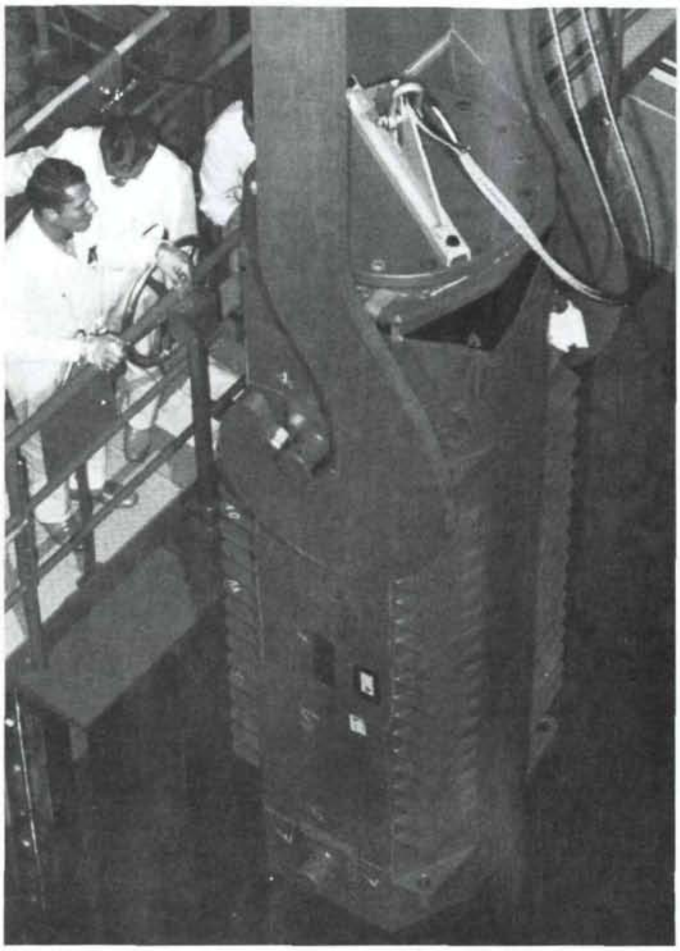
Spent-fuel cask at the nuclear research center in Karlsruhe, FRG. (Credit: KFZ)



Long-term storage and disposal of spent fuel

by Alexander Nechaev, Vladimir Onufriev, and K. T. Thomas

As widely known, both spent fuel and vitrified high-level waste (HLW) are sources of high radioactivity and decay heat. Consequently, spent-fuel assemblies should be stored in cooling media before further management. Decay heat falls rather rapidly with time, induced radioactivity decreases more slowly, and most spent-fuel fission products decay to acceptable levels in 300 to 1000 years.*

Major isotopes of plutonium, americium, neptunium, iodine, technetium, and uranium daughter products will remain radioactive for several million years. Yet from the standpoint of radiotoxicity, the greatest concern extends over about 10 000 years. While institutional controls governing artificial surface structures do not last this long, geological processes do. It is this consideration that makes geological disposal of spent fuel an attractive option.

For any chosen strategy for the nuclear fuel cycle's back-end, long-term storage of spent fuel is assumed to be a highly important part of the integrated waste system. Not only handling operations with spent-fuel assemblies are foreseen, but also packaging and, perhaps, rod consolidation will be done at long-term storage facilities. Disposal of spent fuel in canisters, after long-term storage and without repackaging, is a possibility that also exists.*

Current storage problems

Only two definitive options for the back-end of the nuclear fuel cycle are being considered today: reprocessing (early or delayed), and direct disposal (of spent fuel or radioactive wastes). Storage of spent fuel – on a short-term or long-term basis – is needed to realize either option. (See the diagram on page 17 for a summary of options.)

Studies conducted by IAEA and the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (NEA/OECD) have shown that about 200 000 metric tonnes of heavy metal (MtU) will accumulate by the year 2000 from water-cooled reactors worldwide. Not more than one-fourth of it will be reprocessed.**

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* For more technical data, see *Guidebook on Spent Fuel Storage,* IAEA Technical Reports Series No. 240, Vienna (1984); and "Characterization of Long-lived Radioactive Wastes to be Disposed in Geological Formations", by M. Boeola, Working Document SCK, CEN, Mol, Belgium (1983).

* See *Nuclear Fuel* (28 January 1985) for report of the proposal by the US Department of Energy on the future role of a monitored retrievable storage facility in the waste management system.

** See "Final Report of the Expert Group on International Spent-Fuel Management", IAEA Reg. ISFM/EG/26 (1982), and *Summary of Nuclear Power and Fuel Cycle Data,* OECD (1985).

In the 1990s, some utilities will experience a shortage of storage capacity – despite the fact that capacity of existing, committed, and planned facilities worldwide (at-the-reactor and away-from-reactor) is larger than annual arisings of unreprocessed fuel.*

This storage problem developed because existing nuclear power plants were designed to store spent fuel for about 3 to 5 years of reactor life, allowing for discharged fuel to cool before transport to a reprocessing facility. Countries now are looking for the best way to increase storage capacities, in view of delays in commercial construction of fast breeder reactors (FBRs), high reprocessing prices, and an over-supply of uranium.

Possible storage solutions

There are several options to solve this problem, or to postpone its solution:

- *To transport spent fuel* from a full at-reactor (AR) storage pool to another site within the utility's system where excess space is available. In the United States, this can reduce (by approximately 43%) the cumulative additional capacity needed by 1998.** However, this could entail additional investments for transport casks and some regulatory and licensing difficulties. The option could only postpone the time for final decision. Costs are estimated from US $10 to $40 per kilogram of uranium, depending on the distance.***
- *To expand capacity of existing AR pools* by using compact racks, double-tiers, and rod consolidation. Re-racking and double-tiering are proven technologies, but additional research and development is needed to make rod consolidation a fully licensed operation. The cost of re-racking or rod consolidation is estimated at approximately US $10 per kilogram of uranium.**** This option also could postpone the time for a final decision on long-term storage.
- *To construct new away-from-reactor (AFR) storage facilities* for centralized storage of spent fuel for 50 years and more, when direct disposal or reprocessing will be available. This could be assumed as the only possibility for storing spent fuel, after AR pools are full and before transportation for reprocessing or direct disposal. However, the construction of such a facility is time consuming (not less than 10 years) and a costly operation.

Experience in long-term storage

There are two options for long-term storage of spent fuel:

- *Wet storage,* which is the proven technology for storing oxide fuel for the long term. Zircaloy and stainless-steel clad, water-reactor fuels have been successfully stored (without significant corrosion and fission gas release) in water pools for more than 20 years. Increasing the storage time to 50 years is not expected to cause serious problems.
- *Dry storage,* which refers to storing spent fuel in an air, inert-gas, or carbon-dioxide atmosphere. This is becoming a proven technology. While it is true that demonstration of dry spent-fuel storage is limited, safety calculations in the Federal Republic of Germany have shown that spent fuel could be safely stored in an inert-gas atmosphere for 40 to 50 years. A concept of spent-fuel storage in an unlimited-air atmosphere, developed in Canada and the USA, also is envisaged for storage time of at least 40 to 50 years. (However, the maximum temperature of fuel rod claddings at the moment when they are inserted for storage should be limited to 175°C. The allowable insertion temperature of zircaloy cladding for storage in an inert-gas atmosphere is calculated at about 400°C.* This means that for storage in an unlimited-air atmosphere, spent fuel first should be stored in a water pool or in an inert-gas atmosphere to allow the temperature of fuel rod cladding to decrease to required levels.)

The principal difference between a wet and dry storage facility is that the latter has a modular character and could be incrementally expanded when needed.

Research and development on design, construction, and licensing of AFR storage facilities is being done in many Member States, including Canada, Finland, Italy, Sweden, the United Kingdom, the United States, and the USSR. Centralized facilities for long-term storage of spent fuel are in operation in Sweden and the Federal Republic of Germany. Some countries have announced plans to start constructing such facilities. (See accompanying table for an overview.)

Cost comparisons among different long-term storage options – wet (pools) and dry (metal casks, concrete sealed casks, vaults, dry wells) – are rather difficult because factors vary from country to country. For spent-fuel storage of 40 years, estimates vary from US $45 to $220 for pool facilities, and from US $33

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* This was shown in a 1982 study by the IAEA Expert Group on International Spent-Fuel Management, and was subsequently confirmed in "Status of spent-fuel management in Canada", by D.R. McLean, F.N. McDonnell, *et.al.,* a paper presented at the IAEA advisory group meeting on spent-fuel management in Vienna (March 1984).

** See "Utilities face squeeze in spent nuclear fuel storage space", by E. Anderson, *Chemical and Engineering News,* (1 April 1985).

*** See "Choosing a spent-fuel storage technology", by E.R. Johnson, *Nuclear Engineering International* (September 1984).

**** See *Status of Spent-Fuel Dry Storage Concepts: Concerns, Issues, and Developments,* TECDOC-359 (1985).

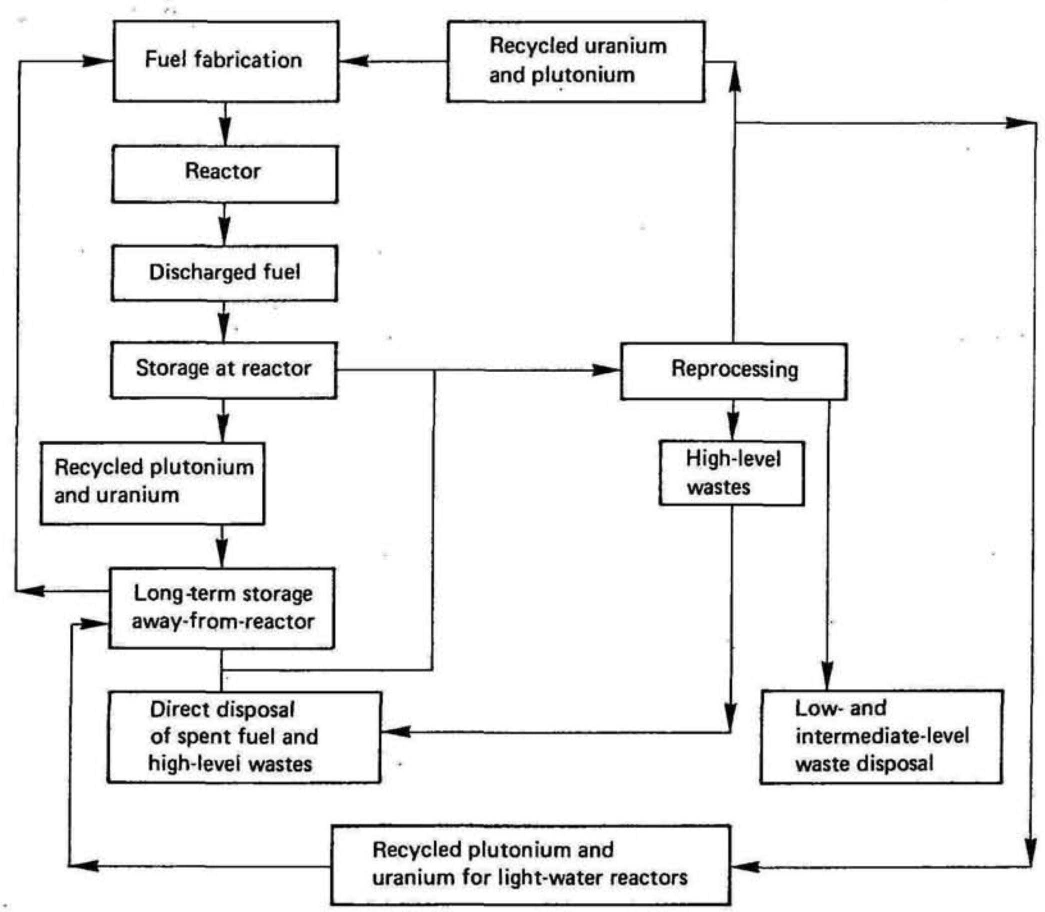
* See "Experience in the Safety Evaluation of Dry Spent-Fuel Storage Casks in the Federal Republic of Germany", by B. Droste; "Interim Dry Spent Fuel Storage – Experience from Safety Analyses in the Atomic Licensing Procedures", by A. Müller; and "Heat Removal from Dry Stored Spent-Fuel Elements", by M. Neumann, papers presented at the IAEA Technical Committee Meeting on Methods Used in the Design of Wet and Dry Spent-Fuel Storage Facilities, Espoo, Finland, 30 September to 3 October 1985 (to be published).

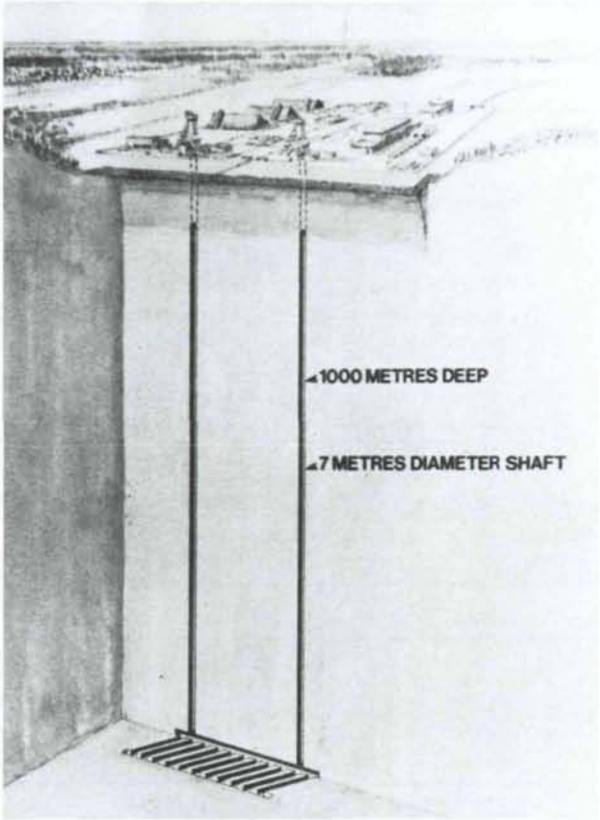
AFR facilities for spent fuel: Storage of 40 years or more

Country	Facility	Type	Capacity*	Status
Federal Republic of Germany	Gorleben Ahaus	Dry storage in casks (castor type)	1500 (420 casks or more)	Gorleben: operational permit received in September 1983 Ahaus: construction stage
Sweden	CLAB	Water pools in an underground cavern	3000 in 4 pools (could be increased)	Operational 11 July 1985 (accepted 6.5 MtU)
Finland	TVO-KPA-STORE	Underground water pools	600 in 3 pools (will be increased to 1270)	in construction stage (will be operational in 1987–88)
USA	MRS	Dry storage in sealed canisters in casks or dry wells	15 000	definition of site (will be operational in 1996)

* Metric tonnes uranium (MtU).

Flow chart of options for back-end of nuclear fuel cycle





One concept for spent-fuel disposal. The shaft runs 1000 metres deep and is seven metres in diameter. (Credit: US DOE)

to $83 for dry storage facilities (estimates in 1984 dollars per kilogram of uranium).*

Based on the accumulated experience in designing, licensing, and constructing the first AFR facilities, the following factors, among others, were taken into account: accumulated volume of spent fuel and its dynamics; climate and seismic conditions; availability of industrial capabilities and national industry infrastructure; public acceptance; and availability of data for safety reports.

Geological disposal options

In the selection of suitable media for geological disposal, the hydrogeological, geochemical, mineralogical and thermomechanical properties, structural strength, and stability of the formations are studied. A variety of geological media, in a number of geological environments, could be considered if suitably designed and engineered.

Geological formations with potential as repository sites are arranged in the following three groups: evaporites (such as salt), sedimentary rock deposits, igneous, and metamorphic crystalline rocks.

* See "Storage of Spent Fuel: Experience and Trends", by A. Nechaev and V. Onufriev, paper presented at the 6th CMEA Symposium "Investigations in the Field of Spent Fuel Reprocessing and Radioactive Waste Decontamination", Pestany, Czechoslovakia (March 1985).

- *Rock salt (halite).* This very common evaporite has received the most attention. It has favourable properties and exists widely as undisturbed units within geological formations, indicating stability over hundreds of millions of years. It exists as a bedded deposit formation or as a large dome pushed upwards by diapirism. Its high plasticity makes it largely impermeable to gases and liquids. Other favourable properties are: good compressive strength, good thermal conductivity, and easy mineability. Potential disadvantages: existence of entrapped pockets of brine, and inclusions whose fluids are known to migrate under certain thermal conditions; the likelihood of adverse canister/rock interactions; poor sorptive qualities; possible salt movement (diapiric); possible future human exploration for salt and associated resources near the emplaced waste; and salt's high solubility in water.
- *Anhydrite (calcium sulphate).* Only thick-bedded or massive anhydrite units at moderate depth are currently being evaluated.
- *Argillaceous formations.* These generally have very low permeability, good sorptive characteristics, and low solubility. Potential disadvantages include: dehydrating of hydrous clay minerals in response to thermal load; low thermal conductivity and adverse effects on rock mechanical properties; presence of organic matter and gases; existence of inhomogeneities; and possible difficulties in mining and keeping excavations open.
- *Igneous and metamorphic rocks.* These are considered by several countries as prime candidates for repositories for deep underground disposal of radioactive wastes. They generally demonstrate long-term stability, high rock strength, good chemical stability, moderately good thermal conductivity, and low porosity. An additional advantage in some countries is the common occurrence of massive and homogeneous formations of little or no economic value. These rocks tend to be brittle, or non-plastic, at depths considered for repositories, and thus are likely to have fractures and other secondary openings. Because of these fractures, they commonly contain groundwater within their secondary openings. The presence of rock inhomogeneities – largely the result of the nature, orientation, and magnitude of fractures – makes the modelling of the hydrogeology difficult.

Other igneous rocks of specific interest are basalt and volcanic tuffs. Basalt occurs principally in large, plateau-like masses which are comparatively young, accumulated on continental areas. It has moderate thermal conductivity and a very high melting temperature; it also has a very high compressive strength, but commonly exhibits fractured or vertical, columnar joints. Where massive, basalt is very impermeable; where fractured and jointed, it can transmit appreciable quantities of groundwater. It has a low ion-exchange capacity unless it is partially altered by the presence of secondary, more sorptive minerals.

Two kinds of tuff, known as welded and zeolitic, are being investigated. Many tuff deposits contain alteration minerals such as highly sorptive clays and zeolites, both in the rock matrix and along primary or secondary fractures. Because of generally high porosity, tuffs usually contain significant amounts of water.

Assessing long-term safety

In selecting a geological repository, it is necessary to take into account possible thermomechanical effects; effects on fluid release and flow; effects on the buffer and backfill materials; geochemical effects; and thermal loading.

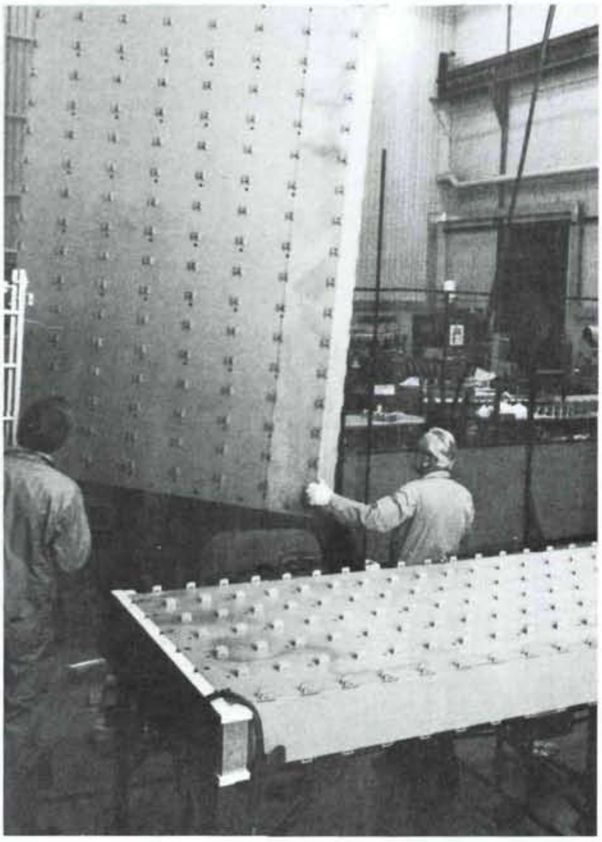
Longer interim storage of spent fuel is advantageous since it facilitates a lower temperature in the repository. Mechanical properties of the rocks are affected by increased temperatures. The long-term impacts of these changes have to be assessed, especially in rocks with high states of natural stress. Mechanical effects are associated with changes in mineralogical composition and water content, which are considerations to be studied in clay and shale formations. Their effects have to be understood for different types of formations, since there is concern that elevated temperatures cause changes in the flow regime near a repository by liberation of previously bound water. In the selection of buffer and backfill materials, their exposure to high temperatures have to be studied in detail.

Radiation emitted by the decay of radionuclides could have a number of possible effects, the importance of which will be very dependent on the specific details of the particular concept of waste disposal. For example, very durable, thick metallic containers would retain almost all the radiation within them. Gamma-radiation effects outside such containers can be ignored. Alternatively, the gamma fields outside thin containers could be appreciable and their effects would need to be assessed. It should be noted that interim storage prior to disposal will substantially reduce the gamma fields and the rate of heat generation.

Retardation in the movement of radionuclides, which depends to some extent on the host medium, takes place due to differences in physico-chemical behaviour between radionuclides and groundwater. The major physico-chemical processes involved here are chemical dissolution, diffusion, ion exchange, sorption, chemical substitution reactions, and ultra filtration. They are dependent on the distribution and nature of the chemical species in solution. The most important physico-chemical parameters are the pH, re-dox (oxidation reduction) potential, the temperature of the solution, and the concentration of other naturally occurring species. The content in groundwater of sulphates, chlorides, iron corrosive substances, and complexing agents have to be assessed.

Site considerations

A final repository can only be built at a site where there is a sufficiently large rock formation with suitable geological, hydrological, and geochemical properties.



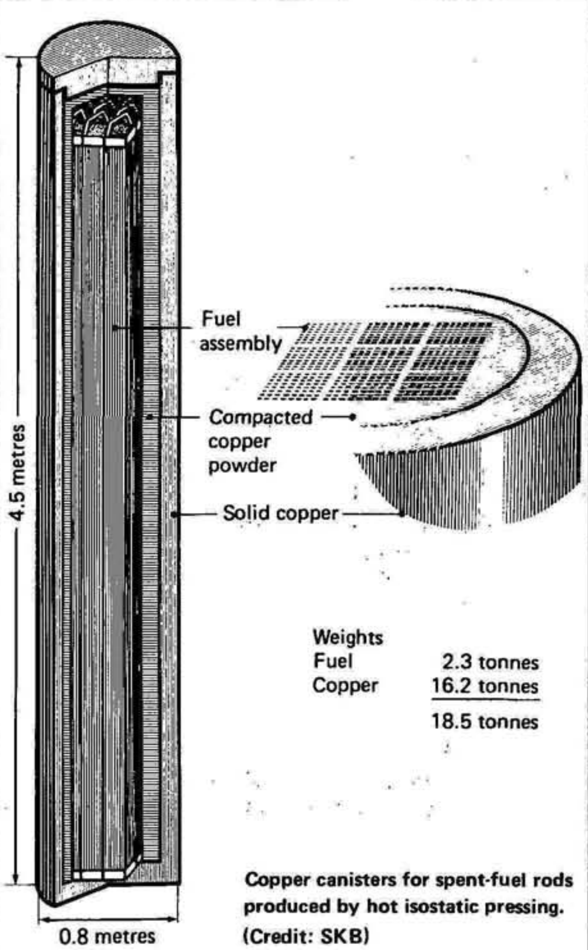
Fabrication of spent-fuel storage racks in Denmark. (Credit: RDM)

Usually safety requirements can be met at a repository depth of about 400 to 500 metres, though depths of up to 1000 metres can be technologically achieved. A system for safe final disposal of spent nuclear fuel can be designed on the basis of current knowledge and built during the next two to three decades, or as required.

Design alternatives are available that take into consideration thermal loading and construction capabilities. Conceptual designs for mined repositories in solid granite, basalt, and boom-clay formations have been made by countries having such formations. The studies include not only the engineering aspects, but also detailed investigations on packaging (both from materials and engineering points of view) and on buffer and barrier materials, as well as on performance and safety assessments. Continuing extensive research and development will enable countries to have more data on which to base the final repository design.

Packaging spent fuel

The packaging of spent fuel has to be seen in the context of the whole disposal system and has different functions, which are determined by the time for interim storage, considerations of transport and emplacement, and the duration of containment. A variety of techniques are technically feasible for spent fuel encapsulation. In Sweden, one option considers use of molten lead or hot-pressed copper, powder fillers to embed fuel rods in



Copper canisters for spent-fuel rods produced by hot isostatic pressing. (Credit: SKB)

a solid matrix within a copper canister. After placement in the holes, canisters are surrounded by buffer materials, such as highly compacted bentonite clays. The repository will then be sealed by filling all tunnels and shafts with a mixture of sand and bentonite clay.

The backfilling and sealing of a repository is important for safe construction requirements, the functions of which are to fill the emplacement holes, tunnels, and shafts; to minimize or prevent water intrusion; to provide rock support and minimize subsidence; to provide chemical and physical protection for waste packages; to contribute to the dissipation of heat; and to ensure retardation of radionuclides by reducing water movement. Spoils from excavations, cements, bitumen, epoxy-based grouts, and polythene, for example, are potential backfilling materials.

After the operating phase of a repository containing spent fuel, no more surveillance, site monitoring, or institutional controls are envisaged. However, the marking of site areas, as well as physical or other controls, are considerations for decision-making by national authorities. Some designs, due to special conditions, build in the option of retrieving disposed material.

Costs for spent-fuel disposal – based on analysis of site exploration and development; repository construction; operation; and decommissioning – have been studied from the viewpoints of sensitivity to design features and optimization. Such costs for underground disposal are expected to represent about 1 to 3% of current electricity generating costs. With the current state of knowledge, the next step would be to set up pilot-scale demonstrations to provide more realistic data and costs for industrial development.

Subject for discussion

Undoubtedly, spent nuclear fuel is potentially dangerous for humanity and active measures are necessary to isolate it from the human environment. This is one of the more important and urgent problems today.

Yet on the other hand, spent fuel also is a unique source of vital elements – world resources that are very limited. For example, reserves of rhodium – which is intensively used in chemical, electrical, and medical fields – are only about 770 tonnes, with the element's concentration in the earth's crust very small. Rhodium concentration in spent fuel, however, is far higher (340 grams per tonne compared to 1.10^{-3} grams per tonne in the earth). Considering that by the year 2050 about 600 000 tonnes of spent fuel can be discharged worldwide, it could become the only source of "new artificial" rhodium reserves (as well as palladium and ruthenium) in the next century.

Defining terms

What differentiates long-term storage from disposal? The IAEA defines the first as "storage of fuel units for an extended period, where special packaging and/or facilities are required. The storage period ends when the fuel units are reprocessed or disposed of".* In this case, there should be provision for isolation, monitoring, environmental protection, and human control. Also expected is subsequent action involving treatment and transportation for final disposal or reprocessing.

On the other hand, spent-fuel disposal is defined as "emplacement of fuel units in an installation affording adequate environmental protection *without intention to retrieve* the fuel units" (italics added).

These definitions are important to national and international waste management strategies. The time period for long-term storage of spent fuel – 50 years or more – is now being considered in many Member States. First demonstrations of final disposal are expected early in the next century.

* See *Spent-Fuel Storage Glossary*, TECDOC-354 (1985).