Report Series

Dossier 2005

Andra research on the geological disposal of high-level long-lived radioactive waste

Results and perspectives

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ANDRA
Agence nationale
pour la gestion des déchets radioactifs

Dossier 2005

The present English version is a translation of the original Dossier 2005 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 terms of concept) and “repository” (in terms of facility or installation) refer to long term management of high level long lived radioactive waste.

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Research on deep disposal of radioactive waste

A general interest task

Andra (French National Radioactive Waste Management Agency) is the public body responsible for the long-term management of all radioactive waste produced in France. Under the supervision of the French Ministries of Industry, Research and Environment, Andra operates disposal facilities adapted for lowest level radioactive waste. In addition, it conducts scientific research programs to study the possibility of high-level or long-lived radioactive waste deep geological disposal. Finally, it maintains an inventory of radioactive waste and provides factual and verifiable information available to the public.

In accordance with the principle "polluters pay", Andra is financed by radioactive waste producers (nuclear power plants, reprocessing plants, research laboratories, hospitals, etc.) proportionally to the volumes produced.

It thus assumes responsibility with regard to the national authority by protecting man and the environment from the risks associated with such waste.

Legislative framework

The French Waste Act of Parliament dated 30th December 1991 entrusted **Andra** with the task of assessing the feasibility of the deep geological disposal for high-level, long-lived waste (HLLL waste) based on a rationale of reversibility, notably through the construction of underground laboratories. Two geological media are considered: **clay and granite.**

The French Atomic Energy Commission (CEA) pursues two other avenues of research: partitioning of long-lived elements, associated with the reduction of the lifetime of the most toxic ones (transmutation), and conditioning and long-term storage (at surface or shallow depth).

The Waste Act stipulates the need *"to comply with nature, environment and health protection"* and *"to take the rights of future generations into account"*, i.e., not leaving them with a pending problem while giving them the possibility to control the process initiated. It also stipulates that at the end of a period not exceeding fifteen years, the Government authorities shall submit a global assessment report on these research activities to the Parliament, as well as a draft law.

Andra scientific objectives

The feasibility study for an underground repository is intended to evaluate the possibility of constructing, operating and monitoring a reversible repository in complete safety for man and environment.

Within this scope, Andra mission entails the following roles:

- general management role, to orient research activities and organise the scientific and technical community involved in this field.
- direct research role. For the clay medium, the Meuse/Haute-Marne underground research laboratory located at Bure is available. For the granite medium, since there is no underground research laboratory available in France, Andra carries out studies to assess the

Aerial view of the Meuse/Haute-Marne underground research laboratory

Standard vitrified waste container (CSD-V)

potential of French granite formations. Foreign underground laboratories in Switzerland, Belgium and Sweden provide significant contributions for both media. In addition, Andra conducts engineering and safety-related studies.

Inspections and assessments

The French National Review Board (CNE) created by the December 1991 Act is composed of French and foreign scientific experts. It examines the research conducted by the CEA and Andra and publishes an annual report. For the purpose of the 2006 parliamentary debate, it is currently preparing a general assessment report on the scientific results achieved so far. In addition, CEA and Andra research activities are monitored and coordinated by the Ministry of Research.

This reviewing process is completed with the regulatory intervention of **the Nuclear Safety Authority (ASN)** and its technical support, **the Institute for Radiological Protection and Nuclear Safety (IRSN).**

Cut-away model of a CSD-C container showing the stack of wafers

What are the types of waste involved?

There are two categories of high-level long-lived waste (HLLL waste).

High-level waste (C waste) accounts for 1% of the volume of radioactive waste produced in France, but 96% of total radioactivity. This type of waste consists of non-recyclable materials resulting from NPP (nuclear power plants) spent fuel reprocessing and gives off large amounts of heat for several tens of years. A temporary storage period is therefore required to allow the waste to cool down prior to its possible disposal in a repository.

C waste is incorporated in a glass matrix with high confinement properties over several hundreds of thousands of years and then poured into stainless steel drums.

Intermediate-level long-lived waste (B waste), more varied, mainly includes metals (fuel claddings), effluent treatment sludges and nuclear plant operating equipment, with a volume and radioactivity both amounting to approximately 4% of the total for all the radioactive waste produced. B waste gives off little heat. It is either compacted or embedded (in bitumen or concrete), and then placed in concrete or steel containers.

Non-reprocessed spent fuels (CU) are not considered as waste because they do contain recoverable materials (uranium, plutonium) which could be reprocessed and then recycled. Their possible disposal is nevertheless taken into account in the studies (in case they are no longer reprocessed in the future).

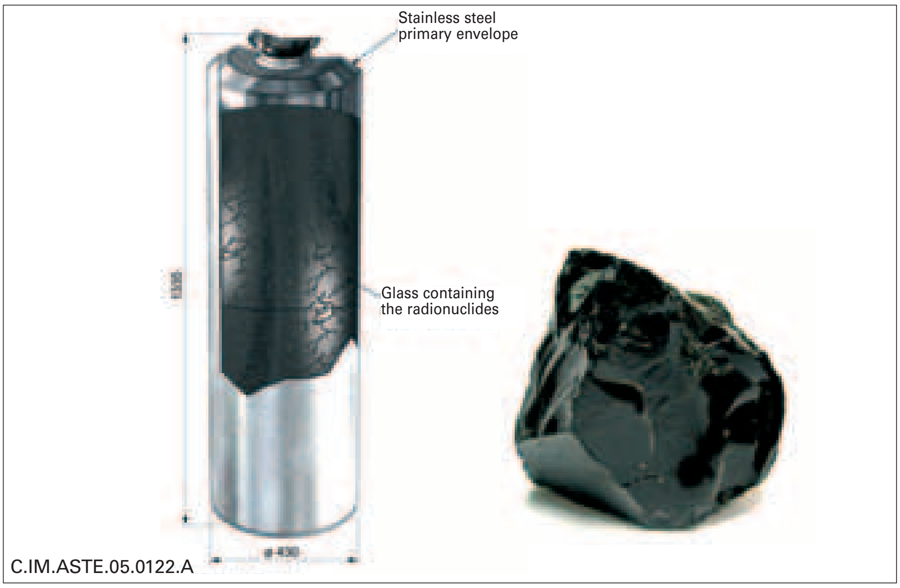

Diagram of an R7T7 vitrified C waste primary package

Research on deep disposal of radioactive waste

What is currently done with this waste?

The HLLL waste generated by EDF nuclear power plants, COGEMA fuel reprocessing plants, CEA research centres and National Defence activities are currently stored in the production facilities, at La Hague and Marcoule for the most part. Despite being stored in complete safety, their toxicity and lifetime call for a specific solution. This temporary situation must therefore be replaced with sustainable and safe management methods. That is the objective of the research conducted within the scope of the 1991 Act.

Current temporary storage facility for C waste

How can protection be ensured?

Barriers must be installed between the waste and the environment so as to effectively isolate (confine) the radioactive substances and chemical elements contained in the waste.

Each waste category is associated with a specific management method and a multibarrier system adapted to the level of radioactivity and the potential duration of toxicity. However, the waste repository principle is always based on multiple safety features: conditioning (waste drums or packages), repository structures (disposal cell or vault), and geological layer. 90% of the radioactive waste produced in France (very low level, low level and intermediate-level waste) is already disposed of according to this principle in the Manche and Aube districts.

Aube waste disposal facility for low and intermediate-level radioactive waste

What quantities of waste need to be disposed of?

Andra has compiled an inventory of existing B and C waste and has also conservatively evaluated future production by current installations based on various hypotheses for spent fuel reprocessing. The studies cover the full range of possible situations, without privileging any future industrial choice in particular. According to the reprocessing scenarios, the volume of B waste amounts to between 70,000 and 80,000 m^3, and that of C waste between 2,500 and 6,300 m^3.

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Designing a safe and reversible disposal system

Repository safety

The repository must protect man and the environment against the possible hazards associated with radioactive waste. It must also reduce at best the possible radiological impact.

Andra has therefore adopted a safety approach that privileges the robustness of the repository over very long periods of time. Certain types of waste will remain radioactive for tens of thousands of years, or even longer. Andra lays particular emphasis on assessing the uncertainties associated with the future of the repository.

Based on these principles, the repository must fulfil three functions:

- **preventing water circulation,** since water can degrade the waste packages and transport the radioactivity contained therein,
- **limiting the release of radioactive substances by the packages** and immobilising them in the repository as long as possible,
- **delaying and reducing the migration of radioactive substances** beyond the repository or geological layer.

> Basic Safety Rule

Basic Safety Rule (RFS) III.2.f was issued in 1991 by the Nuclear safety authority. It sets out the main objectives for a deep repository site:

> absence of seismic risks in the long term,

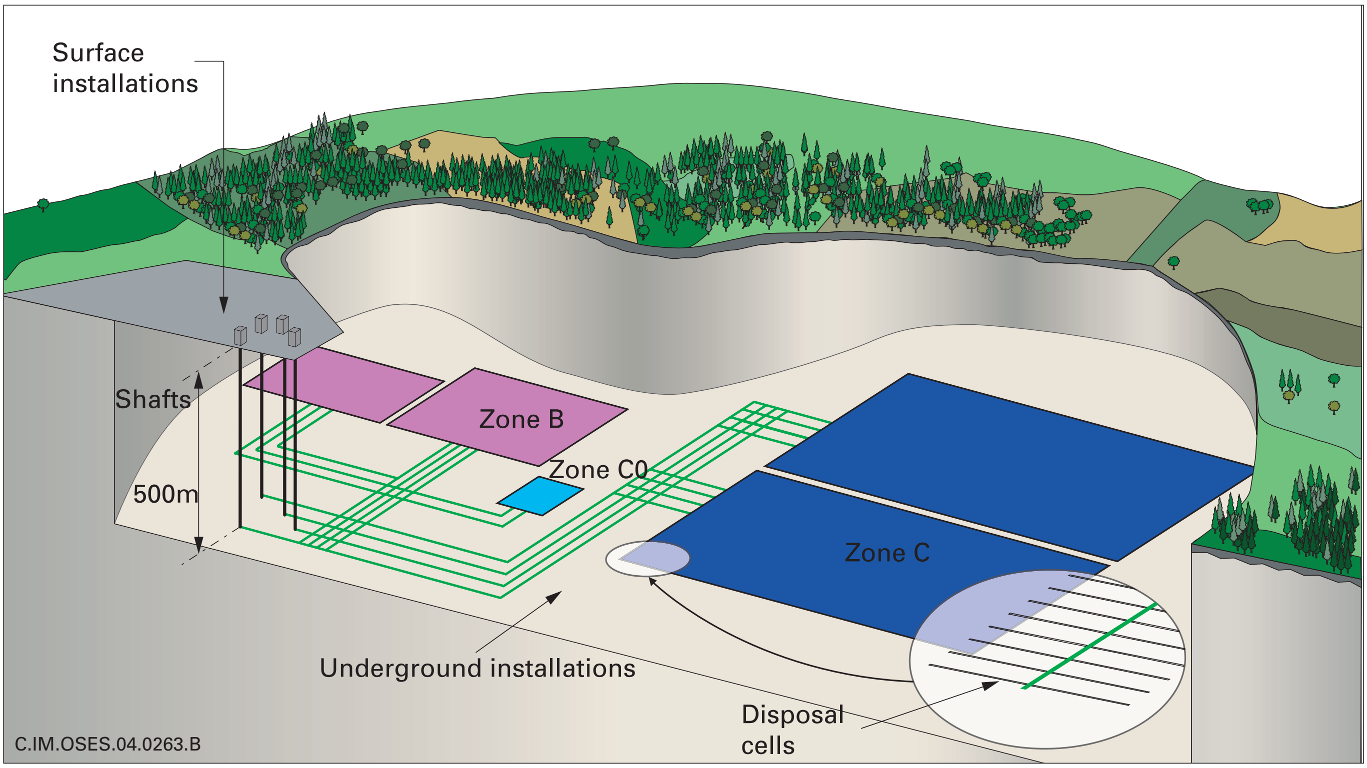
> absence of significant water circulation inside the repository,

> rock suitable to underground installations excavation,

> confinement properties for radioactive substances,

> sufficient depth to keep the waste safe from potential aggressions,

> absence of nearby rare exploitable resources.



Basic diagram of a repository layout during operation

Access shaft of the Meuse/Haute-Marne underground research laboratory

Reversibility: an essential requirement

The 1991 Act refers to reversible or irreversible disposal. Since then, it has been decided to firmly adopt a reversibility rationale.

This reversibility requirement calls for a modest approach with regard to the scientific knowledge available at a given point in time. Associated with the implementation of the 'precaution' principle, it means a cautious management, offering the possibility to modify previous choices regarding radioactive waste management. It entails a progressive approach to the design, construction, operation and closure of the installations, including means to retrieved emplaced waste packages, would another decision be taken.

What would deep geological disposal consist of?

Deep geological disposal consists of emplacing the waste in a geological layer at a depth of several hundred metres. The objective is to isolate the waste from man and the environment for very long periods of time, until the radioactivity has decreased and no longer means a hazard for populations. The repository therefore confines the radioactive substances contained in the waste.

Designing a reversible disposal system allows continuous control over the process. In particular, it allows for the possibility of retrieving the waste whenever necessary or in the event that other management choices are made. Nevertheless, ultimately, the repository must progressively become a passive installation, without monitoring or human intervention, while maintaining the same performance as regards safety.

How long would the disposal system remain reversible?

Reversibility is possible for at least several centuries, with no intervention other than standard maintenance and monitoring tasks.

The reversible disposal system can be initially managed as a temporary storage, with waste emplacement and retrieval. It can also be closed progressively. Andra has defined several levels of reversibility, i.e., closure in several stages. It has established simple and robust repository concepts and has identified durable materials. It has developed processes to facilitate the possible retrieval of the waste packages and has designed the underground installations as independent modules to allow flexible and open-ended management. An observation programme (deformation, temperature and pressure measurements, implementation of data transmission networks inside the engineered structures) has been developed to ensure the technical feasibility of the reversibility process (backward). As a lower level of reversibility is chosen, waste retrieval operations are still possible but will become more complex.

Research on a repository in a clay formation

A long research programme

Geologists examining the wall of the experimental drift at – 445 m

For nearly 15 years, Andra has been conducting a major scientific programme to acquire knowledge on a repository in a clay formation. The most important research tool is the Meuse/Haute-Marne underground laboratory, located at a depth of 490 metres in the heart of a very stiff (indurated) clay formation (argillite). This geological layer, referred to as the Callovo-Oxfordian layer, has been very stable since its formation more than 150 million years ago.

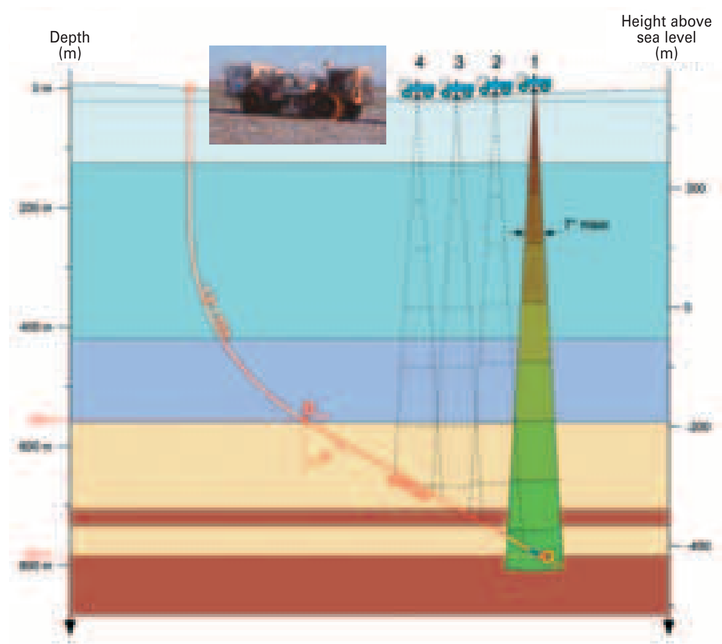
After drilling numerous boreholes since 1994, Andra has studied the Callovo-Oxfordian layer (as its surrounding layers) within the rock formation (in situ), in the laboratory shafts. Experimental drifts at a depth of 445 metres are in service since November 2004, with various experiments intended to confirm site data previously acquired.

In addition to boreholes drilled from the surface, sample analyses and underground studies, the research programme relies on the work conducted in several underground laboratories abroad, particularly the Mont Terri laboratory in Switzerland.

Andra has thus been able to reconstruct the geological history of the Meuse/Haute-Marne site so as to consider its future evolution. This representation serves as the basis for simulations to assess the performance of the disposal system.

Drilling platform

In addition to geological studies, the research programme covers four complementary issues: waste packages and material behaviour to understand the repository evolution over very long periods of time, repository design (waste conditioning, repository architecture, operating



> Over 10 years of research

- > **1,300** km of seismic profiles studied
- > **27** deep boreholes
- > **4.2** km of cored boreholes
- > **2.3** km of argillite cores
- > **30,000** samples taken
- > **100** m of horizontal drifts excavated
- > **40** m of experimental drifts
- > **40** boreholes drilled from the drifts and equipped with **350** sensors

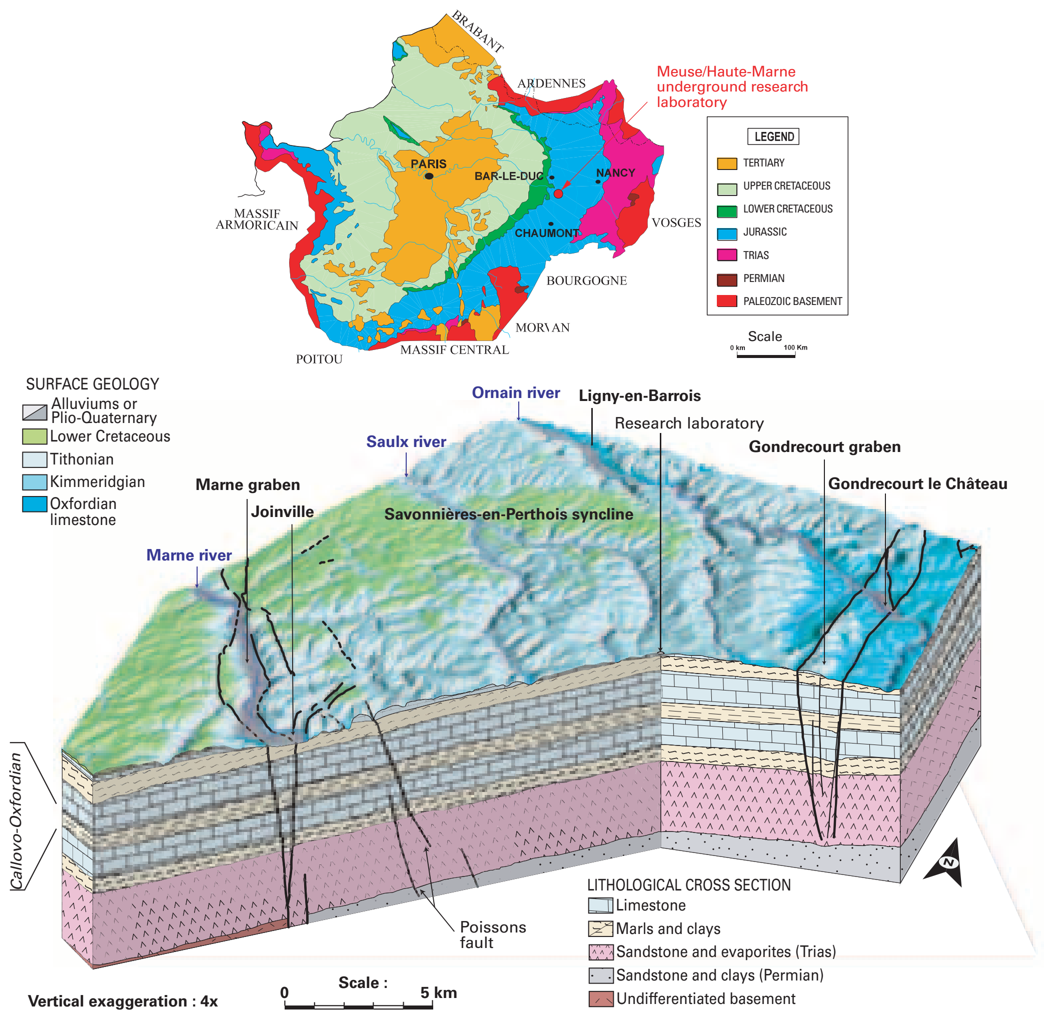
Seismic survey through deviated boreholes

and reversible closure methods), repository evolution, and long-term safety.

Dossier 2005 Argile

The Dossier 2005 Argile submitted to the French authorities consists of five reference knowledge documents containing all data currently available on respectively the geological medium and the biosphere, the materials (steel, concrete, etc.), the radioactive substances, waste behaviour in the repository and the inventory of HLLL waste produced and yet to be produced by existing nuclear facilities.

Core sample library of the Meuse/Haute-Marne research laboratory



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

Based on these data, Andra presents its analysis in three volumes:

- proposal of a repository architecture and management method geared towards safety, industrial feasibility and reversibility,
- analysis of the repository evolution, considering all thermal, hydraulic, mechanical and chemical phenomena in the environment over a period of one million years,
- repository safety assessment and risk analysis, in both normal and incidental situations.

Which scientific organisations has Andra collaborated with?

Andra has worked with a large number of French partners notably: French Geological Survey (BRGM), French Atomic Energy Commission (CEA), French National Centre for Scientific Research (CNRS), Paris School of Mines (Ecole des Mines de Paris), French Petroleum Institute (IFP), National Institute for Industrial Environment and Risks (INERIS), National Polytechnic Institute of Lorraine (INPL), and approximately some other 100 laboratories.

Seven groups of laboratories have been established according to Andra research themes: metal corrosion, clay, concrete, thermo-hydromechanical coupled phenomena, radioactive substances, geomechanics and bio-geoprospective studies. Likewise, three research groups have been created within the scope of the electronuclear cycle backend programme conducted by the CNRS (FORPRO, PARIS, MOMAS).

At the international level, Andra has collaborated with its Swiss, Spanish, German and Belgian counterparts and participated in joint programmes with international organisations such as the European Commission, the IAEA (International Atomic Energy Agency)…

> Meuse/Haute-Marne laboratory: chronological milestones

1992 - Work on repository design and identification of knowledge to be acquired.

1994-96 - Geological survey work on two clay sites: the first one straddling the Meuse and Haute-Marne districts and the other one in the Gard district.

1997 - Initial selection of repository concepts.

1998 - Selection of Meuse/Haute-Marne site by Government decision and definition of the experimental programme, selection of concepts with a broad range of technical solutions.

1999-2001 - Acquisition of further knowledge concerning the Callovo-Oxfordian layer and start of laboratory shaft sinking.

Late 2001 - Dossier 2001 Argile providing an intermediate synthesis of knowledge acquired.

2002 - Based on the Dossier 2001 Argile, revision of scientific programme for 2002-2005 and selection of repository concepts (waste packages and disposal cells).

2003-2004 - Borehole drilling on and around the laboratory site.

October 2004 - Auxiliary shaft reaches - 490 metres.

November 2004 - Availability of the experimental drift at - 445 metres in the main shaft.

Since February 2005 - Excavation of experimental drifts at the bottom of the auxiliary shaft.

Does Andra submit its results to international experts?

In 2001, Andra prepared a first synthesis of its research activities and results. This report was submitted for critical review by a group of independent international experts under the OECD/NEA aegis, who stressed the relevance of the knowledge acquired and the interest of the results. A second review is scheduled in 2005.

Meuse/Haute-Marne site clay

The geological medium is at the core of the repository system. It must ensure the very long-term confinement of radioactive substances to prevent their migration into the environment.

Expected properties of the formation

The geological medium must be very stable in the long term, i.e., with limited exposure to earthquakes and erosion.

While being deep enough in order to avoid surface disturbances, the clay layer must present a homogeneous geological structure and mineralogical composition. Water flow in the rock must be low, as it constitutes the main alteration factor and the major transport vector for radioactive substances. Finally, chemical stability over time and suitability for excavation are also two essential criteria.

Choice of argillite

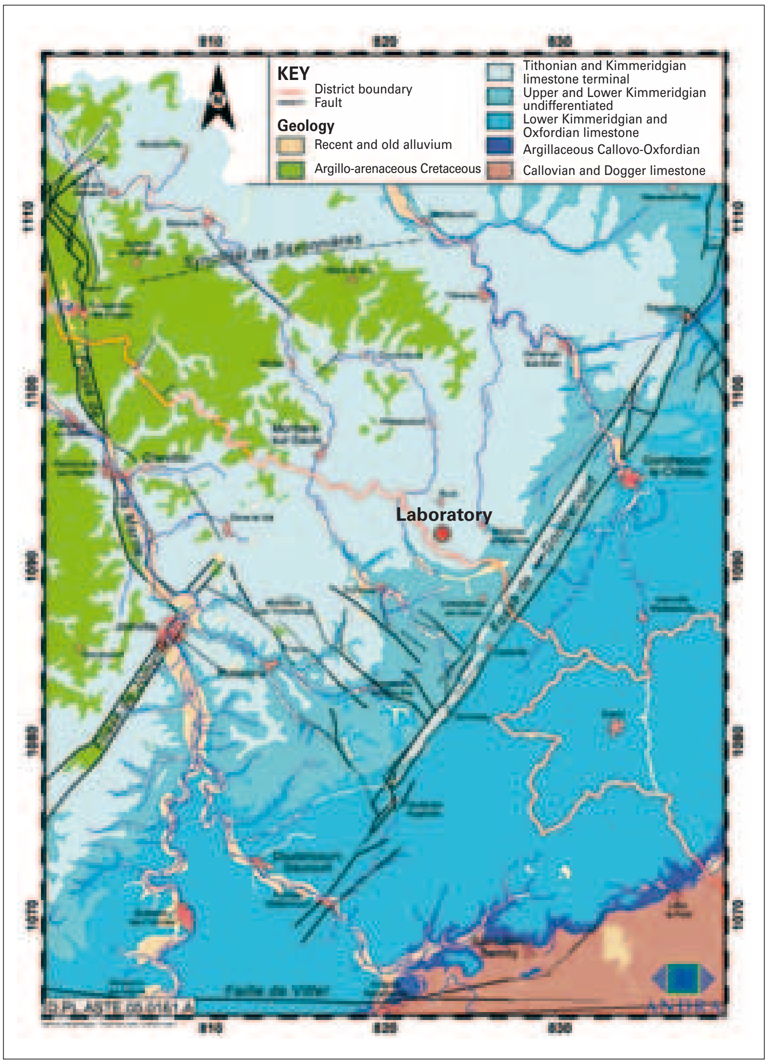
Argillite has excellent properties. It is a stiff (indurated) sedimentary rock with very low permeability. Radioactive or non-radioactive elements dissolved in water move very slowly through this rock because their migration is mainly due to their own motion (diffusion), not to their transport by flowing water (advection). In addition, argillite has the ability to retain a large number of chemical elements. It provides a stable chemical environment and presents a good capacity to absorb chemical perturbations. Finally, argillite has a good mechanical resistance while remaining sufficiently deformable in the long term to adapt to movements that occur very slowly over time.

Meuse/Haute-Marne site

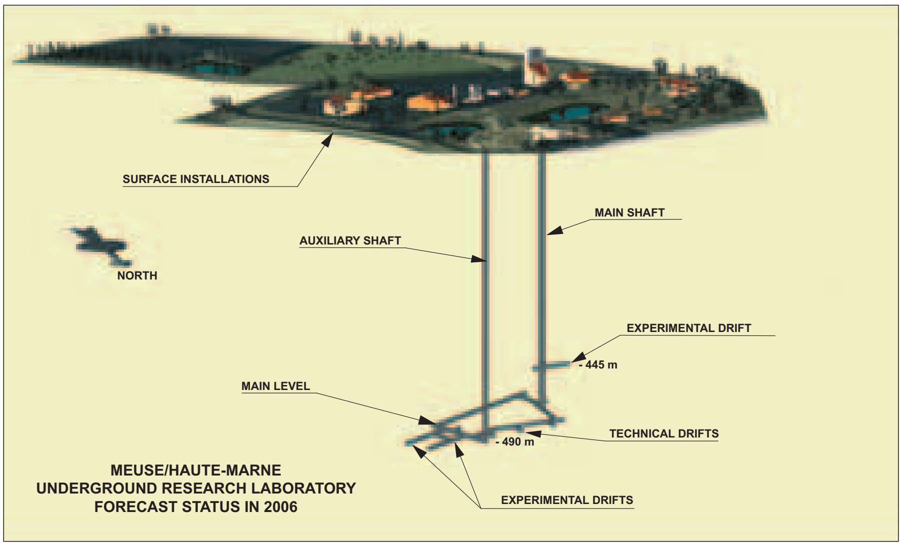
Callovo-Oxfordian argillites

The sector north of the Haute-Marne and south of the Meuse constitutes a geologically simple domain of the Paris basin, with a succession of horizontal layers of limestone, marl and clay rock deposited in ancient oceans.

The layer studied is a clay rock 155 million years old, at least 130 metres thick and located at a depth of between 400 and 600 metres, referred to as the Callovo-Oxfordian argillites.



Geological map of the Meuse/Haute-Marne sector



Major experiments carried out at the laboratory

From the surface:

- analysis of regional seismic profiles,
- drilling of deep boreholes and measurement of mechanical properties, permeability and diffusion,
- drilling of deviated boreholes to survey, at large scale, the geological layers,
- 2D and 3D geophysical survey campaigns (underground auscultation with seismic waves),
- hydro-geological monitoring,
- seismic (earthquake) monitoring network.

Seismic vibrator trucks (Vibroseis) used during the geophysical survey campaign

Within the rock:

- *While sinking the shafts*: layer survey, water collection and flow-rate measurements in limestone layers overlying the Callovo-Oxfordian formation, wall deformation measurements, real-time monitoring of rock mechanical behaviour (via sensors), and assessment of rock damage by excavation.
- *Inside the drifts:* wall deformation measurements, thermal conductivity measurements, monitoring of chemical perturbations, permeability and diffusion measurements for water and radioactive substances, and performance tests on grooves filled with swelling clay[1].

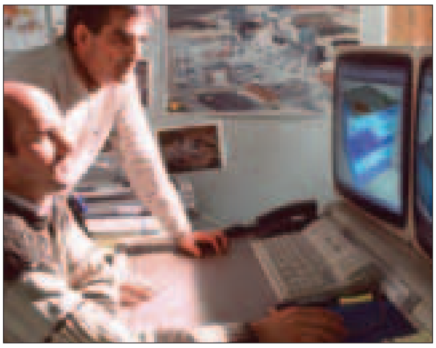
Experimental drift (– 445 metres) of the Meuse/Haute-Marne laboratory

Conclusions from 10 years of research at the Meuse/Haute-Marne site

After 10 years of research, Andra has acquired data confirming that **the Callovo-Oxfordian layer of the Meuse/Haute-Marne site has favourable properties** for an HLLL waste repository:

- the geological environment is stable: very low seismic risk,
- the clay layer is regular and homogeneous over a large surface area. It does not present any fault,
- the Callovo-Oxfordian has a low permeability: very low water flow and argillites with favourable properties to trap and retain radioactive substances over long periods of time,
- the rock can withstand mining excavation work,
- its characteristics are compatible with the reversibility requirements,
- the impact of the engineered materials (cement, concrete, metal, etc.) is very small and limited to the immediate surrounding of the engineered structures,
- water flow in the Callovo-Oxfordian surrounding layers is very slow,
- the results obtained in the underground laboratory can be transposed to a 200 km^2 area.

1 - Very low permeability material that swells as it hydrates.

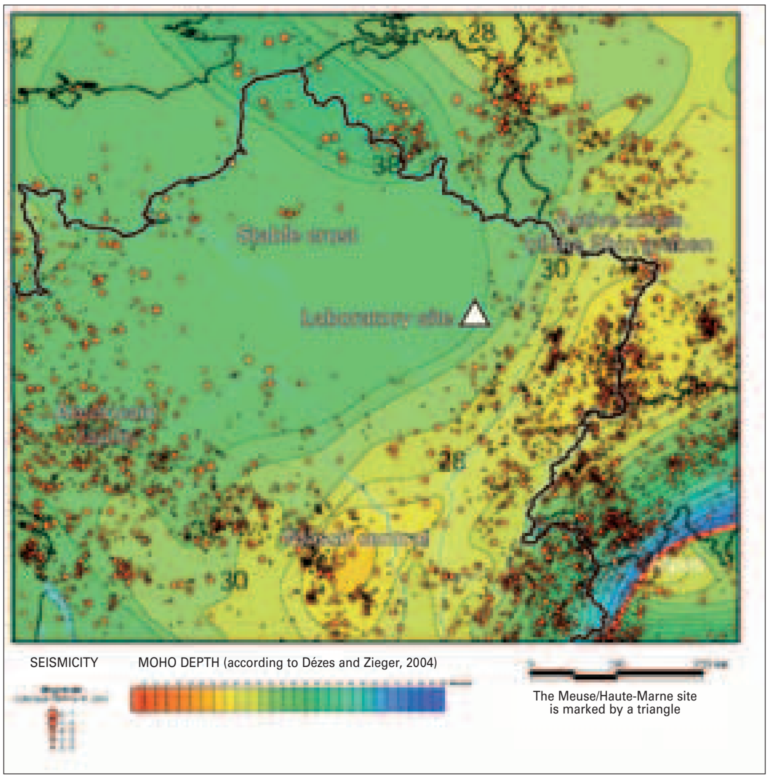


Scientific team of the Meuse/Haute-Marne laboratory

Could the repository undergo an earthquake?

The deformations associated with tectonic plate movements have remained small for the past 150 million years, as in the rest of the Paris basin. They are essentially limited to the Gondrecourt and Marne grabens, on the boundary of the sector studied. Between these faults, the Callovo-Oxfordian layer is regular and practically flat.

Available data confirms that the region has very low seismicity. However, in a cautious approach, the engineered structures proposed for the repository have been designed to withstand a hypothetical earthquake of magnitude 6.1 ± 0.4 at 6 km from the site (most pessimistic hypothesis). Finally, the effect of an earthquake would be, in any case, very low underground.



Seismicity around the Paris basin

Are there natural resources nearby that might be useful in the future?

The site presents no rare natural resources to be preserved. In particular, the aquifer layer located beneath the laboratory does not have the necessary properties to eventually become an exploitable resource for consumption or geothermal applications.

Is the absence of faults confirmed?

This aspect has been particularly studied during the geophysical campaigns.

The 200 km² explored north and northeast of the laboratory revealed no faults in the sector studied. The only known faults are located outside this sector: Marne fault (oriented north-northwest) and Gondrecourt graben (oriented northeast), forming the western, southern and eastern boundaries of the sector.

In the Callovo-Oxfordian layer, none of the boreholes, meaning a drilled length of 2300 meters in all, intercepted a secondary fault. Only a few microstructures with a maximum size of a few centimetres have been surveyed. They are all clogged and do not modify the confinement properties of the layer.

Could radioactive substances migrate out from the repository?

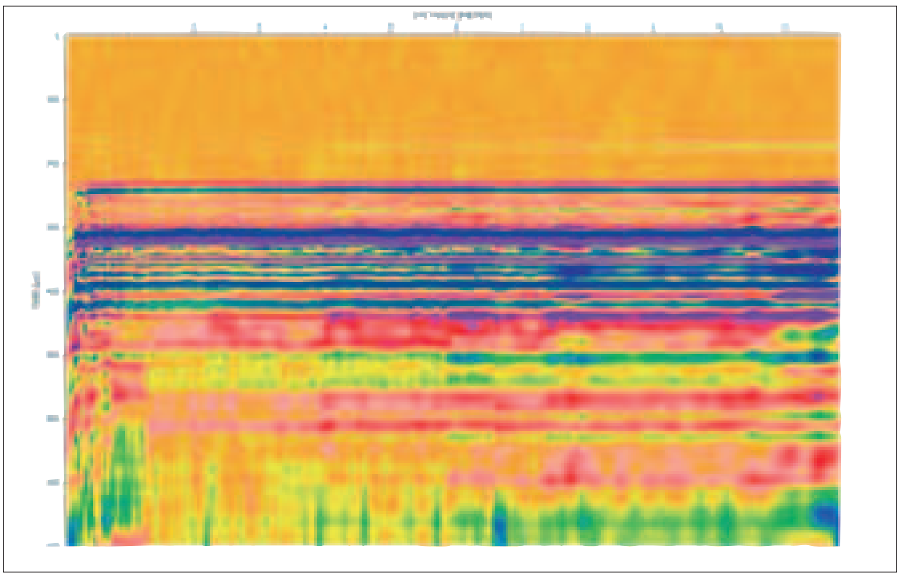
The Callovo-Oxfordian layer has a very low permeability. Water flow is therefore very limited, preventing the possible transport of radionuclides: a drop of water would move away a few centimetres in 100,000 years. In addition, the layer has a large smectite content, a mineral that tends to immobilise elements dissolved in water. Finally, the chemical composition of the interstitial water in the rock causes various radioactive substances to precipitate in solid form, thus preventing their dissolution in water. All of these factors result in most of the radioactivity being trapped within the repository.

A few radioactive substances could nevertheless migrate in the very long term (not before a hundred thousand years), but with no impact on man and the environment.

Could the excavation of the repository drifts damage the host formation surrounding the repository?

The laboratory excavation monitoring has shown that these argillites are very stiff, deform little and slowly.

Drifts excavation creates a damaged zone around the excavated structure, susceptible of constituting a water pathway. At a depth of 450 metres, there is practically no fracturing, but microfissuring may occur around the engineered structures. For example, in the case of a 10 metres



Assessment of the damaged zone based on microseismic measurements

diameter structure, the microfissured zone may reach a few metres. The rock properties are little affected. In particular, its very low permeability is preserved. Moreover, preliminary results suggest that these fissures and fractures tend to heal with time.

Although the introduction of air for ventilation contributes to drying the rock, possibly weakening it, analyses of models and ancient structures show that this phenomenon is slow in argillites and does not exceed the thickness of the damaged zone.

Shaft sinking

Can the rock close up the repository preventing access to the waste packages?

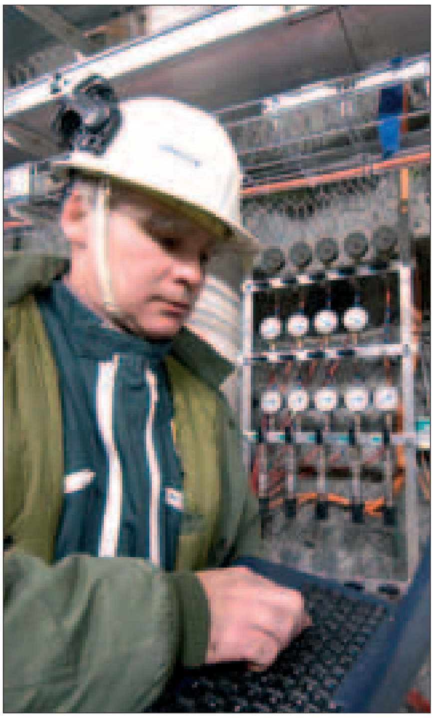
Callovo-Oxfordian argillite can deform with time, but this process is very slow. The displacement of the walls of a repository structure would amount to less than a few centimetres after 1000 years. This provides stable and robust engineered structures over long periods of time, thereby guaranteeing reversibility.

How would the heat released by the waste packages affect the rock?

Certain types of waste give off heat. It is therefore important to examine rock behaviour with respect to heat. Up to approximately 70°C, the argillites remain practically unaffected. They can withstand such temperatures without significant alteration for approximately 10,000 years, and higher temperatures for shorter periods. These estimates can be used to define the acceptable temperatures for a repository. The maximum value adopted for the temperature in the rock is 90°C, and 70°C beyond 1000 years.

What would be the behaviour of the engineered materials in the geological medium?

In the chemical environment of the repository, concrete degradation takes several tens of thousands of years. Once the repository is closed, metallic materials corrode very slowly (absence of oxygen), producing minerals that stabilise their degradation. The studies show also that the chemical impact of corrosion on the argillites is very limited.



Reading of experimental data

Do we have information concerning water flow in the layers surrounding the argillites?

In the layers surrounding the Callovo-Oxfordian, the overall waterflow is horizontal and directed from the plateaux located south and east of the site towards the centre of the basin. Based on the results of the topographic analysis for the past two million years and the predictions regarding climatic changes, it is possible to appraise possible variations in water flow over the next 500,000 to 1 million years. It appears that flow directions will undergo relatively few changes.

To which zone can the results obtained in the underground laboratory be transposed?

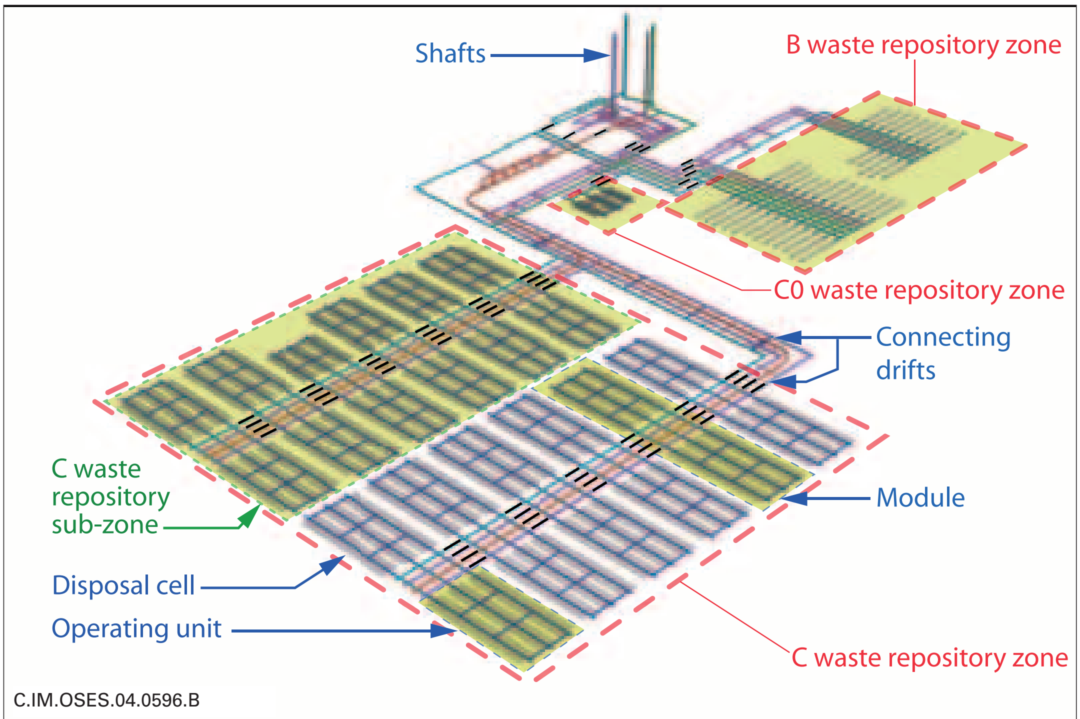
Andra has defined a geographic zone where the properties of the argillites are similar to those found at the laboratory site. After exploring a 700 km^2 area around the laboratory, using precise mapping methods, it has been determined that the transposition zone extends over approximately 200 km^2 to the north and west of the laboratory.

Why does Andra study clay formations in Switzerland?

Between 1996 and 2005, Andra has carried out experiments in the Mont Terri laboratory in Switzerland. The Mont Terri argillites are somehow similar to the Callovo-Oxfordian ones. Andra has tested various tools and methods, acquired scientific data on clay behaviour, validated models and performed full-scale engineering tests. A major result has been achieved: the observations obtained at sample scale remain valid at larger scales.

Repository installations

Andra has designed a simple and robust repository: a modular architecture grouping together packages of the same category and allowing flexible operation.



General organisation of the repository

Safe and reversible architecture

The repository is located on a single level, in the middle of the geological layer, so as to benefit as much as possible from the thickness of the argillite barrier.

It is organised into distinct zones according to package type (B, C, CU), separated from one another and subdivided into modules. The modules are constructed and put into service as the need arises.

The engineered structures are designed to minimise mechanical disturbances. Their architecture is simple, with a generally half-circular cross-section and their dimension is limited. The cells are spaced apart and oriented parallel to the direction of maximum stress in the rock so as to not interact mechanically. A lining supports the engineered structures for several centuries, and void spaces within the cells are limited.

The engineered structures receiving the C waste and spent fuel packages are designed to limit the disturbances associated with the large amount of heat given off, by means of sufficient spacing between cells and a suitable arrangement of the packages. The temperature must remain below 100°C in contact with the packages and 90°C within the rock while the architecture is designed to keep the temperature below 70°C, or even much lower, beyond 1000 years.

The engineered structures are arranged in a dead-end fashion so as to limit water flow. In the event that it is decided to close them, they will be sealed with low-permeability swelling clay plugs.

The cell and package materials (concrete, steel, etc.) are chosen to last as long as possible and preserve a physico-chemical environment that retains the radioactive substances.

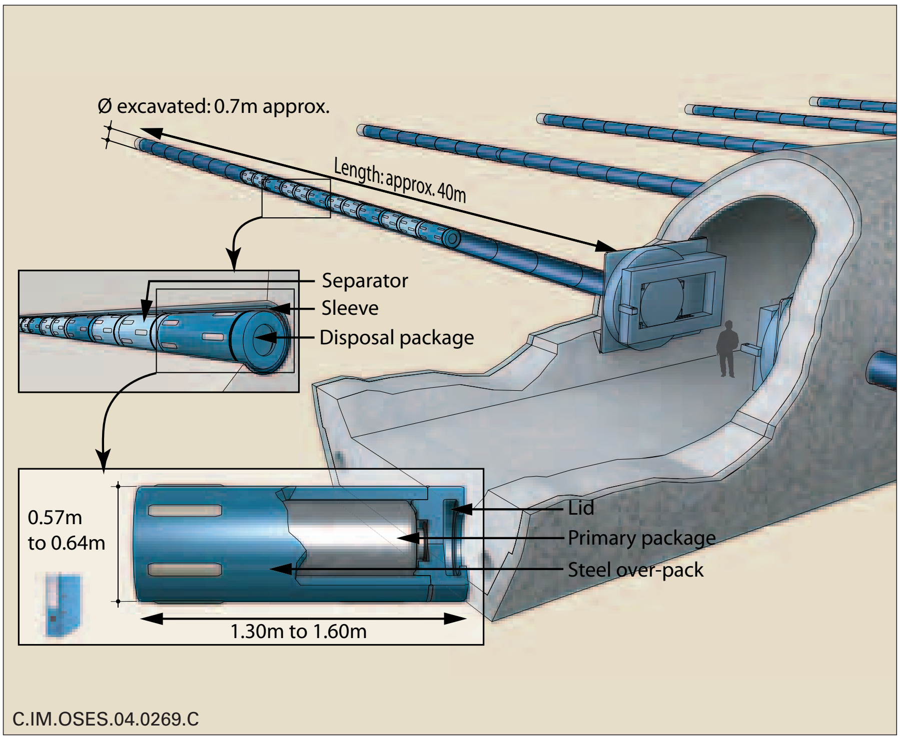
The reversibility requirement is integrated as of the repository design phase. It entails privileging the use of durable materials, maintaining the technical possibility to retrieve the packages, and organising the repository operation or closure in various stages and in a modular manner.

Disposal of B waste

B waste gives off very little heat. The packages delivered by waste producers are placed in high-performance reinforced concrete containers to constitute disposal packages. These parallelepiped containers are approximately 1.5 to 2 metres high and weigh 6 to 25 metric tonnes. They are designed to last several centuries and ensure a good resistance to falls. Prototypes have been used to demonstrate their feasibility and to perform full-scale tests.

The containers are placed in concrete disposal cells 250 metres long and 12 metres in diameter. The cells are equipped with a high-performance concrete circular lining with guaranteed stability for several centuries. A disposal chamber adapted to the geometry of the stacked packages is arranged inside the lining.

Prototypes of standard B waste containers



C waste disposal cell

Disposal of C waste

C waste is confined in a glass matrix wherein the radioactive substances are entrapped. This type of waste gives off large amounts of heat. High temperatures can accelerate the dissolution of the glass in contact with water. In order to prevent water ingress on the glass during its high temperature phase, each C waste package delivered by the waste producer is placed in a leak-tight cylindrical steel container 1.3 to 1.6 metres long and 60 cm in diameter (weight: 1.7 to 2 metric tonnes). The thickness of the container (approximately 5 cm) is calculated to withstand corrosion and ensure leak-tightness for at least 4000 years.

The C waste disposal cell is a micro-tunnel 40 metres long and 70 cm in diameter. It is designed to preserve the container from corrosion and is not ventilated in order to limit the ingress of oxygen favouring corrosion. In order to meet the temperature limits, the cells are spaced approximately 10 metres apart and each one receives a small number of packages (6 to 8).

Possible disposal of spent fuel (CU)

Although the geological disposal of spent fuel is not currently foreseen, Andra has considered this possibility so as to cover all possible configurations.

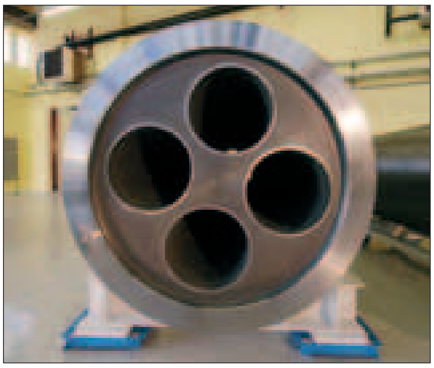
The concept is similar to that used for C waste, but it has been decided to emplace swelling clay between the steel container and the argillites so as to take into account the large amounts of heat given off by spent fuel. Their thick steel container (thickness slightly over 10 cm) can withstand corrosion for 10,000 years. The container itself has been designed to prevent the occurrence of an uncontrolled nuclear chain reaction.

Containers receiving several spent fuel assemblies weigh 43 metric tonnes, while those only receiving one assembly weigh 8 to 10 metric tonnes.

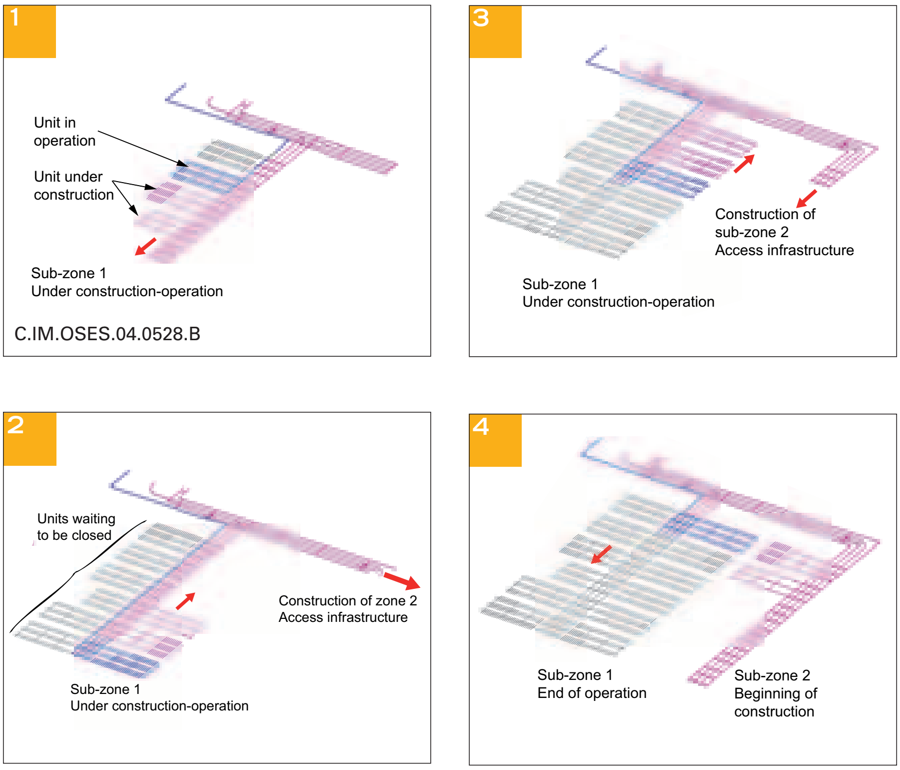
The spent fuel disposal cell is approximately 45 metres long and 2.5 to 3 metres in diameter.

In order to avoid heat accumulation, the cells are excavated approximately 20 metres apart and number of packages per cell is reduced (3 or 4).

Repository installations



Demonstrator of spent fuel disposal package



Phases in the construction and operation of a C waste repository zone

How would the occupational safety be ensured inside the repository?

The underground architecture is designed so that disposal operations can be performed simultaneously with the construction of new cells.

Nevertheless, the design provides for a separation of activities: to avoid all risks of interference, the traffic associated with construction and closure operations is separated from that associated with disposal activities (which present a radiological hazard).

If necessary, personnel can be evacuated via the access shafts and rescue teams can quickly access underground. A smoke evacuation system is also planned in case of fire. The drift network meets all regulatory safety requirements.

How many shafts would connect the repository to the surface?

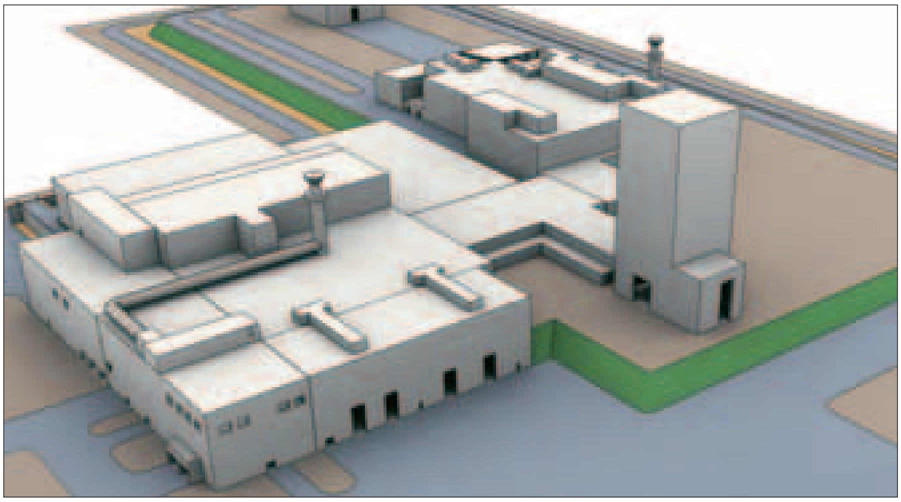
Four shafts connect the surface to the underground installations. These shafts are equipped with reliable systems used in the mining industry and are specialised according to function: waste package transfer, personnel transport, service (transport of muck and large equipment), and exhaust (air return ventilation).

Which installations would be built at surface ?

The surface installations cover approximately 100 hectares comprising various areas:

- nuclear area, where waste packages delivered by waste producers are received and subsequently conditioned in disposal containers,
- industrial area, with the technical facilities and materials required for underground works,
- administrative area.

In addition, a specific area could be set up to receive the excavated muck that might be used as drift backfill.



Surface facilities (project)

The disposal facility in operation

The construction of engineered structures, the industrial operation and closure of repository installations are performed progressively, and can be silmutaneous. This flexibility allows for changes in repository design or management methods according to the lessons learnt feedback. In addition to these main activities, specific maintenance and monitoring activities are required to ensure the reversible management of the disposal system.

2 CLAY

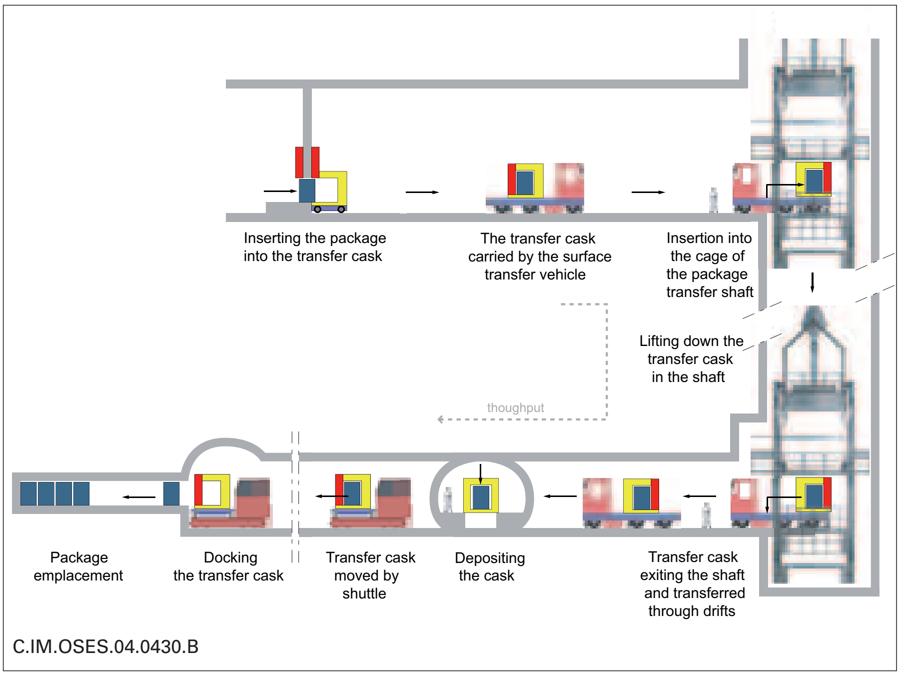
From waste packages reception to their disposal in cells

In the surface installations, waste packages delivered to the site are removed from their transport casks and placed in containers: then they are inspected, and stored temporarily. Most of these operations are performed by remote-controlled devices in shielded compartments, without the presence of humans.

Each container is then placed in a shielding cask ensuring the radiological protection of personnel and then transferred to the underground installations.

For B waste packages, a remote-controlled carriage extracts the container from the cask and emplaces it in the cell. For C waste packages, a mobile robot integrated in the cask pushes the container into the cell. This process is being tested within the scope of a European project (ESDRED).

Spent fuel packages of small diameter can be emplaced using the same methods, whereas those with a larger diameter (i.e., containing 4 fuel assemblies) are lifted by air cushion support pushed by a self-propelled carriage. After a successful preliminary test carried out in Sweden, this process is also currently being tested within the scope of the above-mentioned European project.



Scheme of a disposal package transfer

Stages of the progressive closure of engineered structures

In keeping with the reversibility requirement, the repository would be closed in stages, i.e., disposal cell sealing, backfilling and sealing of drifts and then shafts. Sealing prevents water circulation inside the repository. Drift backfilling limits deformations in the geological medium.

B waste disposal cells are first closed with a radiological protection concrete wall ensuring occupationnal safety, and then by approximately 30 metres of swelling clay in order to prevent water flow. C waste and spent fuel disposal cells are closed with a metal plug ensu-

ring radiological protection, to which is added a 3 metre swelling clay plug.
The drifts are then backfilled and sealed similarly to B waste disposal cells. The shafts are filled with concrete at the base and sealed with swelling clay to a height of 30 metres. They are then backfilled with argillite from the site, with a swelling clay insulating plug (10 to 15 metres) at each porous level.

What are the risks associated with construction and operation? How to prevent them?

The main risks are those encountered in industrial, mining and tunnelling activities: fire, handling and traffic accidents, falling blocks, electrical hazards, etc., calling for conventional preventive measures.

All aspects of repository operation are designed to prevent the risk of radioactive exposure. These measures which are the current standard in the nuclear industry, consist in protection screens, remote-controlled systems and robots, confinement of radioactive materials, limiting the release of radioactive gases and monitoring the absence of contamination.

The risk of criticality (uncontrolled nuclear chain reaction) has been taken into account for spent fuel packages, whereas B and C waste packages do not contain the quantities of materials required for such a reaction. To prevent this risk and similarly to existing storage facilities, packages and cells are respectively sufficiently apart from each other and dry treatment processes are used, since water increases the reactivity of the radioactive elements.

In order to prevent the packages from being damaged by falling, handling heights are limited and the resistance of the containers and casks is over-designed with respect to the possible fall height. The integrity of the primary package is thus preserved in the event of a fall. The risk of falls in shafts has been considered, despite the fact that current mining shaft installations make it highly unlikely. In the event of a fall, a shock absorber limits damage to the cask. C waste and spent fuel containers placed inside the cask withstand the shock, whereas B waste containers may be slightly fissured, without affecting the primary packages. Nevertheless, to avoid this risk, filters are planned so as to trap radioactive substances possibly released into the air of the shaft.

What about the risk of fire?

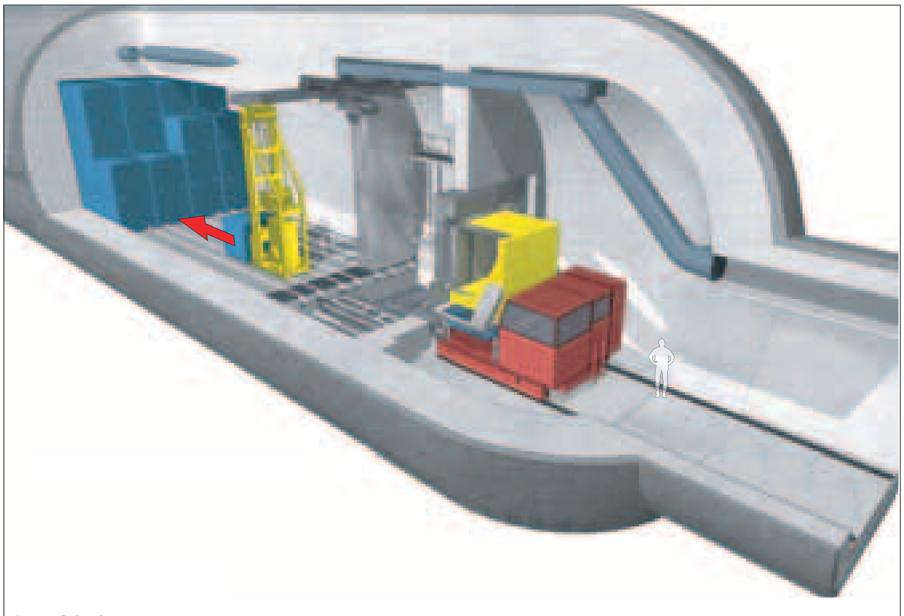
The risk of fire has been assessed in a detailed study. The simulation results show that the repository design (with drifts connected together at regular intervals) allows personnel to escape away from the fire, quickly access a parallel drift supplied with fresh air and reach safely the surface.

In addition, the disposal packages would not suffer damage possibly leading to the dissemination of radioactive substances.

What radioactive dose would a person working inside the repository be exposed to?

The estimated dose would be far below the current regulatory limits, which are 20 mSv/year[2] for personnel and 1 mSv/year for the public.

2 - 1 mSv = one milli-Sievert. The Sievert is the unit to measure radioactivity effect on human beings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Disposal of packages in a B waste disposal cell

Reversible management

Freedom of choice for future generations

The approach to reversibility proposed by Andra can be defined as the possibility to manage the repository in a flexible manner and in stages. The objective is to leave future generations the freedom to make decisions concerning repository management.

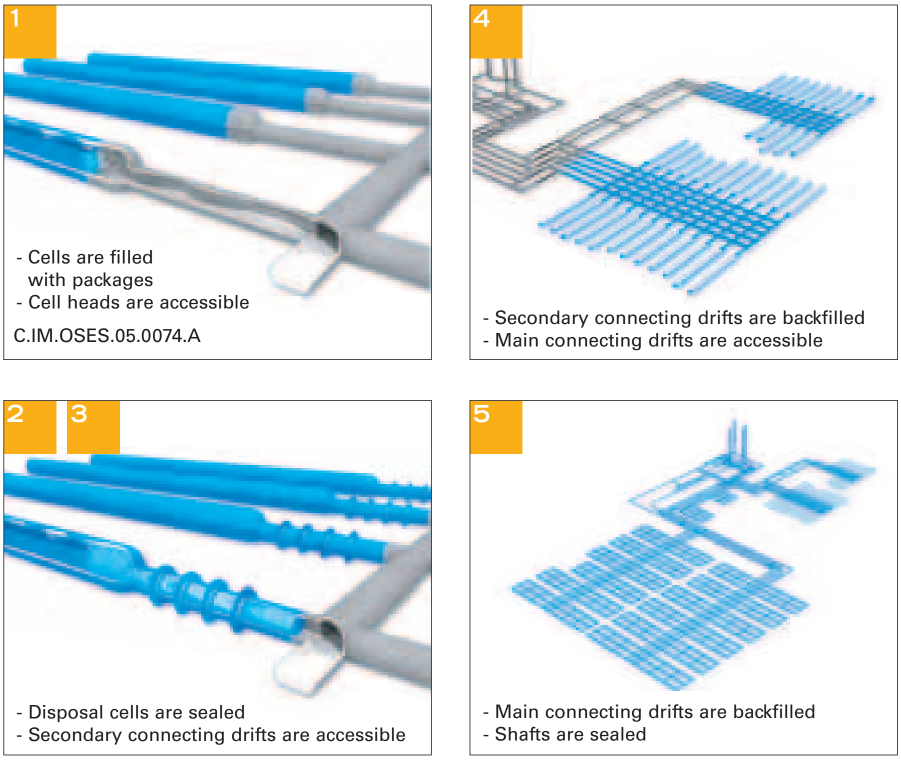
The repository design (modular architecture, simplified operation, dimensioning and choice of durable materials, etc.) is intended to offer the widest possible range of choices. Reversibility means the possibility to retrieve emplaced packages, to intervene in the disposal process and to modify the design of the engineered structures.

Various closure stages

After waste package emplacement: cells are not sealed but closed with devices protecting the personnel. All underground infrastructures remain accessible.

After cell sealing: cells are sealed with a swelling clay plug. Cell heads remain accessible. Due to the slowness of deformation processes and the absence of water for several centuries, cell linings are subject to little degradation.

After closure of a module (several cells): access drifts to C waste and spent fuel modules are backfilled with argillite, but connecting drifts associated with the module remain accessible. B waste modules - since there is only one cell per module - are not concerned. Stability of engineered structures is ensured in the very long term.

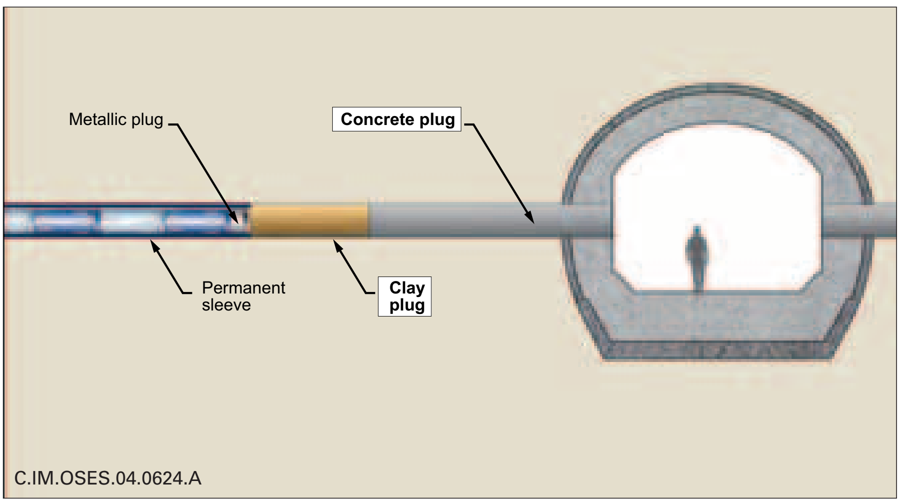


Possible stages in the operation and progressive closure of a repository

After closure of a repository zone: drifts within the zone are sealed and backfilled. Main drifts remain accessible.

Post-closure: this stage begins after backfilling and sealing of main drifts and then shafts. It corresponds to the end of the disposal process. The installation becomes passive, which means that it continues to ensure waste confinement without human intervention.

This progressive process is not the only one. It is a possible option, itself providing flexibility.



Sealed C waste disposal cell

2 CLAY

> Monitoring the repository as input for the decision making process

Choices concerning repository management (maintaining the same level of reversibility, returning to the previous level, switching to a lower reversibility level, etc.) are based on a scientific understanding of the repository evolution over a period of several centuries.

An observation programme will be implemented to obtain feedback intended to improve repository design and management.

Measurement devices (deformation, temperature, pressure, etc.) and data transmission networks will be placed in instrumented observation cells, shafts, drifts, seals and backfills as of their construction. These devices will need to operate for long periods in a difficult environment (radiation and temperature).

The experience acquired in the field of civil engineering provides the best practice guidelines: choice of high quality tools, optimal distribution of redundant observation systems, integration of these means as of the repository design phase.

How long would it be possible to access the waste?

Andra does not set a predetermined duration for reversibility.

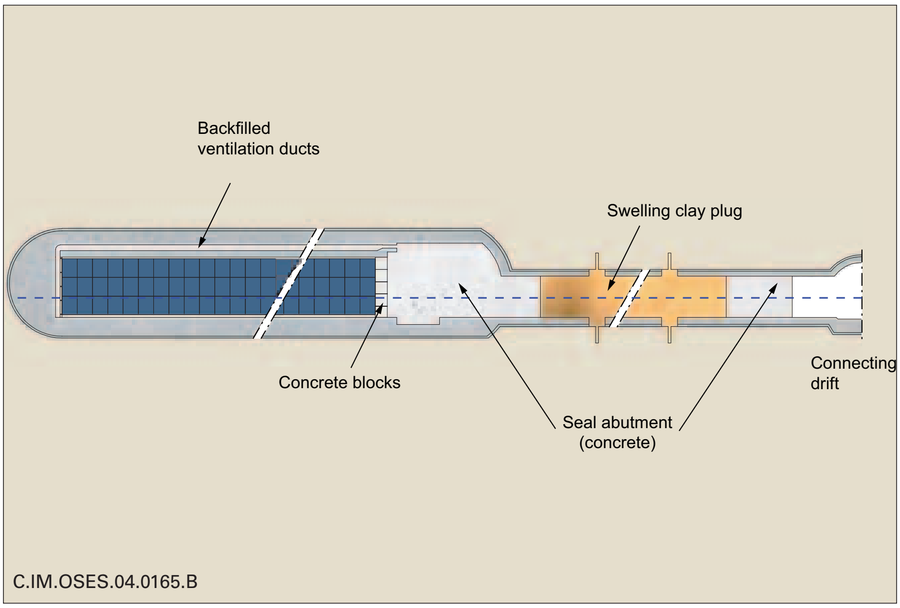
One key issue of reversibility is the mechanical stability of the disposal cells, which will last for at least 200 to 300 years without specific maintenance. Given the safety margins adopted, the cells should remain stable even longer. The observation programme will allow for regular reassessment of their lifetime.

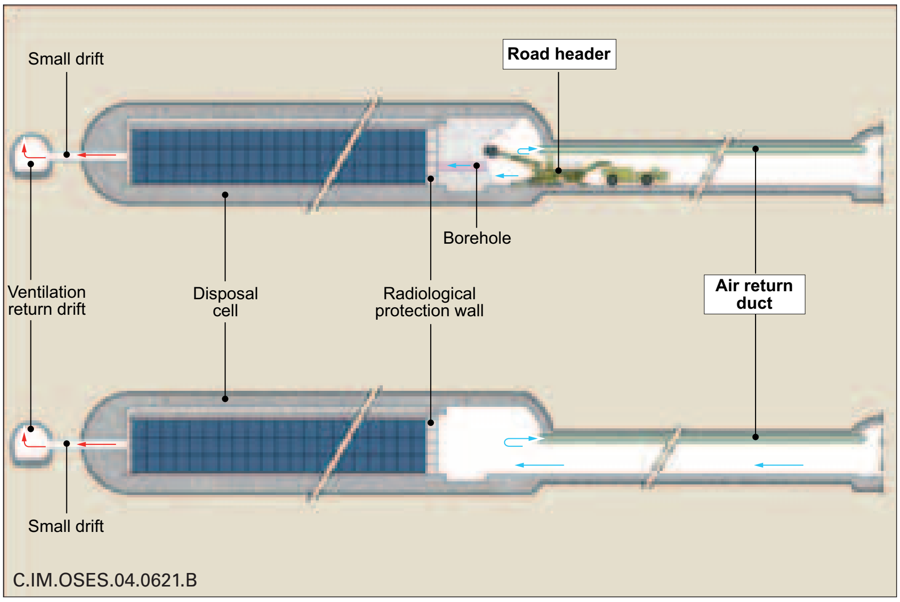
The final stage is the mechanical rupture of the cell lining. Beyond this stage, mining operations and specific radiological protection measures need to be implemented in order to retrieve the waste packages blocked by the geological formation.

To extend this duration, specific technical measures need to be adopted (thorough maintenance, reinforcement of engineered structures, reconstruction, etc.).

How might waste packages be effectively retrieved?

The equipment and methods used to retrieve the waste packages are similar to those used to emplace them. However, conditions vary depending on the stage at which the decision is made. For example, if a seal has already been implemented, it must be deconstructed in order to access the disposal cell again and cell re-equipment is necessary to achieve package retrieval.





B waste disposal cell deconstruction process

Long-term evolution of the repository

A reversible disposal system can be closed in the event that such a decision is taken. It must then be possible for the repository to evolve safely in the long term, without human intervention. Andra has therefore studied the evolution of the repository according to various scenarios to make sure that its impact on the environment is very low in all cases. These studies are based on current scientific and technological knowledge and take into account all kinds of uncertainty, from repository closure up to one million years in the future.

Apprehending the repository complexity

A repository constitutes a complex system comprising numerous components (waste packages, disposal structures, geological medium) and whose evolution depends on various phenomena (thermal,hydraulic,chemical and mechanical). Studies have provided an assessment of the conditions in which radioactive substances might be released by the waste packages and possibly migrate into the environment.

Main evolutions expected

Heat will have little impact

The repository is designed to limit the temperature to 90°C at all points. Maximum temperatures are reached after one or more tens of years, and approximately 1000 years (for C waste disposal cells) and 6000 years (for spent fuel disposal cells) are required to return to approximately 40°C. These durations are much shorter than the time required for deterioration of the waste packages: therefore heat has little effect on the release and transfer of radioactive substances. Moreover, the increase in temperature does not modify the mineral composition of the argillites or their confinement capabilities.

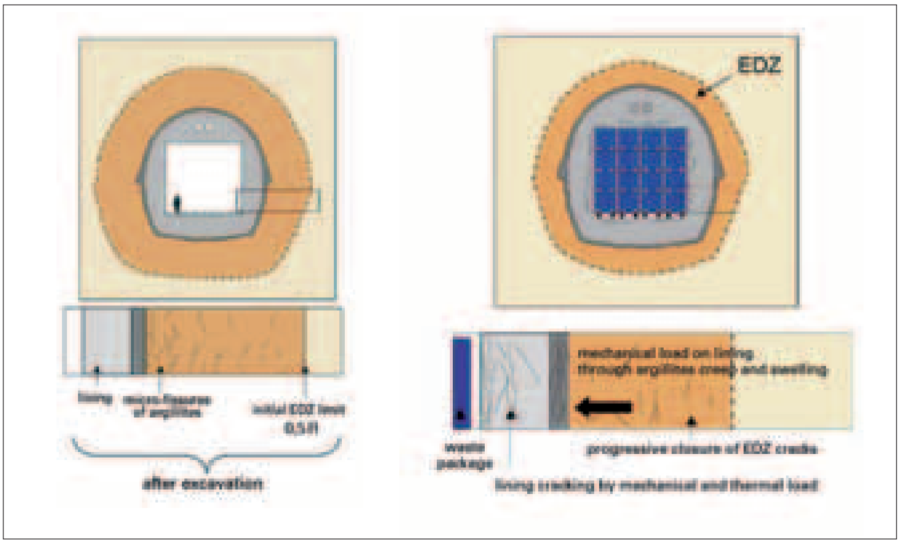
Hydraulic evolution with controlled consequences

The repository disturbs the initial hydraulic equilibrium of the geological formations. These disturbances remain limited to the repository and the Callovo-Oxfordian layer. Between 100,000 and 200,000 years, a new hydraulic equilibrium is established and chemical and mechanical processes develop more significantly.

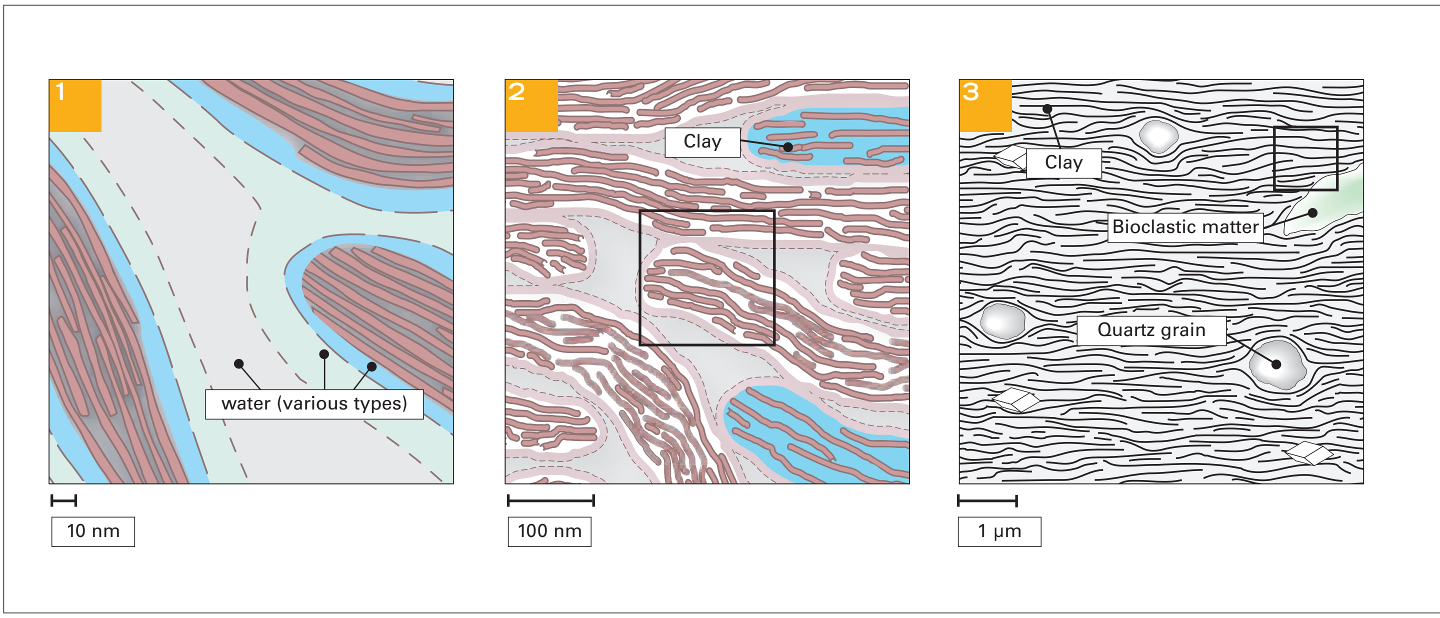
After a few hundred thousand years and up to a million years, climatic changes and erosion will progressively modify the direction of water flows in the layers surrounding the Callovo-Oxfordian, orienting them towards the natural outlets north and west of the Meuse/Haute-Marne site, without changing flow velocity, which will remain very low. The Callovo-Oxfordian layer is too deep to be affected by erosion.

A progressive mechanical evolution

The mechanical effects associated with the repository are limited to the Callovo-Oxfordian layer, within a few metres zone. The excavation damaged zone (EDZ) is characterised by the appearance of micro-fissures whose density decreases as the distance from the wall increases. Slight fracturing may also occur, depending on the depth and orientation with respect to pressure stresses within the rock. The calculation results indicate that fracturing does not occur at a depth of



Evolution of the excavation damaged zone (EDZ)



Schematization of the Callovo-Oxfordian argillite texture and porosity

500 metres and is moderately initiated at approximately 600 metres. At the scale of several thousands to tens of thousands of years, the evolution of the argillites tends to heal these fractures.

Chemical evolution will be slow and limited

Concrete degradation and metal corrosion are very slow processes. Chemical perturbations are limited to a few metres at the most, which is little in comparison with the thickness of the geological layer. The retention properties of the argillites will therefore be preserved.

Waste package deterioration (and the subsequent release of radioactive substances) also takes place very slowly, over periods of up to several hundreds of thousands of years for C waste packages.

> Mobility of radioactive substances

Radioactive substances are grouped into three families according to their solubility and retention in a clay medium:

> Mobile elements (ex: iodine, chlorine)

> Medium mobility elements (ex: caesium)

> Low mobility elements (ex: uranium, plutonium)

The geological repository would mainly comprise medium and low mobility elements.

Slow and limited release of radioactive substances

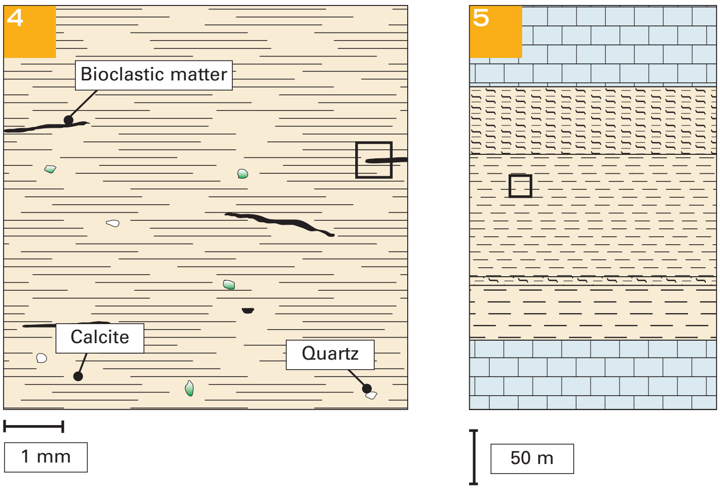
Three barriers prevent the release of radioactive substances: first barrier constituted by the waste packages, second barrier constituted by the disposal cells, and third barrier constituted by the geological medium.

Waste package degradation will take place very progressively over time: package corrosion, concrete degradation, glass matrix dissolution depending on thermal and hydraulic conditions.

It will therefore be possible for radioactive substances to migrate out from the packages. These substances will then be either retained or dissolved, depending on the chemical environment encountered.

The slowness of the diffusion process delays migration, and most of these substances eventually disappear through natural radioactive decay. Only a few mobile elements such as iodine 129, chlorine 36, caesium 135, selenium 79 and carbon 14 migrate significantly outside the cells.

These elements then diffuse very slowly into the argillaceous rock.

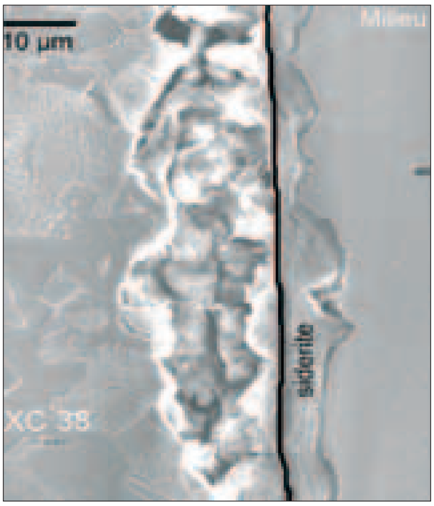


1 & 2 : clay-water system ; 3 & 4 : mineralogical assembly

How long would radioactive substances be retained in the waste packages?

Non-gaseous radioactive substances remain confined for periods of up to several hundred thousand years, depending on the waste packages. The very small quantities of gaseous substances released by B waste packages do not exit the repository, with the exception of carbon 14, which dissolves in water or disperses into the geological medium (due to the particularly small quantities released).

The ingress of water on B waste packages leads to the progressive release of radioactive substances over a period of several tens to several thousands of years (neglecting the possible role of the concrete containers). According to cautious estimates, the C waste and spent fuel containers remain leak-tight for 4000 and 10,000 years, respectively. After their degradation, water comes into contact with the glass and spent fuel assemblies, and these substances dissolve for several hundreds of thousands of years.



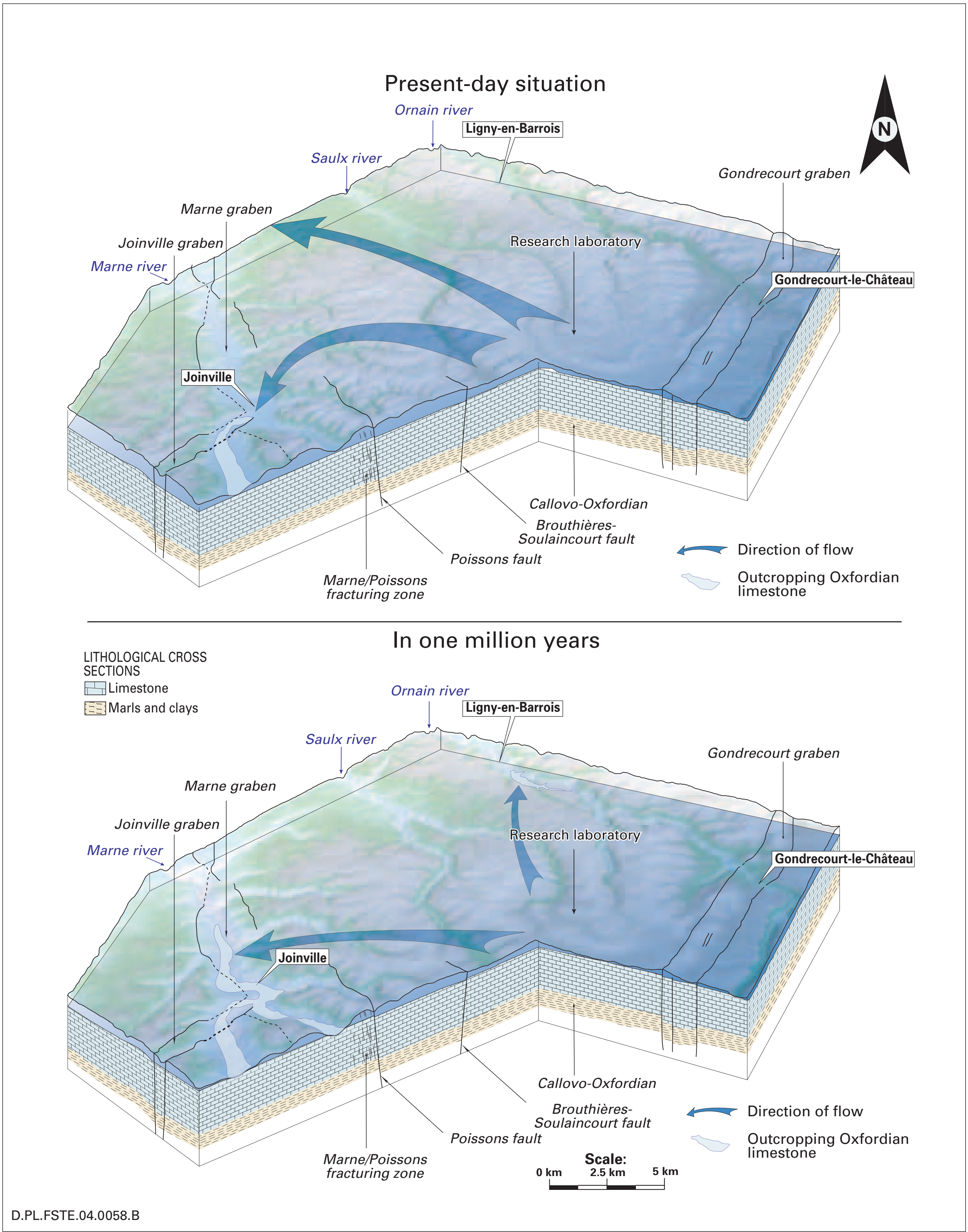
Corrosion process observed with an electronic beam microscope

How long would it take for them to reach the environment?

At least one hundred thousand years are required for the most mobile radioactive substances to be transferred to the boundaries of the Callovo-Oxfordian layer.

Half of the elements moves downwards (Dogger layer), while the other half moves upwards (Oxfordian layer). Only the most soluble elements with the longest radioactive half-lives have enough time to reach the layers above and below the Callovo-Oxfordian during the next million years.

Long-term evolution of the repository



Schematic representation of the evolution of water flows in the calcareous Oxfordian layer, at the current state and in a million years

Repository safety and impact on man

To assess the long-term safety of a repository, Andra has conducted studies to assess its impact on man and the environment.

Several evolution scenarios

Andra has performed calculations in two configurations:

- **Normal evolution scenario,** based on cautious hypotheses. This scenario is not intended to represent the future reality, but rather to encompass the most probable situations through a cautious approach.
- **Altered evolution scenarios,** integrating low-probability events and possible incidents.

In keeping with international practice, the calculations cover a period of million years, integrating climatic evolutions.

The impact of the repository is calculated using modelling: in case of low uncertainty, the most scientifically supported model is used; in case of high uncertainty, a penalising model is adopted. Risks and uncertainties are therefore integrated as of the repository design phase.

> Maximum acceptable impact

The repository impact on man and the environment must be compared with the threshold established by the Basic Safety Rule, i.e., 0.25 mSv/year. This radioactive dose corresponds to one fourth of the regulatory limit for public exposure of non-natural origin and approximately one tenth of the annual dose due to natural radioactivity.

The calculated impact is the individual dose received by a group consisting of most exposed persons. For this purpose, "hypothetical critical groups representative of individuals susceptible of receiving the highest doses, including individuals living in at least partial autarky" have been adopted (Basic Safety Rule RFS III.2.f).

Normal evolution

The repository meets the safety criteria.

Water flow in the repository is very low. Most of the radioactive substances migrate very slowly through the Callovo-Oxfordian layer, and the argillites present good retention properties.

The argillaceous layer delays the release of radioactive substances over hundreds of thousands of years. After one million years, nearly all the radioactive elements are completely attenuated. Only iodine 129 and chlorine 36 show significant flows at the Callovo-Oxfordian layer boundaries.

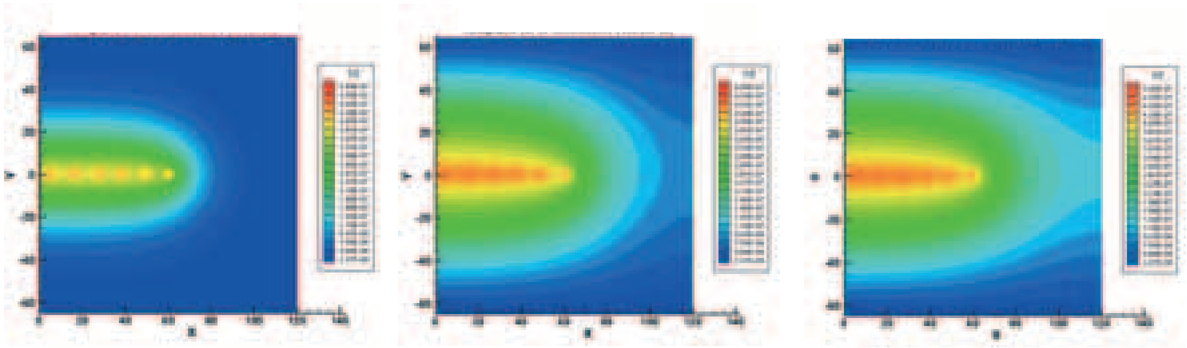
Various safety margins

In order to ensure maximum repository safety, a number of cautious choices have been made: many of the parameters chosen are among the most pessimistic, no favourable properties have been attributed to the layers surrounding the Callovo-Oxfordian (even though they possess some), and impacts on populations have been calculated on the basis of particularly penalising water producing wells.

Altered evolution

Despite their low probability, Andra has explored possible disposal system malfunctions and external failures of human or natural origin. It has been verified that their consequences would remain acceptable. This analysis has been compared with the results of studies conducted at the international level:

- seal failure (drifts and B waste disposal cells) and defective plug (C waste and spent fuel disposal cells): very low impact, due to the layer low permeability and the proposed architecture,
- defective C waste and spent fuel containers: earlier manifestation of impacts, which are substantially the same as in the normal evolution scenario due to the retention properties of the geological medium,
- borehole penetrating the repository at various locations: effect limited to the impact zone, due to repository compartmentalization, sealing and rock properties.



Progression of selenium after 100,000, 500,000 and one million years

What radioactive dose might local populations be exposed to?

Andra has assessed radioactive doses based on penalising criteria. Iodine 129, chlorine 36 and selenium 79 are the main radioactive substances susceptible of reaching the environment in the very long term. Under current conditions as under the future predictable conditions in a million years, the dose is at least 10 times smaller than the limit of 0.25 mSv/year in the case of spent fuel, and 100 times smaller for B and C waste. Therefore, under severe hypotheses, the dose received would be 1000 smaller than natural radioactivity in the case of B and C waste.

> Very cautious parameters

To predict repository evolution, including in the normal evolution scenario, Andra has adopted cautious, even pessimistic parameters. For example:

> Repository located in the thinnest part of the Callovo-Oxfordian layer and at the greatest depth in the transposition zone.

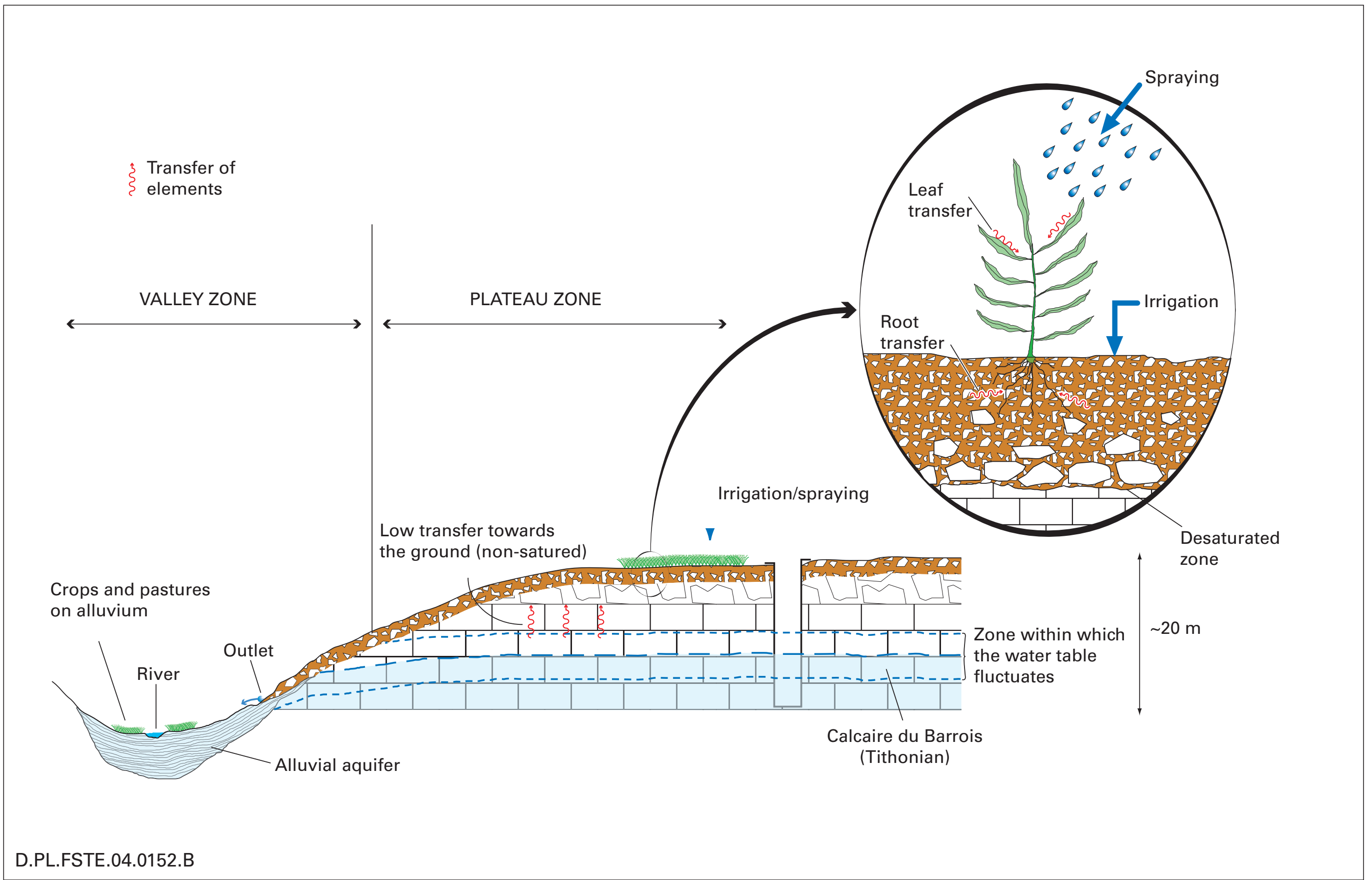
> For B waste, concrete overpacks assumed to be non-watertight.

> For C waste and spent fuel, overpacks with pessimistic lifetimes (4000 and 10,000 years, respectively) as compared to available data.

> Absence of retention properties in layers surrounding the Callovo-Oxfordian.

> Impact of chemical elements

Boron, selenium, nickel and antimony are elements susceptible of being present in high-level long-lived waste. The results of calculations up to a million years show that their impact is negligible.



Model of radionuclide transfers from the geosphere to the biosphere at the Meuse/Haute-Marne site

What would the dose be if all repository safety functions were degraded simultaneously?

Andra has also studied an extreme situation where all safety functions would no longer be normally ensured: permeability of rock and materials higher than expected, very low performance of seals, release of radioactive substances by all packages, and pessimistic values for transport and retention in argillite. The impact would still be smaller than the dose limit of 0.25 mSv/year.

In general, the incidental or altered evolution scenarios only produce a modest increase of the dose, which remains significantly below the regulatory limits.

Even in highly unlikely situations, geological disposal constitutes an efficient and robust concept to protect man and the environment from the waste emplaced therein.

Research on a repository in a granite formation

A global approach

Simultaneously with the research on clay, Andra has studied the possibility of a HLLL waste repository in a granite formation. From 1994 to 1996, it performed geological surveys to site an underground laboratory in the granite of the Vienne department. Following the recommendation by the French National Review Board (CNE), the Government authorities discarded this site. In 1999, the French Government organised a consultation mission to collect the opinions of populations in 15 sites deemed geologically favourable by a committee of national and international experts. This mission could not be completed, so the following year Andra set up a research programme to value the data acquired in foreign underground laboratories and in varied geological contexts.

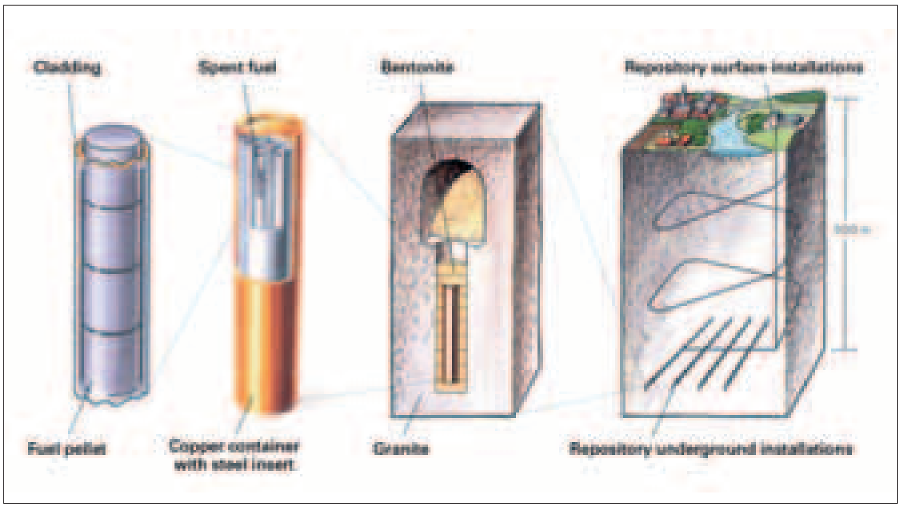
In the absence of a specific site, this research work was not able to assess the feasibility of a repository in a particular location. Its purpose was to assess the general interest of the granite medium and to propose generic concepts capable of meeting the long-term safety objectives within the French geological context.

The research covered four aspects:

- granite medium
- generic design of a reversible disposal system in a granite formation, i.e., architecture, waste conditioning, operation and closure, while sharing certain data used for the research on clay (particularly as regards packages and materials)
- repository evolution (thermal, mechanical, chemical and hydraulic)
- long-term safety analyses

Experimentation in the Äspö laboratory (Sweden)

Research on a repository in a granite formation



Swedish repository concept for the disposal of spent fuels in a granite medium

What knowledge has Andra acquired from foreign granite formations?

Large amounts of information concerning granite have been acquired at the international level. Andra has participated in experiments conducted in the underground laboratories of Sweden (Äspö), Switzerland (Grimsel), Canada (Lac du Bonnet), on the Olkiluoto site (Finland) and in Japan. The main cooperations have involved research on granite formations (geological structure, survey methods, underground water flows, rock capacity to retain radioactive substances), repository structures and safety analyses.

Scientific Co-operations

Andra has engaged in various scientific partnerships, namely with the French Geological Survey (BRGM), the French Atomic Energy Commission (CEA), the French National Centre for Scientific Research (CNRS) and the Paris School of Mines (Ecole des Mines de Paris), notably in order to transpose to the French context, the laboratory results obtained abroad . It has also relied strongly on research conducted in foreign laboratories, namely in Sweden and Switzerland, and has actively participated in studies conducted from the surface in Finland.

Dossier 2005 Granite

Andra has organised its knowledge on granite into five reference knowledge documents. Four of these documents are shared with the Dossier 2005 Argile (those concerning materials, radioactive substances and their migration). The fifth one contains the data available on French granite formations.

Three volumes summarise the knowledge acquired:

- proposal of generic options for safe and reversible disposal system architectures
- analysis of repository evolution
- safety analysis. In the absence of any specific site, the purpose of this analysis is to verify that none of the considered criteria rules out feasibility, and to identify the essential parameters to design a repository and to carry out the works at a possible site.

Characteristics of French granite formations

As in the case of clay, the repository study consists of identifying the characteristics of the geological medium and designing architectures based on these characteristics so as to confine the waste over very long periods, while meeting the reversibility requirement.

What properties are required for a repository?

In the absence of a specific site, the repository design is based on the shared properties of French granite formations.

Granite has interesting properties for an HLLL waste repository: hardness, resistance, low porosity, very low permeability and good thermal conductivity.

Most granite formations extend in depth, offering great flexibility for repository design.

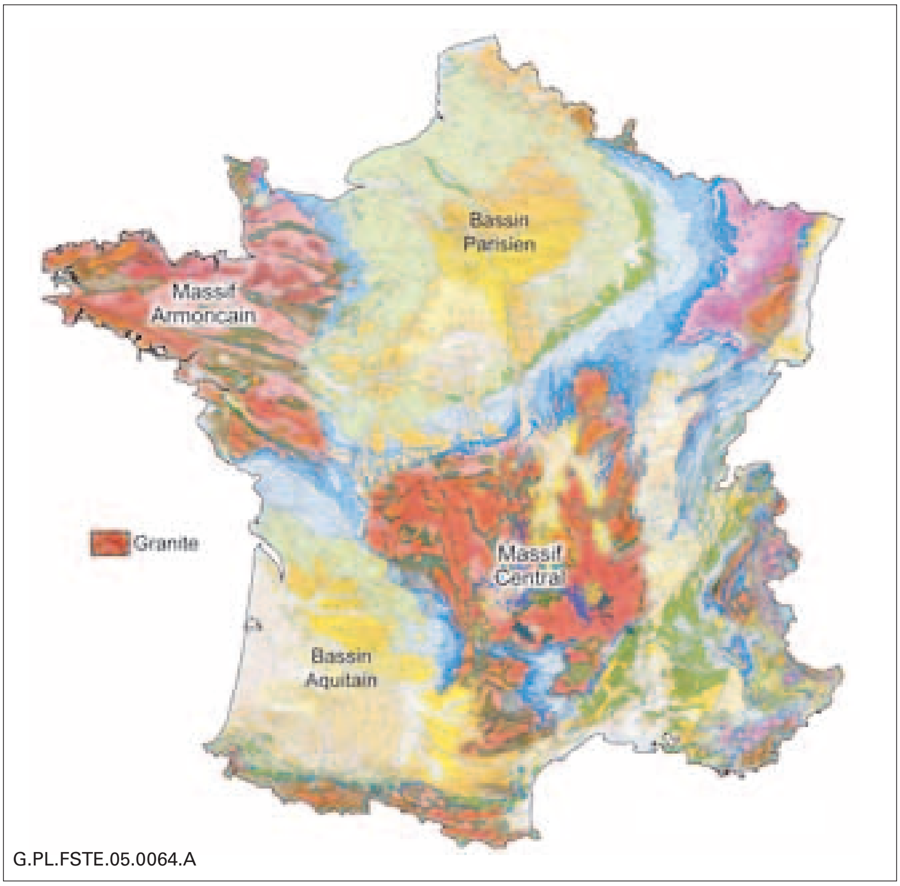
The possible variations in rock composition from one point to another in a formation do not significantly modify its properties. On the other hand, the fractures present in the granite massif must be taken into account. Small fractures (up to a few tens of metres long) can affect the rock local permeability. Faults (up to several kilometres long) are far less numerous and constitute privileged water transport pathways, but this transport occurs deep underground and slowly. Finally, the deep underground chemical environment in granite formations provides the preservation of repository materials and the immobilisation of most radioactive substances.

Different types of granite formations

The granitic zones studied were initially described based on surface mapping and on their deep underground characteristics extrapolated from geological knowledge and calculations. Andra then classified the French granite formations into different categories and appraised their properties for repository design purposes.

The differences between the French granite formations in terms of mechanical resistance and water composition do not put at stake the proposed design options. On the other hand, their thermal properties (for example, with temperatures reaching 17 to 30°C at a depth of 500 metres) can modify the repository dimensioning.

Large fractures are arranged differently depending on the formations.



Location of granite formations in France

Characteristics of French granite formations

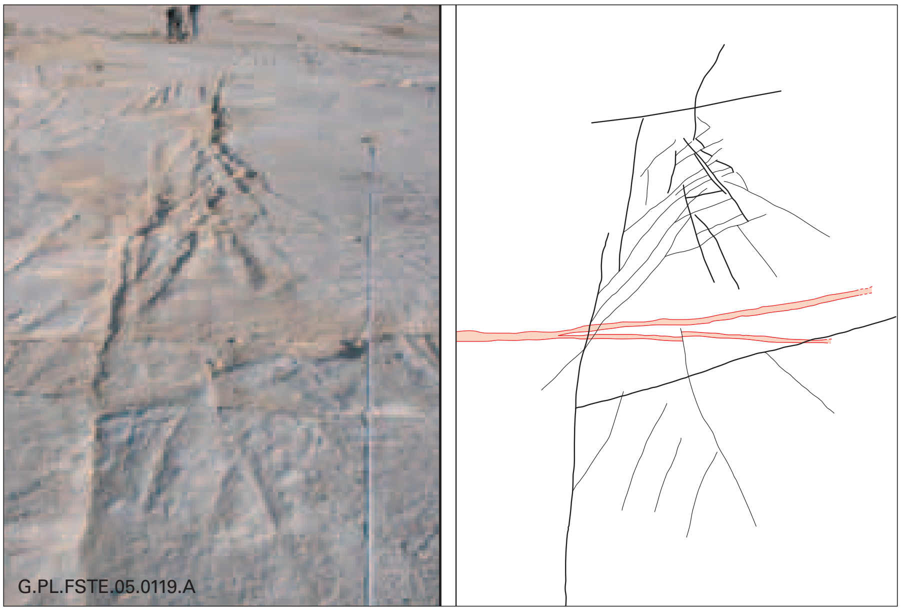
Nevertheless, the zones where a repository could be sited meet characteristics shared by all the French granite formations considered.

Three configurations of massifs were defined, this classification allowing architectures to be adapted and generic safety analyses to be conducted.

Where are the granite formations considered for these generic studies located?

In the absence of a specifically designated site, Andra has studied the various granite formations so as to determine their typology and assess their properties. These studies concerned 78 zones of over 20 km² each, located in the Massif Central and Massif Armoricain formations, quite apart from large faults.

Unfinished obelisk in the Assouan granite quarry (Egypt)



Details of a main fault structure

Can the presence of fractures rule out a repository?

Although fractures in a granite can allow water to circulate and therefore be detrimental, they also give rise to phenomena susceptible of immobilising or delaying the migration of radioactive substances. Indeed, radioactive substances can be entrapped therein, and clogging may also occur. In situ experiments, notably in the Äspö underground laboratory in Sweden, have allowed these phenomena to be understood. Nevertheless, the identification of "sound" (without faults) granite blocks remains of major importance, since such blocks may host a repository.

Repository installations

Repository design adapted to granite fractures

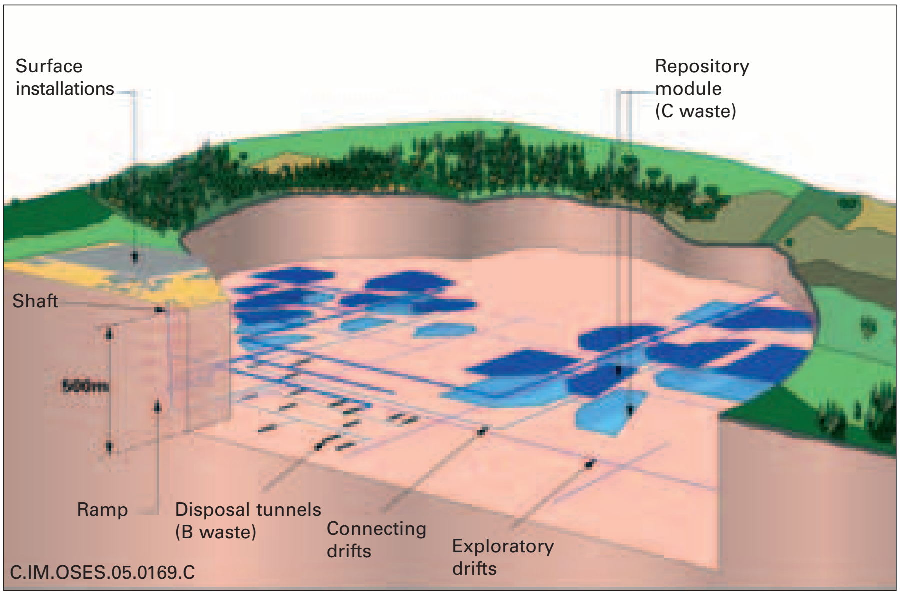


Diagram of a possible repository layout in a granite medium

Located apart from large faults, the repository is divided, according to waste categories (B, C) and spent fuel, in zones sufficiently separated from one another to prevent thermal or chemical interactions between waste packages. Each zone is divided into modules comprising a set of disposal cells. In order to limit water flow, these cells are implemented in granite "blocks" with very low permeability and no faults. The means of access (shaft and/or ramp) connecting the surface to the underground installations are implemented so as to avoid drainage of surface waters.

The thickness available at a depth of between 300 and 1000 metres provides the necessary flexibility to adapt the architecture to granite fracturing. The repository can thus be designed on two levels approximately one hundred metres apart.

Clay seals to prevent water flow

The drifts and means of access of the repository may encounter water conducting fractures. In order to limit water flows in the repository and delay the migration of radioactive substances towards the environment, the drifts and means of access are backfilled during their progressive closure. In keeping with the reversibility rationale, it will still be possible to reopen them and access the waste packages. Swelling clay seals are also implemented in the drifts at locations intersecting the faults. The disposal cells are sealed with low-permeability swelling clay plugs.

Waste disposal packages ensuring long-term leak-tightness

The packages delivered by waste producers are placed in containers to constitute disposal packages. The B and C waste containers are similar to those proposed for the clay medium repository (concrete container for B waste, steel one for C

Copper container demonstrator tested by the Swedish organisation SKB

waste). For spent fuels, Andra has selected the copper container adopted in Sweden and Finland. This spent fuel copper container concept is currently being tested at full scale in the Äspö laboratory (Sweden).

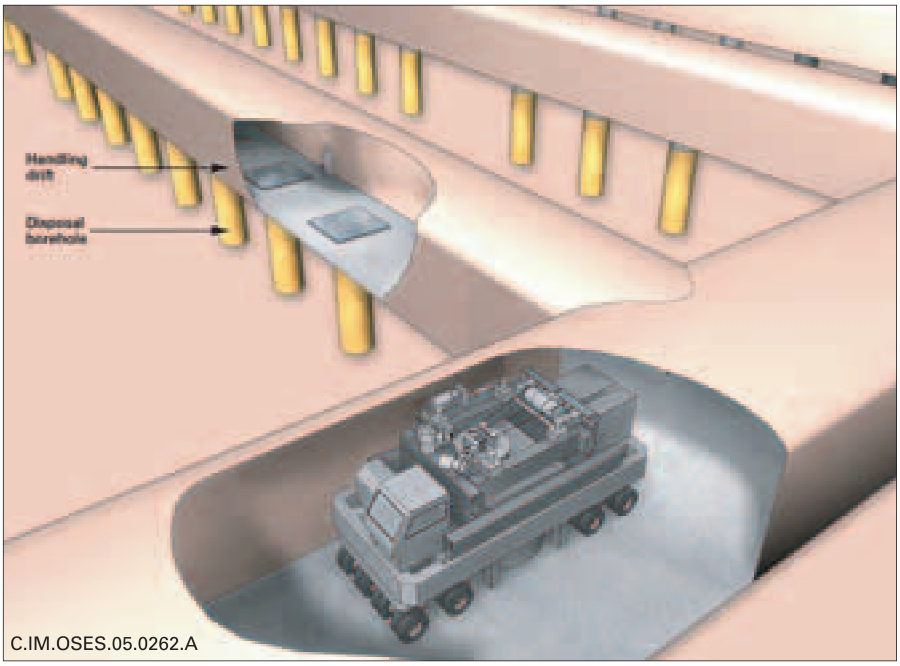
Physical and chemical environment favourable for waste packages

The C waste and spent fuel disposal cells are equipped with a swelling clay barrier that limits chemical contacts between waste packages and granite groundwater and provides shelter from small fractures. The materials constituting the repository, i.e., concrete, steel or copper (for the packages), swelling clay, backfill and seals, provide a favourable physical and chemical environment for waste packages and the retention of radioactive substances.

Architecture limiting the effects of heat

Granite is a resistant rock. The drifts and cells are designed to ensure long-term mechanical stability.

In order to control the consequences of the heat given off by C waste and spent fuel packages, the maximum temperature in the engineered structures is limited to 90°C by restricting the number of packages per cell and spacing the cells apart.



C waste repository concept in a granite medium

What would a disposal cell in the granite rock look like?

The proposed solution for the B waste disposal cell is a horizontal tunnel where packages are stacked in several rows. Its length (70 to 200 metres) is adapted to granite fracturing. It is approximately 10 metres high and 10 to 20 metres wide. Packages are handled by remote control and placed in the disposal cell through a safety dual-gate airlock. Once the cell is closed, the dual-gate airlock is backfilled and the access drift is sealed with a swelling clay plug (preventing water flow). A similar principle is being studied in Japan.

For C waste packages, the principle of a vertical borehole (12 metres long and 2 metres in diameter) has been adopted. This borehole receives between two and five packages, depending on the heat given off, and opens into a drift above. A swelling clay barrier is emplaced between the packages and the rock.

How would the drifts be organised?

The tunnels are implemented at a distance of several tens of metres from water conducting faults while the two-level repository concept makes use of the less permeable rock between the faults.

Is a disposal system in a granite formation safe and reversible?

The principles of safety and reversibility for a disposal system in a granite formation are similar to those for a disposal system in a clay formation.

At this stage, in the absence of a specific site, a detailed safety assessment cannot be carried out. However, the studies conducted so far have not identified any aspect ruling out the feasibility of a granite repository with regard to the long-term safety. For the reversibility requirement, it provides guarantees similar to those of a repository in a clay formation.

Status of progress and new perspectives

Fifteen years of considerable progress in research

Deep geological disposal has been investigated since the 1960's in Western nations. In France, research has progressed significantly since the 1991 Act, with all resources mobilised to produce solid scientific results. Quite significant results have been achieved in all fields of research, yielding a precise view concerning the properties of all repository components.

Assets of the Meuse/Haute-Marne site

In the case of research on the clay medium, highly detailed investigations have been conducted for over 10 years in the Meuse/Haute-Marne site. The underground laboratory has produced important data and constitutes an extremely valuable asset to supplement previously acquired results whenever decided.

Simultaneously with the programme conducted in France, the research performed in foreign underground laboratories has enabled the validation of Andra approach.

Mobilisation of leading scientists

Andra has mobilised the best laboratories available both in France and abroad for each field of research. The production of results has been discussed in accordance with the requirements of the scientific community and the aim for excellence. This guarantees the quality of the work produced.

Regular external assessment

Andra has called on external experts to benchmark its research with the best international practices. In 2002 and 2003, international experts reviewed the results of a scientific report concerning clay (Dossier 2001 Argile) and formulated very encouraging conclusions. Their recommendations were integrated in the Dossiers 2005 Argile and Granite.

The results achieved by Andra and its partners are published in international scientific journals and therefore subject to critical review by the scientific community.

The feasibility of a repository in a clay formation has been established

Favourable conditions in the Meuse/Haute-Marne site

The Callovo-Oxfordian layer has very interesting properties corresponding to those expected for a repository design in a clay medium. These properties are, a priori, met in an area of over 200 km^2.

Engineering studies based on cautious choices have defined simple and robust repository concepts adapted to the characteristics of the argillaceous layer.

Reversibility: a demonstrated priority

Andra has developed an approach beyond the mere possibility of retrieving the waste packages. It can be defined as the possibility of progressive and flexible repository management in stages, to give future generations a freedom of choice. In addition, Andra has decided not to set a predetermined duration for reversibility.

The reversible disposal system can thus serve two purposes. It can be initially managed as a temporary storage, with subsequent retrieval of the waste if so decided. But it can also be closed progressively so as to evolve in a safe manner without human intervention.

No significant impact on the environment

A major achievement of the research programme is the construction of the repository history over the next hundreds of thousands of years so as to understand the system evolution together with the risks and their associated uncertainties.

The analysis results show that the safety objectives have been met. The cautious, even pessimistic choices made allow for significant safety margins. These conclusions are valid for normal situations, but also for altered configurations (failure of repository components or intrusion into the repository).

The consequences for man and the environment comply with applicable regulations and recommendations, with significant margins.

Meuse/Haute-Marne underground research laboratory

A repository in a granite formation is conceivable

The studies concerning granite have shown that a repository in a French granite formation cannot be ruled out. In the absence of a specifically identified site, the analysis is based on the design of generic architectures. Various possible technical options for a reversible disposal system have been considered.

The research relies strongly on programmes developed in Sweden and Finland for a repository in a granite formation. Various experiments have been conducted in partnership with foreign laboratories.

The main uncertainty concerns the existence of granite sites without a too high fracture density, wich would be too demanding for the architectures.

After 2006: what perspectives for research on clay formation?

The research programme conducted over the past 15 years has yielded the necessary information to determine the basic feasibility of a repository in a clay formation. Nevertheless, uncertainties remain.

Without anticipating any decisions that the Parliament may deem necessary, various aspects must be considered in order to assess the perspectives provided by the research results:

- the experiments have been conducted over short periods of time. Legitimate caution suggests that experimental systems should be allowed to pursue knowledge acquisition over the next years,
- repository structures have not been yet tested in full scale. It would be useful to produce , in situ, disposal cell prototypes. An engineering consolidation plan would be necessary if it is decided to gradually focus on an industrial objective,
- a detailed survey of the zone covering over 200 km^2 around the Meuse/Haute-Marne site has not been conducted. Complementary investigations are required to determine the possible location of a repository within this zone,
- finally, certain repository components have been designed using simplified and particularly pessimistic models. Within the scope of a more finalised approach, it would be useful to quantify these safety margins and reduce the yet remaining uncertainties.

If the assessments confirm the relevance of Andra results and if the Parliament decides to pursue research on a geological repository in a clay layer, Andra could then carry on its activities within a finalised perspective.

Initially, the current basic feasibility phase would be followed by a development phase covering a period of approximately five years. This development phase would allow to both address potential issues raised by assessment experts in 2006 and focus on technological implementation.

As well, during this phase, the necessary information to site the possible location of a repository installation would be collected. For example, this could entail a seismic campaign covering a large zone. As far as the Meuse/Haute-Marne laboratory is concerned, it would constitute an essential asset to pursue data acquisition and conduct , directly in situ, technological tests.

This phase could conclude with an overall assessment. Assuming that scientific and technical results receive favourable appraisal, it would then be possible to advance to an industrial development phase. As an indication, such an approach could lead to the effective implementation of an industrial disposal facility by the year 2025.

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