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Choice of method – evaluation of strategies and systems for disposal of spent nuclear fuel

Svensk Kärnbränslehantering AB

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Preface

In Sweden there is a solidly established main line for final disposal of spent nuclear fuel – deposition in the Swedish bedrock based on the KBS-3 method. Recurrent presentation and review of the RD&D programmes and several Government decisions have confirmed this strategy.

Since the mid-1980s, SKB (Svensk Kärnbränslehantering AB, the Swedish Nuclear Fuel and Waste Management Co), has regularly published accounts of the results of completed research and plans for future research on the final disposal of spent nuclear fuel. These accounts have mainly been presented in the research, development and demonstration programmes (RD&D programmes) SKB has published every three years in accordance with the requirements in the Nuclear Activities Act. SKB's plans have thereby been regularly subjected to extensive reviews. These reviews have been carried out by the appropriate regulatory authorities, by Swedish and foreign experts – engaged both by the reviewing authorities and by SKB – and by concerned municipalities, environmental organizations and interested citizens. The Government has expressed its opinion on each research programme and – since the early 1990s – has stipulated requirements for SKB's continued work. Issues surrounding the KBS-3 method, but also alternative methods, have been at the focus of nearly all research programmes.

This report deals with the question of how the spent nuclear fuel is to be disposed of. What are the requirements? What are the alternatives? In the main chapter of the report, a comparison and evaluation are made of the KBS-3 method compared with other strategies and systems for final disposal of spent nuclear fuel. An appendix to the report presents in general terms how the KBS-3 method has evolved from the end of the 1970s up to today.

As a part of the work of gathering supporting material for licence applications for the final repository system, SKB has produced three reports that serve as a basis for the present report: *Principer, strategier och system för slutligt omhändertagande av använt kärnbränsle* ("Principles, strategies and systems for final disposal of spent nuclear fuel", in Swedish only) /Grundfelt 2010a/, *Jämförelse mellan KBS-3-metoden och deponering i djupa borrhål för slutlig förvaring av använt kärnbränsle* ("Comparison between the KBS-3 method and deposition in deep boreholes for final disposal of spent nuclear fuel", in Swedish only) /Grundfelt 2010b/ and *Utvecklingen av KBS-3-metoden. Genomgång av forsknings-program, säkerhetsanalyser, myndighetsgranskningar samt SKB:s internationella forskningssamarbete* ("Development of the KBS-3 method. Review of research programmes, safety assessments, regulatory reviews and SKB's international research cooperation", in Swedish only) /SKB 2010a/. The first report is an update of the comprehensive account of alternative methods provided by SKB in 2000 in the supplement to RD&D-Programme 98, RD&D-K. The second report presents a comparison between the KBS-3 method and the Deep Boreholes concept. This was in response to a request from the Swedish Radiation Safety Authority, among others. Grundfelt's report /Grundfelt 2010b/ also includes a status report on research and development in the area of Deep Boreholes. Söderberg's report describes how the KBS-3 method has been developed from the end of the 1970s up to today. It further describes how the method has been further developed and refined over the years, but also what the supervisory authorities, the Government and other stakeholders have had to say about SKB's proposal. At times the final disposal issue has been at the centre of political interest, which is also illuminated in the report.

Erik Setzman

Head of the EIA Unit

Reading instructions

In this report, strategies and systems for final disposal of spent nuclear fuel are described and evaluated. The purpose of the report is:

- to present different strategies and systems that have been studied and compare these with the chosen method,
- to provide background and reasons for SKB's choice of method; the background includes how the method has gradually been developed, reviewed and solidified over a period of more than 30 years,
- to serve as supporting material for licence applications for the Swedish final repository system for spent nuclear fuel.

Site selection and detailed descriptions of technical solutions, systems, safety assessments, environmental consequences etc are presented and described in other reports and in appendices to the licence applications and are therefore not dealt with in this report.

The report has the following contents:

Chapter 1 provides an introduction to the subject and references to some relevant reports.

Chapter 2 provides an overview of the requirements that apply to systems for disposing of spent nuclear fuel and high-level waste. Both international agreements and Swedish laws and regulations are presented.

An overview of conceivable strategies and systems is provided in *Chapter 3*. More extensive descriptions and evaluations can be found in /Grundfelt 2010a/ and /SKB 2000a/. An up-to-date description of the deep boreholes concept, together with a comparison with the KBS-3 method, can be found in /Grundfelt 2010b/. The chapter begins with some facts about nuclear fuel.

In *Chapter 4*, which is the report's main chapter, the systems and strategies described in Chapter 3 are compared and evaluated, among other things against the requirements in Chapter 2. The emphasis is on a comparison between the KBS-3 method and the Deep Boreholes concept.

How the KBS-3 method has been developed over a period of more than 30 years is described in an appendix to the report. The appendix also describes the development undergone by methods, calculation models etc for safety assessments from the KBS-3 report up to today. Furthermore, the appendix provides an orientation on SKB's laboratories, international cooperation and studies of natural analogues.

Contents

Summary

This report deals with the question of how the Swedish spent nuclear fuel is to be disposed of. What are the requirements? What are the alternatives? In the main chapter of the report, an evaluation is made of the KBS-3 method compared with other strategies and systems for final disposal of spent nuclear fuel. An appendix to the report presents in general terms how the KBS-3 method has developed from the end of the 1970s up to today.

The report is one of a number of supporting documents for SKB's applications for construction and operation of the final repository for spent nuclear fuel. In parallel with and as a basis for the present report, SKB has prepared the reports *Principer, strategier och system för slutligt omhändertagande av använt kärnbränsle* ("Principles, strategies and systems for final disposal of spent nuclear fuel") /Grundfelt 2010a/, *Jämförelse mellan KBS-3-metoden och deponering i djupa borrhål för slutlig förvaring av använt kärnbränsle* ("Comparison between the KBS-3 method and deposition in deep boreholes for final disposal of spent nuclear fuel") /Grundfelt 2010b/ and *Utvecklingen av KBS-3-metoden. Genomgång av forskningsprogram, säkerhetsanalyser, myndighetsgranskningar samt SKB:s internationella forskningssamarbete* ("Development of the KBS-3 method. Review of research programmes, safety assessments, regulatory reviews and SKB's international research cooperation") /SKB 2010a/. The reports are in Swedish, but contain summaries in English. The first report is an update of the comprehensive account of alternative methods presented by SKB in 2000. The second report presents a comparison between the KBS-3 method and the Deep Boreholes concept, plus a status report on research and development in the area of Deep Boreholes. The last report describes how the KBS-3 method has been developed from the end of the 1970s up to today. It further describes how the method has been further developed and refined over the years, but also what the supervisory authorities, the Government and other stakeholders have said about SKB's proposal. At times the final disposal issue has been at the centre of political interest, which is also illuminated in the report.

Different principles and strategies for disposal of spent nuclear fuel and high-level waste have been studied in many countries ever since nuclear power began to be used for large-scale electricity production in the 1960s and 1970s. In the USA in particular, extensive studies were made of all strategies described in this report. The first broad-based Swedish study of how the spent fuel and the radioactive waste from nuclear power should be disposed of was conducted by the AKA Committee (the Swedish acronym AKA stands for spent nuclear fuel and radioactive waste) appointed by the Government at the end of 1972, whose final report was issued in 1976.

Determined efforts to develop a method for managing and disposing of the high-level waste from the Swedish nuclear power plants started as a result of the so called Stipulations Act, passed in 1977. The law required that the owners of reactors – in order to get the Government's permission to fuel the reactors that were planned or under construction but had not yet been taken into operation – should either present an agreement on reprocessing of spent nuclear fuel and show how and where an "absolutely safe" disposal of the high-level waste from reprocessing could take place, or show where and how an "absolutely safe" disposal of spent, unreprocessed nuclear fuel could take place. In order to comply with the conditions in the Act, the nuclear power companies started the KBS Project (the Swedish acronym KBS stands for Nuclear Fuel Safety). The project presented its work in three main reports. The first report in 1977, subsequently called KBS-1, dealt with the management of vitrified waste from reprocessing. The focus in the KBS-2 report in 1978 was on direct disposal of spent nuclear fuel. Both proposals were based on deposition in the bedrock and a multiple barrier system.

In the years around 1980, a new view emerged in Sweden on reprocessing as the main line for dealing with the spent nuclear fuel. Instead of the fuel being regarded as a resource, direct disposal was seen as the most reasonable alternative, in other words the fuel was regarded as waste. The KBS-3 report in 1983 presented the KBS-3 method, entailing encapsulation of the spent nuclear fuel in a copper canister and deposition at a depth of about 500 metres in crystalline rock.

After the KBS-3 report, SKB has, in keeping with the requirements in the Nuclear Activities Act (which replaced the Stipulations Act and other earlier legislation in 1984), submitted an account of the development of the KBS-3 method every three years. In the RD&D programmes, SKB has also described other methods for final disposal of the spent nuclear fuel. This report contains an overview and brief descriptions of the alternatives to the KBS-3 method that SKB has studied and reported on over the years. Table S-1 shows these alternatives and SKB's assessment of them.

The long-term safety of a KBS-3 repository has been assessed in a number of safety evaluations and safety assessments. Both the most recent (SR-Site) and earlier assessments show that a KBS-3 repository, built on the analyzed sites, can satisfy the requirements on safety, radiation protection and environmental protection that are made in laws and regulations. Other alternatives that have been discussed for final disposal of spent nuclear fuel have been subject to relatively comprehensive studies and assessments, but have not been evaluated in a complete safety assessment.

In principle there are two main approaches for managing the spent nuclear fuel. One entails regarding the fuel as a resource, the other as waste.

Utilizing the spent nuclear fuel as a resource constitutes a part of both waste management and nuclear fuel supply. Extracting fissionable materials from the spent fuel and reusing them in new fuel reduces the need for new uranium and thereby the need for uranium mining. The more advanced concepts involving reprocessing, partitioning and transmutation entail that new types of reactors and facilities for separation need to be developed.

To be able to reuse the spent nuclear fuel content of fissionable materials and extract more energy, the fuel must be reprocessed and the fissionable materials uranium and plutonium separated. Reprocessing gives rise to both high-level and low- and intermediate-level waste, which must be disposed of. This strategy thus also requires facilities for final disposal of radioactive waste. The strategy for the high-level nuclear waste (HLW) in the countries that reprocess the spent nuclear fuel is geological disposal, usually employing concepts that resemble the KBS-3 method. Finland has similar geological conditions and also plans to dispose of spent nuclear fuel in a KBS-3 repository.

Table S-1. SKB's assessment of different strategies for disposing of spent nuclear fuel

Strategy	SKB's assessment
Dumping in the sea	Violates international agreements.
Disposal in deep-sea sediment	Violates international agreements.
Disposal beneath the continental ice sheet	Violates international agreements.
Launching into outer space	Resource-demanding, costly, risks in launching.
	Probably requires reprocessing.
Monitored storage	Responsibility transferred to future generations.
	Does not satisfy the long-term safety and radiological requirements.
Reprocessing with recycling of uranium and plutonium	Better resource management, the natural uranium is utilized more efficiently and recycled uranium and plutonium are used for production of electricity.
	Waste must be disposed of in a similar manner as spent nuclear fuel.
	Spent MOX fuel must be directly disposed of.
	More expensive than direct disposal.
	Increased risk that plutonium winds up in the wrong hands.
Reprocessing, partitioning and transmutation	Better resource management, the natural uranium is utilized more efficiently and recycled uranium and plutonium are used for production of electricity.
	Waste must be disposed of in a similar manner as spent nuclear fuel.
	Extensive research is needed.
	Requires an advanced nuclear system including new reactors that have to be in operation for more than 100 years.
Geological disposal	Can satisfy all requirements.
	Can be carried out today.
	Future generations have the option of retrieving the waste.

In the major nuclear power countries and in international research projects, advanced reprocessing, partitioning and transmutation are being studied, i.e. strategies that are applicable if the fuel is regarded as a resource. The aim is to arrive at more efficient processes for utilizing the fuel and converting (transmuting) long-lived radionuclides in the spent nuclear fuel into more short-lived or stable nuclides.

The development of a functioning system for partitioning and transmutation is expected to be costly and take a long time. Even if the development work is successful, some long-lived waste will remain that must be dealt with in a similar manner to spent nuclear fuel. Furthermore, it will take a long time – in the order of 100 years or more – to carry out transmutation of already existing spent nuclear fuel from the Swedish nuclear power plants in facilities for partitioning and transmutation. SKB therefore does not regard transmutation as a realistic alternative for managing spent nuclear fuel from today's Swedish reactors. Nevertheless, it is reasonable that Sweden should participate in the international development work and maintain competence within the country, at least as long as a considerable portion of the country's electricity production is based on nuclear energy. Competence developed in research on partitioning and transmutation is valuable, not just for assessing development and potential in this field, but also for development of safety and fuel supply at existing reactors. SKB therefore intends to continue to follow and support research in the field.

SKB's assessment and evaluation of other strategies and methods for final disposal of the spent nuclear fuel shows that geological disposal is the only realistic alternative. Geological disposal is also the predominant strategy internationally for disposal of spent nuclear fuel or long-lived HLW from reprocessing. Different geological environments – crystalline rock, clay or salt formations – have been studied according to what is available in each country. Four different systems for geological disposal in crystalline rock have been studied in Sweden:

KBS-3 – deposition in a system of short tunnels at a depth of 400–700 metres.

Long tunnels (VLH = Very Long Holes) – deposition in a few parallel tunnels several kilometres long at a depth of 400–700 metres.

WP-Cave – deposition in a rock volume within which the water flux has been reduced by various engineering means.

Deep Boreholes – deposition at a depth of several thousand metres.

The four systems are illustrated in Figure S-1.

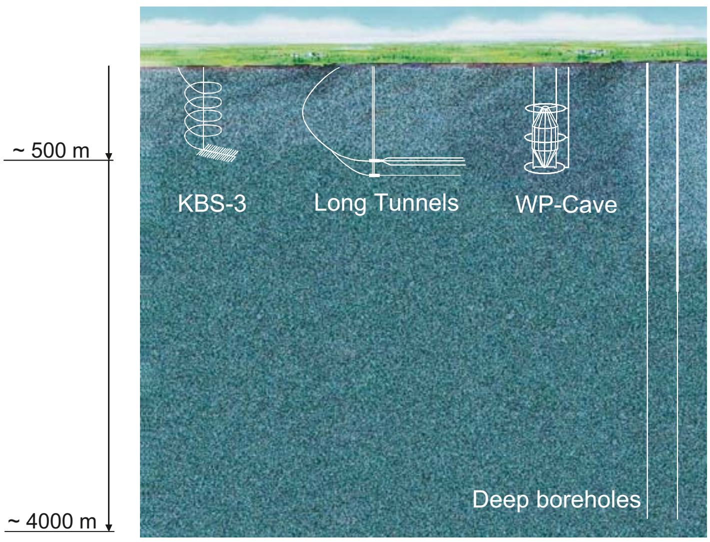

Figure S-1. *Different systems for geological disposal of spent nuclear fuel.*

The different systems for geological disposal differ primarily in the configuration of the actual repository in the bedrock. In the Deep Boreholes concept, the waste will be disposed of in boreholes at a depth of several thousand metres, instead of in a tunnel system at a depth of a few hundred metres. Long-term safety is achieved in all systems, except in the Deep Boreholes concept, by interaction between engineered barriers and the rock. In the case of Deep Boreholes, the expected slow groundwater movements at large depths are assumed to be the most important safety feature.

A comparison between KBS-3 and Long Tunnels (VLH) shows that the alternatives have several similarities. This also applies to some extent to the WP-Cave concept. However, SKB's overall assessment is that the KBS-3 method has advantages, above all when it comes to safety and radiation protection.

The alternative *Long Tunnels (VLH)* has environmental advantages in that the quantity of rock that has to be extracted is much smaller. However, safety during operation is poorer in terms of both working environment and occupational safety. Furthermore, it is much more difficult to retrieve a damaged canister than in KBS-3. With the alternative KBS-3H (horizontal deposition of the canisters), SKB has exploited the environmental advantages of the Long Tunnels concept, while the disadvantages with regard to operational safety and the difficulties of retrieval have been reduced due to the fact that the deposition tunnels are much shorter.

The concept of *WP-Cave* has clear disadvantages compared with KBS-3. The concept is technically complicated. Extensive knowledge accumulation and technology development would be required to refine the technology and the design and to assess safety. The feasibility of building a repository according to the WP-Cave concept that meets the requirements on safety and radiation protection is associated with great uncertainties. SKB's assessment is therefore that WP-Cave is not an interesting alternative.

Knowledge of the KBS-3 method and *Deep Boreholes* differs greatly. SKB has nevertheless made great efforts to evaluate the concept of disposal in deep boreholes and compare it with the KBS-3 method.

SKB's conclusion is that disposal in deep boreholes is not a realistic alternative to KBS-3. No technical breakthrough that could alter this assessment is expected in the foreseeable future. Extensive efforts are required to accumulate the knowledge needed to build, operate and close a final repository in deep boreholes. Furthermore, it is uncertain whether, even after such efforts, deep boreholes can provide a safer final disposal than the KBS-3 method. There is no country that is planning to use the concept of disposal in deep boreholes for final disposal of spent nuclear fuel or high-level waste from nuclear power. Nor is any targeted research and development being conducted for this concept.

A repository according to the Deep Boreholes concept has one advantage compared with a KBS-3 repository: it offers better protection against intrusion and illicit trafficking of nuclear material. However, the KBS-3 system also offers adequate protection in this respect, since unauthorized intrusion into the final repository is a major undertaking that cannot be concealed. In all other important respects the KBS-3 repository is preferable.

The Deep Boreholes concept is not a multiple barrier system. Due to the aggressive environment at great depths (high salinities, high pressure and high temperature), canister and buffer cannot be expected to remain intact in the long run. They could probably not contribute appreciably to the required isolation and retardation of radionuclides.

The KBS-3 repository can more easily be adapted to the bedrock, not least because deposition tunnels and deposition holes can be investigated and characterized in situ. The deposition holes in a KBS-3 repository can be bored from the start in suitable positions, and holes that prove to be unsuitable can be rejected. In the case of Deep Boreholes, the conditions as a whole must be either accepted or rejected. It might however be possible to deposit canisters in limited parts of the hole. Knowledge of the surrounding rock volume can never be as good with the Deep Boreholes concept as for a KBS-3 repository.

Drilling of the very deep deposition holes is a great challenge, and success is threatened by such phenomena as hole deformation and breakout. The technical drilling difficulties involve not only being able to drill deep enough with sufficiently large diameter. A larger diameter also increases the risk of collapse and breakout from the wall of the hole and the risk of an oval hole, causing the drill string and the casings to get stuck. A larger diameter also complicates handling of the casings, since they are much heavier. Nor is it possible to rule out the risk of the canisters getting stuck during the deposition process.

All steps needed to handle and dispose of the spent fuel according to the KBS-3 method have been designed so that they can be controlled and the results verified. This is not possible in the case of disposal in deep boreholes.

In the case of disposal in deep boreholes, accidents can occur with fateful consequences. For example, a canister can get stuck in the hole and break before it has reached disposal depth. As a result, a leaky canister can get stuck in a location with flowing groundwater, without being surrounded by a protective buffer.

It is not known today what the consequences might be for a final repository according to the Deep Boreholes concept in the event of a future glaciation or an earthquake.

In summary, there are great uncertainties associated with the concept of disposal in deep boreholes. Construction, deposition and closure cannot be carried out with the degree of control that is required. Acquiring substantial additional knowledge of disposal in deep boreholes requires great resources and takes a long time. Moreover, it is not likely that such an effort will lead to a system for final disposal that has substantially better chances of meeting the requirements than the KBS-3 method.

Monitored storage for a limited period is, for technical reasons, always included in the management of spent nuclear fuel. Monitored storage can take the form of dry or wet storage. Clab is an example of wet storage. The DRD concept (Dry Rock Deposit) is a variant of monitored storage that is intended for storage for a very long time. Regardless of how the repository is designed, the strategy of monitored storage requires regular inspection and maintenance. It therefore fails to satisfy the requirement of the Nuclear Activities Act on final disposal of spent nuclear fuel, viz. that the the final repository should provide the requisite safety without monitoring and maintenance. Nor does it satisfy the requirement of not leaving undue burdens for future generations.

Many countries count on having to employ monitored storage for a very long time. One common reason is difficulties in finding a site for a final repository that can be accepted by the population in the concerned region and municipality.

It is SKB's opinion that a final repository according to the KBS-3 method can be built, operated and closed in a manner that is controlled in all steps. The safety evaluations and assessments that have been carried out show that the KBS-3 method can satisfy the requirements on safety, radiation protection and environmental protection that are made in laws and regulations.

1 Introduction

In Sweden, the main line for final disposal of spent nuclear fuel is deposition in the bedrock in accordance with the KBS-3 method. This strategy is solidly established as a result of many reports and reviews. But which alternatives have been studied? And how does the KBS-3 method compare with other alternatives? That is what this report is about.

The terms “principles”, “strategies” and “systems” for disposal of spent nuclear fuel are used in this report. These terms are explained in Table 1-1.

The term “alternative methods” is often used without it being clear whether the different methods are a result of the application of completely different strategies or whether they constitute different systems within the framework of the same strategy. A concept is a system or a system variant in an early development stage.

Figure 1-1 illustrates alternative principles and strategies for final disposal of spent nuclear fuel from nuclear power plants. The figure shows that spent nuclear fuel can be regarded either as waste or as a resource. The reason the spent fuel can be regarded as a resource is that it contains substances which, after separation, can be reused to fabricate new nuclear fuel, see Section 3.1. If the spent nuclear fuel is regarded as waste – which is the current way of viewing it in Sweden – there are three principles for management:

- Collection and storage isolated from man and environment.
- Reprocessing and transmutation to reduce the quantity of waste and the time the waste has to be kept isolated.
- Dilution to harmless concentrations and dispersal in the environment.

If the principle *Dilution to harmless concentrations and dispersal in the environment* is applied, the strategy may be to dump the waste in the sea. If the principle *Collection and storage isolated from man and the environment* is applied, several strategies are conceivable:

- Launching into outer space.
- Disposal beneath ice sheet.
- Disposal in deep-sea sediment.
- Monitored storage.
- Geological disposal.

If the spent nuclear fuel *is regarded as a resource*, the strategy is reprocessing and separation of the substances that will constitute new fuel. If the intention is to transform the spent nuclear fuel to another form with a lower content of substances with long-lived radioactivity, the strategy is transmutation after reprocessing and separation (partitioning) of the long-lived substances to be transmuted to more short-lived ones. These processes also produce a waste that must be disposed of by application of one of the principles and strategies based on regarding the spent nuclear fuel as a waste.

Table 1-1. Principles, strategies and systems.

Principle	A general basic approach to solving the problem or task in question. One principle could be to “collection and storage isolated from man and environment”; another principle is “dilution to harmless concentrations and dispersal in the environment”.
Strategy	Technical procedure for applying a given principle. Within the framework of the principle “collection and storage isolated from man and environment,” the strategy of “geological disposal” is one of several alternative courses of action.
Systems	The application of a given strategy requires a number of interacting facilities. Within the framework of the strategy of geological disposal, KBS-3 is an example of a system that consists of an interim storage facility, a plant for encapsulating the fuel in a certain way, and a final repository of a certain design. Disposal in deep boreholes is another system, which could conceivably consist of an interim storage facility, a plant to encapsulate the fuel and a final repository of another design.
System variant	Alternative designs of the facilities that belong to a given system. Examples of variants of the KBS-3 method are vertical or horizontal deposition of the canister.

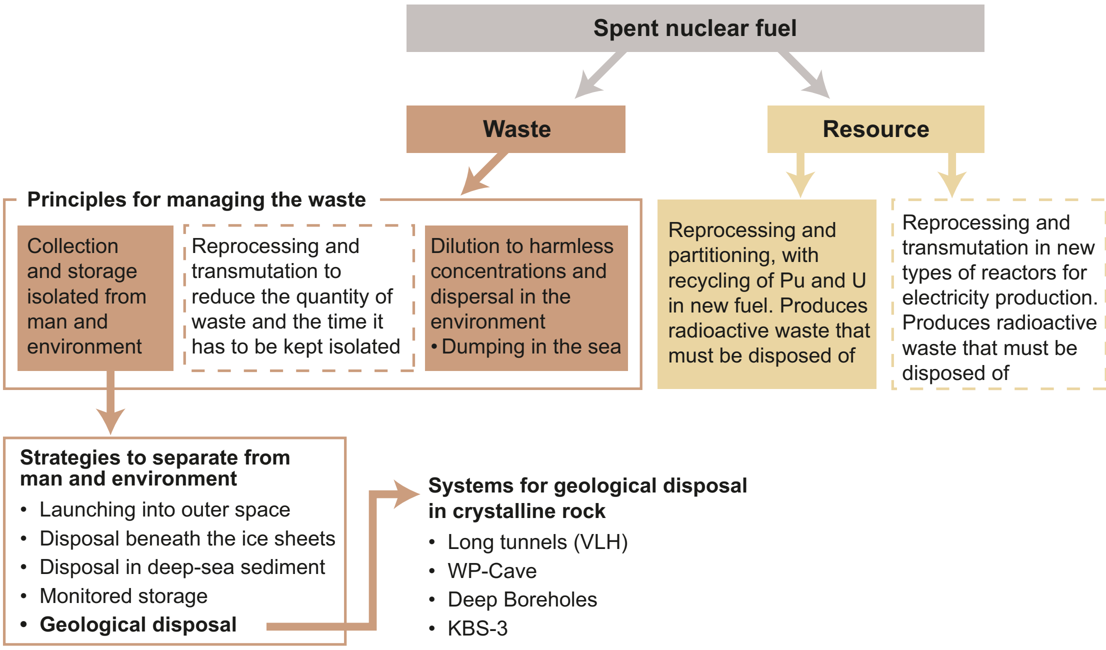

Figure 1-1. *Principles, strategies and systems for disposal of spent nuclear fuel. The principles in the dashed boxes are based on technology that is not available today.*

1.1 Swedish and international studies

Different principles and strategies for disposal of spent nuclear fuel and high-level waste have been studied in many countries ever since nuclear power began to be used for large-scale electricity production in the 1960s and 1970s. An early study on these questions was carried out by the US Atomic Energy Commission and published in 1974, *High-level radioactive waste management alternatives* /U.S. Department of Commerce 1974/. In 1976, the first Swedish public inquiry into the waste issues surrounding nuclear power, the *AKA Committee*, presented information on plans for waste management in some ten or so nuclear power countries (SOU 1976:30).

In all RD&D programmes, SKB has described and evaluated other strategies and methods for disposal of spent nuclear fuel. More comprehensive accounts were given in RD&D-Programme 92 /SKB 1992b/, RD&D-Programme 98 /SKB 1998/ and the supplement to RD&D-Programme 98 (RD&D-K) which SKB published in 2000 /SKB 2000b/. The internationally acclaimed PASS report[1] /SKB 1992a/ served as a basis for the account in RD&D-Programme 92. For the account in RD&D-K, SKB performed a thorough analysis of the choice of strategy and method for disposal of spent nuclear fuel from the Swedish nuclear power plants /SKB 2000a/. In 2000, SKB also reported on what research, development and demonstration would be required to enable the repository concept of Deep Boreholes to be compared with KBS-3 on equivalent grounds /SKB 2000c/.

Since 2000, SKB's work with alternatives to KBS-3 has essentially been focused on following the international development work on two different concepts: partitioning and transmutation and disposal in deep boreholes. General accounts of the state-of-the-art for these two concepts have been included in the RD&D programmes published in 2001, 2004 and 2007, the supplement to RD&D Programme 2007 (March 2009), and most recently in RD&D Programme 2010. The accounts have been based on comprehensive reviews of international and Swedish research reports.

As a part of the work of gathering supporting material for licence applications for the final repository system, SKB has produced three reports that serve as a basis for the present report: *Principer, strategier och system för slutligt omhändertagande av använt kärnbränsle* ("Principles, strategies and systems for final disposal of spent nuclear fuel", in Swedish only) /Grundfelt 2010a/, *Jämförelse mellan KBS-3-metoden och deponering i djupa borrhål för slutlig förvaring av använt kärnbränsle* ("Comparison

[1] PASS, acronym for Project Alternative Systems Study.

between the KBS-3 method and deposition in deep boreholes for final disposal of spent nuclear fuel", in Swedish only) /Grundfelt 2010b/ and *Utvecklingen av KBS-3-metoden. Genomgång av forsknings-program, säkerhetsanalyser, myndighetsgranskningar samt SKB:s internationella forskningssamarbete* ("Development of the KBS-3 method. Review of research programmes, safety assessments, regulatory reviews and SKB's international research cooperation", in Swedish only) /SKB 2010a/. The first report is an update of the account published in 2000 /SKB 2000a/.

Since 2000, a number of major overviews of methods for final disposal of spent nuclear fuel and/or high-level nuclear waste have been published:

Implementing Geological Disposal of Radioactive Waste. Technology Platform. Vision document /IGD-TP 2009/. The document was prepared by representatives of SKB, Posiva (Finland), Andra (France) and the Federal Ministry of Economics and Technology (Germany). The report provides an up-to-date (2008) overview of the programmes for waste management in the EU's 16 nuclear power countries. The work with the report was initiated as a result of the discussion that followed from the EU-funded study *A Co-ordination Action on Research, Development and Demonstration Priorities and Strategies for Geological Disposal* /CARD 2008/.

Sixth situation report on: "Radioactive waste and spent fuel management in the European Union" /European Commission 2008/. In the report, the European Commission concludes that after 30 years of research, it is sufficiently demonstrated that geological disposal now represents the safest and most sustainable option for the long term management of high level waste and spent fuel subject to direct disposal, even though implementation-oriented research and development needs to continue.

Moving Forward with Geological Disposal of Radioactive Waste /NEA 2008/. A Collective Statement by the NEA Radioactive Waste Management Committee. As the title suggests, it is mainly about geological disposal and the reasons in favour of such a strategy, but other strategies are also mentioned.

Geological Disposal Options for High-Level Waste and Spent Fuel. Report for the UK Nuclear Decommissioning Authority /Baldwin et al. 2008/.The report presents possible options for geological disposal of long-lived high-level waste and spent nuclear fuel that could be implemented in the UK. The authors conclude that there are a wide range of geological environments that could be suitable for hosting a geological disposal facility in the UK. Twelve different concepts for geological disposal are described in the report. The description includes design, origin, maturity, constructional, operational and environmental aspects, and which countries have the concept in their programmes. The report sheds light on the geological environments in which each method is suitable. The authors observe that there is a trend in many countries to consider concepts that use "supercontainers" where multiple engineered barriers are included in a single package. The advantage of this concept is that a package, the supercontainer, can be prefabricated in a surface facility.

Resurs eller avfall? Politiken kring hanteringen av använt kärnbränsle i Finland, Tyskland, Ryssland och Japan ("Resource or Waste. The politics of spent fuel management in Finland, Germany, Russia and Japan", in Swedish only) /Kaijser och Högselius 2007/. The report presents the results of a project in SKB's social science research programme. The project analyzed and tried to find answers to the following questions: Why have different countries had such different views and tried to develop such different solutions for spent nuclear fuel management? Why hasn't a globally optimal method been developed on which everyone can agree and that can be used everywhere and by everyone? Why have certain solutions "won" in certain countries, but not in others? The reason why, at the time the report was written, more and more countries had abandoned the idea of regarding the fuel as a resource and were instead focused on direct disposal is discussed at length in the report. The authors provide a historical, sociotechnical and international perspective on these questions.

Managing our Radioactive Waste Safely, CoRWM's recommendations to Government /CoRWM 2006/. The overview is included in the report with recommendations which the Committee on Radioactive Waste Management (CoRWM) submitted to the British Government in 2006. According to CoRWM, geological disposal is the best available strategy for final disposal of radioactive waste. CoRWM nevertheless recommends following and/or participating in national or international research and development programmes for other alternatives for final disposal. CoRWM particularly mentions disposal in deep boreholes, which may emerge as a suitable alternative for certain types of waste.

Lösning eller låsning. Frågan om kärnavfall i några länder ("Solutions with open options. The issue of nuclear waste in some countries," in Swedish only) /Lind 2006/. The report focuses on political and societal issues, while technical aspects are only taken up as a background to the central issues. Industrial countries in Western Europe and North America with significant nuclear power programmes of their own are examined in the report. Slovenia is included as an example of a small country. The report does not deal with Russia, the rest of Eastern Europe or Asia, however.

Radioactive Waste Management. Programmes in OECD/NEA Member Countries /NEA 2005/. Report with fact sheets presenting the waste programmes in 20 OECD countries. The fact sheets contain information on sources and quantities of different types of waste, and how and by whom the waste is managed. There are particulars for each country about where more information can be obtained. The fact sheets are updated regularly and are available on the NEA's website /NEA 2010/.

The comparison of alternative waste management strategies for long-lived radioactive wastes /European Commission 2004/. The overview was compiled in 2004 on behalf of the European Commission's Directorate-General for Research. The report summarizes the results from a larger project within the EU's Fifth Framework Programme. It presents policies and strategies for the management of radioactive waste that have been developed in a number of EU countries. The report deals with spent nuclear fuel, waste from reprocessing and long-lived low- and intermediate-level waste.

The Future of Nuclear Power. An Interdisciplinary MIT Study /MIT 2003/. The study deals with the future of nuclear power. The study reviews the options for reducing emissions of greenhouse gases by expanding nuclear power. Aspects considered include costs, reactor safety, waste management and non-proliferation. When it comes to waste management, the study concludes that the solution with the broadest support is disposal in geological formations, even though all countries seem to have problems implementing their programmes.

The management of radioactive waste. A description of ten countries. This report was produced within the framework of The International Association for Environmentally Safe Disposal of Radioactive Materials (EDRAM) /Lidskog and Andersson 2002/. The study describes the management of radioactive waste in ten of EDRAM's eleven member countries (Belgium, Canada, the UK, Finland, France, Japan, Switzerland, Spain, Sweden, the USA and Germany). For each country, an overview is provided of the status of the programme at the end of 2001, along with specific accounts of technical, economic and socio-political aspects.

2 Requirements on systems for disposal of spent nuclear fuel

This chapter presents requirements on systems for disposal of spent nuclear fuel in Sweden.

The general requirements and premises for management and disposal of spent nuclear fuel are set forth in Swedish legislation and in international agreements and conventions which Sweden has pledged to abide by. The most important agreements in this context are:

- The 1997 Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management /Nuclear Waste Convention 1997/.
- The 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, with 1996 Protocol /London Convention 1972 and 1996/.
- The 1968 Treaty on the Non-Proliferation of Nuclear Weapons /Non-Proliferation Treaty 1968/.

The most important requirements in Swedish legislation are the environmental requirements in the Environmental Code, the safety requirements in the Nuclear Activities Act with associated regulations, and the radiation protection requirements in the Radiation Protection Act with associated regulations.

Laws and regulations, and thereby requirements, change with time. For example, a review of the Nuclear Activities Act and the Radiation Protection Act is currently in progress.

Applicable requirements on a system for final disposal of spent nuclear fuel are presented below under the following headings: overall requirements, safety requirements, radiation protection requirements, requirements on physical protection and safeguards, and environmental requirements[2].

2.1 Overall requirements

Requirements under *the Nuclear Waste Convention* include:

- Radioactive waste should, as far as is compatible with the safety of the management of such material, be disposed of in the State in which it was generated.
- In managing radioactive waste, the parties shall aim to avoid imposing undue burdens on future generations.

Requirements under *the London Convention* include:

- Dumping of spent nuclear fuel may not take place in the sea or on the seabed.

By signing (1968) *the Non-Proliferation Treaty*, Sweden has undertaken to use nuclear energy solely for peaceful purposes and to submit Swedish nuclear materials to control by the IAEA. According to the Treaty, the system for disposal of spent nuclear fuel shall be designed to prevent illicit trafficking in nuclear materials or nuclear waste. The international control is also exercised by Euratom, since the Euratom Treaty applies in Sweden through our membership in the EU.

Requirements under the *Antarctica Treaty* /ATS 1959, 1991/ and the *Antarctica Act* (SFS 2006:924) include:

- Disposal of radioactive waste in Antarctica is prohibited.

Requirements under *the Nuclear Activities Act* (SFS 1984:3) include:

- The holder of a licence for nuclear activities shall ensure that nuclear waste arising in the activities, or nuclear material arising therein that is not reused, is managed and disposed of in a safe manner.
- Final disposal in Sweden of spent nuclear fuel or nuclear waste from another country is prohibited. Exceptions from this prohibition may be granted if special reasons exist and provided this does not impede the implementation of the Swedish programme for disposal of radioactive waste.

[2] The requirements are not reproduced verbatim here, but have been reformulated for ease of reading.

2.2 Safety requirements

The system requirements imposed on a system for disposal of spent nuclear fuel are derived from the *Nuclear Activities Act* (SFS 1984:3) and regulations pursuant to this act (SSMFS 2008:1 /SSM 2008a/ and SSMFS 2008:21 /SSM 2008c/).

2.2.1 Safety functions and barriers

- Safety shall rest on multiple barriers, which are designed so that failure of one barrier leads to only very limited environmental consequences.
- The barrier system shall be able to withstand such features, events and processes that can affect the post-closure performance of the barriers.
- The system used shall be resistant to malfunctions of component parts and possess high reliability.

2.2.2 Design principles

- A facility for final disposal of spent nuclear fuel shall be designed so that the barriers, after closure of the repository, provide the requisite safety without monitoring and maintenance.
- Design principles and design solutions shall be proven under conditions equivalent to those that can exist during construction and operation of the final repository. If this is not possible or reasonable, the design principles and design solutions shall be tested or evaluated in a manner that shows that they have the durability, reliability and operational stability that is needed with a view to their function and importance for the safety of the facility.

2.3 Radiation protection requirements

The radiation protection requirements are taken from *the Radiation Protection Act* (SFS 1988:220) and the regulations (above all SSMFS 2008:37 /SSM 2008d/) issued by the Swedish Radiation Safety Authority (SSM) pursuant to the act. They can be regarded as clarifications of the environmental requirements as regards the harmful effects of radiation.

2.3.1 Radiation protection

- Human health and the environment shall be protected from detrimental effects of ionizing radiation during the time when the various steps in the final management of spent nuclear fuel or nuclear waste are being implemented as well as in the future. The final management may not cause impacts on human health and the environment outside Sweden's borders that are more severe than those accepted inside Sweden.
- A repository for spent nuclear fuel or nuclear waste shall be designed so that the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk. The probability of harmful effects as a result of a radiation dose shall be calculated using the probability coefficients provided in Publication 60, 1990 /ICRP 1991/.
- The final management of spent nuclear fuel and nuclear waste shall be implemented so that biodiversity and a sustainable use of biological resources are protected against the harmful effects of ionising radiation.

2.3.2 System design

- In the final disposal of spent nuclear fuel and nuclear waste, optimization shall be effected and consideration given to the "best available technique", BAT. In SSMFS 2008:37 /SSM 2008d/, SSM defines optimization and best available technique as follows:
- *Optimization* – keeping the radiation doses to humans as low as reasonably achievable, economic and social factors taken into account.
- *Best available technique* – the most effective measure available to limit the release of radioactive substances and the harmful effects of the releases on human health and the environment, which does not entail unreasonable costs. Using the best available technology is also a requirement under the Environmental Code (see below) and SSM's regulations SSMFS 2008:1 Sec. 1 /SSM 2008a/ and 2008:21 Sec. 6 /SSM 2008c/.

2.4 Requirements on physical protection and safeguards

The system for disposal of spent nuclear fuel shall be designed so that the requirements on physical protection and safeguards are satisfied.

By "physical protection" of nuclear facilities is meant measures to protect the facilities against intrusion, sabotage or other actions that could lead to a radiological accident, as well as to prevent illicit trafficking in nuclear materials or nuclear waste. The design of measures is regulated by SSM's regulations on physical protection of nuclear facilities (SSMFS 2008:12 /SSM 2008b/).

Spent nuclear fuel contains substances (mainly plutonium) which can be used for the manufacture of nuclear weapons. There are therefore international agreements to prevent and provide safeguards against the diversion of nuclear material and nuclear waste for possible use in weapons manufacture /Non-Proliferation Treaty 1968/.The Nuclear Activities Act requires that Sweden should fulfil its obligations under international agreements. The Act states that reactor owners are obligated to allow access to their facilities for the authority designated to exercise safeguards, in other words SSM, the IAEA and Euratom. Euratom monitors facilities, while the IAEA also monitors nations. SSM exercises national safeguards.

2.5 Environmental requirements

The following environmental requirements have been derived from *the Environmental Code* (SFS 1998:808):

- Sustainable development which will assure a healthy and sound environment for present and future generations.
- Human health and the environment shall be protected against damage and detriment caused by pollutants and other influences. The best available technology shall hereby be used.
- Land, water and the physical environment shall otherwise be used in such a manner as to secure sustainable management from an ecological, social, cultural and economic viewpoint.
- Reuse and recycling, as well as other management of materials, raw materials and energy shall be promoted so that an ecocycle is achieved.

2.6 Principles for the work of disposing of the spent nuclear fuel

Based on the above requirements, among others, SKB has formulated the following principles for the work of disposing of the spent nuclear fuel:

- Security, radiation protection and environmental considerations shall be in focus in connection with the construction, operation and closure of the final repository.
- The final repository shall be designed to prevent illicit trafficking in nuclear fuel both before and after closure. Long-term safety shall be based on a system of passive barriers.
- The final repository is intended for spent nuclear fuel from the Swedish nuclear power plants and shall be created within Sweden's boundaries with the voluntary participation of the concerned municipalities.
- The final repository shall be established by those generations that have derived benefit from Swedish nuclear power and be designed so that it will remain safe after closure without maintenance or monitoring.

3 Overview of conceivable strategies and systems

This chapter presents the strategies and systems for final disposal of spent nuclear fuel that have been studied and discussed over the years. For each strategy, the conceivable systems are described in brief. Chapter 4 presents SKB's evaluation of the different strategies, among other things against the requirements in Chapter 2. As a background for the following presentation, the chapter begins with some facts about nuclear fuel. The emphasis is on facts of particular relevance for the Swedish nuclear power programme.

3.1 Nuclear fuel

Nuclear fuel is made from uranium mineral. The radioactivity of the fuel increases greatly during the operation of a nuclear power reactor. After about five years the fuel is no longer fit for further use and is therefore taken out of the reactor. The fuel's radioactivity, and thereby its radiotoxicity, is then at its greatest. The radioactive substances then decay and their radiotoxicity declines. But it takes a very long time, about 100,000 years, before the radioactivity has declined to the same level as in the quantity of natural uranium from which the fuel was made. There is a relatively detailed description of the radiotoxicity of spent fuel in /SKB 2007, Chapter 2, in Swedish only/. The account in /SKB 2007/ provides a good introduction to the problem which a final repository for spent nuclear is intended to solve, namely the risk posed by the spent fuel to man and the environment if it is not handled in a responsible manner.

All nuclear power reactors in Sweden are light water reactors (LWR's). Three of the reactors in Ringhals are pressurized water reactors (PWR's), while the other seven Swedish reactors are boiling water reactors (BWR's). The two shutdown reactors at Barsebäck were also boiling water reactors.

The spent nuclear fuel in Clab consists for the most part of uranium fuel from our BWR and PWR reactors. In Clab there is also a small quantity of other spent fuel (MOX fuel from Germany and fuel from the Ågesta reactor, which was in operation from 1964 to 1974).

3.1.1 Nuclear fuel in light water reactors

The content of fissionable (or fissile) uranium (uranium-235) in natural uranium is about 0.7 percent. By far most of the rest is uranium-238, which is not fissionable. Natural uranium cannot be used to power an LWR because the light water[3] "steals" too many neutrons. The proportion of uranium-235 must therefore be raised, which is done abroad in an enrichment plant. New enriched fuel in today's light water reactors has a uranium-235 content of three to four percent. (Natural uranium can, however, be used to power heavy water reactors and gas-cooled graphite reactors). The residual product after enrichment is uranium with a lower concentration of uranium-235 than that in natural uranium, called depleted uranium. As an alternative to enriched uranium, plutonium-enriched fuel, called Mixed Oxide Fuel (MOX), can be used.

During the time the fuel powers the reactor, a series of nuclear reactions take place, whereby various radioactive products are formed. The production of radionuclides in the fuel takes place essentially in two ways: by nuclear fission or by neutron capture.

The most important nuclear reaction is nuclear fission. It is this reaction that releases energy from the fissionable material. The released nuclear energy is transformed into heat, which heats the water in the reactor and turns it into steam. The steam is converted into electricity via a steam turbine connected to a generator. Fission in the fresh fuel mainly occurs in uranium-235.

Nuclear fission is a process where a free neutron reacts with a fissionable atomic nucleus so that the nucleus is split into two (or sometimes more) lighter nuclei, called fission products, and two or three new neutrons are released. These neutrons can then trigger new nuclear fissions, sustaining a chain reaction in the reactor. The fission products consist of many different substances. There are both stable and radioactive substances among the fission products.

[3] Light water, H_2O, is ordinary water. Heavy water, D_2O, is water containing heavy hydrogen, deuterium, instead of ordinary hydrogen.

Neutron capture entails that an atomic nucleus absorbs a neutron and thereby becomes heavier. This reaction can occur with all the atoms in the reactor. An important reaction is neutron capture in uranium-238, which leads to the formation of plutonium-239. Further neutron capture in plutonium leads to heavier uranium isotopes as well as to other transuranics[4] (americium, curium etc.). Some transuranic isotopes – particularly plutonium-239 and plutonium-241 – are fissionable in the same manner as uranium-235. As plutonium is built up in the fuel in the reactor, nuclear fissions will therefore also occur in this element. In a light water fuel with a high proportion of fuel that has been in the reactor for a year or longer, plutonium contributes to a considerable portion of the energy production.

Uranium and all transuranics are radioactive substances, or radionuclides. Some isotopes have very long half-lives. An example is plutonium-239, with a half-life of 24,000 years.

The fuel is in the reactor core for three to five years. During this time it is usually moved to several different positions in the core. Approximately three-quarters of the uranium-235 that was present in the fuel from the start is consumed in the reactor. After that it is no longer suitable for further use. It is therefore taken out of the reactor and transferred to a water pool at the nuclear power plant. After cooling for a year or so it is transported to Clab for interim storage pending final disposal.

Around 95 percent of the spent nuclear fuel is uranium, while just over one percent is transuranics and just over four percent is fission products. When the spent fuel is taken out of the reactor it therefore still contains fissionable substances. The spent nuclear fuel can therefore either be regarded as a waste or as a raw material (resource), which after purification (i.e. reprocessing involving separation of uranium and transuranic elements with fissionable isotopes) can be used for new nuclear fuel. Which substances can be reused depends on in which type of reactor they are to be reused. In the Swedish reactors, light water reactors with slow neutrons, it is mainly the nuclides uranium-235 and plutonium-239, but also plutonium-241, that can be used. In a reactor with fast neutrons, other nuclides can also be used.

The largest portion of the transuranics in the waste consists of plutonium (about 90%). Besides being radiotoxic, plutonium is also a nuclear weapons material. The plutonium that has been formed in a light water reactor (reactor plutonium), however, has a composition that is not suitable for nuclear weapons manufacture. After separation from other substances in the spent nuclear fuel, the material can nevertheless be used for primitive nuclear charges.

3.2 Conceivable strategies and systems

As is evident from sections 1.1 and 3.1, there are two possible main approaches for managing the spent nuclear fuel. One entails regarding the fuel as *a resource*, the other as *waste*, see Figure 1-1. Regardless of whether the fuel is regarded as a resource or waste, facilities are needed for interim storage of the spent nuclear fuel and the high-level waste before it is sent to final disposal.

3.2.1 Fuel as a resource

Utilizing the spent nuclear fuel as a resource constitutes a part of both waste management and nuclear fuel supply. Extracting fissionable materials from the spent fuel and reusing them in new fuel reduces the need for new uranium and thereby the need for uranium mining. The more advanced concepts involving *reprocessing, partitioning and transmutation* entail that new types of reactors and facilities for partitioning need to be developed.

To be able to reuse the spent nuclear fuel's content of fissionable materials and extract more energy, the fuel must be reprocessed and the fissionable materials uranium and plutonium separated. Reprocessing gives rise to both high-level and low- and intermediate-level waste, which must be disposed of. This strategy thus also requires facilities for final disposal of radioactive waste. The strategy for the high-level nuclear waste (HLW) in the countries that reprocess the spent nuclear fuel is geological disposal, usually employing concepts that resemble the KBS-3 method.

[4] Transuranics, or transuranium elements, are elements that are heavier than uranium, which is the heaviest naturally occurring element. Transuranics can only be produced by nuclear reactions.

3.2.2 Fuel as waste

If the spent fuel is regarded as waste, there are several possible strategies. Of these, *dumping in the sea, sub-seabed disposal and disposal beneath continental ice sheets* are not possible alternatives for Sweden, since they violate international agreements which Sweden has undertaken to abide by, see Section 2.1. Nor are any of these strategies in line with the nuclear waste convention, which says that waste should, as far as is compatible with the safety of the management of such material, be disposed of in the State in which it was generated. Dumping in the sea and disposal in deep-sea sediment violate the London Convention, while disposal beneath the ice sheet on Antarctica violates the Antarctica Treaty. Furthermore, current knowledge about continental ice sheets and future climate change is not good enough to be able to determine whether this is a safe alternative.

Launching the spent fuel into space would require enormous quantities of rocket fuel and be very costly. The alternative is also associated with considerable risks, above all in connection with launching. In practice, reprocessing and separation are needed to reduce the waste volumes. Due to the need for reprocessing and the great resources that are needed for launching into space, the strategy is not judged to be the an efficient measure for limiting releases and harmful effects of the radioactive substances; the strategy does not meet the radiation protection requirements, see Section 2.3.

SKB made it clear already in the 1986 RD&D programme that dumping in the sea, sub-seabed disposal, disposal beneath the continental ice sheets and launching into outer space can be ruled out, and then repeated this conclusion in RD&D-K /SKB 2000b, p 50/. No objections to SKB's evaluations of these strategies have been offered by anyone in conjunction with the reviews of the RD&D programmes presented since 1986. The strategies are therefore not dealt with further in this report.

Geological disposal is the predominant strategy internationally for disposal of spent nuclear fuel or long-lived high-level waste from reprocessing. All major research and development programmes in the nuclear waste field include efforts to develop technology for geological disposal.

3.2.3 Monitored storage

Monitored storage of spent nuclear fuel and high-level waste is included as a step in most strategies, and experience exists of monitored storage from all nuclear power countries. It is used for interim storage for up to several decades pending further treatment. Clab is an example of such a facility for monitored storage.

In connection with the review and evaluation of SKB's RD&D programmes, monitored storage has been proposed as a strategy for isolating spent nuclear fuel for a very long time, several thousand years, but then in another type of facility. But neither this concept nor other variants of monitored storage entail final disposal of the waste.

3.3 Reprocessing, partitioning and transmutation

Reuse of the spent nuclear fuel's content of fissionable substances requires reprocessing. *Reprocessing* is an advanced chemical engineering process that involves dissolving the nuclear fuel in acid, whereby the substances can be separated out of the solution. Reprocessing produces new waste forms, both high-level waste with some content of actinides[5], and low- and intermediate-level waste that can also contain actinides. Facilities are needed to process this waste to a form that is suitable for final disposal. Furthermore, storage facilities and repositories are required for the different waste types.

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[5] Actinides (from actinium), series of 14 elements following actinium in the periodic table. The actinides begin with thorium (atomic number 90) and end with lawrencium (atomic number 103). Sometimes actinium is also counted among the actinides, since they have similar physical and chemical properties. All are unstable (radioactive) isotopes; only thorium and uranium have isotopes with half-lives of the same order of magnitude as, or greater than, the age of the earth. Actinides with atomic numbers higher than 92, called transuranics, are formed by nuclear reactions. They all gradually decay to lighter elements while emitting ionizing radiation until a stable end product is reached (lead or bismuth).

There are plants for reprocessing of spent nuclear fuel from light water reactors in France (La Hague), the UK (Sellafield), Russia and Japan. The USA, China and India also have plants for reprocessing of nuclear fuel. Some of the plants reprocess both domestic fuel and fuel from other countries that have opted to reprocess their spent nuclear fuel but do not have their own plants.

Transmutation entails converting one element to another by means of a nuclear reaction – for example, nuclear fission or radioactive decay. Nuclear fission in today's light-water reactors is a form of transmutation. In general, however, transmutation refers to conversion of long-lived nuclides, other than uranium and plutonium, to stable or less long-lived nuclides. Actinides are transmuted by nuclear fission with neutrons. The large quantities of energy that are then released can be utilized for electricity production. Transmutation also produces radioactive waste that must be disposed of, although the quantities of high-level, long-lived waste are smaller. Transmutation requires the continued use of nuclear power for a long time. It also requires that the long-lived nuclides to be transmuted are first separated (partitioned) from the rest of the waste and from the uranium.

The purpose of reprocessing, partitioning and transmutation is to make efficient use of the uranium raw material and to convert long-lived radionuclides in the spent nuclear fuel to more short-lived or stable nuclides. Employing transmutation solely for reducing the quantity of high-level, long-lived waste is not efficient, in terms of either costs or resources.

There are several conceivable systems for reprocessing and transmutation. Here we describe the two main alternatives *reprocessing with recycling of uranium and plutonium* and *partitioning and transmutation.* Reprocessing with recycling of uranium and plutonium is already done today. Partitioning and transmutation (P&T) is the subject of research that is expected to go on for decades before it can be possible to build commercial facilities.

3.3.1 Reprocessing with recycling of uranium and plutonium

In reprocessing, uranium and plutonium are separated by chemical means (the Purex process) from other actinides and from the fission products in the spent fuel.[6] The extracted plutonium is used to make MOX fuel, which can be used in LWR's, for example of the type in operation in Sweden today, or in fast reactors. Reprocessed uranium can either be mixed with plutonium in MOX fuel fabrication or be enriched for fabrication of new uranium fuel. After uranium and plutonium have been separated, other actinides, fission products and certain activation products are left. These substances form a high-level long-lived liquid waste that is vitrified to get it into a manageable and stable form that is suitable for final disposal. The remains of the metal cladding on the fuel rods are also left after the separation process. This is a solid waste that contains small quantities of long-lived substances and must be encapsulated in a suitable manner for final disposal. The process is illustrated schematically in Figure 3-1.

New MOX fuel typically contains three to four percent plutonium-239. Approximately two-thirds of the fissionable material is consumed before the fuel is removed from the core. Theoretically, the spent MOX fuel can be reprocessed again, but in practice this is not done since the plutonium that is extracted in reprocessing also contains heavier plutonium isotopes (heavier than plutonium-239). This makes the plutonium less useful for fabrication of new reactor fuel for LWR's.

The result of reprocessing with recycling of uranium and plutonium is thus that the original spent nuclear fuel has been transformed into high-level vitrified waste, spent MOX fuel for direct disposal and some other radioactive waste from the reprocessing and fuel fabrication.

[6] The Purex process (Plutonium Uranium Redox EXtraction) is a chemical process for separating uranium and plutonium from the spent fuel. The method is based on the fact that different elements dissolve to different degrees in different solvents. The remaining fission products are converted to solid form. They comprise the high-level waste from reprocessing.

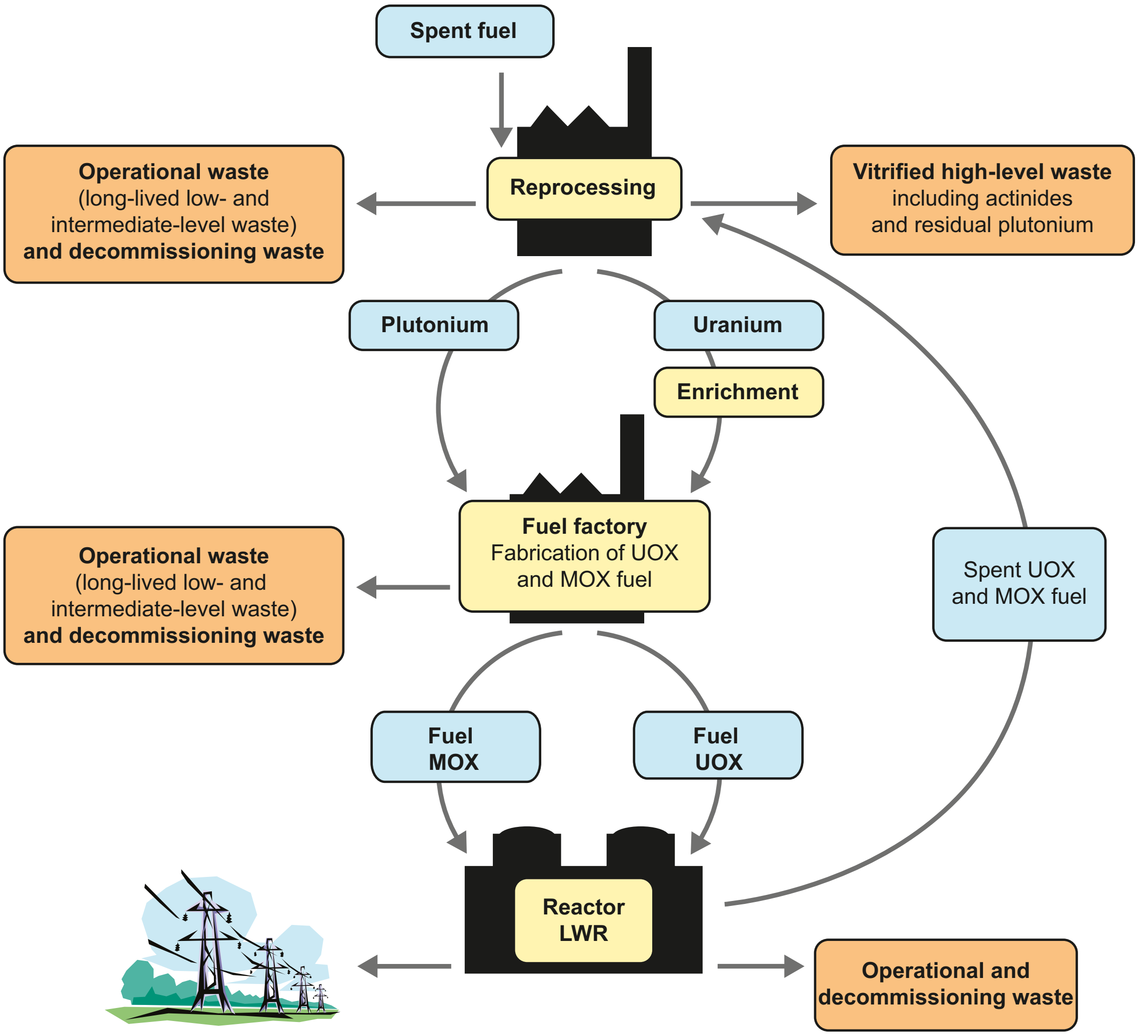

Figure 3-1. *Reprocessing with recycling of uranium and plutonium as MOX fuel. (MOX = Mixed oxide fuel, fuel made of plutonium oxide and uranium dioxide; UOX = fuel made of uranium dioxide; LWR = Light Water Reactor.)*

Viewed in relation to the energy that is produced, recycling of uranium and plutonium reduces the total quantity of actinides to be disposed of, along with the total quantity of plutonium that has to be managed as waste. In principle, however, a similar system is required to deal with the spent MOX fuel and the high-level vitrified waste as in the case of direct disposal of spent nuclear fuel.

MOX fuel was used experimentally for the first time in 1963. MOX fuel has been in commercial use since the 1980s. Today MOX fuel is used in more than 30 reactors in Europe. In Sweden, the Oskarshamn nuclear power plant has obtained a permit from the Government to use MOX fuel in reactors 2 and 3, but the permit has not yet been utilized[7] /KSU 2005/.

[7] In 1969, Oskarshamns Kraftgrupp AB reached an agreement with the owners of the reprocessing plant at Sellafield on the reprocessing of 140 tonnes of spent fuel from the reactors in Oskarshamn. The licence to use MOX fuel in reactors 2 and 3 applies only to MOX fuel made of plutonium from reprocessing of this fuel. Three MOX fuel assemblies have been irradiated in an experiment in Oskarshamn 1. Today (2010), these assemblies are in the fuel pool at Oskarshamn 1 pending transfer to Clab.

3.3.2 Partitioning and transmutation (P&T)

As already mentioned, the purpose of reprocessing, partitioning and transmutation is to utilize the uranium raw material efficiently and to greatly reduce the quantity of long-lived radionuclides by transforming, or transmuting, them to more short-lived or stable substances. Above all, the quantity of transuranics, i.e. elements heavier than uranium, is reduced. Transuranic elements are formed in nuclear reactors by the capture of one or more neutrons by uranium atoms, which are then transformed by radioactive decay to neptunium, plutonium, americium or curium. A few long-lived fission products (e.g. technetium-99, iodine-129) may also be of some interest for transmutation[8].

The long-lived radionuclides can be transformed to more short-lived or stable nuclides by nuclear-physical processes. In theory and on the laboratory scale, a number of such processes are possible, but the only process that has been used thus far for transmutation on a large scale is irradiation with neutrons. Neutrons can split the nuclei in transuranic atoms so that they are transformed into other nuclides. Large-scale transmutation of transuranic elements from spent nuclear fuel must take place in a plant that resembles a nuclear reactor, and since the nuclear fission process releases large quantities of energy the plant will resemble a nuclear power reactor.

The type of waste that arises and the quantities in which it arises are determined by the partitioning processes, the transmutation and the number of recyclings. The content of long-lived radionuclides decreases radically, but some high-level, long-lived waste will always remain and require similar management as in the case of direct disposal of spent nuclear fuel.

A prerequisite for transmutation by neutron irradiation is that the nuclides to be transmuted have been separated from other nuclides in the spent fuel. In particular, residual uranium must be removed in order to avoid the formation of more plutonium and other transuranics. Separation, or partitioning, of the different elements can in principle be achieved by mechanical and chemical processes. In existing reprocessing plants, uranium and plutonium can be separated from each other and from other elements in spent nuclear fuel. With the Purex process (see Section 3.3.1), neptunium can also be separated, although this requires a slight modification of the process.

The goal of current *research on partitioning* is therefore to find and develop processes that are suitable for partitioning of heavier transuranics, and possibly also some fission products, on an industrial scale. The goal of current *research on transmutation* is to define, investigate and develop plants that are suitable for transmutation of the aforementioned long-lived radionuclides on an industrial scale. Figure 3-2 shows a schematic diagram for a system for reprocessing, partitioning and transmutation.

A necessary prerequisite for the processes and plants that may result from this research and development is that they be accepted by society. They must therefore meet very tough requirements on safety, radiation protection and environmental protection. They must be economically defensible and provide good security against the proliferation of fissionable material. In order for the plants and processes to be economically defensible, the large quantities of energy that are released in the transmutation process must be utilized, e.g. for electricity generation.

[8] The reason these fission products attract some interest for transmutation is that both are long-lived (214,000 years and 17 million years, respectively). Furthermore, iodine in particular has high mobility – it accompanies the groundwater. Technetium also has high mobility since it can form negative ions under oxidizing conditions.

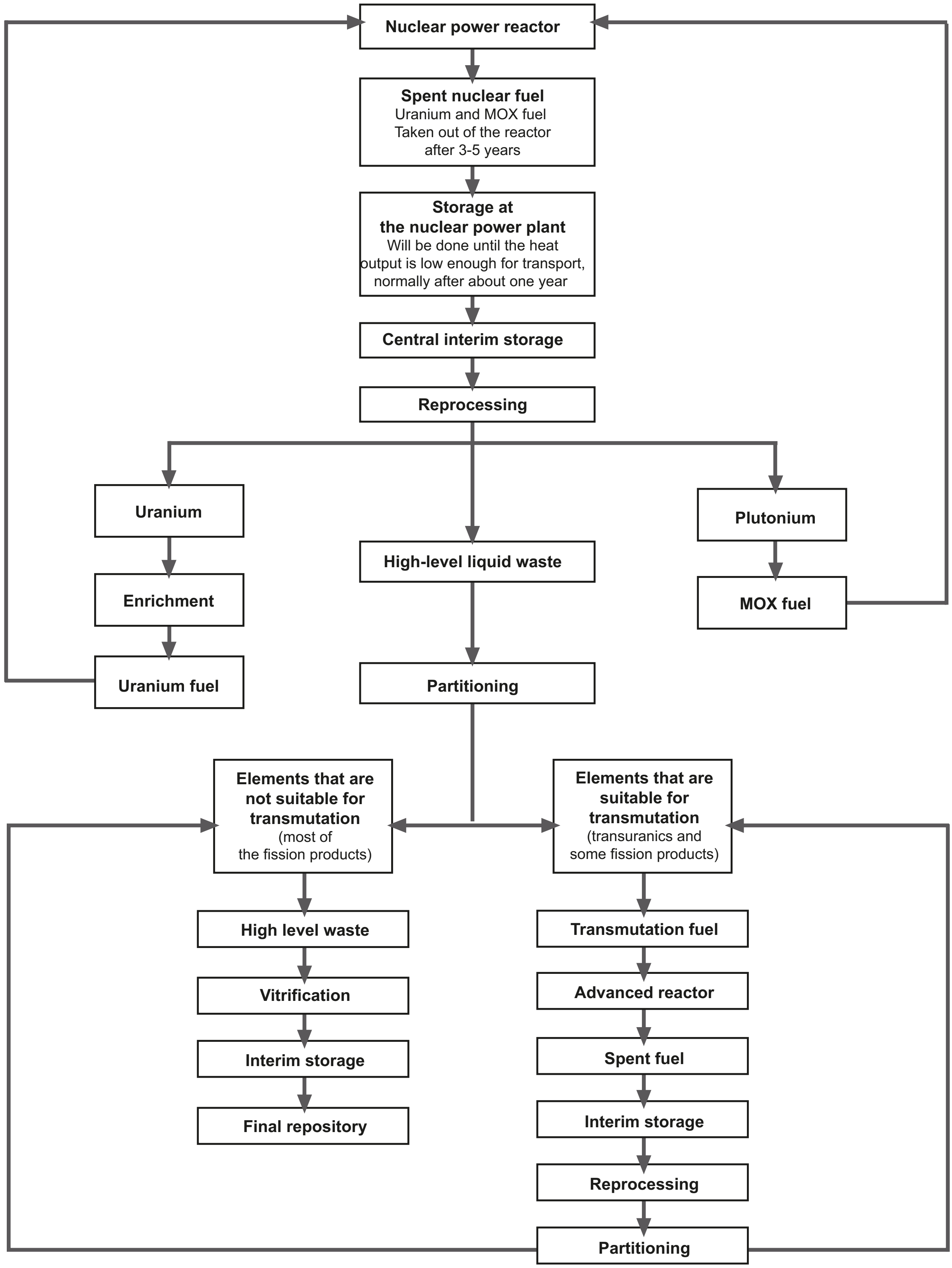

Figure 3-2. *Reprocessing, partitioning and transmutation.*

SKB has submitted reports on the state of research within Partitioning & Transmutation on four occasions during the past ten years. The most recent report /Blomgren et al. 2010/ reveals the following:

- Between 1995 and 2009, SKB was the main sponsor of P&T research in Sweden. Swedish researchers have also received considerable funding from the European Commission by participation in the EU's framework programmes. In October 2009, the Swedish Research Council awarded SEK 36 million to the GENIUS project (Generation IV research in Universities in Sweden), which is a project targeting next generation critical[9] reactors. The first anticipated use of such reactors is generally expected to be partitioning and transmutation of spent fuel from today's nuclear reactors. This backing by the Swedish Research Council has thereby dramatically increased the activity level within P&T, and SKB is no longer the main sponsor in this area.
- The political situation regarding nuclear power has changed dramatically during the last three years in Sweden, Europe and the world. This change affects the conditions for research and development on P&T. P&T research for future energy systems based on advanced nuclear reactors, advanced nuclear fuels and advanced nuclear fuel cycles is attracting considerable interest among students in nuclear disciplines. Interest within the nuclear energy industry has been more limited, but is now increasing, primarily because of the increased interest in fast reactors.
- There was a gradual increase in the EC's funding of research and development on P&T during the period 1990–2003. The financial support has since levelled off. It is unclear today what support will be available in future programmes. Within the Commission the expectation seems to be an unchanged level of funding to ADS research in the foreseeable future[10], whereas funding of research on fast reactors could increase.
- Successful development of Partitioning & Transmutation as a subsystem in concepts with advanced fuel cycles will not eliminate the need for final disposal high-level and long-lived waste. Successful development of P&T may, however, reduce the requirements on the engineered barriers. Compared with the waste from today's reactors, the complex processes will generate a larger quantity of fission products, while the quantity of actinides will decrease. The quantity of low- and intermediate-level waste will increase due to the partitioning processes. This waste will be even more long-lived due to the content of fission products.
- The implementation of partitioning and transmutation to effectively reduce the quantity of long-lived radionuclides that must be placed in a geological repository necessitates a commitment to nuclear power for a very long time, more than 100 years.
- It is important for Sweden to participate in international development efforts while maintaining a reasonable level of competence within the country, at least as long as a large proportion of the country's electricity is based on nuclear energy. Competence developed in research on P&T is valuable, not just for assessing development and potential in this field, but also for development of safety and fuel supply at existing reactors.
- Recently, a generation change has taken place in the Swedish university research groups active in nuclear-power-related research, and at present these activities are growing rapidly, both due to increased interest in research and a greater need for education. The leading scientists in the new generation have all established themselves in projects supported by SKB and SKC[11], and most of them have been involved in P&T research. This research has thereby already played a crucial role in supporting Swedish competence in the field of nuclear power.

[9] Critical reactors: most reactor types are critical, i.e. each nuclear reaction in the reactor initiates a new fission, on average. If fewer fissions are initiated, the reactor is subcritical, and if on average more fissions take place, the process is called supercritical. ADS reactors are subcritical (ADS, Accelerator-Driven Systems for conversion of long-lived nuclides in the spent nuclear fuel).

[10] ADS, Accelerator-Driven Systems for conversion of long-lived nuclides in the spent nuclear fuel.

[11] SKC, Swedish Centre for Nuclear Technology, at the Royal Institute of Technology (KTH).

3.4 Geological disposal

Geological disposal entails utilizing an environment that has been and will be stable over a very long time. The safety of the repository is based on a combination of the natural barrier comprised by the rock, the great depth and the environment at repository depth, plus man-made engineered barriers. The engineered barriers are adapted to conditions at repository depth and designed so that they isolate the spent fuel and prevent dispersal of radioactive substances for long periods of time. Repository safety must be satisfactory even if one barrier should be defective or fail to function as intended. The spent fuel itself has extremely low solubility in water, and most radionuclides that are radiotoxic in the long term have limited mobility in geological environments. The engineered barriers are designed so that they do not require any maintenance after deposition is concluded and the repository has been closed.

Internationally, geological disposal is the predominant strategy for final disposal of spent nuclear fuel or long-lived HLW from reprocessing /Grundfelt 2010a/. Different geological settings have been studied according to the natural conditions existing in different countries. The bedrock being considered in Sweden is crystalline rock that is between one and two billion years old. Clay and salt formations are among the geological media being investigated in other countries.

If human intrusion is disregarded, man and the environment can only be exposed to the radioactivity from the final repository if radionuclides are released from the repository and transported so that they reach surface ecosystems. An environment in the rock is therefore sought where the engineered barriers can be expected to remain intact in a very long time perspective and where the exchange with the surface is small. The groundwater is the medium that can transport radionuclides up to the surface from repositories at great depth in crystalline rock. However, mobile groundwater is lacking in salt formations, a type of geological formation that exists mainly in Germany, but also at the USA's Waste Isolation Pilot Plant (WIPP) for military waste in New Mexico.

A general conclusion from investigations in cored boreholes in Sweden and abroad is that the water exchange with the ground surface declines with depth, while salinity, temperature and rock stresses increase, see Figure 3-3. These conditions affect the design of a repository and its engineered barriers as well as long-term safety.

Sampling of groundwater in boreholes shows that groundwater at great depth is free of dissolved oxygen and that the oxygen that is dissolved in precipitation water is consumed near the ground surface. The absence of dissolved oxygen, i.e. reducing conditions, is favourable for several reasons. It reduces the risk of corrosion of the canister while reducing the solubility of, and increasing the transport resistance for, a number of nuclides. All in all, reducing conditions improve the repository's ability to contain and retard the transport of radionuclides.

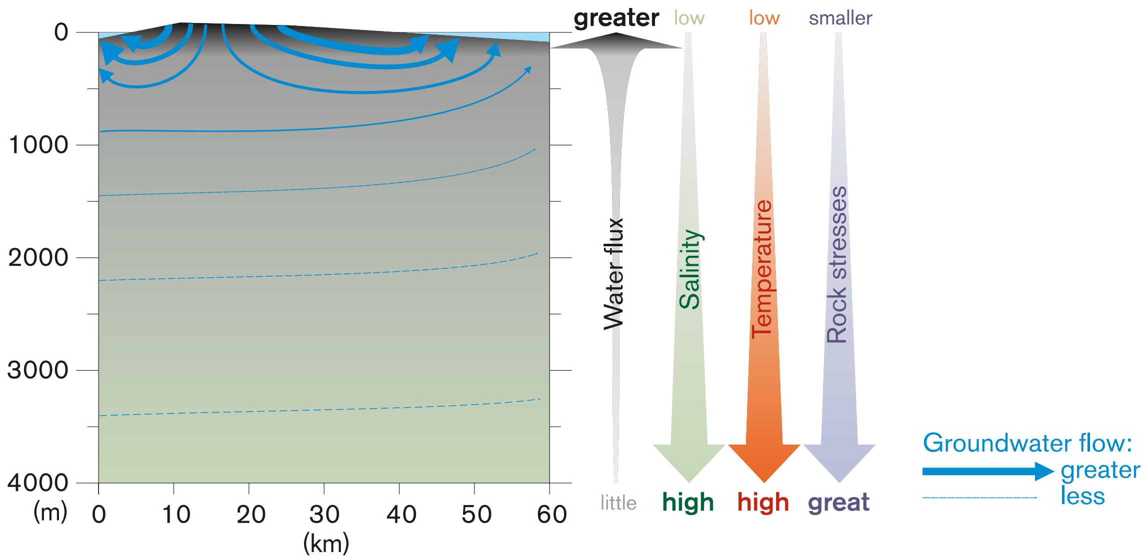

***Figure 3-3.** Some conditions in the bedrock that influence the design premises for a repository, the design of the engineered barriers, and long-term safety.*

A geological repository can be designed in different ways, depending for example on what type of geological formation it is located in. The following alternatives for disposal in crystalline rock have been studied in Sweden /SKB 2000a/:

KBS-3 – deposition in a system of short tunnels at a depth of 400–700 metres.

Long tunnels (VLH = Very Long Holes) – deposition in a few parallel tunnels several kilometres long at a depth of 400–700 metres.

WP-Cave – deposition in a rock volume within which the water flux has been reduced by various engineering means.

Deep boreholes – deposition at a depth of several thousand metres.

The different systems for geological disposal differ primarily in the configuration of the actual repository in the bedrock. An interim storage facility and a transportation system are needed under all circumstances. The same applies to a plant for encapsulation, even though canister types and encapsulation methods are dependent on the design of the actual repository.

In the first three systems, the final repository consists of tunnels, shafts and other rock caverns. A common feature of the two first alternatives, disposal in tunnels of different length, is that the layout of these tunnels is based on the requirement that the temperature on the canister surface may not exceed 100°C, with a view to the thermal resistance of the engineered barriers. This means that the canisters, each embedded in its own buffer, must be deposited at a certain minimum distance from each other. In the WP-Cave system, the fuel is emplaced densely spaced in a limited rock volume, which is surrounded in its entirety by a buffer. This means that the repository must be kept open and air-cooled during a long initial period (more than 100 years), and that the repository and the barriers are exposed to high temperatures. Long-term safety is achieved in all three systems by interaction between the engineered barriers and the rock.

The alternative of disposal in deep boreholes differs in principle from the three others in two important respects. In the first place, the waste will be emplaced in boreholes at a depth of several thousand metres, instead of in a tunnel system at a depth of a few hundred metres. In the second place, the primary safety function differs between disposal in deep boreholes and disposal according to the KBS-3 method. Aside from the fact that the rock is a barrier in both methods, the safety assessments that have been conducted for the KBS-3 method show that the encapsulation of the spent nuclear fuel in the leaktight copper canister is the most essential safety function in the long term. In the case of Deep Boreholes, the expected slow groundwater movements at great depths are assumed to be the most important safety function.

The four systems are illustrated in Figure 3-4.

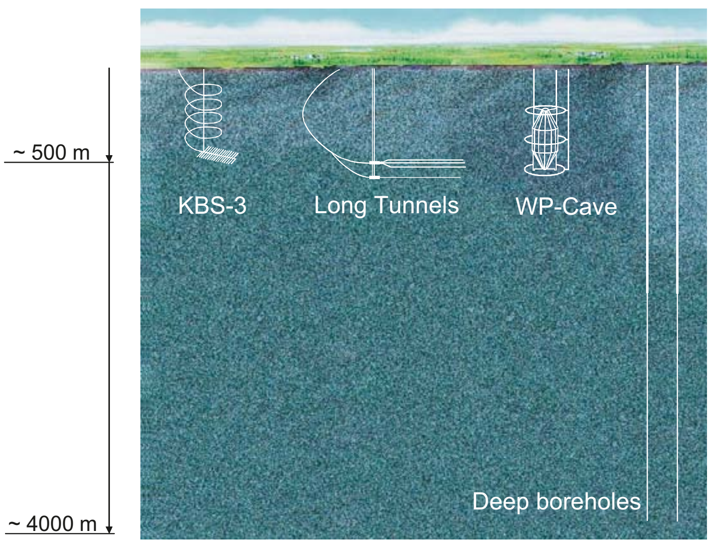

***Figure 3-4.** Different systems for geological disposal of spent nuclear fuel.*

3.4.1 The KBS-3 method

The method involves encapsulating the fuel in copper canisters which are then deposited, surrounded by a buffer of bentonite clay, in deposition holes in a tunnel system at a depth of 400–700 metres in the bedrock, see Figure 3-5. The purpose of the three barriers (canister, buffer and rock) is to isolate the radionuclides in the fuel from the surrounding environment.

The KBS-3 method has been designed with a view to keeping radiation to personnel low during all handling steps. The fuel assemblies are placed intact in the canister, without prior processing. The canister itself provides protection against radiation. Furthermore it is provided with a radiation shield when it is handled.

The canister is delivered ready-made to an encapsulation plant. It is composed of a cylindrical container consisting of a shell (overpack) of copper, with a pressure-bearing insert of cast nodular iron. The insert is provided with channels for placement of fuel assemblies. When the canister is full, a steel lid is fitted on the insert. A copper lid is then welded onto the canister. The canister is about five metres long and has a diameter of about one metre. The thickness of the copper shell is five centimetres. A canister filled with two tonnes of spent nuclear fuel weighs 25–27 tonnes.

The final repository's underground parts comprise ramp, shafts, central area and repository area with deposition tunnels. The canisters are emplaced in vertical holes, surrounded by bentonite clay, in the 200–300 metre long deposition tunnels. The holes have a diameter of 1.75 metres and are about eight metres deep. The deposition holes are spaced at a distance of six to eight metres from each other. The spacing between the deposition holes is dependent on such factors as the thermal conductivity of the rock and the canisters' initial decay heat.

After the canisters have been deposited, the tunnels are backfilled. Other openings will be backfilled when all spent nuclear fuel has been deposited. When tunnels and shafts have been backfilled up to the ground surface, the repository is closed and sealed.

The canisters with nuclear fuel are not intended to be retrieved after deposition. However, the final repository is designed so that it is possible for deposited waste to be retrieved. One reason for retrieval could be that future generations may for some reason want to modify or improve the design or function of the repository or to use the waste for other purposes. However, relatively extensive measures will be required to carry out a retrieval after closure.

Figure 3-6 shows the schematic design of a repository according to the KBS-3 method. The facility consists of a surface part with an operations area containing various service functions, an underground repository part and technical systems. The surface and underground parts are connected by a transport tunnel (ramp), a skip shaft for haulage of rock spoil and bentonite, and an elevator shaft. There is also a ventilation shaft.

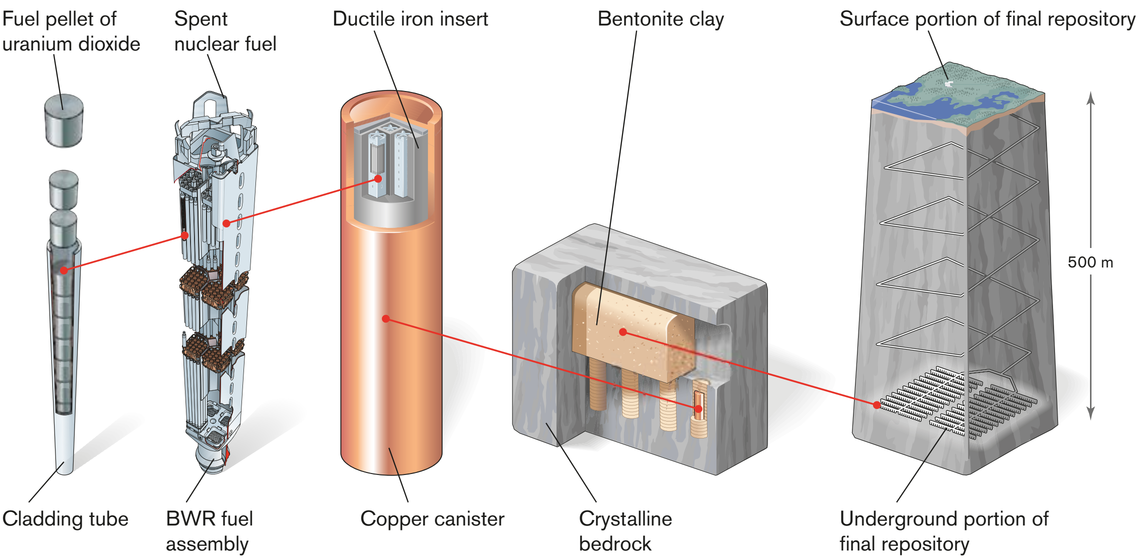

Figure 3-5. *Principles of final disposal of spent nuclear fuel according to the KBS-3 method.*

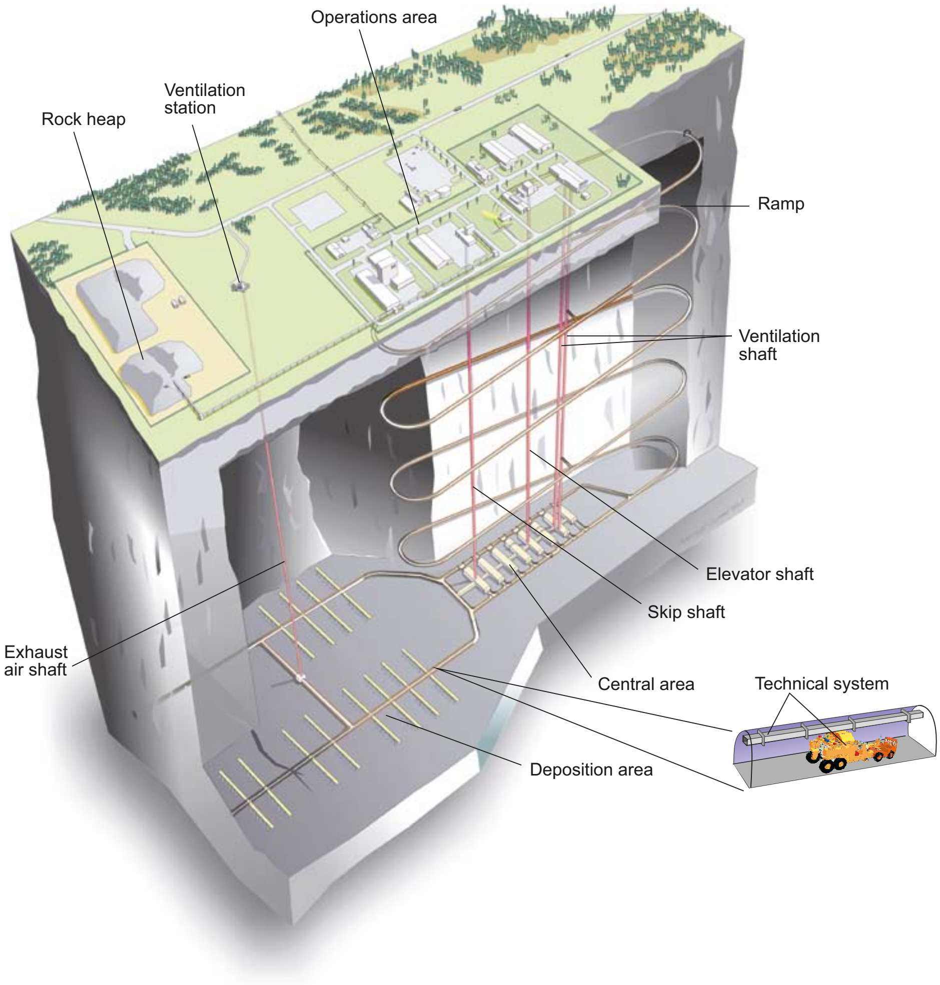

***Figure 3-6.** Schematic layout of a final repository according to the KBS-3 method.*

The leaktight copper canister will keep the spent fuel completely contained. The buffer of bentonite clay will protect the canister against corrosion attack and minor rock movements. If there are any leaky canisters, the buffer, together with undamaged parts of the canister, will prevent water from entering the canister and impede the escape of radionuclides from the canister. The rock provides an environment where the function of the engineered barriers is preserved for very long periods of time. The rock and the great depth of the repository will keep the spent fuel isolated from man and the environment. Radionuclides from leaky canisters are retained and retarded in the rock by low water flux, and by the adherence of the radionuclides to fracture surfaces and pores in the rock.

Due to the fact that the final repository is located in a long-term stable geological environment with no workable minerals, the waste is isolated from humans and the surface environment and the risk of human intrusion is reduced. This means that the repository is not appreciably affected by either societal changes or by the direct effects of long-term climate change on the Earth's surface. The spent nuclear fuel is surrounded in the final repository by several engineered and natural barriers whose primary function is to isolate the fuel. If this isolation should be broken, the secondary safety function of the barriers is to retard any release from the repository. The barriers are passive and consist of naturally occurring materials that are stable over the long term in the repository environment. Being passive means that they function without human intervention and without the active input of materials or energy.

SKB's main alternative is to deposit the canisters in vertical holes, KBS-3V. SKB is also studying an alternative involving horizontal deposition of the canisters, KBS-3H, see Figure 3-7.

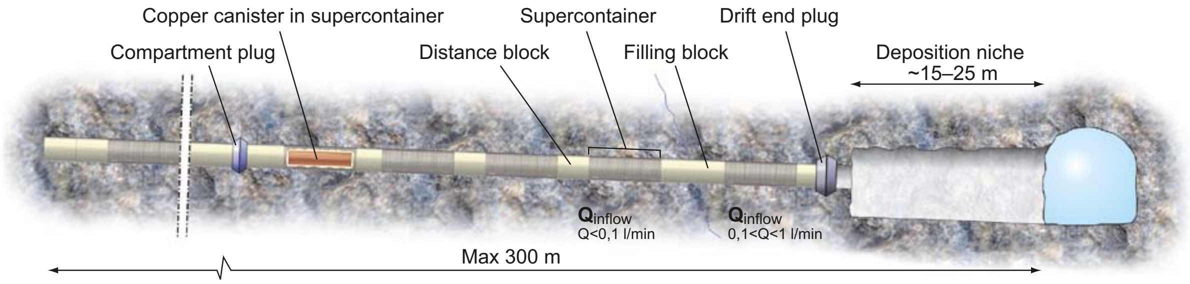

Figure 3-7. *Schematic illustration of a KBS-3H repository.*

In the KBS-3H variant, no deposition tunnels are needed; instead, 100–300-metre long deposition drifts are bored directly from the main tunnel. Packages (called supercontainers) consisting of a canister surrounded by bentonite buffer and a perforated steel cylinder are emplaced in the deposition drifts. A distance block of bentonite clay is placed between successive supercontainers to seal the tunnel so that water flow along the tunnel is prevented and the temperature in the buffer does not get too high. A drift end plug is installed in the mouth of the deposition drift. The plug holds the supercontainers and distance blocks in place until the main tunnel is backfilled. The deposition drifts may be spaced at a distance of 25–40 metres, depending on the properties of the rock.

There are many similarities between KBS-3V and KBS-3H, see Figure 3-8. The fuel is the same in both variants, as are the barriers canister, buffer and rock. Large parts of the facilities above and below ground are identical or similar in both variants. The biggest difference between KBS-3V and KBS-3H is that KBS-3H lacks deposition tunnels. This means that the volume of rock excavated for a KBS-3H repository is much less (about 50 percent) than for a KBS-3V repository, and that the amount of clay used for backfilling is less.

SKB commenced studies of horizontal deposition in the early 1990s. SKB and Posiva have since jointly investigated the potential for horizontal deposition. In addition to technical studies and tests, a preliminary assessment of the long-term safety of a KBS-3H repository has been carried out under the leadership of Posiva. The assessment focused on the properties and processes that are specific for KBS-3H. The conclusion is that KBS-3H offers the potential to meet the safety requirements for a final repository in Olkiluoto (the safety assessment was conducted with site data from Olkiluoto, the site selected for the Finnish final repository). However, further research, development and demonstration is required in order to perform a comprehensive safety assessment. SKB's judgement is that the technology is not sufficiently developed in order for KBS-3H to be an available alternative today. Considerable work remains to be done to determine whether it can be used.

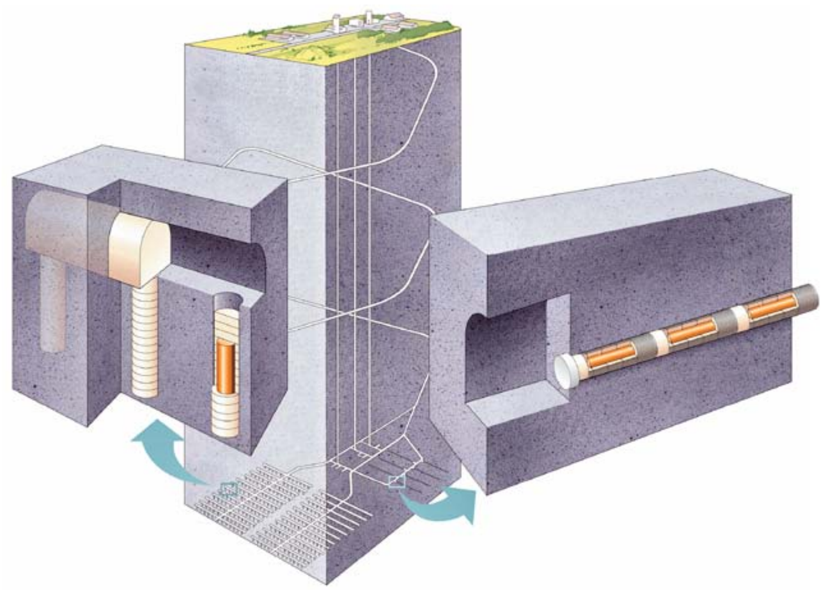

Figure 3-8. *Deposition in vertical holes (KBS-3V) and in horizontal drifts (KBS-3H).*

Long Tunnels (VLH) and WP-Cave

The engineered barriers and materials for a final repository according to the Long Tunnels (VLH = Very Long Holes) alternative are the same as in a KBS-3 repository. But there are no deposition holes or drifts in this alternative; instead, the canisters are emplaced horizontally, one after the other, in approximately 4.5 kilometre long bored tunnels that run alongside each other at a depth of about 500 metres, see Figure 3-9. The distance between the tunnels is approximately 100 metres. An investigation tunnel is bored approximately 100 metres below each deposition tunnel. The volume of rock that is excavated is much less than in KBS-3V, which is an advantage from a resource viewpoint. Deposition, as well as inspection and possible retrieval of deposited canisters, is, however, more complicated than in a KBS-3V repository /SKB 2000a/.

In a WP-Cave repository, the spent fuel is placed in canisters that are deposited densely spaced in a system of tunnels, see Figure 3-10. The tunnels are provided with ventilation shafts and the repository can be air-cooled. The whole tunnel system is surrounded by a bentonite-filled slot. Outside the slot is a hydraulic cage, i.e. a system of tunnels and boreholes that leads the groundwater around the deposition area. The hydraulic cage and the slot enclose a rock volume with favourable hydrological, mechanical and chemical conditions where the fuel canisters are emplaced. Despite the fact that the canisters can be deposited tightly together, the total volume of rock that is excavated is greater than for a KBS-3 repository. This is because the slot and the hydraulic cage occupy a large volume /SKB 2000a/.

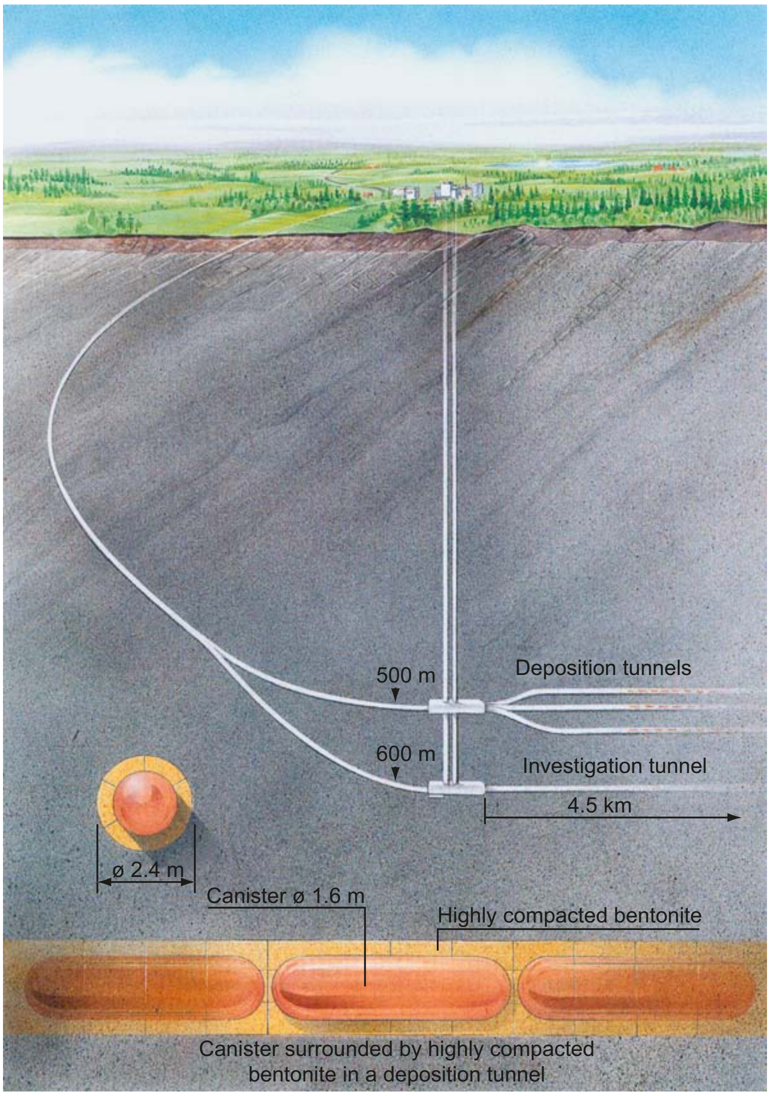

Figure 3-9. *Schematic illustration of a final repository with long tunnels.*

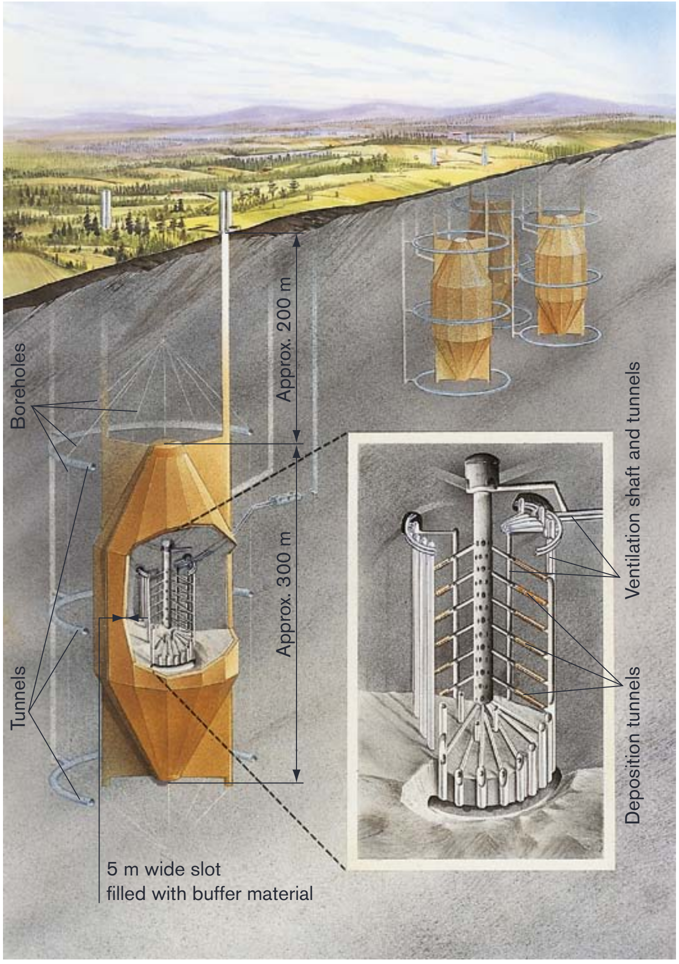

Figure 3-10. *Schematic illustration of a final repository according to the WP-Cave concept. The canisters with the spent fuel are stored in drifts bored radially and with a slight downward slope out from a central shaft. The repository is surrounded by a sand-bentonite barrier and a hydraulic cage of boreholes.*

3.4.2 Deep Boreholes

Back in 1986 – in the first RD&D programme under the Nuclear Activities Act /SKB 1986/ – SKB discussed the possibility of using a system of deep boreholes for final disposal of the spent nuclear fuel. The possibility was also mentioned in RD&D-Programme 89. The alternative was included in the PASS study /SKB 1992a/ and presented in RD&D-Programme 92 /SKB 1992b/. Since then, SKB has kept track of developments in the area. Accounts of the concept have been included in all RD&D programmes. A broad comparison between the KBS-3 method and the Deep Boreholes concept is presented in /Grundfelt 2010b/. The report is also an up-to-date summary of the state of knowledge within the area of Deep Boreholes.

The concept entails that a number of holes are drilled vertically from the ground surface down to great depth in the bedrock. According to the concept presented in the PASS study, the spent nuclear fuel is encapsulated in canisters with an outside diameter of 0.5 metre and a length of five metres, which is smaller than in the KBS-3 concept. This means that more canisters are needed. The canisters are lowered into the holes and stacked on top of one another. Deposition occurs at a depth of between two and four kilometres. The diameter of the borehole is one metre down to two kilometres and 0.8 metre where the canisters are emplaced.

The canisters are surrounded by a buffer consisting of a mixture of bentonite and a deployment mud. Highly compacted bentonite is placed between the canisters. The upper two kilometres of the hole is sealed with a combination of bentonite, asphalt and concrete. Figure 3-11 shows a schematic illustration of the concept.

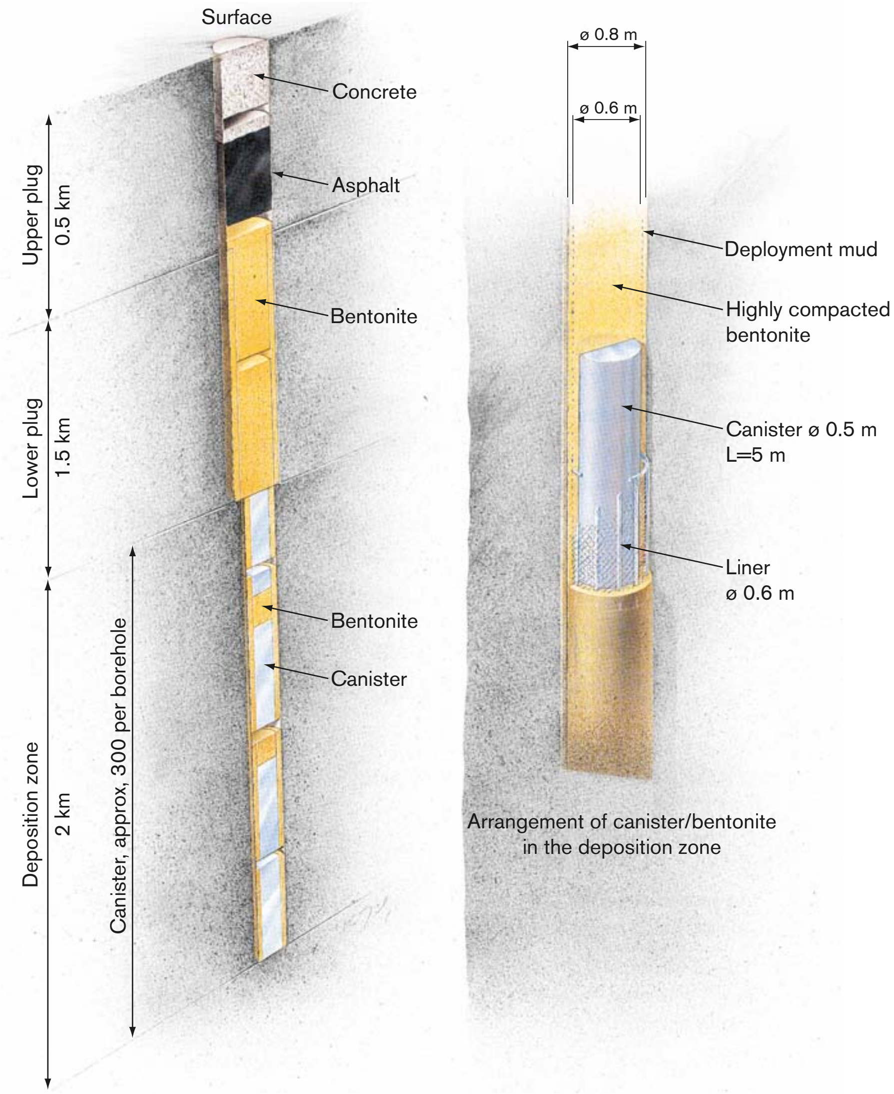

Figure 3-11. *Schematic design of disposal in deep boreholes. Note that the figure is not according to scale (modified from /SKB 1992a/).*

At each deposition hole, equipment is needed for drilling and preparation of the hole, for handling of drilling fluid, for interim storage and radiation-shielded handling of canisters, for lowering of canisters into the hole and for sealing. The surface area required for this handling has been estimated at about 10,000 m^2 per hole. It is uncertain how closely spaced the holes can be. In previous studies, a spacing of 500 metres has been assumed to be sufficient with a view to the risk of "collision" between boreholes that deviate from the vertical and the heat output of the deposited fuel. With modern technology for vertical guidance of the drilling, it should be possible to locate the boreholes closer to each other.

With the currently planned operating times for the Swedish reactors (50 years for the reactors in Forsmark and Ringhals, 60 years for the reactors in Oskarshamn), some 18,000 canisters would be needed, and these would be deposited in some 60 deep boreholes. Assuming 500 metres between the boreholes and 60 holes, the total surface area would be over 13 square kilometres.

Drilling technology and canister dimensions

A consensus prevails that today's technology permits drilling to a depth of about four kilometres in hard crystalline rock, with a diameter at the bottom of the holes of about 445 millimetres, see /Brady et al. 2009, Beswick 2008, Baldwin et al. 2008/. But in order to hold BWR assemblies, the canister must have a diameter of 500 millimetres, which requires a borehole diameter at repository depth of about 800 millimetres. SKB's and others' judgement is that this cannot be achieved with today's drilling technology, see /Beswick 2008/.

If the hole diameter is reduced, the diameter of the canisters must also be reduced, which means they would hold less fuel. A practical limit on how slim a canister can be made is set by the dimensions of the fuel assemblies. From a radiation protection viewpoint, it is not advisable to split up the fuel assemblies. A fuel assembly from a boiling water reactor (BWR) has a maximum width of 134 millimetres. To make room for this, a canister must have an outside diameter of around 300 millimetres, and the borehole must have a diameter of about 400 millimetres, which is deemed possible to drill with today's technology.

A fuel assembly from a pressurized water reactor (PWR) has a maximum width of 214 millimetres. A canister capable of holding such an assembly must have an outside diameter of about 400 millimetres, which requires a borehole with a diameter of about 500 millimetres. It is doubtful whether it is possible to drill such holes with today's technology.

In summary, it is deemed possible with today's drilling technology to drill holes that make it possible to deposit one BWR assembly per canister. But in order for the process to be reasonably economical, each canister should contain at least four fuel assemblies. The drilling technology must be developed to achieve this. SKB's assessment is that technology for drilling four kilometre deep holes, with a diameter of 800 millimetres at the bottom, is possible to develop, but that this poses a great challenge.

The technical drilling difficulties involve not only being able to drill deep enough with sufficiently large diameter. A larger diameter also makes it more difficult to pump up the drill cuttings. In addition, it increases the risk of collapse and breakout from the wall of the hole and the risk of an oval hole, causing the drill string and the casings to get stuck. A larger diameter also complicates handling of the casings, since they are much heavier. Nor is it possible to rule out the risk of the canisters getting stuck during the deposition process.

According to the PASS study's Deep Boreholes concept, the fuel is deposited at a depth of 2–4 kilometres. Others who have studied deposition in deep boreholes mention deposition at even greater depth, for example 3–5 kilometres /Åhäll 2006/. Increased depth poses even greater challenges when it comes to both drilling technology and deposition of canisters.

In order to reduce the number of boreholes and thereby the total surface area needed, it has been suggested that each borehole be branched into multiple boreholes at suitable depth /Åhäll 2006, Chapman and Gibb 2003/, see Figure 3-12. This would reduce both the area needed on the surface and the total quantity of drill cuttings for disposal. The technique of branching boreholes is common in the petroleum industry, where the branch holes usually have a diameter of 165 or 216 millimetres. The branches are relatively easy to achieve in soft rock. The difficulties of achieving a branch are greater in harder rock, since it is difficult to exert sufficient pressure on the drill bit. Similarly, the difficulties increase with greater hole diameter due to the fact that the drill string becomes too stiff. Branched holes with a diameter of 165 or 216 millimetres can be made in granite, but not holes with a larger diameter than 311 millimetres.

Branched boreholes are deemed to be unsuitable as deposition holes for spent nuclear fuel due to the fact that:

- the deposition holes are too slim because the diameter of the branch holes has to be less than that of the main hole,
- the transition between main hole and branch hole cannot be lined with casing and is therefore sensitive to hole deformation and breakout,
- guidance of deposition to the desired branch becomes complicated with multiple branches and many canisters,
- the risk that canisters will get stuck in the hole during deposition increases significantly with branched holes.

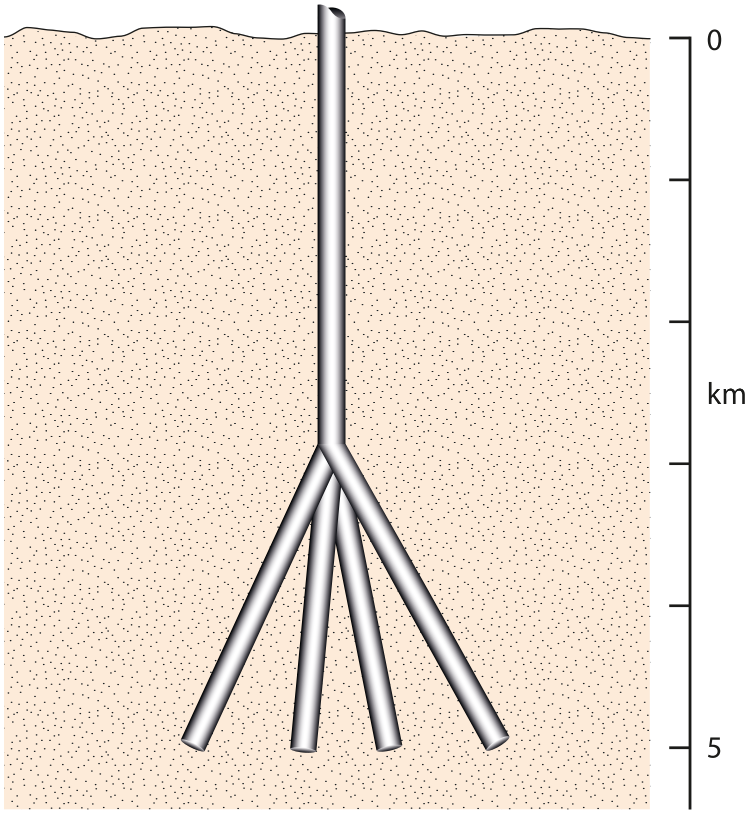

Figure 3-12. Proposed branched deposition hole /Åhäll 2006/.

Canister, buffer, backfill

A canister of titanium with a concrete fill was proposed in the PASS study /SKB 1992a/. A number of other canister alternatives have been discussed, but rejected as being less advantageous or unsafe. Owing to the aggressive environment (high salinity, high pressure and high temperature), it is highly uncertain if even an advanced canister material could keep the fuel contained for an extended period.

The canisters would be surrounded by a buffer consisting of a mixture of bentonite and a deployment mud. The purpose of the buffer is to keep the canisters in place, to counteract transport with flowing groundwater in the borehole and to delay the spread of radionuclides from canisters that have for some reason lost their isolating function. The upper two kilometres of the borehole would be filled with a combination of bentonite, asphalt and concrete.

Long-term safety

In a repository according to the concept of disposal in deep boreholes, the rock itself is the most important barrier for isolating the waste and preventing radionuclides from entering the biosphere. The concept is based on the assumption that the groundwater conditions at great depths are stagnant. The reason is that permeability is generally lower and that the groundwater has high salinity (and thereby also high density) and therefore tends not to mix with the lighter fresh water above. Figure 3-3 illustrates how properties such as water flux, salinity, temperature and rock stresses change with depth. A conceptual model for the uppermost five kilometres of the bedrock in Sweden is proposed in /Juhlin et al. 1998/. Any groundwater movements that do occur at great depth are not believed to have any contact with the ground surface. This means that radionuclides from the deposited spent nuclear fuel could not be carried up to the surface by the groundwater.

The safety of disposal in deep boreholes has never been analyzed in the way that has been done for the KBS-3 method. An important reason for this is that our knowledge of conditions at great depths is not adequate for carrying out a meaningful safety assessment. The Deep Boreholes concept and its function has, however, been examined in a number of studies, see /Grundfelt 2010b/.

International studies of deep boreholes

Several international reports on deep boreholes were published in 2008 and 2009 – two in the UK, one in Canada and one in the USA. They mainly discuss disposal in deep boreholes of special waste types with small volumes, for example plutonium from scrapping of nuclear weapons.

The British Nuclear Decommissioning Authority (NDA) published a study on the Deep Boreholes concept in 2008 /Beswick 2008/. The study focuses on drilling-related questions. Questions concerning encapsulation and deposition technology require further study before it is possible to determine whether the concept may be viable. The overall conclusion in the study is that the Deep Boreholes concept may, under certain circumstances, be a credible option for the UK, but that a great deal of development work would be required on both drilling technology and deposition technology.

The study mentions that the technology for drilling at great depths has been developed strongly within the petroleum industry over the past 25 years. However, practical experience is with holes with smaller dimensions and mainly in sedimentary bedrock. No experience exists from drilling of deep holes with large diameters and in crystalline bedrock.

According to the study, only completely vertical holes should be considered. The possibilities of drilling such deep holes have been evaluated for four different diameters: 300, 500, 750 and 1,000 millimetres free inside diameter in the casings. The diameter of the drilled hole needs to be 20–50 percent larger. With today's experience and existing equipment, it is judged to be possible to drill holes with a free inside diameter of 300 millimetres down to a depth of 4,000 metres. It is even deemed possible to drill holes with a free inside diameter of 500 millimetres down to 4,000 metres with today's technology and further developed equipment, but no experience of this is available as yet. Holes with a free inside diameter of 750 and 1,000 millimetres are not judged to be possible to drill today to a depth of 4,000 metres. It is deemed possible to reach down to 3,000 metres with a hole diameter of 750 millimetres under favourable conditions.

In another study /Baldwin et al. 2008/ done on behalf of NDA, twelve concepts for geological disposal are compared. It is observed in the report that the evaluations that have been done of the Deep Boreholes concept have focused on the feasibility of drilling deep holes. However, not much has been done regarding disposal technology and management of the spent nuclear fuel. According to the study, much is unclear with regard to safety in the handling of the containers, including the risk that the containers will be damaged when they are placed on top of one another. The biggest disadvantage with the Deep Boreholes concept is deemed to be the lack of both a detailed design of the concept and a thorough evaluation of safety, despite the fact that long-term safety is based on the fact that the waste will remain isolated thanks to the great depth. The conclusion in the report is that Deep Boreholes is better suited for disposal of small quantities of high-level waste and fissionable material than for disposal of spent nuclear fuel, especially before the technology for drilling holes with a bottom diameter of approximately one metre is available.

The Nuclear Waste Management Organization (NWMO) in Canada has made a compilation of methods for disposing of spent nuclear fuel /Jackson and Dormuth 2008/. Regarding the Deep Boreholes concept, the NWMO observes that no practical demonstration of this concept has taken place and that bringing it to the same level of understanding as the KBS-3 concept would require considerable additional R&D. They further observe that monitoring and retrievability would be much more difficult for the Deep Boreholes disposal concept.

The report also describes an alternative version of Deep Boreholes that was developed for storage of carbon dioxide. The concept entails deviating the hole at a depth of 3,000 metres so that it is sub-horizontal. According to the report, this approach would reduce stress on the stored canisters, facilitate retrieval and permit monitoring and control for a very long time. The concept is based on the fact that the deeper hydrogeological system is isolated from the system near the surface. According to the report, such geological areas can be found in western Canada.

Sandia, one of the US Department of Energy's energy laboratories, recently published a report on disposal of radioactive waste in deep boreholes /Brady et al. 2009/. The report proposes that the holes be five kilometres deep with a diameter at repository depth of 445 millimetres. According to the report, such holes can be drilled with existing drilling equipment of the type used to drill geothermal wells. The waste is deposited at a depth of between three and five kilometres. After deposition, the upper part of the holes is sealed. The proposed distance between the holes is 200 metres. The holes are lined with casing with an inside diameter of 381 millimetres. The canisters are made of steel casing with a diameter of 340 millimetres and with one fuel package (PWR or BWR) in each canister. The canisters must be strong enough to withstand the waste emplacement (deposition) process, but do not need to possess other isolating properties for the radioactive waste.

The canisters are deposited in crystalline rock. Overlying strata can consist of sedimentary formations. Such formations are found at many places in the USA, which means that final disposal can take place at multiple locations near local storage facilities and nuclear reactors. This reduces the transportation need.

The preliminary evaluation presented in the report is that disposal in deep boreholes may have good potential for excellent long-term safety performance. Features, events and processes requiring further research and development are identified in the report. However, there is no analysis of how the canisters containing the radioactive waste could be deposited in the borehole in a safe manner or what effect an improperly deposited canister could have on safety.

3.5 Monitored storage

Monitored storage is not a method for final disposal of spent nuclear fuel. But monitored storage for a limited period is, for technical reasons, always included in the management of spent nuclear fuel. Many countries count on having to employ monitored storage for a very long time. One reason is difficulties in finding a site for a final repository that can be accepted by the population in the concerned region or municipality.

Extensive experience exists of monitored storage from many countries, and different systems have been developed. They can be divided into wet and dry storage systems. There is an international trend towards increasing usage of dry storage, mainly due to lower investment and operating costs than for wet storage /IAEA 2003/. Day-to-day operation is simpler for dry storage than for wet. Monitoring is still required in both cases.

3.5.1 Wet storage

In wet storage, the spent nuclear fuel is stored in water-filled pools. The water cools and radiation-shields the fuel. To prevent corrosion of the fuel assemblies, the requirements on water quality are stringent. To remove decay heat, the pool water is circulated in a closed system with heat exchangers and cleanup filters. Some of the water evaporates due to the heat emitted by the fuel and must be replaced. Continuous supervision of heat exchange, water cleanup and water supply, as well as monitoring and maintenance of the plant, are required to ensure adequate safety.

Experience from wet storage exists in a number of countries, not least Sweden, where Clab has been in operation for 25 years. There the spent nuclear is stored in water-filled pools about 30 metres below the ground surface. As long as operation and maintenance are handled properly, a wet store is deemed to be able to be operated for at least a hundred years, probably longer, with as good safety as today.

Figure 3-13. Clab is an example of a facility for wet storage of spent nuclear fuel.

3.5.2 Dry storage

There are two variants for dry storage, both of which are used at several places in the world, see Figure 3-14. In one, the spent fuel is placed in specially designed cylindrical, thick-walled containers of metal or concrete, which are stored outdoors or in special storage buildings. The containers constitute radiation shields and prevent the dispersal of radioactive substances. Metal containers can also be used as transport casks. The heat is dissipated through the container to the surrounding air /Jones and Wiborgh 2006/.

In the second variant of dry storage, the spent fuel is placed in thin-walled gastight metal containers. These are then placed in a building with fixed ventilated storage positions of concrete that enable heat to be dissipated. The thin-walled metal container acts as a barrier to the dispersal of radioactive substances. Radiation shielding and protection against mechanical damage is provided by the surrounding concrete structure and the building /Jones and Wiborgh 2006/.

Due to the low thermal conductivity of air, the temperature of the fuel is considerably higher in dry storage than in wet. To prevent corrosion, the air in the containers is often replaced with a suitable gas. Continuous operation consists solely of ventilation and is simpler than in wet storage. As in wet storage, the plant must be monitored and the containers must be checked at regular intervals and maintained if necessary.

Dry storage involves very small safety risks. Safety assessments for dry storage of spent nuclear fuel have been submitted to, and reviewed and approved by, the regulatory authorities in several countries. As long as the storage containers are leaktight, no radionuclide releases can take place. But high temperatures subject the spent fuel, the cladding tubes and the containers to stresses. In a longer time perspective – several hundred years – thermally induced chemical and mechanical processes can cause damage to both fuel assemblies and containers. In dry storage, visual inspection of the fuel assemblies to detect and prevent damage is difficult to perform /Söderman 1997/.

Figure 3-14. Examples of facilities for dry storage. At top left: outdoor storage of thick-walled cylindrical steel containers at Point Lepreau Generating Station (Source: NBPower Nuclear). At top right: CASTOR® containers (thick-walled cylindrical containers of cast iron) in storage building at Gorleben, Germany (Source: IAEA). At bottom left: outdoor storage in NUHOMS® (leaktight steel containers) at Susquehanna nuclear power plant in the USA (Source: IAEA). At bottom right: outdoor storage in CANSTOR® (tight metal containers surrounded by a concrete structure) at Gentilly-2 in Canada (Source: Hydro Quebec).

3.5.3 The DRD concept

Dry Rock Deposit (DRD) is a system for dry storage for a very long time, up to several thousand years. The proposers behind the concept say that more research and development is needed to ensure that the spent nuclear fuel can be disposed of in a safe manner and that the spent nuclear fuel should therefore be disposed of in such a manner that it is easy to monitor until this research has yielded results /Rustan 2000, SKB 2000a/.

The principal difference between the DRD concept and the systems for dry storage that are in operation today is the space surrounding the storage containers. In the DRD concept, the fuel is placed in leaktight containers in a self-draining rock cavern. After deposition the rock cavern is closed. No drainage pumping or cooling is required. The idea is to minimize the need for maintenance and monitoring so that storage can take place for a long time. The fuel is placed in some kind of container, whose design is not described. It can be assumed that the container will be designed to withstand the temperature and atmosphere in the rock cavern so that fuel and container will remain unaffected during the storage period.

The self-draining rock cavern is built in a rock formation that projects above surrounding depressions. The rock formation is surrounded by a vertical crushed zone that is drained via a gently sloping horizontal tunnel. The tunnel is provided with a dust trap where the drainage water can be checked. Cooling is planned to take place via natural circulation, and the storage space is assumed to be self-draining. To keep water from infiltrating from above, the rock is sealed by grouting. The DRD concept is illustrated in Figure 3-15.

Provided the DRD concept can be shown to perform as intended, it may be the least resource-consuming variant of monitored storage in terms of human presence. Some form of surveillance is nevertheless needed, for example in order to prevent illicit trafficking in the spent fuel. Furthermore, it is probable that regular maintenance would be required of containers, rock support and the like.

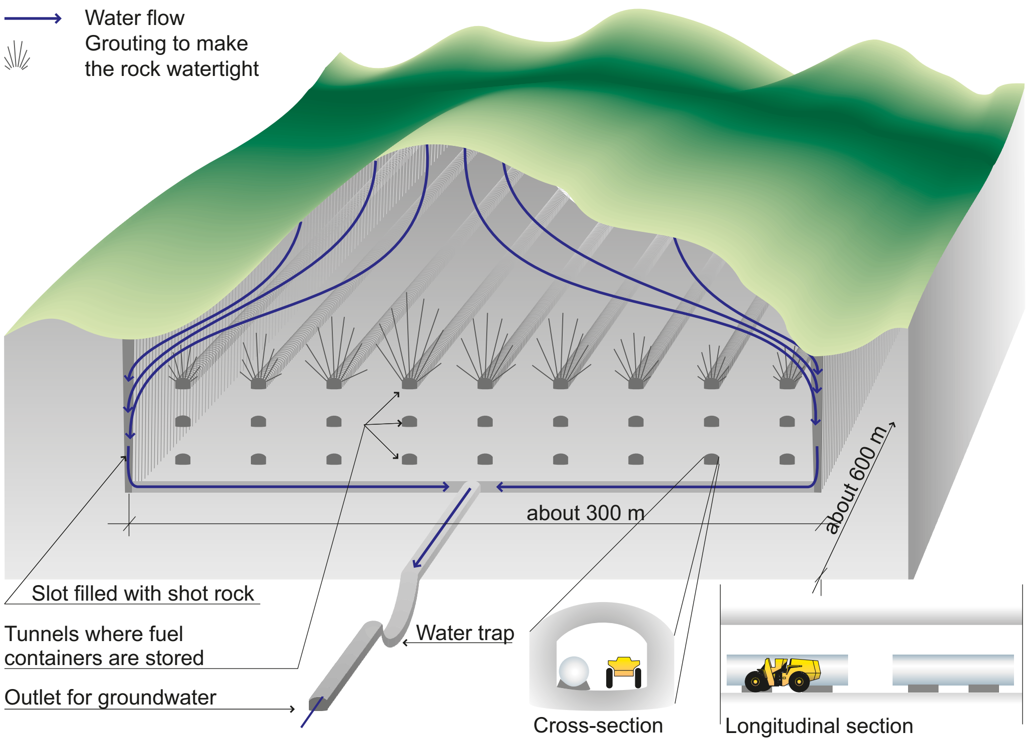

Figure 3-15. *The Dry Rock Deposit (DRD) concept intended for long-term dry storage.*

4 Overall assessment

In Chapter 2, SKB presented the general requirements on management and final disposal of spent nuclear fuel and high-level waste, which can be derived from international agreements, the Environmental Code, the Nuclear Activities Act and the Radiation Protection Act, and from the regulations issued by SSM pursuant to these laws.

Chapter 3 described in general terms the KBS-3 method and other systems for management and final disposal of spent nuclear fuel and high-level waste that have been discussed over the years.

This chapter discusses SKB's evaluation and assessment of relevant alternatives. Section 4.1 contains an overview of the presentation and review of alternative strategies and systems that has taken place within the framework of the recurrent review of SKB's RD&D programmes. Section 4.2 deals with the alternatives that do not satisfy one or more of the requirements in Chapter 2. In SKB's judgement, these alternatives are neither suitable nor possible for final disposal of spent fuel from the Swedish NPP's. This is followed in Section 4.3 by an assessment of the strategy of reprocessing, partitioning and transmutation. The chapter is concluded by an evaluation and assessment of the alternatives within the strategy of geological disposal that have good prospects of satisfying the requirements (Section 4.4). The focus is on a comparison between the KBS-3 method and Deep Boreholes.

Performing a complete assessment of a system for final disposal of spent nuclear fuel and whether it fulfils the requirements presented in Chapter 2 requires results from a safety assessment. The long-term safety of a KBS-3 repository has been assessed in a number of safety evaluations and safety assessments, see section A2 in Appendix 1. Both the most recent and earlier assessments show that a KBS-3 repository, erected on the analyzed sites, can satisfy the requirements on safety, radiation protection and environmental protection that are made in laws and regulations. Other alternatives that have been discussed for final disposal of spent nuclear fuel have not been evaluated in a complete safety assessment. They have, however, been subject to relatively comprehensive studies and evaluations, see /SKB 2000a, Grundfelt 2010a, b/.

4.1 Presentation of alternative strategies and systems in the RD&D process

Since 1986, SKB has produced nine RD&D programmes in accordance with the Nuclear Activities Act: in 1986, 1989, 1992, 1995, 1998, 2001, 2004, 2007 and 2010. In addition, SKB has, on request, submitted supplements to the 1992, 1998 and 2007 programmes. In all RD&D programmes, SKB has claimed that the KBS-3 method is the method that is most suitable to implement in Sweden. Other methods have been described and discussed, in different degrees of detail on different occasions.

Table 4-1 summarizes in brief the accounts of alternatives to the KBS-3 method that SKB has presented in the RD&D programmes. Other methods described by the AKA Committee and the KBS project are mentioned first in the table. In the second column is a condensed summary of what reviewing authorities and the Government have said about SKB's account of methods in the RD&D programmes.

In summary, the regulatory authorities' review and the Government's decisions in response to SKB's presentation of other methods in the RD&D programmes show:

- that the KBS-3 method is the only realistic method for final disposal of the spent fuel from today's Swedish reactors,
- that disposal in deep boreholes is currently not a realistic alternative to the KBS-3 method; SSM has nevertheless requested more background material on Deep Boreholes; this material is now available /Grundfelt 2010b/,
- that Partitioning & Transmutation will not be an alternative to direct disposal of the spent nuclear fuel within the foreseeable future (30–50 years).

Table 4-1. Presentation and review within the RD&D process of alternative strategies and systems /Grundfelt 2010a, SKB 2010a/.

RD&D programme/report and alternatives	Review and Government decision
AKA Committee report (1976) Final disposal in Swedish bedrock of encapsulated vitrified high-level waste from reprocessing. The report identified the possibility of direct disposal of the nuclear fuel; but the technology was not considered to be sufficiently developed. Besides stipulating premises and methods for final disposal of the spent nuclear fuel, the AKA Committee report laid the foundation for a Swedish disposal system with a central interim storage facility for spent nuclear fuel (Clab), a transportation system for spent nuclear fuel and other radioactive waste (m/s Sigyn) and a final repository for low- and intermediate-level waste (SFR).	The reviewing bodies were generally positive to the Committee's proposals. But criticism was levelled at Swedish reprocessing; the Committee recommended direct disposal and emphasized the need for research in the area. The Committee's proposals did not lead to any immediate measures on the part of the Government. After the 1976 election, national policy with regard to nuclear waste management changed. Via the Stipulations Act, the Government (Fälldin I) gave the responsibility to the nuclear power companies. They were to assume responsibility for disposing of the waste themselves. The nuclear power companies quickly responded to the requirements in the Stipulations Act by launching the Nuclear Fuel Safety Project, KBS.
KBS-1 report (1977) The purpose of KBS-1 was to show that the requirements in the Stipulations Act could be met. The report gave an account of disposal of vitrified high-level waste from reprocessing. An appendix to the report contained a status report on the work with direct disposal. KBS-1 served as a basis for the licences to commission Ringhals 3 and 4 and Forsmark 1 and 2.	Extensive review, including by international groups. The main task was to determine if the requirements of the Stipulations Act were met. The Government demanded additional test drilling. When the results from these boreholes became available, the Government found that the requirement of the Stipulations Act of an absolutely safe final disposal of vitrified high-level waste from reprocessing was met.
KBS-2 report (1978) The KBS-2 report presented the alternative without reprocessing, i.e. direct disposal of spent nuclear fuel.	Extensive review, including by international groups. Positive reception for the most part. The Government did not take a stand, since the report was not the basis of an application to commission a nuclear reactor.
KBS-3 report (1983) In-depth account of the direct disposal alternative – the KBS-3 method – based on further studies plus research and development, including at Stripa. The KBS-3 report served as the basis for an application under the Stipulations Act to commission Forsmark 3 and Oskarshamn 3. KBS-3 also served as the basis for continued operating licences for Barsebäck 2, Ringhals 3 and 4 and Forsmark 1 and 2 after the reprocessing contracts with Cogema had been cancelled.[12]	The Government issued operating licences and stated that the method in its entirety had been found acceptable in all essential respects with regard to safety and radiation protection.
RD&D-Programme 86 In a background report to the R&D programme, SKB presented the alternatives to the KBS-3 method. The alternatives to which particular attention were given were an air-cooled repository located at a depth of at least 400 metres (but above the groundwater table), disposal in 5–10 km deep holes, and the WP-Cave concept.	The National Board for Spent Nuclear Fuel (SKN) was in charge of the comprehensive review and commentary process. According to SKN, SKB should continue its studies of WP-Cave and Deep Boreholes, while the system with disposal above the groundwater table should be given low priority. The Government did not make any specific statement regarding alternative methods.
RD&D-Programme 89 The results of SKB's studies of Deep Boreholes (VDH) and WP-Cave were reported. SKB judged that it would be more difficult to demonstrate the safety of a WP-Cave repository, while at the same time the costs would be higher. SKB therefore did not intend to continue its studies of WP-Cave as an integral system. Disposal in deep boreholes (VDH = Very Deep Holes) required more research results to permit a comparison with KBS-3. The studies of deep boreholes should therefore continue. In the programme, SKB also mentioned that they intended to conduct a theoretical study of disposal in long tunnels (VLH = Very Long Holes) beneath the Baltic Sea.	SKN was in charge of the comprehensive review and commentary process this time as well. The Board's conclusion was that the studies of the alternatives with deep boreholes and long tunnels beneath the Baltic Sea should continue. In its decision, the Government emphasized that a binding commitment should not be made to a given management or disposal method until a complete picture is obtained of any potential problems with safety and radiation protection, and said that the alternatives with deep boreholes and long deposition tunnels beneath the bottom of the Baltic Sea being studied by SKB are deemed by the Government to be less suitable for a final repository.

[12] Cogema, then owner of the reprocessing plant at La Hague. Today the plant is owned by Areva NC.

RD&D programme/report and alternatives	Review and Government decision
RD&D-Programme 92 The PASS report served as a basis for SKB's account. The RD&D programme presented WP-Cave, deep boreholes, long tunnels (VLH) and medium-long tunnels (MLH). Long tunnels was now a different concept than in RD&D-Programme 89. It now referred to horizontal 4–5 km long tunnels bored at a depth of 600 metres. Medium-long tunnels was basically the same concept as that which SKB now calls KBS-3H. SKB judged that the medium-long tunnels alternative was promising, but that KBS-3 had technical advantages. Other alternatives were deemed to less interesting.	SKI was in charge of the review and the statement of opinion to the Government. The Swedish National Council for Nuclear Waste[13] made an independent assessment. Both SKI and the Swedish National Council for Nuclear Waste felt that there were strong reasons in favour of the KBS-3 method. But they did not find that SKB's reasons for dismissing other alternatives were adequate. In its decision, the Government ordained that SKB should, in the next RD&D programme, give an account of its assessment of the state-of-the-art regarding which alternatives may be considered for final disposal of spent nuclear fuel and long-lived waste in Sweden.
Supplement to RD&D-Programme 92 (1994) The supplement did not contain any account of alternatives.	–
RD&D-Programme 95 In the programme, SKB described the development work in other countries on partitioning and transmutation. The conclusion was that this development work "may possibly be of interest in the long term to the Swedish nuclear waste programme". SKB therefore intended to continue to give some support to domestic research aimed at a deeper understanding of this concept. SKB also mentioned disposal in deep boreholes and explained that they would keep track of new developments in drilling technology.	SKI judged that the KBS-3 method should continue to be the main alternative in SKB's continued work, but that other alternatives need to be further described and examined, particularly the so-called "zero alternative". Furthermore, SKI judged that P&T did not at present seem to be a realistic alternative for Sweden. SKI did not comment on deep boreholes. The Swedish National Council for Nuclear Waste did not touch upon the question of alternatives in its commentary. The Government stated in its decision: "Even if the KBS-3 method is a reasonable choice for demonstration deposition, SKB should not commit itself to any specific management and disposal method before an integrated and thorough assessment of related safety and radiation protection issues has been presented. In the Government's opinion, SKB must provide an integrated and more detailed account of the alternative solutions to the KBS-3 method that have been presented in previous research programmes. Different variants of the KBS-3 method should also be presented. In particular, the consequences of the case where the planned final repository is not realized in any form (the zero alternative) should be illuminated more thoroughly than has been done to date. The continued work with partitioning and transmutation should be reported".
RD&D-Programme 98 As a basis for the programme, SKB produced a special report entitled "Alternativa metoder. Långsiktigt omhändertagande av kärnbränsleavfall." ("Alternative methods. Disposal of nuclear fuel waste," in Swedish only, /Ekendahl and Papp 1998/). Four basically different lines of action were presented, along with their advantages and disadvantages: • monitored storage, • direct disposal in a deep repository (geological disposal), • reprocessing, possible partitioning and transmutation, followed by disposal in a deep repository, • ultimate removal. SKB's overall assessment was that geological disposal of encapsulated fuel should remain the main alternative. Monitored storage does not meet the requirements on long-term safety. Transmutation technology is not available today and poses many uncertainties. SKB considered the technology to be interesting, however, and therefore wanted to continue to support the research and keep track of developments. Conceivable methods for ultimate removal were not judged to be technically or politically realistic either.	SKI and the Swedish National Council for Nuclear Waste both drew the conclusion that geological disposal was the only reasonable line of action for Sweden. SKI found that the evidence presented thus far indicated that the KBS-3 method is technically realizable, even though a great deal of development and testing work remains to be done. But SKB should demonstrate more clearly that no better method than KBS-3 is reasonably available. The Swedish National Council for Nuclear Waste contended that it is not meaningful for SKB to pursue its own development projects, other than those related to final disposal in Swedish bedrock. However, a compilation of the international state of knowledge on partitioning and transmutation should be included in future RD&D programmes. The Swedish National Council for Nuclear Waste strongly preferred alternatives involving a built repository within the uppermost kilometre of the bedrock to disposal in deep boreholes. However, the Council suggested that SKB should investigate what research and development is needed to enable disposal in deep boreholes to be compared with the KBS-3 method. The Government followed the Council's suggestion concerning research data to enable deep boreholes to be compared with the KBS-3 method. Furthermore, the Government, like SKI and the Swedish National Council for Nuclear Waste, concluded that some form of final disposal in the bedrock appears to be the most expedient method.

[13] Swedish National Council for Nuclear Waste, up to the autumn of 2007 best known by the abbreviation KASAM, has since 1992 been an independent interdisciplinary committee under the Ministry of the Environment. The Swedish National Council for Nuclear Waste's remit is to give advice to the Government concerning nuclear waste and decommissioning and dismantling of nuclear facilities. The Council's members represent independent expertise in different fields of importance for the final disposal of radioactive waste, within technology and the natural sciences as well as within ethics, psychology, jurisprudence and the social sciences. The Swedish National Council for Nuclear Waste carries out independent reviews of SKB's RD&D programmes and publishes an independent assessment of the state-of-the-art in the nuclear waste field at regular intervals (every year starting in 2010).

RD&D programme/report and alternatives	Review and Government decision
Supplement to RD&D-Programme 98: Integrated account of method, site selection and programme prior to the site investigation phase (RD&D-K, 2000) RD&D-K provides a comprehensive overview of the strategies, systems and methods discussed over the years, both in Sweden and internationally. The basis for the account was the reports "Systemanalys. Val av strategi och system för omhändertagande av använt kärnbränsle." ("System analysis. Choice of strategy and system for disposal of spent nuclear fuel," in Swedish only) and "Förvarsalternativet djupa borrhål. Innehåll och omfattning av FUD-program som krävs för jämförelse med KBS-3-metoden." ("Deep Boreholes. Content and scope of RD&D programme required for comparison with the KBS-3 method," in Swedish only) /SKB 2000a, b/. SKB's conclusion after a systematic review and assessment of the various alternatives was that "The KBS-3 method is well-developed and ready to move into the implementation phase… Radiation protection and safety in particular, both long-term and during operation, are the factors that put KBS-3 ahead of the alternatives." Regarding disposal in deep boreholes, SKB wrote that they did not plan any further RD&D initiatives, but intended to follow international development efforts in the area.	After thorough reviews, both SKI and the Swedish National Council for Nuclear Waste found that the Government should now state clearly that the KBS-3 method could serve as a planning premise for the site investigations which SKB intended to carry out. The Government stated that SKB should use the KBS-3 method as a planning premise for the site investigations. At the same time, the Government emphasized that final approval of a specific method for final disposal cannot be given until a decision is made on applications under the Environmental Code and the Nuclear Activities Act for a licence to build a final repository for spent nuclear fuel. The Government also observed that SKB's account "provides further support for the Government's assessment (see Government decision of 24 January 2000) that some form of final disposal in the bedrock is the most expedient strategy for final disposal of spent nuclear fuel". Further, the Government urged SKB, within the framework of the RD&D programmes, to keep track of technology development regarding different alternatives for disposal of nuclear waste.
RD&D-Programme 2001 In the programme, SKB described how they were following technology development within P&T as well as Deep Boreholes.	Both SKI and the Swedish National Council for Nuclear Waste said in their opinions that SKB should continue its programme concerning different alternatives for the disposal of nuclear waste with essentially the same direction and scope as before. The Government repeated what it had said in previous decisions, namely that SKB should continue to keep track of technology development regarding different alternatives for disposal of spent nuclear fuel within the framework of the RD&D programmes.
RD&D-Programme 2004 In the programme, SKB gave an account of the state of knowledge regarding P&T and Deep Boreholes – the alternatives that were "currently" attracting the greatest interest.	SKI emphasized that Sweden must be able to maintain competence in the area of P&T at its current level. This is necessary in order to be able to follow international development work and to retain and enhance scientific and technical competence in areas of importance for nuclear safety. At the same time, SKI emphasized that P&T could not be considered to be a realistic alternative for Swedish purposes. SKI considered the account of Deep Boreholes to be much too cursory. It therefore needed to be clarified prior to the final choice of method and examination under the Environmental Code. The Swedish National Council for Nuclear Waste expressed similar viewpoints as SKI regarding P&T, but said that Deep Boreholes was not a realistic method. The Council repeated what they had said before, that SKB should look for alternatives to the KBS-3 method within the category built repositories within the uppermost kilometre of the rock. The Council believed it to be of great importance for confidence in SKB's work that a coherent and clarifying account be given of alternative methods for the final disposal of spent nuclear fuel. SKB should present such an account not later than in conjunction with the company's licence applications under the Nuclear Activities Act and the Environmental Code. In such an account, SKB should clearly justify its positions on the Deep Boreholes concept. In this context, SKB should also clarify its plans for KBS-3 with horizontal deposition (KBS-3H). The Government did not say anything specifically about the Deep Boreholes concept. However, the Government did reiterate its statement from December 2002 that SKB should – within the framework of the RD&D programmes – continue to keep track of technology development when it comes to various alternatives for disposal of nuclear waste.

RD&D programme/report and alternatives	Review and Government decision
RD&D Programme 2007 In the programme, SKB once again gave an account of the state of knowledge for P&T and Deep Boreholes.	SKI judged that final disposal according to the KBS-3 method is still the most expedient planning premise for final disposal of the spent nuclear fuel from the Swedish nuclear power programme. SKI and SSI both contended that SKB should provide a more carefully prepared and better body of data on disposal in deep boreholes for a comparison with the KBS-3 method. At the same time, SKI emphasized the Deep Boreholes cannot at present be considered to be a realistic alternative to the KBS-3 method. Concerning P&T, SKI essentially reiterated what they had said in their statement of opinion on RD&D-Programme 2004. Both SSI and SKI argued that SKB should, prior to applying for a licence to build the final repository, gather a better body of data on deep boreholes for comparison with the KBS-3 method. The Swedish National Council for Nuclear Waste stated that confidence in SKB's work is dependent on their providing a coherent and clarifying account of alternative methods for the final disposal of spent nuclear fuel. Such an account should be provided no later than in connection with an application for a licence for the final repository. The reasons for SKB's positions on the Deep Boreholes concept should be clearly explained. The plans for horizontal deposition (KBS-3H) should also be clarified. The Government's decision states that SKB must "give an account of the state of knowledge regarding alternative final disposal methods such as deep boreholes".
Supplement to RD&D-Programme 2007 (2009) In the supplement, SKB presents an overview of the strategies and systems for final disposal of spent nuclear fuel that have been discussed over the years. The overview covers both methods which SKB has dismissed and methods that are still being considered. Furthermore, SKB provides a résumé of the accounts and assessments of various strategies and systems that have been published since the early 1980s. Finally, SKB gives an account of the state of knowledge for the alternatives to geological disposal – especially Deep Boreholes, monitored storage and P&T.	Like other reviewing bodies, SSM felt that SKB should gather more background data regarding deep boreholes. SSM called for a) an in-depth expert assessment of feasibility (drilling technology and deposition), and b) a more thorough analysis of the uncertainties surrounding the stability of the groundwater at great depths. SSM deemed these additional studies to be necessary to enable a systematic comparison to be made with the KBS-3 system. The Swedish National Council for Nuclear Waste found that no new information had been presented in the supplement to alter the Council's views. The Council then reiterated the comments it made on RD&D Programme 2007. The Government did not make any specific comments in its decision on the overview SKB had presented (SKB's supplement to RD&D-Programme 2007 dealt with other issues as well). Regarding the supplement as a whole, the Government said that it "assumes that SKB will take the viewpoints of the regulatory authorities into account in RD&D Programme 2010".

4.2 Dismissed alternatives

As is evident from Chapter 3, there are only a few strategies for final disposal of spent nuclear fuel that satisfy international agreements and other requirements. The strategies that do not satisfy the requirements must of course be dismissed as possible options.

4.2.1 Monitored storage

Long-term dry and wet storage require continuous inspection and maintenance. The DRD concept also requires monitoring and some form of maintenance. This means that none of the methods satisfies the requirement of the Nuclear Activities Act on final disposal of spent nuclear fuel, viz. that the final repository should provide the requisite safety without monitoring and maintenance.

Studies of Clab show that in a time perspective of several hundred years, rock reinforcements and concrete structures need to be checked and repaired /SKB 2000d/. In the case of dry storage, it will probably also be necessary to replace or recondition storage containers.

At the facilities for supervised storage that are in operation today, there are systems for physical protection and safeguards consisting of a combination of access barriers, accounting systems, monitoring, and unannounced inspections. In the event of the loss of accounting systems and/or monitoring, the protection of stored nuclear materials is weak.

Environmental, safety and radiation protection requirements can be complied with as long as human supervision and control are maintained. If such measures should cease for some reason, the physical barriers are not adequate to satisfy the requirements. As the name implies, monitored storage requires monitoring. The requirement of not imposing undue burdens on future generations is therefore not met.

4.2.2 Other alternatives that have been dismissed

In Section 3.2.2, SKB concluded that there are several conceivable strategies that are not possible because they violate international agreements. Dumping in the sea, sub-seabed disposal and disposal beneath the continental ice sheets were mentioned in particular.

Another alternative that is mentioned in Section 3.2.2 is launching the spent fuel into outer space. A number of reasons speak against this alternative: it would require large quantities of rocket fuel, it would be very costly, it is associated with considerable risks, and in practice, reprocessing and separation are needed to reduce the waste volumes.

SKB clarified in the 1986 RD&D programme, and then repeated in 2000 in RD&D-K, that these alternatives can be ruled out. No objections to SKB's evaluations of these strategies have been offered by anyone in conjunction with the reviews of the RD&D programmes presented since 1986.

4.3 Reprocessing, partitioning and transmutation

Ever since the early 1980s, there has been a consensus between political decision-makers and the reactor owners that reprocessing of the spent nuclear fuel from the Swedish reactors should be avoided. The reasons for this are both economical and security-related. One of the economic reasons is that new "fresh" nuclear fuel with enriched uranium has been and is still much cheaper than MOX fuel with plutonium from reprocessing. Furthermore, management and final disposal of the high-level waste and the long-lived low- and intermediate-level waste from reprocessing is very costly. The security-related reasons have to do with the fact that there is concern that plutonium from reprocessing could be used to manufacture nuclear weapons.

More advanced reprocessing, partitioning and transmutation, where the spent fuel's content of long-lived radionuclides is radically reduced, requires considerable research and development and several technically complicated nuclear facilities. Research is being conducted in the major nuclear power countries and in international research projects funded by the European Commission. SKB is following this work and has, in all RD&D programmes since 1995, given an account of the state of knowledge and how the work has progressed. Since 1992, SKB has also given financial support to the research teams at the Royal Institute of Technology (KTH), Chalmers University of Technology and Uppsala University who are participating in various EU projects in the field. In 2004, in its report on the state-of-the-art in the nuclear waste field, the Swedish National Council for Nuclear Waste submitted a detailed account and assessment of current technology and its advantages and disadvantages for Swedish purposes /Kärnavfallsrådet 2004, pp 347–411/.

Reprocessing, fuel fabrication and transmutation entail extensive handling of high-level radionuclides, which in turn requires extensive radiation protection measures.

The result of the transmutation will be to exchange the relatively low long-term radiotoxicity of the actinides for a relatively greater radiotoxicity with a shorter time span. If waste management is regarded in isolation, it is doubtful whether this is in line with the law's requirement of optimization and utilization of the best available technology to minimize the radiation doses. The benefit of the produced energy must also be weighed into a complete evaluation.

Plutonium can be used for weapons production. Reprocessing that entails purification of plutonium therefore imposes particularly stringent demands on safeguards. In the current research, considerable efforts are also being devoted to finding processes with build-in protection against diversion of plutonium to weapons manufacture.

The development of a functioning system for partitioning and transmutation is expected to be costly and take a long time. Even if the development work is successful, some long-lived waste will remain that must be dealt with in a similar manner to spent nuclear fuel. Furthermore, it will take a long time – on the order of 100 years or more – to carry out transmutation of already existing spent nuclear fuel. SKB therefore does not regard transmutation as a realistic alternative for managing spent nuclear fuel from today's Swedish reactors. Nevertheless, it is reasonable that Sweden should participate in the international development work and maintain competence within the country, at least as long as a considerable portion of the country's electricity production is based on nuclear energy. Competence developed in research on P&T is valuable, not just for assessing development and potential in this field, but also for development of safety and fuel supply at existing reactors. SKB therefore intends to continue to follow and support research in the field.

4.4 Geological disposal

Within the strategy of geological disposal, the following methods have been the subject of more or less extensive studies /SKB 2000a/:

- The KBS-3 method.
- Long Tunnels (VLH).
- WP-Cave.
- Deep Boreholes.

4.4.1 Long Tunnels (VLH) and WP-Cave

In /SKB 2000a/, SKB presented a comparison and evaluation of the alternatives of Long Tunnels (VLH) and WP-Cave in relation to the KBS-3 method. SKB's overall assessment is still that the KBS-3 method has advantages, above all when it comes to safety and radiation protection.

The Long Tunnels alternative is in many respects equivalent to KBS-3 and has environmental advantages in that the quantity of rock that has to be excavated is much smaller. However, safety during operation is poorer in terms of both working environment and occupational safety. Furthermore, it is much more difficult to retrieve a damaged canister than in KBS-3. With the alternative KBS-3H (horizontal deposition of the canisters), SKB has exploited the environmental advantages of the Long Tunnels concept, while the disadvantages with regard to operational safety and the difficulties of retrieval have been reduced due to the fact that the deposition tunnels are much shorter.

The WP-Cave concept has clear disadvantages compared with KBS-3. The concept is technically complicated, and it is difficult to show that long-term safety can be guaranteed. Extensive knowledge accumulation and technology development would be required to refine the technology and the design and to assess safety. Another disadvantage is that the repository cannot be closed directly after deposition; this cannot be done until the fuel has cooled to a sufficiently low temperature. The feasibility of building a repository according to the WP-Cave concept that meets the requirements on safety and radiation protection is associated with great uncertainties. SKB's assessment is therefore that WP-Cave is not an interesting alternative.

4.4.2 Deep Boreholes

As is evident from Section 3.4.2, SKB and other organizations have been studying disposal in deep boreholes since the late 1980s. In addition to describing the state of knowledge concerning deep boreholes, /Grundfelt 2010b/ presents a comparison between the KBS-3 method and the Deep Boreholes concept.

The review and the comparisons presented in /Grundfelt 2010b/ show clearly that disposal in deep boreholes is not a realistic alternative to KBS-3. No technical breakthrough that could alter this assessment is expected in the foreseeable future. Extensive efforts are required to accumulate the knowledge needed to build, operate and close a final repository for disposal in deep boreholes. Furthermore, it is uncertain whether, even after such efforts, deep boreholes can provide a safer final disposal than the KBS-3 method. There is no country that is planning to use the Deep Boreholes concept for final disposal of spent nuclear fuel or high-level waste from nuclear power. Nor is any targeted research and development being conducted for this concept.

One advantage of a repository according to the Deep Boreholes concept is that it offers better protection against intrusion and illicit trafficking of nuclear material. The great deposition depth means that getting down to the deposited nuclear fuel and retrieving it is a very big project.

A crucial difficulty in judging the Deep Boreholes concept is that very little is known about the actual geological, hydrogeological and geochemical conditions at the great depths in question. However, the groundwater beneath flat areas is expected to have high salinity and thereby high density, which in turn means that the groundwater movements are slow. This situation constitutes the principal safety feature of a repository according to the Deep Boreholes concept. The aggressive environment at great depths (high salinity, high pressure and high temperature) makes it uncertain whether even very advanced encapsulation materials will remain intact in the long term. The engineered barriers, canister and buffer, can therefore not be expected to contribute appreciably to the required isolation and retardation of the radionuclides. The concept is thus not a multiple barrier system.

Siting an area for disposal in deep boreholes is associated with much greater uncertainties than the siting of a KBS-3 repository. The KBS-3 repository can more easily be adapted to the bedrock, not least because deposition tunnels and deposition holes can be investigated and characterized in situ. The deposition holes in a KBS-3 repository can be bored from the start in suitable positions, and holes that nevertheless prove to be unsuitable can be rejected. In a deep borehole, the conditions as a whole must be either accepted or rejected. It might be possible to deposit canisters in limited parts of the hole. Knowledge of the surrounding rock volume can never be as good with the Deep Boreholes concept as for a KBS-3 repository.

Both construction of and deposition in a final repository with deep boreholes are sensitive to disturbances. Drilling of the deposition holes is a great challenge, and success is threatened by hole deformation, breakout, etc. With today's drilling technology it is deemed possible to drill holes big enough to hold a canister with a fuel assembly from a BWR reactor. But in order for the process to be reasonably economical, each canister should contain at least four fuel assemblies (the KBS-3 canister holds twelve BWR assemblies). The drilling technology must be developed to achieve this. SKB's assessment is that technology for drilling four kilometre deep holes, with a diameter of 800 millimetres at the bottom, is possible to develop, but that this poses a great challenge.

The technical drilling difficulties involve not only being able to drill deep enough with sufficiently large diameter. A larger diameter makes it more difficult to pump up the drill cuttings. In addition, it increases the risk of collapse and breakout from the wall of the hole and the risk of an oval hole, causing the drill string and the casings to get stuck. A larger diameter also complicates handling of the casings, since they are much heavier. Nor is it possible to rule out the risk of the canisters getting stuck during the deposition process.

All steps needed to handle and dispose of the spent fuel according to the KBS-3 method have been designed so that they can be controlled and the results verified. This is not possible in the case of disposal in deep boreholes.

Handling of spent nuclear fuel according to the KBS-3 method is based on experience from other activities where protection against ionizing radiation is essential. Among other things, this means that the consequences of accidents can be managed. In the case of disposal in deep boreholes, accidents can occur with fateful consequences. For example, a canister can get stuck in the hole and break before it has reached disposal depth. As a result, a leaky canister can get stuck in a location with flowing groundwater, without being surrounded by a protective buffer.

The safety assessments that have been conducted of the KBS-3 method have shown that the final repository with copper canisters surrounded by a bentonite buffer is resistant to the stresses that can arise in connection with future earthquakes and glaciations. It is not known today what the consequences might be for a final repository according to the Deep Boreholes concept in the event of a future glaciation or an earthquake. This makes it difficult to assess the long-term safety of the Deep Boreholes concept.

4.4.3 The KBS-3 method

A final repository according to the KBS-3 method can be built, operated and closed with full control in all steps. A KBS-3 repository satisfies the overall requirements. It can be built in Sweden. The waste can be managed and disposed of without imposing burdens on future generations. The safety evaluations and assessments that have been carried out show that a repository according to the KBS-3 method can satisfy the requirements on safety, radiation protection and environmental protection that are made in laws and regulations. The method has been developed so far that a final repository can begin to be built during the next decade.

The requirement on multiple barriers can be met. When all fuel has been deposited and the repository has been closed, long-term safety is not dependent upon inspection or maintenance. In Sweden, as well as in other countries, many years of experience exist from construction in rock, mainly in the mining industry and infrastructure projects. The materials in the engineered barriers have been selected with a view towards their durability and function over very long times in the geological environment in question.

Analyses of final repository systems based on the KBS3 method show that a geological repository can be designed so that the calculated risk is significantly lower than the requirements imposed by the regulatory authorities. This applies both during construction and operation and in the long term, after closure. The costs for developing the technology and carrying out deposition can be estimated and covered by funds that have been paid in, and are still being paid in, to the Nuclear Waste Fund. Thus, it is a system that satisfies the requirements on high safety and good radiation protection.

Geological disposal according to the KBS3 method offers good prospects for preventing unauthorized persons from gaining access to the spent fuel. The spent nuclear fuel will be monitored during the operating phase. Retrieving the spent nuclear fuel from a closed geological repository will not be impossible, but it will involve an effort comparable to that of a major industrial or construction project. Given sufficient resources, future generations will be able to access the spent nuclear fuel if they wish.

The KBS-3H variant bears great similarities to KBS-3V. The fuel is the same in both variants, as are the barriers – canister, buffer and rock. Large parts of the facilities above and below ground are identical or similar in both variants.

However, further research, development and demonstration are required in order to conduct a comprehensive safety assessment and determine whether KBS-3H satisfies the requirements on safety and radiation protection. The technology is not sufficiently well developed today for the KBS-3H variant to be a preferred alternative.

4.5 Conclusions

In sections 4.2, 4.3 and 4.4, SKB has presented its assessment of the different strategies, among other things against the requirements in Chapter 2. Table 4-1 contains a brief summary of what reviewing authorities and the Government have said about methods for final disposal of spent fuel in conjunction with their review of SKB's RD&D programmes. Their judgements are summarized in Table 4-2. Of the proposed systems for geological disposal, SKB recommends the KBS-3 method since it is a system that can be built, operated and closed with full control in all steps. The safety assessment that has been performed of a KBS-3 repository in Forsmark shows that the method satisfies the requirements on safety, radiation protection and environmental protection that are laid down in laws and ordinances.

In conclusion, SKB would like to point to the assessment made by the Swedish National Council for Nuclear Waste in its review statement on RD&D-Programme 98 /Kärnavfallsrådet 1999/. The Council concluded that only final disposal deep down in the bedrock is reasonable. Within the framework of this strategy, the KBS-3 method should continue to be prioritized. The Council explained its standpoint in the following way:

The method has, in KASAM[14]'s opinion, several advantages. The method is the best in terms of its adaptability to the conditions in the host rock as they are revealed to be during excavation. The fuel is enclosed in a space-saving, compact module – the canister with the surrounding bentonite buffer. The small dimensions are favourable when it comes to depositing the waste module in a homogeneous rock formation. The fuel is distributed among many canisters, which is an advantage since a smaller quantity of fuel is exposed to groundwater if and when a hole is made in the canister. The deposited modules are radiologically isolated from each other. This facilitates the emplacement of canisters in adjacent holes and any measure, such as retrieval, which may have to be subsequently taken with an already deposited canister. Another important advantage is that a KBS repository consists of a large number of identical modules of moderate dimensions. This facilitates fabrication of the canister, the bentonite buffer and the handling equipment, as well as demonstration and verification of the handling of the waste in a repository prototype of moderate dimensions.

The quote neatly summarizes the fundamental properties of the KBS-3 method. These properties make it a robust method, well suited to achieving the high safety that is required.

Table 4-2. SKB's assessment of different strategies for disposing of spent nuclear fuel.

Strategy	SKB's assessment
Dumping in the sea	Violates international agreements.
Disposal in deep-sea sediment	Violates international agreements.
Disposal beneath the continental ice sheet	Violates international agreements.
Launching into outer space	Resource-demanding, costly, risks in launching. Probably requires reprocessing.
Monitored storage	Responsibility shifted to future generations. Does not satisfy the long-term safety and radiological requirements.
Reprocessing with recycling of uranium and plutonium	Better resource management, the natural uranium is utilized more efficiently and recycled uranium and plutonium are used for production of electricity. Waste must be disposed of in a similar manner as spent nuclear fuel. Spent MOX fuel must be directly disposed of. More expensive than direct disposal. Handling of purified plutonium requires special measures (safeguards) to prevent diversion.
Reprocessing, partitioning and transmutation	Better resource management, the natural uranium is utilized more efficiently and recycled uranium and plutonium are used for production of electricity. Waste must be disposed of in a similar manner as spent nuclear fuel. Extensive further research and development is needed. Requires an advanced nuclear system including new reactors that have to be in operation for more than 100 years.
Geological disposal	Can satisfy all requirements. Can be carried out today. Future generations have the option of retrieving the waste.

[14] KASAM, see note to Table 4-1.

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Development of the KBS-3 method

The development of the KBS-3 method can be followed in the accounts provided by SKB, from the KBS Project up to today, in RD&D programmes, PLAN reports and safety assessments. A detailed account is provided in /SKB 2010a/ with references to these accounts.

In this appendix, we have chosen as our point of departure the KBS-3 repository as it is described in the safety assessments done by SKB. The reason is that the safety assessments constitute clear decision points for the final repository's reference design. The focus in the description is on the development of the engineered barriers, i.e. those parts of the repository that are primarily responsible for the long-term isolation of the spent nuclear fuel. The description is found in the *first chapter* of the appendix.

The safety assessments have also undergone considerable development from the KBS-3 report up to today. Important progress has been made when it comes to methods, calculation models and computer power to carry out the assessments. Another important circumstance is that we have a better body of data and knowledge today in most areas of importance for the safety assessment. This has resulted in greatly improved confidence in the results of the assessments. This is the subject of the *second chapter* of the appendix.

Since the start, research and development has been a very important part of the work with the KBS-3 method. In the late 1970s and early 1980s, important development work was done within the Stripa Project. Since the mid-90s, the Äspö HRL (Hard Rock Laboratory), and a few years later the Canister Laboratory, have been principal resources for SKB's research and development activities. *Chapter A3* provides a brief orientation on this work. The appendix concludes with a brief overview of SKB's international cooperation, *Chapter A4*, and studies of natural analogues, *Chapter A5*.

It is evident from the PLAN reports and safety assessments that the figures regarding how much spent nuclear fuel will have to be disposed of have changed through the years, see Figure A-1. From the beginning the assignment was to manage and dispose of spent fuel from 13 reactors that would be in operation for 30 years. A premise of the KBS-3 project was that nuclear power would be phased out in 2010 and that the quantity of spent fuel would not exceed 7,000 tonnes of uranium. Today the assignment is to build a repository that holds 12,000 tonnes of uranium. The increase is mainly due to much longer operating times, but also to the fact that the reactors are being modified to produce more power. The changes over time are evident from the chart, which is based on the figures in the PLAN reports.

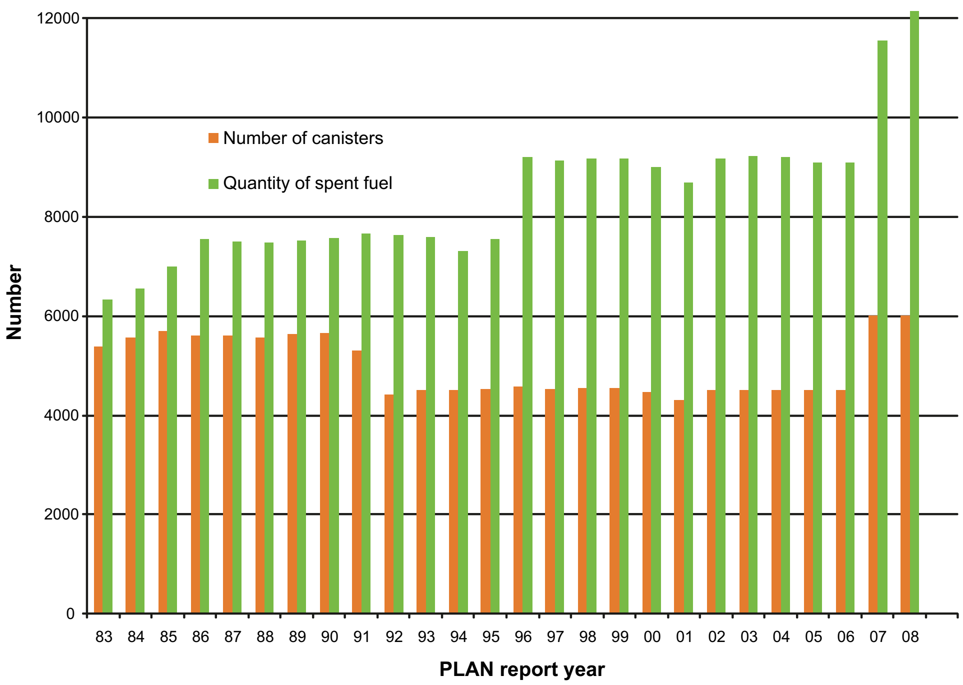

Figure A-1. *Quantity of spent nuclear fuel and number of canisters to be disposed of (source: SKB's PLAN reports).*

A1 Design of the KBS-3 repository

A1.1 KBS-2

In KBS-2 /KBS 1978/, the handling sequence for the spent fuel was described as follows:

After the fuel has been stored for some time in pools at the nuclear power plants, it is transported to a central storage facility for spent nuclear fuel. After a storage period of 40 years, the fuel is transported to an encapsulation station located at the final repository. There the fuel is disassembled and the fuel rods are separated from the metal parts of the fuel assemblies. The reason was the ambition at that time to pack the fuel rods as tightly together as possible to minimize the dimensions of the canister. The quantity of fuel per canister was roughly the same as today, limited then as now by the fuel's heat output.

The fuel rods are encapsulated in a corrosion-resistant container of pure copper with a wall thickness of 20 cm, see Figures A-2 and A-3. The space between the fuel rods and the canister is filled with molten lead. This prevents damage to the canister which could otherwise occur if the canister is subjected to mechanical stresses.

The filled copper canisters are then transferred to a final repository. The repository consists of a system of tunnels about 500 m down in the bedrock, see Figure A-4. The canisters are transported down to repository level via a shaft. There are then deposited in vertical holes and surrounded by a buffer of highly compacted bentonite, see Figure A-5. The spacing between the tunnels (25 m) and between the deposition holes (6 m) is determined with a view to the mechanical properties of the rock and the fuel's heat output. When the repository has been filled with canisters, it is sealed by filling tunnels and shafts with a mixture of quartz sand and bentonite (quartz sand has good heat conduction properties and high purity). Tunnels and shafts are sealed at, for example, fracture zones with compacted bentonite blocks.

The metal parts of the fuel assemblies, which are also radioactive, are compacted and embedded in concrete moulds, which are deposited in tunnels in a separate repository in the rock at a depth of about 300 metres. The disposal tunnels are then filled with concrete.

KBS-2

Fuel

The fuel rods are disassembled prior to encapsulation. The metal parts of the fuel are compacted and embedded in concrete cubes. Deposition of 9,000 tonnes of fuel[15] (13 reactors, 30 years' operating time).

Canister

Lead-filled copper canister with a wall thickness of 20 cm.

Buffer

Highly compacted bentonite.

Backfill

Mixture of quartz sand and bentonite.

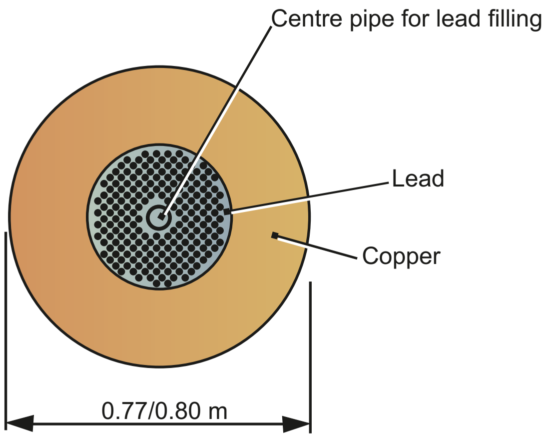

Figure A-2. *Canister design according to the KBS-2 report. The canister diameter is 77 cm; at the top the diameter is 80 cm to enable the canister to be gripped for lifting, see Figure A-3 /SKB 2006a/.*

[15] The fuel quantity is given as quantity of uranium.

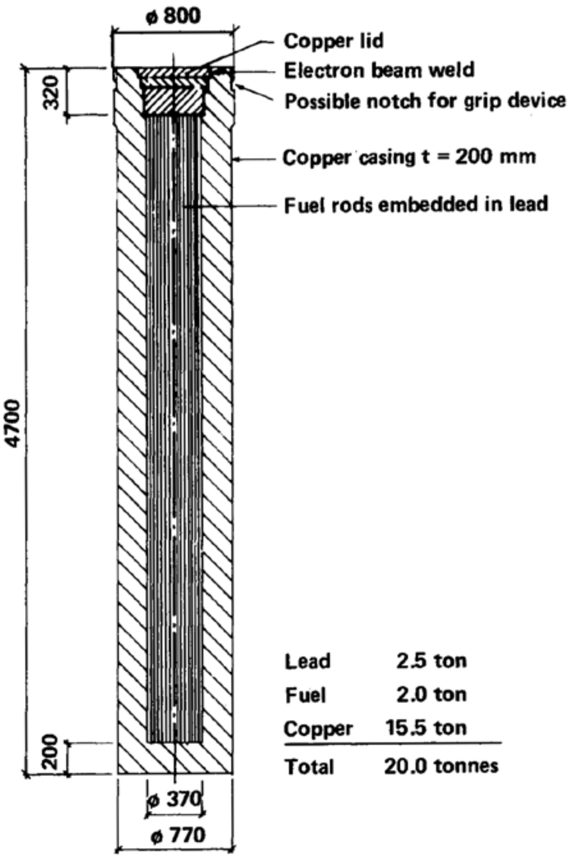

Figure A-3. *Canister design according to the KBS-2 report. Longitudinal section through the copper canister with fuel rods embedded in lead /KBS 1978, Volume II, Figure 5-1 page 136/.*

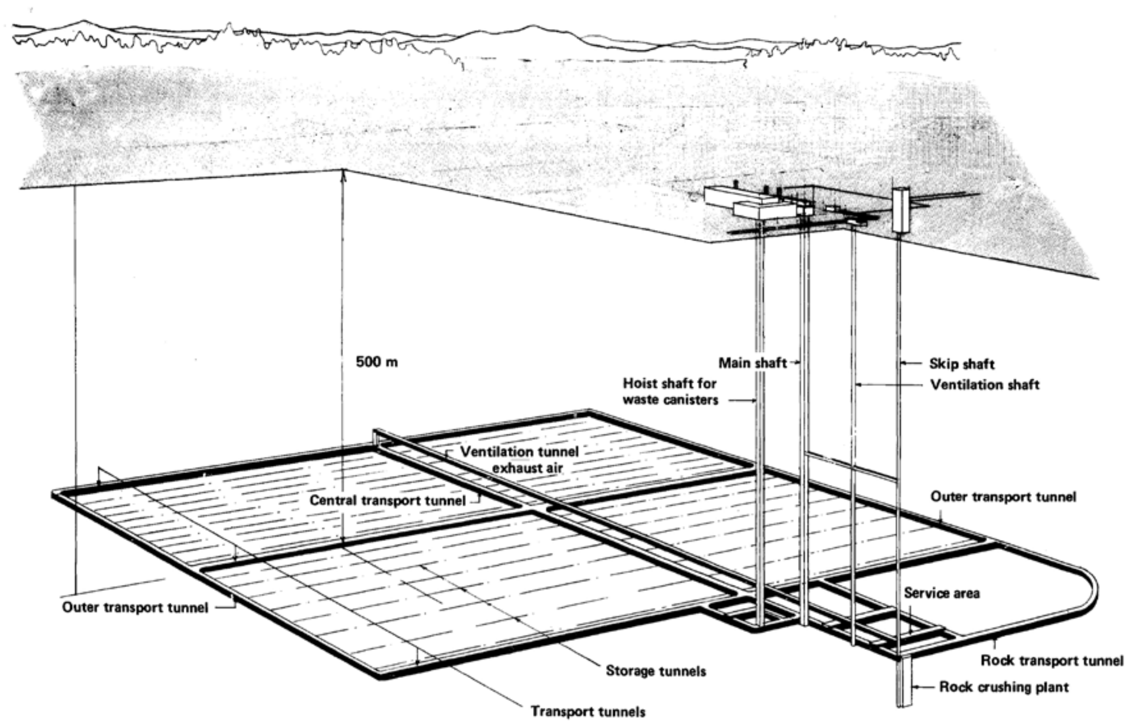

Figure A-4. *Perspective drawing of final repository for spent nuclear fuel. The encapsulation plant is located on ground level. The final repository consists of a system of parallel disposal tunnels situated 500 metres below the ground surface /KBS 1978, Volume I, page 44/.*

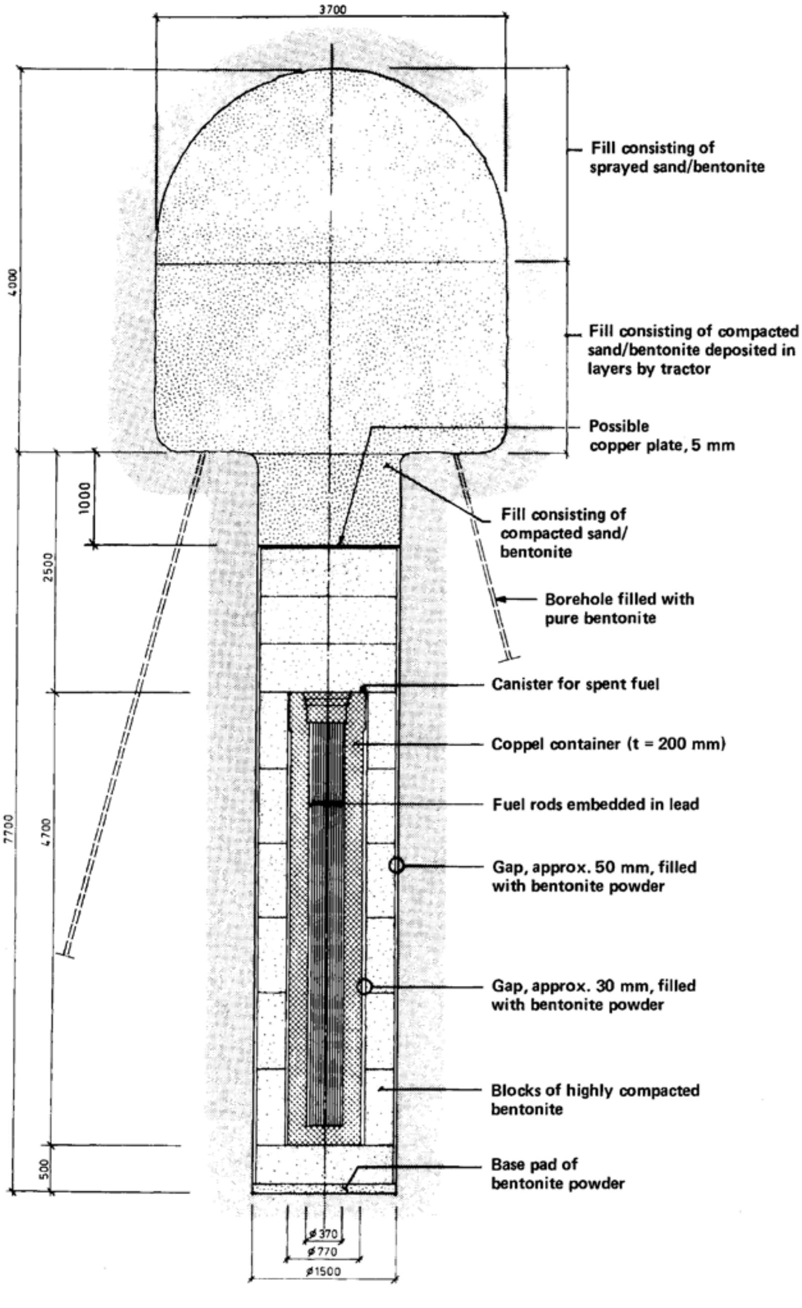

Figure A-5. *The sealed final repository. The canister is surrounded in the deposition hole by blocks of highly compacted bentonite. The tunnel is filled with a mixture of quartz sand and bentonite. A copper plate may be placed on top of the bentonite blocks to serve as a diffusion barrier /KBS 1978, Volume I, page 30/.*

A1.2 KBS-3

Figure A-6 shows how the KBS-3 report illustrated the handling sequence for spent nuclear fuel and Figure A-7 how KBS-3 presented sealing of the final repository /SKBF/KBS 1983/.

KBS-3 had abandoned the idea of disassembling the fuel bundles prior to encapsulation, in part because it would be very time- and resource-consuming, and in part because it entailed a higher risk of fuel damage. The BWR elements' boxes and the PWR elements' boron glass rods would, however, be removed, but not compacted as in KBS-2. Instead they would be embedded in concrete moulds and deposited at a depth of about 300 metres a kilometre or so from the repository for spent nuclear fuel.

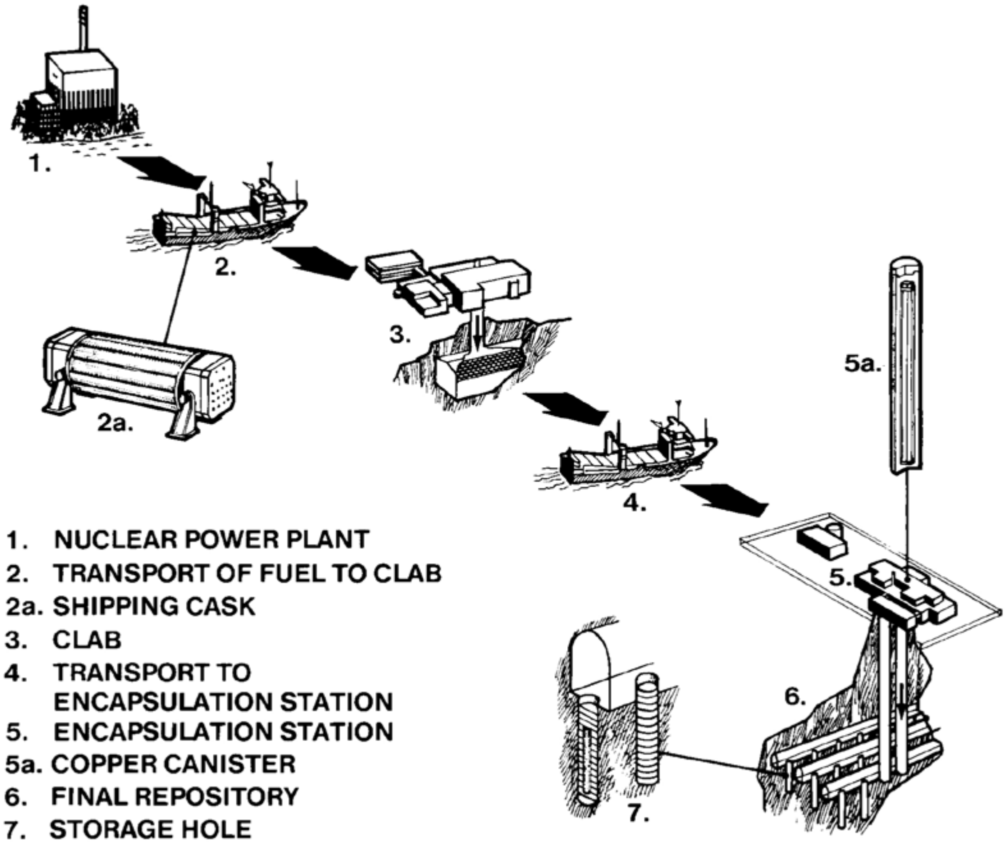

Figure A-6. *Handling sequence for spent nuclear fuel /SKBF/KBS 1983, Part I, page 2:5/.*

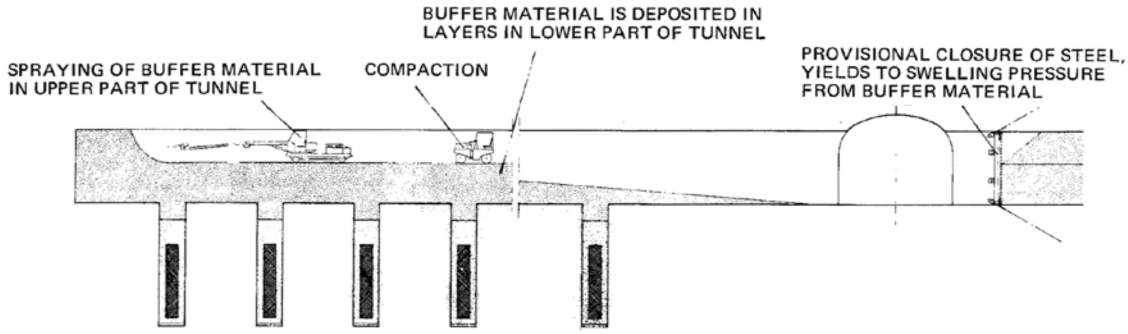

Figure A-7. *When the final repository is sealed, the tunnels are filled with a mixture of quartz sand and bentonite. The lower layer is deposited by tractors and vibrorolled. The upper part of the tunnel is filled by spraying /SKBF/KBS 1983, Part I, page 4:16/.*

Studies now showed that the thickness of the copper shell could be reduced to 10 cm, but since deposition of whole fuel assemblies, instead of separated rods, required more space, the outside diameter of the canister was now the same as in KBS-2.

Two alternative canisters were studied in the safety assessment KBS-3, see Figure A-8. In the one alternative, the spent fuel was placed in a canister where the voids were filled with molten lead, after which the lid was welded on by electron beam welding. In the other alternative, the copper canister was filled with copper powder, after which the lid was put on and the whole package was pressed in a furnace at high pressure and high temperature to a homogeneous body (HIP, hot isostatic pressing). In both alternatives, the canister was to be prefabricated of oxygen-free copper.

KBS-3

Fuel

The fuel assemblies are encapsulated whole but without fuel boxes and boron glass rods. Fuel boxes and boron glass rods embedded in concrete moulds. Deposition of 6,000 tonnes of fuel (12 reactors, 25 years' operating time)

Canister

Two alternative copper canisters:

• Canister filled with copper powder, after which the canister was treated in a furnace for hot isostatic pressing.

• Lead-filled canister.

Both with 10 cm copper thickness.

Buffer

Highly compacted bentonite.

Backfill

Mixture of quartz sand and bentonite.

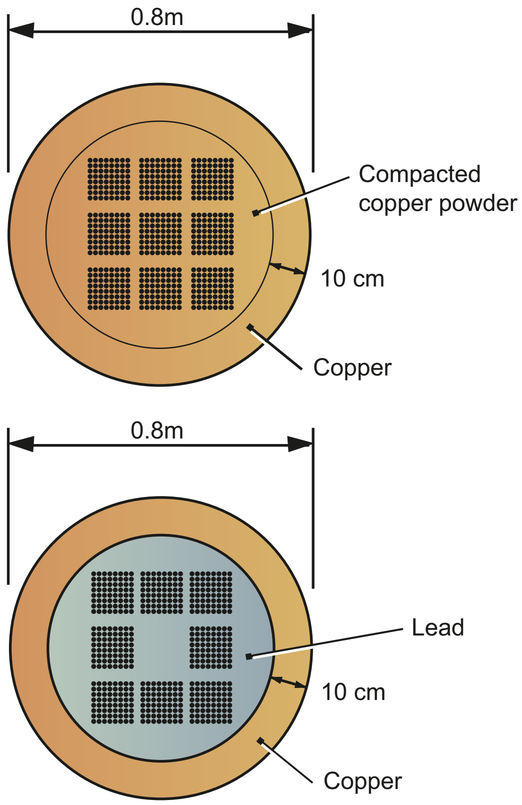

Figure A-8. *Canister design with the two variants studied in the KBS-3 report's safety assessment /SKB 2006a/.*

A1.3 SKB 91

The reference canister in the safety assessment *SKB 91, Final disposal of spent nuclear fuel. Importance of the bedrock for safety.* /SKB 1992c/ was based, with certain modifications, on the lead-filled canister from the KBS-3 safety assessment. The outer shell of copper had been reduced from ten to six centimetres, but the number of BWR fuel assemblies and the outside dimensions were the same, see Figure A-9.

The buffer was assumed to consist of the bentonite clay MX-80. Tunnels and shafts were to be backfilled with a mixture of quartz sand and bentonite (10–20 percent bentonite). Fracture zones were plugged with highly compacted bentonite blocks. The final repository was assumed to be located at a depth of 300–700 metres.

SKB 91

Fuel

The fuel assemblies are deposited whole but without fuel boxes and boron glass rods. Fuel boxes and boron glass rods embedded in concrete moulds. Deposition of 7,800 tonnes of fuel (12 reactors that are in operation until 2010)

Canister

Lead-filled copper canister with 6 cm wall thickness.

Buffer

Highly compacted bentonite.

Backfill

Mixture of quartz sand and bentonite (10–20 percent bentonite) alternated with plugs of highly compacted bentonite blocks.

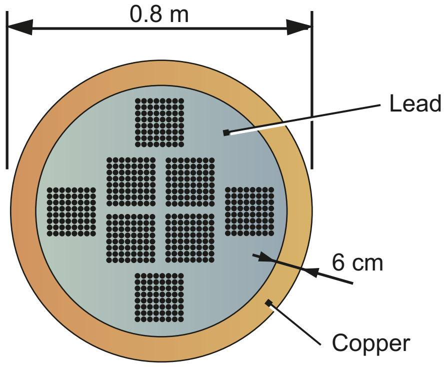

Figure A-9. *Canister design according to the SKB 91 safety assessment /SKB 2006a/.*

A1.4 PASS study

In 1992, SKB carried out *Project Alternative Systems Study (PASS)* where different disposal alternatives and canister designs were compared /SKB 1992a/. In the case of the KBS-3 method, three different designs of the copper canister and two alternative steel canisters were studied.

- Copper/steel canister (composite canister). A canister consisting of an outer copper shell over an inner steel canister that lends mechanical stability to the structure.
- Copper/lead canister. A copper canister that is filled with molten lead to obtain the desired mechanical stability. Encapsulation takes place at high temperature.
- Copper canister. A solid copper canister made by hot isostatic pressing of copper powder (HIP). Encapsulation takes place at high temperature.
- Steel/lead canister. A thin-walled steel canister that is filled with led to lend it the desired mechanical stability plus additional barrier function. Encapsulation takes place at high temperature.
- Steel canister. Self-supporting.

The copper/steel canister was recommended in the PASS study and RD&D-Programme 92 /SKB 1992b/. An important reason was that encapsulation could be done without elevated temperature, reducing the risk of fuel damage. The recommended canister had a copper thickness of five centimetres. In the PASS study, it was assumed that the void in the fuel-filled canister would be filled with a particulate material, such as quartz sand, glass beads, boron glass or lead shot, see Figures A-10 and A-11.

PASS study

Canister

Canister containing whole fuel assemblies without fuel boxes.

The canister consists of an outer copper shell over an inner steel canister. The steel canister was to be filled with e.g. quartz sand, glass beads, boron glass or lead shot.

5 cm copper thickness.

Deposition of approx. 7,900 tonnes of fuel.

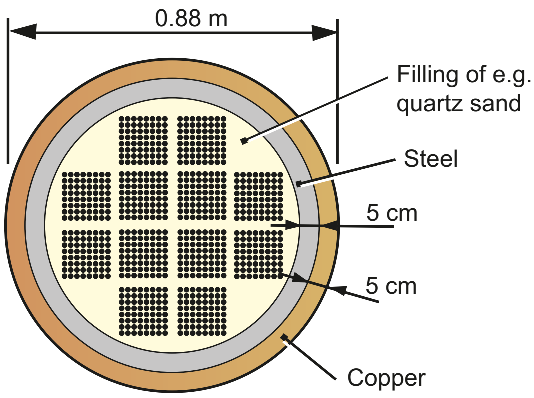

Figure A-10. *Canister design according to the PASS study /SKB 2006a/.*

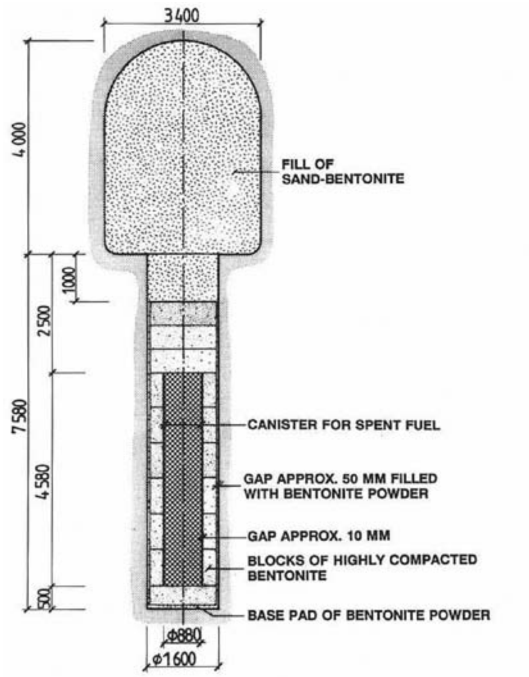

Figure A-11. *Design of canister, buffer and backfill according to the PASS study /SKB 1992a, Fig. B1-14/.*

A1.5 SR 95

SR 95 /SKB 1995/ described not only the final repository for the spent nuclear fuel, but also the final repository for other types of long-lived waste. The two repositories were assumed to be located on the same site. In order to prevent the large quantities of concrete that were used for the low- and intermediate-level long-lived waste from disturbing the chemical conditions in the area for the spent nuclear fuel, the repository parts were placed at a distance from each other. Deposition of the spent fuel was assumed to take place in two stages. In the first stage, about ten percent of the fuel would be deposited in a separate repository area. The spacing between the canisters was set at 6 metres and between the tunnels at 40 m. The design factor was that the temperature in the buffer must not exceed 100°C. In order to cover uncertainties of various kinds in the control parameters and in the calculation method, the limit value for the calculated temperature was set at 80°C.

In SR 95, the canister consisted of two components: a cast insert and a copper shell. The cast insert replaced the steel cylinder as a pressure-bearing component. The insert of cast steel was fabricated in two equally long parts, welded together in the middle. The insert had individual channels for the fuel assemblies. Just like in the PASS study, the canister contained twelve BWR assemblies. Compared with the canister in SKB 91, which contained eight BWR assemblies, the outside diameter of the canister was therefore larger, see Figure A-12. Fabrication of a cast insert was simpler and cheaper than the alternative with a steel tube while at the same time the canister was mechanically stronger. The material for the insert was either cast steel or cast iron. Because the void inside the canister was smaller, the risk of criticality was also smaller. In the case of the BWR fuel, the fuel could be encapsulated with or without boxes. If the boxes were included, the canister was longer and slightly more expensive. To minimize the risks of handling damage, it was decided to let the BWR boxes remain in place.

A study of different buffer materials /Werme and Eriksson 1995/ showed that only montmorillonite and saponite with sodium as the principal absorbent ion could be considered (smectite types). The clay that would be used should have a smectite content of at least 50 percent.

The thickness of the bentonite buffer is determined by the desired mechanical, chemical and hydraulic function and the desired capacity for gas migration. It was also necessary to consider the buffer's capacity to conduct heat away from the canister so that the temperature increase in the buffer is not too high. Allowing for this and the requirement of good barrier capacity to prevent nuclide transport, it was decided that the thickness of the buffer should be 35 centimetres. The thickness of the buffer underneath the canister was determined to be 50 centimetres and on top of the canister 150 centimetres, see Figure A-13.

SR 95

Fuel

The fuel assemblies are deposited whole (including fuel boxes). Deposition of 6,500 tonnes (12 reactors, operating time 25 years), 7,800 tonnes (12 reactors in operation until 2010) or 9,900 tonnes of fuel (12 reactors, operating time 40 years)[16].

Canister

Copper canister with 5 cm wall thickness with a cast steel insert with channels for the fuel assemblies.

Buffer

Highly compacted bentonite with a smectite content of at least 50 percent and a thickness of 35 cm around the canister.

Backfill

Mixture of crushed rock and bentonite (10–20 percent) compacted in situ in the tunnels. This is alternated with plugs of highly compacted bentonite blocks.

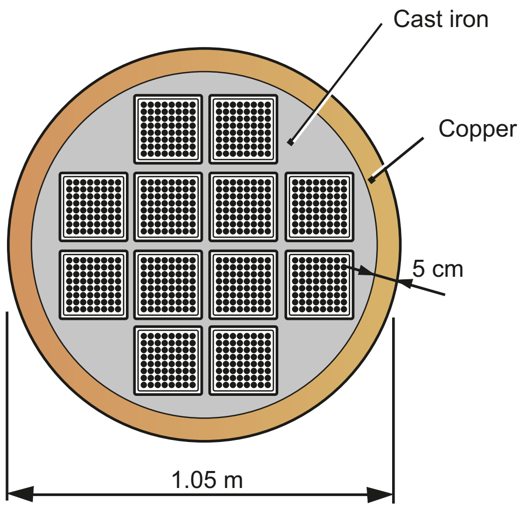

Figure A-12. *Canister design according to SR 95 /SKB 2006a/.*

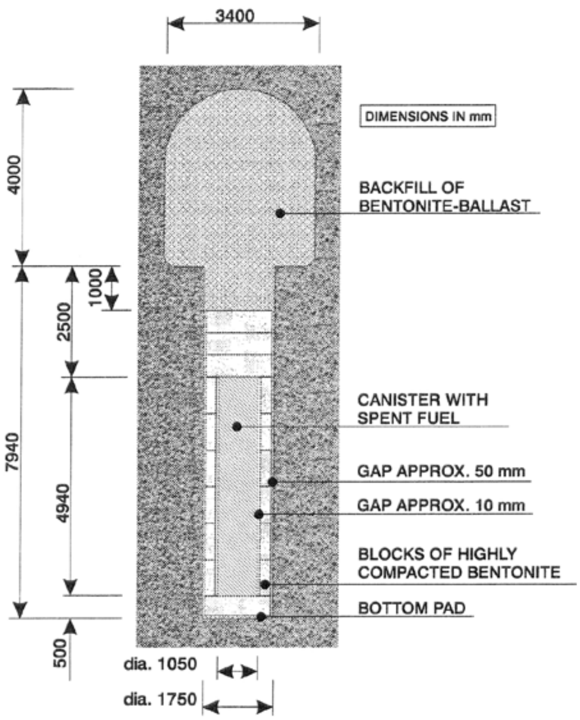

Figure A-13. *Design of canister, buffer and backfill according to SR 95. When the buffer has been water-saturated and swelled out, the gaps between canister and buffer and between buffer and hole wall disappear /SKB 1995, figure 5.2-2/.*

A backfill material with a mixture of 10–20 percent bentonite and the rest aggregate was chosen as a reference in SR 95. The aggregate consisted of the rock spoil that is excavated during the construction of the final repository. The rock was to be crushed to a suitable particle size and mixed with the bentonite and deposited in horizontal layers while being compacted. The properties of such a material had been studied and found to be comparable to the properties of the previously recommended quartz sand mixture. The reasons for using crushed rock instead of quartz sand were both environmental and economic.

Figure A-14 shows how the final repository and its function were illustrated in SR 95.

[16] The figures on nuclear fuel quantity were taken from PLAN 94 /SKB 1994/.

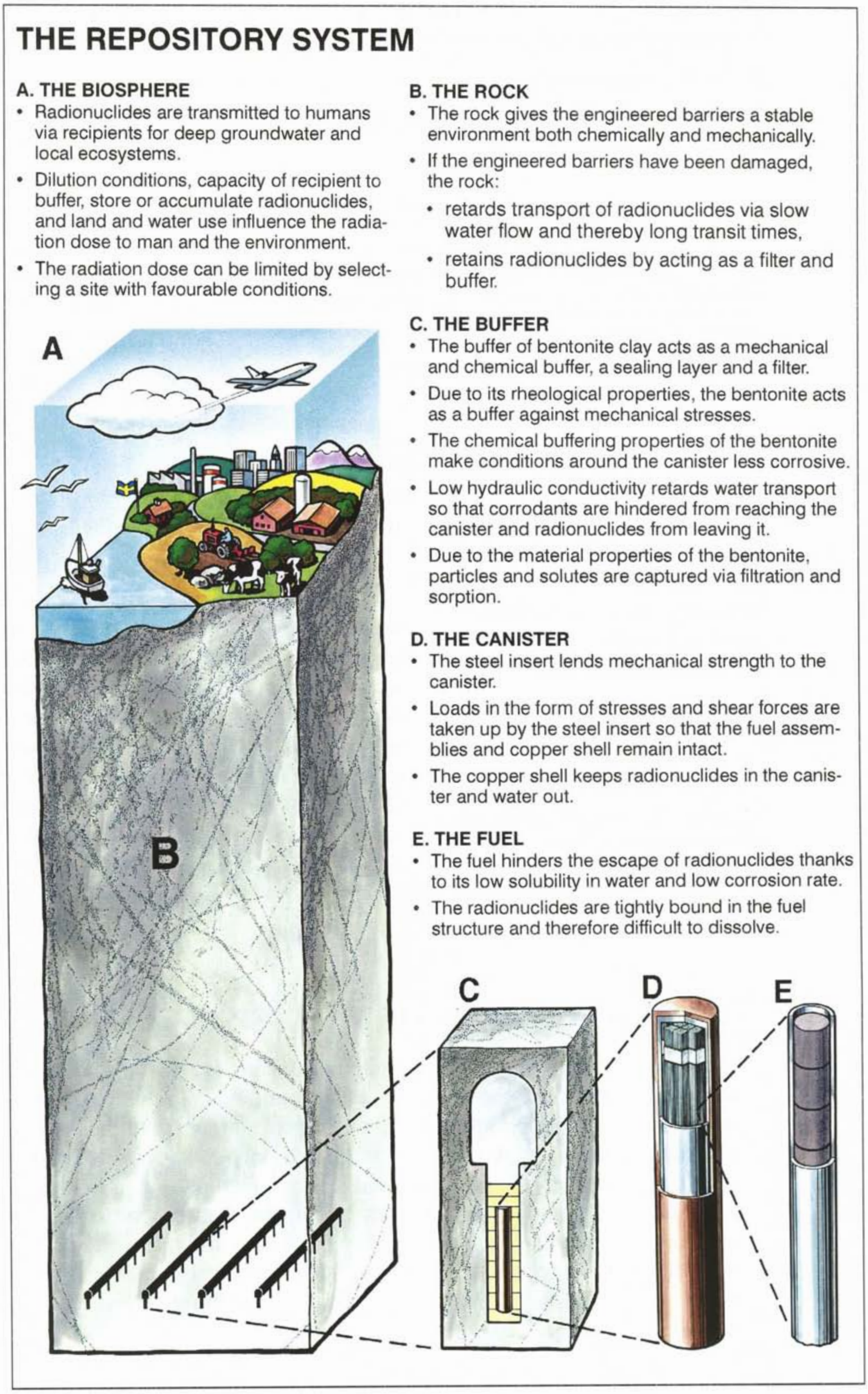

Figure A-14. *The final repository and its function according to SR 95, Figure 9.1-1.*

A1.6 SR 97

SR 97 /SKB 1999a/ assessed the long-term (post-closure) safety of a final repository with site data from three sites. In parallel with SR 97, a preliminary facility design and a safety assessment were prepared for a repository for long-lived waste /SKB 1999b/. In order to utilize information and data from SR 97, it was assumed that the repository for long-lived waste was co-sited with the deep repository for spent fuel. It was noted, however, that the siting was not definite and that locating the repositories completely separate from each other was also being considered.

Deposition of 8,000 tonnes of fuel was assumed in SR 97, including about 5,000 tonnes of BWR fuel, see Figure A-15.

The canister consists of an inner container of cast iron and a shell of copper, Figure A-16. The cast iron insert provides mechanical stability while the copper shell protects against corrosion in the repository environment. The copper shell is 5 cm thick and the canister takes the form of an approximately 4.8 metre tall cylinder with a diameter of 1.05 metres.

The insert has channels where the fuel assemblies are placed and is available in two versions: one for twelve BWR assemblies and one for four PWR assemblies. The fuel channels are fabricated in the form of an array of square tubes. The walls and bottom of the inner container are then fabricated by pouring nodular iron around the channel array.

The copper canister is fabricated either of drawn seamless tubes or by welding together two tube halves of rolled plate. A bottom is attached by an electron beam weld.

After fuel has been placed in the canister, the insert is closed with an O-ring-sealed lid fastened with a bolt. The copper shell's lid is then attached by an electron beam weld, and the canister's leaktightness is tested by ultrasonic and radiographic inspection.

The canister weighs a total of about 25 tonnes when filled with 12 BWR assemblies. One canister holds about two tonnes of fuel.

The buffer is assumed to consist of the bentonite clay MX-80, a natural clay from Wyoming or South Dakota. The designation MX-80 specifies a certain grade and particle size of the dried and ground bentonite. MX-80 bentonite consists mainly of the smectite mineral montmorillonite (65–80 percent), where the clay particles are smaller than 2 µm. The exchangeable ions in MX-80 consist predominantly of sodium, and the material is therefore called sodium bentonite, see Figure A-17.

The backfill consisted of a mixture of 15 weight-percent bentonite clay (MX-80) and 85 weight-percent crushed rock.

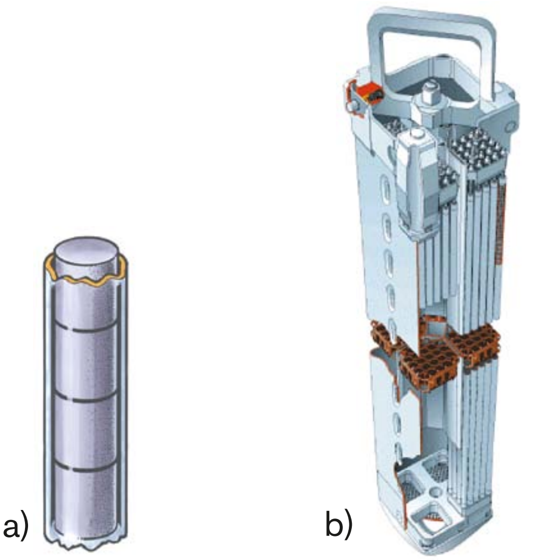

Figure A-15. *Fuel and fuel assemblies according to SR 97 /SKB 1999a, Figure 5-2/. a) Cylindrical fuel pellets with a diameter of approximately 1 cm in cladding tubes of Zircaloy. b) Fuel assembly of type SVEA 96. The assembly consists of 96 fuel rods and has a height of approximately four metres.*

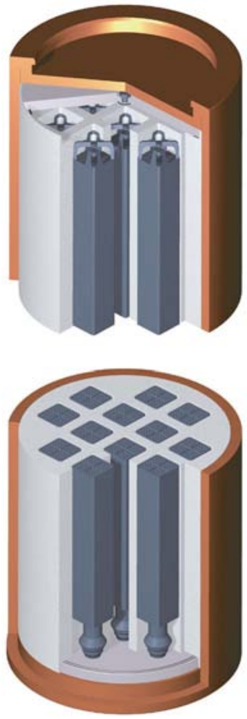

Figure A-16. Copper canister with cast iron insert for BWR fuel /SKB 1999a, Figure 5-4/.

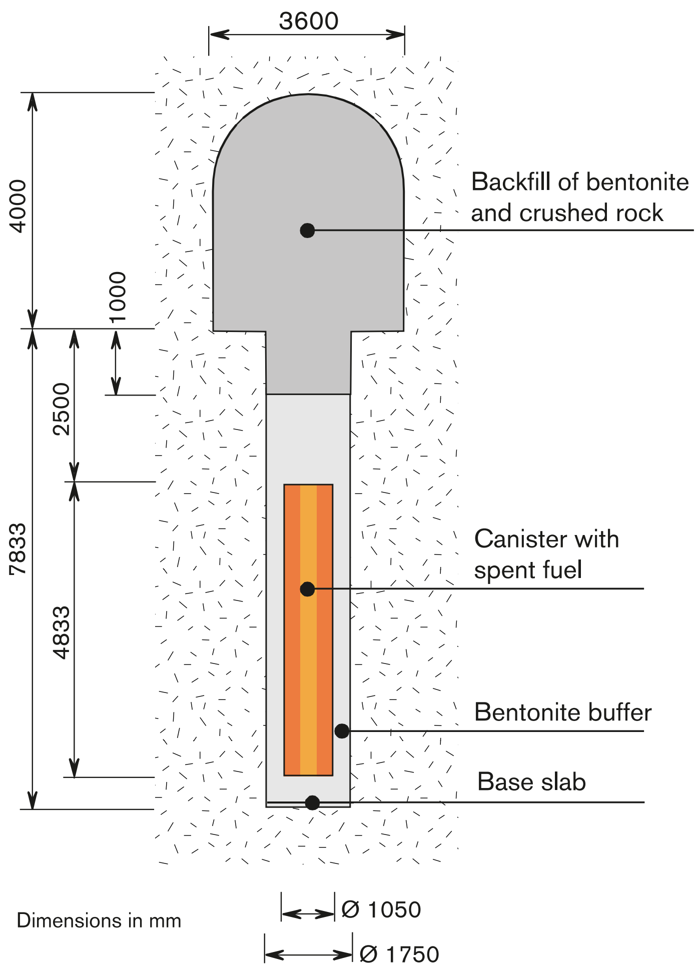

***Figure A-17.** Deposition hole with bentonite buffer and canister. The figure also shows the backfilled deposition tunnel above the deposition hole /SKB 1999a, Figure 5-6/.*

A1.7 SR-Can

The total quantity of fuel obtained from the Swedish nuclear reactors will depend on operating time, energy output and fuel burn-up. With an operating time of 40 years for all reactors except for Barsebäck 1 and 2 (which were taken out of service in 1999 and 2005, respectively), the total quantity of spent fuel has been estimated at about 9,300 tonnes. To allow for uncertainties in the scope of the Swedish nuclear power programme, the analyses in SR-Can were based on a repository with 6,000 canisters, equivalent to around 12,000 tonnes of spent fuel.

The reference canister in SR-Can was essentially the same as in SR 97, see Figure A-18 /SKB 2006b, Chapter 4/. The canister was assumed to be fabricated as a seamless tube. Lids and bottoms are machined to the desired dimensions from hot forged blanks. Lids and bottoms are welded onto the copper canister by friction stir welding.

Two types of bentonite were analyzed for the buffer in SR-Can: one a natural Na-bentonite of Wyoming type (MX-80) and the other a Ca-bentonite (Deponit CA-N). SKB said that the two buffer materials that were studied were merely examples of possible alternatives; no final choice of buffer material had yet been made.

Two concepts were also analyzed for backfilling of the deposition tunnels:

- The tunnel is filled with pre-compacted blocks. The space between the rock and the blocks is filled with bentonite pellets. The blocks are made of a mixture of bentonite of buffer quality (30 weight-percent) and crushed rock (70 weight-percent, particle size max. 5 mm). The uppermost metre of the deposition hole is backfilled with the same material as the tunnel.
- The tunnel is filled with pre-compacted blocks. The space between the rock and the blocks is filled with bentonite pellets. The blocks are made of Friedland clay, a naturally swelling clay with approximately 50 percent smectite. The uppermost metre of the deposition hole is filled with bentonite blocks of the same material and with the same dimensions as the buffer blocks placed on top of the canister.

As is evident from Figure A-19, the deposition tunnel now has a larger cross-section than in SR 97.

When a deposition tunnel has been backfilled, it must be sealed with a plug pending backfilling of the transport tunnel. The plug must withstand the pressure from the groundwater and the swelling pressure while preventing water flow. The plug is made of concrete of low-pH grade, i.e. concrete that emits a leachate with a pH of less than 11. The plug is assumed to be left in the final repository, but it has no long-term safety functions.

Other tunnels and shafts were assumed to be backfilled according to the first alternative for the deposition tunnels, i.e. with pre-compacted blocks of crushed rock and bentonite.

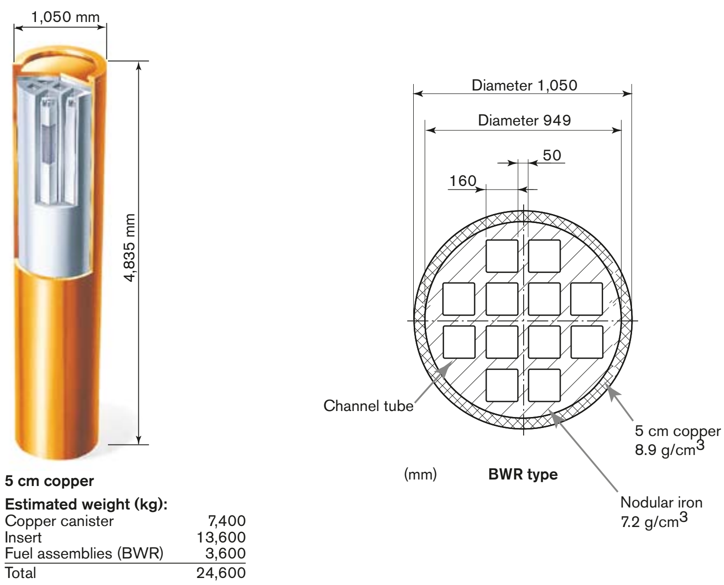

Figure A-18. *Reference canister in the SR-Can safety assessment /SKB 2006b, Figure 4-5/.*

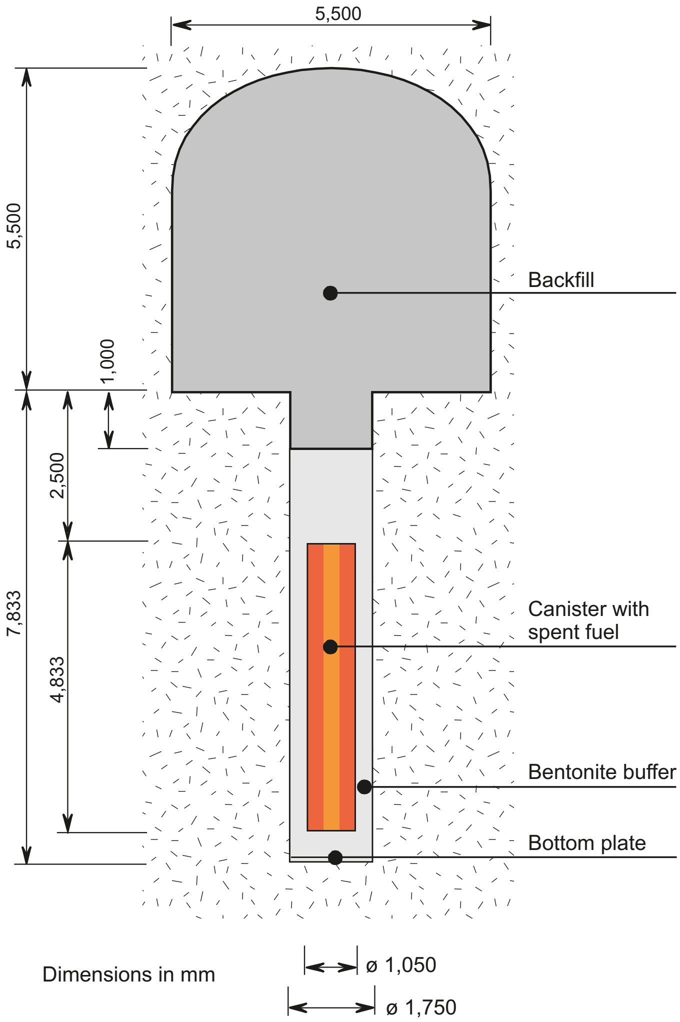

Figure A-19. *Deposition hole and deposition tunnel according to SR-Can /SKB 2006b, Figure 4-4/.*

A1.8 SR-Site

SKB carried out the safety assessment SR-Site /SKB 2011/ as a basis for applications for licences to build and operate a final repository for spent nuclear fuel in Forsmark. In the assessment (and in the application), the repository is located at a depth of about 470 metres and holds 6,000 canisters, equivalent to 12,000 tonnes of spent nuclear fuel. The assessment is based on the following reference design.

A1.8.1 The canister

The reference canister in SR-Site is essentially the same as in SR 97 and SR-Can, see Figure A-20. The canister is assumed to be fabricated as a seamless tube. Lids and bottoms are machined to the desired dimensions from hot forged blanks. Lids and bottoms are welded onto the copper canister by friction stir welding.

A1.8.2 Buffer

The buffer is made of bentonite clay of type MX-80. Other materials may also be considered. The geometric arrangement is shown in Figure A-21.

A1.8.3 Backfill

The deposition tunnels are backfilled with blocks and pellets of bentonite clay. The reference design is shown in Figure A-22. A concrete plug is installed in the mouth of each deposition tunnel.

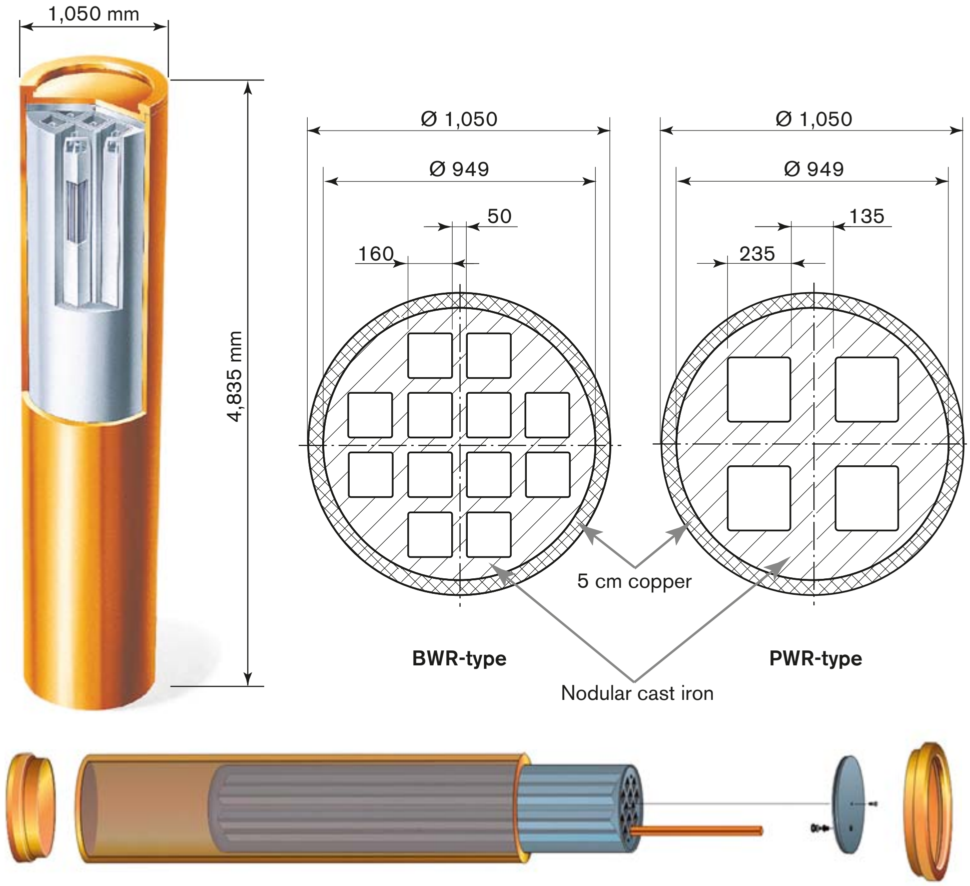

Figure A-20. *Reference canister in SR-Site safety assessment /SKB 2011, Figures 5-8, 5-9/.*

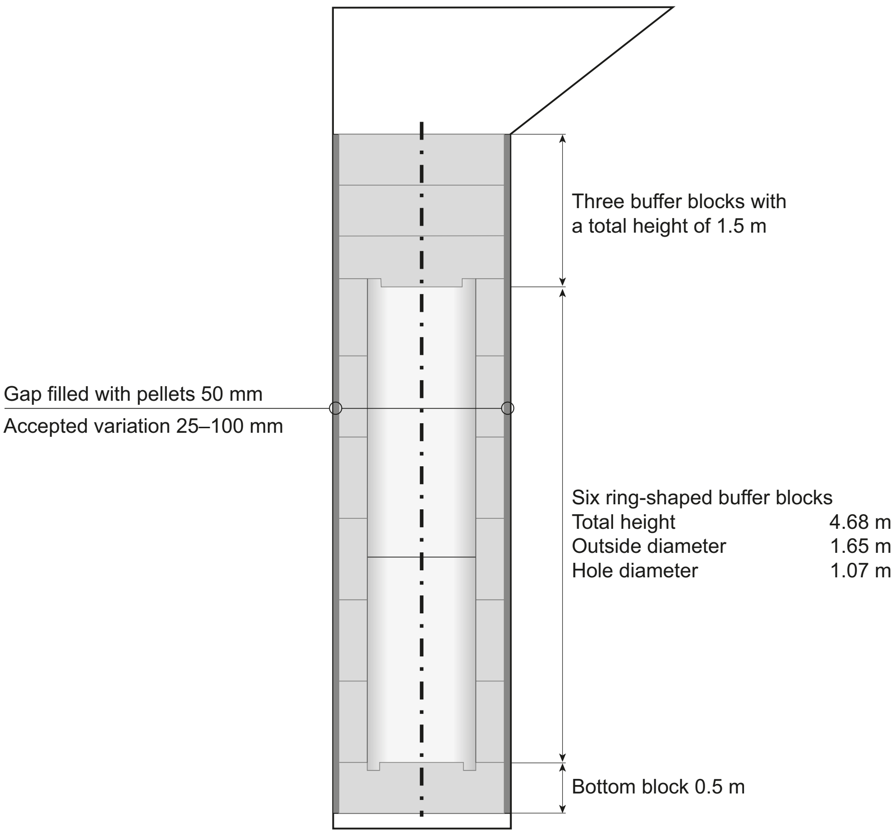

Figure A-21. *Reference design of the buffer /SKB 2010b, Figure 12-1/.*

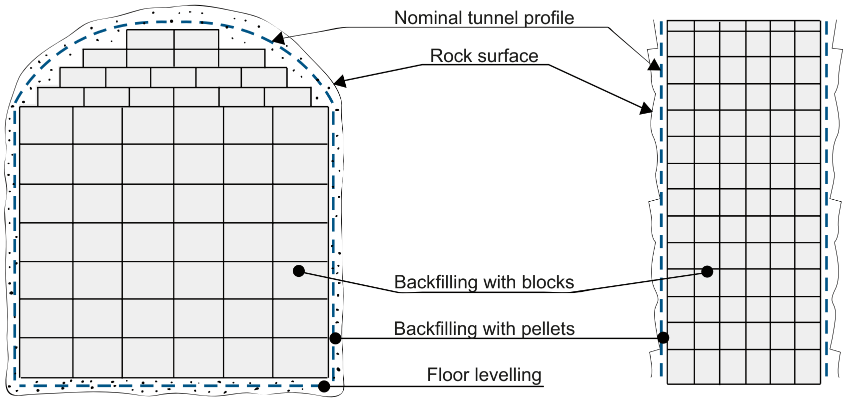

Figure A-22. *Reference design for backfilling of deposition tunnels /SKB 2010b, Figure 13-1/.*

A1.8.4 Closure

The following reference design for closure of the repository is analyzed in SR-Site:

- main and transport tunnels plus the lower part (from 470 to 200 metres depth) of ramp and shafts are sealed in the same way as the deposition tunnels, i.e. with blocks and pellets of bentonite clay,
- the central area and the upper part (from 200 to about 50 metres depth) of ramp and shafts are sealed with crushed rock that is compacted,
- to hinder intrusion in the repository, the uppermost parts (from about 50 metres depth up to the ground surface) are sealed with coarser rock material,
- investigation boreholes are sealed with perforated copper tubes filled with highly compacted bentonite.

A2 Safety assessments

In order to determine whether a final repository for spent nuclear fuel meets the requirements on long-term safety, a safety assessment is performed. The safety assessment and the premises it is based on are presented in a safety report. There is no standardized method for carrying out safety assessments. Different methods and variants are used by different organizations all over the world. Differences in approach are dependent partly on different national conditions and partly on the fact that the methods are progressively developed and refined. There are nevertheless many common features in the safety assessments that have been carried out since the mid-1990s. This is evident, for example, from the survey conducted under the auspices of the OECD/NEA at the end of the 1990s /NEA 1997/. The NEA report gives recommendations on what elements a safety assessment report should contain. All of these elements are included in SKB's safety assessments SR 97, SR-Can and SR-Site. The requirements on long-term safety are formulated by the regulatory authorities; currently applicable requirements are set forth above all in the Swedish Radiation Safety Authority's regulation SSM 2008:37, see Section 2.3 in this report.

The long-term safety of a final repository according to the KBS-3 method has been assessed in a number of safety evaluations and safety assessments. The first safety evaluations based on actual site data were done in conjunction with the KBS-3 study. The first big safety assessment after KBS-3 was presented in SKB 91. SKB 91 was then followed by the comprehensive assessment in SR 97. During the site investigation phase, SKB carried out both safety evaluations and a safety assessment, SR-Can, for the two investigated sites. Finally, SKB has carried out a safety assessment, SR-Site, as a basis for applications for licences to build and operate a final repository in Forsmark.

SKI has carried out two safety assessments of final repositories according to the KBS-3 method for the primary purpose of building up its own competence in reviewing SKB's safety assessments. The SKI safety assessment Project-90 was published in 1991 /SKI 1991/, and the results of the more comprehensive SITE-94 /SKI 1997/ were published in 1997. In Finland, first the nuclear power company TVO and subsequently Posiva have carried out several safety assessments of final repositories according to the KBS-3 method.

The safety assessments have been reviewed by Swedish regulatory authorities and international expert panels. This has made valuable contributions to the development and improvement of methods and calculation models for performing safety assessments, from the assessment in the KBS-3 report up to SR-Site. Furthermore, research and development – not least at the Äspö HRL – has contributed to a more comprehensive and reliable body of material for the safety assessments. At the same time, a dramatic improvement has occurred in the ability to carry out advanced assessments due to the fact that computing capacity has increased steadily. The most important task for the early safety assessments was to identify what features were particularly important for long-term safety. This also created a basis for determining what research was particularly urgent.

A2.1 KBS-3

The main purpose of the safety assessment in the KBS-3 report /SKBF/KBS 1983/ was to show that the requirements of the Stipulations Act on safe management and disposal of spent nuclear fuel could be met. The assessment in KBS-3 was based on bedrock data from the study sites Fjällveden, Gideå and Kamlunge.

Based on a probable sequence of events, the consequences of e.g. initial canister damage, radionuclide transport with colloids, earthquakes and human intrusion were analyzed. The consequence of release to well, lake and peat bog were analyzed.

The conclusions of the safety assessment were in brief that the copper canister and buffer function were judged to remain intact for at least one million years. If canisters were damaged or had initial defects, the consequences for humans in the vicinity of the repository would be much lower than the norms and guidelines for radiation protection stipulated by the radiation protection authority at that time for nuclear activities.

A2.2 SKB 91

The SKB 91 safety assessment /SKB 1992c/ had several purposes. One was to examine how the long-term safety of a final repository is affected by the properties on the site; another was to gather background data for systematic analyses where parameters that influence safety are varied. A secondary purpose was to examine a system of rational procedures for carrying out safety assessments.

SKB 91 differed in several respects from the assessment in the KBS-3 report. The knowledge base had grown, which made it possible to take into account parameters that had previously been treated in a simplified fashion. In KBS-3 it was assumed that the effect of the canister in preventing the leakage of radionuclides is lost entirely when it has been penetrated by a single hole. It was further assumed that radionuclides reach the biosphere at the same instant as they reach a major fracture zone. Such simplifications were avoided wherever possible in SKB 91. Increased computational power in computers and new models made it possible to take into account the variability in the permeability of the rock and the site-adapted repository layout.

In SKB 91, SKB refers to a symposium on systematics and tools for safety assessments arranged by the IAEA, the OECD/NEA and the CEC in the autumn of 1989 in Paris. Experience from the symposium and the subsequent evaluation was summarized in a collective opinion /OECD/NEA 1991/. In this it was observed that a satisfactory methodology for assessing long-term safety is available today.

Long-term safety can be affected by changes in the repository's future environment. Scenario analysis therefore occupies a central position in the safety assessment. Another important aspect is to show that no important phenomena or environmental conditions have been omitted. When SKB 91 was conducted, international efforts had been made to formalize the assessment and establish acceptable practice /OECD/NEA 1992/.

Site data (topography, geology, hydrogeology etc.) from the Finnsjön site were used in the SKB 91 safety assessment. However, the site description was considerably less comprehensive than the one SKB had used as a basis for SR-Site. Compared with the safety assessments SKB has done more recently, the scenario analysis and the analysis of the repository's evolution were also more limited. SKB 91 dealt with the repository's post-closure safety. The conclusion in SKB 91 was that a repository constructed deep down in the Swedish crystalline basement with long-term stable engineered barriers fulfils the safety requirements stipulated by the regulatory authorities with ample margin.

SKB 91 was reviewed by the regulatory authorities and others in conjunction with the review of RD&D-Programme 92. SKI stated in its review that future safety assessments must be more comprehensive in different respects.

A2.3 SR 95

The main purpose of SR 95 /SKB 1995/ was not to carry out a "real" safety assessment, but to prepare a template for how assessments of long-term safety should be carried out and reported. In addition to the actual template, SR 95 contained an illustrative compilation of then-available methods and numerical tools for carrying out assessments of long-term safety, application of scenario methodology and handling of uncertainties. The structure of the report in the form of the template presented in SR 95 was then further developed in SR 97.

A2.4 SR 97

The SR 97 safety assessment /SKB 1999a/ was presented in December 1999. The assessment had four concrete purposes:

1. serve as a basis for demonstrating the feasibility of finding a site in Swedish bedrock where the KBS-3 method for deep disposal of spent nuclear fuel meets the requirements on long-term safety and radiation protection that are defined in SSI's and SKI's regulations,
2. demonstrate methodology for safety assessment,
3. serve as a basis for specifying the factors that serve as a basis for the selection of areas for site investigations and for deriving which parameters need to be determined and which other requirements ought to be made on a site investigation,
4. serve as a basis for deriving preliminary functional requirements on the canister and the other barriers.

An overview of the methodology employed for the work with SR 97 is provided in Chapter 4 of the main report /SKB 1999a/.

The execution and presentation of the SR 97 safety assessment was based entirely on a systems perspective. Another distinguishing feature was the endeavour to find a balance between different aspects of the repository's evolution. In previous analyses, the emphasis on radionuclide transport, i.e. the repository's retarding function, was often very strong. In SR 97 there was a greater focus than before on the most fundamental function, isolation /SKB 1999a/.

Fictitious repositories were assessed in SR 97 with actual bedrock data from three different sites: Äspö (called Aberg in SR 97), Finnsjön (Beberg) and Gideå (Ceberg). The intention was to use data from the three sites to shed light on different conditions in Swedish granitic bedrock as regards geology, groundwater flux, water chemistry, nearness to coast, northerly or southerly location, surrounding biosphere, etc.

Both the KBS-3 study's safety evaluation and the safety assessment in SR 97 are based on descriptions of an initial state a final repository and a site, after which they consider different possible scenarios, accidents and extreme events that could happen, concluding with an evaluation and assessment of the whole body of material. The system description, choice and analysis of scenarios and evaluation methodology were considerably more advanced in SR 97 than in the KBS-3 study. To this can be added the increase in knowledge and the huge improvements in computer technology that had occurred during the period between the KBS-3 study and SR 97.

The methodology that was applied in SR 97 was to first describe the properties of the repository when it has just been closed and then analyze the changes in the system over time due to internal processes in the repository as well as external influences. The future evolution of the repository system was analyzed in five scenarios. The first was a base scenario where the repository was assumed to have been built according to specifications and where present-day conditions in the surroundings, including climate, were assumed to persist. The four other scenarios showed how the evolution of the repository differs from that in the base scenario if the repository contains a few initially defective canisters, in the event of climate change, in the event of earthquakes, and in the event of future inadvertent human intrusion. In all scenarios, various relevant processes were taken into consideration: thermal, hydraulic, chemical, mechanical and radiation-related. The ultimate purpose of the analyses was to examine the ability of the repository to isolate the waste by means of the canisters and to delay a possible release of radionuclides if canisters are damaged. The time perspective for the analyses was at most one million years.

SR 97 was subjected to extensive review, both internationally and nationally. The main conclusion of the International Review Team was: *The KBS-3 disposal concept has the essential elements of a sound concept for the disposal of spent nuclear fuel in a geologic repository. It provides defence-in-depth through a set of passive barriers with multiple safety functions. The concept is based on well-established science and a firm technological foundation, is well defined, and appears to be implementable. SR 97 provides a sensible illustration of the potential safety of the KBS-3 concept that takes account of the conditions in Swedish bedrock, based on data from three sites. The documentation is generally well written and the arguments are well presented, but there is room for improvements in the completeness of arguments, traceability and transparency /SKI 2000/.*

A2.5 SR-Can

The SR-Can safety assessment /SKB 2006b/ was a preparatory step to the SR-Site assessment, which will serve as a basis for SKB's applications for licences to build and operate a final repository. SR-Can was preceded by an interim version, which focused on the methodology for safety assessments /SKB 2004/. The interim version was reviewed, with the support of an International Review Team, by SKI and SSI. The regulatory authorities' viewpoints were taken into account in the SR-Can safety assessment.

In addition to the interim report, preliminary safety evaluations were performed /SKB 2005a, b, 2006c/ for the two sites. The main purpose of these evaluations was to establish whether previous assessments of the suitability of the candidate areas for a final repository, with respect to long-term safety, persisted in the light of additional data from boreholes and other data that had been collected at the sites. Furthermore, they were supposed to provide feedback for continued site investigations and site-specific repository design.

SR-Can had the following purposes:

1. To make a preliminary assessment the safety of KBS-3 repositories at Forsmark and Laxemar with canisters as specified in the application submitted for the encapsulation plant.
2. To provide feedback to canister development, to facility design for the final repository, to continued site investigations, to SKB's programme for research on issues of importance for long-term safety and to future safety assessments.
3. To give SKI and SSI an opportunity to review SKB's preliminary safety analysis report prior to considering the applications for a final repository for spent nuclear fuel.

SR-Can was based on the site data that were available after the initial site investigation in Forsmark and Laxemar.

In summary, SR-Can showed that a KBS-3 repository at the two sites is deemed to fulfil SSI's risk criterion, but that it is urgent to obtain more site data from the candidate area in Laxemar. The assessment also yielded important results in the form of feedback to SKB's research programme by indicating questions that require further study. These include the question as to whether heat from the spent fuel could cause the rock nearest the deposition holes to crack, and the question as to whether the buffer could, after a very long time, disappear out into rock fractures that might intersect a deposition hole.

SR-Can was reviewed by SKI and SSI jointly /SKI 2008/. The main purpose of the regulatory authorities' review was to provide feedback to SKB for the work with SR-Site. To assist in their review, the regulatory authorities assembled three international review groups. One group reviewed the use of data from the site investigation, one reviewed the engineered barriers, and the third group reviewed the methodology used in SR-Can. In addition, certain detailed technical and scientific issues were reviewed by external experts and consultants. The concerned municipalities, Oskarshamn and Östhammar, as well as the environmental organizations that formally follow SKB's work, were offered an opportunity to submit viewpoints to the regulatory authorities. In the summary, the review led to the following findings /SKI 2008/:

- SKB's safety assessment methodology is largely in accordance with the authorities' regulatory requirements, but parts of the methodology need to be further developed prior to licence application.
- SKB's quality assurance of the safety assessment SR-Can is insufficient.

- Prior to licence application, a better knowledge base is needed with respect to certain critical processes with a potentially great impact on the risk from the repository, such as erosion of the buffer in deposition holes.
- SKB needs to verify that the assumed initial state of the repository is realistic and achievable.
- The account of the risk of early releases should be strengthened.

A2.6 SR-Site

The SR-Site safety assessment serves as a basis for SKB's applications for licences to build and operate a final repository in Forsmark /SKB 2011/. Besides supporting applications, the assessment has the following purposes:

- Assessing the safety of a KBS-3 repository at Forsmark.
- Providing feedback to continued design of the repository, to SKB's programme for research and development concerning issues of importance for long-term safety, to detailed characterization during construction and operation, and to future work with safety evaluations and safety assessments.

The goal of SR-Site has been to analyze, based on information on the bedrock from completed site investigations, whether a KBS-3 repository at Forsmark has the potential to satisfy the regulatory authorities' requirements on safety and radiation protection. In addition to information from the site investigations in Forsmark, SR-Site is based on a documented reference design of canister, buffer, backfill, underground openings and closure, including reference methods for fabrication/production, installation and inspection of these barriers.

SR-Site is based in several important respects on the SR-Can safety assessment:

- The methodology and structure of SR-Site is based on SR-Can.
- Experience from the work with SR-Can and the regulatory authorities' review has been taken into consideration, for example when it comes to updating of the methodology and the scope of the assessment.
- The results of SR-Can have, together with a number of supplementary assessments, comprised the basis for determining design requirements with respect to long-term safety. These design requirements have then comprised premises in the work of developing the repository design that has been assessed in SR-Site.

In summary, SR-Site shows that a KBS-3 repository in Forsmark satisfies stipulated requirements on safety and radiation protection.

A3 Laboratories

A3.1 Stripa

Not long after it was started, the KBS project established an underground laboratory in granite next to the abandoned iron mine in Stripa, 15 kilometres northeast of Lindesberg. The two-fold purpose was to study the natural geological barrier in a representative environment (granitic crystalline bedrock) and to test different properties of the proposed engineered barriers.

The hard rock laboratory in Stripa aroused international interest by providing a then-unique opportunity to quickly initiate field tests in granitic rock at a depth of 350–400 metres. In 1977, a project called *the Swedish American Cooperative Program (SAC)* was started, co-sponsored by SKB and the US Department of Energy. The aim was to develop technology for measuring certain properties – e.g. thermodynamic, geophysical and geochemical – of the Stripa granite. The results of this programme, which was concluded in 1980, were reported in some 50-odd reports.[17]

[17] Altogether, SKB published 54 reports in the series *Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns in Crystalline Rock – Technical Information Reports.*

The results of the SAC programme aroused broad international interest, resulting in *the Stripa Project*. This started in May 1980 as an autonomous project with the OECD/NEA as the principal and SKB as the coordinating party. Other parties were institutions with similar missions in Finland, France, Japan, Canada, Switzerland, Spain, the UK and the USA.

The Stripa Project was implemented in three phases between 1980 and 1992. During the first two phases, research was conducted primarily in four main areas:

- Geohydrological investigations of the Stripa granite and tracer tests in simple and complex fracture systems.
- Chemical investigations of the groundwater in the Stripa granite.
- Technology for detecting and characterizing fracture systems in granite.
- Studies of bentonite clay for use as backfill and sealant in fracture-filled bedrock.

An important step towards large-scale experiments was the BMT test, in which a KBS-3 repository was simulated on a half scale with electric heaters in six deposition holes.

During the third phase, the research was focused on three main areas:

- *Site Characterization and Validation;* by means of stepwise investigations, followed by a compilation and prediction phase, a limited rock volume and its properties were characterized and finally validated.
- *Improvements of Site Assessment Concepts and Methods;* continued development and improvement of the technology and the methods for investigation of rock that was begun during phases 1 and 2.
- *Sealing of Fractured Rock;* test and evaluate the long-term stability of materials that could be used to seal fractures in the rock and develop technology for injecting these materials into fractures in the rock.

The results of the Stripa Project were presented during the period 1981–1992 in nearly 170 reports (Stripa Project Technical Reports). SKB published a summarizing account in 1993 /Fairhurst et al. 1993/. SKB summarized the most important results in RD&D-Programme 92.

A3.2 Äspö

SKB proposed building the Äspö Hard Rock Laboratory (HRL) in RD&D-Programme 86. Preliminary investigations were initiated in the autumn of 1986, and construction began on the facility in the autumn of 1990. It was finished five years later and could be put into operation. Important tasks for the Äspö HRL have been and are to test methods for site investigations, to develop technology for the final repository, to train personnel for site investigations and work in the final repository, to provide data as a basis for the safety assessment, and to inform the public and decision-makers of the research and technology that is conducted for construction of the final repository.

The Äspö HRL represents a continuation of the tradition of international cooperation begun in 1977 in the Stripa Mine. Besides SKB, eight organizations from seven countries are participating in the research at the Äspö HRL today: Finland, France, Japan, Canada, Switzerland, the Czech Republic and Germany.

This international cooperation in the Äspö HRL has made and makes it possible to gather the world's foremost experts within many different areas to exchange ideas and experience regarding questions of importance for the geological disposal of radioactive waste. An example is the cooperation that is taking place in so-called Task Forces consisting of members from the participating organizations. Such Task Forces exist for e.g. modelling of groundwater flow and of engineered barriers. The results of the international cooperation are presented in a separate report series, Äspö International Progress Reports, and in the Äspö HRL's annual reports.

The underground part of the Äspö HRL takes the form of a tunnel running from the Simpevarp Peninsula to the southern part of the island of Äspö. Beneath Äspö the main tunnel descends in two spiral turns to a depth of 450 metres. From the main tunnel, smaller niches and tunnels branch out to places where the different experiments and tests are performed, see Figure A-23.

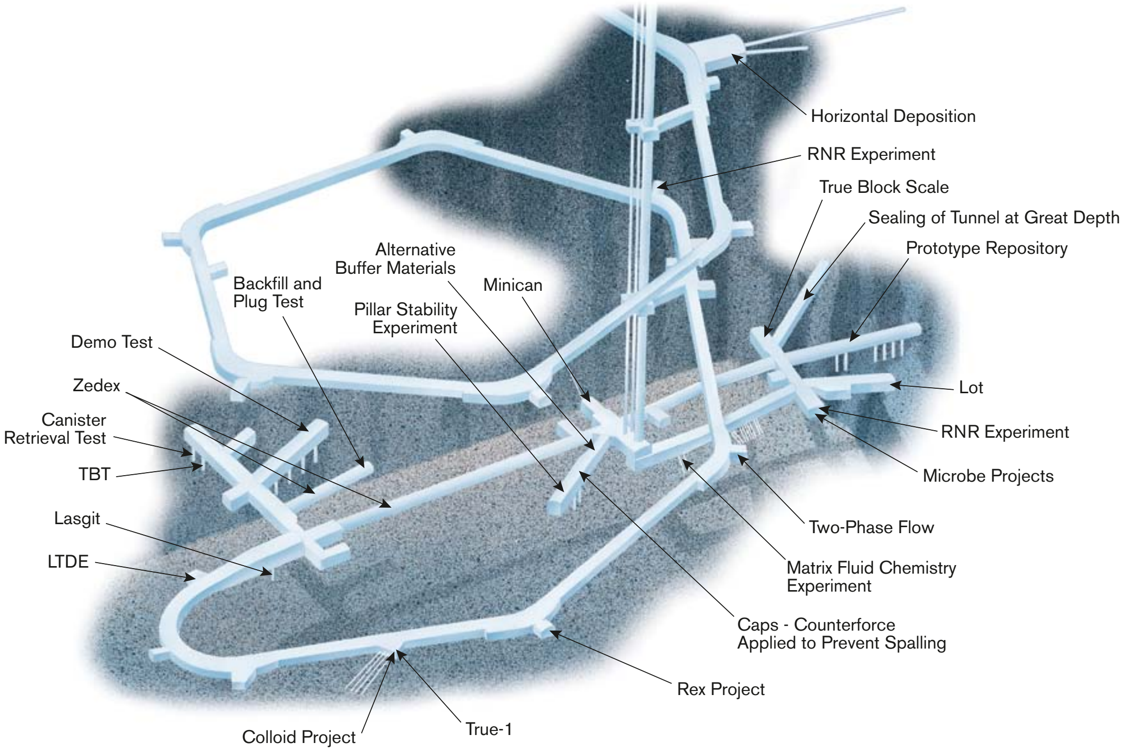

Figure A-23. *The various experiments in the Äspö HRL are conducted in niches and short tunnels located along the main tunnel. Some have been concluded, but most are still in progress.*

In 2007 the Äspö HRL was complemented by the Bentonite Laboratory, which is located on the surface. There tests and experiments are performed on buffer and backfill.

Research and development activities are pursued within three main areas: geoscience, natural barriers and engineered barriers. In the RD&D programmes, starting with RD&D-Programme 95, SKB has presented results from completed projects and its plans for the coming years. Current projects are described in the Äspö HRL's annual reports. The most recent annual report was published in July 2009 /SKB 2009/.

Research within *geoscience* is a fundamental part of the work at Äspö. The goal is to develop geoscientific models and to gain a greater understanding of the properties of the rock mass and of measurement methods.

An important purpose of the work on *natural barriers* is to further develop and test calculation models for groundwater flow, radionuclide transport and chemical processes at repository level. This includes determining the values of the parameters that are required as input data to conceptual and numerical models. Examples of projects are:

- The True experiments – studies of the rock's capacity to retard the transport of radionuclides,
- LTDE – studies of the rock's sorption and diffusion properties,
- The Colloid Transport Project – studies to find answers to questions regarding how colloid transport should be treated in future safety assessments. The project includes field experiments at the Grimsel test site in Switzerland.
- Microbial Projects – studies of microbial processes, such as the ability of microbes to mobilize and bind radionuclides, microbial effects on chemical stability in environments with deep groundwater, and bio-corrosion.
- Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes – an international cooperation project aimed at evaluating the utility and reliability of hydro and transport models.

The goal of activities in the area of *engineered barriers* is to demonstrate the function of the parts of the repository. Scientific and technological knowledge is used practically in the work of developing, testing and demonstrating methods and procedures used in the construction and operation of the final repository. The work includes testing and demonstrating how the repository parts will evolve under realistic conditions. A number of full-scale projects have been and are being carried out at the Äspö HRL. Some examples:

- The Prototype Repository – has been built so that design, materials and rock are wherever possible the same as in the future final repository. The purpose is to demonstrate the integrated function of the repository barriers and to have access to a full-scale reference for predictive modelling of the evolution of the final repository and the barriers. The Prototype Repository has a total of six deposition holes – four in an inner tunnel section and two in an outer one. The following parameters are recorded in the Prototype Repository: saturation of the buffer and backfill with water, heating of the rock, how stresses affect the rock, and how the chemistry changes during a transitional phase. Construction of the Prototype Repository and the first few years' operation were included in the EU's Fifth Framework Programme. Data collection and monitoring of the evolution of the experiment have been under way since 2003, when the outer section was sealed. The outer section of the Prototype Repository will be mined in 2011.
- Lot – Long Term Tests of Buffer Material. The purpose is to validate models and hypotheses that describe physical features and properties of the bentonite buffer related to microbiology, radionuclide transport, copper corrosion and gas transport under conditions similar to those in a KBS-3 repository.
- Backfill and Plug Test – investigation of the and mechanical function of different backfill materials. The test is also a demonstration of different methods for emplacement of backfill and installation of the tunnel seal. The innermost part of the section is backfilled with a mixture of crushed rock and bentonite, while the outer part is backfilled with crushed rock.
- Canister Retrieval Test – test of technology for retrieving canisters after the surrounding bentonite buffer has been water-saturated. The experiment was concluded in 2006 by freeing the canister by means of a retrieval method developed by SKB. The method, involving chemical dissolution of the bentonite by injection of a saline solution and lowering of a mixer, worked as intended.
- KBS-3 repository with horizontal deposition (KBS-3H) – a research programme that is being carried out in cooperation with Posiva. The objective is to develop and analyze KBS-3H to such a level that the alternative can be compared with KBS-3V, permitting a well-founded choice to be made between the two alternatives.
- The ZEDEX Project – studies of the excavation-disturbed zone (EDZ) in conjunction with different tunnelling methods (drill-and-blast and full-face boring).
- Sealing of tunnel at great depth – test and demonstration of tunnel sealing with silica sol as the grout. The purpose is to study whether silica sol can be used at the high water pressures prevailing at repository depth.
- In situ testing of corrosion of miniature canisters – studies of the corrosion process inside a broken canister. Five miniature copper canisters with cast iron inserts are being exposed to both naturally reducing groundwater and groundwater that has been equilibrated with bentonite for several years. Chemical conditions, corrosion of test pieces and changes in the size of the canister are measured and analyzed continuously in the experiment.
- Sealing of investigation boreholes – testing of different concepts for sealing investigation boreholes.

A3.3 Canister Laboratory

In the Canister Laboratory, which was inaugurated in the autumn of 1998, SKB is developing and demonstrating methods for fabricating, sealing and inspecting copper canisters. The emphasis is on testing and perfecting the technology for welding the lid on the canister and inspecting the weld joints to make sure they are leaktight. Two different welding methods have been studied: electron beam welding and friction stir welding. Today the focus is on friction stir welding. Equipment for ultrasonic and radiographic testing is used to inspect the weld joints.

Both welding methods have been developed in cooperation with The Welding Institute (TWI) in England. In the mid-1990s, TWI made a prototype machine for electron beam welding. The machine was delivered to SKB's Canister Laboratory at Oskarshamn in 1997, installed in 1998 and put into use the following year. This marked the start of the development work on full-scale welding of copper lids and copper tubes.

At the same time, a new method – friction stir welding – for welding primarily of aluminium alloys had been invented, patented and developed by TWI. In the late 1990s, SKB and TWI, working at TWI's facilities, developed a simple prototype machine for trial welding of copper rings. The tests were so promising that SKB ordered a welding machine for full-scale tests. The machine was installed in the Canister Laboratory in 2003.

An important task for the Canister Laboratory will be training of the personnel who will handle the canisters in the encapsulation plant.

A4 International cooperation

Ever since the start of the KBS project in the autumn of 1976, collaboration in various forms with foreign experts and international organizations has been an integral part of SKB's research and development work.

Among other things, SKB has participated actively in the work on nuclear waste issues that is pursued within the various committees and working groups that are more or less permanently tied to the IAEA, the OECD-NEA and the EU, as well as other international bodies that work on matters of relevance for nuclear waste management in Sweden.

SKB realized early on that extensive activities in the nuclear waste field were being pursued in various countries, mainly involving experiments, model development, site investigations and data compilations, of which Swedish efforts represented only a small portion. An important part of SKB's programme was therefore *to keep track of and learn from the research and development that is taking place in other countries in a carefully planned and efficient manner*, something which was facilitated by *the keen interest that exists internationally in the Swedish work* /SKB 1986/. The Stripa Project (see Section A3.1) is an important example of early international cooperation. Participation in EU-funded projects, the Grimsel test site in Switzerland, The Underground Research Laboratory in Canada and the Olkiluoto Research Tunnel are examples of subsequent collaborations.

Today SKB has bilateral agreements on information exchange with organizations in eight countries: Finland, Japan, Canada, Switzerland, Spain, the UK, Germany and the USA. The Äspö HRL (see Section A3.2) has played and is still playing an important role in the international cooperation.

RD&D-Programme 2004 contains a general presentation of SKB's international cooperation. The account is essentially still applicable. A couple of examples of important cooperation projects are mentioned below.

A4.1 Fuel leaching – Spent Fuel Workshops

An early forum for information exchange was the Spent Fuel Workshops, to which SKB took the initiative in 1981. At these workshops, researchers exchanged in an informal way results and experience from studies of corrosion of spent nuclear fuel. Originally the participants came only from Sweden, Canada and the USA, but later participants were invited from other countries as well. These workshops are still being held, at intervals of one or two years.

A4.2 The URL Project

In the 1970s, Atomic Energy of Canada Ltd (AECL) – which was then responsible for nuclear waste issues in Canada – decided to establish an *Underground Research Laboratory (URL)*at a depth of 240–420 metres in a granite formation. The site in southeastern Manitoba was chosen in 1979, geological investigations were begun a year later, and a shaft was sunk to the 250 metre level in 1983. The purpose of the URL Project was essentially the same as for the Äspö HRL. SKB participated in several projects at the URL, which was in operation until 2004.

A4.3 INTRACOIN, HYDROCOIN, INTRAVAL and DECOVALEX

In 1980, SKI took the initiative to an international project called *INTRACOIN (*International Nuclide TRAnsport COde INterncomparison study). The study, which was concluded in 1984, was aimed at comparing different computer programs that described how radionuclides are transported in the bedrock. During the course of the project, the idea arose of expanding the study to include an international comparison and verification of different computer programs for calculation of groundwater flow. Fourteen organizations in eleven different countries participated in the project, which was called *HYDROCOIN* (HYDROlogic COde INtercomparison study) and took place during the period 1984–1987. The results of the projects were presented in 1992 by SKI and the OECD/NEA in a joint report /OECD/NEA, SKI 1992/. A continuation of these projects was initiated in 1987 in the form of the international project *INTRAVAL* (INTernational TRAnsport model VALidation) , whose purpose was to validate different computer programs that were used to calculate nuclide transport with the groundwater in the bedrock and were therefore judged to be of great importance for the work of conducting a long-term safety assessment for a final repository for spent nuclear fuel. This initiative also came from SKI. SKB participated actively in one-third of the 18 test cases which were ultimately included in the project. A summary report from the project was published by the OECD/NEA and SKI in 1996 /OECD/NEA, SKI 1996/.

SKB also participated during the early 1990s in yet another international project that had been initiated by SKI. This project was called DECOVALEX (DEvelopement of COupled models and their VALidation against EXperiments in nuclear waste isolation) and was aimed at developing coupled models for the purpose of being able to describe conditions in the near field of a repository with greater realism /SKB 1992b, p 133/.

A4.4 Finland

SKB's cooperation with Posiva, its counterpart in Finland, occupies a unique position in its international cooperation. This is because Posiva has also chosen the KBS-3 method for final disposal of its spent nuclear fuel. The organizations are therefore cooperating in most fields of relevance to the final repository. Joint tests and experiments are being conducted or are planned in both the Äspö HRL and Posiva's Underground Laboratory ONKALO at Olkiluoto. One of the bigger cooperation projects involves testing and evaluation of the horizontal deposition alternative, KBS-3H. Canister fabrication and sealing technology is another area where SKB and Posiva are cooperating. The most important common issues are development of the KBS-3H method and development of methods and evaluation of materials for backfilling of deposition tunnels, manufacturing trials with different methods at suppliers, and developing the technology for inspecting the canister's components.

Cooperation with organizations in Finland (first TVO and later Posiva) began back in the 1980s. For example, Finland participated in the Stripa Project from the start. Other areas of cooperation were: experience and technology for site investigations, work with the future Äspö HRL, properties of clays, studies of the importance of ice ages, deposition methodology, canister design and safety assessment /SKB 1989, Part II, p 177/. In the mid-1990s, the cooperation between SKB and Posiva gradually expanded to include more and more areas.

A5 Natural analogues

The assessment of the long-term safety of the final repository mainly relies on the results of laboratory experiments and measurements in the field. As a complement to experiments in the laboratory and in the field, SKB also studies natural analogues. These are phenomena in nature that can illustrate how and to what extent migration of radioactive substances has occurred under conditions similar to those that would prevail in a final repository for spent nuclear fuel. The advantage of natural analogues is that they provide an opportunity to study processes that have been going on for much longer times than can normally be followed in an experiment in the laboratory or in the field. Normally, measurement data from natural analogues are not used directly in assessments of long-term safety. However, models in the safety assessment are tested on natural analogues to make sure that they work as intended.

SKB has been involved in a number of projects concerning natural analogues since the early 1980s. Interest in natural analogues is international. It has thus been common for stakeholders from different countries to start joint projects to study the most interesting analogues. The advantages lie not only in shared work and shared costs, but also in the fact that more researchers have an opportunity to participate. Having many participants with different backgrounds means that different interpretations can lock horns with each other, which in turn leads to a critical evaluation and reduces the risk for hasty conclusions.

In 2000, an overview was published of all the natural analogues that have been studied at different places in the world, as well as how they have been used in various contexts, see Figure A-24. SKB participated in the work with the overview the RD&D programmes 2001 /Miller et al. 2000, SKB 2001/.

Some examples of projects concerning natural analogues in which SKB has participated are given below.

A5.1 Poços de Caldas and Cigar Lake

The analogues Poços de Caldas and Cigar Lake consist of ore deposits with uranium. They have taught us a great deal about the importance of oxidation in a near-field around the waste.

The Poços de Caldas Project involved studies of natural analogues to the release and dispersal of radionuclides from a final repository. The project took place during the latter part of the 1980s and was reported in SKB's research programmes in 1986, 1989 and 1992. The investigations that were conducted were associated with the thorium deposit in Monto de Ferro and the Osamu utsumi uranium mine in the Poços de Caldas area in Minas Gerais in Brazil. SKB was the project manager for the project, which was carried out in cooperation with Brazil, Switzerland, the UK and the USA. There is a general summary in RD&D-programme 92 of the conclusions from the project and its nearly 30 reports.

There is a very rich uranium deposit at Cigar Lake in the province of Saskatchewan in northern Canada. The ore body lies at a depth of 430 metres and shows no traces of radioactivity on the ground surface. It was formed about 1,300 million years ago and has an average uranium concentration of 14 percent, reaching in places up to 55 percent. The ore body is surrounded by a 20 metre thick layer of clay that effectively stops the radionuclides from reaching the environment via the groundwater. The clay also stops water flows from overlying rock formations. The deposit can be regarded as the natural equivalent of the final repository SKB plans to build. SKB reported the results from the project in RD&D-Programmes 95 and 98.

***Figure A-24.** Natural analogues of the fuel, the canister and the buffer can be found all over the world /SKB 2001, Figure 11-1/*

A5.2 Oklo

In the early 1970s, natural reactors were found at Oklo in Gabon (West Africa) that had been active some two billion years earlier. Nuclear fissions had taken place in the uranium and given rise to a large quantity of fission and activation products. These "natural reactors" were investigated in the 1970s, and the results were reported at several international meetings. Specific aspects of interest for final disposal of spent uranium fuel were studied starting in the early 1990s within the framework of the Oklo Project under the leadership of CEA in France and with funding from the EC. The project was reported in RD&D programmes 95, 98 and 2001.

A5.3 Maqarin

At Maqarin in northern Jordan there are active, and in central Jordan fossil, hyperalkaline springs. A whole series of typical cement materials have been formed as a result of the water's reactions with minerals in these areas. The water in the springs resembles pore water in concrete, providing a chemical analogue of wet concrete in a repository. SKB participated – at times as coordinator – from the early 1990s in an international project together with organizations from Canada, Switzerland and the UK with the overall purpose of studying these conditions as an analogue of concrete in a final repository. The project was reported in RD&D programmes 95 and 2001.

A5.4 Palmottu

A uranium mineralization was discovered at Palmottu Lake in Finland in the late 1970s. It forms a 1–15 metre thick, steeply dipping zone that extends about 300 metres down into the rock. The conditions were studied during the 1980s and early 1990s by Finnish authorities as an analogue of a final repository for spent nuclear fuel, with SKB as an observer. During the latter part of the 1990s, the studies were expanded into an international project with support from the EU. SKB contributed to the project with its own equipment for different tests and measurements. The Palmottu Project was reported in RD&D programmes 95, 98 and 2001.

A5.5 The Greenland Analogue Project

In order to study how the water flow and the water chemistry in the rock around the Nuclear Fuel Repository would be affected by an ice age, SKB, together with its sister organizations Posiva and NWMO, started a large research project on western Greenland in 2009 (the Greenland Analogue Project, GAP). Researchers from the UK, the USA, Canada, Denmark, Finland and Sweden are collaborating in the project. The purpose is to improve our knowledge of how the ice cover affects the groundwater flow and the water chemistry around a repository in crystalline rock under glacial conditions and during permafrost. This is being done by means of investigations in boreholes through the ice and the bedrock at the edge of the ice sheet /SKB 2010b/.

References

See list of references, pages 57–60.