BACKGROUND REPORT TO R&D-PROGRAM 86

Handling and final disposal of nuclear waste

Alternative disposal methods

September 1986

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HANDLING AND FINAL DISPOSAL OF NUCLEAR WASTE; ALTERNATIVE DISPOSAL METHODS

Background report to R&D programme 86

INTRODUCTION

The present report discusses the implications of the terms "alternative design" and "alternative barriers". Furthermore, different schematic methods for final disposal and different components that can be included in a system for final disposal are presented. The ideas for the different methods, components or designs come from many sources. Some have long been identified in Swedish or foreign discussions concerning the management of nuclear waste, others are concepts discussed within SKB or proposed by SKB's consultants for inclusion in the R&D programme.

The ideas have been compiled in the report without any attempt to identify their authors.

The choice of design and site for a final repository shall be based on a comprehensive body of information concerning, among other things, possible alternative designs. However, the research programme must also be oriented with regard to factors that are not dealt with in this report, for example development potential within different R&D areas, availability of validated models and verified data, opportunities for international cooperation etc.

An outline of R&D activities during the period 1987-1992 based on these premises is presented in R&D programme 86 /1/.

CONTENTS

1 BACKGROUND

According to the Act on Nuclear Activities, SKB shall see to it that the comprehensive research and development that is required for the safe handling and final disposal of nuclear waste is carried out.

This demand on comprehensiveness means that the R&D work shall cover both different possible waste forms and different methods for achieving an acceptable safety in handling and final disposal.

The R&D activities carried out to date have been based on certain premises and frames for the Swedish waste management programme. Some of these are also judged to be valid for the further R&D work. New premises are introduced as a consequence of the broadening of the scope of the activities. The present review of alternative methods for the final disposal of radioactive waste is based on the following premises:

- The Swedish nuclear energy programme comprises the operation of the 12 existing reactors until the year 2010.
- Final disposal shall be effected in a commonly occurring rock type in the Swedish bedrock.
- The R&D work shall provide a basis for effecting a final disposal with an acceptable safety for the society and good efficiency and economy.
- Long-term safety should not be dependent on surveillance or future corrective measures.
- Interim storage of the fuel is assumed to take place in CLAB.

Spent nuclear fuel is the only waste form discussed in this report. The research and development that is being conducted on waste forms or final disposal methods that are not being considered in Sweden will be followed to the extent that this knowledge is judged to be of value for Swedish waste disposal research.

A suitable final repository for spent nuclear fuel in crystalline rock must be demonstrated to be technically feasible, provide acceptable safety and be cost-effective.

Acceptable safety means that the final repository shall protect the biosphere from possible harmful effects of the waste by:

- radiation shielding,
- preventing harmful dispersal of radionuclides,
- preventing inadvertent intrusion.

Furthermore, final disposal shall be effected using methods that permit safe handling.

The R&D shall study different alternative designs for a repository system for spent fuel in crystalline rock, alternative means for achieving adequate safety in the repository and the costs of the various alternatives.

A near-surface final repository does not offer the same potential for long-term protection against dispersal of radionuclides and physical protection against human influence or intrusion as a deep repository. In order for such a facility to offer adequate protection, constant surveillance of the repository site is required. Facilities for final disposal that require a long period of surveillance are not regarded as *final* repositories in this context. However, some designs of the total system that include an initial period of surveillance will be discussed.

In the case of deep geological disposal in Swedish rock, groundwater is the only realistic transport medium for conveying radioactive materials from the repository to the biosphere. The transport of radioactive materials to the biosphere can be prevented, limited or retarded by means of employing a number of different principles:

- by preventing the water from coming into contact with the waste,
- by limiting the water flow around the waste,
- by controlling the solubility of the waste in the near field, and
- by controlling the transport of the radionuclides in the surrounding geosphere.

The release-limiting effects can be influenced via the repository's natural environment by the choice of repository site and via measures of a technical nature that control the near-field environment of the waste. Examples are different forms of treatment or conditioning of the waste and the construction of release-preventive barriers around the waste.

The cost of a final repository is influenced, not only by costs for safety measures as outlined above, but also by the design and location of the repository and by the engineering of parts of the repository that have no direct bearing on safety. Alternative designs and executions may include:

- The handling, form and conditioning of the waste.
- The execution of the engineered barriers.
- Adaptation of the repository to other parts of the nuclear energy system.
- The geometric design of the repository.
- The technical execution of construction, deposition and sealing.

A final repository can be designed in a virtually unlimited number of ways, all of which differ from the others in one or more details. The systematic review of alternatives has therefore been based on alternative designs of subsystems or elements that can be incorporated in the repository system. These can then be combined to give different systems with due consideration for the integrated performance of the elements and requirements on technical feasibility, adequate safety and good economy.

Systematics are discussed in Chapter 2, a brief presentation of the different alternatives that have been identified is given in Chapter 3, after which Chapter 4 summarizes the R&D work required in order to be able to compare the alternatives for the purpose of finally being able to define one or more feasible proposals for a practical final disposal scheme in Sweden.

2 SYSTEMATICS

2.1 General

There are many different principles that can be applied to design a geological final repository for radioactive waste. For all conceptual designs, adequate safety is based on the choice of site-specific premises and on the design of different release-preventive measures.

The release-preventive measures can be technically designed or executed in different ways.

The discussion of possible alternative repository designs has been systematized below in the following groups:

A - System design concepts.
B - Site-related alternatives.
C - Release-preventive measures.
D - Technical design and execution.

Naturally, any categorization of the alternatives involves areas where the borders between the groups are diffuse or where the groups overlap each other. For example, the choice of a conceptual system design is influenced by the sites that are available and the release-preventive barriers that must be built up in order to achieve a given level of safety. Similarly, different release-preventive barriers often have repercussions on the technical design, just as the quality of execution of a barrier has repercussions on the effect of its performance as a release-preventive barrier.

The intention here is, without exaggerated formality, to sort the alternatives into groups to which they primarily seem to belong. Alternatives listed are those judged to be worth investigating by virtue of their technical, safety-related or economic advantages.

2.2 Alternatives not dealt with

In addition to the alternatives dealt with further on in the report, there are a number of proposals on how final disposal should be executed that do not conform to the premises discussed in Chapter 1. Some of these alternatives will be briefly commented on here.

Final disposal with retrievability

The future residual value present in spent nuclear fuel - with respect to eg residual energy content, content of precious metals or unusual isotopes etc or with respect to the salvage value in the materials incorporated in the barriers - may diverge radically from the present-day value. It has therefore sometimes been suggested as a requirement that the repository be designed in such a way that retrieval of the waste is facilitated. Another reason given for retrieval is that the safety assessments may change in such a way that society wishes to alter the design of the final repository.

As far as Swedish conditions are concerned, it can be stated categorically that every form of final disposal in crystalline rock entails that the waste is fixed and, in principle, retrievable - in contrast to final disposal in salt and plastic clay strata. Depending on how the waste is conditioned and how the repository is sealed, however, the costs of retrieval will differ. The costs of retrieving the waste will change successively when the fuel is encapsulated, when the waste is deposited and when the repository is sealed.

One disturbing consequence of simplifying retrievability in the long-term storage phase is that these measures can also influence the passive barriers for isolation or retardation of radionuclides. The importance of this influence is system-specific.

With the 40-year interim storage of spent nuclear fuel in CLAB planned today in Sweden and with the possibilities that exist to prolong the storage period considerably, it is judged preferable to prolong the storage period in CLAB if reasonable doubt should exist as to the most appropriate method for final disposal of the spent nuclear fuel.

The value and costs of achieving different degrees of retrievability must be assessed separately for each design. Since a simple retrievability from CLAB now exists over periods that are considerably longer than the length of realistic economic forecast periods, it is not meaningful at the present stage to impose demands on greater retrievability. Such judgements can better be made at a stage immediately before the detailed design of the repository is to be determined.

As far as the safety argument is concerned, suffice it to say that a safety analysis of the long-term effects of final disposal cannot be accepted as reliable if it cannot be shown that it has been based on phenomena which are so well integrated in the basic body of scientific knowledge that any significant change must be regarded as unreasonable.

For the reasons given above, final disposal systems with retrievability are not dealt with as separate alternatives.

Disposal in deep-sea sediments

Internationally coordinated studies have long been conducted concerning the possibilities of disposing of radioactive waste in deep-sea sediments.

Since the main thrust of Swedish research has been in the direction of disposal on territory under Swedish control and with technology available within the country, deep-sea sediments are not judged to be an alternative that should actively be studied. However, similar problems and questions can arise in connection with a siting of a repository below the Baltic Sea, which is sufficient reason for following international research in this area.

Reprocessing of spent nuclear fuel

At present, Sweden has contracts for the reprocessing of nuclear fuel with clauses that give the reprocessor the right to return the radioactive waste to the country of origin. The possibilities of transferring these contracts are being explored. In this way, the final disposal scheme could be limited to applying to spent nuclear fuel alone.

Until SKB has succeeded in transferring these contracts, SKB must follow developments within the reprocessing field, including how different waste categories will be conditioned. These studies are influenced to a great extent by direct contacts with the reprocessor and with the reprocessor's other clients, and are therefore not dealt with here.

Even if all reprocessing contracts are transferred, SKB will still have an interest in following developments within the reprocessing field, particularly within the areas of actinide chemistry and fuel dissolution.

Transmutation

One of the fundamental problems with radioactive waste is that some of the constituent nuclides have very long half-lives. If such nuclides were to be separated and irradiated with neutrons, a considerable reduction of their half-lives could be obtained, although usually at the cost of a higher initial activity. This method of reducing the problems associated with the long-lived radioactive waste by means of transmutation of long-lived nuclides has sometimes been presented as an alternative to long-term waste isolation.

However, transmutation is not currently a commercially available method, nor is it expected to be until a large-scale introduction of fast reactors has taken place in the world. Transmutation requires access to most of the reprocessing technology as well as a development of chemical separation technology for special radionuclides (for example Np, Am, I, Cs, Zr, Nb).

In view of this state of affairs and the Swedish parliamentary decision to phase out Swedish nuclear enery production by the year 2010, transmutation is not judged to be an alternative of interest for the management of radioactive waste in Sweden. Nevertheless, the chemical advances made within the field should be of interest and will be followed.

Launching of radioactive waste into space

An alternative to disposal of radioactive waste in the bedrock would be to launch the waste into a stable orbit around the earth or the sun.

In order for this to be a realistic possibility in terms of energy, however, the less active material that dominates the mass of the spent nuclear fuel must be separated. In other words, large parts of a reprocessing process must be carried out before the waste is launched into space, just as in the case of transmutation.

Advances in space technology may make this method a realistic alternative in the future. But in view of the fact that development work in this field is closely tied to the aerospace industry and the reprocessing industry, the method is not expected to be the subject of research efforts in Sweden.

2.3 Sorting systematics

Following is a description of the systematics for sorting of alternatives that is applied in this report.

Group A - System design concepts

Ideas and system solutions for the final disposal of spent nuclear fuel that differ in principle from those previously investigated within SKB are discussed within this group.

Examples

- Systems with a much shorter or longer decay period prior to closure of the final repository.
- Systems for disposal above the groundwater table.
- Deep boreholes.

Group B - Site-related alternatives

The site-specific conditions that are of safety-related importance for a final repository vary within wide limits. But this variation is not random; many parameters are systematically coupled to each other, and once a site has been selected, a large number of natural environmental parameters have also been defined and set.

In practice, the site investigations cannot be controlled by the purpose of fulfilling precisely defined requirements on parameters of safety importance. Sites believed to have a generally suitable character must be investigated and the given parameter combinations that exist there must either be accepted or rejected en masse. For this reason, siting alternatives are regarded as a special group.

It is not meaningful to designate every possible repository site in Sweden as an alternative, since large numbers of potential sites are spread out virtually all over the country, and since there seem to be great similarities among the sites as regards geological and hydraulic characteristics. However, certain preconditions can sometimes be defined for a repository site that are so specific, or limit the potentially available sites to such a degree, that they can thereby be said to constitute distinctly separate alternatives. Examples are the alternative of locating the repository in Gabbro or the requirement that any leakage must always take place to salt water.

Other preconditions, such as tunnel stability or requirements on low gradients or low permeability, make such small demands or can be met in so many ways that most potential repository sites can be acceptable. In other words, they do not define distinct alternatives, but merely provide a number of possible variants for virtually all alternatives. Often, for example, geometric design and depth can be varied relatively freely within each site in order to meet such requirements.

Examples of factors that are dealt with in the group "site-related alternatives":

- Rock type.
- Surface conditions (topography, groundwater, recipient).
- Repository site.

Group C - Release-preventive measures

As mentioned in Chapter 1, transport with the groundwater is judged to be the only realistic mechanism that can carry significant quantities of radioactivity from the repository to the biosphere. Release-preventive measures can be divided into three main groups:

C1 Encapsulation of fuel.
C2 Limitation of groundwater flow.
C3 Limitation of radionuclide solubility.

Encapsulation of the spent fuel is done for the purpose of surrounding the waste with a watertight layer in order to prevent early contact with groundwater. Encapsulation alternatives are categorized according to material (for example metals such as Cu, Ti, Fe; ceramics such as Al_2O_3, TiO_2; composites). A canister made of a given material may have a number of alternative manufacturing methods, structural designs or sizes.

Limitations of the groundwater flow around the canister/waste can be achieved by means of different types of drained systems, by means of flow barriers of eg clay or by means of gradient-reducing methods such as hydraulic cages. For each alternative method, many variants can be obtained by varying the imperviousness and layer thickness of applied materials and by choosing repository depth according to the permeability of the bedrock.

Examples of alternative methods for limiting the groundwater flow in the near field are:

- Dry systems achieved by active or passive drainage, ventilation or liquid displacement by means of gas production.
- Flow barriers consisting of surrounding layers of low-conductive materials such as moraines, clays, $Mg(OH)_2$, cement.
- Injection of grout into fracture systems and sealing of boreholes, tunnels and shafts with plugs.
- Hydraulic cages around the repository or diversion of the groundwater through channels intentionally left open.

The solubility of different waste substances in groundwater can be limited by chemical conditioning of the zone around the waste, for example by the right choice of materials for the canister and the buffer, or by the use of additives in the near field aimed at binding specific substances or creating environments favourable for safety.

Examples are

- Filling of the cavities in the repository with uranium ore or depleted uranium.
- Fe(II) or copper powder in the buffer in order to control Eh.
- pH stabilization through bentonite buffer.

Group D - Technical design and execution

Certain alternatives for design or alternative methods for executing parts of the final repository system may be based on technical or economic considerations. Even though they are not primarily aimed at influencing safety, they constitute elements that must be taken into consideration by both the scenario assessment and the safety assessment.

Such alternatives may pertain to:

- layout, design of rock caverns, tunnels or deposition positions, technology for rock works (eg full-face boring, controlled blasting),
- transport, handling and deposition methods,
- utilization of tunnels for codeposition of low- and intermediate-level waste, decommissioning waste etc,
- methods for manufacture or application of barriers (different degrees of prefabrication versus application in place), chronological planning of construction, deposition and sealing (eg rapid versus gradual construction or sealing).

3 REVIEW OF ALTERNATIVES

A review of ideas or proposals for alternative principles, methods or elements in the final repository system is presented below in accordance with the systematics defined in Chapter 2. Each alternative is discussed according to the following outline:

1. Description of the principle of the alternative and how it differs from other alternatives, especially the one described in KBS-3.
2. The advantages/benefit and disadvantages/ restrictions that may be entailed by application of the alternative. Relationships with other system elements. What variants are possible with the alternative in terms of eg materials, dimensions or execution.
3. The knowledge gaps that must be filled in order to be able to judge the value of the alternative. The following aspects should be dealt with:
   - Technical feasibility,
   - Safety-related acceptance,
   - Cost and scheduling aspects.
4. An assessment of necessary research activities and their priorities.

3.1 Group A - System design concepts

List of alternatives:

A1 Earlier or later final disposal.
A2 Systems above the groundwater table.
A3 Deep-hole deposition.
A4 WP-cave.

A1 - Earlier or later final disposal

1 Principles

As a basis for planning, a 40-year storage period for the waste between discharge from the reactor and sealing of the final repository has been assumed in the R&D programme submitted together with KBS-3. This storage period allows the radioactivity and residual heat in the fuel/waste to decline.

Internationally, certain countries have striven for shorter interim storage periods (USA, West Germany), while others plan for longer interim storage (France, Great Britain). Shorter or longer interim storage periods have also been discussed in Sweden.

At the request of the National Board for Spent Nuclear Fuel, SKB has explored the consequences for planning, safety and costs of different timetables for the handling of spent nuclear fuel /2/.

2 Advantages and disadvantages

Interrupting interim storage earlier for waste conditioning and deposition would lead to higher radiation and residual heat from the fuel during handling. Extending the storage period would reduce these effects. The radiation field affects the shielding requirements during handling and can, via radiolysis, influence the solubility of the waste matrix in the event of early canister penetration. The temperature influences the groundwater flow and chemical equilibria in an initial phase and can also influence the long-term stability of certain buffer materials.

The study was based on the encapsulation and depositon method described in the KBS-3 report. It concludes that changing the planned deposition date from the year 2020 to either 2005 or 2080 does not lead to any clear time-dependent threshold effects in the technical or safety-related conditions. Deposition before 2005 is not judged to be practically feasible in view of the necessary planning and research. Postponing deposition substantially beyond the year 2080 may require dry storage of the fuel. No other safety-related effects of importance have been demonstrated.

3 Evaluations and assessments

Based on present-day grounds for judgement, it is found that an acceptable level of safety can be achieved regardless of when the first deposition is made after the year 2005. Technically, handling of the fuel in connection with encapsulation and deposition is simpler the longer the storage period is, as long as the fuel retains its integrity. Given a normal real rate of interest, the economic benefit of postponed investments outweighs the higher costs of prolonged operation of CLAB.

It should, however, be borne in mind that alternative repository design or barrier systems may be more sensitive to changes in the deposition date than the KBS-3 method is. In order to make it possible to optimize the deposition date within reasonable limits regardless of disposal method, the sensitivity of the different alternatives to variations in temperature and radiation field should be examined.

4 Research required

- The marginal costs of changes in those system parts that have a bearing on temperature should be reported. Examples are depth, amount of fuel per canister, deposition density etc.
- Further research should be planned for studying the effects of higher temperatures (for example 125 or 150°C) on geochemistry, buffer stability, corrosion, solubility and groundwater turnover. Some material is available abroad.
- Deeper studies of alpha-radiolysis in combination with higher temperatures and of how temperature-affected rock stresses influence the flow of groundwater in the near field.

Priority
Since a change of deposition date is possible for all alternative repositories, this alternative does not require any special research to be initiated, but requires that the sensitivity of the different alternatives to variations in temperature and radiation field be analyzed in parallel with evaluation of the alternative.

A2 - Systems above the groundwater table

1 Principles

The repository is to be situated in a geological formation that permits a depth of about 400 m or more and where topographical conditions also permit drainage by gravity to a large body of water.

Encapsulated spent fuel is placed in rock caverns that are ventilated by natural draught. The air dries the seeping groundwater and transports it from waste cavities towards colder drained cavities.

2 Advantages and disadvantages

As long as the waste heat generates enough air change to dry rock walls and keep the relative humidity <<100%, running water cannot affect canisters or liberate and carry anything away from the waste matrix. Ventilation and heating of the rock can cause surface loosening in rock walls. In the event of clogging of the drainage system, running water can fill the repository completely or partially.

3 Evaluations and assessment

Even if the drying effect only persists for a limited time and the repository site makes special demands on topography (mountain districts), the alternative can be combined with late closure and active drainage in other repository locations. Heating due to residual heat and ventilation of the rock caverns takes place in all alternatives in the initial phase. For these reasons, a repository design with ventilated cavities for canister should be studied.

Whether or not dry repositories are judged acceptable depends not only on technical feasibility, but also on how society regards the requirement of surveillance at facilities that are not backfilled and passively sealed.

4 Research required

- A clarification of society's attitude towards surveillance, possibilities of retrieval of the fuel and similar questions.
- Studies of canister corrosion under humid conditions.
- A study of ventilated repository layouts with heat conditions calculated for at least 1000 years.
- A study of effects of ventilation in rock shafts, surface loosening, long-term stability in tunnels and shafts etc.

Priority
The first point should be discussed during the next few years. Point 2 should be included among general considerations in the canister studies. See also A4 - WP-cave.

A3 - Deep-hole deposition

1 Principles

By depositing radioactive waste at great depth below the surface of the ground, it is possible to achieve such long travel times that the waste, for this reason alone, has time to decay or be diluted to a harmless concentration before it reaches the biosphere. Very great depths have often been discussed (5-10 km), but even a few kilometres could be of interest.

In order to reach these depths (5-10 km) from the surface with holes of sufficient diameter, powerful drilling rigs of the type used for oil drilling are required. Through loose soil strata and in fractured rock, the boreholes must be provided with some kind of lining (eg steel pipe), which may have to be removed before the borehole is sealed.

The waste to be deposited may consist of dismantled or chopped-up fuel rods, but also of fuel assemblies or high-level waste from reprocessing. The waste should preferably be placed in a canister. It should be possible to limit the requirements on the canister to what is needed for handling and lowering into the deposition hole.

No waste is placed in the upper part of the borehole, and after deposition the borehole should be sealed to the same imperviousness and durability as the surrounding rock.

2 Advantages and disadvantages

If the transport velocity in the rock can be proven to be sufficiently low, the entire safety philosophy can be based solely on the long travel time, a stable bedrock and a workable borehole sealing method.

With this method, all work can be done from the surface and from a central area from which the boreholes fan out with depth.

However, the method contains a number of uncertain factors, of which the most important are:

- our knowledge of rock conditions at these depths is very incomplete today,
- drilling of holes with the diameters described above in hard rock has never yet been done in the world. Russian drilling on the Kola penninsula should provide some experience,
- all handling of the waste must be done by remote control and in well shielded chambers above the ground.

3 Evaluations and assessments

The disposal method described may prove to be economically favourable. It may also be of interest to study deep-hole deposition at a depth of a few kilometres.

Drilling of holes of the diameters and depths in question may be associated with high costs. However, technology within this area is progressing rapidly in connection with oil drilling, and a long time remains until actual deposition will start. In addition to the large diameters, sufficient straightness must also be achieved in the drilling.

Unlined rock walls in the deposition zone may cause problems in connection with the lowering of waste bodies in the event of rock fall.

The risk of dropping the waste during lowering or the risk of the waste getting stuck must also be taken into account. The temperature at great depths may entail complications. The risk of criticality must be assessed.

4 Research required

- Qualified cost estimates must be carried out within an area where we lack reliable knowledge. International cooperation should therefore be striven for.
- Methods for investigating rock quality and groundwater conditions at great depths must be developed.
- Methods for handling of the waste both before deposition and during application in the hole must be explored.
- Methods for borehole plugging and backfilling should be analyzed.
- The risk of accidents such as dropped waste container, rock collapse in the hole and stuck waste canister in the hole must be analyzed.
- Effects of high rock temperatures (100-200°C) should be investigated.
- The risk of criticality must be estimated for different hole diameters and methods of technical execution.

Priority

An assessment of the potential for economic advantages should be able to determine the need for special research. The development of new technology for deep-hole drilling is judged to be so expensive and of such a long-term nature that SKB should merely follow the ongoing technology development that is being carried out for other purposes.

A4 - WP-Cave

1 Principles

WP-Cave is a repository concept where a large quantity of fuel (1500 tonnes of uranium) has been assembled in a repository cavern which is cooled in an initial phase by air circulation via heat exchangers /3/. The fuel is encapsulated in iron canisters (3.5 tonnes/canister) and placed in drilled holes on several levels emanating from a central shaft. The drilled holes are lined with iron sheet and the sheet is fixed to the rock with concrete.

After approximately 100 years, the cooling equipment can be removed and the repository is permitted to fill with water. Up to this time, the spent fuel is retrievable.

At a distance of about 20 metres, the repository cavern is surrounded by a 5 m thick, completely enclosing bentonite layer in order to prevent water flow through the repository. A further 20 m out, the facility is surrounded by a hydraulic cage consisting of regularly spaced boreholes emanating from an interconnected tunnel system. The purpose of this system is to equalize the hydraulic gradients over the repository.

2 Advantages and disadvantages

Owing to a longer active cooling period, a larger quantity of fuel can be emplaced per unit surface area in the rock without assumed temperature limits in the rock outside the bentonite layer being exceeded.

However, corrosion and temperature conditions during the water filling phase are difficult to quantify. Large quantities of spent nuclear fuel that can circulate in the system in dissolved or colloidal form constitute a difficult-to-estimate criticality risk.

A 5 m thick bentonite layer should provide long travel times for any radioactivity leaking to the flowing groundwater. This effect is reinforced by the fact that the hydraulic cage can reduce the hydraulic gradients and enhances the effect of film resistance. Hydrogen-forming corrosion of iron in the near field can give rise to pumping effects in the repository, which can cause outward transport of activity.

3 Evaluations and assessments

Since CLAB is already in operation and a storage there can easily be prolonged, the need of a further prolonging of retrievability is judged to be less interesting.

If different repository designs prove to be feasible at an acceptable level of safety, the cost is a main argument for allocating priorities. Realistic cost analyses should therefore be carried out here as well as for other alternatives.

As far as the technical basis for evaluating WP-Cave is concerned, certain assessments have been made within a project study ordered and paid for by SKN.

4 Research

- An overall cost study to determine the economic potential of the idea.
- An overall performance study of WP Cave during different time phases.
- Hydrogen-forming corrosion of iron (cf C1:2).
- Chemical effects of concrete on the repository's near-field environment and on the geosphere (cf C2:4).
- Design and long-term effects of hydraulic cages (cf C2:1).
- Corrosion and solubility in two-phase systems.
- Consequences of gas pressure buildup under a bentonite dome.
- Criticality calculations.

Priority

The overall studies concerning performance and costs are in progress within SKB today and will provide a basis for an allocation of priorities to the detailed research. Many of the elements or components included in the WP system or problems that need to be studied to assess its feasibilty are also elements or problems within other repository designs.

According to present-day planning, SKB's work will be concentrated on establishing the fundamental conditions for how systems with different materials interact during the long-term passive storage period. This will then serve as a basis for a comparison between alternative designs. The questions enumerated above are of central importance for the utilization of iron and concrete in many different repository designs. Only then are studies of sizing and optimization judged to be meaningful.

3.2 Group B - Site-related alternatives

List

- B1 Siting in gabbro.
- B2 Siting below salt water or brackish water.
- B3 Deposition in old oil reservoirs.
- B4 Deposition in old uranium mines.
- B5 Siting below CLAB.
- B6 Siting at the 1500 metre level.

B1 - Siting in gabbro

1 Principles
The repository is placed in the rock type known as gabbro. Repository depth and conceptual design can be the same as in the granite concept. Differences in detailed design of the barriers can be occasioned by differences in groundwater chemistry and groundwater turnover.

2 Advantages and disadvantages
As a rule, gabbro has lower thermal conductivity than granite and gneiss, which means that a repository for a given quantity of spent nuclear fuel must be made larger. This may, but need not necessarily, affect the construction costs.

Data from Sweden and Canada show that gabbro can, in terms of permeability, be at least equivalent to gneiss and granite at greater depths. It is possible that suitable gabbro deposits may be less permeable than those investigated so far.

Geochemically, gabbro can be expected to offer certain advantages, namely greater reducing capacity, higher reducing rate and higher sorption. Diffusion of the radionuclides into the rock matrix may, on the other hand, be less than in granite and gneiss. Gabbro may offer a better working environment in the repository with a lower risk of silicosis, a lower risk of cave-in, a lower radiation level and less radon in the "mine" air.

Other basic rock types, such as ultramafites, may exhibit similar properties.

3 Evaluations and assessments
Gabbro and similar rock types constitute a small portion of the Swedish bedrock. The number of gabbro deposits of sufficient size is limited, and many of them are located in areas far from existing nuclear power plants and good transport routes. This makes it more difficult to find suitable study sites than in the case of granite and gneiss. A prerequisite for low water flow is that the gabbro body is not intersected by other rock types. Homogeneous gabbro bodies appear to be rare.

One argument against a siting in gabbro is that ore finds have sometimes been made in these formations and in the contact zone with surrounding rock types. One criterion for site selection is to avoid rock types that may become workable in the future. It is easy to avoid known deposits. The possible presence of unknown ores not yet discovered should also be taken into consideration. However, this risk is reduced by the site investigations, where many of the most sensitive ore prospecting methods are employed.

The presence of ultramafites in Sweden is limited to the mountain regions, and these bodies are even smaller than the gabbro bodies. Workable ores are often found in connection with ultramafites as well.

4 Research required
Besides the geological investigations, siting in gabbro requires special studies of how the repository is to be designed in view of temperature conditions. The way in which the special groundwater chemistry influences the design of barrier systems must be analyzed.

Priority
In connection with the evaluation of previous results and experience on which R&D programme 86 has been based, the question of gabbro investigations has also been considered. The results of investigations and general experience of gabbro show that it is relatively difficult to find sufficiently large homogeneous formations among gabbro massifs. These massifs are furthermore relatively scarce in comparison with gneiss or granite areas. The benefit of further knowledge concerning gabbro is judged to be marginal, and further investigations of this rock type are not a prerequisite for the execution of final disposal.

Extensive gabbro investigations are therefore of low priority.

B2 - Siting below salt water or brackish water

1 Principles
The repository is situated in such a manner that escaping radionuclides could not reach the biosphere in any other way than by outflow to a brackish or salt water recipient. This prevents radionuclides from reaching humans directly via drinking water. With certain repository sitings, thicker clayey sedimentary rocks can also provide a separation between the surface water and the deeper-lying groundwater.

2 Advantages and disadvantages
The advantage of the alternative is that the normally important exposure pathways for radionuclides via drinking water directly to man or via drinking water and animals to man can be disregarded. Similarly, another exposure pathway, irrigation-vegetables-man, is of less importance. Moreover, a much better dilution is normally obtained in the primary recipient.

Owing to land uplift, the life of the Baltic Sea as a brackish water sea is difficult to estimate.

3 Evaluations and assessments
Being able in a safety analysis to disregard intake via

drinking water and irrigation of animals and vegetables can, together with the higher dilution in sea recipients, provide a 10-fold reduction of the estimated maximum individual doses.

Technically speaking, however, the alternative entails a more difficult site investigation with a greater risk of misinterpretation compared to siting alternatives where the surface of the rock is accessible for direct study.

Impermeable sediment strata can greatly extend the groundwater pathways along which leaking radionuclides can reach the biosphere. At the same time, they can also lead regional gradients from the shore far out underneath the seabed.

4 Research required

- A cost comparison should be made between accesses via tunnel and elevator shaft.
- An assessment of residual land uplift should be carried out.
- The criteria for acceptable safe final repositories should be clarified, particularly in view of the time spans over which normal scenarios are to be applied.

Priority - medium-high. Should be reevaluated if the studies of rock areas near the coast (for example at SFR or CLAB) provide sufficiently interesting results.

B3 - Deposition in oil/gas reservoirs in sedimentary rock

1 Principles

The repository is arranged in a depleted oil or gas reservoir, whose existence can be taken as proof that the rock above possesses very low permeability.

2 Advantages and disadvantages

The advantages are evident from the principle. Disadvantages: The impervious rock that contains the oil or gas has been penetrated by exploration or production holes. The stability of the structure may have been affected by the fact that the pressure conditions have been changed during the pumping-out process. High organic content in the bedrock.

3 Evaluations and assessments

Present-day knowledge of how depletion of an oil or gas reservoir affects the geological stability of the reservoir appears to be far too incomplete to permit a safety analysis.

4 Research required

A survey can be made of the experience of the oil and gas industry with stabilities in depleted gas reservoirs. Otherwise, there does not seem to be any need for other research than a general follow-up of the foreign programmes in which sedimentary rock types are being studied as possible disposal media.

Priority - low.

B4 - Deposition in old uranium mines

1 Principles

The repository is arranged in a rock type that is so rich in natural uranium that the deposition of spent fuel does not essentially alter the geochemical situation overall. Furthermore, a considerable dilution of the uranium-like radionuclides in the fuel is obtained through exchange reactions.

2 Advantages and disadvantages

The advantages are evident from the principle. In addition, solubility limits may be encountered due to uranium-saturated groundwaters.

Disadvantages

- The site may constitute an economically interesting natural resource.
- Swedish uranium deposits are usually associated with fracture mineralizations.
- Potential uranium mines studied to date are located near the surface.

3 Evaluations and assessments

In view of the phase-out of nuclear power decided on by the Swedish parliament, it would not appear meaningful to couple final disposal in Sweden to possible future uranium mines.

The scientific studies of the chemical effects that can be exploited of (eg slower uranium matrix dissolution, coprecipitation processes for the actinides) can also be motivated by the alternative C3:1, which involves backfilling empty cavities in the repository with depleted uranium or uranium ore.

4 Research required

General gathering of knowledge without any priority.

B5 - Siting below CLAB

1 Principles

The encapsulation plant and final repository for long-lived waste are located at or near CLAB (within approx 10 km) so that external transports can be avoided.

2 Advantages and disadvantages

Advantages:

- Cost savings on the order of SEK 3-4 billion are obtained, 1985 price level;
- There are no transports outside the facility (CLAB, encapsulation plant and final repository), which reduces the risks of transport accidents;
- The repository is located on a site where nuclear activity has already been established;
- Coordination gains can be made in the operation of all plants.

Disadvantages:

- Since only a limited area is available, less good geological and hydrological conditions would have to

be compensated for by means of more extensive engineered barriers.
- The construction work must be carried out in close conjunction with the CLAB facility under operating conditions.

3 Evaluations and assessments
Certain preliminary studies of the technical feasibility of such cositing indicate good possibilities for coordination. The final assessment of feasibility is, however, completely dependent on whether available rock in the vicinity of CLAB is acceptable from the standpoint of safety.

If the vertical shaft to repository level is replaced with a sloping access tunnel, the deposition area can be located anywhere within a 5-10 km radius of CLAB.

In view of the large potential savings that stand to be made by cositing with CLAB, possibly less good rock can be compensated for by locating the repository at greater depth (about 700-800 m) or by distributing the waste more sparsely over the repository surface compared to previously discussed alternatives. If a long access tunnel is driven out under the Baltic Sea, the siting offers the possibility of extremely low groundwater gradients and good dilution conditions in a brackish water recipient in the event that radionuclides should leak from the repository.

4 Research required
In order to be able to determine how realistic it is to locate a final repository together with CLAB, the following research is required:

- A detailed cost analysis of possible savings in encapsulation plants and the transportation system.
- A general bedrock survey covering an area within a radius of 10 km of CLAB in order to determine the general suitability of the area for locating a repository for spent nuclear fuel.

Priority - high

B6 - Siting at a depth of 1500 metres

1 Principles
Professor Markus Båth has proferred a theory that the properties of the Swedish bedrock, in terms of fracture frequency and groundwater turnover for example, undergo relatively rapid change at a depth of somewhere between 1200 and 1500 metres /4/. These views are based inter alia on the results of measurements performed in a number of refraction seismic profiles.

2 Advantages and disadvantages
Since groundwater movements in the canister environment are of great importance for both canister life and dissolution rate, it may be justified to take such discontinuities into account when choosing the level of a final repository. If a rapid improvement of the properties of the rock does occur, such information is of importance both in modelling of groundwater flow and in choice of the optimal depth for a final repository. The disadvantages are mainly related to a 15°C higher rock temperature at this level and higher costs associated with the construction of the repository.

3 Evaluations and assessments
Experts differ in their opinions in this regard. If discontinuities should be found to exist and if the hydraulic conductivity of the rock should be found to decrease much more rapidly than the previously assumed exponential decrease with depth, then the advantages of a reduced water turnover must be weighed against the more restrictive temperature conditions at the depth in question. Since the feasibility studies in the KBS-3 report have shown that a sufficiently low rate of water turnover can already be found at a number of locations in Sweden at a depth of about 500 m, the gain would appear to be dubious.

Another problem area is that greater local differences may exist in groundwater chemistry in areas with more stagnant water. This can make it more difficult to predict solubility and corrosion conditions if the stagnant state is disturbed by the construction of the repository.

Nevertheless, this question has been taken up for discussion and may also be of fundamental importance to our understanding of groundwater flow in rock. Research should therefore be conducted to investigate the existence of the discontinuity.

4 Research required
Research should be conducted to examine the scientific basis for Båth's theory, including certain experiments to verify or repudiate the interpretations. If the results should confirm the existence of Båth's discontinuity, a borehole should be drilled to a level below the discontinuity in order to permit an investigation of fracture frequency and hydraulic conductivity.

Priority
The first-mentioned research should be given high priority and be coordinated with the construction of an underground research laboratory. Some information on rock at greater depth is being obtained through an exchange of information with NAGRA.

3.3 Group C - Release-preventive measures

List

C1 – Canister materials.
  1. Passive materials.
  2. Corroding materials.
  3. Ceramics.
C2 – Barriers to flow.
  1. Hydraulic cages.
  2. Injection grouting of rock.
  3. Buffer stability.
  4. Concrete.
  5. NAGRA's gas embolism.
C3 – Limitation of nuclide solubility.

C1 - Canister materials

Introduction

The high-level waste, whether it be vitrified high-level waste from reprocessing or irradiated reactor fuel, requires enclosure in an outer container (canister) for basically two reasons. During handling of the waste in the deposition facility, the waste must be packaged in tight containers that prevent the escape of radioactivity. After deposition, it is furthermore desirable to guarantee that no radioactivity will leak from the waste during a given period of time.

The length of this period of zero release cannot be defined at the present time. Better knowledge of the properties of the waste, the hydrological/geological conditions in the bedrock and the dispersal of the radionuclides in the geosphere is needed in order to establish the optimal period for zero release. Accepted estimates span a very wide range, 10^3 - 10^5 years.

Depending on what length of time is striven for, a number of different canister materials may be considered. For practical reasons, the canister materials can be divided into the following classes:

a. Completely or partially thermodynamically stable materials (eg gold, copper).
b. Passive materials (eg stainless steel, titanium, Hastelloy, aluminium).
c. Corroding (sacrificial) materials (eg lead, steel).
d. Non-metallic materials (eg ceramics - Al_2O_3, TiO_2).

During the KBS work, copper has been the main alternative. But glass, ceramic and titanium/lead canisters have also been studied. The corrosion properties and manufacturing technology for a copper canister are relatively well known after the research work for the KBS-3 report, even though supplementary investigations still have to be carried out. During the next 3 years, the focus in the research activities for canister materials will lie on alternative materials, ie types b, c and d. Some follow-up of the possibilities of using composite-material canisters or sacrificial anodes will be done.

Regardless of choice of canister material, ie to some extent regardless of what period of time for absolute containment is striven for, both Swedish and foreign assessments and research results show that canister penetration will most likely be caused by local corrosion or delayed fracturing.

SKB will therefore concentrate its research activities concerning alternative canister materials on local corrosion and fracturing. The type of local corrosion that is most critical varies from material to material and is therefore dealt with separately for each material.

C1:1 Passive materials

1 Principles

Passive materials are being studied as potential canister materials in a number of countries: Stainless steel (316L) for the tuff repository in the USA, titanium (and titanium alloys) for salt repositories in the USA and granite repositories in Canada and Hastelloy in France. Since titanium has been studied previously in the Swedish programme and has moreover proved to have great advantages in the fact that general corrosion is very low, titanium has been chosen as a representative of the category of passive materials. Moreover, both the USA and Canada have large programmes for studies of titanium corrosion. The results from Canada in particular are directly applicable to Swedish conditions.

The general corrosion of titanium under repository conditions is extremely low, as has already been established by previous KBS investigations. Like all passivated materials, titanium can be sensitive to local corrosion.

2 Advantages and disadvantages

The general corrosion of titanium under repository conditions is extremely low. A titanium canister could therefore be made thin-walled, which provides great advantages in terms of both canister manufacture and sealing.

The greatest disadvantages with a titanium canister lie in the fact that titanium, like all passivated materials, can be sensitive to local corrosion, mainly crevice corrosion and hydrogen embrittlement.

In the use of Ti, as well as of Cu, the value of the material must be included in the assessments both for cost reasons and for the reason that the repository may come to be regarded as a future mine.

3 Evaluations and assessments

The technical feasibility of this alternative has already been explored in KBS-1 /5/.

General corrosion is so low that long canister life can be expected, provided that local corrosion can be ruled out. In the Canadian (AECL/WNRE) programme, which assumes a geology similar to the Swedish one, special attention has been devoted for a number of years to local corrosion, primarily crevice corrosion and hydrogen embrittlement. During the next few years, the influence of radiolysis on the corrosion and hydrogen embrittlement of titanium will also be investigated within the Canadian programme.

In view of the relatively large research programmes in the USA and especially Canada, the Swedish programme should be designed during the next few years to supplement the Canadian programme in particular. This should not entail any difficulties, since similar coordination already exists between these countries' programmes for studies of spent fuel. Moreover, an exchange of information already exists between Swedish and Canadian researchers within the framework of the cooperation agreement between AECL and SKB.

4 Research required

Considering the thrust of the investigations in Canada, it may be valuable, at least in an initial phase, to supplement these investigations with studies of the more fundamental aspects of titanium corrosion and embrittlement. Knowledge of these phenomena is important in order to be able to make reliable predictions of canister life.

For titanium studies, investigations of hydrogen embrittlement should be given priority. The comparative Canadian studies of pure titanium and Ti-12 (0,7%Ni, 0.3%Mo) have given indications of the focus of the programme.

Important points are:
- the influence of alloying elements on the corrosion rate for Ti-Ni-Mo alloys,
- the composition of the passive film on Ti alloys,
- the importance of the phase composition for general and local corrosion on Ti alloys,
- the composition of the metal phase during active dissolution,
- studies of the diffusivity of hydrogen in the oxides,
- studies of hydrogen reactions on different surface conditions,
- the importance of the alloy composition for the solubility of hydrogen in the alloy,
- reactions between radiolysis products (eg H_2O_2 and H_2) with Ti and Ti alloys.

Good Swedish resources exist within these areas.

As a first stage, prior to detailed planning of the research programme, a thorough review of the literature should be carried out. Contacts should then be established with AECL in particular, in order to define the areas where Swedish and foreign research efforts complement each other and where each country's resources can best be utilized.

Priority - medium-high, to be coordinated with other canister material research

C1:2 Corroding materials

1 Principles

Corroding materials are being studied as potential canister materials in England, Switzerland and the USA, among other countries. The principle is that although a thick-walled canister of such a material does corrode, it corrodes at a relatively slow rate and in a predictable manner in the repository environment.

For economic and production-related reasons in particular, carbon steel is the most interesting material within this category.

The corrosion properties of carbon steel are relatively well known and corrosion under repository conditions in granitic rock has been studied in England and Switzerland (cast steel).

2 Advantages and disadvantages

In terms of both material costs and manufacturing costs, carbon steel is a cheaper alternative than the reference material, copper.

The disadvantage is its considerable higher corrosion rate. However, a better understanding of such factors as radionuclide dispersal and retardation in the geosphere as well as a deeper knowledge of the leaching properties of the spent fuel may show that the extremely long canister lives that can be obtained with copper are not necessary from the standpoint of safety. Reducing conditions are guaranteed, which is advantageous with regard to the outward transport of actinides and technetium.

3 Evaluations and assessments

Technically speaking, the manufacture and sealing of a steel canister should present fewer difficulties than is the case for the copper canister.

Experimental data obtained abroad show that the corrosion rate under repository conditions may be acceptable. However, to establish the service life of a canister made of corroding material, long extrapolations from short-term experiments in laboratories or in-situ tests are required. Such extrapolations are only justified if they can be supported by a sound mechanistic understanding which can serve as a basis for mathematical models for the corrosion processes involved. Models must be able to be tested and validated against short-term experiments of various kinds.

For materials such as steel, models of this kind are essential not only for general corrosion, but also to a high degree for pitting and crevice corrosion.

4 Research required

The development of models for corrosion of carbon steel has been begun at Harwell in England, mainly with a focus on low- and intermediate-level waste. The results have been promising. It would be fruitful to apply the experience gained at Harwell to a Swedish final repository.

The modelling and the experimental programme required for such models should be complemented with specific studies of the corrosion of steel under reducing conditions. Competence and resources for doing this are available at Swedish universities and research institutes. Of particular interest are the kinetics of hydrogen gas evolution in connection with the corrosion of iron under reducing conditions, especially in the presence of sulphides.

Priority

In view of the fact that steel is an attractive material from the standpoint of both manufacture and economy, studies of steel corrosion are judged to have high priority.

C1:3 Ceramics

1 Principles

Ceramics as canister materials have previously been studied in KBS-2, and work is also being pursued in Switzerland and Canada.

Ceramics, such as Al_2O_3 and TiO_2, "corrode" or dissolve extremely slowly in groundwater and could theoretically provide very long-lived canisters.

Moreover, the raw materials for ceramics are cheap compared to the metals that may be used for long-lived canisters.

Since Al_2O_3 has been studied previously in the Swedish programme and a basic competence has evolved, this material should be chosen for further studies. TiO_2 may be suitable as an alternative material. This material has also been studied in recent years in Sweden as a potential canister material, and the competence that has evolved in these studies should be exploited.

Concrete has long been used as an encapsulation material for low- and intermediate-level waste. An encapsulation of fuel channels and the like in concrete is also described in KBS-3. A further investigation of the possibilities of using concrete as a canister material primarily requires studies of the consequences in the near field and the geosphere to which the highly basic conditions created by concrete leaching give rise (see C2:4).

Foreign R&D will naturally be followed for other ceramics as well.

2 Advantages and disadvantages

Ceramics can be highly durable in groundwater and can be used to make canisters with a very long life. Moreover, the raw materials are generally inexpensive, providing the manufacturing technique does not make high demands on purity.

Disadvantages are complicated manufacture of the canister and, above all, sealing. Due to their brittleness, ceramics also require more careful handling during deposition etc.

3 Evaluations and assessments

Previous KBS studies have shown that manufacture and sealing are technically feasible.

Experimental investigations show that the chemical resistance of ceramic canisters is extremely good.

Previous Swedish investigations have shown that delayed fracturing is probably the greatest problem.

4 Research required

To begin with, efforts should be focussed on clarifying mechanisms for delayed fracturing in the repository environment. There is good reason to assume that at least certain mechanisms are independent of the material.

In order permit acceptable predictions to be made of the life of ceramic canisters, the study of mechanisms for delayed fracturing is being given top priority.

Compared to metal canisters of alternative materials, however, ceramics are judged to have lower priority.

Studies of the effects of high pH are discussed in Section C2:4.

C2 - Flow barriers

C2:1 Hydraulic cages

1 Principles

In connection with final disposal of radioactive waste in rock, groundwater is the only realistic transport medium up to the biosphere. By establishing man-made water flow paths in the rock around the waste, it is possible to reduce the hydraulic gradient over the waste's near field and thereby reduce the turnover of groundwater in the region.

2 Advantages and disadvantages

A lower groundwater turnover in the waste's near field reduces the quantity of corroding substances that can be transported to canisters in the repository. At the same time there is a reduction of the rate of release from the waste matrix of substances that are bound in the matrix or that are solubility-limited. The difficulties are associated with uncertainty as to how effectively a limited number of boreholes can couple fracture systems with different pressures, how long established flow channels can be kept open and how effectively fracture systems with channelling can be short-circuited.

3 Evaluations and assessments

Even if the long-term stability and function of hydraulic cages is doubtful, the "short-term effect" (ie the effect during the first 1000 years) should be so favourable that this application should be studied for different geometric designs of the repository. It is possible that not even the short-term effect can be quantified in the safety analyses until the fracture zone studies have created a greater understanding of what fractures and fracture zones look like and how clay fillings and mineralizations influence and alter the flow of water.

The design of a hydraulic cage should particularly take into account the risk that clogging of a channel can give rise to a more unfavourable gradient situation in the waste's near field than the one which originally existed.

4 Research required

A preliminary study of the design of hydraulic cages and their effects should be initiated. A detailed study may need to apply the results of the fracture zone study.

Priority - medium.

C2:2 Injection grouting of rock

1 Principles

Rock fractures close to deposition holes, boreholes, tunnels and shafts are filled by means of injection grouting with material that prevents groundwater flow.

2 Advantages and disadvantages

Groundwater flow in the near field of the waste can cause migration of substances harmful to canisters or of radionuclides. The injection of sealant material in rock fractures prevents groundwater flow. Such injection grouting of the rock around deposition holes is a method that effectively prevents flow with the use of small quantities of material and can reduce the requirements on untreated rock.

Injection grouting of rock that surrounds sealing plugs in shafts, boreholes and tunnels can increase the effectiveness of these barriers to groundwater flow. Only small possibilities exist, however, to check the filling of groundwater-conductive fractures precisely with known technology.

Injection at high pressure into the fracture systems in the rock can lead to irreversible widening of fractures.

3 Evaluations and assessments

A suitable fracture grouting method and knowledge of to what degree it is possible to seal fractured rock can lead to altered judgements of what is regarded as acceptable rock in both the stage of selection of a geological formation and in the stage of constructing the repository. The focus should be on research and development of methods for the repair of disturbed zones around shafts and deposition holes and treatment of those regions of poorer rock that are penetrated by plugged exploratory boreholes.

4 Research required

- Laboratory studies of fracture grouting materials including their rheology and chemical-mechanical stability. Both synthetically prepared materials and geological materials should be included.
- Method development for injection grouting in the laboratory and in the field.
- Development of methods for monitoring and inspection of rock mass during grouting.
- Studies and experiments concerning long-term stability and long-range interaction with fracture-filling minerals or materials in the near field.

Priority - medium to high, and adapted to possible interest for international cooperation.

C2:3 Buffer materials

1 Background and principles

Highly compacted bentonite is a swelling buffer material that can be used in connection with the final disposal of high-level waste or spent nuclear fuel according to NAGRA and KBS. By surrounding the canister completely with a swelling clay, an impervious barrier is obtained against groundwater flow up to the canister surface. All transport through the barrier must take place by means of diffusion processes.

Owing to the residual heat in the fuel, the bentonite will be subjected to a temperature rise dependent on the quantity of waste in the canister, the thermal conductivity of the materials, the geometry of the deposition holes and the design and geological conditions of the final repositories. Smectite, the main constituent of bentonite, can be transformed to illite with reduced swelling capacity and higher hydraulic conductivity as a result. Knowledge of the kinetics of the smectite/illite transformation and possible thermodynamically stable phases in mixed layering of illite/smectite is essential for quantitatively describing the effects of temperature. The ratio between K^+ and other cations plays a role in available models.

Limitations in the stability of the buffer materials caused by temperature constitute important premises for repository design. Alternative designs, where the flowtight layer is located at a given distance from the canister in order to permit higher temperatures at the canister surface, or materials with higher temperature resistance should be evaluated.

2 Discussion

The degree of illitization of bentonite varies depending on the combination of temperature and time, so that a high temperature peak of short duration can be equivalent to the effect of a relatively low temperature over a long period of time.

The consequence of illitization is reduced swelling capacity and increased hydraulic conductivity. The conductivity increase can be estimated to be a couple of orders of magnitude under compact conditions and for complete illitization. Other effects may also occur, eg mineral alteration, which gives cementation and lower pH. Knowledge of these effects should be increased in order to permit a more accurate evaluation.

The supply of potassium is usually so small that complete illitization takes such a long time that it can be neglected in practice.

3 Research required

- A systematic survey of different possible buffer materials is already under way.
- Further studies need to be carried out as regards the limitations on temperature that need to be established for different applications and buffer thicknesses.
- In order to permit a detailed sizing of buffer layers that can be allowed to degrade to some extent, temperature modelling must be improved.
- The effect of various additives aimed at controlling chemical conditions in the near field must be clarified (cf C3).

Priority - medium.

C2:4 Concrete

1 Principles

In most studies carried out to date of how a final repository should be arranged, the use of natural materials with high, geologically proven stability is striven for.

In the everyday use of building materials, however, certain man-made products have proven to be so suitable for different purposes that they are used virtually everywhere.

If concrete can be shown to be acceptable in the repository, an established casting technique could be used for deposition of the waste canisters and for backfilling of rock caverns in the repository.

2 Advantages, disadvantages and evaluations

Large quantities of cement, mainly of the Portland type, are already being used for encasement of low- and intermediate-level waste.

The chemical environment in water-saturated concrete is such that most important radionuclides have lower solubility and are sorbed more easily than would be the case in the undisturbed groundwater environment. The reason for this is the high pH, which is due to the presence of calcium hydroxide and small quantities of alkali hydroxides.

A passing of the dissolved radionuclides from the pore water in the concrete to the groundwater in the rock is not expected to give rise to colloids, since the rock-groundwater environment generally has higher solubility (and lower sorption) of radionuclides.

Owing to its high content of calcium hydroxide, the concrete acts for a long time as an effective sink for carbonate ions from the groundwater. This reduces porosity, prevents carbonate complexation and provides the conditions necessary for coprecipitation of eg strontium and radium.

Organic surfactants are added to the concrete to give it the desired technical properties. The sorption tests that have been conducted do not indicate any negative effect of this treatment. Over the very long time perspective, however, the importance of such additives for radionuclide chemistry, canister corrosion etc must be analyzed and evaluated.

Bacteria that attack concrete are known, eg thiobacillus concretivorus. However, in addition to hydrogen sulphide, this also requires plenty of oxygen and should therefore not present any problem in a final repository. It may be a good idea to examine the microbial importance of any additives to the concrete.

The structure and composition of the different chemical phases that hold together the solidifying concrete are far from well known, despite the fact that concrete is such a common structural material. The occurrence of persisting slow processes, such as continued hydration and crystal growth, cannot be ruled out. It is difficult to foresee what this may mean for the strength and shape stability of the concrete in a very long time perspective. Structural concrete of the modern type has not existed for more than about 50 years.

Many of the components of concrete are relatively readily soluble and even strongly reactive, eg calcium hydroxide. In the long run, this may be of importance for the mechanical properties of the concrete.

A high pH from the cement can affect other encapsulation and backfill materials and possibly also the host rock.

3 Research required

Long-term stability

The studies that have been made of 70-year-old concrete from the wall of a power station tunnel for water in Porjus indicate that the changes are very small /6/. Nothing particularly remarkable is found in the crystal structure, nor does calcium hydroxide appear to have been dissolved out or carbonated to any great extent, despite the large amount of water that has run past the tunnel wall over the course of the years.

It should not be impossible to set up models of how concrete can be altered chemically or even structurally based on the transport conditions in the near field. Such a modelling should be based on laboratory investigations of "old" concrete in order to obtain reasonably realistic alteration rates.

Strength and fracture content are nearly impossible to judge in the long time perspective. Here it will undoubtedly be a question of very conservative assumptions. The chronological development of chemical properties in the concrete and chemical influence on the environment as well as porosity should, on the other hand, be predictable.

The possibilities of developing new types of concrete with clay or special additives should be explored.

Near-field chemistry

The importance of the concrete's high pH needs to be analyzed. The effect of high pH on groundwater, backfill and encapsulation material can be analyzed theoretically and experiments are not needed to begin with.

It should be possible to predict the effects of the groundwater on the concrete, for example carbonation, with the aid of transport calculations and what is known about chemical effects on the concrete and groundwater composition.

Sorption

What particularly needs to be investigated is the importance of the chemical effect of the concrete on sorption in the surrounding rock, ie whether the calcium ions, hydroxide ions, organic additives etc that are liberated from the concrete can seriously disturb the normal sorption processes out in the rock.

Priority - high, and coordinated with research for SFR and WP-Cave. Similar studies abroad, mainly for operating waste from power reactors and alpha-emitting waste from the reprocessing process, should be monitored (cf D3).

C2:5 NAGRA's gas embolism

1 Principles

In the Swiss final repository concept that is presented in "Project Gewähr", thick-walled iron canisters are proposed for the high-level vitrified waste from reprocessing in France. Iron corrodes with the formation of hydrogen in an oxygen-free environment. The bentonites, which are proposed in the Swiss concept as backfill material, have low diffusivity to hydrogen. A high concentration of hydrogen next to the canister surface has an inhibiting effect on the corrosion, but it is unclear whether it is stopped completely. The possibility can therefore not be ruled out that hydrogen gas will build up at the surface of the canister and form "bubbles".

NAGRA has discussed a solution for "Project Gewähr" where the canister is surrounded immediately adjacent to its surface by a layer of sand with such a grain size that the hydrogen gas displaces the water around the canister /7/. When water can no longer reach the canister, except for small quantities of moisture in the form of water vapour, the corrosion process will cease.

This solution has not been completely evaluated. But the idea is interesting and should be examined more closely and developed, possibly in cooperation with NAGRA.

2 Research required

The described idea should be studied in greater detail, possibly in combination with different buffer materials (C2:3) and the study of iron canisters (C1:2).

Priority - medium.

C3 - Limitation of nuclide solubility

The buffer material in a waste repository fulfils several functions:

(1) Mechanical barrier - capacity to take up movement
(2) Heat-conducting medium
(3) Barrier against free water exchange - flow barrier, diffusion barrier
(4) Chemical barrier

Bentonite was chosen as a suitable buffer material at an early stage in the KBS project. Bentonite fulfils criteria (1) - (3) above, but is also acceptable according to (4). However, no systematic studies of possible alternative materials or attempts to optimize the function of the bentonite by the use of additives have been made within the KBS project. Some suggestions on possible additives etc for the purpose of chemically altering the near-field environment of the waste in a favourable way are presented below.

1 Additives to bentonite

Additives can improve the function of the bentonite as a chemical barrier. Naturally, the mechanical properties of the bentonite, as well as changes in stability etc as a result of the additives or high pH, must be studied. Concentrations being considered are 0.5-1%.

1.1 pH and carbonate control

The retention of actinides in particular can be improved if the pH can be kept at a high level, provided the carbonate content is limited at the same time. High-capacity materials such as bentonite have a considerable pH-buffering effect. As a rule, the pore water has a pH above 9, which is advantageous. However, the carbonate content of the pore water appears to be regulated by the solubility product for calcium carbonate, which can lead to high carbonate contents at low calcium contents. An additive that gives both high pH and good carbonate control is needed. High calcium concentrations might affect the bentonite's mechanical properties.

A survey should be made of the effects of adding sulphate-free cement (calcium silicate - calcium hydroxide - calcium aluminate); the cement environment buffers the pH to above 12.5, and the carbonate concentration is, as a rule, $<10^{-6}$M.

1.2 Eh control

For the multivalent actinides (U, Np, Pu), as well as for Tc, it is advantageous if they exist in their lower oxidation states. The redox potential should be brought down to $E < 0.25\text{-}0.06\ \mathrm{pH}$ (V) in the backfill material.

Priority should be given to studying the effects of the following additives:

Additions of Fe(II) (<1%) in the form of:

☆ $Fe_3(PO_4)_2(s)$ (vivianite),
☆ Fe(II) silicate (natural Fe(II) silicate mineral),
☆ $Fe_3O_4(s)$ (possibly slow kinetics),

☆ UO_2 (reduces other actinides!).

Addition of metal:

☆ Pb,
☆ "Stainless" steel, iron.

Metals and metal compounds should also be able to serve as sulphide traps. Sulphide, which may be formed from sulphate through microbial activity under reducing conditions, is limited by the solubility product of the corresponding metal sulphide. The risk of gas-evolving corrosion and its consequences must be taken into consideration.

1.3 Chemisorption - complexation

The addition of chemisorbing substances or selective sorbent materials could reduce the mobility of individual elements. Coprecipitation phenomena can also be of importance here.

The following additives, in concentrations of less than 1%, should be given priority:

- Phosphate mineral; sorbent for actinides.
- Attapulgite; potential sorbent for actinides.
- Heavy metal compounds such as Pb, Cu and As can constitute potential sorbents for iodine (poor experimental verification) or sulphide.

2 Alternative materials

The main disadvantages of bentonite are that

- the material is not thermodynamically stable under all conceivable repository conditions.
- a release of colloidal particles under certain chemical conditions cannot be ruled out; these particles can serve as radionuclide carriers. An inventory of alternative materials should be made (cf C2:3).

A clay with high ion exchange capacity and good uptake of actinides and cesium, and probably with acceptable mechanical properties, is illite. Illite represents a more stable phase than montmorillonite under the chemical conditions that are expected to prevail; a transformation of montmorillonite to illite is, incidentally, conceivable in the repository environment. A mixture of eg bentonite/illite (or 2-layer barriers) should be evaluated.

As a rule, amorphous oxides are transformed to crystalline phases or chemically to new compounds with consequences for the mechanical properties of the buffer. An inventory should be made of possible oxide materials. One interesting material is concrete, for example in combination with a plastic clay barrier. The mechanical properties of the concrete might possibly be improved and porosity reduced by small additions of sheet silicates (montmorillonite, illite) to the concrete. (Cf C2:4)

3 Research required

According to the above discussion, the effects of the following additives to bentonite or other buffer materials should be evaluated:

- Sulphate-free cement for pH buffering and reduction of dissolved carbonates in the groundwater.
- Fe(II) in the form of $Fe_3(PO_4)_2(s)$, vivianite natural Fe(II) silicate or $Fe_3O_4(s)$.
- UO_2 (cf B4) or metals (such as Pb, Fe) for control of redox conditions.
- Phosphate mineral or attapulgite as sorbents for actinides.
- Heavy metal compounds as sorbents for iodine.

Alternatives to bentonites should also be studied with the above function in mind. Examples:

- Bentonite/illite in mixture or as two-layer barrier.
- Non-crystalline oxides.
- Concrete.

Priority - medium to high

3.4 Group D - Technical design and execution

Even though certain parameters in the design of a repository may be fixed by safety-related considerations, there are others that can be selected or adapted for the purpose of cost optimization of the repository design. An example of this in the KBS-3 method is the geometry of the repository and the distribution of deposition holes in it. If the deposition tunnels are spaced far apart, their mutual heat effects will be less. This permits a larger quantity of waste to be emplaced in each deposition hole without the temperature limits being exceeded and permits the length of tunnel excavated per tonne of waste to be reduced. Similarly, it is possible to reduce the excavated volume by drilling vertical or horizontal deposition holes between widely spaced tunnels, and then emplacing a number of waste canisters in a row.

Most such possibilities for optimization are affected to a high degree by site-specific conditions. There is, however, an inherent interest in knowing the maximum possible gains that stand to be made by means of such optimizations. Cost comparisons of different designs will therefore be made without the designs being designated directly as alternatives.

Another type of optimization can be illustrated with the following example based on the KBS-3 concept.

If a repository system does not offer a sufficiently high level of safety, the performance of the safety barriers can be improved by:

- increasing the wall thickness of the canister so that more canister material has to corrode before penetration occurs,
- increasing the thickness of the buffer so that the interaction of the canister and the waste with the groundwater is reduced, resulting in longer canister life and slower waste dissolution,
- increasing the depth of the repository so that the travel distance of the groundwater to the biosphere is longer, at the same time as the rate of water turnover in the rock around the waste decreases,
- a combination of these measures.

For such optimizations, the marginal safety effects of altered barrier dimensions or execution must be determined for the alternatives studied.

In addition to background information of the above general character, a number of specific design alternatives to the KBS-3 method can be defined as examples of technical design of deposition, barrier manufacture and practical handling.

List
D1 - Canister deposition in the tunnel.
D2 - Sand-filled canisters.
D3 - Emplacement of low- and intermediate-level waste in SFL.

D1 - Canister deposition in the tunnel

1 Principles

Canisters for spent fuel could conceivably be emplaced in tunnels, for example as in KBS-1 in a backfill that in compacted in situ, or as in NAGRA Project Gewähr 1985 in a bored tunnel with highly compacted blocks of bentonite applied between the canister and the rock.

2 Advantages and disadvantages

The volume of the rock repository can be minimized with a full-face-bored tunnel that is fully utilized as a "deposition chamber".

Canister packages with buffer material arranged in advance and transported and deposited in the tunnel may allow better controlled and more efficient handling.

Compared with deposition in holes drilled from the tunnel, where the canisters will be located at a distance from the disturbed zone around the tunnel, the canisters in tunnel deposition will be situated completely within a disturbed rock zone surrounding the tunnel. The canisters may thereby affect each other chemically to some degree.

As the alternative studies progress from the study of feasibility and safety performance to optimization and practical method adaptation, the technical design and execution of all repository components must be given increasingly high priority.

3 Evaluations and assessments

It is probable that the development of full-face boring will lead to economic advantages for alternatives with canister replacement in tunnels, since material consumption can be reduced. The differences in the environment between the different deposition alternatives are dependent, among other things, on the disturbed zone.

4 Research required

- The technology for executing horizontal holes and the manner in which these holes affect the surrounding rock will be studied under realistic conditions.
- Development of methods for application of buffer material, monitoring and control.
- In addition, some development of near-field models and modelling of groundwater movements in the disturbed zone around the tunnel will probably be required.

Priority - medium

D2 - Sand-filled canisters

1 Principles

Canisters are subjected to very high pressures in the repository after closure. One alternative to canister concepts investigated to date is to allow the rock-water-buffer pressure to be carried by a sand filling instead of a self-supporting canister design or a homogeneous metal fill (as in KBS-3).

2 Advantages and disadvantages

By sand filling (or filling with glass beads), the heating of the fuel canister that is required, for lead filling and hot isostatic pressing according to KBS-3 can be avoided. Furnaces and cooling positions can thereby be eliminated. Furthermore, a larger internal volume is obtained for fission gas and helium.

Disadvantages that have been mentioned are related to the non-homogeneous stresses that are introduced in the point of contact between the canister wall and the grain of sands, the risk that the grains will be crushed and the risk of impurities entering the system.

Ion-exchanging materials such as smectite or zeolite could be used for canister filling.

3 Evaluations and assessments

The economic advantages of not having to heat the fuel-filled canister are judged to be so great that even high costs for filling material should be able to be accepted.

In terms of safety, it is an advantage not to have to subject the fuel rods to heating. It may be necessary to introduce a buffer zone for the temperature in order to permit tight welding of the metal canisters.

The buildup of gas pressure in spent fuel is so slow that the hydraulic pressure at a level of 500 metres is not reached until after about one million years. However, if requirements on the performance of the final repository permit a location closer to the surface, the internal gas pressure could constitute a limit on the life of the canister.

4 Research required

All systems studied thus far have assumed that the whole fuel-canister package has to be heated at some stage of the encapsulation procedure. An estimate should be made of the costs directly related to this.

An analysis should be made of what consequences the uneven distribution of pressure between the canister and the fill material has for different canister materials.

A review should be made of possible materials for the fill, including a suitable grading of the particle size distribution and temperature consequences.

Priority - high

D3 - Emplacement of low- and intermediate-level waste in SFL

1 Principles

An obvious way to reduce the costs of final disposal of the different waste types in Sweden is to coordinate their disposal. No systematic analyses of such options have been performed.

Since the studies that have been done thus far have been aimed at demonstrating the feasibility of a safe final disposal, the procedures described have been kept as simple and uncomplicated as possible.

2 Advantages and disadvantages

The advantages lie in being able to utilize the SFL chambers that have been excavated for the purpose of transport and construction for the deposition of eg low- and intermediate-level waste from CLAB or from the decommissioning of nuclear facilities.

However, this procedure entails an extensive need for analyses of possible interactions between the different waste types and possible effects on the sealing of the repository.

3 Discussion

The effects that can above all be expected are associated with organic materials that may be present in the low-level waste and metals, primarily steel, in the decommissioning waste.

The immobilization of certain waste types in concrete or bitumen may also affect the environment in a repository.

Many of these questions will be dealt with in the safety analysis of SFR. In addition, certain "alternative studies" will provide direct information in the matter, for example corrosion of steel canisters and the effect of concrete in the final repository.

4 Research required

A survey should be made of characters and quantities of types of waste suitable for codeposition in SFL. Based on the results of this survey and different alternative final repository designs, studies of interaction effects for nuclides should be conducted.

Priority - medium.

4 RESEARCH

The research and development that has been given priority within SKB through 1983 has been aimed at demonstrating the feasibility of a safe final disposal.

Future research will mainly be aimed at providing information as a basis for:

- Site selection.
- Development of systems, development of technologies within unestablished areas and optimization of repository design.
- Design of layouts and structures.
- Construction and operation.

The Act on Nuclear Activities and its preparatory works emphasize that research at this stage should provide a comprehensive illumination of the different possibilities that exist for final disposal and emphasize the value of retaining freedom of choice during the coming years.

In order to permit a comprehensive evaluation of various conceivable final disposal methods, certain research work is required. This research will be aimed at shedding light on the natural conditions for final disposal in Sweden and at a broad review of different possibilities for introducing or designing engineered barriers in the system or for optimizing the safety systems. Other research is also required aimed at a deepening of knowledge within certain critical fields. This latter research will be discussed in another context.

The following list enumerates the different research activities required to shed light on different alternatives that may be considered, based on the premises that currently apply in Sweden.

Investigation of natural conditions

- Site investigations will be carried out in accordance with the present-day programme, including investigation of coastal sites.
- Assessments of residual uplift in order to ascertain the possibilities of a repository siting that guarantees for a certain period of time that any radioactive releases will end up in salt or brackish water.
- An investigation of possible discontinuities in the fracture content of the rock down to a depth of about 1500 metres.

Investigations of the near-field environment around the waste

- Analyses of the effects of temperatures above 100°C on buffer material and rock in the near field to determine the limits for allowable thermal loading in the repository.
- A systematic analysis will be performed of the effect of using concrete in the repository on important near-field or geosphere processes.
- Radiolysis phenomena are crucial parameters in the choice of canister thickness.

Investigations of release-preventive measures

- A systematic analysis of different forms of "getters" or chemical buffers should be commenced, including their effects on the rest of the system and the geosphere.
- The structure and effect of hydraulic cages must be studied. The studies should be coupled to the fracture zone project and should focus on long-term effects.
- Borehole plugging and grouting. The studies will concentrate on long-term performance and possible interactions of different materials with other components in the repository system.
- The study of canister materials will be extended to - besides Cu, Ti and ceramics - iron.
- Efforts to quantify the probability of delayed fracture should be initiated.

Investigation of design and execution methods

- Sand-filled canisters or other canister fillings that do not require heating and slow, controlled cooling should be studied.

The above outline of R&D work for SKB's future activities is based on an inventory of ideas and aims at establishing a broad knowledge basis for the final selection of method and site for final disposal of spent nuclear fuel in Sweden. There are other reasons as well why certain R&D measures should be given priority over others. Examples of such reasons are that databases or models are not sufficiently refined to permit realistic comparisons between alternatives, that available instruments do not give sufficiently detailed data for evaluations of certain designs or that methods for analysis of safety are costly and imprecise. A future research programme must take all such viewpoints into account, as well as, where possible, the development potential of different research areas.

Further grounds for allocating priorities among the different R&D activities come from the many scientists that have been asked by the Ministry of Industry and others to review the KBS 1-3, and from the large but often unquantified safety margins or simplified assumptions in the KBS reports.

The research activities that need to be initiated during the period 1987-1992, based on all of these grounds, is presented in the 1986 R&D programme /1/.

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