Progress of the Swedish Radioactive Waste Management Program

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Abstract
The implementation of the Swedish radioactive waste management system is making good progress. A central interim storage facility for spent nuclear fuel and a sea-based transportation system for spent fuel and other radioactive residues are already in operation. An underground final disposal facility for low- and medium-level waste from reactor operation is under construction. For the remaining steps (final disposal of spent fuel and long-lived radioactive residues) one concept has been developed and approved. Research and development work is continuing, to provide the basis of a final decision on disposal method and site for around the year 2000. This decision will be based on a broad evaluation of available alternative designs.

Introduction

The safe and efficient management of radioactive waste from nuclear energy production in Sweden is the responsibility of the owners of its nuclear reactors. This responsibility also includes financing of the total costs. To fulfil their obligations, the four utilities that operate nuclear reactors in Sweden have formed a special company, the Swedish Nuclear Fuel and Waste Management Company (SKB). SKB is responsible for all handling, transportation, and storage (temporary and permanent) of spent fuel and radioactive waste from nuclear power plants. Furthermore, SKB is responsible for the planning and construction of all facilities required for the management of spent fuel and radioactive waste and for the comprehensive research and development work necessary to provide such facilities.

The Swedish Nuclear Power Program

Sweden's nuclear power program consists of 12 nuclear reactors located at four different sites, with a combined capacity of 9,650 MW of electric power. In 1985 the last two reactors of this program, Forsmark 3 and Oskarshamn 3, reached full power and were taken into commercial operation. The nuclear power plants generated 42% of Sweden's total electric power in 1985. In 1986 this figure is expected to increase to 45–50%, the remainder being hydro-power (Figure 1).

According to a decision by Parliament, no more

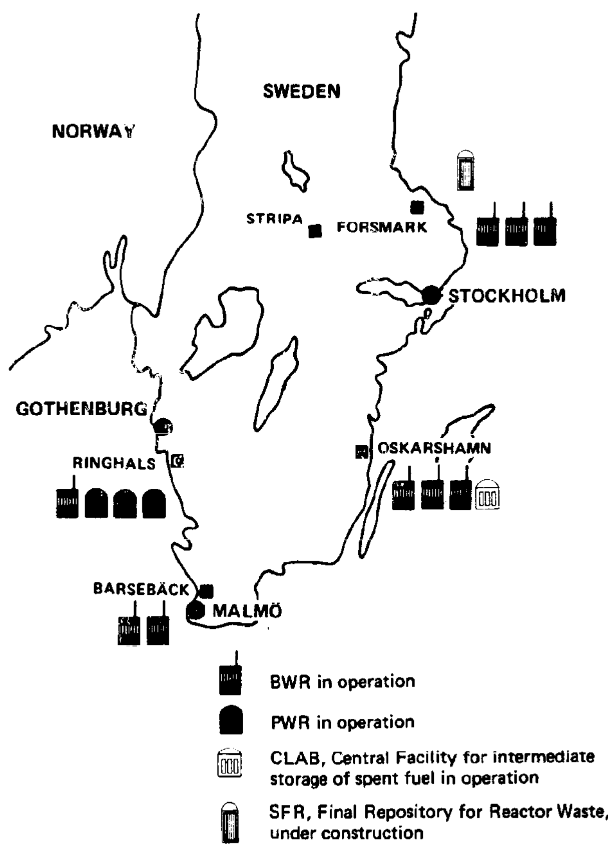

Figure 1 Swedish nuclear power reactors.

Keywords: nuclear waste management, storage, disposal, spent fuel management, Sweden, decommissioning, costs.

reactors are to be built in Sweden, and the existing ones shall not be operated beyond the year 2010. This decision was taken after an intense debate on the nuclear issue during the 70s and a referendum in 1980. The exact time-schedule for the phasing out of nuclear power has yet to be established. In the wake of Chernobyl, the debate on nuclear power has revived and the time-schedule is at present being evaluated by a government commission.

The influence of this evaluation on the work performed within the waste management program is, however, expected to be limited. It will only have an impact on the size of the facilities to be constructed.

Radioactive Waste Management in Sweden

A complete system has been planned for the management of all radioactive residues from the 12 nuclear reactors and from research facilities. The radioactive residues generated by the operation of the Swedish reactors consist of spent nuclear fuel and various kinds of low- and medium-level reactor waste. In addition, decommissioning waste will be generated in the future when all reactors are decommissioned and dismantled.

The accumulated amounts of waste from the operation of the 12 Swedish reactors up to the year 2010 have been estimated at about 7,800 metric tons (calculated as uranium) of spent fuel, 90,000 m^3 of low- and medium-level reactor waste, and around 115,000 m^3 of decommissioning waste. In addition to this, approximately 10,000 m^3 of low- and medium-level waste will be produced at the research facilities in Studsvik, and from the use of radio-elements in industry, medicine, and research.

An overview of the management scheme for these radioactive residues is shown in Figure 2. The basic strategy of the Swedish radioactive waste management

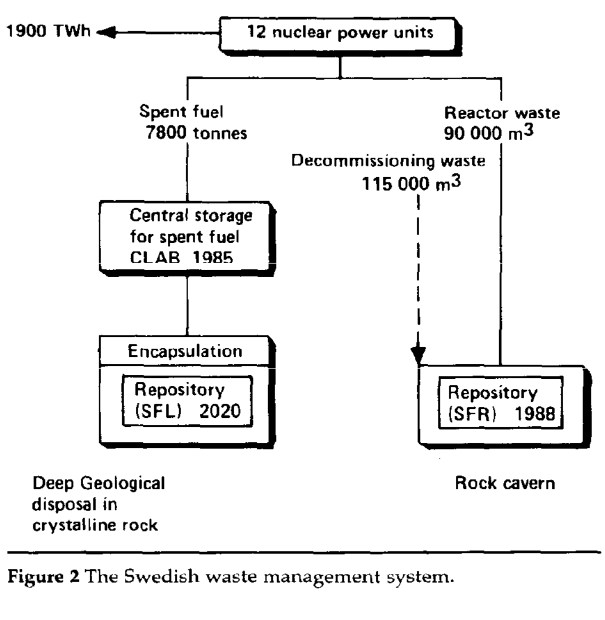

Figure 2 The Swedish waste management system.

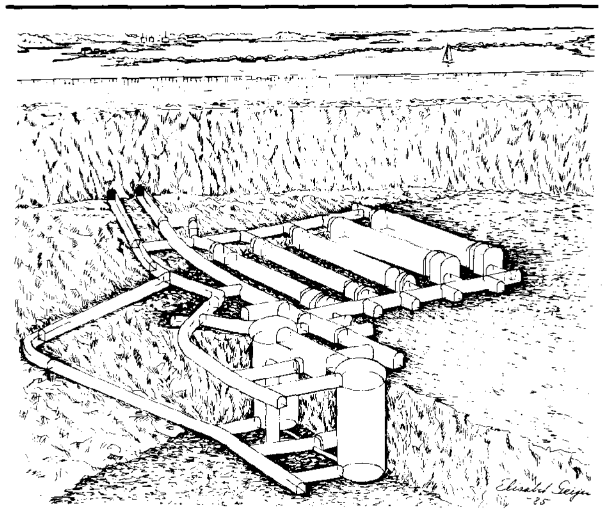

Figure 3 Overview of tunnels and storage chambers in SFR.

is that short-lived waste (< 500 years) should be deposited as soon as feasible without interim storage; whereas for spent fuel and other long-lived wastes, an interim storage of 30–40 years is foreseen, prior to final direct disposal in crystalline rock formations. A central facility for interim storage of spent fuel (CLAB) has been in operation since July 1985.

This once-through strategy has been judged to be the most rational and cost-effective solution in Sweden under the prevailing conditions. It is also, at present, the politically preferred option. In addition, the fairly long period of time that is assumed for interim storage of spent fuel provides freedom of choice among various management options up to the year 2000, when a final decision has to be made.

Management of Low and Medium Level Waste

Both the reactors and the CLAB facility will produce operational waste with a relatively short life, such as ion exchange resin, filter materials from water cleaning systems, etc. The low- and medium-level waste is conditioned at the reactor sites and at Studsvik. Ion exchange resins and filter materials are packaged and solidified, or dewatered, to facilitate further handling. Concrete and bitumen are currently employed for solidification. Most of the combustible waste is sent to Studsvik for incineration [1].

The operational waste is at present being stored in specially built facilities at the reactor sites and at Studsvik, but will, from 1988 onwards, be transported to the central repository for final disposal of low- and medium-level reactor waste, called the SFR (Figure 3). Some very low-level wastes will be disposed of by shallow land burial at the reactor sites.

Final Repository for Reactor Waste – SFR

The waste generated by reactor operation, some of

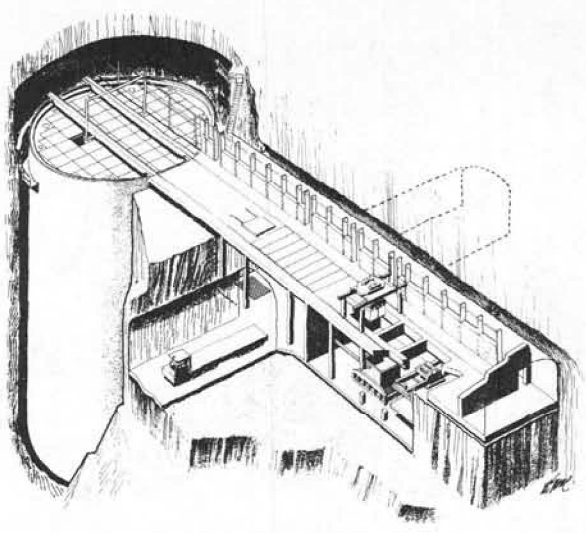

Figure 4 Handling of waste in SFR silo.

which has to be isolated for up to 500 years, will be disposed of in crystalline rock in a central underground facility known as the SFR. It is currently under construction near the Forsmark nuclear power plant, 200 km north of Stockholm [2].

The entire repository is situated in rock 50 metres below the sea bed, about 1 km outside the Forsmark harbour. The repository consists of rock caverns of various designs, depending on the type of waste to be disposed of (Figure 4). The medium-level waste, which contains most of the activity, will be deposited in a silo-like concrete structure cast inside a cylindrical rock cavern, and the waste will be isolated from the surrounding rock by concrete walls and a layer of clay backfill (bentonite) between the silo and the rock. The low-level waste will be deposited without extra barriers in the rock caverns designed for the particular type of containers being used for such waste.

When the repository is filled, the entrance tunnels will be plugged with concrete to seal the caverns. When the entire repository has been sealed, the transportation tunnels will also be sealed at ground level to prevent future access. After sealing of the repository, no further surveillance will be needed.

The SFR will accommodate all the 90,000 m^3 of low- and medium-level waste generated in Sweden up to the year 2010. The first phase, now under construction, will have a capacity of 60,000 m^3. Scheduled for commissioning in 1988, the repository is planned to be extended at the end of the 1990s. Later, when the reactors have been decommissioned, another extension will be made to accommodate the decommissioning waste.

The location of the SFR below the sea bed is advantageous from the point of view of safety. Under the horizontal seawater table, the driving forces of the ground water flow in the fissures of the rock are almost eliminated, and very little transportation of radioactive substances can take place in the almost stagnant water around the repository.

Management of Spent Fuel

The most important and crucial part of the waste management system is the handling and disposal of spent fuel. The main features of the Swedish once-through scheme for direct disposal are briefly as follows:

After discharge from the reactor, the spent nuclear fuel is stored in the storage pools at the power plants for at least a six-month period. The fuel is then transported to the central interim storage facility for spent fuel, the CLAB. Here the fuel will be stored for a period of 30–40 years, and thereafter transported to encapsulation and final disposal.

CLAB – Interim Storage Facility for Spent Fuel

In the CLAB, which was placed in operation in July 1985, the principle of wet storage in pools is applied. The CLAB facility (Figure 5) is situated on the east coast of Sweden, adjacent to the Oskarshamn power plant [3]. The facility constitutes a fundamental strategic element in the Swedish spent-fuel management scheme. It will ensure uninterrupted nuclear power production, and it will provide ample time for R&D work, site selection, system design, and optimization for the development of a permanent repository.

The facility consists of underground storage pools in a rock cavern and a receiving building on the surface. The storage pool, now built, can hold 3,000 tonnes of spent fuel, which will cover Swedish needs up to the mid-1990s. One or two additional expansions will be required to accommodate all the spent fuel and core components from the 12 Swedish reactors: about 8,000 tonnes. The total receiving capacity is 300 tonnes per year, or about 100 spent-fuel shipping casks (Figure 6).

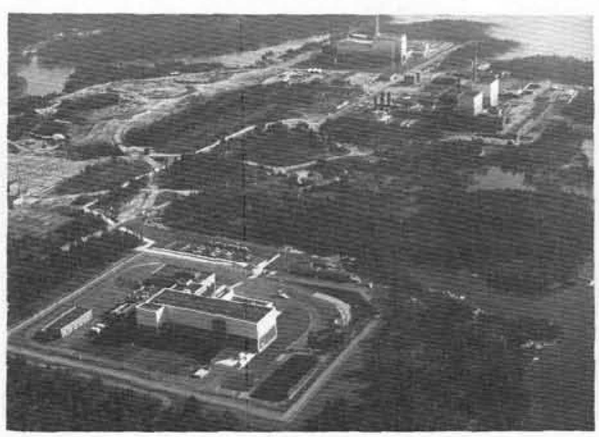

Figure 5 Aerial view of CLAB at Oskarshamn.

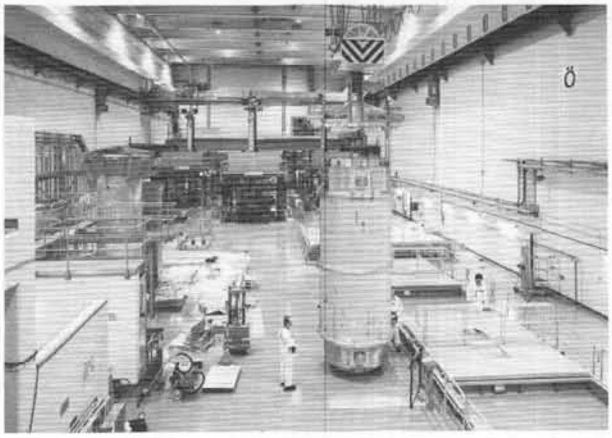

Figure 6 Handling of cask at CLAB.

Transport System for Spent Fuel and Radioactive Waste

All the Swedish nuclear power stations, as well as storage facilities, are located on the coast. It has therefore been deemed expedient to develop a sea-transportation system for the nuclear waste. A ship (Figure 7) was launched in 1982 that can take 10 fuel casks, each with a weight of about 80 tonnes. Each cask can hold 17 BWR or 7 PWR fuel assemblies. The fuel is transported dry and cooled by natural air convection. The casks are mounted on transport frames that are handled by a terminal vehicle. The same equipment will also be used to transport low- and medium-level waste in steel containers. Each container has a transport weight of up to about 120 tonnes.

Final Repository for Spent Fuel

In accordance with present plans, facilities for the final disposal of spent fuel and long-lived waste will not be required until the year 2020. Consequently, construction work has not yet commenced on these facilities. Extensive research on the matter has, however, been performed in Sweden since the mid-70s. It has resulted in concepts for the final disposal of waste from reprocessed fuel (KBS-1), as well as for the direct disposal of spent fuel without reprocessing (KBS-3) [4, 5]. These concepts have been evaluated by the government and have been found to be acceptable with regard to safety and radiation protection. Based on these evaluations, the government has granted loading permits for six reactors in 1979 and 1984.

However, before a decision regarding the construction of a repository is taken around the turn of the century, other concepts will also be explored. The purpose of this is to develop a disposal system that fulfills the requirements of safety and is optimized from a technical and economic point of view. The study of alternatives is thus in the interest of the utilities. It is also required by law.

Figure 7 M/S Sigyn.

The KBS-3 Concept

Final disposal of spent nuclear fuel according to KBS-3 is shown schematically in Figure 8. The fuel is encapsulated in copper canisters, that are deposited 500 metres down in the crystalline bedrock. The deposition is made in bore holes at the bottom of tunnels, one canister in each bore hole. In the bore hole the canister is surrounded by a buffer of bentonite clay. When the repository is full, all shafts and tunnels are backfilled and sealed.

The safety of the KBS-3 disposal system is based on the multibarrier principle, by which the waste is

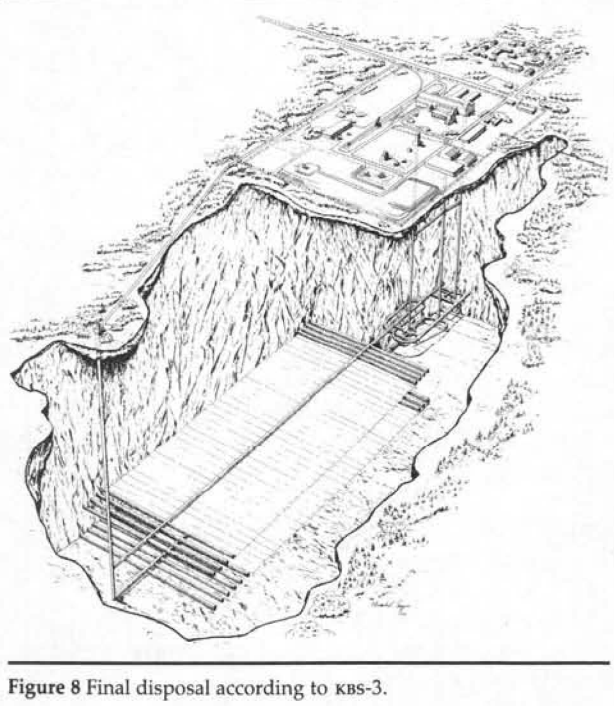

Figure 8 Final disposal according to KBS-3.

isolated from the environment by a number of mutually redundant barriers. The barriers are:

1 the rock mass, with its slow water transport and high capacity for absorption of radionuclides;
2 the almost impermeable bentonite buffer;
3 the highly corrosion-resistant copper canisters;
4 and the low solubility of the spent fuel.

Based on the results of the KSB-studies it may be concluded that:

1 Swedish bedrock is stable enough for a repository;
2 there exist in Sweden bedrock areas of acceptable size that are well suited for a repository;
3 the spent fuel can be surrounded by man-made barriers of long service life;
4 combinations of natural and man-made barriers can be designed to such a quality that the radiological impact on man will be insignificant.

Research and Development

In KBS-3, *one* feasible method has been demonstrated. Considerable work remains to be done in order to develop the optimal method, however. The future work will consist of:

1 continued research and development work, in order to deepen further the scientific knowledge that constitutes the base for the performance and safety assessment;
2 studies and evaluation of alternatives to the methods and concepts investigated so far;
3 optimization of systems in terms of technology, economy, and resource utilization, in view of the improved scientific knowledge base;
4 investigation for site selection

In September 1986 a comprehensive plan for future R&D work will be presented to the Swedish government. The basis for planning the R&D work is the overall timetable shown in Figure 9. This timetable is based on forty years interim storage of spent fuel in the CLAB. An application for licensing of a repository is foreseen around the year 2000.

Alternative Disposal Concepts

As a base for the optimization of the disposal system, a number of alternative disposal concepts will be studied and evaluated from the point of view of safety, technical feasibility, acceptability, and economy. All alternatives will, however, be based on disposal deep in Swedish crystalline bedrock. The word 'alternative' is used here in a broad sense. It includes changes in the materials and general layout envisioned by the existing concepts, as well as more profound changes in the concepts themselves. Also, alternative sites for the repository will be studied.

Examples of materials for which studies have been initiated during the last years are carbon steel for canisters and cement for grouting purposes, in the

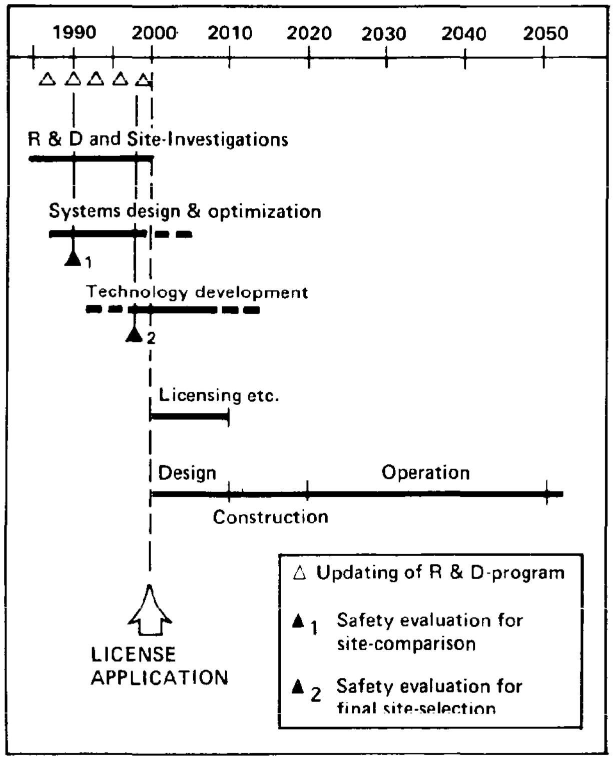

Figure 9 General timetable for realization of a final repository for spent fuel.

nearby rock. The layout of KBS-3 has been designed to keep the temperature increase low. The maximum temperature of the buffer has been limited to 100°C. If a higher temperature could be allowed, a higher waste load per canister could be used, or, alternatively, a more close-packed layout.

An example of a concept that is based on a somewhat different philosophy than that of KBS-3 is shown in Figure 10. This concept, the WP-Cave, is at present being evaluated by SKB [6]. The main features are:

1 a large amount of encapsulated fuel (> 1500 tonnes), concentrated in a central cavern that will be ventilated and cooled for about 100 years;
2 the cavern and surrounding rock surrounded by a five-metre-thick buffer layer of sand/bentonite;
3 this structure is surrounded by an hydraulic cage, consisting of a number of horizontal annular tunnels connected by drill holes.

The temperature in the cave will be limited to about 60°C during the ventilation period, and will rise to about 140°C after closure. The purpose of the buffer is to cut off the streaming of water between the inner and outer rock mass, and to delay the migration of radionuclides out of the repository. The hydraulic cage has the dual function of draining the inner rock mass during construction and operation, and of limiting the

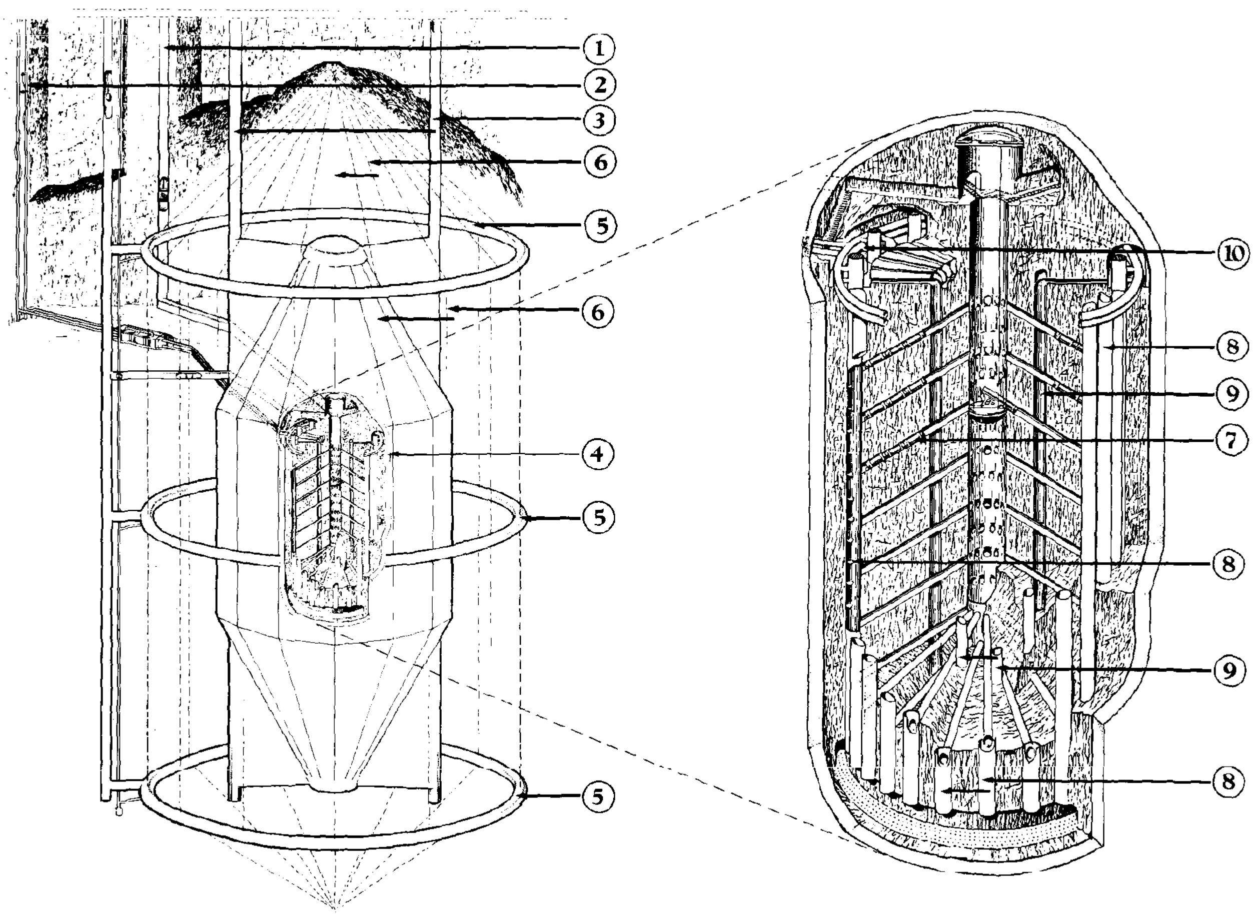

Figure 10 WP-Cave concept for final disposal.

hydraulic gradient over the repository after the central cavern has been water-filled.

Site Investigation and Selection

The investigation and selection of a site for the final repository is technically and economically very important, and of great political and public interest. The site will be chosen on geological, demographic, and economic grounds. Fourteen sites have been investigated since 1977 (Figure 11). On eight of these a full investigation program has been carried out.

The investigation program included 10–14 core bore holes, drilled to a depth of 500–1000 metres. Geophysical, hydrological, and geochemical measurements were made on the surface and in the bore holes. A program to improve measurement techniques is being pursued in parallel, and the results from this are being applied in the site investigations.

The investigations have confirmed that Sweden's bedrock, dominated by granite and gneissic formations of great age, provides acceptable conditions for safe disposal at many locations. In order to be able to choose among different sites, more studies at depth will be needed. Also, factors other than the geological conditions must be allowed for in the final decision.

At the beginning of the 1990s, a couple of sites will be chosen for more detailed study, including a pilot shaft down to the foreseen repository level. Final site-selection will be made at the end of the 1990s.

General R&D

The safety assessments performed until now have been based on several pessimistic assumptions. Circumstances, barriers, and factors that are insufficiently known are not accounted for if they work towards increased safety. Analysis methods and data are persistently chosen to give an upper limit for the calculated consequences.

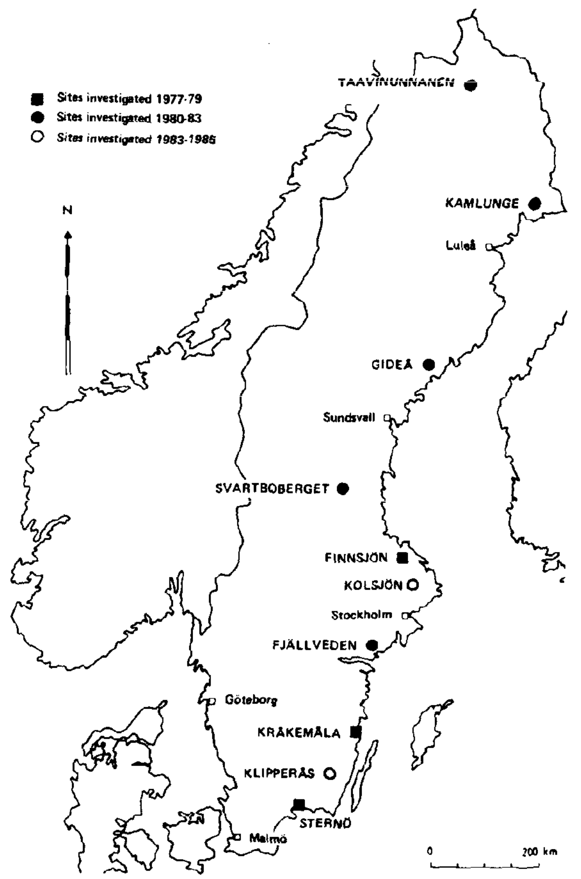

Figure 11 Sites investigated in Sweden.

It is important to improve knowledge in areas of key interest for the performance of the repository. Some important areas being studied [7] for a repository located in Swedish bedrock are:

1 leaching behaviour of spent nuclear fuel;
2 groundwater chemistry and its interaction with materials in the repository;
3 properties of materials used;
4 groundwater transport in the rock mass and in fracture zones;
5 radionuclide transport in fractured rock;
6 stability of the bedrock.

The results of these research areas are applicable, whatever alternative concept may be developed. The study of alternatives, however, provides input concerning environmental factors, etc. Of special interest are the studies of natural analogues that can provide a long-term proof of the validity of the models and data used.

Cooperation and exchange of information on an international or bilateral basis is an integrated part of the R&D-activities of SKB. As an example, an international research project is being executed in Stripa, an abandoned iron mine in central Sweden, with the participation of nine OECD countries. Different aspects of the geological and engineered barrier systems are being investigated on a large scale and in a realistic underground environment in Stripa.

Costs and Financing

According to Swedish law, all costs for the management of radioactive waste, including the decommissioning of the nuclear power plants, have to be borne by the owners of these plants. The costs are covered by a fee determined annually by the government. The basis for the fee is a cost calculation of all the activities for the back-end of the nuclear fuel cycle, which is carried out by SKB each year [8]. The cost calculation is based on a scenario for the back-end, including the construction and operation of all necessary facilities and equipment.

The experience gained from the construction of the CLAB and SFR facilities is very valuable as a background for the cost data. The construction cost of the CLAB was SEK 1.7 billion (Can $350 million) and is expected to be SEK 0.8 billion (Can $150 million) for SFR phase 1. The total cost incurred through 1986 for the back-end of the nuclear fuel cycle was SEK 5.3 billion (Can $ 1.1 billion). This figure includes, besides the CLAB and the SFR, costs for reprocessing services, the R&D program, and the transportation system. The estimated future costs (at the January 1986 price level) are about SEK 39 billion (Can $ 7.8 billion). The value of the corresponding electricity produced at the nuclear power plants is about SEK 500 billion.

Many of the costs will be incurred fairly far into the future. The total expenditure will be spread out over a period of more than 70 years. Figure 12 gives a rough account of the distribution in time. If the reprocessing costs are excluded, the breakdown of costs is roughly:

Interim storage of spent fuel	21%
Encapsulation and final disposal of spent fuel and long-lived wastes	39%
Final disposal of operation and decommissioning wastes	4%
Transportation of wastes	8%
Decommissioning and dismantling of nuclear power plants	19%
Miscellaneous including R&D and pilot facilities	9%

The fee for 1986 is SEK 0.019/kWh (Can $ 0.004/kWh), which corresponds to a total cost for the Swedish utilities of SEK 1.2 billion/year (Can $ 240 million/year). The fee is paid into funds, one for each utility, at the Bank of Sweden. The funds are administered by the state authority, SKN (The National Board for Spent Fuel), which also allocates money from the funds to the various waste management activities performed by SKB.