SAFE HANDLING AND STORAGE OF HIGH LEVEL RADIOACTIVE WASTE

A Condensed version of the proposals of the Swedish KBS-Project regarding

- Reprocessing waste
- Spent fuel

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THE KBS PROJECT, INTRODUCTION

Introduction

This publication gives a brief summary of two reports from the KBS Project. The background of the KBS Project is also presented in the initial sections.

Stipulation Law

Following a change of Government the Swedish Parliament in April 1977 enacted a "Law concerning special permission for charging nuclear reactors with fuel" - "the Stipulation Law".

§ 2 of this law stipulates that:

"If an application for final approval for the commissioning of the nuclear reactor has not been submitted to the Nuclear Power Inspectorate as of October 1976, the reactor may not be charged with nuclear fuel without the special permission of the Government. Permission may be granted only providing that the reactor owner

1 has produced an agreement which adequately satisfies the requirement for the reprocessing of spent nuclear fuel and has demonstrated how and where an absolutely safe final storage of the high level waste obtained from the reprocessing can be effected, or

2 has demonstrated how and where an absolutely safe final storage of spent, unreprocessed nuclear fuel can be effected."

(Unofficial translation).

Objective of the KBS Project

KBS was formed by the four nuclear power utilities in Sweden: Statens Vattenfallsverk (The Swedish State Power Board), Oskarshamnsverkets Kraftgrupp AB (OKG), Sydkraft AB and Forsmark Kraftgrupp AB (FKA). KBS was given the task to meet those

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KBS short for KärnBränsleSäkerhet = Nuclear Fuel Safety requirements of the Stipulation Law which pertain to the handling and final storage of spent nuclear fuel or high level waste.

Thus, more specifically the objective of the KBS Project is:

- to demonstrate how high level waste or spent fuel can be handled and finally stored,
- to demonstrate where a final storage of high level waste or spent fuel can be located, and
- to analyse the safety of the proposed arrangements for handling and storage.

KBS was organized as an independent project within Svensk Kärnbränsleförsörjning AB (SKBF - Swedish Nuclear Fuel Supply Company).

The result of the project work has been presented in two reports corresponding to the two optional alternatives given by the Stipulation Law. The first report deals with the final storage of vitrified waste and is entitled

> Handling of Spent Nuclear Fuel and Final Storage
> of Vitrified High Level Reprocessing Waste

It was published in December 1977. The second report deals with the final storage of spent fuel which is not reprocessed. It is entitled

> Handling and Final Storage of Unreprocessed Spent
> Nuclear Fuel

and was published in June 1978.

This booklet gives a brief summary of these reports outlining facilities required and describing the safety of the handling and of the final storage.

Legal situation in January 1979

The first KBS report dealing with vitrified waste was used to support applications to the Government for the permission to load nuclear fuel to two nuclear reactors. In a decision of October 5, 1978 the Government refused to grant such permission on the ground that it had not been shown that a suitable rock formation large enough to host the appropriate amount of waste is actually available. In other respects the Government accepted the methods and conclusions reported by KBS. Supplementary geological investigations are now in progress in order to provide the additional information required by the Government.

HANDLING OF SPENT NUCLEAR FUEL AND FINAL STORAGE OF VITRIFIED HIGH LEVEL REPROCESSING WASTE

A summary of the first KBS report of December 7, 1977.

Background

The "Stipulation Law" states that new nuclear power units may not be commissioned until the owner has shown that the waste problem can be solved in an absolutely safe manner. In response to the Bill proposing the Stipulation Law, the nuclear power industry decided in December of 1976 to attack these problems immediately, for which purpose it formed the Nuclear Fuel Safety Project (Projekt Kärnbränslesäkerhet, KBS). Following is a summary of the first report from KBS entitled "Handling of spent nuclear fuel and final storage of vitrified high level reprocessing waste".

The special explication of the Stipulation Law Bill states that proposals for solutions must include detailed and comprehensive information to permit a safety evaluation. In addition, it should be concretely specified in which form the waste or the spent fuel is to be stored, how the storage facility is to be designed and how transportation is to be effected. In order to fulfill these requirements, KBS describes the facilities and transportation systems in relatively great detail.

The following stages of handling and transport of the fuel on its way to final storage are dealt with in the report.

1 The spent nuclear fuel is stored at the power station or in the central fuel storage facility awaiting reprocessing.

2 The fuel is reprocessed, i.e. uranium, plutonium and waste are separated from each other. Reprocessing does not take place in Sweden. The high-level waste is vitrified and can be sent back to Sweden in the 1990s.

3 Vitrified waste is stored for about 30 years awaiting deposition in the final repository.

4 The waste is encapsulated in highly durable materials to prevent groundwater from coming into contact with the waste glass while the radioactivity of the waste is still high.

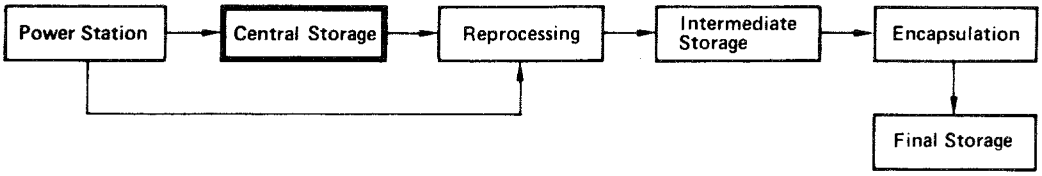
5 The canisters are emplaced in a final repository which is built at a depth of 500 m in rock of low permeability.

6 All tunnels and shafts are filled with a mixture of clay and sand of low permeability.

A detailed analysis of possible harmful effects resulting from normal acitivties and from conceivable accidents is presented in a special section.

Following is a brief description of the various handling stages from the time the fuel leaves the power station to its final storage deep in the Swedish bedrock.

Central storage facility for spent fuel

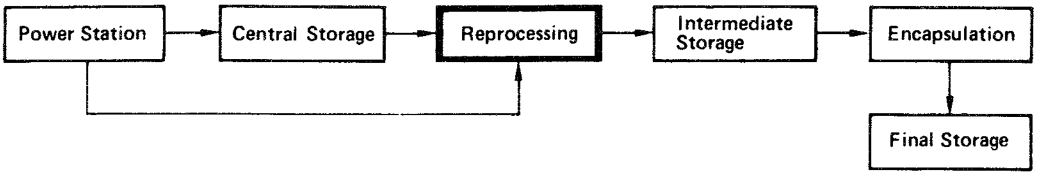


All nuclear power stations have storage pools for spent nuclear fuel. These pools are required so that the fuel can be removed from the reactor core if necessary and so that the spent fuel can be stored for a period of time before it is sent on to reprocessing or further storage elsewhere.

The capacity of the reprocessing plants which exist in the world today is sufficient for only a small portion of the spent fuel which is discharged from nuclear power stations.

Expansions are planned, but various political considerations, especially in the USA, make it unclear to what extent nuclear fuel will be reprocessed in the future. This necessitates the expansion of storage capacity for spent nuclear fuel. The Swedish Nuclear Fuel Supply Company (Svensk Kärnbränsleförsörjning AB) has designed a central storage facility for spent nuclear fuel from all of Sweden´s nuclear power plants. A siting and licencing application was submitted to the Government in 1977.

Reprocessing of spent fuel



The spent fuel contains uranium, plutonium, other heavy elements (so-called "transuranium elements") and fission products. It is primarily the fission products which constitute the high-level waste. Both uranium and plutonium can be used in new fuel. These elements should therefore be separated from the spent fuel. This process is called reprocessing. Fig. 1 is a diagram illustrating the reprocessing of spent nuclear fuel.

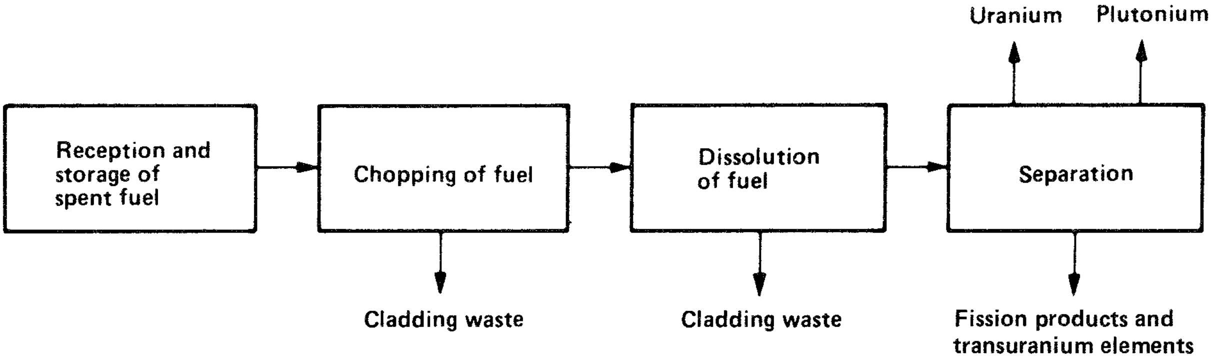


Figure 1. Schematic diagram of reprocessing of spent fuel.

After reprocessing, the high-level waste is in liquid form. The solution contains fission products and small amounts of uranium and plutonium. All of the transuranium elements are also present in the waste solution. After a period of storage, the waste is calcinated to solid form. The high level waste is then melted together with vitrifying substances to form a homogeneous glass. The glass is cast into cylindrical containers made of stainless steel. A lid is welded on so that the container is hermetically sealed.

According to the terms of the reprocessing agreement signed for the Barsebäck 2 reactor, waste cylinders containing vitrified waste will be returned to Sweden no earlier than 1990.

The waste cylinders

The vitrified waste is thus enclosed in stainless steel containers (see Fig. 2). Each container contains high-level waste from one tonne of spent fuel. If all of the waste from 13 reactors which are operated for 30 years is reprocessed, 9 000 waste cylinders will be obtained.

The vitrifying agents in the waste glass are silicon dioxide and boron dioxide. The advantages of this so-

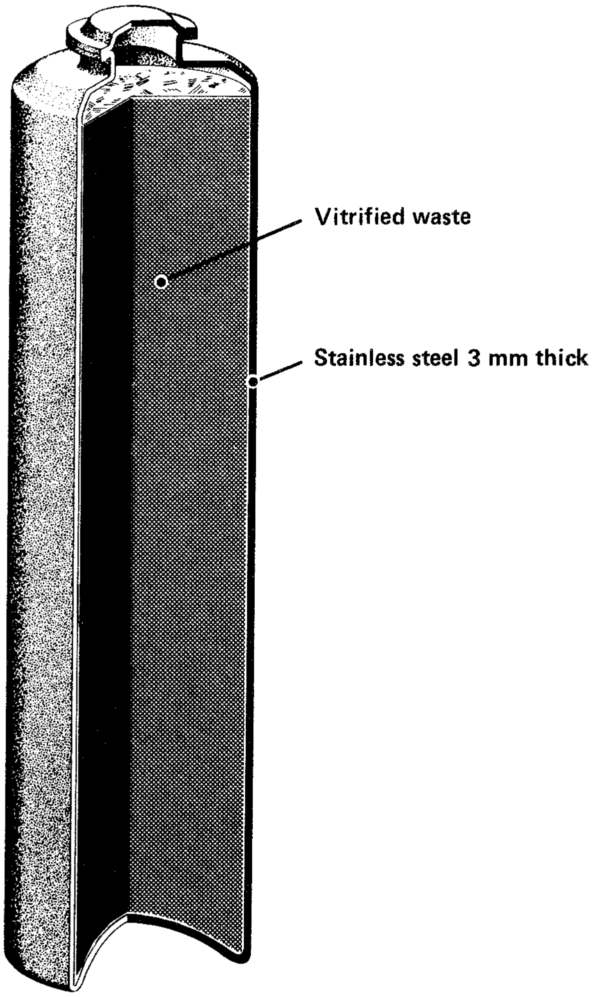


Figure 2. Waste cylinder. One stainless steel cylinder contains 150 litres of vitrified high-level waste. The container is 1.5 metres long and has a diameter of 0.4 metre. The waste cylinder weighs 450 kg, including 380 kg of glass matrix, 40 kg of high-level waste and 30 kg of stainless steel.

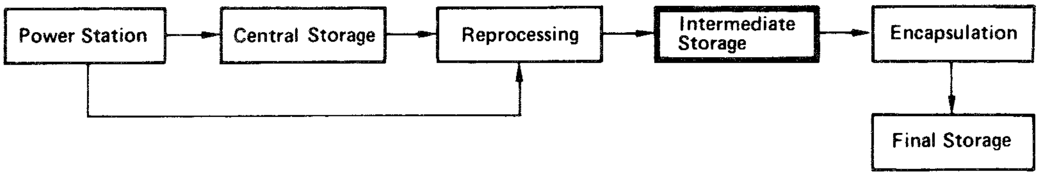
called "borosilicate" glass are good chemical resistance, good mechanical properties and a very low leaching rate. The leaching rate in particular is important. Tests show that it takes 3 000 years for flowing water to dissolve a 1 mm layer of glass.

The composition of the waste glass is as follows:

Constituent	Percent by weight
Vitrifying agents	89.9
Fission products	9.0
Uranium dioxide	0.76
Plutonium dioxide	0.01
Oxides of transuranium elements	0.33

This means that each waste cylinder contains 40 kg of radioactive material, of which 40 g is plutonium.

Intermediate storage facility



When the waste cylinders arrive in Sweden, they are first transported to an intermediate storage facility. The purpose of intermediate storage is to allow the heat flux from the waste to diminish. This simplifies final storage. An intermediate storage period of 30 years is foreseen. During this time, heat generation decreases to approximately one-half. However, this storage period can be extended, the only drawback being that the waste must be supervised. The time during which the waste is kept in intermediate storage can also be used for further development and improvement of the technique for the final storage of the high-level waste.

Most of the intermediate storage facility will be situated underground with a rock cover about 30 m thick (see Fig. 3). This provides good protection against external forces such as acts of war and sabotage. An entrance building with administration and service quarters as well as ventilation inlets and outlets will be built above the ground.

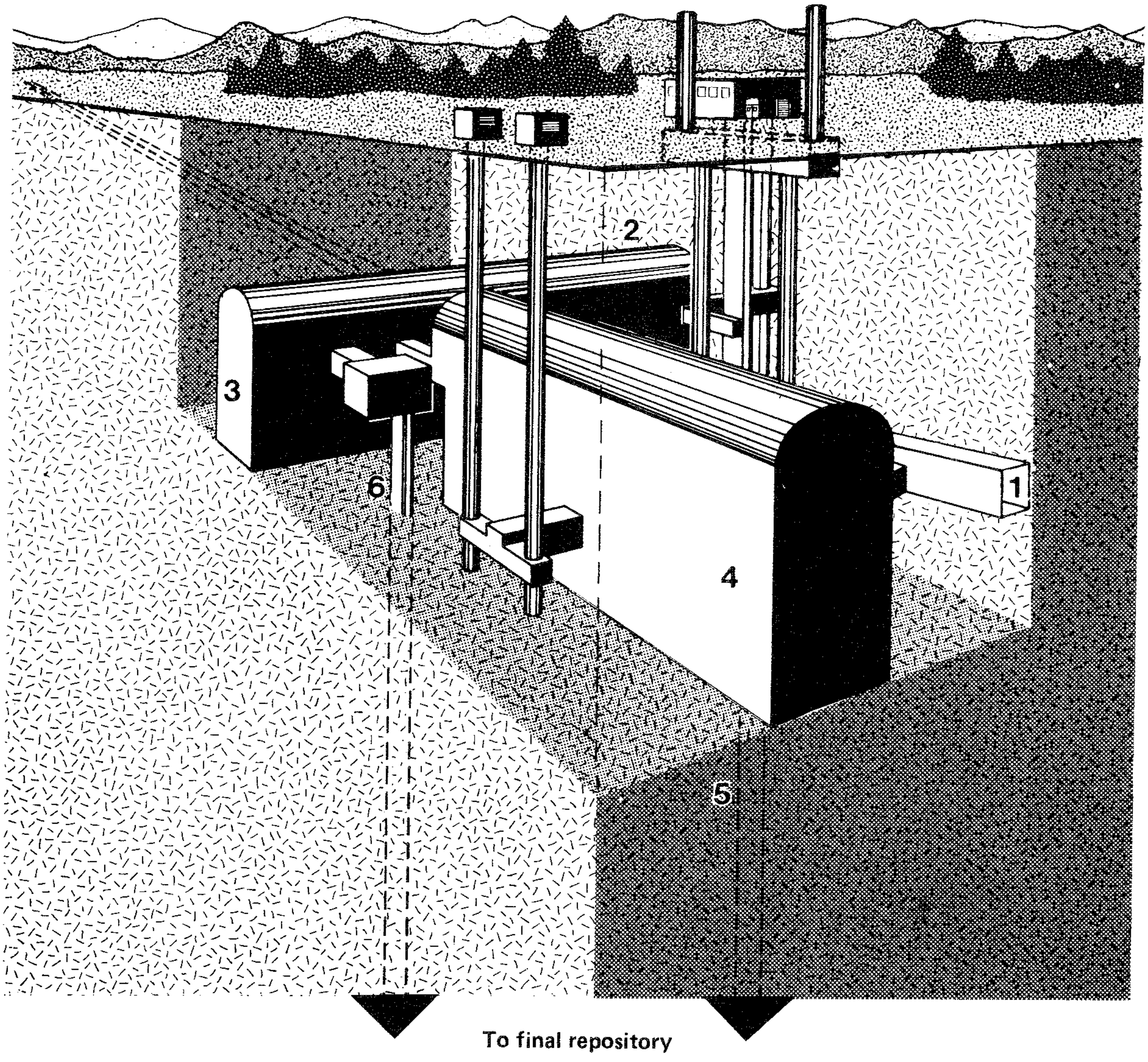


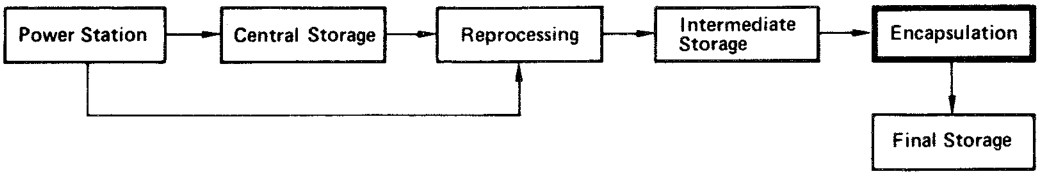
Figure 3. Perspective drawing of plant for intermediate storage and encapsulation. It is located underground with a rock cover approximately 30 m thick. The plant can be located above the final repository.

1 Access tunnel
2 Receiving station
3 Encapsulation station
4 Intermediate storage
5 Main shaft
6 Hoist shaft for waste canisters

The waste cylinders arrive at the intermediate storage facility in radiation-shielded transport casks on a trailer. They are unloaded in the receiving station. If a waste cylinder is damaged or contaminated by radioactive substances it can be provided with an outer container. The waste cylinders are then transferred inside a radiation-shielded transfer cask to the intermediate storage facility, where they are placed in steel pits in concrete trenches covered by a concrete slab. Each trench contains 150 steel pits each with room for 10 waste cylinders. The facility has 4 trenches for a total capacity of 6 000 waste cylinders.

The facility is cooled by air. The ventilation system has ample reserve capacity. Even if all fans break down, natural air convection will provide sufficient cooling to keep the temperature of the waste glass below that at which damage to the waste glass can occur. Since the waste cylinders are clean, the air which is discharged to the atmosphere is not contaminated with radioactivity. The ventilation system can be equipped with filters and equipment to measure radioactivity.

Encapsulation of the waste cylinders



An encapsulation station is located adjacent to the intermediate storage facility (see Fig. 3). Following storage in the intermediate storage facility, the waste cylinders are transferred in radiation-shielded transfer casks to the encapsulation plant. Here, the waste cylinder is provided with a canister of lead and titanium (see Fig. 4).

In the final repository, the waste canisters will eventually come into contact with groundwater in the rock. The canister is made of titanium and lead, two materials with good resistance to corrosion. The canister completely prevents leaching of the glass during the period when the toxicity of the waste is very high. The lead also serves as a radiation shield,

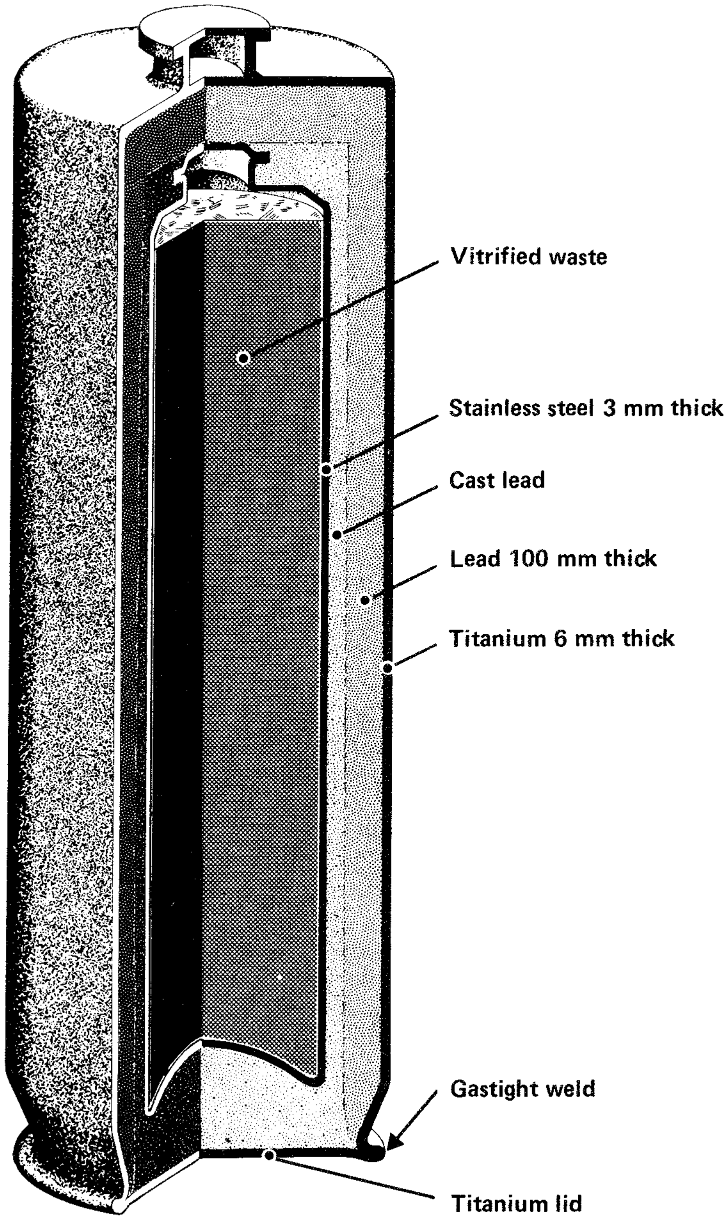


Figure 4. The encapsulated waste. The waste cylinder is provided with a canister of titanium and lead. The canister is 1.8 metres long and has a diameter of 0.6 metres.

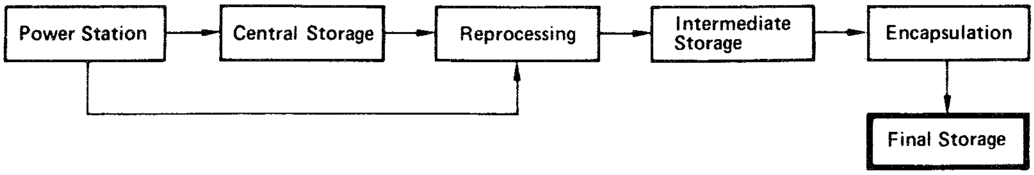
keeping the external radiation level low and preventing radiolysis of the groundwater. Radiolysis converts water into oxygen and hydrogen. This formation of oxygen could otherwise hasten the corrosion of the canisters.

The life of the titanium casing can be expected to be at least 1 000 years. If the titanium is penetrated, pitting can occur on the lead surface which is exposed. But the service life of the lead lining is estimated to be at least 500 years.

In order to be on the safe side, KBS has assumed that the canister will remain intact for only 1 000 years - a period of time which is much less than the probable service life of the canister.

The work in the receiving section and in the encapsulation station is performed in closed cells by remote-control. Personnel are protected against radiation by thick concrete walls and radiation-shielded windows. Such work has been performed for many years in a similar intermediate storage facility in Marcoule, France. The technique is therefore proven and no insurmountable problems have arisen.

Final repository



In the final repository, the encapsulated waste is received for final disposal. The final repository is situated in rock at a depth of about 500 metres under the intermediate storage facility.

The final repository consists of a system of parallel storage tunnels with appurtenant transport and service tunnels. A number of shafts lead from the surface down to the final repository (see Fig. 5). When fully complete, the final repository will cover an area of approximately 1 km^2. The geometric layout of the tunnel system will be adapted to the geological conditions prevailing on the selected site. Vertical holes drilled in the floor of the storage tunnels will constitute the final storage compartments for the waste canisters.

The canisters are transferred to the final repository in a radiation-shielded transfer cask mounted on a

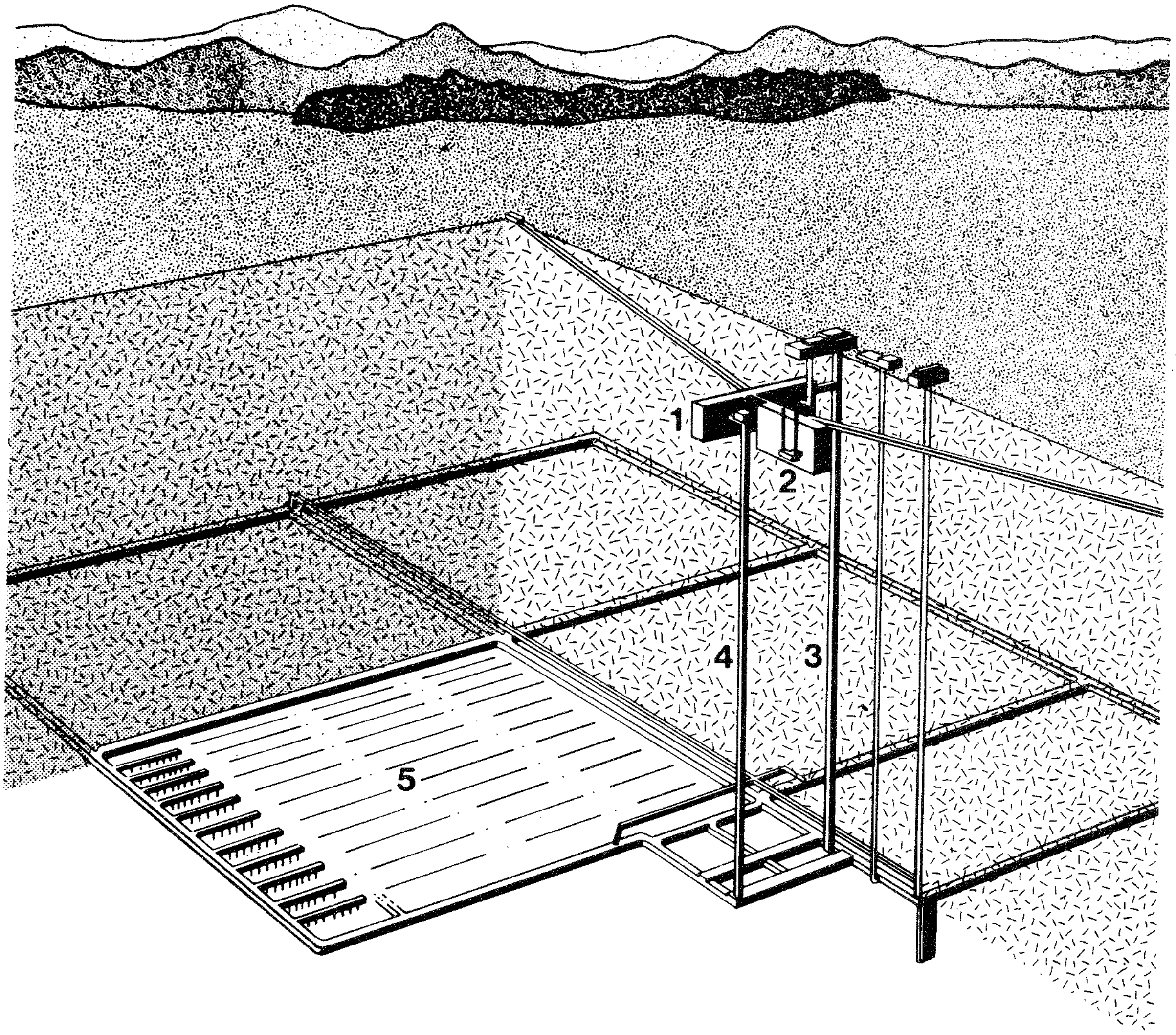


Figure 5. Perspective drawing of final repository with plant for intermediate storage and encapsulation. The final repository consists of a system of parallel storage tunnels situated 500 m below the surface.

1 Receiving and encapsulation station
2 Intermediate storage facility
3 Main shaft
4 Hoist shaft for waste canisters
5 Final repository

wagon which runs on rails. They are then taken down to the storage tunnels in an elevator. The elevator is equipped with safety devices which eliminate the possibility of a serious accident. The transfer cask is taken through the tunnel system in the final repository to the hole in which the canister is to be deposited. The canister is lowered into the hole onto a bed of quartz sand and bentonite - the buffer material. The fill is compacted so that it is stable and of low permeability. Finally, a lid is placed on the hole.

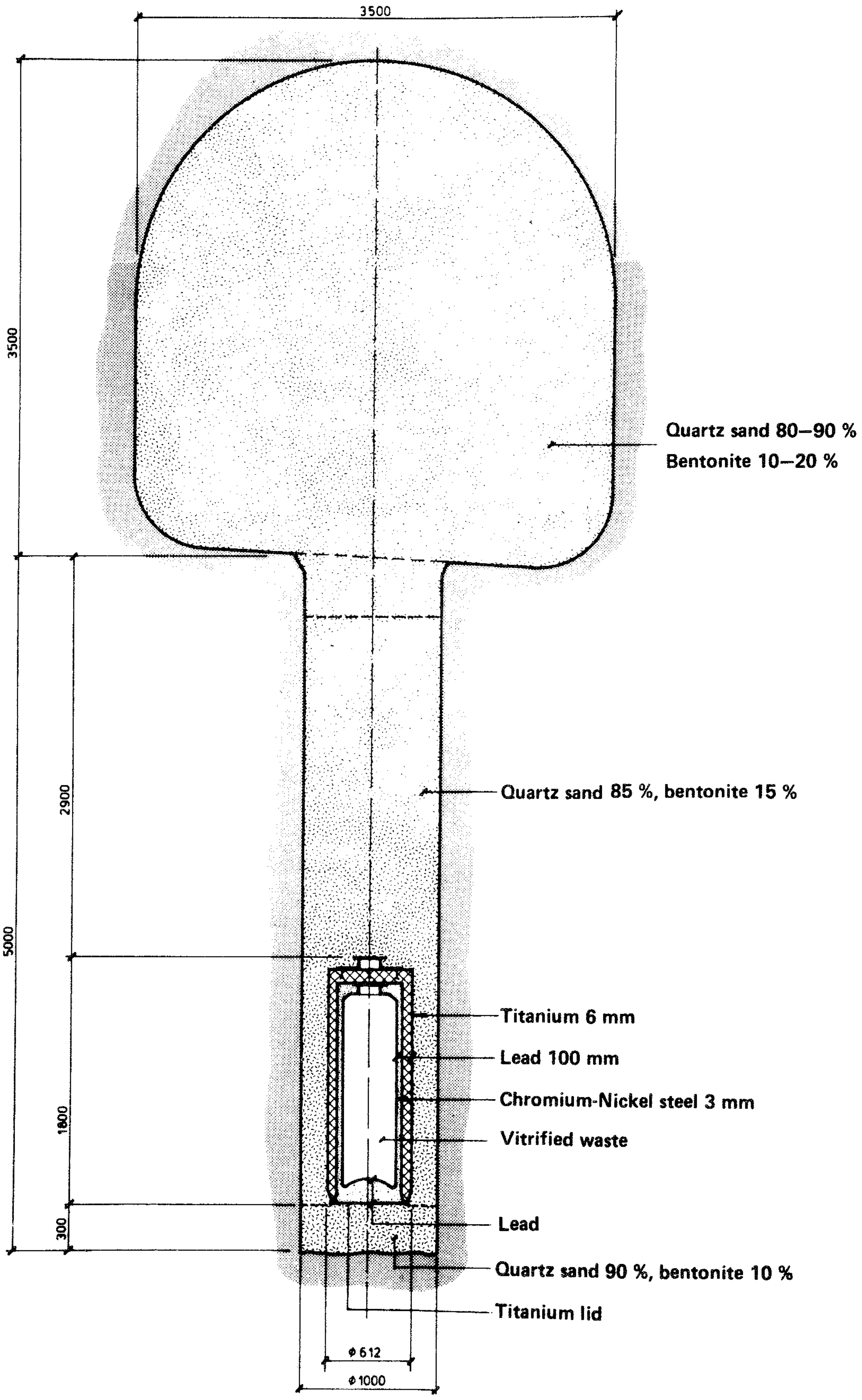


Figure 6. Sealed final repository.

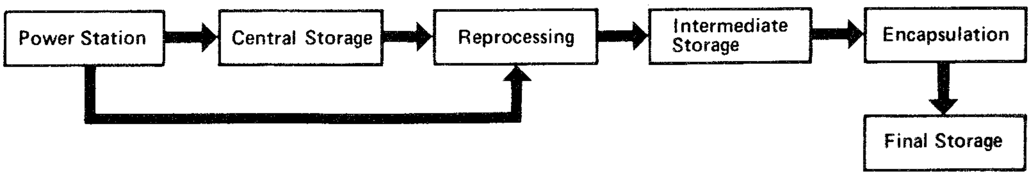
Deposition is begun when approximately one-fourth of the storage tunnels have been completed. The facility is designed in such a manner that the continued construction work and the simultaneous deposition work are completely separated from each other.

The system for handling of the canisters is similar to that which is used in the intermediate storage facility and is based on known technology. The method of applying the buffer material is based on the robot spraying technique which has been used for many years in tunnelling work. The applicability of the method for the buffer material has been confirmed by practical tests carried out for KBS.

When the final repository has been filled, it can be kept open and under surveillance as long as is deemed desirable. The facility can then be sealed and finally abandoned. When it is sealed, the tunnel system is filled with the sand/bentonite buffer material (see Fig. 6). In this way, all of the cavities in the rock are filled with a material which possesses at least as low permeability as the surrounding rock.

When, at some time in the future, the canister material has been penetrated, the encapsulated waste will come into contact with the groundwater. By that time, the toxicity of the waste will have diminished considerably and the leaching rate for the waste glass is, as was mentioned above, very low. Storage holes, tunnels and shafts are filled with a buffer material of quartz sand and bentonite. The buffer material possesses low permeability to water and also retards most of the waste elements owing to its iron-exchanging capacity.

Transportation system



The transportation of spent nuclear fuel and other radioactive material is subject to special regulations issued by the International Atomic Energy Agency (IAEA). The transport casks which are currently in use (see Fig. 7) weigh between 30 and 70 tonnes and can transport between 1 and 2.5 tonnes of nuclear fuel. During the period 1966 - 1977, approximately 700 tonnes of spent nuclear fuel have been transported from light water reactors to European reprocessing plants. Transports of spent fuel from Sweden to England have been by boat.

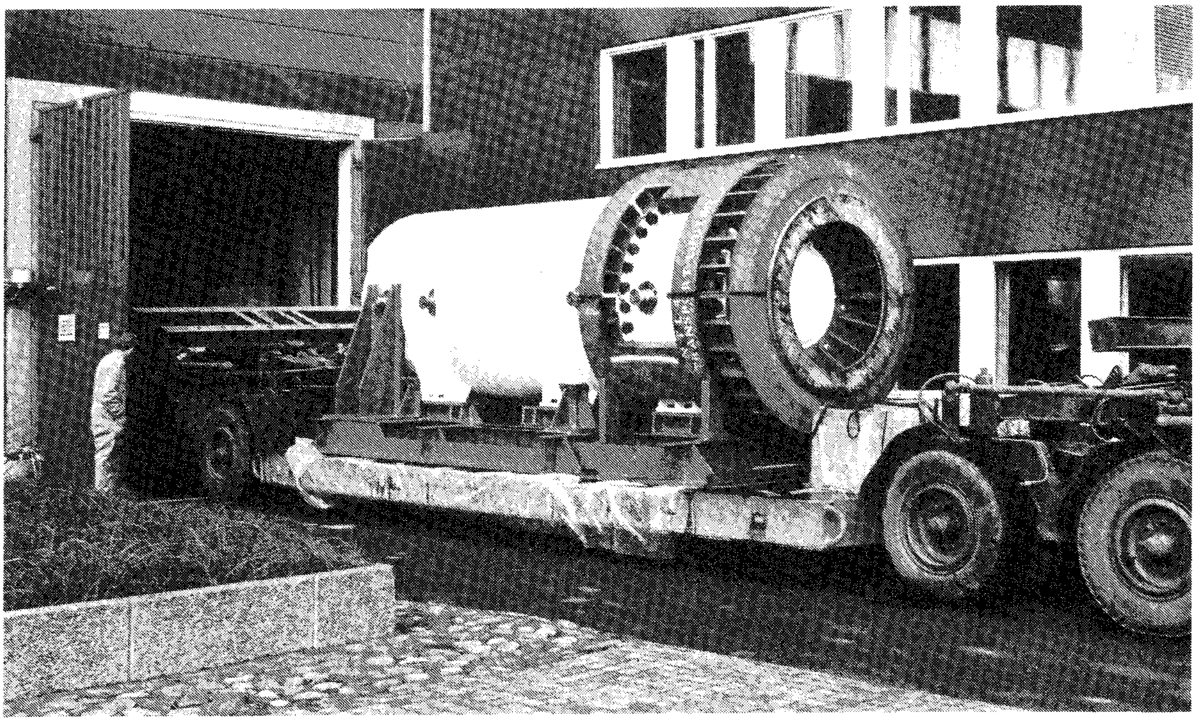


Figure 7. Trailer and transport cask outside of the Oskarshamn plant. This equipment has been used to transport spent fuel to the harbour for further shipment to the reprocessing plant at Windscale.

A transport cask must meet the safety requirements specified by the IAEA regulations. This means that it must be able to withstand:

- A nine-metre fall onto a hard surface
- Free fall from a height of one metre onto a solid steel cylinder with a diameter of 15 cm
- Heating to 800°C for 30 minutes
- Submersion in water to a depth of 15 metres for eight hours

The Swedish Nuclear Fuel Supply Company is investigating various possibilities for building up a Swedish transportation system. The annual discharge of fuel from 13 reactors will be approximately 1 400 fuel assemblies. This corresponds to approximately 300 tonnes of uranium per year. This fuel is planned to be transported by sea to the central storage facility. Ordinary ships can be used, but a ship designed especially for this purpose would be more expedient. A suitable size of such a ship should be 1 000 tonnes dwt, which could carry 8 transport casks. Such a ship would have to make about 20 runs per year if all of the spent fuel is to be reprocessed.

Transportation of the spent fuel to the reprocessing plants and of the waste cylinders from the reprocessing plants will be handled by the reprocessing company. The waste cylinders will be transported in transport casks similar to those used for spent fuel.

Geological investigations

The feasibility of a safe final disposal of high-level waste deep underground has been under consideration for some time in various countries. Different types of geological formations have been studied, for example salt, clays, shales and crystalline rock. In Sweden, interest has been concentrated on Pre-

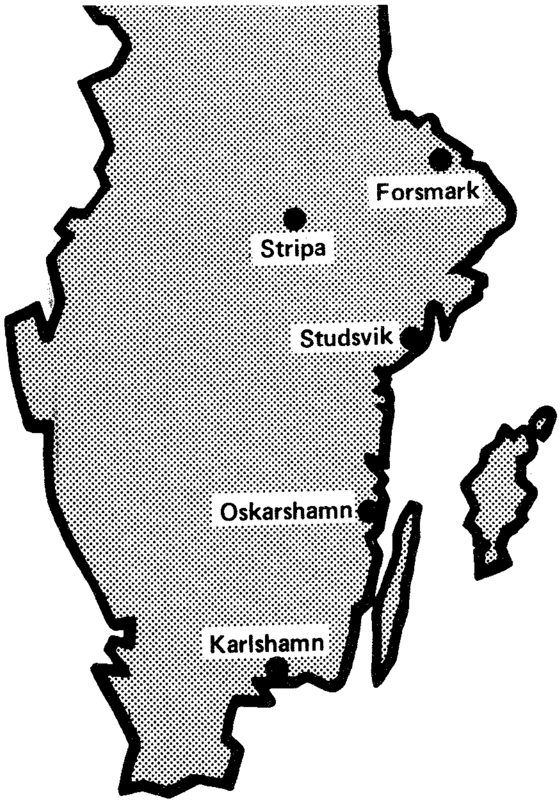


Figure 8. Map of KBS study areas. Test drillings down to a depth of about 500 m have been undertaken at Karlshamn (Sternö), north of Oskarshamn (Kråkemåla) and at Forsmark (Finnsjö). The KBS experimental station is located at Stripa. Field experiments have been conducted at Studsvik.

cambrian crystalline bedrock.

The geological investigations carried out by the Geological Survey of Sweden (SGU) on behalf of KBS has been aimed at establishing whether the Swedish Precambrian bedrock can be used for final storage. Field investigations have been performed at five sites, three of which have been selected for further study. In addition, geological and rock mechanical tests have been carried out in the abandoned Stripa Mine. The locations of the studied areas are shown in Fig. 8. It should be emphasized that the work was not aimed at finding a suitable site to be proposed for the location of a future rock repository - the geological surveys comprise one phase of the work aimed at satisfying the requirements of the Stipulation Law to demonstrate where an absolutely safe final storage of high-level waste can be effected.

The studied areas contain our most common types of rock, namely granite, gneiss and gneiss-granite. These areas are representative of large parts of south-eastern Sweden.

Of the studied areas, the Karlshamn area is geologically the best-known. It is located in a part of western Blekinge where the interrelationships between bedrock structures and groundwater conditions have been studied thoroughly. It is the only one of the KBS study areas where it has also been possible to make observations in existing rock caverns.

The bedrock in the area is a grey gneiss which contains few fractures and little groundwater. The fracture systems alternate, and the fractures do not exhibit any pronounced main directions. On the basis of data on the leakage of water into the rock caverns, the permeability of the surrounding rock can be calculated.

The core drilling which SGU has carried out within the area to a depth of 500 metres shows unchanged good conditions at these depths as well. This is due to the fact that the gneiss has been a rigid and highly resistant body ever since its folding more than 1 300 million years ago.

Displacements along fracture zones have been small for a very long period of time, approximately 0.02 mm per

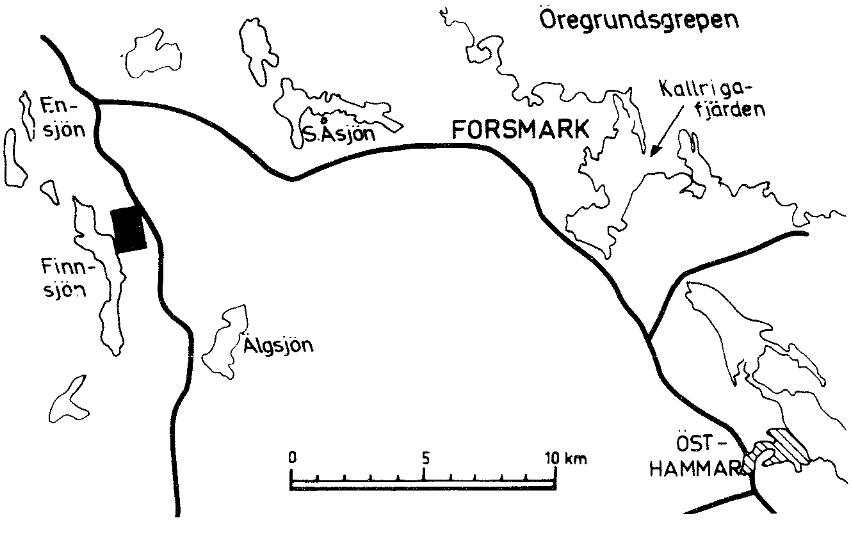


Figure 9. The Finnsjö study area.

million years. On the basis of obtained data, the groundwater flow at a depth of 500 m can be calculated to be no more than 0.2 litre per m^2 and year.

The Finnsjö area is located 16 km westsouthwest of the Forsmark nuclear power plant in the northern part of Uppland County. Geological and geophysical surveys have been conducted here, and three core boreholes have been studied. The area is composed of primary granite, which is a uniform, weakly gneissified granite. The central parts of the area are characterized by large blocks of little-fractured bedrock interspersed by fracture zones.

On the basis of measured values for water permeability, the groundwater flow at a depth of 500 m can be calculated to be approximately 0.1 litre per m^2 and year, although larger flows occur in some fracture zones. The Finnsjö area represents a very common type of crystalline precambrian rock in Sweden.

The Finnsjö area (see Fig. 9), has been chosen as a reference area for some of the KBS studies. The path of the groundwater through the bedrock has been studied. In general, the groundwater flows down into the rock in elevated areas and then up towards the surface in valleys (see Fig. 10). The influence of the topography on the groundwater flow often extends down to a depth of several thousand metres.

The Kråkemåla area is located 7.5 km north-northwest of the Oskarshamn nuclear power plant at Simpevarp, near Götemaren Lake. Geological and geophysical surveys have been conducted here as well, and three core boreholes have been studied. The area is composed of a very uniform, undeformed granite. The groundwater flow in the less previous sections has been calculated to be about 0.15 litre per m^2 and year. Considerably larger flows are found in the crush zone within the area.

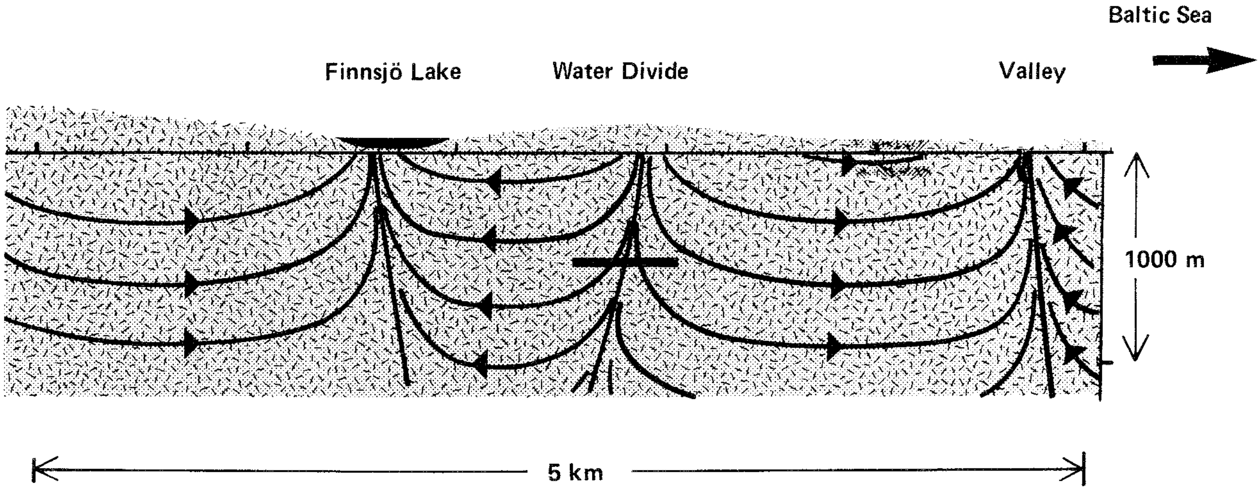


Figure 10. Schematic illustration of the flow pattern of the groundwater at Finnsjö Lake. The water volume is greatest nearest the surface of the ground: each flow line represents ten times as much water as the flow line below it. The repository is marked with a heavy line under the water divide. The groundwater movement through the repository is downward and does not reach above a depth of 500 metres until the outflow areas (lake and valley).

KBS has an experimental station in the Stripa mine, 15 km north of Lindesberg. Immediately adjacent to the mine is a granite massif which is directly accessible at a level 350 m below the surface. Here, working methods are being tested, studies are being made of how mining and heating affect the rock and the composition of the groundwater and its movement at great depth are being analyzed. The testing work is being conducted in collaboration with Lawrence Berkely Laboratory, with financial contributions from the United States Department of Energy.

A great many studies have been conducted and the results carefully evaluated. Groundwater datings show, for example, that the transit time of the groundwater to the surface of the earth from a rock repository in an inflow area can amount to several thousand years. Changes around a rock repository caused by the blasting work and the heat generated by the waste are very local. The risk that new flow paths for the groundwater will be created by such changes is negligible.

The studies at Karlshamn, Finnsjö and Kråkemåla show that all three areas possess the fundamental prerequisites for a safe rock repository for high-level waste, providing that the repository is designed with consideration to local conditions. At the present level of knowledge, the Blekinge coastal gneiss area is the most attractive from a geological viewpoint.

Safety

The Stipulation Law requires that final storage be absolutely safe. As is noted in the KBS report, no human activity can be said to be absolutely safe in the strictest sense of the term. However, the statement issued by the Committee on Commerce and Industry concerning the Stipulation Law Bill makes it clear that such a draconian (inhumanly stringent) interpretation of the term "absolutely safe" is not intended.

A comprehensive safety analysis has been carried out by KBS. Various safety measures in the handling chain as well as estimated normal releases of radioacitivty have been analyzed. Incidents, accidents and failures and their consequences have been studied. Finally, the manner in which a slow dispersal of radioactive elements could take place and the possible effects of ectreme events have been thoroughly analyzed.

Safety in connection with handling

Transports of spent fuel and other radioactive material are already being done today, and experience shows that safe transports can be performed without any great difficulties. During transport, the special transport cask constitutes a safe containment.

In the safety analysis carried out by KBS, it has been calculated that the worst transport accident which could conceivably occur is that the ship carrying the waste collides and is then ravished by fire. The probability of such an accident is approximately one in 300 000 years. Even in the event of such a severe accident, little radioactivity would be released.

The intermediate storage facility is designed on the basis of experience from a facility in France. The French facility has been in operation for ten years, during which time no release of radioactivity has been detected. The emplacement of the facility in rock protects it against acts of war and other external forces.

The final repository has been placed at a depth of 500 metres, since groundwater flow is low at that depth and any contaminated water will be diluted considerably before it reaches the vicinity of the ground surface. Considerable experience exists from construction works in rock at such depth, primarily within the mining industry. The great depth also protects against meteorite impacts and acts of war - not even a very powerful nuclear explosive could cause damage at such a depth.

The great depth also protects against the effects of an ice age. The bedrock which has been studied has been subject to the effects of some ten or so glaciations without that the water flow and the fissure content have become unacceptably high.

In summary, the safety analysis shows that the dispersal of radioactive elements which could occur in connection with the normal operation of the facilities or in connection with accidents in the various stages of the handling of the spent fuel and the high-level waste, is insignificant.

Safety in connection with long-term storage

The dispersal of radioactive substances from a final repository can only take place via the groundwater. The final repository must be arranged so that such a dispersal cannot cause damage to organic life. The radioactivity of some of the radioactive elements contained in the waste declines very slowly. The dispersal of these elements must be either prevented or retarded over a long period of time. In order to keep the levels of radioactive elements which could conceivably spread to organic life under unfavourable circumstances sufficiently low, the final repository has been designed with a number of barriers (see Fig. 11). From the inside out, these barriers are as follows:

- The waste glass, which is a borosilicate glass
- The canister of stainless steel, lead and titanium
- The buffer material of quartz sand and bentonite
- The bedrock with low groundwater flow.

The crystalline bedrock which is chosen for the final storage of high level waste must be highly impervious and the groundwater flow must have a low velocity, so that only very small quantities of water will reach the repository. Such rock exists at many places in Sweden. The groundwater must also have to travel a very long way before it reaches the ground surface. Chemical processes in the fracture system in the rock prevent and retard the further dispersal of radioactive substances, so it takes thousands of years before such substances reach the surface.

The buffer material of quartz sand and bentonite also constitutes a barrier. The permeability of the buffer material can be made at least as low as that of the surrounding rock. Bentonite, which is a

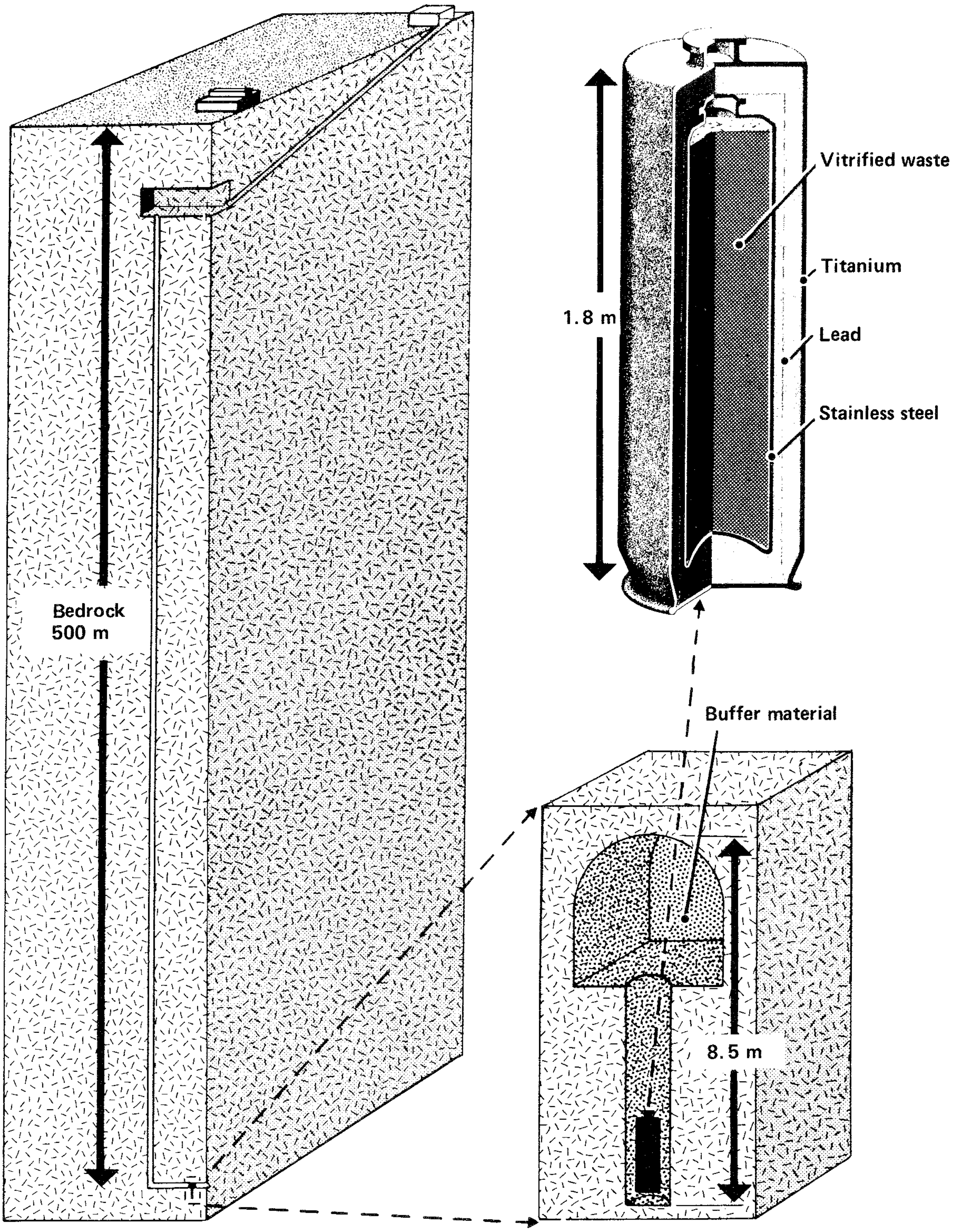


Figure 11. Schematic illustration of the proposed final repository. A number of barriers shall prevent and retard the dispersal of radioactive elements from the waste. Innermost is the vitrified waste. It is encapsulated in three metallic layers: Stainless steel, lead and titanium. The canister is surrounded by quartz sand and bentonite (buffer material) in a storage hole 500 metres below the surface in impervious crystalline bedrock.

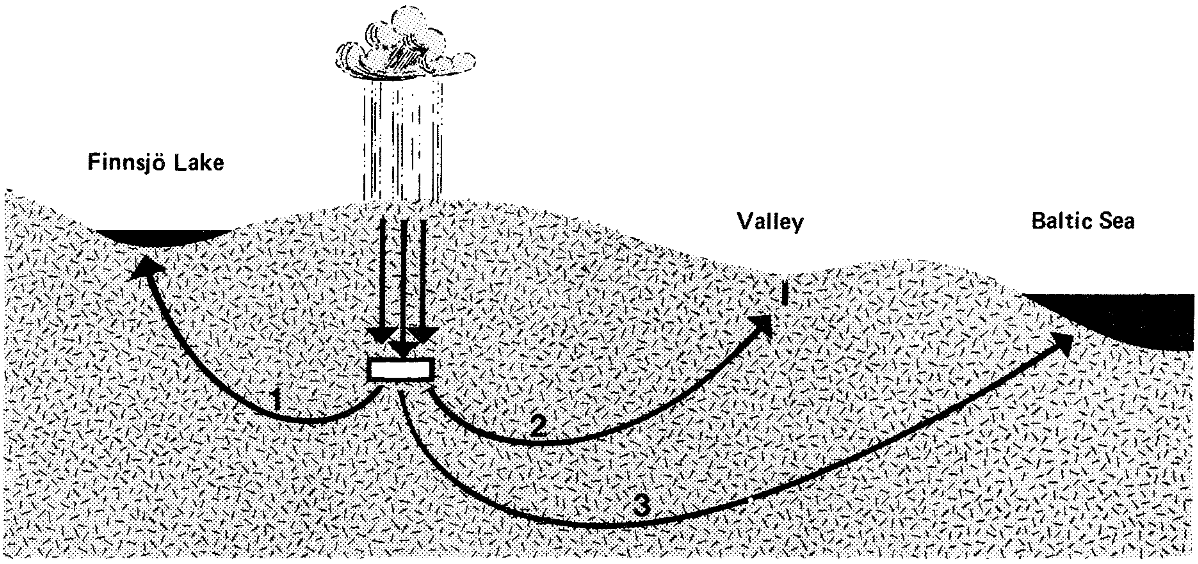


Figure 12. Three typical cases for dispersal of the radioactive elements to the biosphere have been studied in the safety analysis:

1 Dispersal to Finnsjö Lake
2 Dispersal to a deep-drilled weel
3 Dispersal to the Baltic Sea

naturally occurring clay material, also possesses ion-exchange properties. This means that dissolved substances will be retarded by the bentonite, and the radioactive substances will migrate at a much slower velocity than the water.

In order for the groundwater to reach the waste glass, the metallic layers of the canister must be destroyed. Titanium and lead both possess very good resistance to corrosion. In order for the glass to be exposed, large quantities of metal must be carried away by the groundwater. The fastest way for this to occur is for the metal to be attacked locally, whereby pitting makes a hole through the metals. Such a corrosion process is estimated to take at least 1 000 years and probably considerably longer. Even with heavy pitting, the groundwater will only come into contact with a small portion of the waste glass.

The innermost barrier is the waste glass itself. The high-level waste is melted together with vitrifying substances into a homogeneous glass mass. This borosilicate glass exhibits a very low leaching rate: only 0.0003 mm glass is dissolved per year in flowing water. This corresponds to 1 mm in 3 000 years. With

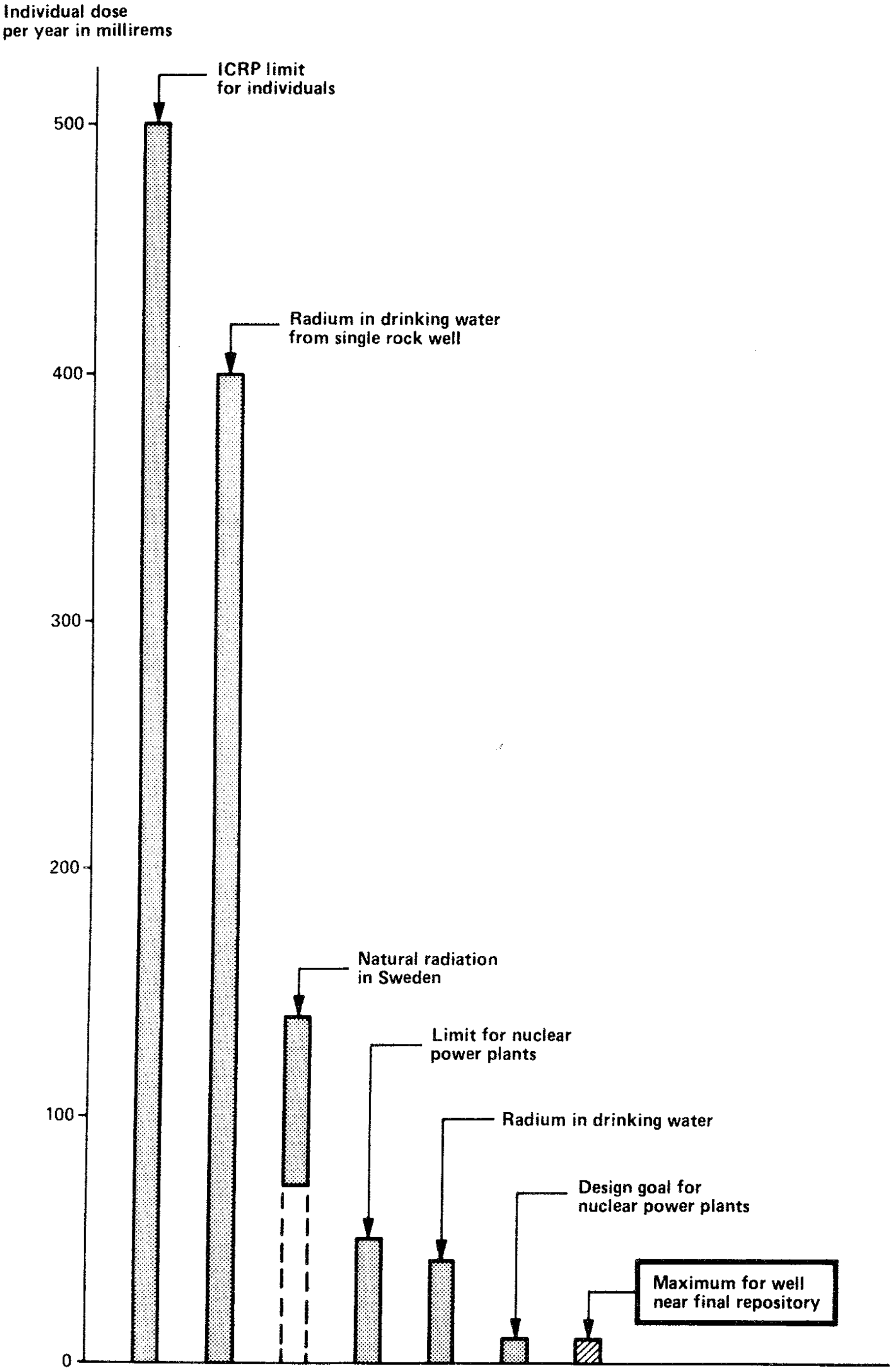


Figure 13. Comparison between different radiation doses and limits. The highest radiation dose which the radioactive waste could give rise to under unfavourable circumstances (13 millirems) is only one-tenth of the natural radiation from bedrock and the atmosphere in Sweden (70–140 millirems) and approximately one-fortieth of the ICRP limit for individuals (500 millirems).

virtually stationary water, which is closer to the actual situation in a final repository, the leaching rate is considerably lower.

At every point where uncertainty exists, the safety analysis is based on assumptions and data which contain safety margins. Even with these conservative assumptions, the radiation doses from the long-term storage of nuclear waste in a final repository to large population groups will be extremely low and the long-term health effects negligible.

The group of people who could be exposed to radiation from radioactive elements from the final repository consists of persons who obtain water from a deep--drilled well in the vicinity of the repository (see Fig. 12). This group of people could, under unfavourable circumstances, receive a dose increment of max. 13 millirems per year. This corresponds to approximately one-tenth of the natural radiation to which the population of Sweden is subjected each year. This maximum increment will occur approximately 200 000 years after the waste has been deposited in the final repository.

The maximum radiation dose from the final repository is compared with some other dose values and limits in Fig. 13.

KBS thus consider that the design of the final repository which it has proposed satisfies the requirements imposed by the Stipulation Law on an absolutely safe final storage of the high-level waste obtained from the reprocessing of nuclear fuel.

HANDLING AND FINAL STORAGE OF UNREPROCESSED SPENT NUCLEAR FUEL

A summary of the second KBS report of June 28, 1978

Background

The "Stipulation Law" of 1977 states that new nuclear power units may not be commissioned until the owner has shown that the waste problem can be solved in an absolutely safe manner. For this reason, the nuclear power industry formed the Nuclear Fuel Safety Project (Projekt Kärnbränslesäkerhet, KBS). The Stipulation Law gives two alternatives. In accordance with the first alternative, the reactor owner shall produce an adequate reprocessing agreement and shall show how and where an absolutely safe final storage of the high-level reprocessing waste can be effected. In accordance with the second alternative, the reactor owner shall show how and where an absolutely safe final storage of the spent, unreprocessed nuclear fuel can be effected. The first alternative is dealt with in the first KBS report entitled "Handling of spent nuclear fuel and final storage of vitrified high-level reprocessing waste", published in December of 1977. Following is a summary of the report submitted by KBS on the second alternative of the Stipulation Law entitled "Handling and final storage of unreprocessed spent nuclear fuel".

In the most recent report, the following stages in the handling of the fuel on its way to final storage are proposed:

1 The spent fuel is stored at the nuclear power

plant for at least six months.

2 The fuel is then transported to a central storage facility for spent nuclear fuel.

3 The fuel is stored in the central fuel storage facility for 40 years.

4 The fuel is transported to an encapsulation station.

5 In the encapsulation station, which is located above ground in connection with the final repository, the fuel rods are separated from the other parts of the fuel assemblies. The fuel rods are enclosed in copper canisters and the cavities are filled up with lead. Other radioactive material is embedded in concrete cubes.

6 The copper canisters are taken to a final repository which is built at a depth of approximately 500 metres in the bedrock. The copper canisters are surrounded by blocks of highly compacted bentonite - a clay which possesses very low permeability and which swells considerably upon absorbing water.

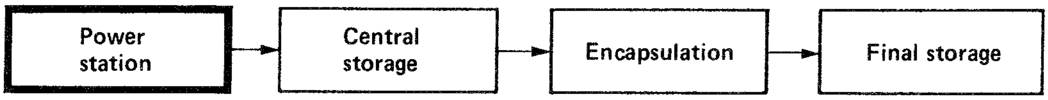
7 The facility can be kept open as long as surveillance is deemed desirable. It is then sealed by filling all tunnels and shafts with a mixture of quartz sand and bentonite.

8 The concrete cubes containing the metal components of the fuel assemblies are deposited in a separate repository at a depth of 300 metres in the bedrock. This repository is sealed with concrete, sand and bentonite.

The proposed procedure entails a safe handling and final storage of the spent nuclear fuel. When the final repository has been sealed, there are a number of barriers against the dispersal of radioactive substances. Safety in the various handling stages and in the final repository are analyzed in a special section of the report.

Following is a brief description of the various stages from the removal of the spent fuel from the reactor to final storage deep down in the Swedish bedrock.

The nuclear power stations and the nuclear fuel



In a nuclear power plant, heat is generated by the fission (splitting) of heavy atoms in the nuclear fuel. The heat converts water to steam which drives turbines and generators.

There are two types of reactors in operation in Sweden: ASEA-ATOM´s boiling water reactor (BWR) and Westinghouse´s pressurized water reactor (PWR). Six reactors, 5 BWRs and 1 PWR, are currently in operation. Two more have been completed and four reactors are under construction. All of these reactors are located at four places in the country: Ringhals, Barsebäck, Oskarshamn and Forsmark. One more reactor was approved by the Swedish Parliament in 1975 (see Fig. 14).

Nuclear fuel consists of cylindrical pieces, pellets, of uranium dioxide. They are enclosed in cladding tubes, several metres long and finger-thick, made of a zirconium alloy. The tubes with pellets are called fuel rods. In a Swedish boiling water reactor (BWR), a bundle of 63 fuel rods constitutes a fuel assembly. The fuel assembly weighs about 300 kg (see Fig. 15).

In the new Westinghouse reactors, 264 rods make up a fuel assembly. Such a PWR assembly weighs about 670 kg (see Fig. 16).

The waste facilities described in the following are

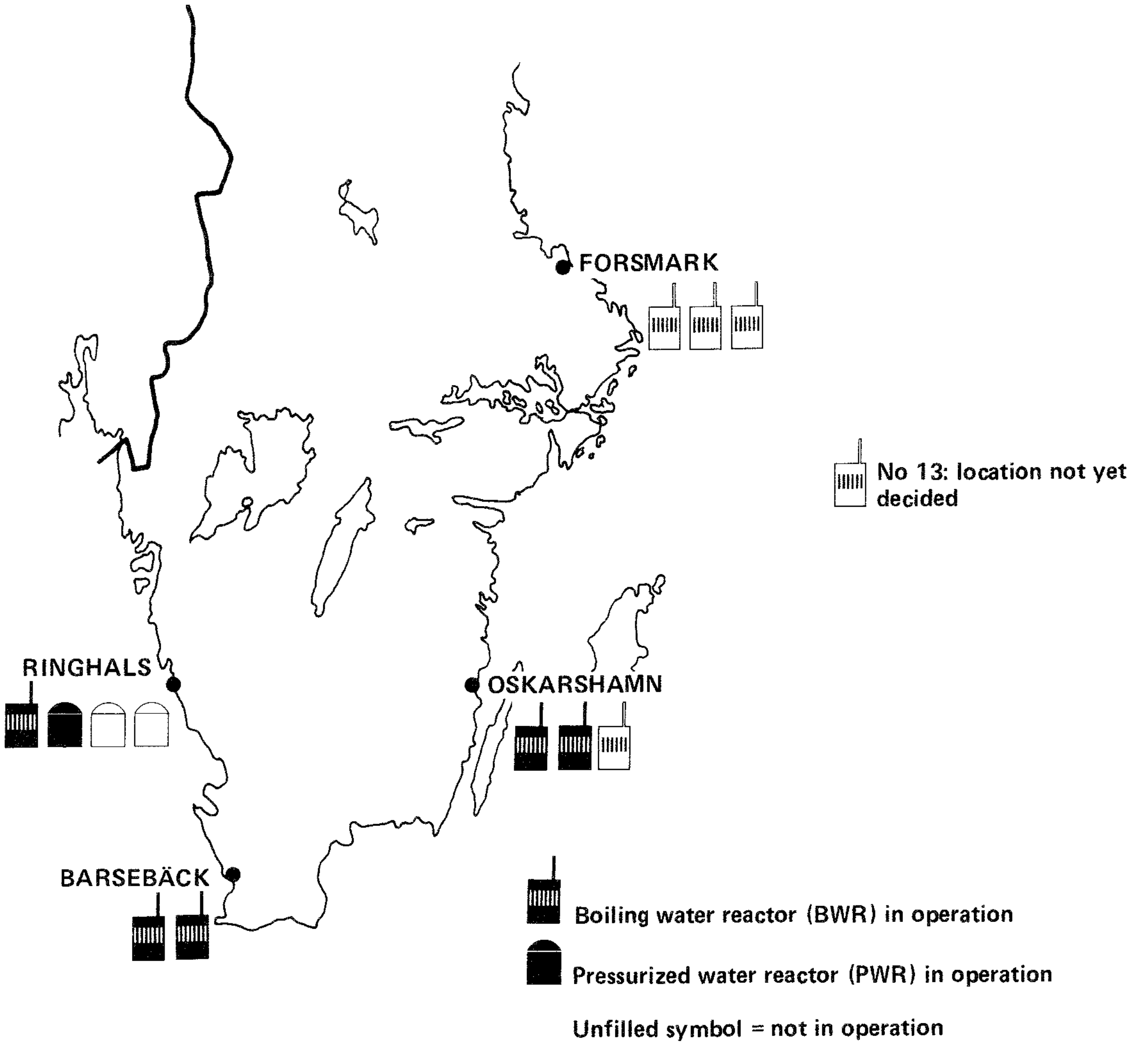


Figure 14. The Swedish nuclear power program in accordance with the 1975 parliamentary resolution.

intended for spent nuclear fuel from 30 years of operation of 13 reactors. The total quantity of spent fuel then amounts to about 9 000 tonnes.

Nuclear power plants have their own storage pools for spent fuel. They are required when the reactor is emptied of fuel in connection with service inspections and when the spent fuel is stored before being sent to reprocessing or to a central fuel storage facility.

The spent nuclear fuel is stored in the pools for at least six months after having been taken out of the reactors. During this period of time, the fuel decays and cools considerably.

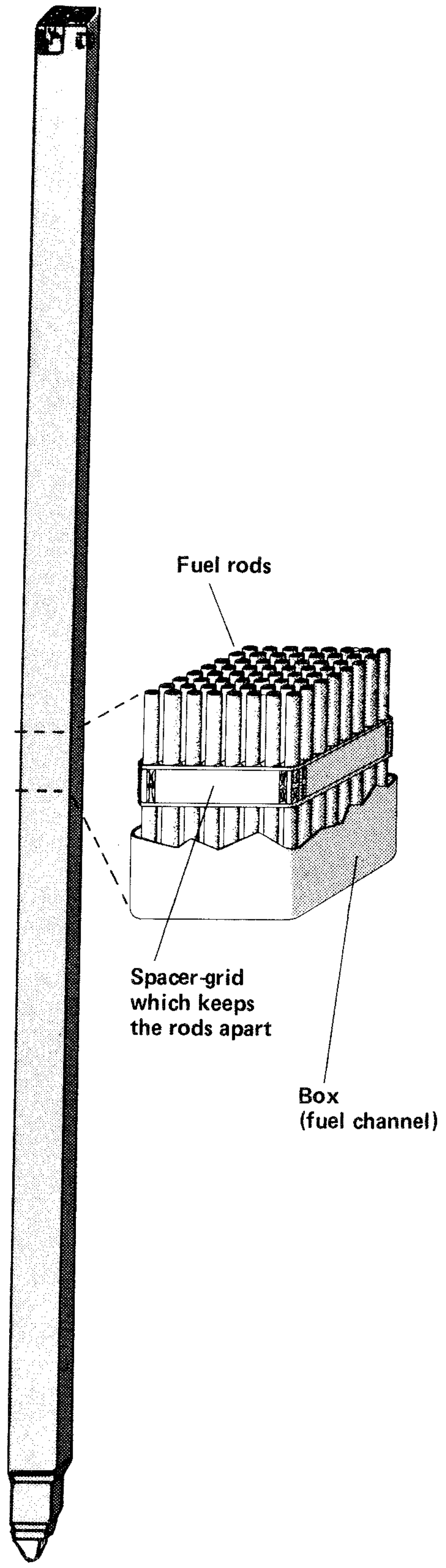


Figure 15. Fuel assembly for a boiling water reactor (BWR).

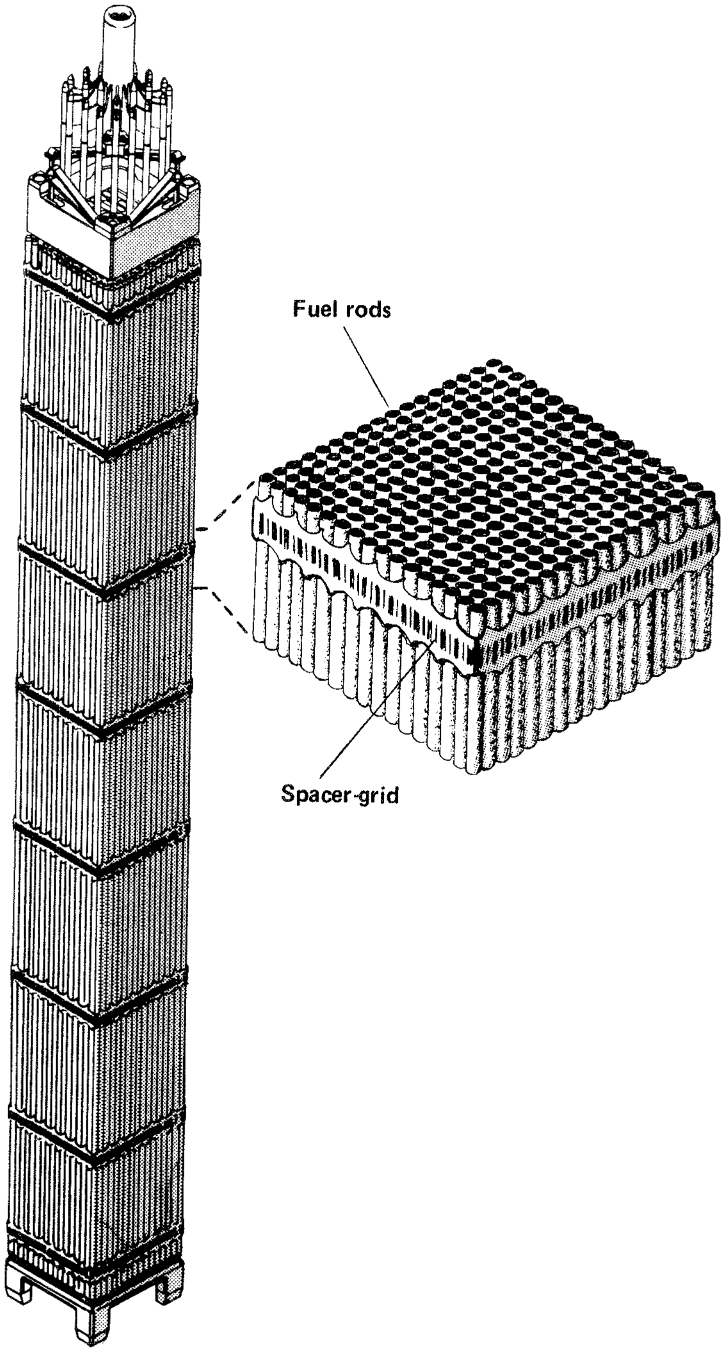


Figure 16. Fuel assembly for a pressurized water reactor (PWR).

COMPOSITION OF THE SPENT FUEL

The fuel pellets contain two types of uranium: fissionable uranium-235 and non-fissionable uranium-238. When uranium-235 is split, radioactive nuclides known as fission products are formed. The high-level waste consists mostly of such fission products. Plutonium and some other heavy elements, known as transuranium elements, are also formed in the fuel. Most of the fuel - - both before and after irradiation - consists of uranium-238, which is not fissionable.

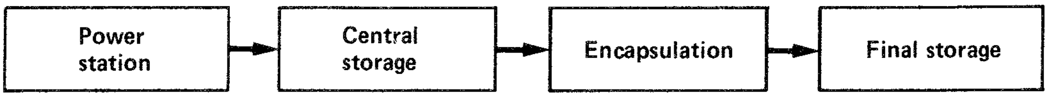
Composition of spent nuclear fuel (percent)

Constituent	BWR	PWR
Uranium-235 (fissionable)	0.7	0.9
Uranium-238 (non-fissionable)	95.6	94.5
Plutonium	0.7	1.1
Other transuranium elements	0.1	0.1
Fission products	2.9	3.4

The fission products consist of a large number of radioactive elements. Many of these elements decay rapidly and thus have a very short life. In the final storage of spent fuel, it is the fission products with long life which must be safely stored for a very long period of time. For the first 500 - 1 000 years, strontium-90 and cesium-137 account for most of the radiation. In the longer run, tecnetium-99 and iodine-129 are important radiation sources.

The spent fuel also contains uranium, plutonium and other transuranium elements. These nuclides are converted by radioactive decay to other nuclides, daughter products, which are also radioactive. In the very long time perspective - millions of years - uranium and the daughter products of uranium, such as radium, are responsible for the residual radioactivity.

Transportation



Special regulations issued by the International Atomic

Energy Agency, IAEA, govern the transportation of spent nuclear fuel and other radioactive material. A transport cask must meet a number of safety requirements, including that it must be able to withstand a fall or 9 metres onto a hard surface as well as heating to 800°C for 30 minutes. The transport casks which are currently in use weigh between 30 and 70 tonnes and can transport between 1 and 2.5 tonnes of nuclear fuel. Such casks have been used for the transportation of spent fuel from the Oskarshamn power station to England.

When 13 reactors are on-line, approximately 1 400 spent fuel assemblies will be discharged from the Swedish reactors each year. With the larger type of cask which is currently being manufactured, this corresponds to approximately 100 transport casks. The casks are planned to be transported to the central fuel storage facility by sea. Ordinary ships can be

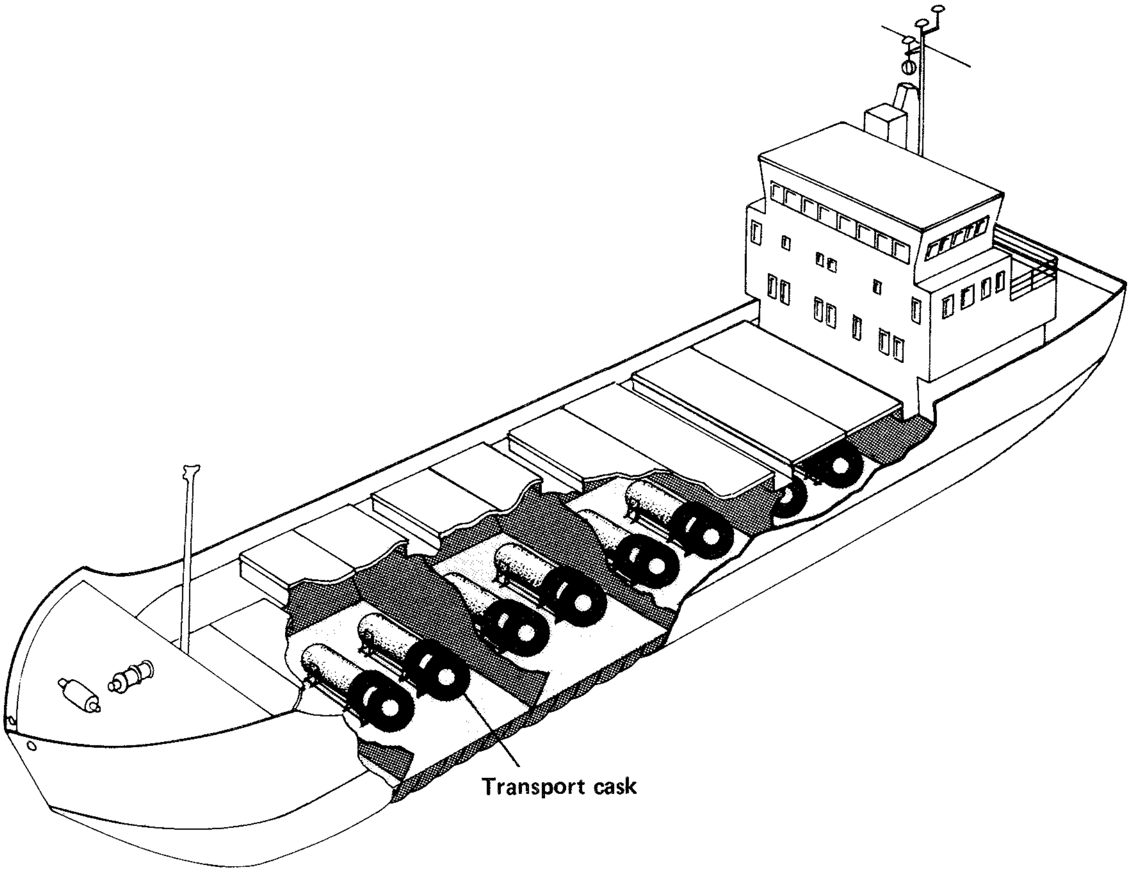
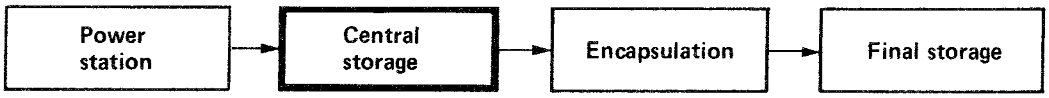


Figure 17. Ship for transport of spent nuclear fuel.

used, but ships designed especially for this purpose would be more expedient. Such a ship should weigh about 1 000 tonnes dwt and be able to carry eight transport casks (see Fig. 17). Such a ship would have to make about a dozen runs per year to the central fuel storage facility. The fuel would then be kept at the central fuel storage facility for about 40 years.

Central storage facility for spent fuel



Regardless of whether the spent fuel is to be reprocessed or disposed of without reprocessing, additional storage space is required for spent fuel. For economic reasons, a central facility is preferable to an expansion of capacity at the individual nuclear power stations. Such a central facility for the storage of spent fuel from all of the Swedish nuclear power stations is currently being planned and designed by the Swedish Nuclear Fuel Supply Company. The storage principle is the same as that employed at the nuclear power plants, i.e. the fuel assemblies are stored in water pools, whereby the water provides the necessary cooling and radiation shielding. Fig. 18 shows a schematic illustration of the design of the central fuel storage facility. A siting and licensing application was submitted to the Government in November of 1977, with Forsmark, Studsvik and Oskarshamn indicated as alternative sites.

In the KBS proposal for the handling of unreprocessed fuel, it has been assumed that the spent fuel will be stored in water pools for 40 years before being emplaced in the final repository. However, this

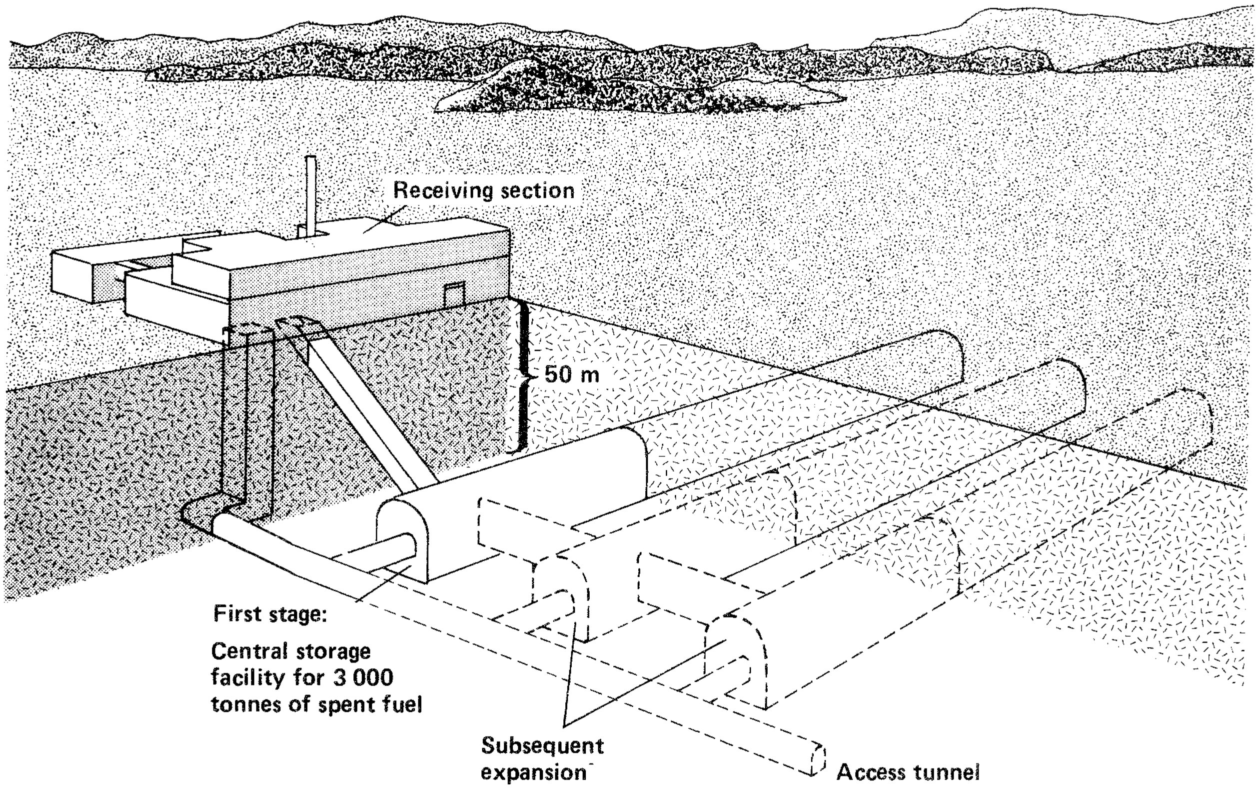
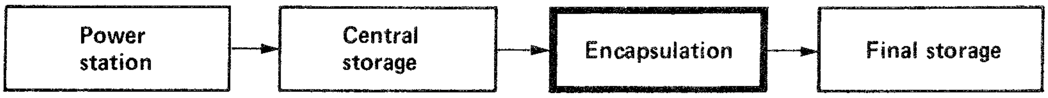


Figure 18. The central fuel storage facility expanded to a capacity of 9 000 tonnes.

storage period can be varied, its length being primarily a question of finding the optimum solution based on technical and economic consideration.

Encapsulation of spent fuel



From the central fuel storage facility, the spent fuel is transported to an encapsulation station. It is proposed that this station be located above ground and in connection with the final repository. In addition to service buildings, the station consists of a receiving section and an encapsulation section. Much of the work in the encapsulation station is performed in radiation-shielded cells by remote control.

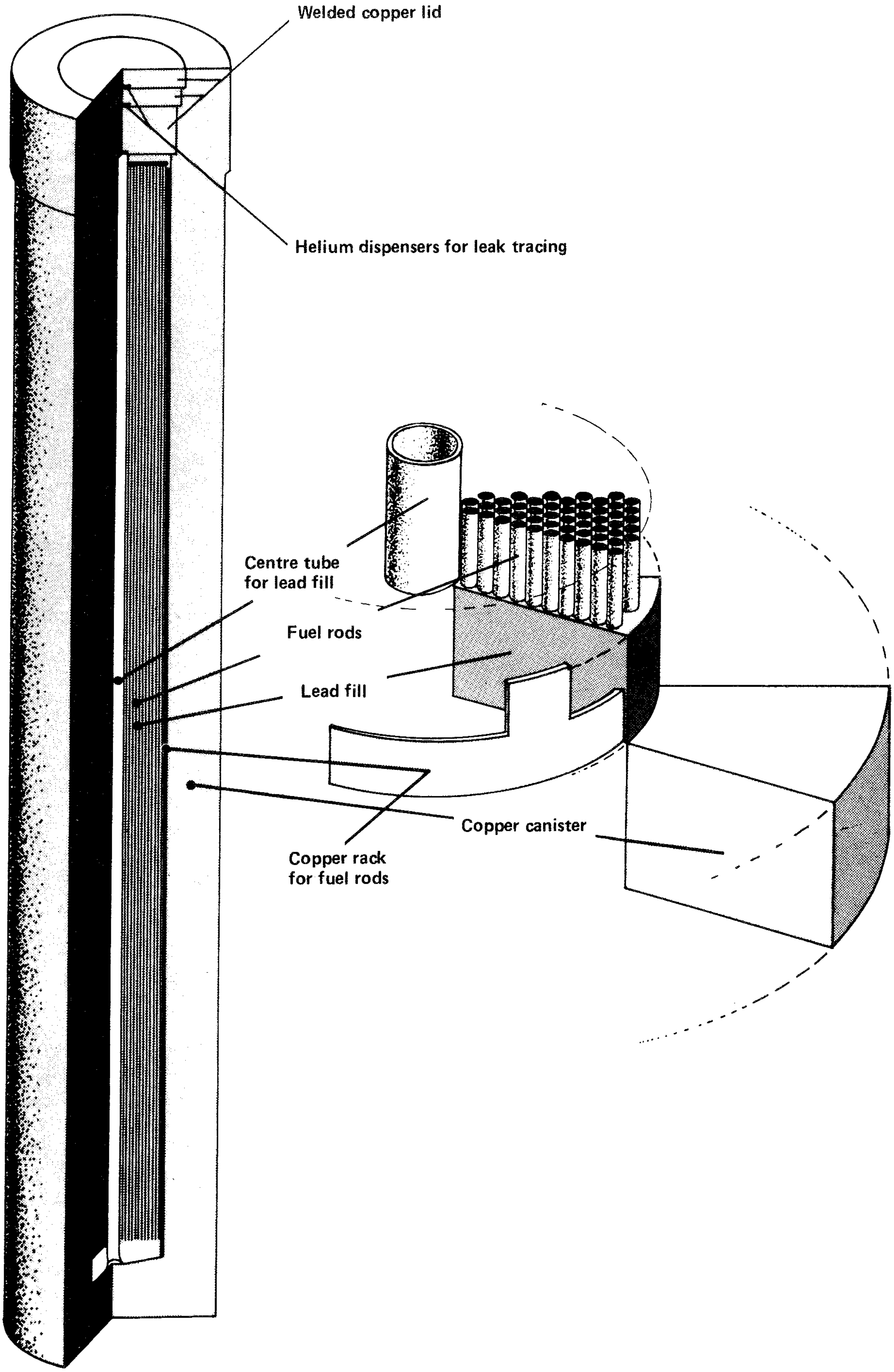


Figure 19. The encapsulated waste. The copper canister is 4.7 metres long and has a diameter of 0.8 metres.

In the encapsulation station, the spent fuel is dismantled and the rods are separated from the other parts of the fuel assembly. The fuel rods are placed in canisters made of pure copper. Such a canister has walls 20 cm thick and is 4.7 metres long. The spaces between the fuel rods and between the rods and the canister are filled with lead. A series of lids is welded on and the canister is subjected to meticulous material inspection (see Fig. 19).

When the copper canister is full, it weighs about 20 tonnes. The finished canisters are transported in an elevator down to the final repository. The total number of canisters will be approximately 7 000 when all of the fuel from 30 years of operation of 13 reactors has been disposed of.

The canisters may be made of other materials besides copper. ASEA has developed a canister made of aluminium oxide compacted into a hard ceramic material by means of a special pressing method. The canister is 3 metres long and weighs 2 tonnes. It can hold approximately 150 rolled-up fuel rods. The canister, its lid and a metallic casing are pressed together to form a seamless body.

The metal components of the fuel element which have become radioactive after use are embedded in concrete cubes, moulds, in a special section of the encapsulation station. The total number of concrete moulds will be approximately 1 200. It is proposed that these concrete moulds be emplaced in special tunnels 300 metres below the surface in the bedrock for final storage (see Fig. 20).

The metal components are much less radioactive than the fuel rods and decay to a harmless level much sooner. Their handling is therefore considerably simpler. This waste does not have to be stored as deep down in the bedrock as the spent fuel rods and

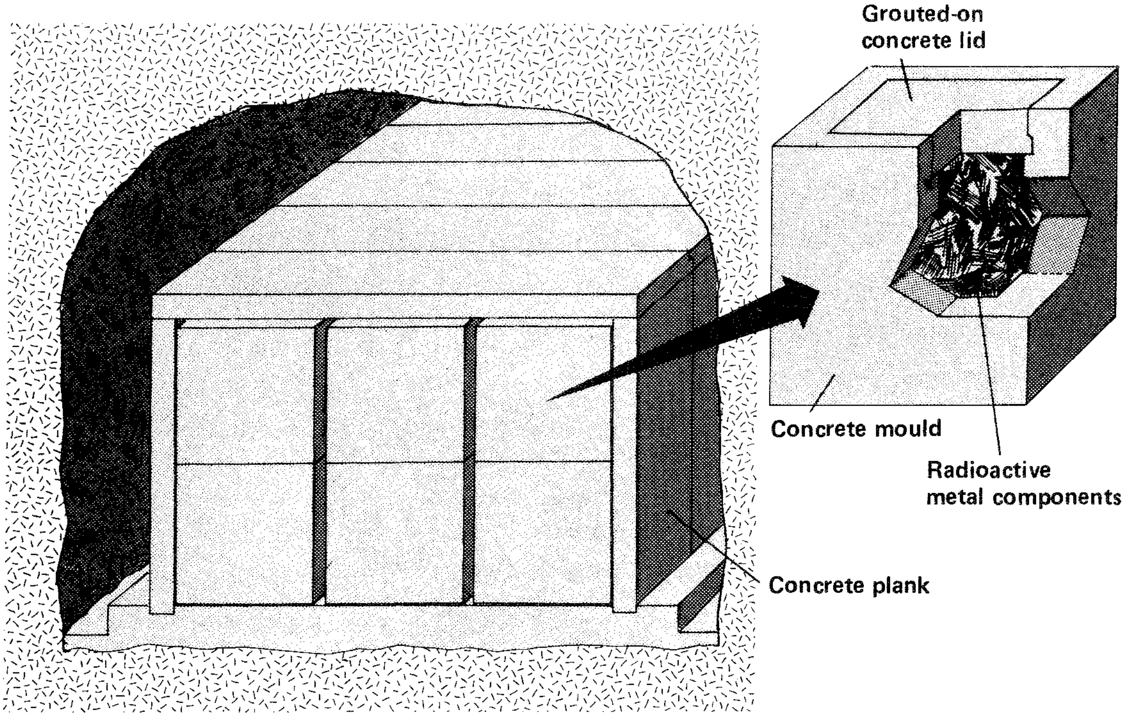
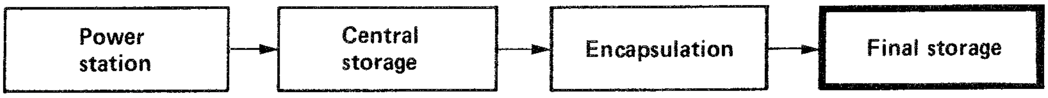


Figure 20. Final repository for concrete moulds containing radioactive metal components from the fuel assemblies.

can also be enclosed in a simpler manner.

The final repository



In the final repository, the copper canisters are received for final disposal. The design of the facility is similar to that of the corresponding facility for vitrified waste.

The final repository is situated in impervious crystalline bedrock at a depth of 500 metres and consists of a system of parallel storage tunnels, transport tunnels and service rooms. A number of shafts lead from the ground surface down to the tunnel system (see Fig. 21). When completed, the final repository will cover an area of about 1 km^2. The geometric configuration of the tunnel system will be adapted to the geological conditions prevailing on the selected site.

9-metre-deep holes, one for each waste canister, are drilled in the floors of the storage tunnels. The hole is lined with rings of highly compacted bentonite, a type of clay which exists in nature. Pressed bentonite is also deposited above and below the canister. When groundwater penetrates into the bentonite, the bentonite swells considerably and effectively fills all cavities under high pressure. In this manner, the

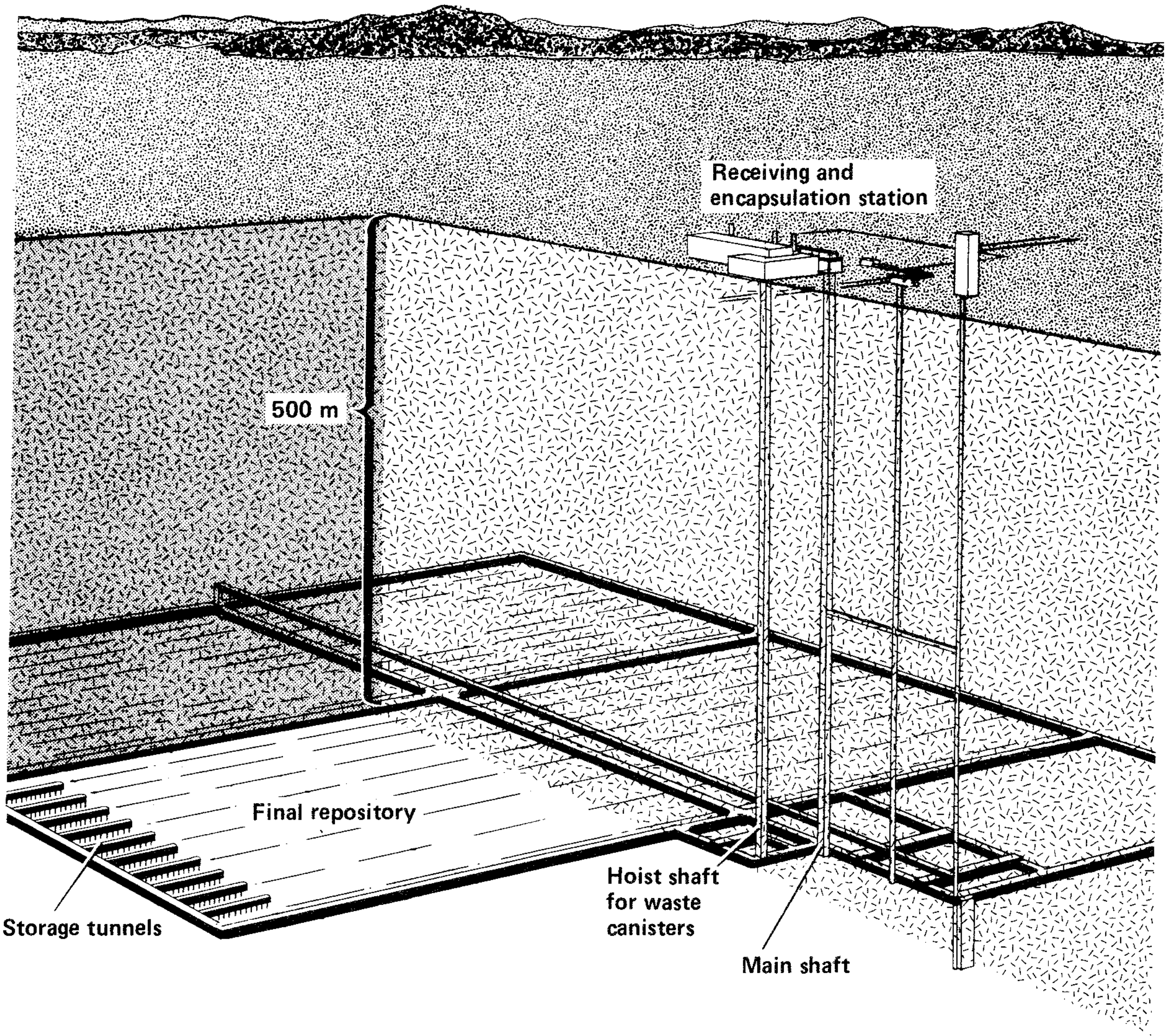


Figure 21. Perspective drawing of the final repository.

bentonite forms an impervious buffer between the canister and the rock.

The canisters are handled by remote control and with radiation shielding. However, the copper canister in itself is such a good radiation shield that some work can be performed in its vicinity without any additional shielding.

Deposition work is begun when approximately one-fourth of the storage tunnels have been completed. The repository is designed in such a manner that the continued construction work and the simultaneous work with the waste are completely separated from each other.

The repository can be kept open for as long as surveillance is deemed desirable. The tunnels are then filled with a buffer material which consists of a mixture of quartz sand and bentonite. When the entire repository is full and is to be abandoned, shafts and all other spaces are filled with the same buffer material. The buffer material is prepared and packed so that it possesses at least as low permeability as the surrounding rock. Fig. 22 shows such a sealed storage hole.

Geological investigations

The feasibility of a final storage of high-level waste deep underground has been under consideration for some time in various countries. The Geological Survey of Sweden (SGU) has carried out geological investigations on behalf of KBS in order to establish whether Swedish Precambrian bedrock can be used for final storage. The results of these studies were presented in the first KBS report (on reprocessing waste) and are applicable in all essential respects to the final storage of unreprocessed nuclear fuel as well. Since the first report was compiled, however,

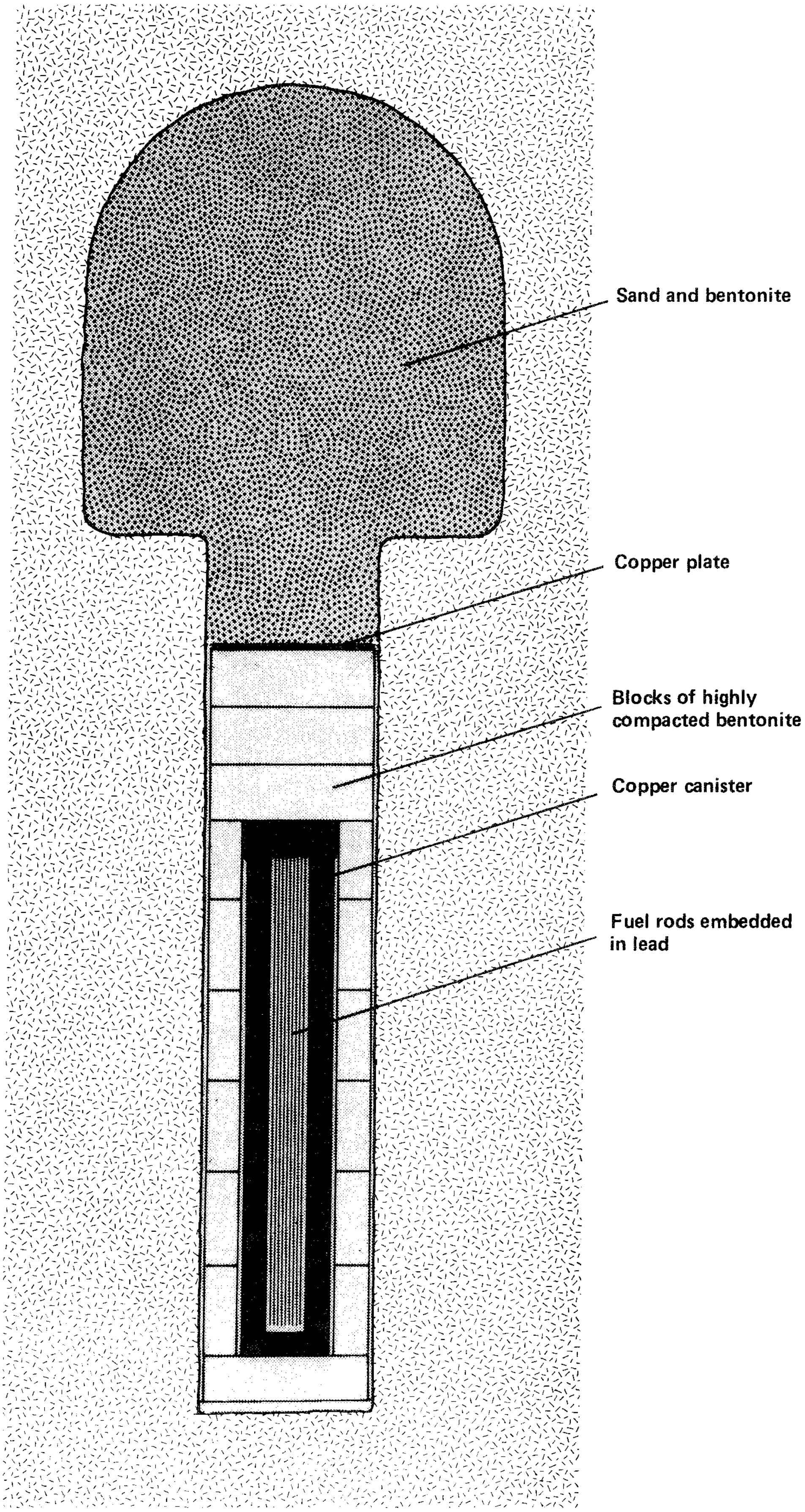


Figure 22. Sealed final repository.

SGU has concluded the investigations, so that the second report is based on more complete data.

The surveys have been aimed at determining what conditions with respect to the bedrock and the groundwater are decisive for long-term safety if a storage facility is built in Swedish bedrock. Which type of rock is most suitable? Is the rock formation of sufficient extent, both horizontally and vertically? Are there any fracture or crush zones which could jeopardize safety? What is the chemical composition of the groundwater? What is the water flow rate? How does the groundwater reach the surface and how diluted does it become along the way? What is the capacity of the bedrock to retain certain waste substances if they should get out into the groundwater?

Test drillings have been undertaken at five sites, three of which have been selected for closer study. In addition, geological and rock mechanical tests have been performed in the abandoned Stripa Mine. The locations of the studied sites are shown in Fig. 23.

The investigations at Karlshamn, Finnsjön and Kråkemåla show that all three sites possess the fundamental prerequisites for a safe rock repository for high-level waste or spent fuel. But it should be emphasized that the work has not been aimed at finding a suitable site to be proposed for the location of a future rock repo-

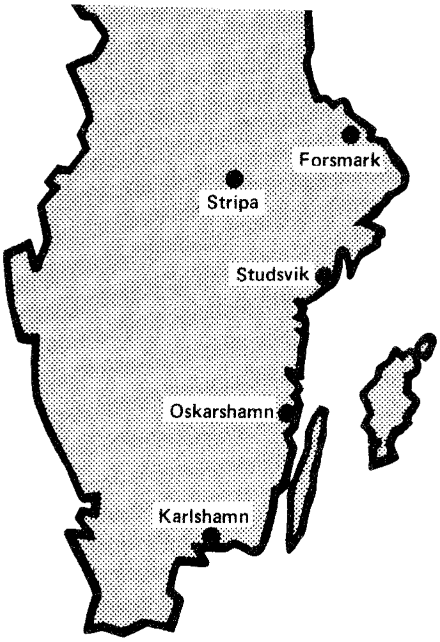


Figure 23. Map of KBS study areas. Test drillings down to a depth of about 500 metres have been undertaken at Karlshamn (Sternö), north of Oskarshamn (Kråkemåla) and at Forsmark (Finnsjön). The KBS experimental station is located at Stripa. Field experiments have been conducted at Studsvik.

sitory - the geological investigations comprise one phase of the work aimed at satisfying the requirements of the Stipulation Law to show where a safe final repository can be situated. The chosen areas are therefore only examples of such sites.

SOME RESULTS FROM THE GEOLOGY PROGRAM

A survey of the history and evolution of the bedrock in Sweden shows that the Precambrian crystalline bedrock has constituted a markedly stable unit in the geology of Europe for more than 600 million years. Moreover, during the past 25 million years, the trend has been towards increasing stability. There is therefore virtually no possibility that such widespread rock movements could occur that the safety of a rock repository located at a depth of several hundred metres could be jeopardized.

The possibility of local fracture movements in the bedrock cannot be excluded, but they will not lead to any significant changes in the permeability of the bedrock or damage to the waste canisters.

Over the past two million years, Sweden has been subjected to 10-20 glaciations. These have not lead to any fracturing of the bedrock at great depth. A future ice age cannot differ radically from the previous ones in this respect.

Even severe earthquakes have had very limited effects on tunnels and rock caverns. Only weak earth tremors occur in Sweden. Their effect on a deep-lying rock repository would be completely negligible.

Completed rock caverns as large as the proposed final repository already exist in Sweden. In many cases, measurements in these rock caverns show remarkably low water infiltration and good rock stability. Many of the rock caverns have been heated to temperatures equal to those which have been calculated for a final repository for high-level waste without any adverse effects.

The groundwater flow pattern is characterized by downward flow at groundwater divides and upward flow under valleys. In between, the groundwater flow is predominantly horizontal. Since both topography and bedrock permeability are largely determined by the structure of the bedrock, the groundwater flow pattern will persist for a very long time.

The groundwater flow time has been calculated by means of a three-dimensional model over an area of 30 km^2 around the study area at Finnsjön. The calculations show that a rock repository at a depth of 500 metres can be located here in such a manner that the flow time of the groundwater from the edges of the repository to the surface of the ground is more than 3 000 years. The flow time for the study area at Karlshamn for groundwater from a depth of 500 metres to the surface is probably hundreds of thousands of years.

Studies of uranium ores have shown that uranium and its decay products are not despersed by the groundwater under oxygen-free conditions.

Measurements of oxygen content and other parameters of Swedish groundwater from great depths show that the water is virtually oxygen-free. The groundwater therefore lacks the ability to dissolve and disperse uranium to any appreciable extent, even if it should come into direct contact with spent fuel in a final repository.

Dispersal of radioactive elements

Radioactive elements from the spent nuclear fuel must pass through a number of barriers in order to reach the surface of the ground and living organisms. In order for this to occur, the following events must take place:

- The copper canister must be broken down or destroyed by corrosion. The same applies to the lead and the zirconium surrounding the fuel pellets.
- The uranium dioxide pellets must be dissolved in the groundwater.
- The bentonite buffer must be penetrated by the radioacitve elements.
- The groundwater must transport the radioactive elements through the bedrock to the surface of the ground.

The different barriers (see Fig. 24) retain the radioactive elements in the final repository and the bedrock until most have decayed and become harmless.

The copper canister comprises a highly durable barrier against the dispersal of radioactive elements from the fuel. The canister also acts as a radiation shield, facilitating handling and preventing radiolysis (chemical breakdown due to irradiation) of the groundwater outside the canister.

The copper canister can be destroyed either by mechanical stresses which breaks it or by corrosion. However, the mechanical strength of the canister is so great that movements in the bedrock and uneven pressure distribution in the buffer material shall not be able to cause it to fail.

Copper is highly resistant to corrosion. Calculations show that less than 60 kg copper per canister can be

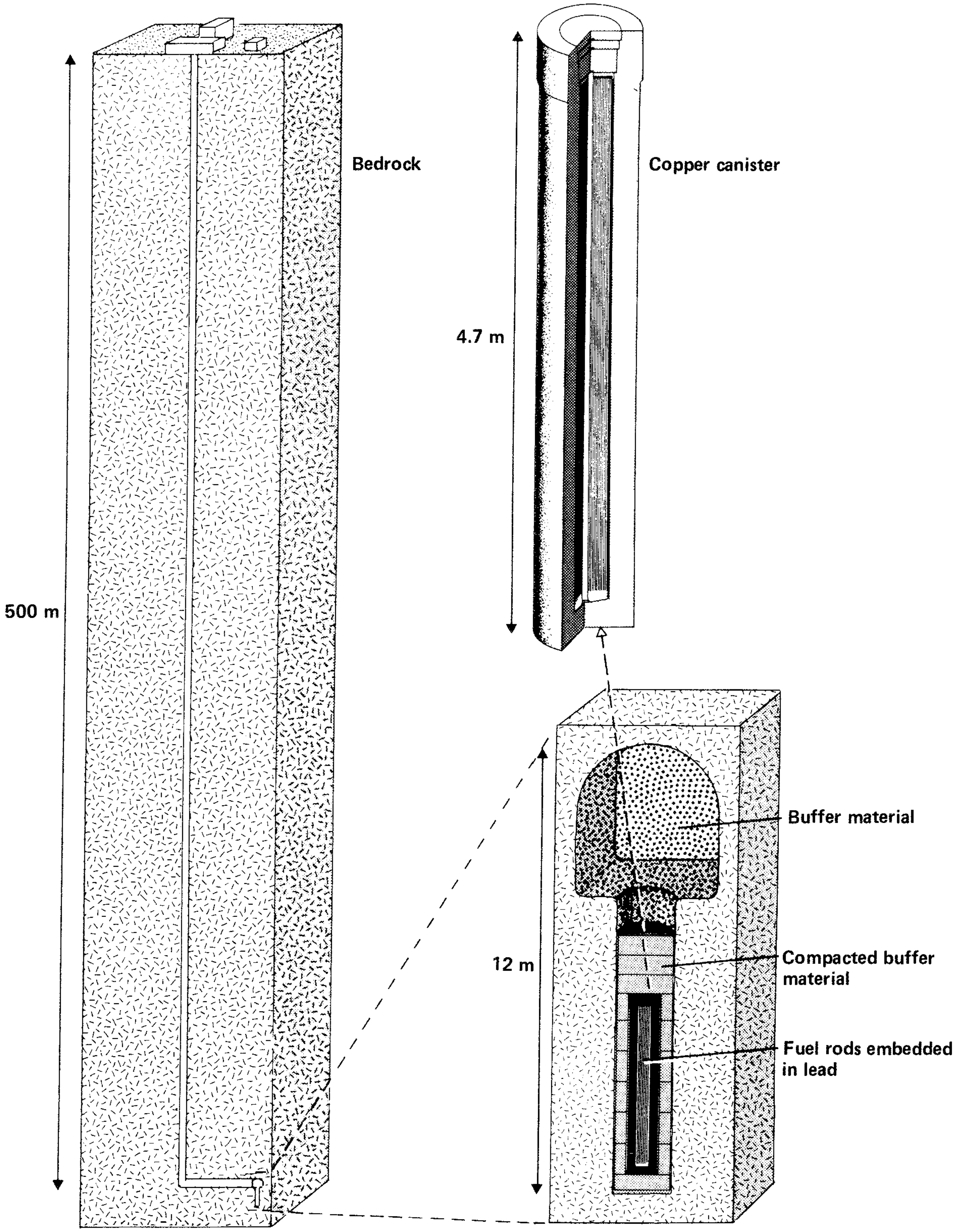


Figure 24. Schematic diagram of the proposed final repository. A number of barriers prevent and retard the dispersal of radioactive elements from the waste.

corroded away over a period of one million years. This corresponds to a layer 0.5 mm thick. Nor is copper subject to severe pitting - the maximum depth of penetration after one million years is estimated to be 60 mm. The canister wall is 200 mm thick.

The quantity of copper which would be required to manyfacture the waste canisters is very small in comparison to the total copper consumption in Sweden.

The uranium dioxide pellets are a ceramic material and therefore dissolve very slowly in water. Studies show that even if very unfavourable assumptions are made, it would take more than one million years for the uranium dioxide in the canister to be dissolved completely.

The water which - if and when the copper canister is penetrated - comes into contact with the pellets flows at a very slow rate and will therefore be saturated with dissolved substances, further retarding dissolution. Of the elements which have been studied, cesium is leached most rapidly, plutonium and other transuranium elements most slowly. However, cesium and many other elements have lives which are considerably shorter than the life of the copper canister and will therefore not be able to disperse.

Bentonite is a naturally occurring clay mineral which is formed from volcanic ash. Bentonite is used in foundry and oil-drilling technology. Blocks made of highly compacted bentonite will be used in the storage holes. The quantities which are required for final storage constitute a small portion of world production.

The permeability of the compacted bentonite is so low that the material is virtually impenetrable by water. The transport of ions through the bentonite can therefore only take place by diffusion (mixture due to molecular movement between different substances).

Bentonite is an ion-exchanger, i.e. the positively charged ions in the clay are replaced by other positive ions. Most of the radioactive elements which diffuse through the clay will therefore be greatly retarded.

When the final repository has been sealed, the original groundwater conditions will eventually be restored. Water will then penetrate into and be absorbed slowly by the bentonite. It is estimated that this process will take hundreds of years. Owing to the very low water flow rate, a maximum of a litre or so of water per year will come into contact with each canister.

Many of the most important radioactive elements are retarded so much that one-millionth or less of the original radioactivity is left after they have passed through the bentonite. Uranium takes a couple of million years to pass through the bentonite buffer.

The bedrock at a depth of 500 metres is very impervious, even though there may be local fracture zones. Measurements and calculations show that the water flow in the rock is less than 0.2 litre per year and m^2. The radioactive elements which could possibly come into contact with the groundwater in a very distant future will be transported by the water in the fissures in the bedrock. Most of the elements migrate much more slowly than the water owing to the fact that they react with the surfaces of the fissures. As a result, positively charged ions will be retarded considerably and it will take up to thousands of times longer for the ion to migrate up through the rock than for the water.

During transport, the radioactive elements will decay and certain new ones will form. Radium, for example, is formed from uranium. The total quantity of radioactive elements gradually declines.

Some hydrophilic elements, such as iodine, are not retarded. They reach the surface of the ground as fast as the water, but are diluted greatly along the way. After 100 000 years, measureable but harmless levels of iodine may have reached living organisms.

Safety in connection with handling

Transports of spent fuel and other radioactive material are already being done today, and experience shows that safe transports can be carried out without any great difficulties. During transport, the special transport cask constitutes a safe containment.

In the safety analysis carried out in the first KBS report, it was found that the worst accident which could conceivably occur is that the ship carrying the spent fuel collides and is then ravished by fire. The probability of such an accident is extremely low (approximately one in 300 000 years). Even in the event of such a severe accident, little radioactivity would be released.

The proposed handling chain includes storage in water pools for about 40 years. Many years of experience have been gained with such storage. Neither corrosion nor material defects have occurred to any significant extent.

Small quantities of radioactive elements can be released from damaged fuel rods during storage. Most of this leakage takes place during storage at the reactor, where the radioactive elements are disposed of by the cleaning system. Similar systems will be provided for cleaning and decontamination at a central fuel storage facility.

Encapsulation involves certain operations which must be given special consideration in order to ensure absolutely safe handling. But considerable experience has been gained in Sweden with the handling of spent nuclear fuel. Radiation doses to personnel in the encapsulation station are kept low by remote control of all fuel handling, either under water or in radiation-shielded cells. Special cleaning systems prevent dispersal of radioactive elements to the environment.

Analyses of accidents which could conceivably occur despite all precautions show that such accidents would result in only a very small release of radioactive elements. Damage caused by external forces such as sabotage and acts of war has also been analyzed.

The final repository is located at great depth. This imposes special requirements on occupational safety. Assessments of occupational safety in connection with work in the final repository are based on experiences gained from rock caverns and mines.

The radiation from the copper canister is no higher than the radiation involved in similar routine work which is carried out today under good radiation protection conditions.

Safety in connection with final storage

The radioactive elements in the spent nuclear fuel must be kept isolated from living organisms for a very long period of time. The final repository must therefore be located and designed in such a manner that it is protected against:

- Far-reaching natural changes (rock movements, ice ages, meteorite impacts).
- Human activities (war, sabotage, mining works).
- Slow degradation of the canister and transport of radioactive substances to the ground surface.

Rock movements could conceivably damage the canisters. However, the properties of the canister and the buffer material permit movements of a few centimetres to occur without the integrity of the canister being affected. The earthquakes which could conceivably occur in Sweden would not lead to any significant displacements.

During the most recent two million years, Sweden has experienced 10-20 ice ages. They have not led to any continuous fracturing of the bedrock at greath depth. It is therefore considered impossible that a new glaciation could affect the final repository.

If a meteorite should hit the surface of the earth directly above a final repository, a crater would be created which could weaken the rock cover or, at worst, destroy it completely. Studies of meteorite impacts which have occurred over a period of 2 000 million years show that the probability of a meteorite impact which would create a crater approximately 100 m deep over a surface area as large as the final repository (1 km^2) is around 1 in 10 trillions per year. History also confirms the assumption that a meteorite impact is not a risk which need be considered in this context.

Of all possible acts of war, only large nuclear detonations could affect a sealed repository. Ground detonations of nuclear devices of 10-50 megatons create craters in the rock with a depth of 100-200 metres. Thus, the rock is not penetrated, but weakened. However, any release of radioactivity from the final repository would only represent a fraction of the radioactivity caused by the bomb, which would remain in the area for a long period of time. Effective acts of sabotage are impossible after the final repository has been finally sealed and are not considered to constitute any appreciable risk during previous handling either.

It is conceivable that knowledge of the final repository could be lost in a distant future. But there is scarcely any reason for people living at that time to perform mining works at these depths, as the repository is located in our most common rock, which has no valuable minerals. Moreover, if such future people can carry out advanced mining works, they will probably also be capable of detecting and protecting themselves against radioactivity in the final repository.

The slow dispersal of radioactive elements

The spent fuel is surrounded by a number of barriers in the final repository. Each of these barriers provides protection against dispersal. But they possess different properties and thereby different functions which reinforce and complement each other.

The service life of the copper canister is expected to be more than 1 million years. During this time, most of the radioactive elements will disappear. After 1 million years, uranium and its decay products, e.g. radium, will be present in the spent fuel. This means that the consequences of the final storage will be roughly the same as the storage of uranium dioxide which has not been used in any reactor.

If it is assumed that the copper canister has a service life of less than 1 million years, the dispersal of radioactive elements could take place earlier. However, the chemical conditions existing in the final repository are such that it would take millions of years for all of the uranium to be dissolved. In this case as well, the consequences would be equivalent to those of the storage of unused uranium dioxide.

In the assessment of the safety of the final repository, the consequences of various courses of events which are less favourable than those which are most probable have also been studied.

The Swedish Corrosion Institute, which has evaluated the service life of the canisters, is of the opinion that it is realistic to expect that they will last for hundreds of thousands of years. The safety analysis therefore assumes that the first canisters will break down after 100 000 years and then continue to break down at a uniform rate during a period of 400 000 years. Leaching of the fuel has then been assumed to take an additional 500 000 years.

In order for radioactive elements from the final repository to reach living organisms, they must be transported with the groundwater. The groundwater can come into contact with water at the surface of the ground in a number of ways. Three such paths have been studied: a deep-drilled well, a lake and the Baltic Sea. The case which would give rise to the largest radiation dose is the deep-drilled well.

On the basis of these assumptions concerning canister penetration and leaching time, two different hypothetical cases for dispersal of the radioactive elements have been studied. The first, referred to as the "main case", assumes a water flow time from the repo-

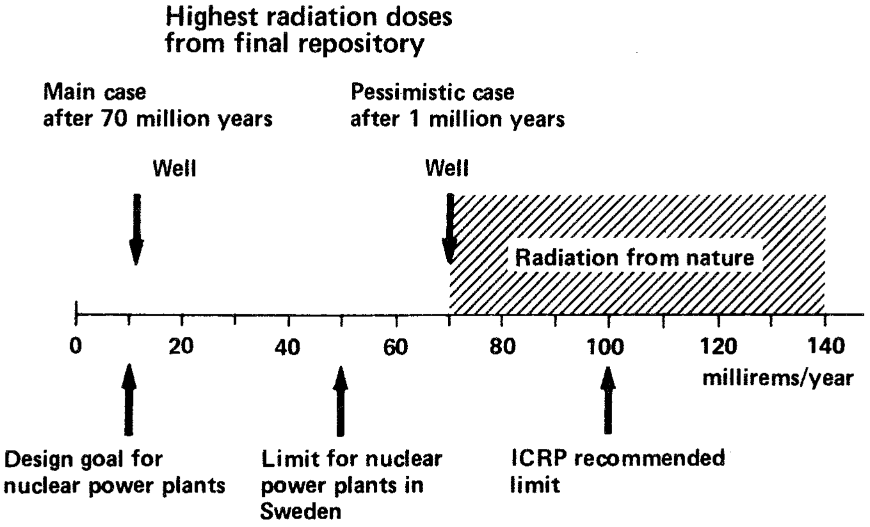


Figure 25. Comparison between different radiation doses and limits. ICRP is the Internaional Commission on Radiological Protection. Natural radiation from the bedrock and the atmosphere varies from place to place and lies within the hatched area in Sweden.

sitory to the surface of 3 000 years in combination with known retention factors. The second case, referred to as the "pessimistic case", assumes a water transit time of 400 years and much lower retention factors.

In both cases, the highest radiation doses to individuals in the "critical group" are calculated (see Fig. 25). The critical group consists of persons who live in the vicinity of the repository and take all of their water from a nearby deep well. This group will probably be relatively small in any case, since the water supply is limited.

RADIATION DOSES TO THE CRITICAL GROUP

Main case

During the period from 100 000 to 1 million years after disposal, when deterioration of the canisters and dissolution of the fuel has been assumed to be in progress, the radiation dose is calculated to be 0.5 millirems per year, which is less than one-hundredth of the natural radiation level. The dose derives mainly from iodine-129, which is not retarded by the rock. The largest doses - which come from radium and uranium - are not expected to appear until after 70 million years, at which time the radiation dose is calculated to be 11 millirems per year, approximately one-tenth of the natural radiation level.

Calculated maximum radiation dose to the critical group

Element	Number of years before element reaches surface	Radiation dose mrems/year
Fission products		
iodine-129	100 000	0.4
cesium-135	1 million	0.007
Heavy elements		
radium	70 million	10
uranium		0.7
protactinium		0.5
thorium		0.2

Pessimistic case

In this case, the radiation doses appear during the period from 100 000 years to around 3 million years after deposition. The maximum radiation dose is calculated to occur after about 1 million years and to amount to about 70 millirems per year.

Radium makes the dominant contribution to the radiation dose in this case as well.

The limit recommended by the International Commission on Radiological Protection for persons who are exposed to radiation over a series of years is 100 millirems per year. Even in the pessimistic case, the calculated radiation doses from the final repository are below this limit. In the main case, the radiation dose is roughly one-tenth of the limit (see Fig. 25).

The copper canister is expected to be free of material defects, but in order to illustrate the consequences of such defects, this case has also been considered. The radiation doses do not occur until after 3 000 years, but one or a few damaged canisters do not change the overall picture.

It is proposed that radioactive metal components from the fuel assemblies be stored in concrete moulds in a separate repository at a depth of 300 metres. This waste mainly contains radioactive elements which are so short-lived that they decay in the repository. The calculated maximum radiation dose from those elements which remain would, in the most unfavourable case, be equivalent to one-hundredth of the natural radiation.

The possibility that a self-sustaining chain reaction - of the samt type as occurs in the reactor - could be initiated in the final repository is virtually nil. Even if such a reaction should nevertheless occur, its consequences are expected to be insignificant.

The health hazards resulting from a dispersal of radioactivity from the repository are extremely low, even in the most unfavourable cases. This applies to both nearby residents and the rest of the population for all future time. Assuming the usual relationship between radiation dose and health effect, the calculated radiation doses in the main case would give rise to a maximum of two cancer cases among the entire world population during the period of 500 years when the highest doses occur. The number of genetic defects would be no more than one-tenth of a case during the same period.

Time perspective

The time spans discussed here are of such an order of magnitude that they are scarcely conceivable in our

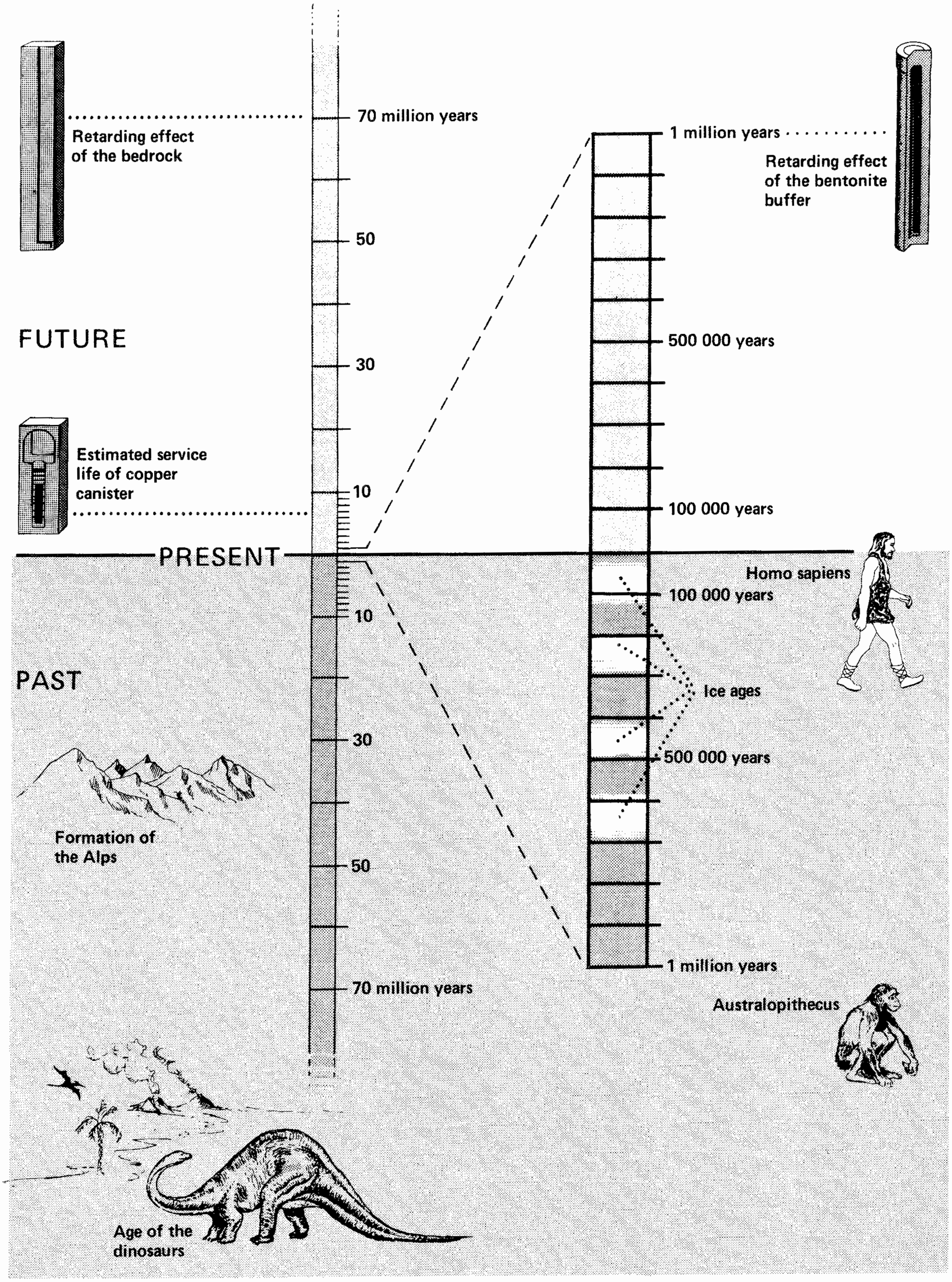


Figure 26. Comparison between time spans for barrier durability and the same time spans backwards into the past.

normal frames of reference. A better overview of the situation may be obtained by considering the future sequences of events divided into different phases.

During the phase extending <u>several thousand years</u> into the future, the copper canisters will remain completely intact, with the possible exception of a few isolated canisters which were defective from the start. Leakage from these canisters gives rise to completely negligible radiation doses. During this phase, the final repository can therefore be regarded as being "absolutely safe", regardless of how this concept is defined.

For the phase extending <u>several thousand years to several hundreds of thousands of years in the future</u>, the calculations show that there is no chance of any dispersal of radioactive substances to living organisms. During this phase as well, it can therefore be stated with certainty that the final repository meets the requirements of being "absolutely safe".

During the phase extending from <u>several hundreds of thousands of years onward</u>, a number of radioactive elements may spread to living organisms. The radiation dose increment after approximately 1 million years is lower than the variation in the doses deriving from natural radiation sources. In the time perspective of millions of years, it does not appear to be meaningful or reasonable to discuss the impact of a final repository in relation to present-day standards. Nor has any attempt at such an evaluation been made within other areas of human endeavour which could have long-term environmental impact. The impact of radiation on living organisms will be dominated by natural background radiation. In comparison, the impact of the final repository would be small locally and negligible globally.