AN UNDER GROUND REPOSITORY FOR RADIOACTIVE WASTE IN SWEDEN

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ABSTRACT

The Swedish final repository for radioactive waste, SFR, is now being commissioned and the first waste is planned to be emplaced there in April 1988. It is a repository built in the bedrock under the Baltic Sea and located close to Forsmark nuclear power plant. Geological surveys have been carried out at repeated intervals to provide data for characterization of the host rock and the hydraulic conditions in the repository area. SFR has been situated under the sea in order to minimize the groundwater flow in the repository area. Engineered barriers have been used to further reduce of the groundwater flow inside the caverns and through the waste after closure and sealing. Assessment of post-closure safety indicates that the radiological impact on the environment will be practically nil.

Measures have been taken to minimize the exposure of personnel during the operating period by the use of biological shields and remote controlled handling of the waste. Safety assessments show that radiological risks during the operational phase are very low.

NATIONAL POLICY FOR LLW AND ILW IN SWEDEN

Short lived LLW and ILW from operation of the Swedish reactors will be disposed of in a central repository (called SFR), along with similar types of radioactive wastes from other industries, research and medical activities. LLW with a very low activity content (below 300 kBq/kg) will be disposed of at some of the reactor sites by means of shallow land burial.

Disposal volume in SFR is required for 90,000 m^3 of waste packages. This is the estimated amount of operating LLW and ILW produced in Sweden up to the year 2010, when the nuclear power plants are planned to be decommissioned. SFR can be extended with caverns for decommissioning waste in the future, but this is not covered by the present license.

According to Swedish law, primary responsibility for safe management and final disposal of the radioactive waste lies with the owners of nuclear utilities. This responsibility also includes financing of the total costs.

The four power utilities in Sweden producing electricity in nuclear power plants are joint owners of SKB, the Swedish Nuclear Fuel and Waste Management Co. SKB's functions are to plan, build, own and operate systems and facilities for the transport and disposal of spent nuclear fuel and radioactive waste. SKB's work in this field is overseen mainly by the Swedish Nuclear Power Inspectorate, SKI, and the National Institute of Radiation Protection, SSI.

The regulatory authorities in Sweden have not issued any specific regulations governing the design of a repository for radioactive waste. They have instead reviewed a preliminary safety report prepared by SKB based on a preliminary design of the repository. Based on this report, the authorities recommended the Government issue a license to construct and operate a repository with specified requirements. One requirement was that a final safety report should be presented by SKB and approved before deposition of the first waste. This report is now being reviewed by SKI and SSI.

SITING AND DESIGN OF THE REPOSITORY

Site Selection

Based on consideration of the geological and hydrological conditions in Sweden, it was early decided that the repository should be located underground in rock caverns. Another primary requirement was that it should be located adjacent to one of the five nuclear facilities: Barsebäck, Forsmark, Oskarshamn, Ringhals or Studsvik (the research center).

These sites were evaluated on the basis of available geological data and other information of importance for site selection. This work showed that the bedrock was better at the sites in eastern Sweden. The next phase of geological surveys was therefore carried out at Forsmark, Oskarshamn and Studsvik. Different locations of the repository on the sites were also considered during this phase. The surveys included geophysical tests and geological mapping of the area.

Geological and hydrogeological conditions at both Forsmark and Oskarshamn were found to be suitable for siting of the planned type of underground repository. When all factors, technical and economical, were estimated Forsmark came out as the best choice. A program for more detailed geological surveys was then conducted as a base for the preliminary design and the safety analyses

Repository Design

The repository is located near the Forsmark nuclear power plant on the Baltic Sea on the east cost of Sweden. Two 1 km long access tunnels head from the harbour area down and out to the repository under the sea. 60 m of rock covers the repository caverns under the seabed (see Fig. 1).

The first construction phase, which has now been completed, includes buildings on the surface, tunnels, operations buildings and rock caverns for 60,000 m^3 of waste. A second phase for an additional 30,000 m^3 of waste is planned to be built and commissioned around the year 2000.

As mentioned above the concept for SFR is based on consideration of geological and hydrogeological conditions in Sweden. There are many areas with good bedrock for the excavation of rock caverns at a reasonable cost. But the rock mass almost everywhere is saturated with groundwater. A repository in the Swedish bedrock therefore had to be a "wet repository" (Fig. 1).

In order to minimize the groundwater flow in the repository area, SFR has been situated under the sea. The hydraulic gradients there are very small due to the fact that the sea acts as an equalizer on the hydraulic regima in the rock below. The undersea location also ensures that no well will be drilled in the vicinity of the repository for at least 1, 000 years while the area is covered by the sea (the rate of land uplift is at present 6 mm/y). The brackish seawater also provides a good recipient with a high dilution capacity.

Various types of caverns

There are different caverns for ILW and LLW in SFR. The ILW packages containing most of the activity will be disposed of in a silo structure. This cavern is 70 m high and 30 m in diameter. Inside is a 50 m high concrete silo surrounded with a buffer material. Bentonite is used to give a low permeability. A compacted mixture of sand and bentonite (90/10) is used at top and bottom and granulated pure bentonite is used for the fill around the silo. The waste packages are subsequently grouted in with concrete in the cells inside the silo.

LLW and ILW containing a smaller portion of the activity content will be disposed of in 160 m long caverns with various cross selections . Three types of caverns are used. The cavern with the largest cross section is equipped with machines for remote controlled handling, similar to those used in the silo. The waste is deposited in a concrete structure, and finally a concrete cap is cast over the waste (Fig. 2).

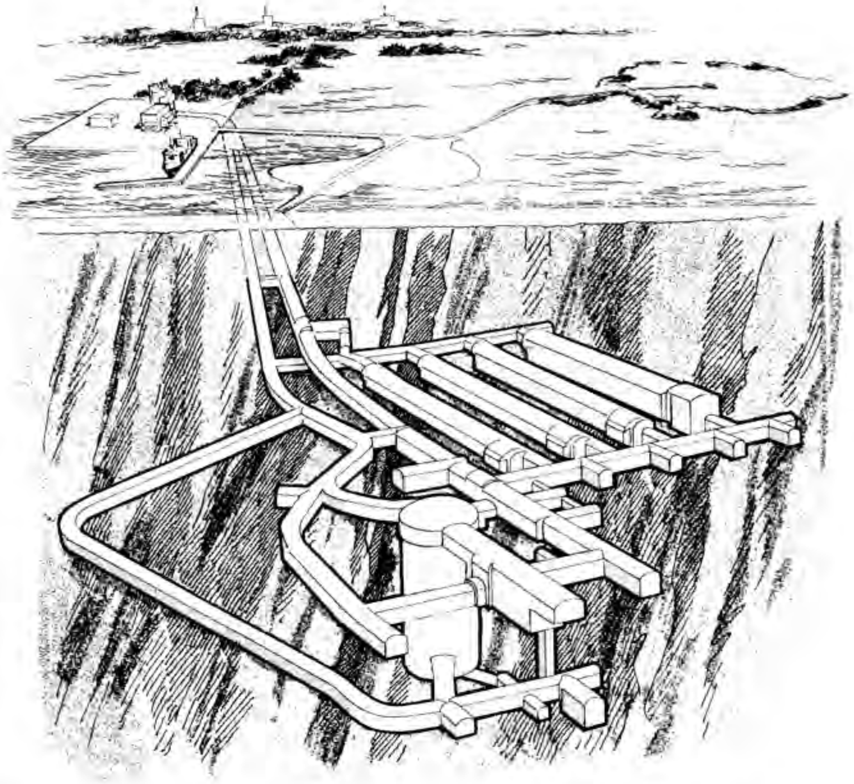

Fig. 1. General Plan of the Repository with Tunnels and Caverns Built During the First Construction Phase.

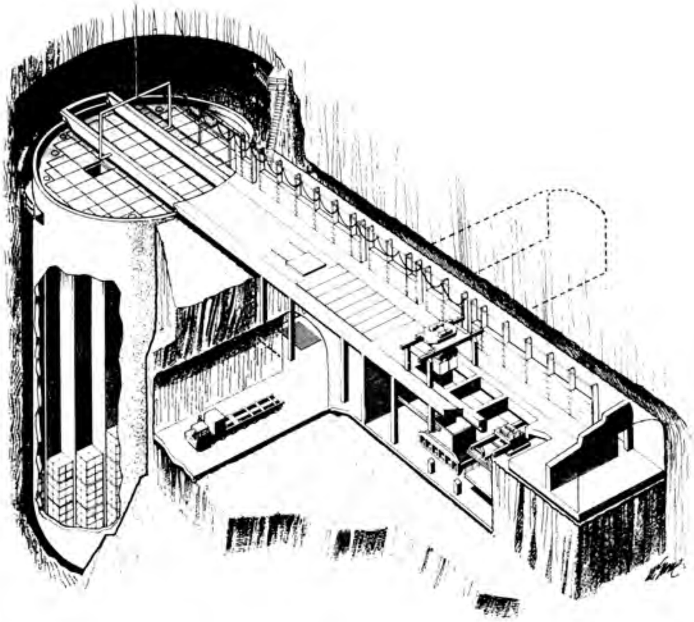

Fig. 2. Silo Repository With Remote Controlled Handling of ILW.

Fig. 3. Rock Cavern With the Forklift Truck Handling Containers for LLW..

LLW is handled with an ordinary fork lift truck in one of the caverns, Fig. 3. The waste is deposited in standard freight containers, which also are used for transport to SFR. This cavern will be sealed without any backfill inside. The third type of cavern is mainly intended for special concrete tanks with dewatered ion exchange resins. Backfilling with concrete and sand will be carried out when the cavern is sealed.

OPERATING PERIOD

SFR is planned to be operative from 1988 to 2013 for the receipt of operating waste (90,000 m^3). SKB has contracted the Swedish State Power Board for on-site operation and maintenance. A staff of 20 persons is stationed on the site today and they are participating in the commissioning of the repository.

Waste packages and transport

All wastes are conditioned at the reactor plants before transport to SFR. The waste consists for the most part of ion-exchange resins and filter materials from different water treatment systems. This waste contains most of the activity and is normally solidified in cement or bitumen. Cement solidification is done in concrete moulds (1.2 m on a side). Bitumen solidification is done in standard 200 l drums. Low-level resins from the condensate clean-up system are merely dewatered and stored in large transportable concrete tanks.

These types of ILW are transported to SFR in shielded containers. The gross weight of the container is limited to 120 Mg. A specially designed ship (M/S Sigyn) is used for transport from the utilities to SFR. Loading and unloading is done with terminal vehicles. LLW is transported in standard freight containers, which are also deposited in the repository.

Operation of SFR

Measures have been taken to minimize the exposure of personnel by the use of biological shields and remote-controlled handling of the waste. The conservatively calculated dose from routine operation is 25 mmanSv/y. The terminal vehicle can be operated by remote control during the transport of containers in the tunnels. Unloading of ILW packages is done with remote-controlled machines or a forklift truck with a shielded cab for the driver (see Fig. 4).

Since all waste is conditioned in its package the risk of airborne activity is practically nil. The main occupational hazard during the operating period is associated with radon from the host rock. The ventilation system is designed to supply enough air to meet hygienic limits. The risk of a fire is generally very low. Vehicles and electrical equipment can, cause a fire, but the probability of a fire in the waste is considered to be extremely low. In order to reduce the consequences of a fire, the repository is divided into several fire zones, and water sprinklers are installed in some areas. Groundwater seeping into tunnels and caverns (700 l/min) is collected in a drainage system and pumped directly to the sea. This groundwater will not come into contact with the waste and can therefore not be contaminated during the operating period.

ASSESSMENT OF POST-CLOSURE SAFETY

SFR has been designed to permit a simple and controllable as well as a safe disposal of the radioactive waste. It is intended to ensure isolation of the waste from the biosphere so that radiation in the immediate vicinity does not exceed the design dose limit, 0.1 mSv/y. Safety during the post-closure stage will not be dependent on supervision and corrective measures. Safety assessments have been performed for a fully expanded repository for operating waste, SFR-1 (90,000 m^3 with a total activity content of 10^{16} Bq).

After the operating waste has been deposited, the repository will be closed and sealed. According to current plans this will take place at the earliest in 2013, but in the safety assessment it is assumed to take place in 2010.

When the repository is sealed pumping will be interrupted and the repository filled with water. Depending on the waste unit and the manner of deposition in various caverns, the dissolved non-sorbing isotopes may be transported to the groundwater by diffusion or flow. The extent of this transport is determined by the design of the repository and by the groundwater flow in the surrounding rock. The waste packages are designed and emplaced in various caverns in such manner as to prevent the waste from destroying the repository barriers, for example by swelling or production of gases.

The safety assessment is performed for two time periods. The first covers the time during which the seabed above SFR is still covered by the brackish water of the Baltic Sea, the Salt Water Period. The second covers the time after the drying out of the seabed and after the formation of a freshwater-based ecological system, the Inland Period.

The Inland Period is assumed to commence 2,500 years after sealing. Only then will sufficient land uplift have occurred to permit the formation of permanent lakes and shore sediments so that a freshwater ecology will be established at the depth needed for drinking water wells. During this period, the ground surface above SFR will form a recharge and the groundwater will reach the biosphere in a small lake situated approximately 1 km from SFR.

Water flows in the bedrock have been calculated using methods to ensure that they are not underestimated. Two regional 3-D groundwater models have been utilized for the analyses. Model 1 is based on the potential differences between the groundwater level on land and the sealevel. Model 2 has been constructed to take into account a single

Fig. 4. Unloading of Transport Containers From M/S Sigyn to the Terminal Building at SFR.

test result from a borehole with pressurized groundwater. This model yields water flows of between 0.2 and 0.5 l/m^2y, which have been used as boundary conditions for the local flow model.

It has been assumed that the direction of flow is in the least favorable direction, i.e. directly upwards towards the seabed and that the groundwater flow takes place in a strongly channelized form. As a result sorption in the surrounding rock could not be taken into account in the safety assessments at this stage. It has therefore been assumed for the various caverns and for all calculated cases that the radioisotopes leaking into the surrounding bedrock are transported without delay to the biosphere.

The Salt Water Period

Reference cases and variations for the different parts of the repository have been presented in the final safety report for the Salt Water Period

Some examples of data used for the technical barriers are given in Table I.

Rock cavern for LLW (BLA) All the radioisotopes are assumed to be dissolved in the water volume available in the repository and released to the groundwater at the same rate as the water is replaced in the rock cavern. It is assumed that no sorption takes place in the repository.

Rock cavern for concrete tanks (BTF) During the initial period, only those isotopes that have diffused through the concrete will be able to reach the biosphere. After 100 years, there is a possibility that the concrete may be degraded. Groundwater-flow will then constitute the essential transport mechanism. It is then assumed that the flow will carry the radioisotopes to the free water volume surrounding the waste in the rock cavern. It is further assumed that the isotopes will be transported from the cavern at the same rate as the water is replaced inside.

A variation analysis has been performed for the case where the isotopes released by flow are not mixed into the water volume of the rock cavern but are carried up directly to the biosphere via cracks in the concrete and subsequently via channels in the rock. The release of isotopes would then increase by a factor of about 30. Due to the fact that the solidated block of wastes rests on a macadam base and there is permeable material in the gaps between the waste and the walls of the rock cavern, this case is considered to be unlikely.

Rock cavern for ILW (BMA) The radioactive waste packages in this cavern consist mainly of ion-exchange resins solidified in cement or bitumen. The waste packages are placed in cells in a large concrete structure. The radioisotopes are assumed to be dissolved in the water in the concrete cells and in a state of equilibrium with the isotopes absorbed into the concrete. Some cracks may form in the walls of the concrete cells. It is therefore assumed that a transport out to the coherent water volume in the rock cavern will take place through flow.

A number of variation analyses have been performed. Because the concrete cells are surrounded by permeable

TABLE I

Some Examples of Data Used for the Technical Barriers in the Safety Analyses

		Concrete		Pure Bentonite	
		Fresh	Degraded	Fresh	Degraded
Hydraulic conducivity,	(m/s)	10^{-11}	10^{-7}	10^{-10}	
Effective diffusivity,	(m^2/s)	$3\cdot10^{-12}$	10^{-10}	10^{-10}	
Pore diffusivity,	(m^2/s)	$2\cdot10^{-11}$	$5\cdot10^{-10}$	$1.6\cdot10^{-10}$	
Distribution coefficients,					
C	(m^3/kg)	1	0	0	
Fe, Ni, Co	(m^3/kg)	0.5	0.001	0.2	
Cs	(m^3/kg)	0.001		0.2	0.005
Pu	(m^3/kg)	1	0.3	1	0.5

material, it is more probable that the main transport from the cells will take place via diffusion and not flow. In that case the dose would be reduced by a factor of 10. If cracks in the waste cells were in direct contact with water-bearing cracks in the rock, the rate of release could be increased by a factor of 40. Due to the design of the repository, this case is considered to be unlikely.

The Silo repository During the time period discussed in this section it is assumed that all radioisotope transport is governed by diffusion. No limits of solubility have been applied except a Kd-governed sorption. As for the conventional caverns, a water flow is assumed to carry the isotopes to the biosphere without delay. Most of the transport takes place through the top of the silo. There is some risk of gas production in the silo-repository, mainly by anaerobic corrosion of steel. The silo has therefore been designed so that gas can be led off without water being expelled.

The estimated total dose commitment for individuals in the most exposed group from all parts of the repository for this period is shown in Fig 5. The dominant isotope is Cs 137.

The Inland Period

In calculating radioactive releases during this period, it has been conservatively assumed that all radioisotopes that have not decayed remain in the repository and constitute a maximum source term for the estimates of the consequences. Furthermore it is assumed that the water flow in the rock has increased by a factor of 10 compared with conditions during the Salt Water Period, due to the new gradients resulting from the land uplift. The direction of the groundwater flow around the repository has been changed from an upward direction to a flow parallel to the ground surface to the recipient lake.

Simultaneously with these changes, the concrete undergoes gradual degradation. The sorptive properties of the concrete have been assumed to deteriorate to such an extent during this period that the concrete only absorbs in a manner corresponding to that of the original pure aggregate material. For the silo repository it is furthermore assumed that the bentonite has degraded so that the main release takes place in the form of flow through the silo structure.

The leakage of radioisotopes from all parts of the repository is assumed to take place with the groundwater to the nearest freshwater recipient. This has been assumed to be a lake 1 km away in the direction of the groundwater flow. It is assumed that there is a small farm that uses the lake for fishing and irrigation. The inhabitants of the farm take their drinking water from a well located in an area that receives the groundwater flow from the repository area. The estimated total dose commitment for individuals in the critical group is shown in Fig. 6. The dominating isotope is C 14 for the first period up to 3,000 years, then Pu 239. The dose calculations have been carried forward as far as to 100,000 years after sealing to show how the values drop. The maximum dose is obtained as a sharp peak of nearly 0.1 mSv/y which drops within a hundred years or so to a more stable level of 0.01 mSv/y.

The initial brief peaks are an effect of the calculation method which assumes that the formation of the lake coincides with two things: first, a 10 times higher groundwater flow than that assumed during the salt water period; second, the sorption properties are assumed to have deteriorated instantly. Apart from the brief peak, the dose situation is dominated by the plutonium isotopes 239 and 240 at a total

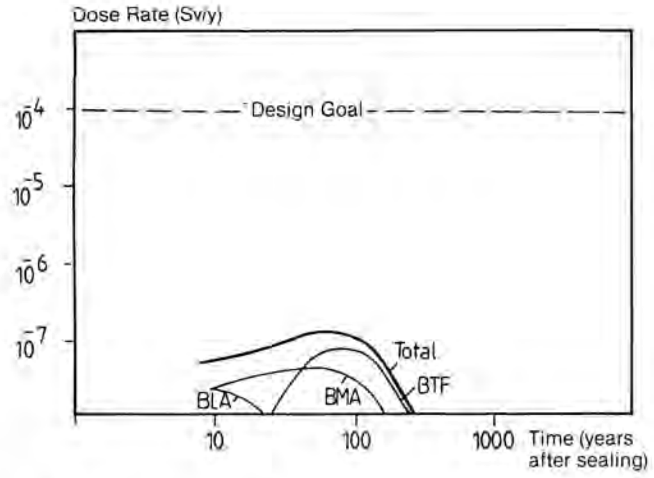

Fig. 5. Calculated Individual Dose During the Salt Water Period, Broken Down Among Different Parts of the Repository.

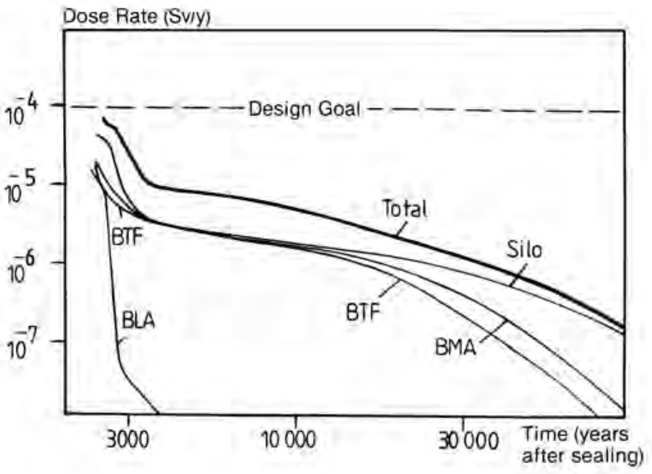

Fig. 6. Calculated Individual Dose Rate During the Inland Period, Broken Down Between Different Parts of the Repository.

level just under 0.01 mSv/y. This declines at the same rate as the decay of plutonium 239.

CONCLUDING REMARKS AND SOME DATA

The information gained from the construction period was very encouraging. The results of the geological surveys corresponded very well with the actual conditions found when the tunnels and caverns were excavated. The host rock proved to be very competent for the purpose. The construction of buildings and concrete stuctures in the repository as well as the manufacture and installation of the various systems have been carried out successfully. The following were milestones in the project:

- PSR and license application, March 1982.
- License granted, start of construction work, June 1983.
- Excavation of tunnels and caverns finished, April 1986.
- Construction and installation work finished, January 1988.
- Total cost of the first phase: SEK 740 million
- Estimated cost of the second construction phase, 25 years of operation and sealing (at 1987 price level) is: SEK 660 million.

SFR has been designed to provide a safe final disposal of short lived LLW and ILW. The design is based on the geological and hydrological conditions in Sweden. The safety assessments have been performed to determine the safety of the repository in relation to the criteria applied by the Swedish authorities. Data and analytical methods have been selected so that the environmental impact of the repository will not be underestimated.

The safety assessments show that the dose commitment to individuals in the most affected group during the Salt Water Period is very low. The dose will fall short of current design goals for other plants in the nuclear power cycle by a good margin, 0.1 mSv/y. Analyses of potential impact on the environment during the Inland Period show that the dose commitment will fall short of the current design goal in this case as well.