to the corrosion of the retrieval device tracks**

Ventilating the cell with dry and fresh air prior to cell sealing and the absence of oxygen supply in the following phase should largely mitigate corrosion of the tracks and associated attachment points. The track system may sustain a minor degree of corrosion. In any case, it is possible to provide a track-cleaning device in the cleared area as the packages are withdrawn, thus obviating all risk of jamming at a long distance from the cell head section. The tracks are secured to the floor via a large number of attachment points; a minor degree of corrosion would not affect the mechanical operation thereof.

- **Risks related to the presence of contaminated gases or hydrogen in the cell**

The cell is ventilated during the retrieval operations. The risk of explosive atmosphere is managed by an atmospheric inspection and a ventilation process provided under conditions identical to those prevailing at the time of initial installation.

10.4.2 Retrieval of C waste (and spent fuel) packages

10.4.2.1 Design factors favourable to package retrieval

The design of the packages and disposal cells is characterized by three major elements favourable to a retrieval operation, where required: the existence of a durable handling set, the durability of disposal containers and the presence of ceramic elements insulating the packages from the cell sleeve.

- **Durability of the cell sleeve stability**

The first design factor favouring retrieval of the packages is related to the dimensioning of the sleeve. The thickness of this sleeve is calculated to reduce longitudinal and radial deformations over a period of one or several hundred years. It contributes to the preservation, during this period, of the handling clearance between the sleeve and the package and facilitates retrieval if necessary (Figure 10.4.9).

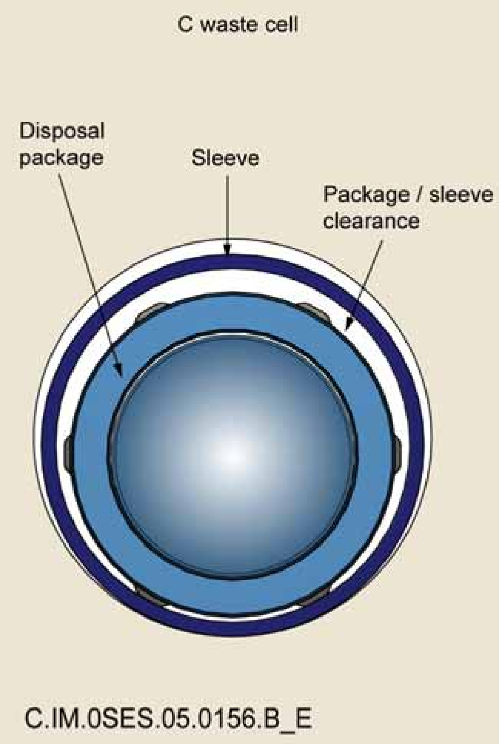

Figure 10.4.9 Functional clearance between a package and the sleeve in a C cell

- **Durability of disposal containers**

The second design factor favourable to the retrieval of packages is the durability of the disposal containers (4,000 years for C waste packages and 10,0000 years for spent fuel packages).

- **Insulation of the disposal packages using ceramic elements**

The third design factor favourable to the retrieval is related to the presence of ceramic pads fixed to C and CU2 type spent fuel disposal packages. For CU1 type spent fuels, one similar provision consists in coating with ceramic the tracks attached to the sleeve on which the packages are installed. Ceramic avoids steel-to-steel contact with the sleeve and prevents sticking by corrosion which is likely to occur when two same type steels are in contact. The radiological protection plug is coated with ceramic for the same reason.

10.4.2.2 Retrieval conditions at the “After package installation” stage

This stage corresponds to a configuration in which all of the C or spent fuel packages have been installed in the cell (Figure 10.4.10). A metal plug is placed inside the cell to protect the personnel in the access drift from radiations. The cell head section is equipped with a) the shielded trap door used to introduce the packages, and b) with a simple leaktight cover. These mechanical devices may be opened at any time for the purpose of withdrawing the packages. The ventilation system of the access drift is maintained in service with a reduced output. The flow can be temporarily re-established during intervention by personnel.

During this stage, the emplaced packages may be managed as under storage conditions over a 100-year to multi-century period. However, package retrieval may be preceded by an operational inspection phase of the cell head section.

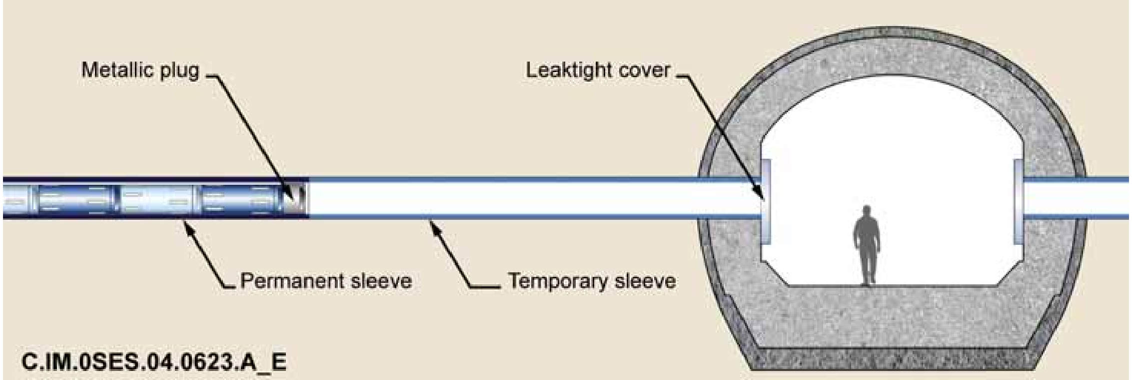

Figure 10.4.10 C Cell at end of operation

- **Prior serviceability inspection process of the cell head section**

Thermal modelling demonstrated that the temperature of the drift walls does not exceed the 60°C regulatory threshold, even when taking into account ventilation shutdown immediately after loading all of C or spent fuel repository zone. Where ventilation in the module or disposal area concerned has been shut down, it is necessary to restart it prior to performing any work for the purpose of reaching regulatory ambient air temperature values. These values are between 26 and 32°C depending on the type of the work station and air relative humidity conditions. The duration of such a ventilation notification is roughly estimated at several hours.

For safety purposes, it is then possible to check that the atmosphere in the cell is in compliance with the expected state. This check may be performed via inlets provided in the shielded trap door or leaktight cover.

If the shielded trap door is no longer inplace, the leaktight cover replacing it is removed to perform a visual and dimensional inspection of the cell head section. To do this, the operators are protected from radiations by the metal radiological protection plug. The purpose of the inspection is to check the condition of the temporary sleeve and the handling mark of the metal plug. The functional clearance between this plug and the sleeve is also checked.

These visual, dimensional and temperature inspections may be conducted using standard equipment. It mainly includes cameras, laser optical appliances and thermometers.

After these inspections, the cell is re-equipped with a shielded trap door for fitting the transfer cask and handling equipment.

Now the transfer cask is ready to permit the package retrieval process. The time for reconditioning the cell is estimated at a few days.

- **Package retrieval process**

The required retrieval equipment is similar to the equipment used to install the packages. It consists of a transfer cask fitted with fixed equipments and a moving robot. The fixed equipments include a winch and a hydraulic power unit.

The specific components of this equipment with respect to the disposal equipment are mainly the robot and associated winch. Even though the robot pushing C waste packages or the overhead lifter for spent fuel packages can be used to withdraw packages, use of more suitable equipment may be considered for this particular purpose.

Two complementary functions are assigned to this specific equipment. The first function is to overcome the friction forces resulting from a possibly corroded sleeve by applying a significant tensile force to the package to be withdrawn. The second function is related to the possibility of package-to-sleeve adhesion, even if this is unlikely to occur because of the precautions taken to prevent this phenomenon (sealing of the cell, ceramic pads). To deal with this situation, if it does occur, the robot is designed to be capable of lifting the top section of the package (or plug) and thus "separate" the package from the sleeve.

The robot is connected to the fixed equipment via an umbilical chord. The function of this umbilical chord is to transmit to the package the tensile strength exerted by the winch and supply the robot with hydraulic fluid.

The transfer cask is designed to be fitted at the head of the cell under the same conditions as during the emplacement operations.

- **Description of the pulling robot and associated winch**

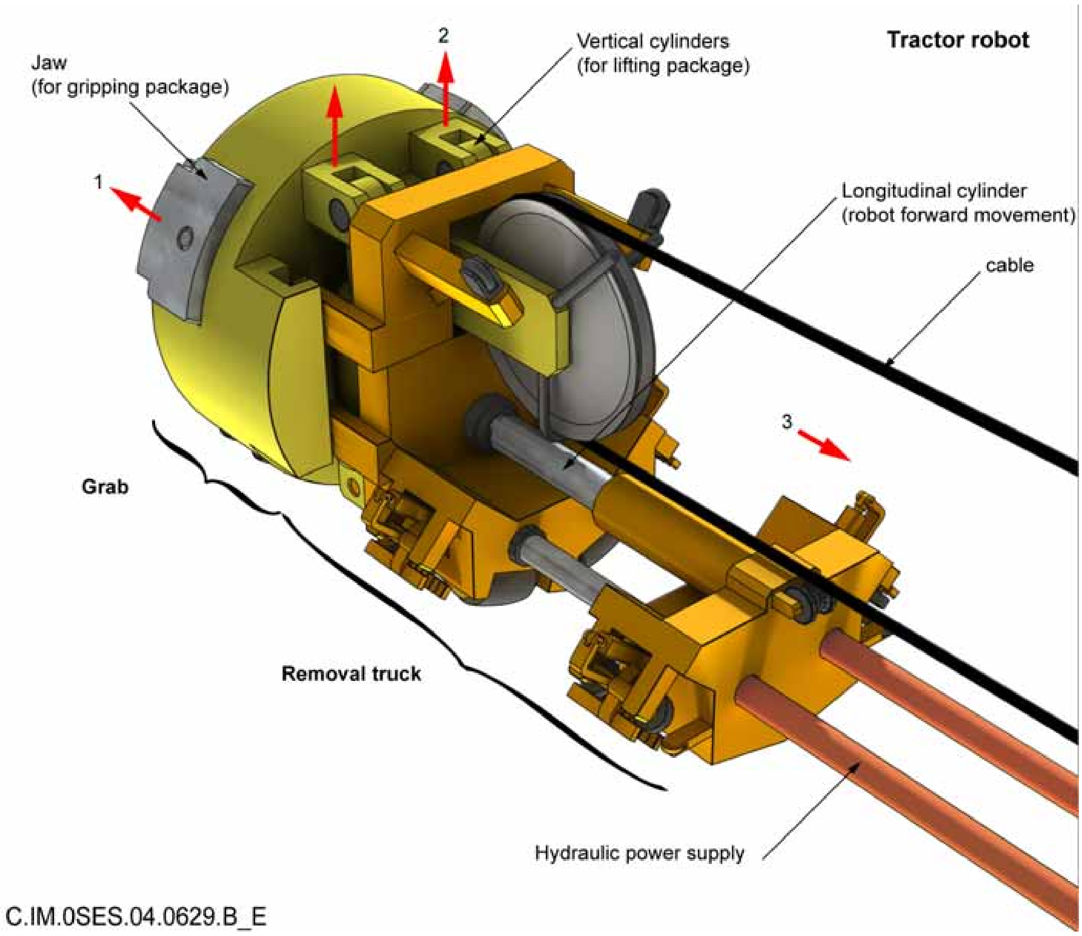

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Figure 10.4.11 Example of a pulling robot used to retrieve packages

The pulling robot (Figure 10.4.11) is an entirely hydraulic apparatus. It assumes three successive functions: traversing of the robot body from the transfer cask to the package to be withdrawn, package pickup and lifting of head of the package. A preliminary study confirmed that its size is comparable to that of the pushing robot used for installation. It is comprised within a cylinder of a diameter equivalent to that of the retrieved package and of a length of less than 2 metres.

As for installation, package pickup is performed by a tie-down device consisting of three hydraulically-powered jaws.

The robot is traversed similarly to the robot used for emplacement purposes. The principle consists in a step-by-step forward movement by means of a longitudinal cylinder and side cylinders. One advantage of this system is that it is rather insensitive to a damage sleeve surface condition. It also provides an opportunity to exert a significant thrust if necessary.

Pick-up of the package top section–a function specific to retrieval operations–is carried out using two vertical hydraulic cylinders located at the head of the retrieval carriage which slightly lift the package top section to facilitate the retrieval operations (Figure 10.4.12).

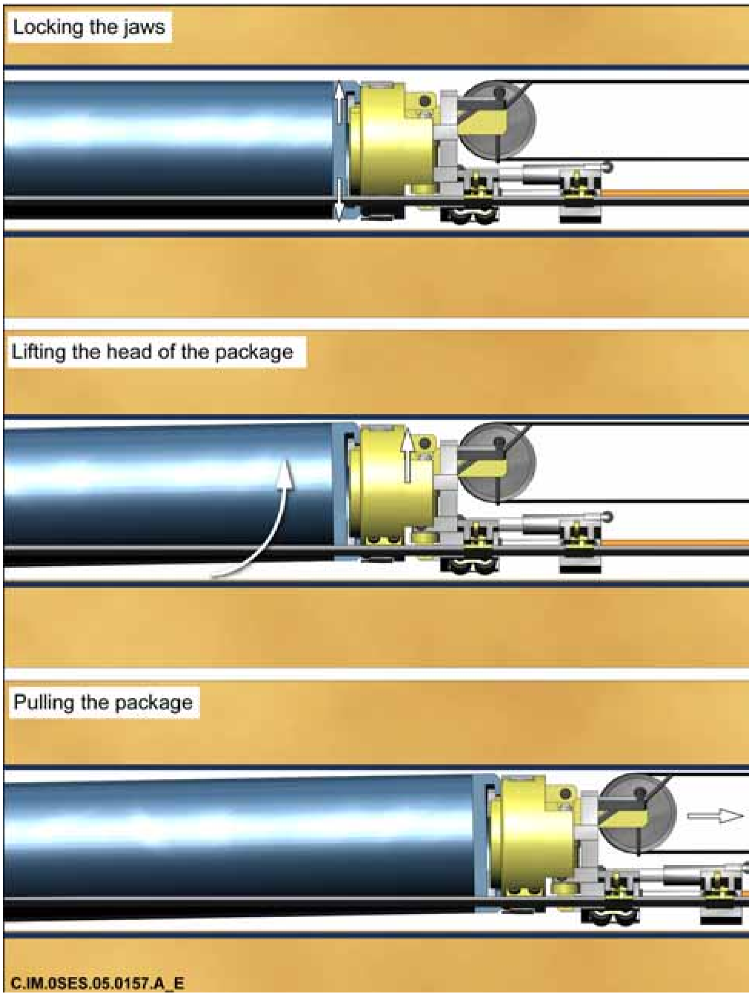

Figure 10.4.12 Pickup and retrieval principles of disposed packages

The retrieval winch considered is capable of producing a tensile strength of about 160 kN for packages C and 800 kN for spent fuel packages. The tensile force is transmitted to the robot and to the package to be retrieved via a multi-cable pulley system.

Like for installation, all the operations are carried out semi-automatically under the supervision of an operator located in the control station of the docking shuttle by following a reverse procedure from that used for installation.

10.4.2.3 Retrieval conditions at the “After cell closure” stage

The "after closure" stage corresponds to the configuration in which the cell is sealed by a plug of swelling clay mechanically constricted by a concrete plug (Figure 10.4.13). The access drift is still accessible.

At this stage, package retrieval remains technically feasible. However, like in the previous stage, this operation shall be preceded by a cell head section reconditioning phase.

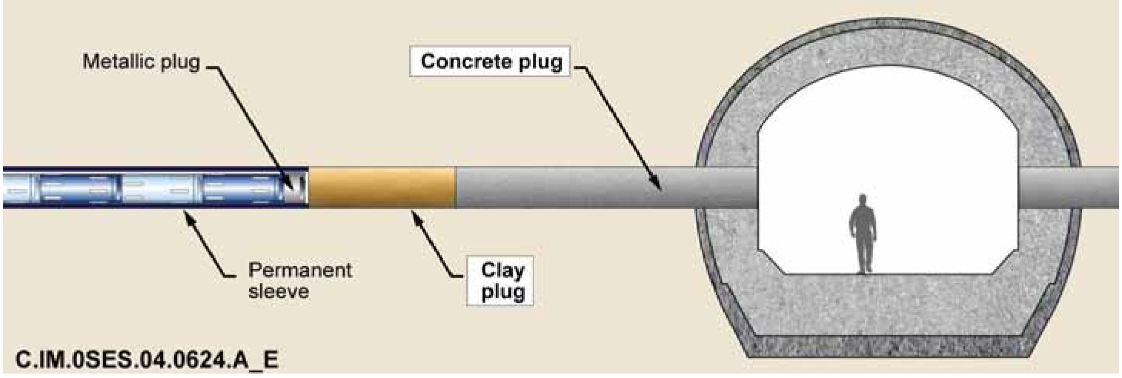

Figure 10.4.13 C Cell sealed

- **Prior cell head section reconditioning process**

This process is distinguished from the previous one in that access to the package requires partial deconstruction of the seal and reconstruction of the cell head section.

Like in the previous stage, it starts with the cell atmosphere inspection. However, it shall be carried out through the seal via a small-diameter bore. For safety purposes, this bore shall be performed in a neutral, air-locked atmosphere. Inspecting the atmosphere then allows to check the cell is in compliance with the expected state.

Deconstructing the seal and reconditioning the cell head section

Deconstructing the cell seal consists in removing the seal and installing a support casing (Figure 10.4.14).The support casing is intended to facilitate later installation of the temporary sleeve. The diameter of the support casing is 200 mm larger than that of the permanent sleeve to account for a 1% potential deviation of the boring axis. This operation may be performed using a horizontal boring machine (external motor micro tunnel borer and retractable tool); installation is carried out when the support casing is fitted.

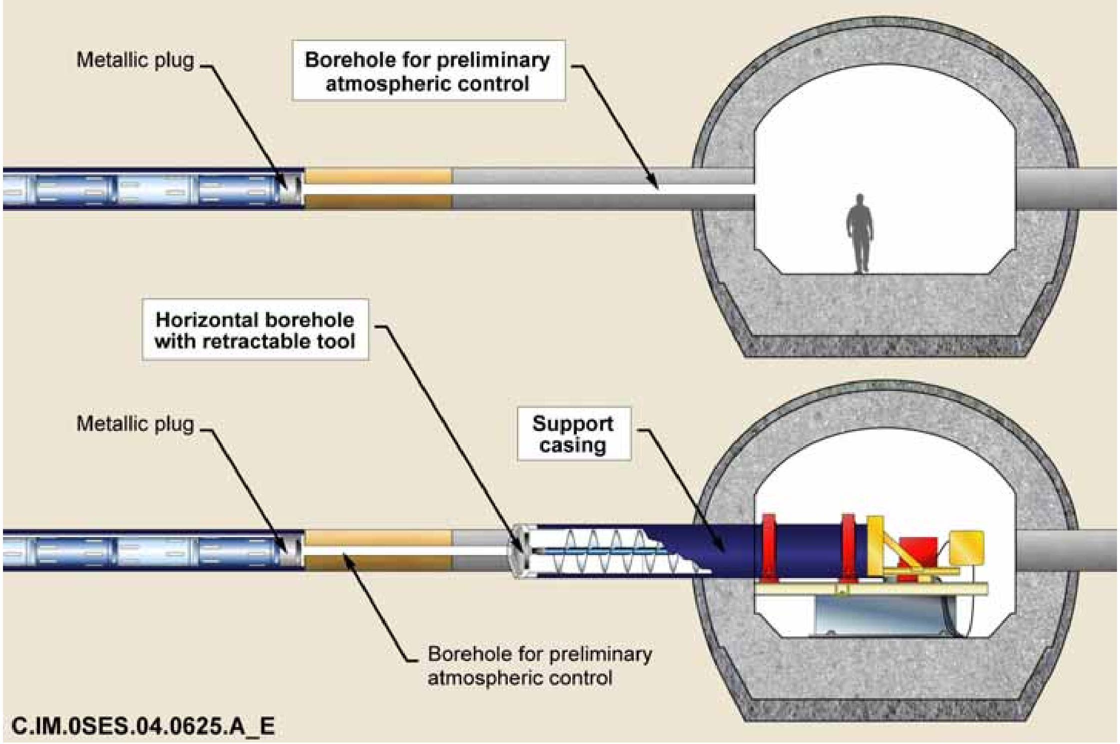

Figure 10.4.14 C Cell seal boring

This operation is complete when a boring tool on the micro tunnel borer comes into contact with the head of the cell's permanent sleeve. The boring head may then be retracted to finish pushing the support casing and withdraw the micro tunnel borer.

Once the support casing is installed, the temporary sleeve may be connected to the permanent sleeve (Figure 10.4.15). The inside diameters of both sleeves shall be chosen identical in order to minimize junction discontinuity. The temporary sleeve is brought into contact by the tube pusher of the equipment used previously. Proper alignment between both sleeves is made possible by a tapered-end centring tool pushed by a string of rods. Correct alignment between both sleeves is ensured by a connecting collar placed at the end of the temporary sleeve. This collar is placed on top of the permanent sleeve end and mechanically connects both sleeve sections.

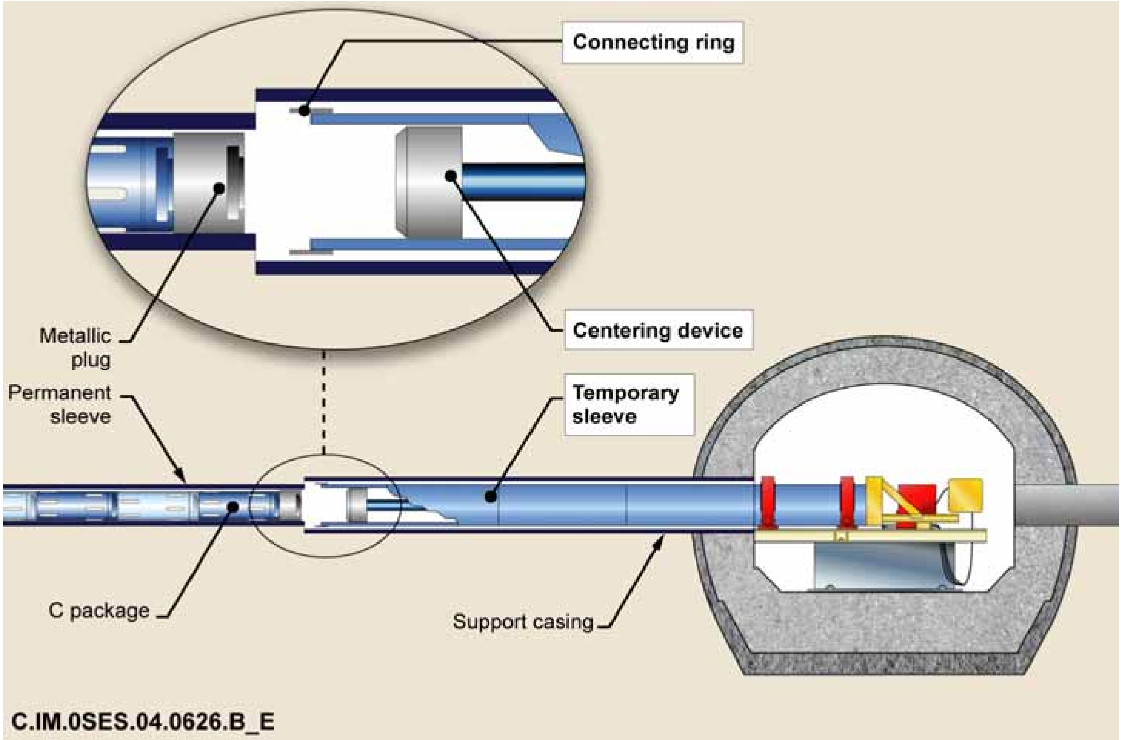

Figure 10.4.15 Reconstructing C cell head

The temporary sleeve is then aligned on the permanent sleeve using the laser optical appliance. The axis of this 9-m long tube shall be aligned on the permanent sleeve's axis in order to avoid all risks of jamming in the blend. Then, it is welded on the support casing at the entrance to the cell head section.

Re-equipping the cell head section

Re-equipping consists in re-installing the shielded trap door following a procedure similar to that used for installation. Now the cell is ready to permit the package retrieval process (Figure 10.3.16).The duration of the cell reconditioning process is estimated at about one week.

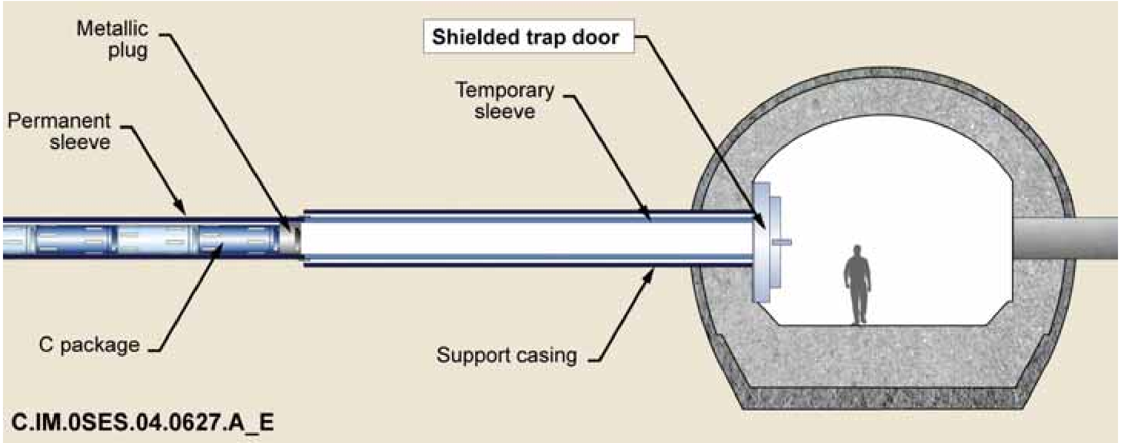

Figure 10.4.16 C Cell after reconstruction

- **C waste and spent fuel packages retrieval process**

Once the cell has been reconditioned, the retrieval process is the same as the one described in the previous stage.

However, correct operation of the process and serviceability of the retrieval equipment described above are contingent upon the condition of the cell and packages. A number of phenomena may interfere with this operation. These phenomena are, for the most part, related to the risks induced by the changes in the packages and in the work over a very long period of time. The main risks and corresponding safety measures are described in the following section.

10.4.2.4 Analyzing the situations likely to hinder package retrieval from the cell

The main risk likely to hinder package retrieval is related to an obstruction of the functional clearance resulting from a corroded or mechanically deformed sleeve.

If despite all the provisions made to prevent or mitigate corrosion the sleeve or package should become locally or extensively corroded, the presence of corrosion products would result in the swelling of the corroded surface, which could render package retrieval unfeasible or even lead to jamming if the functional clearances were to be completely obstructed. This unlikely last risk is prevented by the existence of a durable functional clearance between the package and the sleeve (approx. 3 cm for C waste packages and 8 cm for spent fuel packages). Even when considering a highly penalizing corrosion speed of 1 mm per century, the clearances will not become obstructed for several centuries. Package “sinking” risks are also prevented by the presence of sliding runners for C waste and CU2 type spent fuels packages or rails for CU1 type spent fuels packages which maintain the lower package generatrix above the sleeve.

Lastly, mechanical jamming of the disposal packages can also be considered should the dimensions of the cell sleeve change. However, this is prevented by using a sleeve thickness calculated to limit longitudinal and radial deformations over a 100-year to multi-century period of time. Thus, during this period, the handling clearance is maintained between the sleeve and the package.

10.4.2.5 Retrieval conditions at the “After closing of module drifts” stage

Deconstruction of the seals on the connecting drifts may be carried out by using the same process as that described for the deconstruction of the B cells seal.

The backfills are also deconstructed by using traditional mining techniques: of the “roadheader” type. These processes can be used for backfills whose temperature reaches 55°C provided machinery with air-conditioned cabs is used and the air in the drift is cooled down as backfill removal progresses. The use of air-conditioning systems is common practice in deep, high-temperature mines, particularly in South Africa.

The condition of the drift liner shall be inspected as backfill removal progresses and, if applicable, reinforced with rockbolts or arches according to proven techniques used in the civil engineering or mining field.

Seal deconstruction operations are expected to last approximately one week. The rate at which backfill will be removed from the site is estimated at 60 to 200 m per month and per drift, depending on the need to provide reinforcement to the drift liner.

Access to all the cell of a module requires the removal of approximately 60,000 m^3 of backfill. The time required for this operation is approximately the same as that needed for digging the initial drifts.

The cell reconditioning and package retrieval processes to be implemented for retrieval operations are those described in the previous paragraphs.

10.4.3 Package retrieval capability: Conclusion

As long as the repository closing process is not commenced, there is total package retrieval capability (like under storage conditions) over multi-century periods (typically 200 to 300 years) during which cell mechanical stability is ensured. If this stage were to be extended beyond that time, specific interventions should be scheduled (package retrieval, possible cell maintenance and improvement work, etc.).

After repository closure has commenced, package retrieval operations are possible if preparatory work for restoring access to the cell is conducted prior to retrieval. Naturally, the preparation conditions for access to the cells depend on the level of closure reached. As the closing process progresses, preparatory work becomes more extensive (relatively proportionately to the string of drifts to be cleared), but does not pose unsurmontable technical problems. The ability to carry out the package retrieval operation per se is solely contingent upon sustained geometric and mechanical integrity of the cell sleeve. The capability to withdraw the packages from the cell is little or not influenced when moving from one stage of the closing process to the next. In fact, as long as the cell sleeve is stable, i.e. as long as the functional clearances between the packages and the sleeves are maintained, package retrieval may be performed by using procedures identical or similar to those used for installation. Thus, technically speaking, the ability to retrieve the packages is feasible throughout the operational life of the cells, i.e. at least two to three centuries. If this possibility is to be extended while the closing process has commenced, one should go backward to the access to the cells to schedule specific interventions such as those discussed above.

10.5 Conclusion

The possibility to manage the disposal process in a reversible manner results firstly from the stability of the repository structures designed to last maintenance-free over very long periods of time.

The choice of durable wall liners provides the operator, over a period of several centuries and as long as the closing process has not started, with the opportunity to readily retrieve the packages using resources identical or similar to those used for installation. Under these circonstances, management of the packages is carried out under storage-like conditions. The stability of connecting structures – shafts or drifts – does not imply time limits at this phase because these structures, unlike the disposal cells, can be maintained on a regular basis. Thus, the repository may be kept in a totally reversible state, as long as the disposal cells are intact, i.e. for a period of two or three centuries and maybe more.

Additionally, the modular design of underground architecture allows a progressive implementation of the disposal process, as pertains to the emplacement of waste disposal packages in their disposal cells, as well as to the closure of repository structure. The first stage of emplacing waste disposal packages into disposal cells initially only concerns a fraction of the waste inventory. As far as closure is concerned, the progressive approach to a disposal process translates into a succession of stages. Each stage is preceded by a decision-making milestone which only concerns the contents of the upcoming stage. Thus, the first stage of the closing process only concerned the sealing of the cells of certain modules, with the other architecture components remaining accessible and maintained.

In addition to this gradual development, observation methods implemented as early as the construction of the structures allow to keep track of their evolution and more accurately assess how long they will remain stable after one century of existence. Repository observation and surveillance are tools supporting disposal management. The decisions to be made when moving from one stage to the next are based on the scientific understanding of the structures and their environments.

Progressive closure of underground facilities leads to a progressive reduction of the reversibility level. At the same time, this progressively precludes the need for human intervention, given the passive safety objective. However, a package retrieval operation remains technically possible after sealing the cells and backfilling the tunnels. The removal of the backfilling materials is not technically challenging and the maintained integrity of the cells for several centuries would facilitate the retrieval operation proper.

Lastly, it is also important to point out that a progressive disposal process provides the opportunity to benefit from the feedback of the initial process phases and improve, accordingly, the design of the repository structures as well as construction, operating and closing equipment and processes. Particularly, the possible coexistence of cells, drifts or modules in different reversibility states provides for different management scenarios and allows to test a variety of configurations, whereby the overall flexibility can be reinforced.

11

Operational Safety

Note: the text in this chapter is identical to that in Chapter 4 of the “Safety assessment of a geological repository” volume

As for any other industrial facility, the various disposal activities (construction, operation and closure) can present a risk to personnel, members of the public and the environment.

This chapter presents a preliminary operational safety analysis on the basis of the current level knowledge of the disposal facilities and takes into account the experience of other comparable facilities. This analysis makes it possible to ensure that risks are brought under control through provisions in the design of the repository and operation in compliance with safety functions[146] defined by Andra.

Within the context of this analysis, a preliminary evaluation of the dosimetry with the installations in operation is presented.

A summary of the risk analysis is also set forth. It highlights certain particular risks for which additional studies have been carried out on account of their specific characteristics or their impact on the design of the repository and its equipment.

This chapter goes on to offer an analysis of the particular abovementioned risks, namely, the risk of explosion associated with the emission of gas by certain waste packages, the risk of fire breaking out in underground installations under construction and in operation, the risk of a cage falling down the package descent shaft during transfer operations and the risk of a B waste package falling during its emplacement in a cell. Finally, a summary of the analysis is given by way of conclusion.

11.1 Evaluation of the dosimetry with the installations in operation

The operation of the facilities in which nuclear waste is received, conditioned, handled and disposed presents radiological risks to persons on account of the nature of the waste packages. There are several types of risk: the risk of external exposure (by irradiation) and the risk of internal exposure (by inhalation or ingestion).

This section presents a preliminary assessment of the dosimetry that takes into account the preventive measures envisaged to counter the radiological risks. These measures must ensure exposure of persons does not exceed the annual dose rate constraints set by Andra in the form of radiological protection targets of 5 mSv for personnel working in the nuclear zone and 0.25 mSv for members of the public outside the site [37].

This dosimetry evaluation informs the approach to the design of these installations from the point of view of radiological risk but is not, at this stage, part of an approach to optimise the doses received.

11.1.1 The nature of radiological risks and measures envisaged

The various radiological risks that affect the facilities are set forth in the following sections.

11.1.1.1 External exposure risk

Waste packages are sources of external exposure (associated with β, γ and neutron radiation) from the moment they are received in the surface installations until they are placed in the underground disposal facilities.

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[146] The safety functions defined (cf. Section 2.4) are as follows:
- Protection of persons from radiation,
- Containment of radioactivity,
- Control of the criticality risk,
- Removal of residual heat of disposal packages,
- Removal of the radyolisis gases emitted by some packages.

Transport transfer casks containing the primary waste packages delivered to the disposal site have a radiological protection function and their structure is designed specifically for the radiological characteristics of the waste transported. Once the primary packages have been removed from transport transfer casks, they are handled and placed in disposal packages inside cells which are not accessible to operators who work by remote control from behind radiological protection shields (walls, shielded windows).

During transfer operations and up until emplacement in the disposal cells, control of the risk of external exposure takes the form of the interposition of radiological protection shields[147] between sources of radioactivity and personnel to reduce radiation flux. Disposal package transfer transfer casks, C and spent fuel cell access ports and B cell doors fulfill this role. The effectiveness of these protections would be controlled by means of apparatus that measures the level of irradiation, either installed permanently or used by the radiation protection teams.

Radiological protection or distance from the control station of the vehicles used to transfert or handle the packages in the cell would also contribute to the reduction of doses received by personnel.

During closure operations, definitive radiological protection shields are installed such as blocks of concrete to replace the doors of the B waste disposal cells and metal plugs of C and spent fuel cells (cf. Chapter 5). These devices would facilitate any reverse operations (package retrieval) as decided.

11.1.1.2 Internal exposure risk due to the inhalation of radioactive gas emitted from disposal packages

Some B waste disposal packages (B2 and B5) emit small amounts of radioactive gas (tritium, carbon 14, etc.).

In surface installations, the limited number of waste packages present is such that the amount of gas emitted is negligible. In addition, most of the operations are carried out in cells that are not accessible to personnel.

During the course of disposal package transfers to the disposal cells in the underground installations, traces of radioactive gases are emitted from these packages in the transfer drifts and released via the ventilation circuit.

In the disposal cells where a large number of packages are disposed of ventilation with exhaust of the air by means of ducts to the ventilation shaft (cf. Section 6.4) removes these gases preventing them from affecting personnel present in the underground installations.

11.1.1.3 Risk of internal exposure due to the inhalation of radon gas emitted from the rock in the underground repository installations

This risk, present from the beginning of construction activities, is associated with the level of radon naturally exhaled from the rock in which the underground installations would be situated. Given the argillite nature of the Callovo-Oxfordian formation, this risk is limited. It can be controlled by permanent ventilation of the underground drifts which would expel the radon and its descendants.

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[147] The nature of the material from which these screens are made depends on the type of radiation emitted by the radioactive source:
- In the case of γ radiation, heavy materials such as steel, concrete and lead glass are used.
- In the case of neutron radiation, specific materials (with boron or cadmium, etc.) or hydrogenated materials.
- α and β radiation do not need any particular type of screen as they are stopped by the package envelope.

11.1.1.4 Internal exposure risk through ingestion of radioactive materials

In surface installations, this risk could be related to the dispersion of radioactive particles from transport transfer casks, waste packages (primary packages, disposal packages) or transfer transfer casks.

In surface installations, the management of this risk would depend on the organisation of the receiving and preparing facilities into containment systems[148] in order to prevent the dispersion of radionuclides towards areas in which personnel circulate or into the environment. These installations would also be equipped with filtering devices on their ventilation circuits, as is done in existing nuclear facilities of the same type[149]. Finally, it is important to mention that non contamination inspections[150] of transport transfer casks, waste packages and transfer transfer casks would be carried out systematically.

11.1.1.5 Criticality risk

The criticality risk corresponds to an uncontrolled nuclear chain reaction. This is initiated by an increase in neutron activity in fissile materials (uranium-235, plutonium-239 and plutonium-241).

The safety-criticality tests showed that B waste and C waste packages do not contain enough fissile materials (critical mass) for this type of reaction. Spent fuel packages are the only type affected by this risk [55]

In surface nuclear installations, in the case of spent fuel[151], the absence of the inflow of water into the conditioning cells must be ensured to eliminate the risk of criticality as is practiced in similar existing storage facilities on waste production sites.

In underground installations, package transfer and emplacement in the repository is carried out dry. There is no criticality risk associated with this.

11.1.2 Dosimetric evaluation on site and around the periphery of the site

This preliminary evaluation, based on the radiological characteristics of the packages summarised hereafter takes into account the measures envisaged (radiological protection shields, non-contamination inspections, monitoring, etc.).

11.1.2.1 Data taken into account

- **External exposure**

The equivalent dose rate (EDR) values relating to primary packages are given for different types of package (cf. Table 11.1.1).

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[148] The principle of a containment system is to create a difference in air pressure between adjacent areas.

[149] These filtering devices are, however, justified when taking accident situations into account, in particular for the reception and conditioning of bare spent fuel whose surface would be contaminated by corrosive products deposited and activated during transfer from the fuel assembly in the reactor (cf. 11.2.2.2).

[150] The acceptance thresholds could be those established by transport regulations, that is to say, labile (not fixed) surface contamination restricted to 4 Bq/cm^2 in β,γ emitters and 0.4 Bq/cm^2 in α emitters [110]

[151] The presence of water, which attenuates the energy of the neutrons and slows them down, makes them more reactive to fissile materials and increases the reactivity of the system. In addition, the procedures used for conditioning the packages are dry procedures, no water is used.

Table 11.1.1 Equivalent dose rate in contact with primary packages [3]

Type of package		Nature of contents	Maximum EDR[152] in contact with the primary package ($Sv.h^{-1}$)
B	B1, B7.2	Compacted activation products	25
	B2	Bituminised waste	2
	B3, B7.1, B7.3, B8	Compacted or cemented technological waste	0.5
	B4	Cemented cladding waste	0.5
	B5	Compacted cladding waste with or without technological waste	15
	B6	Cladding waste and technological waste in drums	2
C0	C0	Vitrified waste	150
	Other C	Vitrified waste	250
SF	CU1 (UOx)	Spent fuel assembly	25
	CU2 (MOx)	Spent fuel assembly	15
	CU3	Spent fuel	150

- **Internal exposure**

Exposure through inhalation is associated, on the one hand, with radioactive gases and aerosols emitted by some B waste packages between their reception at surface installations and subsequent emplacement in the disposal cell, and on the other, with radon gas emitted naturally by the geological environment into the drifts of the underground installations.

Radioactive gases emitted by the packages

Some packages contain traces of radioactive gases. Measures to reduce the release of these gases were presented in Chapter 4. However, these measures do not apply to packages that also generate hydrogen due to radiolysis (B2 and B5.1 waste packages). For B5.1 reference packages, the most pessimistic case, the adopted release rates (in becquerels per hour and by primary package) are roughly 400 for tritium, 14 for carbon and 7,000 for krypton 85.

Radon gas emitted by the rock in the underground installations

The radon exhalation rate from the rock varies according to various factors such as : ventilation and nature of drift lining. At this stage, the value used corresponds to the average value observed in France.

11.1.2.2 Dosimetric evaluation

The dosimetric evaluation [107] is carried out for each type of work station identified on the disposal site and for the public around the periphery of the site.

- **Dosimetric evaluation for personnel operating in nuclear installations**

The results are presented by distinguishing between the different work stations in the surface and underground installations (cf. Table 11.1.2).

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[152] In the case of slightly or highly exothermic packages, the values given here correspond to a packages with an age of 5 years in the case of B1 packages, 10 years for B5 and SF3 packages, 20 years for C0, 60 to 70 years for SF1 (UOx) and 90 years for SF2 (MOx).

External exposure

The exposure of personnel to ionising radiation is a function of the nature and annual flow of the waste packages received as well as the operating process. The latter is defined by the mode of operation of the installations and equipment (local or remote operation or operation from a control room) as well as by the time required to carry out different operations related to the running of the facilities (cf. Chapter 9).

Based on this data, the dosimetric evaluation is carried out as follows:

- The annual dose is evaluated for each production-related activity, taking into account the number of times this operation is repeated throughout the year. The average dose received by an operator is calculated based on the estimated total number of operators planned for each of these operations;
- With respect to activities that are not directly related to production (control room, monitoring, etc.), the dosimetric evaluation is calculated directly for the station in question.

Internal exposure

Exposure through the ingestion of radioactive materials has been considered negligible on account of the preventive measures taken.

There are two component factors to exposure through the inhalation of radioactive gases:

- For B waste packages which emit radioactive gases, the scenario used is that of the transfer of a B5-1 waste disposal package in a transfer cask to a poorly ventilated drift. The exposure of personnel estimated on the basis of activity concentrations and dose coefficients related to inhalation for tritium and carbon 14 are negligible (of the order of 10^{-3} mSv per year);
- As far as doses related to radon emitted by the geological environment is concerned, the annual value used is 0.5 mSv for all operators working in the underground installations, both the nuclear zone and the construction zone.

Results

Table 11.1.2 Estimate of the annual dose received by the operators (mSv/year/person) operating in nuclear installations

Activity	Type of package	Annual dose per operator (mSv/year/ operator)
Nuclear surface installations		
Reception of primary packages	B / C	2.1
	SF (UOx)	4
Control of primary packages	B / C	1
	SF (UOx)	1
Insertion of empty containers	B / C	1.3
	SF (UOx)	1
Preparation of disposal packages	B	1.5
	C	1.5
	SF (UOx)	1.4
Control of disposal packages	B	1
	C	0.9
	SF (UOx)	0.8
Placement of disposal packages in transfer casks and inspection of transfer transfer casks at the surface	B	1.6
	C	0.9
	SF (UOx)	1
Surface control room	/	0.5
Surface monitoring	/	2.3
Surface maintenance	/	3.7
Underground nuclear installations		
Transfer and emplacement of the disposal packages in cells	B	1.2
	C	1.3
	SF (UOx)	4
Installation of cell plugs	C	0.6
	SF (UOx)	0.9
Transfer transfer cask inspection at the bottom	B	0.9
	C	1.1
	SF (UOx)	0.8
Underground control room	/	0.5
Underground monitoring / maintenance	/	2.2

It is clear from these results that the highest values, between 2 and 4 mSv/year, would be associated with the reception of primary packages, the transfer and emplacement in the cell of disposal packages and monitoring and maintenance of the installations. The values associated with other activities would be less than 2 mSv/year.

Doses received by personnel on site would therefore be lower than the limit set by Andra (5 mSv/year) and well below the statutory limit (20 mSv/year).

- **Dosimetric evaluation for members of the public around the periphery of the site**

External exposure is not taken into account for members of the public in this evaluation on account of the distance between them and the nuclear installations.

The internal exposure associated with the radioactive gases emitted by some B waste packages and released into the environment has been estimated on the basis of the assumption that the repository has completed operations, that is to say, with the entire inventory of B waste taken into account (cf. Chapter 3). This preliminary estimate was made at the periphery of the repository site, taken as 500 m from the exhaust air chimney. The calculation, which takes into account the radiological activity released by the waste packages and a transfer factor in man that combines all three means of exposure shows that the annual dose for a member of the public of the order of 1µSv, would be negligible.

Internal exposure associated with radon gas diffused by broken rock stored above ground or related to emissions from the underground installation ventilation system will depend on a number of factors: the radon exhalation rate from the argillites, ventilation flow in the underground installations and the height of the exhaust air chimney, length and type of open drifts (drifts under construction or in operation) and local atmospheric conditions. As in the preceding case, it can be considered negligible when the nature of the geological environment and experience in comparable facilities is taken into account.

Although the emission of radioactive gas from the underground installations appears to be negligible, it would, nonetheless, be monitored by measuring the radioactivity of the air as is conventionally done in the context of the operational surveillance of a nuclear facility.

11.1.3 Conclusion

Given the measures employed to counter the radiological risk in the design of the installations and their mode of operation, the doses received by the personnel on site or by a member of the public at the periphery of the site should be below the annual limits fixed by Andra for radiolological protection, and well below statutory limits. It should also be remembered that these are preliminary estimates and do not take into account any subsequent optimisation approach.

11.2 Risk analysis

This section assesses the risks identified in the installations for all disposal activities (construction, operation and closure) and proposes associated reduction measures. It distinguishes between "internal" risks related to work carried out in the facilities and "external" risks, related to the environment (which are dealt with in a more generic fashion).

The risks examined in the context of the study are those that are liable to have an impact on people or the environment. However, the operational consequences (deterioration of work tools, drop in production) are not dealt with at this stage.

This assessment [107] can be used to highlight certain particular risks which have been the subject of additional studies (cf. Sections 11.3 to 11.8) on account of their specificity or their impact on the design of the repository and its equipment.

11.2.1 Methodology

The analysis begins by identifying sources of danger associated with disposal activities. It has been carried out with the support of experts in the different technical fields concerned (nuclear installations, shaft transfert equipment, underground tunnels, etc.) that have used standard danger lists[153] and have brought their experience with comparable installations to bear.

This analysis, which has been structured around physical components (surface installations, access shafts, underground installations) and activities (construction, operation, closure), systematically takes account of compliance with operational safety functions. It offers the most exhaustive view possible at this stage in the studies of the risks likely to be encountered by personnel and the environment.

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[153] Among the standard danger lists, the MADS (Methodology for the Analysis of the Malfunction of Systems) and the MOSAR (Method Organised for a Systematic Analysis of Risks) approaches are the most frequently used in the risk analysis of an industrial installation.

The risks are characterised by a source of danger and risk reduction measures. The latter comprise preventive measures to prevent or minimise the occurrence of risk, as well as protective measures that are taken to rule out or mitigate the effects (cf. Figure 11.2.1). Monitoring measures complete the risk reduction measures.

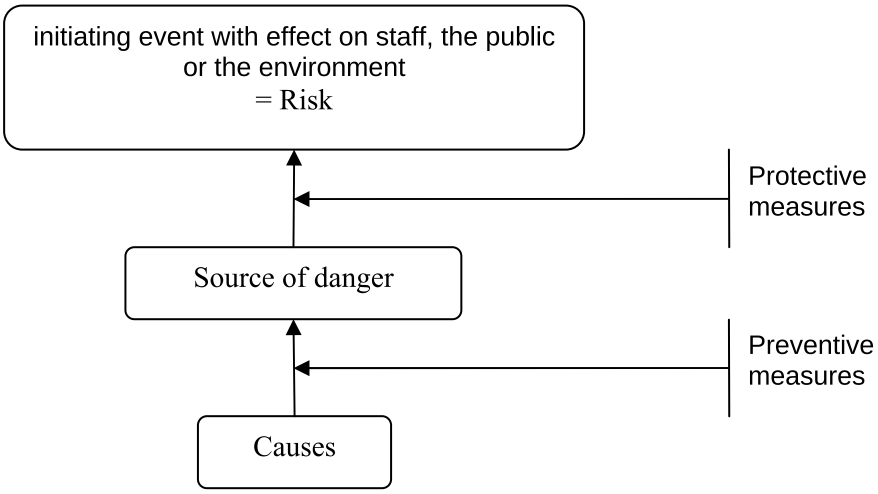

Figure 11.2.1 Risk characterisation

This characterisation enables a qualitative judgement to be made on the remaining degree of residual risk in spite of the risk reduction measures proposed. This expert appraisal is carried out as a function of the likelihood of the risk arising and the significance of its potential consequences for personnel, members of the public and the environment.

11.2.2 Internal risks associated with the disposal process

All internal risks identified are presented by risk type distinguishing successively between "conventional" risks, which are typically common to all industrial installations, and radiological risks, which are associated with the presence of nuclear waste packages.

11.2.2.1 Conventional risks

- **Listed risks**

The main conventional risks to be taken into account during the disposal process [107] are the risk to personnel of being crushed as a result of loads falling, falling blocks in drifts, objects falling down shafts, the risk of being crushed by equipment (crushed by a moving part during maintenance operations in shafts, etc.), the risk of being thrown from a vehicle, the risk of a collision between vehicles, the risk of a fall associated with work at heights (in the shafts in particular), the risk of electrocution and the risk of fire.

Risks inherent in the working environment (noise, dust, carbon dioxide and carbon monoxide gas emitted by motors….) which are different from the above risks on account of their fairly long term effect must also be monitored and controlled in underground installations in particular.

The other risks listed do not hold the same degree of importance. Among these, two types of risks related to a temporary loss of ventilation in the installations are noteworthy. These are the risk of explosion associated with the emission of small amounts of explosive gases from some B waste packages (B2, B5) which seems improbable given the ventilation throughputs planned for the installations which would ensure the dilution of these gases. However, a specific study has been carried out into this risk in support of this analysis. The risk associated with the presence of exothermic packages (C waste and spent fuel packages) should also be mentioned even if the temperatures of the metal envelope of the transfer casks in which they are transported do not exceed approximately thirty degrees and could not cause burns to personnel.

- **Risk reduction measures**

The risk reduction depends first of all on prevention, by selecting specially adapted, reliable, well maintained equipment fitted with all necessary safety systems, and on training personnel, raising awareness of the different types of risks encountered, compliance with procedures and on-site traffic regulations and the wearing of personal protective gear.[154].

In the underground installations, the installation of physical protection systems (for work in shafts in particular), the use of equipment operated from control stations that are some distance from the work face, the equipping of safety networks on work sites (fire-fighting water network, communications network, etc.) as they progress also contribute to reduce the risks faced by personnel.

Of all the risks mentioned, the risk of fire is different from the others because it has collective consequences and requires specific provision for the evacuation of personnel.

In surface installations, the risks of fire are limited: the electric (or electronic) cabinets appear to be the main possible source of ignition. The measures to prevent, detect and limit the consequences of fire that would be used would comply with the Labour Code and the Basic Safety Rules (*Règles Fondamentales de Sûreté*) RFS I.4.a [108] and RFS II.2 [109]. Feedback on experience of nuclear installations with similar functions to those carried out in the repository would also be taken into account. The main provisions concern the choice of fire-retardant materials, the limitation of the calorific load of the installations (associated with the choice of handling by means of travelling crane or electrically driven vehicle), the sectorisation of areas that present a fire risk and the fire stability of structural components. The installation of fire detection systems, control of ventilation with a smoke extraction system and existence of evacuation routes (with clearances protected by overpressure, non-fumigation chambers, etc.) also play a role in the safety of personnel.

In underground installations, the principles adopted are those of a ventilation system with smoke extraction and connections between adjacent drifts to facilitate the evacuation of personnel. It is more difficult to make reference to other existing installations (road/railway tunnels, underground mines) as the solutions used are specifically related to the configuration of each installation.

- **Summary**

A summary of the analysis (cf. Table 11.2.1) is presented per type of activity (construction, operation, closure). Work associated with the possible retrieval of disposal packages has also been envisaged.

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[154] This personal protective gear includes safety shoes, safety earmuffs, dust-masks and autonomous breathing apparatus (self rescuers) to be used in the presence of fumes.

Table 11.2.1 Summary of the main conventional risks associated with the disposal process

Activities / Risks	Construction	Operations			Closure	Potential package retrieval
		Surface installations	Transfer surface / U/G installations	Underground installations		
Persons crushed associated with a falling object	X	X	X	X	X	X
Persons crushed by equipment or vehicle	X	X	X	X	X	X
Persons falling associated with work at heights	X		X	X	X	X
Electrocution	X	X	X	X	X	X
Fire (surface)	X	X	▨	▨	X	X
Fire (underground)	X	▨	X	X	X	X
Pollution and nuisance in the work environment	X				X	
Explosion related to the release of explosive gases	▨	X		X	X	X
Temperature rise related to heat released by packages	▨		▨			

X Risk to be taken into account
☐ Negligible risk
▨ Not applicable
☐ Risk is the subject of additional study

The following conclusions can be drawn from this table:

- The analysis shows no particular differences as regards the type of risks between the various construction, operation, closure and even package retrieval activities.[155]
- The main risks listed that correspond to conventional risks for which preventive measures are known do not require specific studies to be undertaken at this stage in the project.
- Additional studies are, however, justified in the case of risk specifically attached to a disposal activity such as is the case for the risk of explosion associated with some B waste packages (cf. Section 11.3) or if it has a significant impact on the design of the facilities and equipment, as in the case of the risk of fire in underground installations (cf. Section 11.4).

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[155] The risks related to the potential retrieval of waste packages would not be distinguished from risks identified either as these techniques and the equipment used for this work would be very similar to those used during emplacement.

11.2.2.2 Radiological risks

Radiological risks (external exposure risks, internal exposure risk and potentially criticality risk) likely to be encountered during the course of the disposal process could be associated with radiological protection failures, interventions carried out close to a source of radioactivity or a fire or fall affecting waste packages.

Having taken account of their specific characteristics, these risks are analysed individually and emphasis is placed on measures to reduce the risks envisaged.

- **Failure of the radiological protection provided by the doors, vents and shielded windows of nuclear cells in surface installations, transfer transfer casks, access ports of the C and spent fuel disposal cells and doors of the B disposal cells**

These events could be the result, for example, of clearance between moving parts that is not compliant with the initial dimensioning. Measures required to counter this risk would be a specific maintenance programme for moving parts associated with radiation detection monitoring of the nuclear cells, transfer transfer casks and disposal cells.

- **Failure of radiological protection during the course of an intervention**

Equipment malfunction may lead to its immobilisation when being used to carry or handle a package (primary package or disposal package) and intervention by maintenance personnel may be required to repair the equipment in question. This situation would result in the external exposure of personnel if the latter had to operate near the source of radiation.

Preventive measures would be those conventionally used in nuclear facilities currently in operation, namely, appropriate maintenance of the equipment used and redundancy of certain component parts (motorisation, etc.).

Where intervention carried out on equipment in cells is concerned, the existence of emergency systems enabling the waste package to be put down and the equipment returned unloaded to its maintenance area would remove all risk of the exposure of personnel. In the latter case, it would, however, be necessary to ensure there is no malfunction of the closure system of the irradiating zone of the cell[156] by first monitoring the level of radiation in the maintenance area prior to any operation.

- **Fire in a nuclear cell of the surface installations**

A fire in the disposal package manufacturing cell would have a fairly insignificant heat rating given the low calorific load of the equipment installed.

Taking feedback from the experience of nuclear facilities into account in the design of installations, limiting the calorific loads present and possibly installing thermal protections around some equipment should be sufficient to limit the power of a fire and prevent it from spreading and affecting the packages resulting in radiological consequences.

- **Waste transportation or handling vehicle fire**

The fire of a transport transfer cask vehicle (containing primary packages from waste producers), a transfer transfer cask vehicle (containing waste disposal packages) or B waste emplacement equipment in the disposal cell could have radiological consequences in addition to the direct consequences of the fire (cf. Section 11.4).

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[156] The system usually employed consists of locking in the opening of the maintenance area with the closure of the irradiating cell and, if possible, locating the maintenance area at some distance from a potential field of radiation from the sources of radioactivity present in the cell.

On the surface, the transport transfer cask vehicle leaves the waste reception area as soon as the transfer cask has been set down which limits the presence of the main cause of the risk. Furthermore, the transport transfer cask is designed to resist fire up to 800°C for 30 minutes in accordance with transport regulations [110].

In underground facilities, there is no industrial reference directly applicable to the transfer vehicle as well as to the B waste emplacement equipment. It has therefore been necessary to make simulations on the basis of assumptions regarding the heat ratings involved and the nature of the exchanges in the course of the fire. These studies are presented in Sections 11.5 (Transfer transfer cask transporter) and 11.6 (B Waste emplacement handling equipment).

- **Primary package falling in surface nuclear installations**

Primary packages could be dropped and damaged during handling. The foreseeable consequences of this could be a breach of one or more of the primary packages and the dispersion of radioactive material in the installations and subsequently into the environment via the ventilation. A fall could also result in the surface contamination of a package missed during other inspections becoming airborne (cf. 11.1.1.4).

Preventive measures are specific to each type of equipment. Equipment systems must be sized for loads greater than those envisaged, must ensure a degree of redundancy in some components and intrinsically safe devices must be designed for the possibility of malfunction (for example, keeping the grab closed in the event of a power failure). Training of personnel and maintenance are also very important in countering this risk. In addition, the mechanical procedure used must give priority to handling packages at a height lower than the height from which they are known to withstand being dropped.

As the protective measure to be used to take care of a potential release of radioactive materials, a filtered ventilation system could be installed on the ventilation circuit of the primary package reception and disposal package manufacturing cells.

This measure might be justified for some primary B waste packages, such as the bituminised sludge package, which is not totally protected from the possibility of the crimping of its lid failing and opening in the event of impact.

This measure would also apply to installations receiveing bare spent fuel assemblies which, if dropped during the handling operations that are necessary until they are placed in disposal packages, could result in the rupture of the cladding of the fuel rods. The main provisions for the management of this type of risk could be similar to those used for the dry unloading of this type of fuel in the reprocessing plant (Cogema T0 facility in La Hague).

- **B Waste disposal package drop during emplacement**[157]

Carring the waste disposal package in the low position over the whole length of the disposal cell limits the risk of it falling during the package lifting and emplacement. During this operation, an error in the positionning of the expected position of the package to be emplaced, or the malfunction of the lifting system, could result in a fall from a height of 4 to 6 m in the case of packages placed on the highest levels of the stacks.

Several provisions are envisaged to limit the occurrence of this risk and its consequences:

- The emplacement procedure with a row of waste disposal packages placed on the ground followed by a second layer and so forth limits the risk to a case in which a package might tip on its side;
- Monitoring the package emplacement cycle (validated step by step by the operator, visual inspection using cameras) and checking that the emplacement position matches the cell map beforehand should prevent any error in positioning when the package is being set down;

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[157] The procedures envisaged for emplacement in the cell of C and SF packages (cf. Section 9.3) require a handling height of less than 2 meters. Because of this, these drop cases are not dealt with.

- The selection of design options of the equipment to ensure good stability (cf. Section 9.3) with the load in all positions and, on the lifting system, provisions such as brakes and safety sensors, redundancy of various components of the lifting system, double electric power supply, device for lowering the load in the event an anomaly is detected, etc. should prevent the risk of a package being dropped. These various systems should be regularly inspected;
- In the event a package were to fall, the disposal packages provide protection from the primary packages contained.

To quantify the deformations of the B waste disposal packages in the event of a fall and to examine what the consequences would be, one initial approach has been to carry out a simulation study to verify the resistance of the package when dropped (cf.Section 11.8). These results are expected to be validated by full-scale B2 and B5 waste disposal package drop tests during 2005.

- **Uncontrolled cage displacement or drop when loaded with the B, C or spent fuel disposal package transfer cask in the shaft**[158]

Experience acquired in mines with this type of transport and the combined preventive measures and inspections are such that the likelihood of the cage falling is extremely low[159].

The preventive measures that serve to counter this risk involve both the design of equipment (independent braking systems on the driving pulley, bundle of independent cage suspension cables [160], etc.) and maintenance, control and operating procedures. A cage anti-drop system could foreseeably be added to these measures to provide an additional safety system which would be independent of the cage's command and control system. The principle of this system would be to use cables suspended in the shaft as braking cables which would stop the cage in the event of overspeed. In order to limit the stress to which these cables would be subjected in the event a load were to be exerted upon them, they would be connected to shock absorbers that would dissipate a large part of the kinetic energy associated with the movement of the cage.

Two kinds of measures would be employed to limit the mechanical consequences of the uncontrolled displacement of a cage or of a cage falling down the shaft:

- An end of travel braking system, similar to the kind installed by law in mines, some metres below the bottom station would stop a cage passing its stopping point if its speed does not exceed approximately 10 m/s. This would deal with a case of cage displacement associated with the malfunction of the braking system when it reaches the stopping point.
- In the case of speeds in excess of 10 m/s, a shock absorber composed of “honeycomb” type material and installed at the bottom of the shaft would have the advantage of being a passive system capable of absorbing substantial amounts of energy. Laboratory tests have provided the characterization of the behaviour of this material for high speed impacts (cf. Figure 11.2.2).

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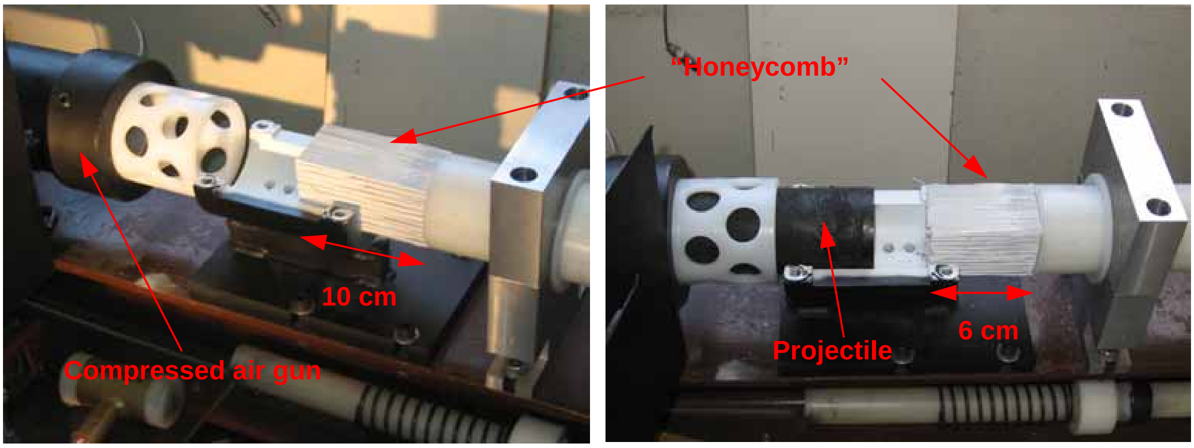
[158] Other drop cases have been envisaged involving the direct drop of the transfer cask transporter down the shaft (cage not in position) or the transfer cask falling through the floor of the cage (subsequent to impact or as a result of structural weakness). The identification of these two cases, which would appear even more improbable than the preceding one [111], serves, above all, to justify the reinforcement of preventive measures associated with access to the cage and the regular inspection of the condition of the shaft and the cage.

[159] In Germany, a study carried out for the Gorleben radioactive waste repository project [111] estimates that for a comparable facility, the probability of a cage falling down the shaft is 5.10^{-7}/year (for 5000 hours of operation per year).

[160] The study envisages a system with 10 independent suspension cables which allows loads of around one hundred tonnes to be transported. Shutdown is triggered in the event a single cable breaks which makes the successive breakage of all multi-cables unlikely.



Before crash **After crash**

Figure 11.2.2 Honeycomb material crash test (Impact Speed 200 km/h)

These different measures are illustrated in Figure 11.2.3.

Quantifying the effect of the shock absorber on the packages transported in the cage required simulation studies presented in Section 11.7 to be undertaken. They show that at the moment of impact, the shock absorber and the cage would absorb the largest part of the energy. The metal structure of the transfer transfer cask would be misshapen but not split open. Primary packages should remain intact even if, in the case of B waste packages, the concrete envelope of the disposal package were damaged.

However, given the uncertainties associated with the sequence of events leading to a cage falling down a shaft that would not be covered by the aforementioned simulation studies, radioactive material release scenarios have also been envisaged in Section 11.7 in order to obtain an order of magnitude of the radiological consequences resulting from the drop and to ensure that the technical means exist, if required, to limit their impact to an acceptable level for the environment.

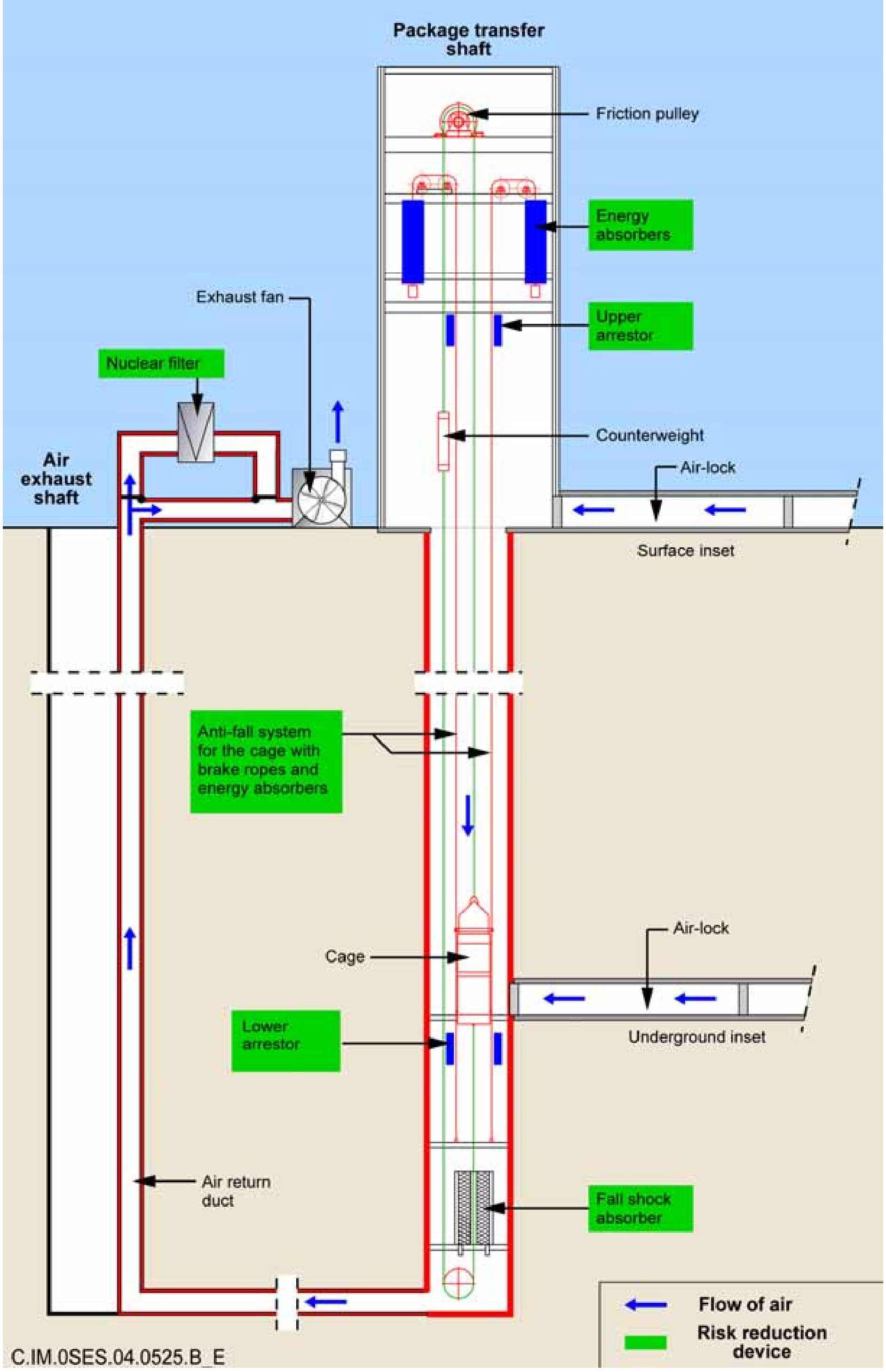


Figure 11.2.3 Schematic diagram of the devices envisaged to reduce risks during waste disposal package transfer in shaft

- **Risk of criticality associated with a cage loaded with a used fuel package transfer transfer cask falling down a shaft**

A drop scenario involving a cage loaded with a transfer cask containing a spent fuel disposal package which would entail serious damage to said package (modification of its internal geometry, fracture and contact between spent fuel bundle elements) and an inflow of water could lead to a risk of criticality.

Given the measures envisaged to counter the risk of a cage falling down the shaft, such a level of damage to the package does not seem likely. However, an additional precaution would be to ensure the absence of water (or other hydrogenated fluid) in the shaft to rule out the possibility of this risk entirely. This would mean prohibiting the installation of pipes in the waste transfer shaft and also providing a water evacuation system at the bottom of the shaft.

The other dangerous situations envisaged [55] do not appear to bring about a risk of criticality.

- **Summary**

A summary of the analysis (cf.Table 11.2.2) is presented per type of activity (construction, operation, closure). The potential retrieval of disposal packages has also been envisaged.

Table 11.2.2 Summary of radiological risks associated with the disposal process

Activities / Risks	Operations			Closure	Potentiel package retrieval
	Surface installations	Transfer surface / U/G installations	Underground installations		
Failure of radiological protection associated with equipment	x		x	x	x
Failure of radiological protection during the course of an operation	x		x	x	x
Radiological protection failure / loss of package containment associated with a fire in a cell of the surface installations	x	▨	▨	▨	▨
Radiological protection failure / breach of package containment associated with a primary package falling in the surface installations	x (B and bare spent fuel)	▨	▨	▨	▨
Radiological protection failure / loss of package containment associated with transporter or handling vehicle fire.	x		x	▨	x
Radiological protection failure / breach of package containment associated with a B waste package falling during emplacement or removal.	▨	▨	x	▨	x
Radiological protection failure / loss of package containment / criticality[161] associated with uncontrolled displacement or a cage falling down the shaft when transporting a transfer cask.	▨	x	▨	▨	▨

x Risk to be taken into account

☐ Negligible risk

▨ Not applicable

■ Risk is the subject of an additional study

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[161] The risk of criticality only concerns used fuel.

The following conclusions can be drawn from this table:

- The analysis shows no notable differences as regards the nature of the risks between package emplacement and removal. Operations associated with the possible removal of packages from the repository would be the reverse of operations carried out during emplacement;
- Closure activities do not present risks associated with the handling and transfer of the packages. On the other hand, special attention will be necessary to counter the possible failure of radiological protection during operations carried out at the entrance of disposal cells;
- The analysis lists conventional risks such as radiological protection failure for which the preventive measures and controls are known and do not require special studies to be undertaken at this stage in the project;
- It may also be considered that the risks of a package falling and fire in surface installations do not justify additional studies at this point given the feedback on experience available from similar existing surface nuclear facilities;
- The radiological risks associated with the transfer and emplacement of packages in the disposal cell, on the other hand, have called for further study. The risks induced by transport or handling vehicle fires must take into account their characteristics and the fact that the fire would occur in a semi-confined space. Similarly, package drop scenarios refer to drop heights that are different from the usual handling heights in surface installations, in particular during transfer cask transfer in shafts. These various risks will be dealt with respectively in Sections 11.5 and 11.5 for fire risks and Sections 11.7 and 11.8 for risks associated with drops.

11.2.3 Risks associated with the repository external environment

11.2.3.1 Earthquake

The sector covered by the study is a low seismic activity zone. The surface installations would have to be dimensioned in accordance with current aseismic regulations. In addition, measures would have to be taken to prevent any loss of safety function liable to have a radiological impact on operating personnel and the public.

The measures consist of dimensioning buildings (stability of all buildings) for a safety margin computed earthquake [112] in order to protect the sources inside these buildings and equipment which could, directly or indirectly, be a cause of dissemination of radioactive material.

Underground engineered structures withstand seismic loads better than surface installations due to attenuation with depth. It has been shown that the earthquake [36] would not have a significant impact deep underground.

11.2.3.2 Meteorological risks

The main risks only concern surface installations and have no impact on underground activities. They mainly concern rain and snow fall, extreme temperatures, lightning and wind.

11.2.3.3 Aircraft impingement

Independently of the direct physical consequences, the impingement of an aircraft on surface installations could result in the loss of safety functions leading to the exposure of personnel to radiation and its release into the environment.

This risk could be dealt with in accordance with the principles set out in Basic Safety Rules (*Règles Fondamentales de Sûreté*) RFS I.1.a [113] which recommends an evaluation of the probability of an impingement on "targets" within the facilities for which the loss of safety functions could have serious consequences. This evaluation is specific to the location of the site and takes different types of air activity into account: general aviation, commercial aviation and military aviation. The objective is to ensure that the probability of aircraft impingement leading to an unacceptable release of radioactivity is less than 10^{-7} per year. Above this value, the risk of impingement must be incorporated into the dimensioning of the installations in question.

In such a case, the measures employed to protect the installations, in particular those containing sources of radiation, would consist of dimensioning the concrete engineered structures to ensure that they are capable of withstanding aircraft impingement and marking out the highest obstacles (shaft superstructures) with beacons.

11.2.3.4 Risks associated with the loss of power and utilities

Even if this event is improbable (it could occur, for example, as a result of extreme weather conditions) and may not put personnel present in immediate danger, it could cause difficulties because of the large number of systems that would be stopped: ventilation, lighting, pumping and transfer cage. Preventive measures consist of redundant sources of power and emergency supplies (generators, batteries, etc.) for essential systems.

11.2.4 Summary

The operational safety analysis is based on the systematic analysis of risks supported by input from experts in the various technical domains concerned.

The construction of the various facilities is no different from the construction of other surface industrial installations or underground engineered structures (mines, tunnels, etc.). Because of this, the risks associated with this activity are the conventional risks (crushing, falls, etc.) listed in all construction work for this type of installation. No further studies are required at this stage but would, however, be taken into account during the detail design of structures and equipment.

Nuclear activity in the surface installations of the repository, which includes the reception, preparation and storage of waste packages, is comparable to activities carried out in the French nuclear facilities where the packages originate. Because of this, the analysis did not require specific studies of the repository installations themselves.

Nuclear activity in the underground installations, including the transfer of transfer casks (containing waste disposal packages) in the shafts and drifts and the emplacement of waste disposal packages in their cells, is carried out at the same time as drift and cell construction work. This is a specific issue, even though underground repositories exist all over the world[162] and it is proposed that the design should ensure that these activities remain independent of each other by separating the respective traffic circuits and ventilation systems.

The closure activity does not entail any additional elements over and above those included in other activities. There is no particular difference between the closure of surface installations and that of a conventional dismantling site. The closure of underground installations, which takes the form of backfilling and sealing drifts and shafts, would be comparable to construction work in terms of site organisation and the type of equipment used.

The analysis has highlighted the risks that require particular attention on account of their specific characteristics or their impact on the design of the repository and its equipment.

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[162] These disposal facilities include the Waste Isolation Pilot Plant (WIPP) in New Mexico, USA, where transuranium waste packages (comparable to some B waste packages) are disposed of in underground installations access to which is via 650 m-deep shafts [114] and the SFR in Sweden where low- and intermediate-level waste packages are disposed of at a depth of between 60 and 100 m.

These risks are the risk of explosion associated with the emission of gas from some waste packages (cf. Section 11.3), the risk of fire in underground installations (cf. Section 11.4) focusing on scenarios that would involve disposal packages (cf. Section 11.5 and 11.6) and the risks involved with the transfer of packages of radioactive material with the shaft drop scenario (cf. Section 11.7) and B waste disposal packages falling in cells (cf. Section 11.8).

This analysis is based on the current understanding of the main risks identified on the basis of current knowledge of the installations. It may evolve with the expansion of installation definition studies.

11.3 Study of the risk associated with the emission of explosive gases from some B waste packages

Most of the B waste packages (B2 and B5 in particular) emit gases between the time of their arrival at the surface installations and their emplacement in the underground disposal cells. These gases are caused by radiolysis which is associated with the effect of ionizing radiation (β, γ) emitted by radioactive materials on hydrogenated products present in the waste packages (organic materials, water in the conditioning matrix).

These radiolysis gases are mainly hydrogen (more than 90% of the gaseous releases) and, to a lesser extent, methane[163]. The emission of these gases can cause an explosion if their concentration exceeds their lowest explosive limit[164].

The purpose of this section is to ensure that the emission of these gases by B waste packages is not liable to entail a risk of explosion [107].

11.3.1 Waste package characteristics

Waste packages affected by the release of explosive gases are mainly B2 and B5.1 type packages that contain organic matter.

Table 11.3.1 Emission rates of explosive gases released by some B waste packages

Primary package	Nature and contents of the primary package	Emission rates of explosive gases (H_2, CH_4) (l/drum/year)
B2.1 **B2.2**	Metal drum with bituminised sludge	- 10 liters/drum/year (average value) - 57 litres/drum/year (maximum value corresponding to a minority of drums)
B5.1	Container with hulls and end caps and technological waste (including organic waste)	- 10 litres/drum/year (average value) - 500 litres/drum/year (maximum theoretic value for pacakages corresponding to a maximum value of organic compounds and a maximum activity value)

Average values of gas emitted from the packages have been used for simulations in the surface installations and in disposal cells as they correspond to several hundred or several thousand packages; on the other hand, the theoretical maximum values has been used for simulations relating to the phase in which a transfer cask loaded with a disposal package is transferred in the drift.

The concentration of gases in a given installation has been estimated as a function of its ventilation characteristics. The per hour air renewal rate is taken as being equal to 2 in installations in surface nuclear facilities. For the ventilation of B waste disposal cells, the data used are an airflow of 3 m^3/s which corresponds, for a 250m-long cell full of packages, to an air renewal rate per hour of 5.

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[163] Radiolysis is also the cause of the release of very small amounts of carbon dioxide and carbon monoxide. These gases are diluted by the ventilation of the installations as are those produced by vehicles with thermal engines.

[164] The lowest explosive limit is the minimum concentration of gas above which there is a risk of explosion in the presence of a source of ignition. The lowest explosive limit is 4 % for hydrogen and 5.3 % for methane.

Hydrogen emitted by the waste disposal packages dilutes homogeneously in the free space below the disposal packages[165] and it should be noted that ventilation remains in operation until the time when a cell is sealed.

Estimates were based on the pessimistic hypothesis of a constant outgassing rate over the duration of the operation and closure activity of the repository.

11.3.2 Analysis during the operational phase

This analysis is described in accordance with the logic of the cycle followed by the packages: storage of primary packages, storage of disposal packages, transfer of waste disposal packages to underground facilities, emplacement of waste disposal packages in disposal cells.

11.3.2.1 Surface storage (primary and disposal packages)

A simulation, carried out based on the assumptions previously described, indicates that the hydrogen content in the atmosphere in the storage area is negligible under normal ventilation conditions (with the content varying from 10^{-6} to 10^{-7} in the various surface storage areas), and that the time taken to reach the explosive limit of 4.10^{-2} (4 %) in the event of a ventilation failure is several decades. There is therefore no risk of an explosion in these areas.

11.3.2.2 Transfer of waste disposal packages

Hydrogen is also produced inside the transfer transfer cask during the transfer of the packages from surface installations to the disposal cell. The existence of the transfer cask door construction clearances and, where applicable, the presence of a vent, will allow the hydrogen produced by the packages to be diluted in the atmosphere of the spaces through which the transfer cask passes and there will be no risk of an explosion, given the low hydrogen emission rate compared to the ventilation flow rates in the various installations.

11.3.2.3 Disposal cells

The simulation was carried out with a ventilation failure in a 250 m long disposal cell filled with type B5.1 packages. Hydrogen was then concentrated in the top 15 cm of the disposal cell, above the waste disposal packages.

Under these conditions, the time taken to reach the 4% explosive limit is around 30 days. There is therefore no risk of explosion, even assuming a temporary ventilation failure.

11.3.3 Analysis during the closing phase

As far as the risk of an explosion is concerned, this phase can be sub-divided as follows.

11.3.3.1 Disposal cell sealing phase

The sealing process would begin by fitting a radiological protection shield consisting of concrete blocks fitted with pipes for maintaining the ventilation in the cell (see 5.1.6). This stage is followed by the construction of a concrete retaining plug which fills the top of the cell and thus isolates the waste disposal packages from the access drift. Under these conditions, the release of hydrogen into the access drift would be very slight and could not be the source of an explosion, all the more so since this drift will be ventilated throughout the fitting of the seal swelling clay core.

11.3.3.2 Post disposal cell-sealing phase

The backfilling work may be carried out in two stages: backfilling of the type B waste repository zone infrastructure then, at a later date, backfilling of the remainder of the infrastructure before complete closing of the repository.

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[165] Hydrogen, being lighter than air, will tend to migrate above the packages towards the top of the cell.

This backfilling work is isolated from the disposal cells by seals and cannot cause an explosion.

However, if it was decided to return to a cell after sealing, such an operation would only be possible after renewing the atmosphere in the disposal cell beforehand in order to vent away any hydrogen present (see chapter 10). This would require special provisions to be made, of the sort practiced in fire-damp producing coal mines, to avoid any risk of ignition when the ventilation system is put back in place.

11.3.4 Conclusion

The risks associated with the emission of explosive gases (essentially H_2) by certain type B waste packages are controlled during the operational phase by ventilating the various installations, which dilutes their content. An interruption to the ventilation poses no real danger as a long period of time is available to carry out any repairs

The closure steps of the disposal process pose no explosive hazard, except in the event of a return to a cell after it has been sealed. In such cases, it will be necessary to re-establish the ventilation in order to extract the gases accumulated in the disposal cell, taking the necessary safety precautions during its installation.

11.4 Study into the fire hazard in underground installations

Fire remains one of the major preoccupations in an underground environment, since it develops in a semi-confined space, and the associated smoke and toxic gases may spread through the drifts into the installations, impede personnel evacuation and endanger a large number of persons.

Feedback from fires in underground structures indicates that the calorific potential of the drifts themselves being low, only the machinery and equipment can be the source of a major fire. According to a study of Swedish mines [115], the three main causes of machinery fires are electrical short-circuits (around 50 %), oil leaks on hot surfaces (around 25 %) and engine over-heating (approximately 10 % of cases). However, the risk of a collision causing a fire is low, given the slow speeds and low frequency of vehicles passing each other.

The essential fire prevention measures required in underground installations are as follows:

- preferred use of non-flammable materials that do not propagate fires and do not emit toxic smoke,
- control of inflammable products present (justification of product choice and use, maximum authorised quantities, transport conditions and utilisation procedures etc.),
- restrictions on the quantity of fuel for machinery with thermal engines, protection of sensitive components and choice, where possible of electrically-powered machinery with low heat load if the type of activity allows,
- implementation of machinery and equipment inspection, maintenance and operating procedures (driving licences for machinery, fire permits etc.) and personnel training in effective reactions in the event of an anomaly.

Fire detection equipment (with smoke, flame or temperature detectors) are also useful to allow rapid intervention in order to get the fire under control before it takes hold. These systems are preferably installed as construction work advances.

Fire protection measures consist, firstly, of providing personnel with first aid fire-fighting equipment, with extinguishers and a pressurised firemain fitted close to the work site. Fixed automatic extinguishing systems, fitted in hazardous areas (fuel or oil storage) and systems on board vehicles could also be effective means to be provided.

Over and above these fire precautions, underground installations should be fitted with a smoke extraction system enabling personnel to be evacuated under acceptable temperature, visibility and toxicity conditions. The installation of warning and alarm systems[166] and a centralised command post able to monitor the situation and direct operations would also contribute to the organisation of this evacuation under the safest possible conditions.

This section assumes that a fire has developed despite the preventative measure described above. Its purpose is to study the various representative fire scenarios, assess their consequences (temperature rise, smoke emission, toxic gas emission) and ensure that the personnel evacuation conditions are satisfactory. It does not deal with fires liable to have radiological consequences, which require further discussion and which are dealt with in sections 11.5 and 11.6.

11.4.1 Fire simulations

Simulation studies [107] have been carried in order to understand the potential consequences of the various fire scenarios envisaged, according to their characteristics.

11.4.1.1 Description of the various fire scenarios

The plant and machinery used to build the structures (diggers, rock bolters, transporters etc.) or conduct operational activities (transfer cask transporters etc) and a few items of special machinery (conveyer belts for carrying excavated material etc.) may cause potentially high-temperature fires[167]. This type of fire is characterised by its high thermal power, the quantity of toxic gases and the amount of smoke given off.

Determining its thermal power requires a realistic scenario to be defined. In the case of an item of plant machinery, the fire-producing event used in the scenario is usually a liquid fuel leak associated with a hot point (spark etc.). The liquid leakage rate considered determines the initial strength of the fire. The fire’s duration depends on the machinery’s calorific potential: the quantities of fuel or oil form a major part of this potential, immediately available in the event of a fire; tyres contribute to increasing the duration of the fire and the amount of smoke produced. It is also assumed that the oxygen in the air is in sufficient quantity and that the seat of the fire is not extinguished by smothering.

The summary of the results for all the various items of machinery studied show that there are two major categories of machinery fire. Diesel or diesel-electrical machinery (dump trucks, loaders, excavators, bolting and drilling machines etc.) is that which produces fires which generate the most heat, approaching 25 MW, whilst electric transporters have a maximum thermal power of around 15 MW.

In order to overcome the problems associated with modelling of curves presenting transient phenomena, the fire simulations have used standard curves defined by the CETu (French tunnel studying centre), which cover the above in terms of power and duration. These curves, derived from feedback from tunnel fires, correspond to road vehicle fires with respective total powers of[168] 30 MW and 15 MW. Also associated with each type of fire are carbon monoxide emissions and smoke production.

Figure 11.4.1 which represents the evolution of the thermal power of a 30 MW fire over time, is an example of the standard curves which all have the same profile, with a start ramp, a levelling off and a descending ramp.

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[166] An intersting approach would be to provide personnel with an individual voice system linked to an internal network and centralised command poste. In normal conditions, this system would be used for work organisation; in case of fire, it would be the best real-time alarm system.

[167] Another type of high-risk fire would be one in an inflammable product store, but this type of fire is not considered at this stage of the study, partly because its location and size are unknown and partly because this type of installation can more easily be the subject of special fixed fire-fighting facilities.

[168] Generally speaking, for this type of fire, two thirds of the total power is dissipated by convection, the other third being dissipated by radiation.

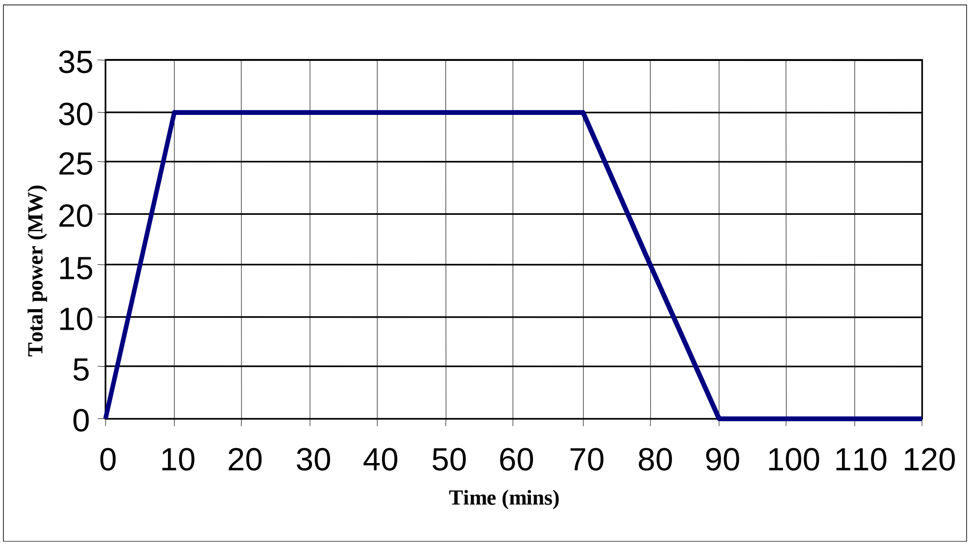

Figure 11.4.1 *Standard total thermal powerfor a 30 MW fire*

11.4.1.2 How fires develop

In an underground environment, fires emit smoke as they develop which spreads throughout the drift (fire with smoke de-layering) or forms localised pockets at the top of the drift (fire with smoke layering) depending on the ventilation conditions encountered.

- **Fires with smoke de-layering**

Fires with smoke de-layering give off smoke which gradually spreads through the drifts, turning the atmosphere opaque, and often hindering the evacuation of personnel. This type of fire, produced when the air speed in the drift is greater than 1 m/s, is characterised by a uniform mixture of air and smoke throughout the drift's cross section at a given distance from the fire.

In the case of a repository, fires in type C waste and spent fuel disposal cell access drifts, ventilated by an inflow of fresh air throughout the drift's cross section, and exhausting the smoke via a smoke-clearance vent at the end of the operational unit, would be of this type.

For this type of fire (see Figure 11.4.2), personnel preferably escape by heading towards the connecting drift supplied with fresh air. If this is not the case, personnel downstream of the fire can head for the first interconnecting drifts in order to reach the adjacent access drift supplied with fresh air (with a maximum distance of 200 m to be covered thanks to the layout of the interconnecting drifts) then into the connecting drift.

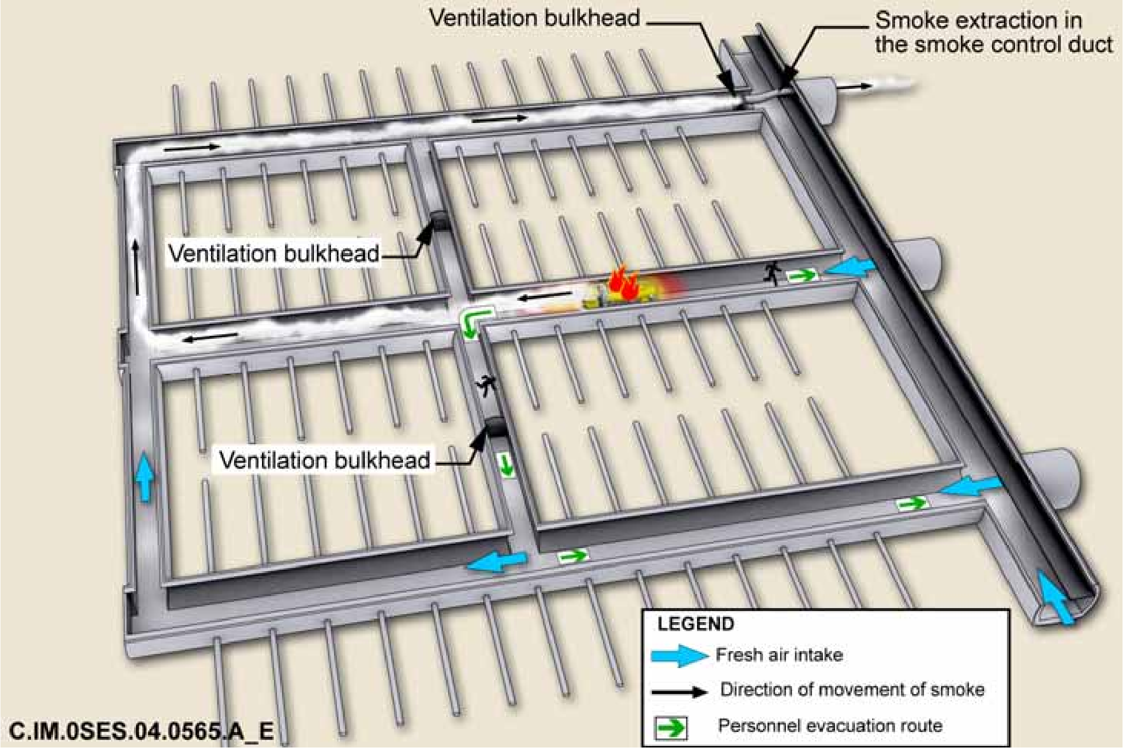

Figure 11.4.2 *Smoke circulation and evacuation in the case of a fire in an operational type C (or CU) unit*

- **Fires with smoke layering**

Fires with smoke layering lead to the smoke forming pockets at the top of the drifts (see Figure 11.4.3). It is then the temperature conditions associated with the radiation from this smoke which pose the main hazard to personnel. This type of fire occurs in the presence of a low airflow in the drift (under approximately 1 m/s) with smoke which spreads either side of the seat of the fire.

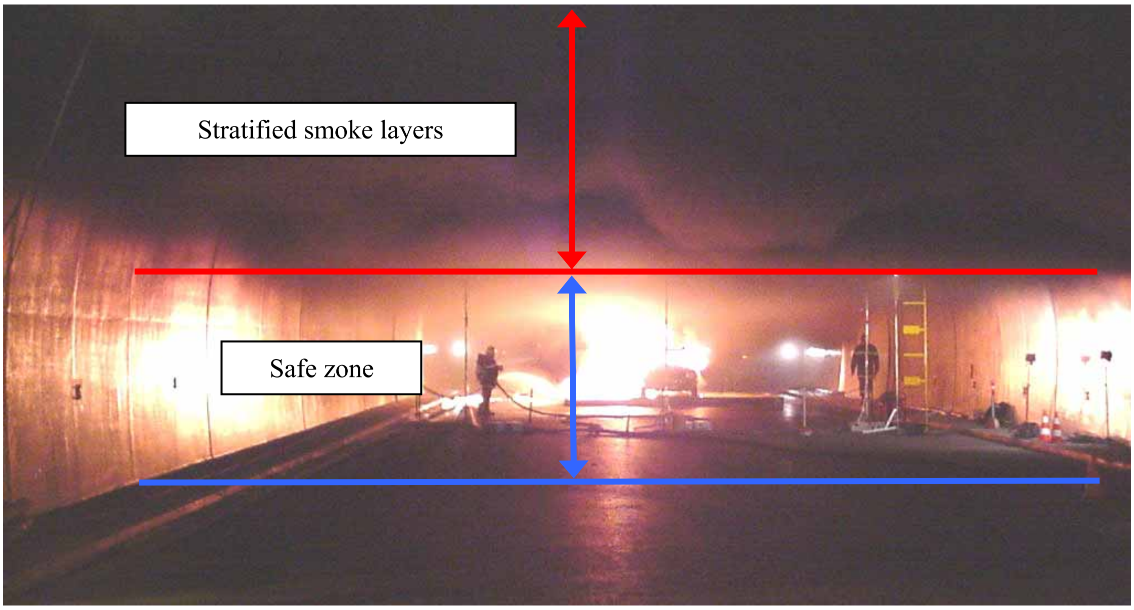

Figure 11.4.3 *Qualification tests on the smoke control system in the Orelle tunnel (SFTRF and SETEC) – example of a fire with smoke stratification.*

In a repository, fires in connecting drifts, with smoke extraction by vents fitted at regular intervals, would be of this type.

Depending on their position with respect to the fire, personnel can escape upstream or downstream of the fire, via the nearest interconnecting drift, in order to regain the adjacent connecting drift supplied with fresh air. The maximum distance to reach these interconnecting drifts varies from 100 m in secondary connecting drifts, inside repository zones (see Figure 11.4.4) to 400 m in main connecting drifts.

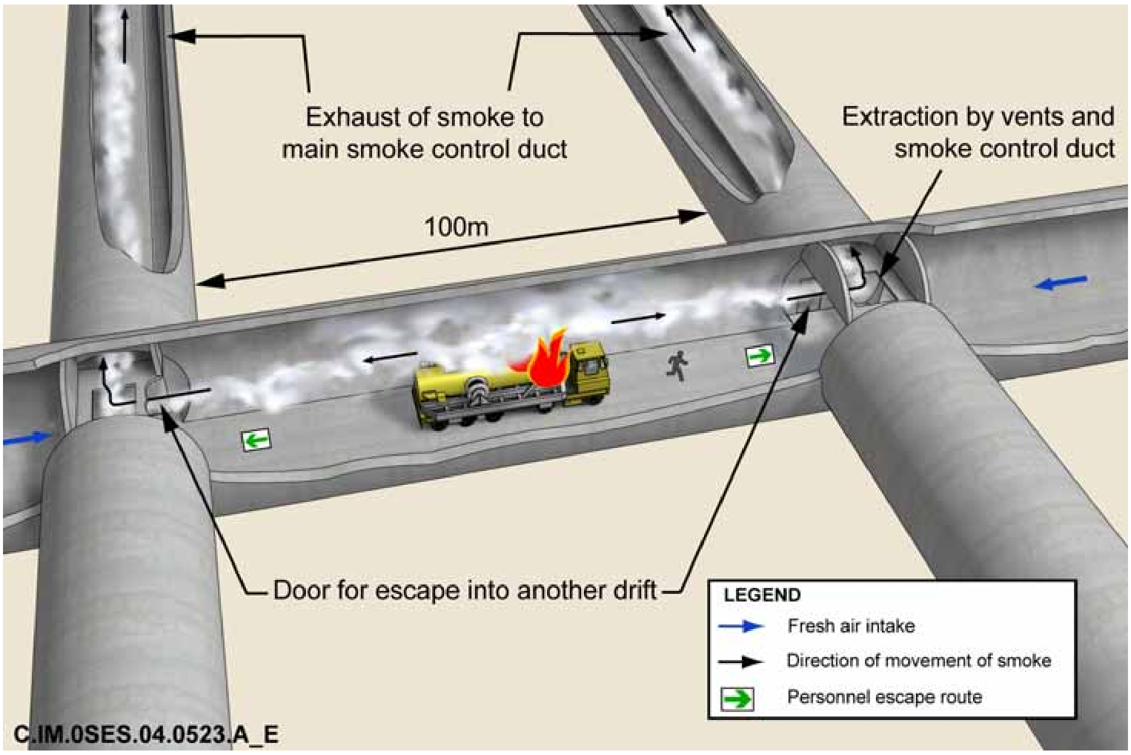

Figure 11.4.4 Case of a fire in a connecting drift:evacuation either side of the fire

- **Particular case of a fire in a dead end drift**

A fire in a dead-end drift is a special intermediate case between the two previous cases. On the one hand, it is similar to a fire with smoke de-layering as the smoke is only extracted via the site air extraction duct but, on the other hand, the short distance between the seat of the fire and this smoke extraction point limits the smoke encroachment into the drift.

There are two possible situations (see Figure 11.4.5) : if personnel can escape upstream of the fire into the ventilation airflow, they head for the adjacent drift supplied with fresh air via the nearest interconnecting drift; otherwise they head for the mobile refuge[169] to await rescue.

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[169] This mobile refuge, fitted with fire-resistant walls, has compressed air and water storage tanks.

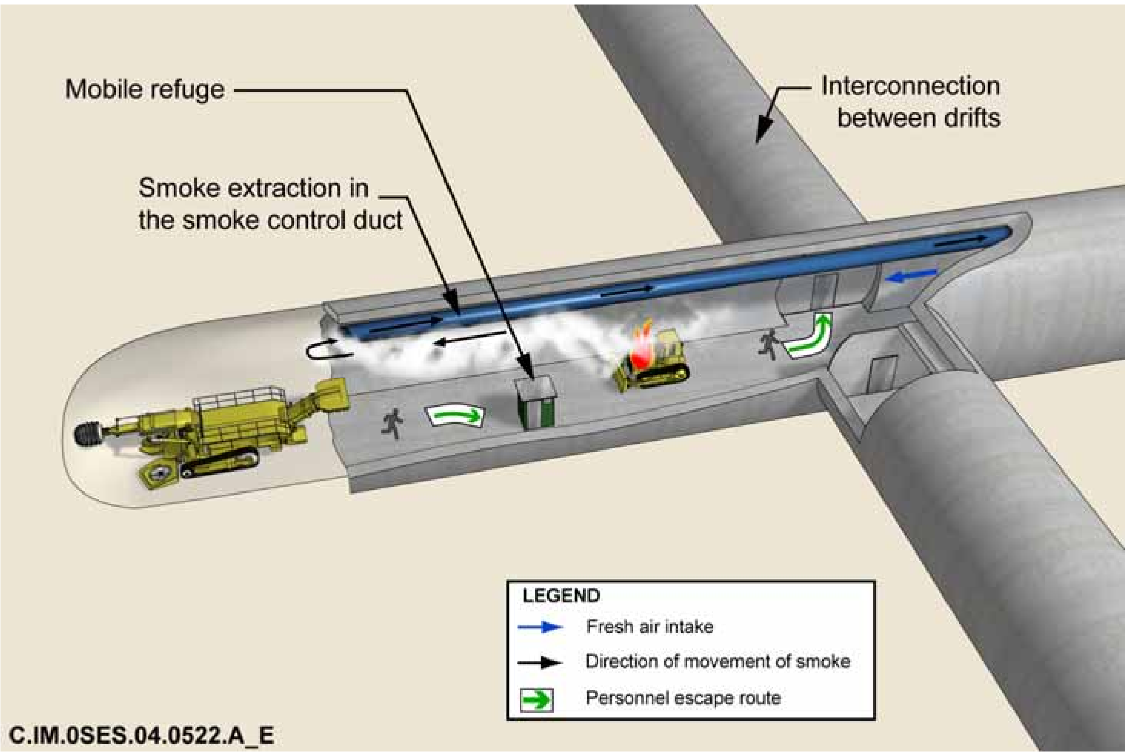

Figure 11.4.5 *Fire in a dead-end drift: personnel evacuation via an interconnecting drift into an adjacent drift or sheltering in a mobile refuge*

In all the above scenarios, personnel must then head via connecting galleries supplied with fresh air to the personnel transport shaft in order to return to the surface.

11.4.2 Simulation of personnel evacuation conditions

The results of these preliminary simulation studies are presented, as before, by type of fire as the personnel evacuation conditions are directly linked to whether or not smoke layering occurs.

11.4.2.1 Fire with smoke de-layering

The example given is a machinery fire with a thermal power of 15 MW in a type C cell access drift during nuclear operation. This power represents the maximum power of the machinery used.

The example used is that of a fire just after an intersection, which corresponds to a maximum evacuation distance before reaching the next interconnecting drift of almost 200 m.

The data obtained[170] (temperature, carbon monoxide concentration and air/smoke mixture opacity) are comparable with the permissible thresholds for survival and escape conditions for this type of fire. The temperature shall not exceed 80°C for more than 15 minutes. The carbon monoxide content shall not exceed figures within a range estimated at between 500 ppm for 60 minutes and 3000 ppm for 10 minutes. Finally, an opacity greater than 0.3 m^{-1} corresponding to a walking visibility of 7 m starts to hinder personnel evacuation; it becomes difficult with an opacity greater than 1 m^{-1} (visibility less than 1.5 m).

The results of the simulations are presented, emphasising personnel evacuation conditions in accordance with two assumptions: the normal evacuation speed is 1 m/s; that of a group having to evacuate a casualty would be 0.5 m/s.

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[170] The temperature changes have been calculated by applying the thermal convection laws in a turbulent air flow. The changes in opacity and the carbon monoxide concentration were digitally simulated, as for the temperature, using the Camatt (tunnel transient anisothermal monodimensional computation) software.

- **Temperature**

The diagram [downstream distance from the fire (m) / time since outbreak of fire (s) / temperature (°C)] highlights the influence of the smoke clearance system[171] the operation of which deflects the rise in temperature of the air in the drifts downstream of the fire ventilation airflow.

The simulation (see Figure 11.4.6) shows that the evacuation of personnel located downstream of the fire should be possible under acceptable conditions even for personnel close to the seat of the fire. Personnel escaping at normal speed reach the interconnecting drift in an atmosphere at a air temperature of below 30°C, and between 40°C and 50°C if they are slowed down by the presence of a casualty. These conditions remain acceptable with respect to the 80°C threshold mentioned previously.

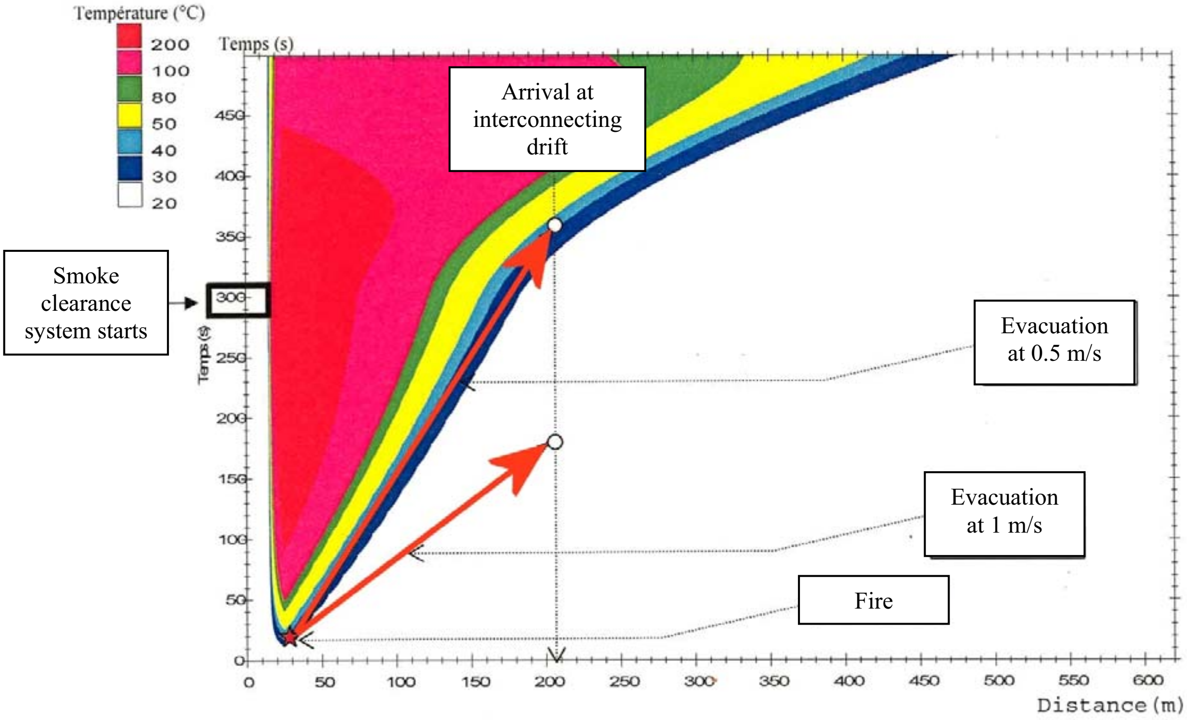

Figure 11.4.6 *Spatio-temporal evolution of the air temperature (°C) in the case of a fire in a type C waste cell access drift during nuclear operation – Representation of the movement of personnel located downstream the fore ventilation airflow*

- **Carbon monoxide concentration**

Using the same approach as before, the simulation shows that persons located downstream of the fire ventilation, escaping at normal speed, can reach the interconnecting drift under healthy conditions. At an evacuation speed reduced to 0.5 m/s, personnel arrive at the interconnecting drift in an atmosphere whose a carbon monoxide content (pf around 200 ppm) is still below the 500 ppm threshold.

- **Opacity**

The simulation shows that personnel escaping at 1 m/s can reach the interconnecting drift without being hindered by the opacity, which remains under 0.10 m^{-1}, corresponding to a visibility of around 10 metres.

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[171] It was considered that that the smoke clearance installations would be started up 5 minutes (300 seconds) after the outbreak of the fire and that a stable state would be established after 8 minutes. These data come from experiments in underground structures

However, with a slow evacuation speed (0.5 m/s), personnel would quickly be caught up by smoke, with a mean opacity of around 0.6 m^{-1}, or a visibility distance reduced to 2 m. In this case, personnel may have to wear their individual breathing apparatus for the final few metres before reaching the interconnecting drift.

11.4.2.2 Fire with smoke layering

The example used is that of machinery with a thermal power of 30 MW in a connecting gallery. This case, which corresponds to a fire involving heavy construction machinery, is an envelope case compared with that of a package transporter which would have a lower thermal power (15 MW).

The propagation, height and temperature of the layer of smoke were determined analytically, using knowledge of stratification phenomena observed in the case of road tunnels. The effects associated with radiation emitted by the smoke from the fire are comparable with the permissible threshold for thermal effects on humans (2 kW/m² for persons not equipped with protection[172]).

The results of simulation (see Table 11.4.1) show that escaping personnel are subjected to a maximum heat radiation level of 0.9 kW/m² after 100 m in the case of an evacuation at the slower speed (0.5 m/s), which corresponds to satisfactory conditions.

Table 11.4.1 Heat radiation received during evacuation in the case of a fire (30 MW) with layered smoke in a connecting drift

Heat radiation received by personnel (kW/m²)		
Speee of personnel movement / **Location with respect to seat of fire**	0.5 m/s	1 m/s
100 m	0.88 kW/m²	0.38 kW/m²
200 m	0.56 kW/m²	0.38 kW/m²
400 m	The smoke does not reach this distance due to the starting of the smoke clearance system	0.36 kW/m²

11.4.3 Conclusion

In underground repository installations, two types of fire can develop: fires with smoke layering (in connecting drifts) or smoke de-layering (in access drifts to type C or spent fuel waste cells). In both cases, simulations conducted tend to indicate that the design of the underground infrastructure, with clusters of parallel drifts connected at regular intervals by interconnecting drifts, enables personnel to escape from the location of the fire under satisfactory conditions, quickly reach a parallel drift supplied with fresh air (clear of the smoke circuit) then return to the surface under good conditions.

In a few cases (fire with smoke de-layering and slow evacuation speed) it cannot be excluded at this stage that the smoke might catch up with the escaping personnel and that they may have to use their personal breathing and eye protection.

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[172] This radiant rating corresponds to a maximum smoke temperature of around 200°C, wich would induce an air temperature lower than 80°C in the healthy zone (cf. Figure 11.4.3)

A special case is that in which a fire develops during work in a dead-end drift. Personnel may find themselves between the fire and the end of the drift, unable to reach an interconnecting drift in order to escape. In this situation, they would have to take shelter in a mobile refuge (equipped with compressed air and water) which would be designed to be fire-resistant and smoke-proof. Once there, personnel would wait to be rescued by a rescue team which should arrive at the scene of the fire in order to act as quickly as possible.

Feedback from underground work sites indicates that particular effort must go into preventive measures and personnel training, with regular exercises in order to learn essential emergency reflex actions. If personnel are well trained and have adequate resources in order to intervene effectively in the event of a fire, they generally manage to extinguish the fire before it has time to develop. The use of specialised personnel, equipped with full fire fighting gear, would only be required in about 10 % of fires [115].

11.5 Study of the consequences of a fire in a vehicle transporting the transfer transfer casks (B, C and CU)

The transfer transfer casks for waste disposal packages are loaded in the nuclear surface installations on a transport vehicle. This vehicle brings the transfer casks to the package transfer shaft and places them on a metallic support in the cage, which lowers them to the underground installations. The transfer casks are then recovered by a vehicle similar to the one used on the surface and transported by this vehicle to the disposal cells.

In addition to the usual consequences resulting from a fire (temperature increase, smoke, …) treated in the previous section, if this vehicle is on fire, it could have radiological consequences if the fire impacts on the protection ensured by the transfer cask (protection against external exposure) and the primary package (maintaining the containment).

The purpose of this section is to estimate by means of simulation studies [107] whether radiological consequences may result and propose, if necessary, additional measures to prevent this risk or protect against it.

11.5.1 Assessment of the consequences of a fire in the transport vehicle on the transfer transfer cask and its contents

This assessment is based on the assumption of a fire breaking out in a transfer cask transfer vehicle (B, C or spent fuel) despite recommended preventive measures (cf. section 11.4). The nature of transfered packages, the evolution of their characteristics versus the temperature to which they are raised and the main characteristics of the transfer transfer casks are referred to in Table 11.5.1.

Table 11.5.1 Main characteristics of the packages and transfer transfer casks

Primary package (internal temperature)	**Specific data related to the temperature conditions**	**Disposal package**	**Transfer transfer cask**	
			Materials	**Thickness (mm)**
B2.1[173] **bituminised sludge** (ambient temperature)	softening at 40°C flash point at 230°C spontaneous combustion at 350°C	Concrete package (with 4 primary packages in vertical position)	Steel Thermal shield [174]	180 to 220 20
CSD-V vitrified wastes (64°C at waste core)	Crystallisation of the glass : 450°C	Metallic overpack (with a CSD-V package in horizontal position)	Internal steel Neutrophage External steel	200 to 230 140 to 150 20
CU1 spent fuels UOx (87°C at centre of assembly)	Embrittlement of the fuel clad above 500°C	Metallic container (with 4 spent fuels in horizontal position)	Internal steel Neutrophage External steel	70 120 20

11.5.1.1 Definition of a fire scenario

The vehicle used to transfer the transfer casks is a self-propelled electric transport vehicle on tyres. The reference fire studied is located in the underground installations. It was defined from the specific characteristics of the vehicle and the recommendations of the Road Tunnel Study Centre (CETu) ; it corresponds to a fire with a heat rating of 15 MW for a duration of one hour (cf. section 11.4).

The fire breaks out and spreads in a connecting drift with a ventilation rate under normal operation of approximately 30 m^3/s, which increases to 50 m^3/s after the smoke removal system is started.

11.5.1.2 Data related to the simulation studies

The simulation uses a finite elements method for an elaborated description of the temperature distribution taking into account the non linearity of heat exchanges.

The heat produced by the fire is transmitted from the source of the fire to all the components of the transport vehicle and the transfer cask by a convective flow and a radiant flow representing 2/3 and 1/3, respectively, of the total heat rating of the fire[175] :

- The convective rating appears in the fumes emitted by the fire source. They are mixed with the air circulating in the drift, they envelop the transfer cask and exchange heat with it,
- The radiant rating is related to the radiation generated by the fire source. It is applied differently depending on the transfer cask's geometric form. In the case of cylindrical transfer casks (C waste and SF packages), it is uniformly applied to the vehicle's flat bed, the transfer casks' frame and their lower half cylinder. For parallelopiped transfer casks containing B waste packages, half of the rating is applied to the lower surface in contact with the vehicle's flat bed and half to the side surfaces.

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[173] The bituminised sludge package was retained among the various B waste packages because it is the most risky in terms of ignition.

[174] For some B waste packages (B4, B5), a neutrophage material whose characteristics would allow it to play the role of a thermal shield is to be used like for the C and CU waste packages.

[175] This breakdown corresponds to the recommendations of the CETu (Road Tunnel Study Centre) for a fire in this type of vehicle.

11.5.1.3 Results related to a fire on the transfer transfer cask, the disposal package and the waste package of bituminised sludge (B2)

Table 11.5.2 shows the results of the fire simulation with the maximum temperatures which would be reached at the external surfaces of the transfer transfer cask, the disposal package and the primary packages. It also gives the duration required from the outbreak of the fire to reach this maximum temperature.

Table 11.5.2 Temperatures estimated at the transfer transfer cask, the disposal package and the primary package of bituminised sludge (B2) obtained by numerical simulations under fire conditions

		Maximum temperature reached (°C)	**Time to reach Tmax from the outbreak of the fire**
Transfer transfer cask	Lower surface	900	~ 1 h
	Side surfaces	455	~ 2 h
	Upper surface	127	~ 1 h
Disposal package	According to the surface	from 203 to 561	~ 3 h
Primary package	Container body	143 (in lower surface)	~ 16 h
	Wastes	< 120 (except in package base)	~ 16 h

The simulations show that there isn't any risk of igniting the bituminised sludge wastes because the integrity of the transfer cask, the disposal package and the envelope of the primary package is preserved, preventing any contact by a flame with the bituminised matrix. Spontaneous combustion of the bituminised products, which requires a temperature on the order of 350°C, is also impossible. The only consequence of the fire on the wastes would be a softening of the bituminised matrix.

The temperatures determined show that the transfer cask could be slightly affected from a mechanical viewpoint because of its large thickness.

Thanks to the protective effect of the thermal shield incorporated in the transfer cask's structure, the concrete envelope of the disposal package would be subjected to temperatures on the order of 500°C, which would not effect the waste package integrity.

The metallic envelope of the primary packages, which is not thermally affected by maximum temperatures on the order of 150°C (cf.Figure 11.5.1), would not be damaged by the fire.

Therefore, these results refute the assumption of a deterioration of the primary waste package and a loss of containment.

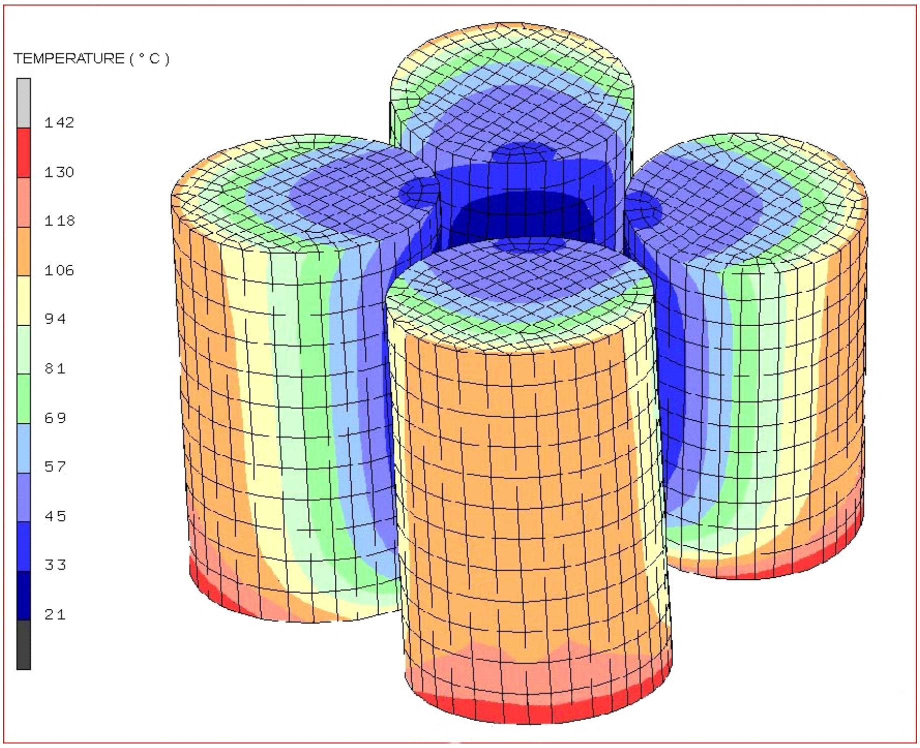

Figure 11.5.1 Temperature distribution in the primary packages of bituminised sludge (B2.1)[176]

11.5.1.4 Results related to a fire on the transfer transfer cask, the disposal package and the vitrified waste (C) package

In the case of C waste packages (cf. Table 11.5.3), the simulations show that the transfer cask's thickness and the presence of the PPB neutrophage material (Plaster Polyethylene Boron), which acts as a thermal shield, would allow limiting the temperature at the wastes to approximately 90°C.

This result appears to be a maximum value, given that the temperature on the external surface of the transfer cask is estimated at approximately 1 400°C, while experience shows that fires in an underground environment normally reach temperatures between 800 and 1200 °C [116], [117].

The integrity of the disposal package (over pack / container) therefore appears to be guaranteed and the temperature reached in the primary package would not be liable to change the characteristics of the vitreous matrix of the C wastes.

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[176] In this figure, the fire source is located under the packages, and the concrete envelope of the disposal package is not represented.

Table 11.5.3 Temperatures estimated at the transfer transfer cask, the disposal package and the primary package C obtained by digital simulations under fire conditions

		Maximum temperature reached (°C)	**Time to reach Tmax from the outbreak of the fire**
Transfer transfer cask	External surface	1410	~ 1 h
	Plaster polyethylene boron	1347	~ 1 h
	Internal surface	71	~ 4 h
Disposal package	According to the surface	70	~ 23 h
Primary package	Container body	71 to 83	from 23 h to 27 h
	Wastes	92	~ 30 h

Considering the fire's temperatures, the transfer cask may be affected by steel creep phenomena and PPB adhesion defects. This would necessitate checking the radiological protection level before performing any transfer cask recovery operation.

11.5.1.5 Results related to a fire on the transfer transfer cask, the disposal package and the assemblies of spent fuels (CU1)

The results related to the fire on a vehicle transporting a transfer cask of spent fuel lead to the same comments as in the case of C waste packages.

The thermal stresses would not induce any mechanical consequences on the spent fuel assemblies. There would not be any risk of damage because they would only be subject to a rise of about 15 degrees with respect to their initial temperature.

As previously, the results obtained refute the assumption of a deterioration of the spent fuel packages provoking radiological consequences.

Table 11.5.4 Temperatures estimated at the tranfer transfer cask, the disposal package and the spent fuel (CU1) obtained by numerical simulations under fire conditions

		Maximum temperature reached (°C)	**Time to reach Tmax from the outbreak of the fire**
Transfer transfer cask	External surface	1280	~ 1 h
	Plaster polyethylene boron	1250	~1 h
	Internal surface	271	~2 h
Disposal package	Container	98	~4 h
	Insert	69	~8 h
	Cladding	67	~9 h
Assembly of spent fuels	Assembly centre	100	-

11.5.2 Conclusion

During the transfer phase between the surface installations and the disposal cells, the fire on a transfer cask transport vehicle would not have any thermomechanical consequences capable of affecting the integrity of the transfered waste packages, which have a two-fold protection: the transfer transfer cask, with one of its components serving as a thermal shield, and the disposal package.

Nevertheless, it would be necessary before any action required as a result of the accident is taken that the level of radiological protection ensured by the transfer transfer cask be checked. In case this level is insufficient, it might be necessary, for example, to use movable radiological protections.

11.6 Study of the consequences of a fire on the emplacement vehicle (fork lift) of B waste disposal packages

In the surface installations, the B waste disposal packages[177] are placed in the transfer transfer cask by an electric powered handling vehicle, or fork lift. These packages are then moved in this transfer cask up to the disposal cell where they are handled by the same type of vehicle to emplace them in a cell.

In addition to the usual consequences resulting from a fire (temperature increase, smoke, …), if this handling vehicle of the B waste disposal packages is on fire inside the disposal cell, it could have radiological consequences if the fire affects the function of maintaining the containment of the primary package.

The purpose of this section is to estimate by means of simulation studies [107] whether radiological consequences may result and propose, if necessary, additional measures to prevent this risk or protect against it.

11.6.1 Assessment of the thermomechanical consequences of a fire on the waste disposal package and the primary packages contained in it

This assessment is based on the assumption of a fire breaking out in a waste disposal package handling vehicle despite the preventive measures taken (cf. section 11.4). The characteristics of the waste disposal package were previously described in Table 11.5.1.

11.6.1.1 Definition of the fire scenario

The retained scenario is the scenario which would take place while handling the type B2 waste packages because the bituminised matrix of the wastes for this type of package is the most sensitive to a temperature rise. On the other hand, the case of the fire on the underground vehicle was preferentially studied because this vehicle appears to have a higher heat potential than the surface vehicle.

The fork lift (emplacement vehicle) used to transfer the disposal packages from their transfer cask to their final emplacement in a disposal cell would be a self-propelled electric vehicle on rails. The fire considered would occur during the transfer of the disposal package between the cell's entrance and the already disposed of packages. The fire would be electrically caused and would imply the vehicle's batteries and motors as the origin. The scenario takes into account the installation of a 2 cm thick thermal shield between the vehicle's motor section and the handling section.

The fire's characteristics were defined based on the vehicle's characteristics ; the fire corresponds to a heat rating of 3 MW for a half hour duration. This fire breaks out in a cell where the ventilation rate is on the order of 3 m^3/s.

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[177] This illustrative case doesn't concern the C and CU waste packages directly emplaced from the transfer cask into their cells without requiring the use of an additional vehicle.

11.6.1.2 Assumptions related to the simulation studies

The methodology used is similar to that indicated for the fire during a transfer of packages (cf. 11.5.1.2). The only difference is due to the fact that the disposal package is located laterally with respect to the fire source located at the vehicle batteries. Under these conditions, it is assumed that the radiant rating applied to the package side corresponds to half the total radiant rating and that 50 % of this rating is distributed over the side surface directly attacked by the fire and 50 % over the four adjacent sides.

11.6.1.3 Thermal behaviour of the disposal package and the primary package of bituminised sludge B2 during the fire

Table 11.6.1 gives the results of the simulation with the estimations of temperatures which would be reached at the various surfaces of the disposal package and at the primary packages during the fire. It also indicates the time required from the outbreak of the fire to reach the maximum temperature.

Table 11.6.1 Temperatures estimated at the disposal package and the packages of bituminised sludge obtained by digital simulation of fire conditions

		Maximum temperature reached (°C)	**Time to reach T max from the outbreak of the fire**
Disposal package	Side surface, from side of the fire source	521	~ 30 min
	Adjacent surfaces	319	~ 30 min
	Opposite side	134	~ 30 min
Primary packages located on the side of the fire source	Container body	98	~ 4 h
	Wastes	66 to 97	~ 3 h

The simulations show that there isn't any risk of igniting the wastes because of the protection offered by the concrete envelope of the disposal package, which prevents any direct contact by a flame with the bituminised matrix. Spontaneous combustion of the bituminised matrix, which requires a temperature on the order of 350°C, is also impossible. The only consequence of the fire on the wastes would be a softening of the bituminised matrix related to its heating. Additional protection measures such as the shutdown or reduction of the ventilation flow in a cell (fire shut-off valve) could also be retained to isolate that cell and reduce the fire's intensity.

The primary packages would be subjected to temperature levels less than 100°C for the two most exposed packages on the fire side, which would not damage their metallic envelope and would not affect the contained bituminised wastes. Their average temperature would be around forty degrees (cf. Figure 11.6.1.

The concrete envelope of the disposal package would be subjected to temperatures on the order of 500°C, which should not affect its integrity. On the contrary, its mechanical properties may be altered and a scaling phenomenon is liable to occur on its surface[178].

In any case, the results obtained refute the assumption of a deterioration of the package of bituminised sludge provoking radiological consequences.

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[178] Tests showed that fibre concrete packages of comparable thickness subjected to an average temperature of 800°C for 30 min could undergo superficial scaling phenomena on the surface in contact with the flame, but without the concrete bursting.

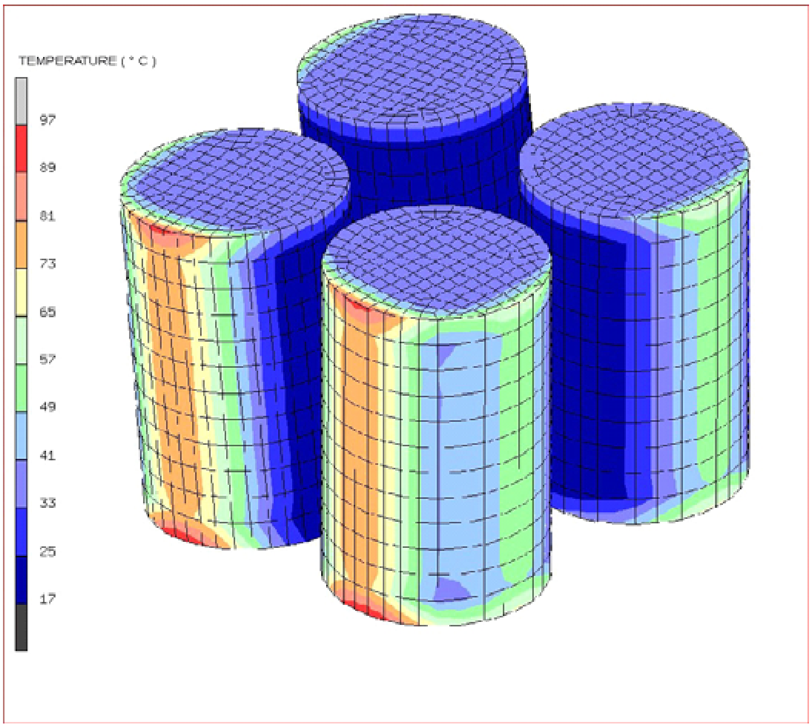

Figure 11.6.1 Temperature range at the primary packages of bituminised sludge (B2.1) in the case of a fire in a disposal cell[179]

11.6.2 Conclusion

Fire on the handling vehicle used to emplace the packages of bituminised sludge in the disposal cell should not have any radiological consequences because the concrete envelope of the disposal package and a thermal shield placed between the fire source and the package effectively protect the primary packages. On the other hand, the temperature which should be limited to about a hundred degrees is not of the kind to provoke the spontaneous combustion of the bitumen.

11.7 Study of the consequences of a cage fall during the transfer of the disposal package in a shaft

A free fall of the cage from the surface[180] is retained as the accidental scenario of falls in a shaft.

Within this context, the studies consist of, first of all, estimating the mechanical consequences of the fall on the various components of the moving body (cage, transfer cask, disposal package, primary packages) before assessing the radiological consequences of a potentiel loss of containment of the transfered waste packages and a release of radioactive materials [107].

They also include a risk analysis of the criticality [55] which may result from the cage fall during a transfer of spent fuel packages.

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[179] The fire source is placed laterally to the left of the packages and the concrete envelope of the disposal package is not represented.

[180] The cage fall accidents related to a mechanical failure of the system are extremely rare. In France, the last serious accident known occurred at Reumaux (Lorraine) in 1925. It was due to a brake failure which caused a cage fall over approximately 600 m with the last 170 m in free fall after the cable broke (it was a drum winch). There was neither an anti-fall system nor a shock absorber in the shaft bottom. 55 miners were killed in this accident, while all of the 28 miners in the upper compartment of the cage were rescued alive.

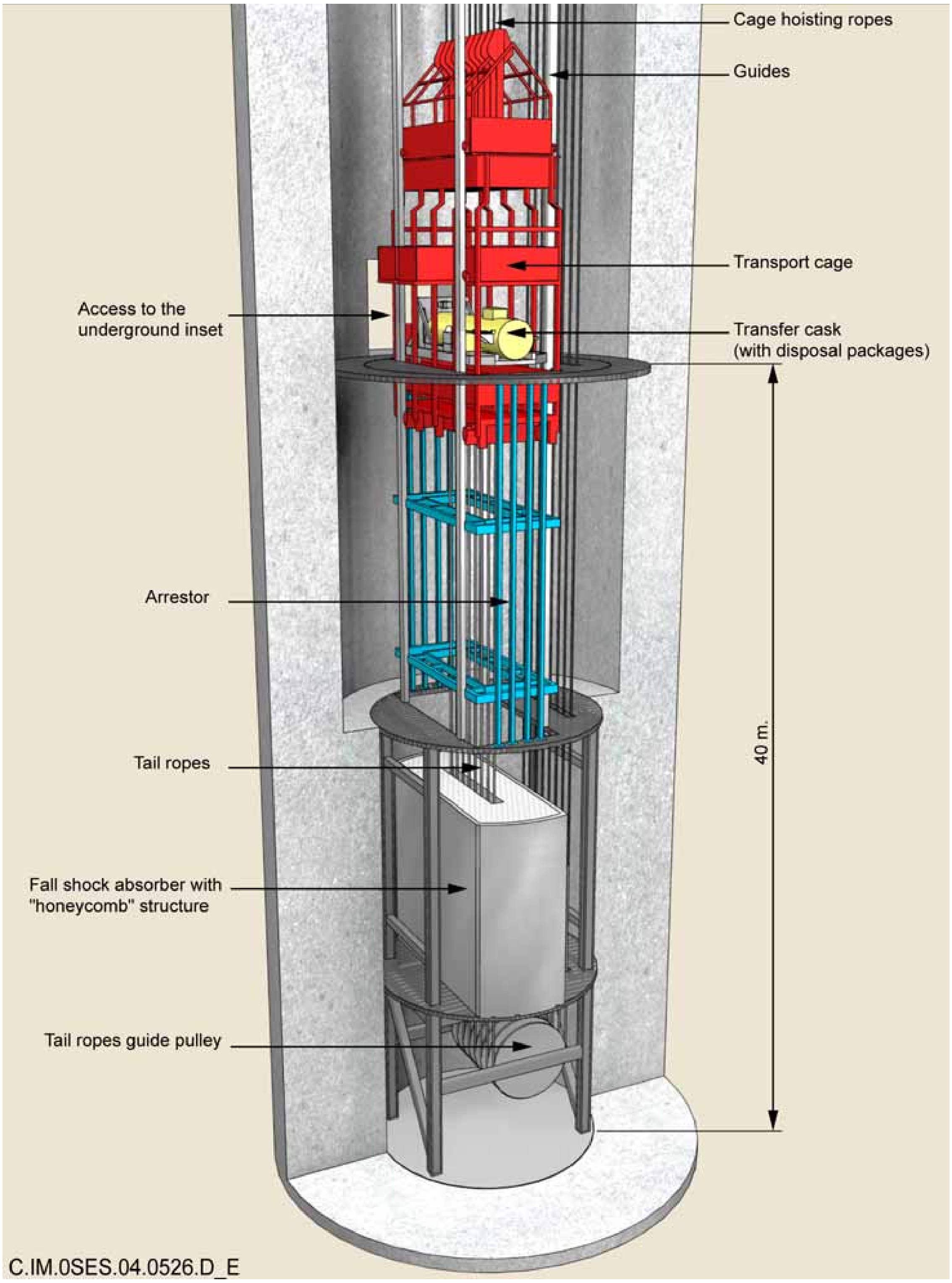

Figure 11.7.1 *3D representation of the lower section of the shaft equipped with the fall shock absorber system*

11.7.1 Assessment of the mechanical consequences of a cage falling in a shaft

This assessment was made for the following B, C waste and spent fuel disposal packages (cf. Table 11.7.1).

Table 11.7.1 Main data related to the studied cases of a fall in a shaft

Primary package	Disposal package	Transfer transfer cask (load weight)
B2.1 : bituminised sludge [181]	Concrete package[182] (with 4 primary packages in vertical position)	Parallelopiped transfer cask (approx. 40 t)
CSD-V : vitrified waste	Metallic over-pack (with a CSD-V container in horizontal position)	Cylindrical transfer cask (approx. 50 t)
CU1[183] : spent fuel assemblies	Metallic container (with 4 spent fuel assemblies in horizontal position)	Cylindrical transfer cask (approx. 100 t)

11.7.1.1 Fall scenario

The imagined scenario is that of the cage in free fall[184] over the entire height of the shaft, which would impact on a fall shock absorber system placed at the shaft bottom[185].

This scenario, which is overestimating for the fall height, doesn't take into account :

- An action of the cage anti-fall system,
- The possible braking effect due to a rubbing or a jamming of the cage's suspension cables during the fall,
- The effect of the end-of-travel braking stop at shaft bottom.

11.7.1.2 Data related to the simulation studies

The numerical simulation approach[186] is split into steps where the fall's consequences on the cage, the transfer cask, the disposal package and the primary package(s) transported are successively quantified. The condition of each element of these objects at the end of the fall is characterised by its plastic deformation, which corresponds to the cumulative total of all the types of deformations undergone (expansion, deformation, …). The corresponding coefficient expressed in % can be compared to the acceptable characteristic value (VCA) of the material making up this element. The risk of breakage is analysed versus the values of the deformation coefficient and the location, shape and extension of the deformed zone.

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[181] The B2.1 disposal package was retained to represent the family of B waste packages because it corresponds to the most fragile primary package (metallic container of small thickness).

[182] For the simulation, the characterictics of the fiber reinforced concrete package without rod reinforcement have been used, as this package is more vulnerable to the effect of a drop than the package made of rod reinforced concrete.

[183] The CU1 packages (UOx), which contain several assemblies, appear mechanically more fragile with respect to the risk of a fall than the CU2 package (MOx), which contains only one assembly.

[184] In this scenario, the breaking of the cage suspension cables has also as a consequence the fall of the counterweight over about fifty metres down to the shaft bottom.

[185] Several technical elements condition the sizing of the shock absorber : the highest weight transported, the limitation of the deceleration of the transfer cask to a value not causing major mechanical damage, the limitation of the crushing of the shock absorber to half its height. In order to minimise the effect of the impact on the moving body, it is also planned to use a fall shock absorber with an upper stage having a crushing threshold less than that of the lower stage so that it operates in the most progressive possible way.

[186] The fall simulation studies were carried out with the software Radioss, which allows studying by finite elements any strongly non linear behaviour of a structure subjected to forces from almost static up to rapid dynamic forces. Radioss temporally integrates the non linear dynamic equations by an explicit approach.

11.7.1.3 Consequences of a cage falling in a shaft

After an analysis of the fall's energy balance, the primary package's condition is examined to find out whether the damages caused by the fall on the shock absorber are or aren't liable to be evidenced in the end by a loss of containment and a release of radionuclides.

- **Energy balance**

The energy balance illustrated by the fall of the C waste transfer cask (cf. Figure 11.7.2) shows that the largest part of the incident kinetic energy was transformed during the impact into internal deformation energy in a very short time.

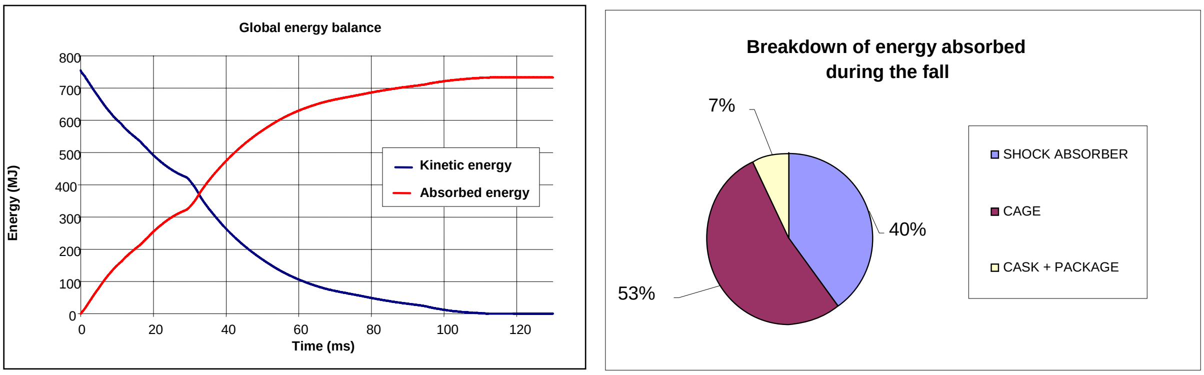

Figure 11.7.2 Energy balance of a fall in a shaft of a cage transporting a transfer cask with C wastes

More than 99 % of the shock's energy is absorbed by the shock absorber, the cage and the transfer cask. The disposal package absorbs less than 1 % of the energy. This distribution remains valid for the falls of B waste and spent fuel packages.

- **Mechanical consequences of the fall on the primary waste packages**

The estimation of the deformations observed on the primary packages allows understanding the risk of a loss of containment of radioactive materials through the following two elements of estimation:

- The maximum value of the deformation coefficient of the primary package, which is only an indication (because a high deformation value limited to a few mesh elements is not significant),
- The surface of the primary package for which the deformation coefficient is greater than the acceptable characteristic value (ACV), which means a risk of breakage.

The results of the simulations (cf. Table 11.7.2) show that for all the B, C and spent fuel packages there isn't any risk of loss of containment of the radioactive materials since no deformation value is greater than the ACV of the materials making up the primary package. However, it should be noted that the B waste packages are the primary packages which undergo the greatest deformations and there persists an uncertainty particularly for the type B2 waste packages on the behaviour of their crimped lid to the shock.

Table 11.7.2 Estimations of the deformations undergone by the packages at the end of the fall on the shock absorber

Package types	**Location**	**Maximum deformation (%)**	**ACV (%)**	**Surface for which the deformation exceeds ACV**
B (B2.1)	Primary package	25.9	35	No over-extension is observed for the various types of packages. Their envelope would not be broken
C (CSD-V)	Primary package	0.3	35	
CU1 (bare assemblies)	Square compartment of the disposal package containing fuel assembly	1.2	26	
CU1 (assemblies in canister)	Cylindrical canister containing the fuel assembly	17.4	40	

The results obtained from the simulation studies underline the advantage of installing in the package transfer shaft a fall shock absorber. This absorber should allow preventing the breakage of the metallic envelope of the transfer transfer cask in case the cage falls.

Inside this transfer cask, first estimations tend to show that the C waste primary packages, as well as the tubes or claddings containing spent fuel should resist the shock without breaking. Regarding the B waste primary packages, a damaging of some of the most fragile packages (such as the type B2 packages) can't be completely excluded.

11.7.2 Assessment of the radiological consequences of a cage falling in a shaft

By taking into consideration the results obtained from the studies on the mechanical consequences of a cage fall, it could be considered that there is no loss of containment of radioactive materials during the transfer of packages in a shaft.

However, because of the uncertainities on how the fall in a shaft takes place and the definition of the moving body, scenarios of a release of radioactive materials were imagined in order to estimate the associated radiological risk [107].

11.7.2.1 Scenarios of a release of radioactive materials

The assumption is made of the transfer transfer cask being opened, the disposal package being broken, and the primary package being broken, which would lead to a release of radioactive materials in suspension in the shaft atmosphere and rejected into the environment. The studied packages are those which have the most penalising radiological content within each category. Thus, the B5 package (B waste), the C3 package (C wastes) and the CU1 package (for spent fuels) are retained.

Various data sets were retained for the quantities of radionuclides liable to be freed and released into the shaft's atmosphere. The data related to the B5 packages were defined by analogy with the observations made during the compacting operations (the energy has the same order of magnitude as during a fall and during a compacting). The data related to the C packages are linked to fall test results. Regarding the spent fuels, the parametric approach corresponds to assumptions on the extent of deterioration of the assembly, together with a more or less important breakage of the rods and crushing of the contained fuel pellets.

11.7.2.2 Data related to the simulation studies

The existence of doors at the shaft landing stations (cf. Figure 11.2.3) and the prohibition of access to the shaft zone during a package transfer operation are measures which should allow preventing any radiological risk to the persons present in the underground structures. Consequently, no estimation was made for the personnel assigned to the underground installations.

The radiological consequences of a possible radioactive reject into the environment at the outlet of a ventilation shaft were estimated taking into account all the potential exposure paths :

- The exposure related to the passing by of the reject plume induces an external exposure and an internal exposure by inhalation,
- The exposure related to the deposits left by the plume induces an external exposure, an internal exposure by inhalation subsequent to the return in suspension and an internal exposure by the ingestion of foods.

11.7.2.3 Results

The simulation studies show that the phenomenon of an instantaneous suspension at the moment of the impact appears to be preponderant compared to the suspension phenomenon related to a sweeping of air circulating in the shaft. The released radionuclides would be completely delivered to the environment with potential consequences on people at the site limit, which is assumed to be 500 m from the reject outlet.

The preponderant ways of exposure would be for the three types of wastes the inhalation due to the passing by of the radionuclide plume and, to a lesser extent, food ingestion.

The preliminary results obtained from the simulations would lead to considering measures to reduce the risk, for example, by filtering the exhaust air of the underground installations. With this type of arrangement[187], which is commonly used in the existing nuclear surface installations, the total exposure dose would be on the order of 1 mSv[188] for a person at the site limit.

Another imaginable measure would consist of isolating the shaft zone (descent shaft of the packages and the air exhaust shaft) and then making an assessment of the state of events before taking an action adapted to the nature, scale and extension of the contaminated zone.

11.7.3 Analysis of the risk of criticality

On the basis of the disposal package concepts defined to date and for the movement of a single disposal package in the shaft, the accidental fall situations for the B and C waste disposal packages don't present a risk of criticality, regardless of the geometry of the disposal package after the fall. [55].

For the spent fuel packages, the damaging of the assemblies (detachment of the rods, breakage of the clads, …) and the moving of them closer together after the cage fall could induce a phenomenon of criticality if, in addition, water ingress occurred within the assemblies [55].

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[187] It may be interesting to subordinate the cage lowering movements to the start of the filtering unit to avoid continuous filtering with large air volumes. This type of operation was retained in the American transuranium waste repository of the WIPP, New Mexico [114], where the filtering unit installed on the air exhaust shaft is not started except if an incident occurs.

[188] This value is to be compared with the fact that specific arrangements are regulatorily planned with respect to the public when accidental situations increase doses to more than 10 mSv.

Such a damage level doesn't seem probable as it appears from the fall simulation results. However, as a precaution, design measures aimed at preventing any water from being in the shaft would have to be retained (cf. § 11.2.2.2) to completely exclude this risk.

11.7.4 Conclusion

In the transfer phase of packages in the shaft, the risk of the cage falling represents a very low probability of occurrence because of the recommended preventive measures. Despite these arrangements, should the moving body free fall in the shaft, the presence of a fall shock absorber in the shaft bottom would allow limiting damage to the transfer transfer cask, which would preserve its mechanical integrity according to the results obtained from the simulation studies.

However, due to the uncertainties of the fall simulations (definition of the moving body, fall conditions), the possibility of a release of radionuclides into the environment at the reject point was considered. In order to assess the radiological consequences of such an event, various illustrative cases were defined under a parametric approach. Thus, technical solutions could be proposed to limit the release of the radionuclides : one solution would consist of trapping the radionuclides by a filtration of the exhaust air at the ventilation shaft ; another would be to isolate the area comprising the waste transfer shaft and the reject point to prevent any risk of spreading. In both cases, the installations would have to be securised and control measures taken before proceeding, if necessary, with decontamination operations.

The risk of criticality associated with a fall of a spent fuel package is not imaginable because of all the arrangements proposed to limit package damaging and because of the absence of water in the shaft.

11.8 Study of the consequences of a B waste disposal package falling during its emplacement in disposal cells

B waste disposal packages are emplaced by a vehicle remotely controlled by an operator located outside the cell. After the risk analysis, an accidental scenario was retained where a package would fall in a disposal cell while being stacked at the upper level of a package pile, that is, at a maximum height on the order of 4 to 6 m (cf.Figure 11.8.1). This scenario is an envelope scenario with respect to the handling operations in all the facilities.

The simulations [107], supplemented with actual size fall test, first characterize the mechanical consequences of the fall on the waste packages and then estimate what could be the possible radiological consequences.

11.8.1 Assessment of the mechanical consequences of B waste packages falling in a disposal cell

The assessment of the mechanical consequences of a package falling was made for the two types of containers considered: standard container and container with reinforced retention capability. They are represented by a type B2.1 package and a type B5.2 package respectively. Their main characteristics are listed in Table 11.8.1.

Table 11.8.1 Main characteristics of the disposal packages studied [41]

Primary package Nature of the wastes	Number of primary packages per disposal package	Type of container	Weight of the demonstrators (t)
B2.1 : bituminised sludge	4	Standard container (the body and the prefabicated lid are in fiber and steel rod reinforced concrete)	6.1
B5.2 (CSD-C) : mix of hulls and end caps, and technological wastes	4	Container with reinforced retention capability (the prefabicated body and the poured in place individual lids are in fiber reinforced concrete)	12.3

11.8.1.1 Fall scenario

The retained fall scenario is based on the assumption of a flipping and turning over of the waste disposal package followed by a vertical fall of the package onto a corner of the cover on a rigid soil. The centre of gravity of the package is located vertical to the point of impact. For the primary package located near to the impacted corner., this configuration appears more severe than the case of a ″fall on a flat surface″ or a ″fall on an edge″.

Figure 11.8.1 Installation of the drop-test demonstrator (package B5.2 - CEA/CESTA Test Centre - Gironde)

The fall height of 6 m[189] corresponds to the maximum handling height in of the disposal packages during emplacement in the disposal cells.

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[189] The fall height is defined as the distance at the start of the fall between the point of impact (lower corner of the cover) and the ground.

11.8.1.2 Data related to the simulation studies and to the fall tests

The simulation studies were conducted with the same approach as for the studies of a fall in a shaft (cf. § 11.7.1.2). The software used takes into account the complexity of the occurring phenomena (materials subjected to plastic deformations and even breakage) and the variety of materials making up the disposal package.

The fall tests were carried out on a thick reinforced concrete slab covered with anchored steel plates. The demonstration models used are identical in terms of dimensions and mass to the disposal packages as shown in Section 4.1, however, the packages contain no radioactive material.

11.8.1.3 Simulated evaluation of the mechanical consequences of a disposal package falling

The purpose of the simulations is to estimate whether the damages caused to the primary packages by the fall of the disposal package will eventually result in a loss of containment and a release of radionuclides.

- **Energy balance**

The energy balance shows that the greatest part of the incident kinetic energy is transformed during the impact into an internal deformation energy. The concrete container of the disposal package absorbs 90 % of the incident kinetic energy. The primary packages receive the remaining 10 %.

- **Consequences of the fall on the primary packages**

Generally, the results (cf. Table 11.8.2) are given for the metallic canister of the primary package most exposed at the moment of the fall, which is the one in the immediate vicinity of the point of impact.

The criteria retained is the deformation of the canister of the primary package as compared with the acceptable characteristic value (ACV) of the material this canister is made of.

Table 11.8.2 *Deformations observed on the metallic canisters of B waste primary packages subsequent to a fall in a disposal cell*

Package type	Description of the fall (m)	Maximum deformation of the canister of the primary package (%)	ACV (%)
B2.1	Fall on a corner of the lid Height of fall 6 m	8	35
B5.2		9	35

The results indicate limited damage to the upper part of the primary package envelope with a maximum deformation value of close to 10%, significantly less than the allowable characteristic value. There is therefore no risk of this envelope rupturing.

11.8.1.4 Lessons learned from the demonstration model drop tests

The first drop tests of demonstration model B2.1 and B5.2 carried out show that the disposal packages were damaged but retain their mechanical integrity.

- Demonstration model B2.1 after the fall (cf. Figure 11.8.2), shows the crushed corner of the lid revealing some of its reinforcements. The reinforced lid absorbed the greatest part of the energy related with impact while the body of the demonstration model itself shows little visible damage. Although the interface between the container and the lid is cracked, both elements remain joined (thanks to the tie rods provided for this purpose).
- Demonstration model B5.2 (cf. Figure 11.8-2), absorbs the energy during impact to the corner and lateral surfaces. Diagonal cracks leading from the impacted corner and are visible. As regards the lid, it has fine cracks around the concrete plugs cast above the primary package housings.

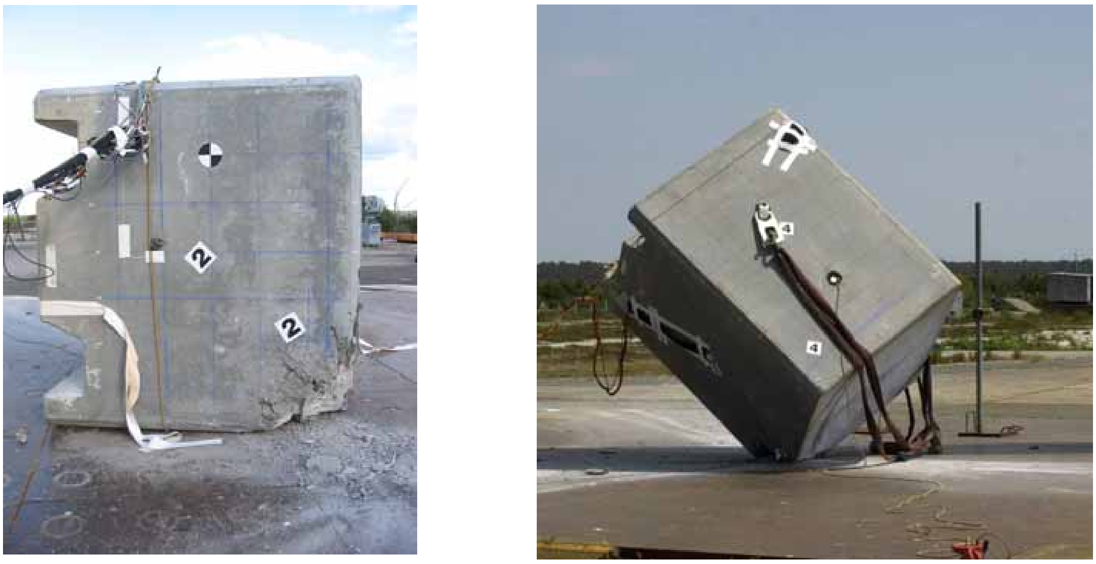

Figure 11.8.2 Appearance of the demonstration model after the drop (left, demonstration model B2.1; right, demonstration model B5.2)

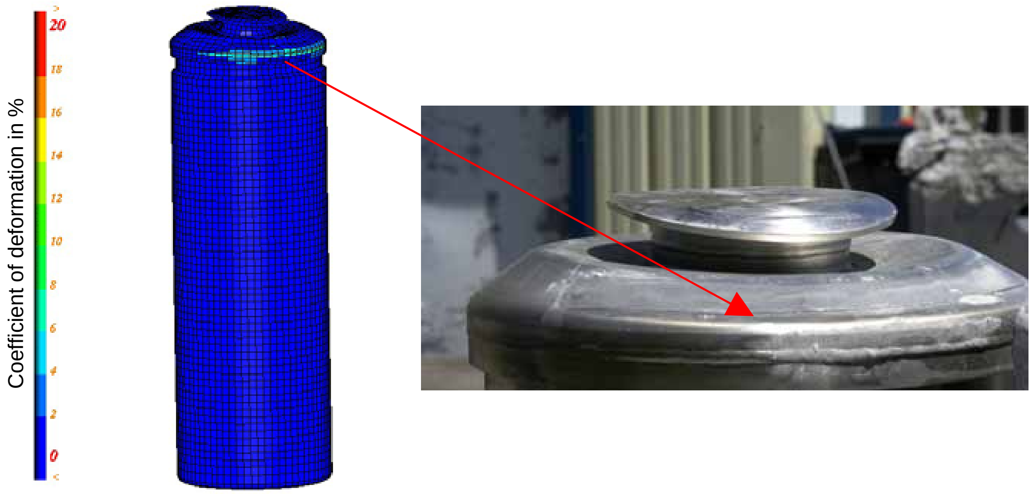

Figure 11.8.3 Comparison between simulation and fall test in the case of the primary package close to the impacted corner of demonstration model B5.2

In all cases, the primary packages taken from the demonstration models after the drop test show slight deformation to the upper part of their envelopes (which impacted the lid when hitting the ground), but no evidence of rupture. These observations are consistent with the results of the simulations (cf. Figure 11.8.3).

The studies and tests carried out show that a disposal package that falls during emplacement in the cell is not liable to result in a loss of primary package containment.

11.8.2 Assessment of the radiological consequences of a fall of B waste disposal packages in a disposal cell

The results of the studies and tests on the mechanical consequences of B packages falling in the disposal cell gives grounds for believing that there would be no loss of containment of radioactive material should such an event occur.

However, scenarios involving the release of radioactive materials in the case of B2 disposal packages have been envisaged, assuming that the package lid comes off at the moment of impact. This hypothesis was not considered in the case of B5 disposal packages given its different design comprising cast individual lids fully integral with the container body.

11.8.2.1 Retained assumptions

Following the detachment of the lid from the disposal package at the moment of impact, a primary package (or primary packages) could be damaged to some extent which could result in a release of radioactive material which would be suspended in the atmosphere of the repository cell. The contaminated air would circulate in the return air circuit before being rejected into the atmosphere at the exhaust shaft.

Various assumptions were retained concerning the quantities of radionuclides liable to be released in the cell. In one case, one single package shows a local tear and, in another case, it is supposed that the lid of the four primary packages is detached. The nature of the matrix of bituminised sludges was also taken into consideration, because it has a good ability to immobilise the radioactive wastes.

11.8.2.2 Radiological consequences of a fall of B2 packages in a cell

The simulation studies show that the phenomenon of an instantaneous placement in suspension at the moment of the impact appears preponderant compared to the phenomenon of a continuous placement in suspension by the leaching of the radioactive materials through ventilation in the cell.

The preponderant ways of exposing the public would be the inhalation due to the passing by of the radionuclide plume and, to a lesser extent, food ingestion.

Simulations show that the dose received at 500 m from the rejection outlet would be less than 0.001 mSv, regardless of the scenario retained. This negligible dose would not generate consequences to people or to the environment.

11.8.3 Conclusion

During the transfer and handling operations of the B waste packages in the disposal cells, no fall should occur because of the recommended preventive measures. Nevertheless, if it should happen that the package would flip over and fall on the cell floor in spite of these arrangements, this fall would cause mechanical deteriorations of the disposal package. Simulations show that the primary package should not suffer a loss of containment and should not release radioactive particles. However, for the packages of bituminised sludge (B2), scenarios were studied where particles are released in the disposal cell and then in the environment via the ventilation circuits. The radiological consequences were then estimated, and construed to be negligible for the public.

11.9 Synthesis of the analysis

The risk analysis performed covers the industrial activities of construction, operation and closure of the repository of long-lived radioactive wastes. Conducted together with the design studies, the purpose of this analysis at this stage in the project's study is to give technical orientations and propose tested measures to reduce risks guaranteeing reliable operation and allowing the operational safety functions defined by Andra to be satisfied. This systematically conducted analysis has benefitted from feedback from existing industrial installations.

The assessment of the dosimetry with the installations in operation showed that the doses received by the personnel and the public would be less than the annual requirements set by Andra, that is, 5 mSv for the workers and 0.25 mSv for the public.

The risk analysis made a distinction between conventional risks, traditionally encountered in any industrial installation, the risks related to waste packages, and the risks related to the environment outside the repository.

In the surface installations, conventional risks exist at a more or less high degree throughout the various disposal activities. These are mainly crushing risks (fall of handled loads, being hit by a vehicle, …), fall risks related to work at heights, electrization risks, as well as the risk of fire... These risks do not justify additional studies at this stage, but will have to be carefully considered during the detailed design of the facilities and of their equipment.

In the underground installations, these risks are also present. Among them, the risk of fire was covered by an additional study considering its influence on the design of the installations. This study ensured that the solutions recommended for the design of the infrastructures and their operation would allow evacuating people under satisfactory safety conditions.

The risks related to the waste packages are mainly radiological risks. They are present during the operating activity of the repository and to a lesser extent during the closure activity. These risks may be associated with radiological protection defects, with interventions performed in the vicinity of a radioactive source, as well as a fire or a fall affecting the packages themselves. The considered arrangements which benefit from feedback from similar industrial installations allow these risks to be controlled.

The risks related to the repository environment (earthquake, weather conditions, airplane crash, …), estimated based on the usual practices of French nuclear installations and taking into account the local characteristics of the site, do not raise any specific problems.

The operational safety analysis conducted did not reveal at this stage elements which could jepoardise the technical feasibility of the construction and operation, the closure of the repository and its reversible management by steps (with, in particular, the possibility of reversing the disposal process).

12

Synthesis

The study shows from an engineering viewpoint the feasibility of a repository of high-level and long-lived intermediate level wastes in the studied argillite formation. The presented options show that there are concrete technical solutions to the questions raised by the feasibility of a repository. These options were retained at this stage for their simplicity and their robustness.

They cover all the existing French high-level and long-lived intermediate level wastes as well as those engaged by the total number of nuclear plants. To do this, various assumptions for the production and conditioning of future wastes were made. The diversity of the primary waste packages could be taken into account by structuring the inventory model using "reference packages" representative of all the problematics introduced by this diversity. It should be noted that not withstanding any management choices the study has also explored, beyond the B wastes (medium-level activity and long-lived) and C wastes (high-level activity), the case of spent fuels if it were decided not to recycle them.

The presented options are adapted to the clay formation studied by the underground research laboratory of Meuse/Haute Marne. To do this, the study was based on the body of knowledge progressively acquired during the extensive work conducted on the site since 1994 (geophysical and bore-hole operations, tests on samples, data acquired during the sinking of laboratory shafts, an experimental drift at -445 metres). In particular, the repository architecture takes into account the geometric aspects of this formation (thickness, depth, …), as well as its mechanical and thermal characteristics. The presented options stress the favourable properties of the studied formation in terms of containment (very low permeability, low hydrogeological gradients, retention capacity and geochemical properties).

Special attention was paid to the reversibility of the repository in response to the expectations which were expressed first in the Law of 30 December 1991, and then at different stages. Reversibility has therefore significantly influenced the architecture options. It offers great flexibility for the management of the disposed packages and the control of the disposal process. Safety also strongly influenced the design choices made. It represents indeed one of the major objectives, aimed at eventually guaranteeing passive safety, ensured by the facility itself.

The studied options were compared to those considered in other countries within the framework of international scientific and technical exchanges and cooperations. Many points in common were discovered, such as the disposal package design, the thermal sizing criteria, or even the structures installed during the closure of a repository. A certain drawing together can be observed over the last few years in terms of progressive management and reversibility of a repository, even though there are still notable differences in the reversibility approach, a particularly developed requirement in France. Generally, differences exist between the proposed technical solutions at the international level, which are most often explained by the specific geological context of each country (clay or non clay formations, generic approach or specific approach for a particular site), the waste packages and the inventories taken into account as a reference (retreatment wastes or spent fuels, number of electronuclear power plants).

At the stage of a feasibility assessment, it should be noted that the studied options cannot be considered as optimised. Also, without changing the presented design principles, a few study perspectives can be outlined in view of improving the design.

12.1 Simple and robust technical options

In order to assess the feasibility of a repository in the studied clay formation, Andra retained technically simple and robust options considering the current limits of knowledge and technology.

The simplicity of the studied options favours understanding how a repository works at various time scales. For example, the separation of the various types of wastes in separate zones avoids interactions which would complicate this understanding. The assessment of a repository's performances in terms of reversibility and safety is made easier.

The existence of uncertainties over the scientific data was taken into account during the studies, whether the uncertainities relate to the knowledge acquired at this stage or whether they are inevitably inherent to the large time scales implied by the long-term safety functions of a repository. Faced with these uncertainties, the choice of robust options was systematically favoured.

For example, considering the mechanical behaviour of argillites, prudent work assumptions were retained at this stage, which probably led to the sizing of the underground structures linings with some margins. At the location of the seals, ways were proposed and studied to hydraulically interrupt the argillite ring which could be fractured in the vicinity of the excavations.

The simplicity and robustness of the presented options render them also realistic from an industrial and economic viewpoint. The feasibility of realising the various components of a repository was checked based on proven processes in industry (excavating of underground cavities, installing ground supports and liners, etc.). The existence or the possibility of designing resources to operate the installations was also shown based on today’s available technologies (receipt, preparation and emplacing of packages, ventilation and maintenance of the installations). Generally, the technological feasibility of the presented options is based on feedback from industry, favouring analogies particularly in the field of underground work and nuclear installations. On some specific aspects, this was completed by tests : building of disposal container demonstrators, development of tests related to backfilling and sealing of underground structures.

12.2 The reversibility rationale taken into account in the architecture

The demand for reversibility was integrated in the proposed architecture. Concretely, this concerns the durability conferred to the structures and to the disposal packages, the modular structuring of the installations and the choice of simple processes for disposal which are easily reversible.

Thus, a reversible disposal is evidenced, first of all, by a flexibility of management of the emplaced packages similar to that of a surface storage. The waste packages can be retrieved as easily as they were emplaced without damaging the structures and the packages themselves. The studies showed that this possibility applied as a minimum to 100-year durations (one to several centuries) without any particular maintenance. If desired, longer durations could be planned, but requiring special work on a more extensive scale (work on the packages, reinforced maintenance and cell strengthening, reconstruction…)

Contrary to surface storage, a repository can also be closed to passively ensure the containment of the wastes and long-term protection of man and the environment. In a search for flexibility in the control of the disposal process, the proposed options offer the possibility of a progressive closure.

To do this, several successive stages were identified rendering the repository more and more passive. At each stage, free choice is offered for the process’ control, with the possibility, here again for durations on the order of a century, to wait before moving ahead to the next stage, or to go back, until the packages are retrieved. To support the disposal process management, it is technically possible to monitor the behaviour and evolution of the repository during the stages. It amounts to identifying, if necessary, the need for an action, such as a structure or a piece of equipment requiring maintenance, or increasing confidence in knowledge and scientific models. Within this framework, the possibility of making ″control″ structures was examined ; these could be more extensively instrumented.

We checked that the repository’s level of reversibility, comparable to a surface storage in the initial stages, reduces progressively as the stages are passed through down to the lowest level, which corresponds to the complete closure of the facility. Nevertheless, after this closure, it is still technically possible to return to the repository structures and remove the disposed wastes.

This reversibility is not paradoxical with respect to the operational safety of a repository or its safety over a longer term. On the one hand, the search for durability in the architecture to favour reversibility does not introduce any new risk and a priori moves in the direction of safety. On the other hand, the observation and surveillance of the repository, which are associated with the implementation of reversibility, allow managing the disposal process in an informed manner. For the technical options studied, we also checked that the possibility of extending - within the 100-year limit previously mentioned - each stage in the disposal process did not have any significant impact on the long-term evolution of the facility.

The reversible management of the packages and the disposal process implies human decisions and actions up to the complete closure : maintenance, observation and surveillance, closure work. The facility will only become fully passive afterwards. This active management supposes a continuity in the social and technical systems. But it also makes much less likely a gradual forgetting and an abandoning of the facility before its complete closure.

Another factor was underscored by the study : the progressive construction of the repository facilities by successive modules. This also allows for a flexibility in the management of the repository development. It also allows a certain “reversibility in the repository design″ : the design of the new structures may be modified to take into account in particular the experience acquired by the implementation and observation of the previous structures.

12.3 Safety in the architecture

The presented architecture was designed to respond to the expected safety functions of a repository. This traditionally concerns operational safety, but also, specifically in the context of a repository, the safety after the closure. This latter is based on the objectives laid down in the basic safety rule no. III.2-f.

One should note, without being exhaustive, the modular architecture and tree-like structure of dead-end elements, the arrangements taken in terms of structure dimensions and choice of materials to limit disturbances (thermal, mechanical, chemical, in particular), the special role of the high-level waste containers, the systems constructed during the closure stages (backfills and seals).

The robustness of the presented options, in light of the uncertainties of knowledge, participates strongly in the repository safety approach. The simplicity of these options contributes to their demonstrability with respect to the safety objectives.

Arrangements were also introduced in the architecture in order to increase the repository’s performance in the case of abnormal operations. As a result of this, the underground installations were subdivided into independent units. Systems which complement each other or are redundant were adopted (for example, architecture and seals to prevent potential water convection).

It should be recalled that the safety aspect in a repository’s architecture was taken into account by means of an iterative approach such as recommended by the basic safety rule. These iterative steps led to interim appointments with the Safety Authority. Note also the international review of the Dossier 2001 Clay under the aegis of the OECD’s Nuclear Energy Agency, whose main instructions were taken into account in the study.

Finally, recall that the presented architecture was covered by a study on the long-term behaviour and evolution and a safety assessment given, respectively, in the two other volumes of the Dossier 2005 Clay.

12.4 Outlook

The presented options contribute to establishing from an engineering viewpoint the feasibility of a reversible and reliable repository. Nevertheless, they must not be considered as frozen and final. In fact, they are not aimed at this stage at a technical or economic optimisation.

To concretely illustrate this, a few possible development perspectives were identified.

In terms of an overall architecture of a repository, an installation in the middle of the layer was retained. In order to optimally use the geological medium's characteristics, this installation level in the layer could be specified with the possibility of moving it to a greater depth. This influences the geotechnical behaviour of the structures, which vary according to installation level (rock resistance and mechanical stresses), as well as the respective role of the undisturbed argillite thickness between the repository and the over- and underlying geological formations, with respect to the containment of the radionuclides released by the packages.

Another parameter of the architecture is the adoption of a tree-like structure of dead-end elements. This increases the robustness of the long-term hydraulic behaviour of the respository. The application may be refined by more strongly taking into account certain operational aspects (structure accessibility, ventilation, management of incidental situations).

Prudent assumptions were adopted for the geotechnical sizing of the structures (drifts, B waste disposal cells, in particular). This sizing may be specified – structure form, support and liner definition, excavation sequencing – to adjust it to the local geotechnical characteristics of the rock. To do this, resorting to a short-term observation (a few years) of the laboratory drifts would allow understanding more precisely the deferred in situ behaviour of the rock.

In terms of the management strategy of the various structures, we retained minimising maintenance loads ; in practice, the structures were designed analogously to public road tunnels in which availability requirements are particularly high. Depending on the structures, a more subtle strategy may be examined, such as recourse to a periodic examination and an accrued maintenance in the image of mining practices.

For the sizing of C wastes and spent fuels disposal cells, the retained thermal criteria (limit temperatures in the repository) are consistent with respect to those normally considered at the international level. Similarly, the studied concepts are based simply on heat dissipation by conduction in the rock without taking into account ventilation. Ventilation may offer a greater flexibility for the thermal design of the repository, but its interest should be examined taking into account the induced constraints (more complex architecture).

The structure sizes were defined in a reasonable way regarding the technological requirements (excavation, transfer and emplacement of the packages) ; this avoided complicating the feasibility demonstration. Optimisations may be studied, allowing in particular a reduction of the total volume of the excavations.

The study showed the interest of having very small C wastes disposal cells cross sections (in practice, close to that of the disposal packages) : this option limits the excavated rock volume, as well as the disturbances induced in the geological medium, and favours heat dissipation in the rock.

For the spent fuels, if it were decided not to recycle them, it was retained to insert a swelling clay buffer between the packages and the rock by increasing the section of the cells ; this choice results from the uncertainties on the thermomechanical behaviour of the argillites over the long term (the reduction of heat from the spent fuels is slower than that from the C wastes). As knowledge and observations in the laboratory progress, the interest in such an option (pertaining to the long-term behaviour) may be reviewed.

These various perspectives for design improvement do not change the relevance of the options presented for the repository and a fortiori the conclusions of the study in terms of technical feasibility. From a rationale of optimisation, the study of such perspectives may be accomplished by extending the iterative approach of data acquisition, design and safety assessment employed up to now.

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