Feasibility of Safe Terminal Disposal of Spent Nuclear Fuel

by B. Nilsson and T. Papp

BACKGROUND

During an early period of the nuclear power era the general thinking was that spent nuclear fuel should be reprocessed, thus making the remaining uranium in the fuel available for power production. The plutonium separated from the spent fuel was also assigned a value as breeder reactor fuel. Several concurrent factors have led to a more diversified view, and now it is a seriously discussed option to regard spent nuclear fuel as waste. There is no unanimous opinion internationally as to which of the two options should be preferred: reprocessing and final disposal of the resulting wastes or direct disposal of spent fuel. The choice of approach depends on the answers to the following questions:

- What military, political and health hazards are combined with the separation of pure plutonium?
- What is the potential of breeder technology?
- What developments in the costs of reprocessing and in natural uranium prices are anticipated?
- What is the technical and financial feasibility of safe terminal storage of spent nuclear fuel?

Only the last question will be dealt with in the following.

COMPARISON OF THE OPTIONS

The basic prerequisites for terminal storage of high-level reprocessing waste on one hand and of spent fuel on the other are different mainly because of the substantially greater content of long-lived heavy radionuclides in the spent fuel. Of special importance are neptunium-237, plutonium-239 and -240, americium-241 and -243 and the decay products radium-226 and thorium-229.

Figures 1 and 2 give a general illustration of how a "hazard index" for the two types of waste varies with time. The curves are based on light-water reactor fuel with a burnup of 33 000 thermal megawatt-days/tonne uranium (MWd(th)/(tU), a power density of 34.4 MW(th)/tU and an enrichment of 3.1% uranium-235. Also, the rate of heat generation decays more slowly in spent fuel than in reprocessing waste as shown in Figure 3.

It is obvious then that safe disposal of spent fuel requires more extensive measures than the disposal of high-level reprocessing waste.

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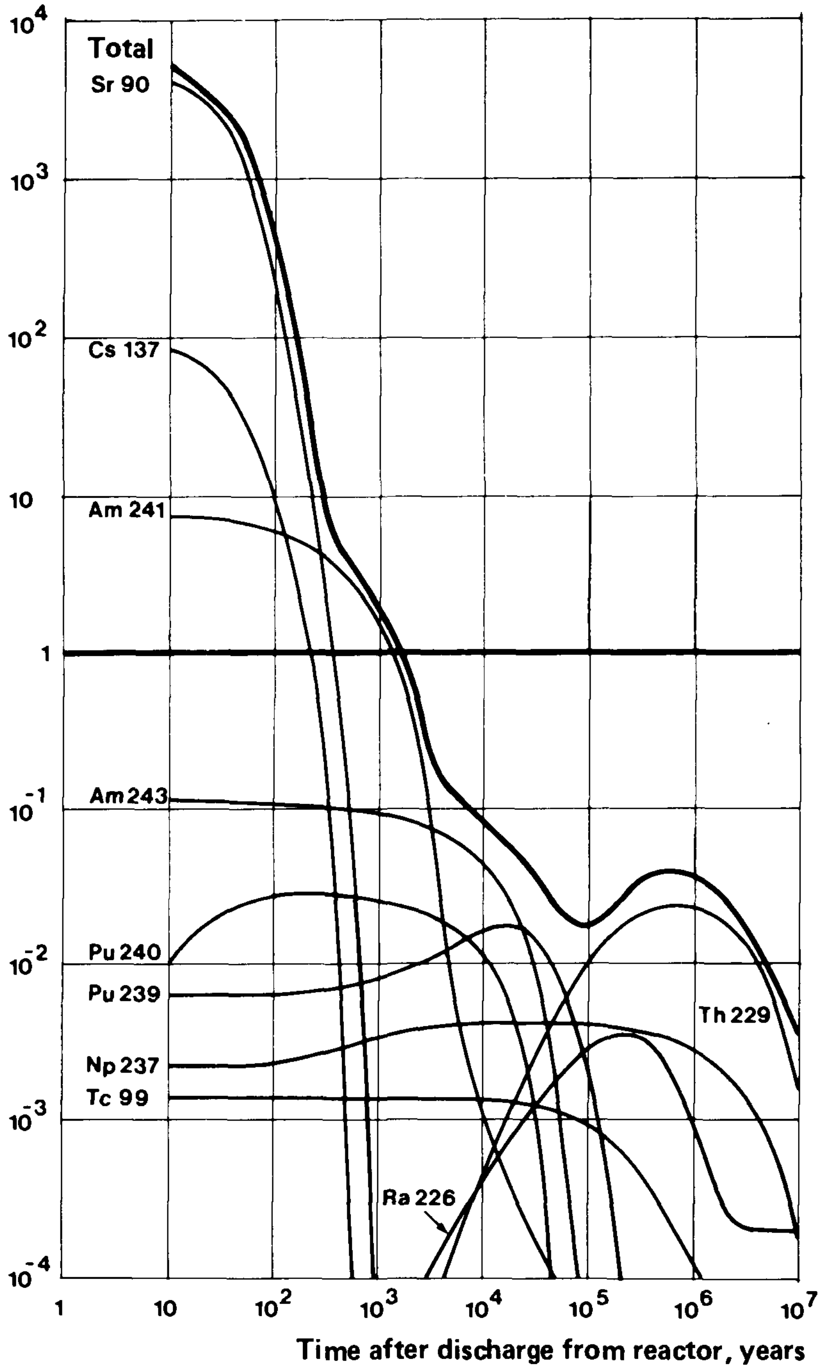

Figure 1. Potential hazard index for different nuclides in high-level waste from 1 ton of spent fuel.

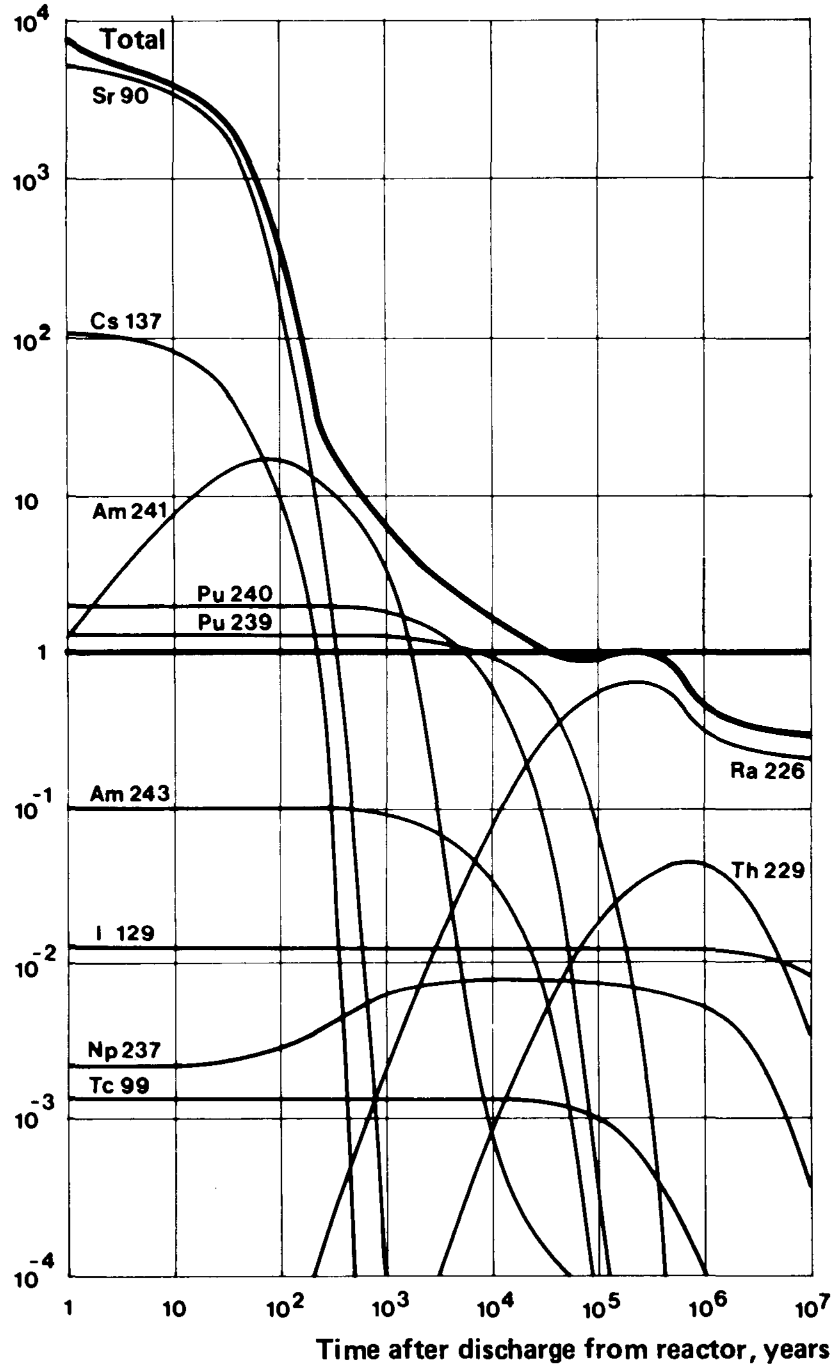

Figure 2. Potential hazard index for different nuclides in 1 ton of spent fuel.

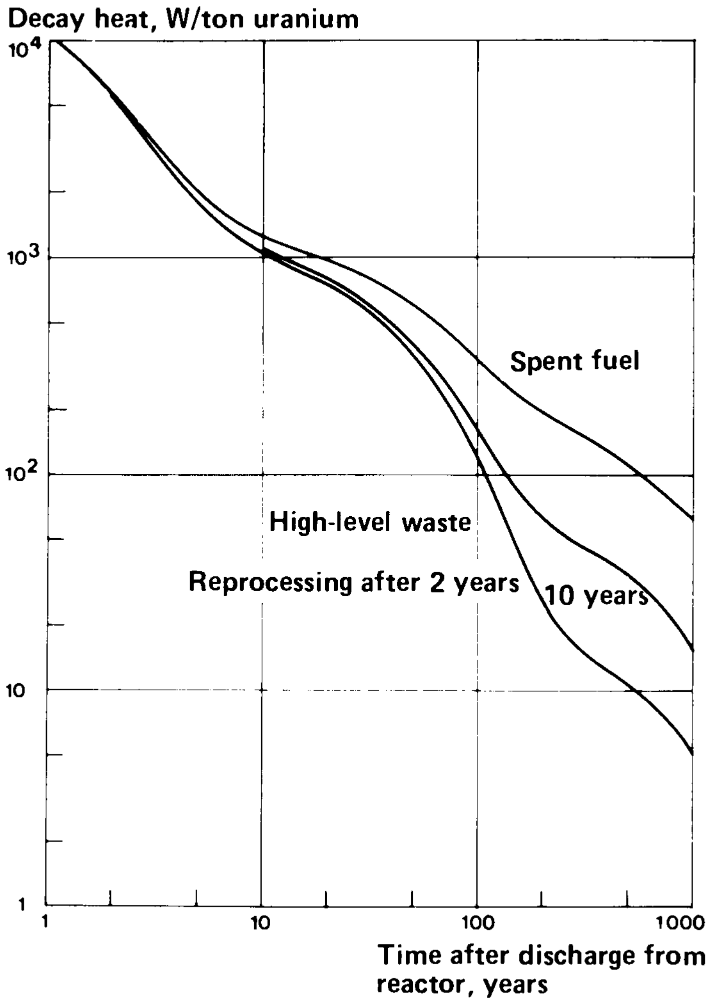

Figure 3. Decay heat in spent fuel and high-level waste from a pressurized-water reactor.

THE MULTIBARRIER CONCEPT

In April 1977 the Swedish Parliament adopted a law requiring that the owner of a new reactor had to give convincing evidence that an absolutely safe method for final storage of spent fuel or high-level radioactive waste from reprocessing of nuclear fuel could be achieved, before the reactor could be given permission to be fuelled. As a consequence of this law, the nuclear power utilities in Sweden organized a group — the KBS project — to study the matter. In December 1977 a report was published on the safe storage of vitrified high-level waste from reprocessing of spent fuel Ref. [1] followed, in September 1978, by a second report on final storage of spent unreprocessed fuel Ref. [2]. The reports are based on a system of multiple barriers, both engineered and natural, isolating the waste or spent fuel from the biosphere to a degree high enough to reduce the effects on the environment to acceptable levels. These barriers have different protective properties and functions which both reinforce and complement each other.

The safety assessment was based on a worst-case analysis of the consequences of breakdown or malfunction of the various barriers.

The present discussion is based mainly on the experience gained during the preparation of the above-mentioned reports. As Sweden is dominated geologically by crystalline rock, no other types of host formations are dealt with. It must be kept in mind, that the reports were prepared only to show that safe final storage is possible within the constraints of today's technology. Neither the reports nor this article implies that the presented concept is the only or even an optimum solution with regard to technology or economy.

General Requirements

In order to limit the consequences of leakage of radioactive substances into the biosphere, the concentrations that may occur in the various compartments of nature must be limited. This can be achieved either by isolating the waste long enough so that the radioactivity of the waste will have decayed to acceptable levels, or by distributing the release over such long times or great areas that unacceptable concentrations will not occur. In the KBS-studies a combination of these methods is used.

From Figure 2 it can be seen that the decay time can be divided into two phases. During the first phase, about the first 1000 years, the relative hazard of the waste is very high and dominated by those fission products in the fuel giving off beta and gamma radiation. The second phase has — from a practical point of view — an almost infinite duration because the hazard is dominated by very long-lived alpha-emitting actinides or their decay products. The relative level of hazard during the second phase is a factor of 1000 lower than during the first phase. After the first million years the hazard index of spent fuel is dominated by radium-226, a daughter of uranium-238.

The consequence of this is, of course, that absolute isolation cannot be guaranteed during the second phase, whereas it may well be feasible during the first phase. The protection of the environment during the second period must be guaranteed by limiting the release rate.

The barriers utilized to limit the release rate during the second phase must be of such a nature that their functioning can be predicted for geological times. These predictions can obviously not be done for engineered barriers as human experience of materials under different environmental conditions is too short to allow for extrapolations of this magnitude. Consequently a very high degree of reliability and predictability is needed for the natural barriers during the second phase.

The KBS concept

The system of barriers described below is based on the KBS concept of deposition of spent fuel in copper canisters in individual boreholes at the bottom of a tunnel system 500 m deep in good quality crystalline rock. The annulus between the canister and the rock walls of the boreholes will be filled with a compacted clay (bentonite) that has a considerable capacity of swelling when taking up water.

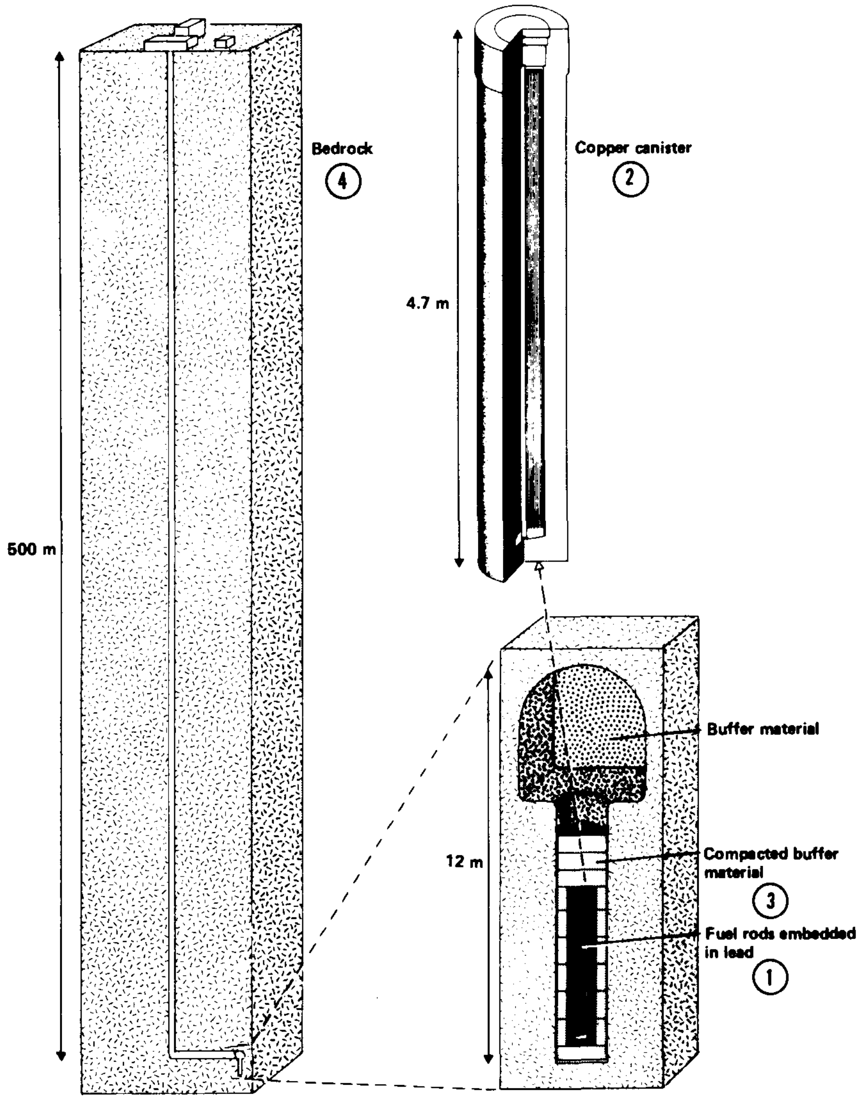

Figure 4. Schematic diagram of the proposed final repository. A number of barriers prevent or retard the dispersal of radioactive elements from the waste.

The different barriers illustrated in Figure 4 are:

① The low solubility of the fuel matrix
② The canister
③ The buffer material
④ The physical and chemical properties of the bedrock.

The crystalline rock

By "good quality crystalline rock" is meant here a rock with acceptable mechanical characteristics, having only minor fissures that occur infrequently and thus with a low water conductivity over sufficiently large volumes. The volume of good quality rock should be situated in an area with low tectonic activity and be surrounded by identified zones of weakness, where release of tensions can take place without affecting the rock in the immediate surroundings of the repository. The area should also have a flat topography which limits the hydraulic gradient. The low conductivity and gradient will limit the groundwater flow and the transport capacity regarding corroding agents which could affect the canister material. At a later stage the low transport capacity of the groundwater limits the dissolution rate of the radioactive material.

Another aspect of importance is the chemistry of the deep groundwater. In the KBS concept the reducing state of the groundwater, which has been verified at depth in Swedish bedrock, is a necessary characteristic. The presence of oxidants is a critical factor for corrosion as there is a great difference in the solubility of the actinides at the different valence states that prevail in oxydizing- and reducing waters.

The 500 metres of rock overlaying the repository will also provide protection against surface effects such as glaciation and military actions.

The fuel matrix

The UO_2 matrix has a very low leaching rate, although some of the fission products collect in the cladding gaps of the fuel rods. The dissolution rate of the waste is, however, not governed by the leach rate but by the available amount of water and the mass transport capacity through the immediate surroundings of the fuel.

The canister

A copper canister has been proposed for encapsulation of the fuel in the KBS concept, Figure 5. The copper provides an absolute barrier against leakage from the fuel for a very long period. This fact is not significantly affected by minor initial defects in a single or a few canisters. The copper will also provide shielding against radiation. The service life of the canister is governed by the concentration of oxidizing agents in the groundwater and the amount of water coming into contact with the copper surface.

The buffer and the backfill

The annulus between the canister and the rock wall of the deposition hole will be back-filled with highly compacted blocks of bentonite. When it takes up groundwater that seeps into the deposition holes, the bentonite will swell and thereby fill all crevices and spaces with a plastic clay having a very low water conductivity ($10^{-12}-10^{-13}$ metres/second). This

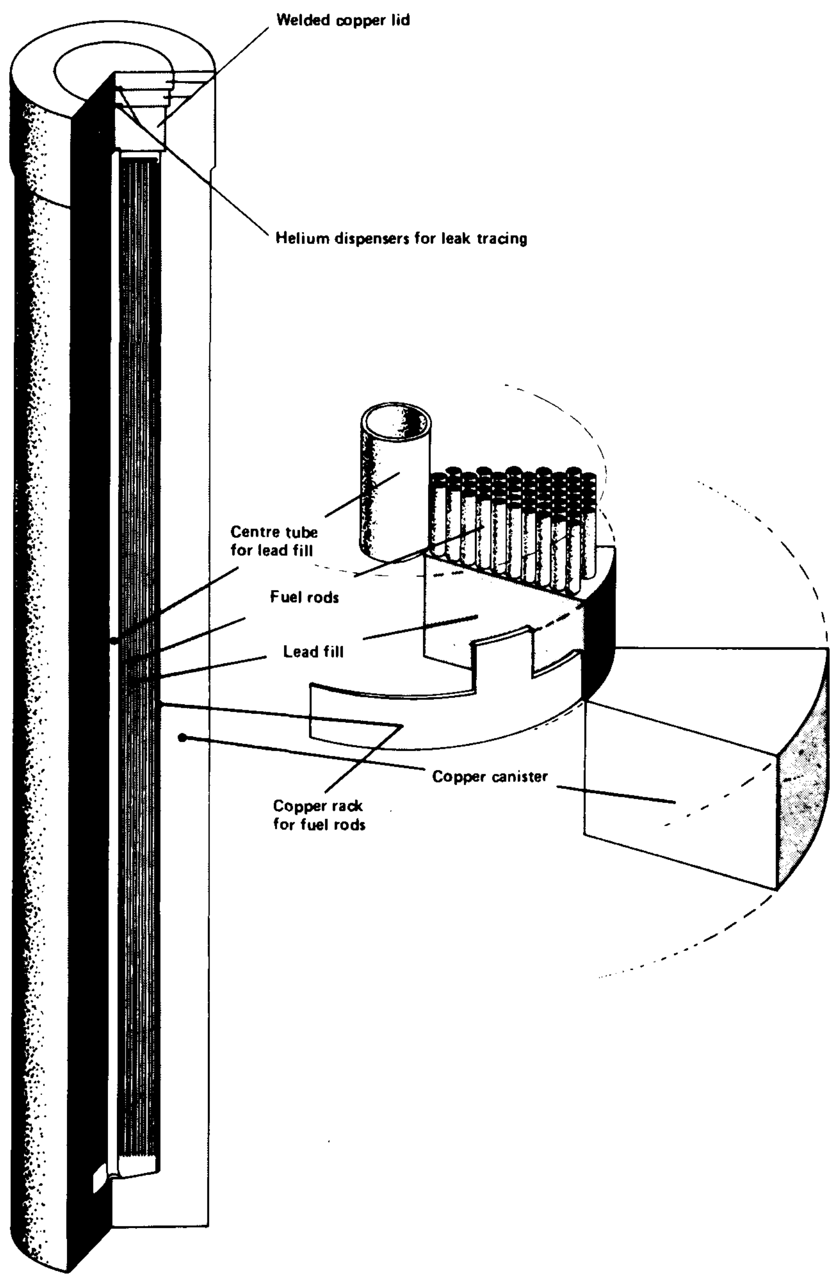

Figure 5. The encapsulated waste. The copper canister is 4.7 metres long and has a diameter of 0.8 metres.

means that mass transport can only occur by diffusion. The bentonite will also provide a large ion exchange capacity and thereby cause a substantial delay in the migration of substances through the buffer zone.

The buffer material, which can be regarded as a semi-natural barrier, will also stabilize the chemical environment around the canister and provide mechanical protection against small rock movements.

The geochemical rock barrier

If the copper canister loses its integrity due to corrosion, and the radioactive substances dissolve and start to migrate through the buffer mass, they will ultimately reach the groundwater in the fissured rock. The transport time of groundwater from the repository may be calculated if the characteristics of the rock mass are known well enough. The waste substances will, however, move much more slowly than the groundwater due to sorption effects and precipitation onto the surfaces of the fissures and the material filling these fissures. Most likely there will also be substantial diffusion into the rock mass surrounding the water-bearing fissures. The degree of retention is dependent on the characteristics of the various waste substances in the prevailing chemical environment.

What Barrier Function is Achievable?

In the KBS-study a series of very unfavourable assumptions were used as input for the safety analysis. The barrier effects could still be shown to keep the doses to the most exposed group lower than the limits recommended by ICRP and also lower than those resulting from natural radiation normally occurring in the environment.

In the KBS study it has been shown that

- rock masses large enough and with hydraulic conductivities below 10^{-9} metres/second exist in Sweden;
- a copper canister of 20 cm thickness would give an absolute isolation of at least hundreds of thousand years in the existing groundwater chemistry;
- the time needed to dissolve and transport all the waste through the buffer layer would be at least 500 000 years;
- the groundwater transport time from 500 metres depth to the surface could be around 3000 years if the rock mass was chosen with low conductivity and a low topographic profile;
- the chemical retention of the important radioactive substances in the flow paths through the bedrock would give delay times so great that the maximum doses would not occur until more than a million years had passed.

COSTS

A feasibility study could not be regarded as complete without mentioning the estimated costs. A first approximate estimate has been done of the investment and operational costs for the whole handling sequence from the discharge of the fuel from the reactor, through intermediate storage during 40 years to the final disposal and closure of the repository. The total cost, disregarding interest, has been calculated to be 5–10% of the power production cost in a system of 12 reactors.

CONCLUSIONS

The results of the KBS study indicate clearly that safe terminal storage of spent nuclear fuel in crystalline rock is feasible with the technology available today and at a safety level that is well within the limitations recommended by the ICRP. This statement is not only based on the fact that the doses calculated in the KBS study were acceptably low, but even more on the freedom to choose the dimensions of the engineered barriers as well as depth of the repository and to some degree the quality of the host rock.

The KBS report on spent fuel has been sent for scientific review by the Swedish Government to several domestic and foreign institutions and experts. A great majority of the reviewers have declared as their opinion that the KBS concept shows a technically feasible way to implement safe terminal storage of spent nuclear fuel. Keeping in mind the conservative assumptions used in the KBS studies and the ongoing comprehensive scientific efforts in several countries it seems obvious that more optimal solutions will be available within the near future.

This article does not discuss the question of whether spent nuclear fuel should or should not be treated as waste and deposited irretrievably deep in the ground. The aim is simply to give the background to our conclusion that safe terminal storage of spent fuel in crystalline rock is feasible with the techniques available today.

References

[1] Handling of Spent Nuclear Fuel and Final Storage of Vitrified High-Level Reprocessing Waste, KBS Project, Stockholm (1977).

[2] Handling and Final Storage of Unreprocessed Spent Nuclear Fuel, KBS Project, Stockholm (1978).