SPENT FUEL AND RADIOACTIVE WASTE MANAGEMENT
GENERAL CONSIDERATIONS AND APPLICATION IN SWEDEN

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SUMMARY

Spent fuel and radioactive wastes of different types are generated in the course of electricity production in nuclear power reactors and in other uses of nuclear energy and radioactive materials. Historically a large proportion of the waste emanates from nuclear research establishments. Since a few years the vast majority of the material, however, is generated at the about 400 nuclear power plants now in operation around the world.

The spent nuclear fuel contains uranium and plutonium as well as waste products from the fission process. The uranium and plutonium can be reused after reprocessing as fuel material for nuclear reactors. Alternatively the spent fuel can be regarded as waste and be disposed of without reprocessing. The decision on whether the fuel shall be reprocessed or not is made on both economical and political grounds and can thus differ from country to country.

The radioactivity content and the physical and chemical form of the wastes, and thus their potential harmfulness varies over a wide range for different kinds of waste. For instance the activity content of the spent nuclear fuel or the high active waste from reprocessing is such that the material must be shielded and cooled for some decades. It also contains substantial amounts of long-lived radionuclides which necessitates that it is disposed of in such a way that it is isolated for many thousands of years.

Some low-level waste on the other hand might only be expected to be radioactive due to the fact that they come from an environment where radioactive material could exist.

Different management strategies are thus necessary for different kinds of waste. In this paper a general overview is given of the principles adopted in a number of countries utilizing nuclear energy and as a special example the Swedish approach is described. The paper covers various aspects of waste management including handling, treatment, conditioning and packaging, as well as interim storage, transports and disposal. Some considerations of the decommissioning of the nuclear installations are also given.

Although the emphasis is put on the management of waste from nuclear power production, it is clear that the same methods can be used also for waste from the use of radioisotopes in medicine, research and industry.

INTRODUCTION

Generation of nuclear energy as well as use of radioisotopes in research medicine and industry gives rise to radioactive residues, additional to the natural radioactive substances surrounding us.

This addition of artificial radioactive substances causes concern, because it is more concentrated and contains substances of high level activity as well as substances of lower level activity but with very long duration.

Furthermore, recovery of uranium from its ores causes a redistribution of naturally occurring radioactive substances. This could be of concern if the mill tailings are not properly managed, but in principle, however, the mining and milling of uranium ores do not create an additional source of radiation.

The debate or the issue of radioactive wastes and their management is very understandable as the public is confronted with the fact that some residues from nuclear power generation release radioactivity of almost instant mortal level if no protection is provided, and other maintain their radiotoxic character over a period many times exceeding history of man.

Hence there are two questions to answer. The first is: Can such wastes be managed and ultimately disposed of in a way that is safe even over very long periods of time? If there is proof of such feasibility the second question is: What are the conditions and measures to reach the objective, i.e. a practical disposal system be acceptable for the society both from the point of view of safety and of economics.

There is a third question also discussed in connection with choice of strategy for the nuclear fuel cycle in relation to reprocessing or not, namely: Does the spent fuel from nuclear power plants increase the risk of proliferation of nuclear weapons material?

This paper will mainly discuss the first two topics and only briefly touch upon the third.

Good progress is being made in many countries on the safe management of spent fuel and radioactive waste. In the early days up to the early 1970ies most work was concerned with the reprocessing of the spent nuclear fuel and with the treatment and conditioning of the waste. Although also some work on direct disposal was done at an early stage, it is essentially during the last decade that the disposal studies have yielded substantial results.

The importance of an efficient management system of the back end of the fuel cycle work is obvious, and it is now being strongly persued in all countries with a large nuclear program.

In parallell with the technical development concerning the management of spent fuel and radioactive waste also the legal and administrative aspects have evolved. The radioactive waste issue has in some countries been regulated under special laws, such as the Nuclear Waste Policy Act of 1982 in the US and the Financing Act of 1981 in Sweden. These acts regulate the sharing of responsibility between the waste producer and the national organisations.

Life length	Radioactivity level High	Intermediate	Low
Long (thousands of years)	Spent fuel Fission product concentrates from reprocessing	Fuel cladding hulls and sludges from reprocessing Certain core components	Alfa-bearing scrap from reprocessing
Short (a few hundred years)		Ion-exchange resins Discarded components Decommissioning waste	

Table 1 Examples of waste classification

The organizational solution chosen in different countries can vary. In many countries a national agency is responsible for performing the disposal operations, while in other countries such as Sweden all work necessary to handle and dispose of the waste in a safe way shall be performed by the producer.

The financing of the waste management is normally arranged according to the "polluter pays" principle, ie the waste producer pays all the costs. As there is often a rather long time lag between the production of the waste and the final disposal of it, especially for the spent nuclear fuel or the high-level waste, different kinds of funds are used for collecting the necessary means.

TYPES OF WASTES AND ITS CLASSIFICATION

The activity concentration in the waste from a reactor station varies greatly depending on where in the station it has been generated all the way from vertually inactive trash to the spent fuel, which has a very high activity content. The different types of waste therefore impose different demands on handling and final disposal.

From the handling point of view it is practical to distinguish between low-level, intermediate-level and high-level waste. Low-level waste can be handled and stored in simple packages, without any special protective measures. Intermediate-level waste must be radiation-shielded for safe handling. High-level waste requires not only radiation shielding but also cooling for a certain period of time in order to permit safe storage.

From the point of view of disposal it is more appropriate, however, to classify the waste according to their dangerous life-length, which in turn depends on the decay half-lives of the constituent radioactive substances. A distinction is made between short-lived and long-lived wastes.

Short-lived waste will have decayed to a harmless level in less than a few hundred years. Such waste can be disposed of at or near the surface. Long-lived waste remains radioactive for many thousands of years and requires a more qualified final disposal.

	Volume in disposal cubic meter	Activity content PBq
Spent fuel	10 000*	10 000
Core components and internals	20 000	100
Operating waste	100 000	1
Decommissioning waste excl.internals	100 000	0.01

* after encapsulation

Table 2 Total volume of waste from the Swedish nuclear power program of 12 reactors in operation for about 30 years. For comparision the total activity content after 100 years is also given.

Waste from nuclear reactors

The waste from nuclear reactors is usually divided into the following groups in terms of their subsequent handling:

spent nuclear fuel
operating waste (reactor waste)
core components and reactor internals
decommissioning waste

The **spent nuclear fuel** contains approximately 99 % of the radioactive substances that are formed in a nuclear power plant. The activity is to a large degree bound to the ceramic uranium dioxide matrix that constitutes the fuel, and that is enclosed in sealed metal tubes.

The activity level of the fuel decays quite rapidly during the first decades. Between 1 and 40 years after the fuel has been discharged the activity decreases by a factor of 10. It then takes almost a thousand years for the activity to decrease by yet another factor of 10. This is due to the large amount of long-lived radionuclides in the spent fuel, which also puts special requirements on the disposal.

If the spent fuel is reprocessed the bulk of the activity, except for the plutonium that has been separated, is concentrated in the high-level waste. The high-level waste that is normally vitrified must thus be handled and disposed of in a similar way as the spent nuclear fuel.

During reprocessing also other wastes are generated, such as cladding hulls and process wastes. These are normally low- and intermediate level, but could contain substantial amounts of long-lived activity, which must be taken into account for disposal.

During the operation and maintenance of the reactor stations **operating waste** is generated. This mainly consists of ion-exchange resins from water clean-up, replaced components, protective clothing, plastic covers etc. The operating waste is low-and intermediate level waste and mainly contains short-lived radionuclides. Similar waste also comes from spent fuel storage and from research facilities.

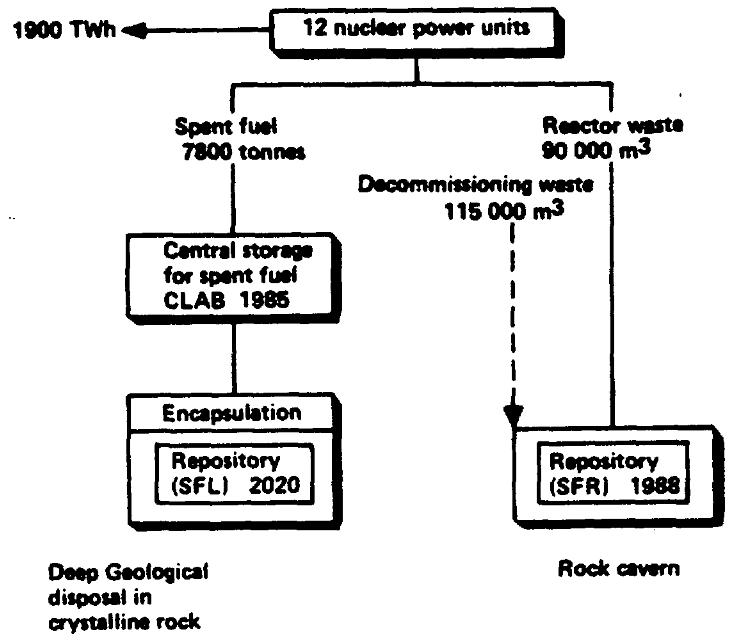

Figure 1 Swedish waste management scheme

Components located in or near the reactor core, **core components**, are exposed to a strong neutron flux and become activated. Some of these components have a high activity level, when discharged from the reactor. The life-length of this activity is however short and it decays rapidly. They also contain a certain amount of long-lived radionuclides, which needs to be taken into consideration for disposal.

When a nuclear reactor is **decommissioned**, parts of the facility are radioactive and must therefore be disposed of in a safe manner. Most of the activity is found in the reactor vessel and its internals, that are similar to the core components. The remainder is similar in activity levels to the operating waste.

STRATEGY FOR WASTE MANAGEMENT

With respect to the differences in activity level and content of long-lived radionuclides, different waste management strategies can be adopted for different waste types. In figure 1 the strategy chosen in Sweden is shown.

The basic principle is that short-lived wastes should be deposited as soon as feasible without interim storage, as there is no large advantage to be gained from this.

For the spent nuclear fuel and other long-lived wastes an iterim storage period of 30-40 years is foreseen prior to disposal. During this period the activity level and heat emission will decay about a factor of ten, which is advantageous for the disposal.

MANAGEMENT OF SPENT NUCLEAR FUEL AND HIGH-LEVEL WASTE

Management options

As indicated earlier the spent nuclear fuel contains 99 % of the radioactivity that is generated in a nuclear reactor. It also contains uranium and plutonium, that could be reused as fuel material.

For the management of the spent nuclear fuel two main options exist (1):

Reprocessing meaning the chemical separation and recovery of the plutonium and uranium from the spent fuel and the conditioning and disposal of the radioactive wastes.
Direct disposal meaning the disposal of conditioned spent fuel with no intention of recovery for reprocessing or any other purpose.

Till about a decade ago it was considered almost an axiom that the spent nuclear fuel should be reprocessed and that the fuel material should be reused. The best use of the reprocessed material would be in the fast breeder reactors that was being developed. In fact the breeders made reprocessing necessary.

Since the end of the 70ies a number of countries have started to investigate also the non-reprocessing direct disposal route. The reasons for this have been both technical, economical, and political.

For instance the slow-down in the development of fast breeder reactors has diminished the need for plutonium. The separated plutonium is now to a certain extent used in light water reactors instead at a lower value.

The economy of reprocessing has also become less advantageous due to the continued low price of uranium and the increasing price of reprocessing.

Politically in the US the concern that widespread reprocessing could contribute to a proliferation of weapon material caused the Administration to postpone reprocessing indefinitely and initiated the INFCE study. Other countries such as Sweden has also taken the position not to reprocess for economical and proliferation reasons.

Other countries such as France, Japan and the UK are pursuing the reprocessing route, the main reason for this choice being the conservation of energy resources. This is especially important for France and Japan, who are strongly dependant on import of raw material for energy production, and who foresees a continuing and expanding use of nuclear energy.

In case the direct disposal route is chosen it normally involves a certain period of interim storage of the spent fuel before disposal. This means that the final choice whether the fuel should be disposed of without reprocessing or not does not need to be taken for a number of years.

Management steps

Irrespective of what option is chosen for the management of the spent nuclear fuel certain management steps have to be taken that are similar for

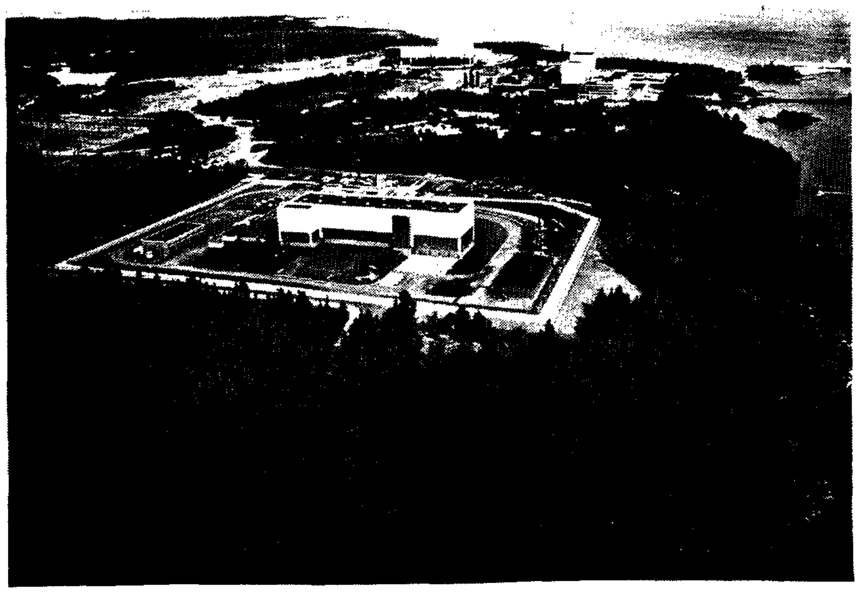

Figure 2 Aerial view of the Swedish interim storage facility CLAB

both options. These are:

Interim (or cooling) storage of spent fuel
Transport of spent fuel and high-level waste
Encapsulation and disposal of the spent fuel or high-level waste.

For the *reprocessing option* also the steps *reprocessing* and *conditioning of* the wastes must be considered.

Interim storage

The interim storage of spent fuel in water filled pools can be considered as a mature technology. There has been more than 30 years experience of this around the world. In most cases the water pools are located at a reactor station or at a reprocessing plant. Recently also separate away from reactor (AFR) storage facilities have been built, such as the Swedish CLAB facility.

During the last decade a growing interest in dry storage techniques have evolved following claims of economic and safety advantages. At Gorleben in the Federal Republic of Germany a facility for dry storage of spent fuel in casks have been built. Also other dry storage concepts are studied, eg in connection with Monitored Retrievable Storage studies in the US.

Transport

For the transport of spent nuclear fuel special heavily shielded transport casks are used. These are designed to withstand severe accidents without release of radioactivity. Over 15 000 spent fuel shipments have been made within the OECD countries over the last 30 years, and the transport technology is thus well demonstrated.

Similar transport casks can be used for the transport of high-level waste.

Reprocessing

Reprocessing of gas-cooled reactor fuel has been done since about 20 years in the UK and in France. Reprocessing of spent LWR fuel started later and is at present only performed in France, Japan and FRG. The total capacity is less than 500 tonnes/year. New reprocessing plants are, however, being built or planned in these countries and in the UK, which will increase the capacity to more than 4000 tonnes/year around 2000. The arising of spent fuel in the OECD-countries is estimated to be about 9000 tonnes/year at that time, which means that more than 50 % of the fuel must be stored.

The reprocessing technology is well proven which has been demonstrated by the operation of both pilot and commercial plants.

The high-level waste from reprocessing will normally be incorporated into a glass matrix. In France vitrification has been made commercially for about ten years. Also the interim storage of the vitrified waste have been demonstrated.

Final disposal

Two basic requirements can be placed on a final disposal system. It has to be technically and economically feasible for today's society, and its behaviour has to be predictible over timespans equal to the toxic life of the wastes. For such a system it is required that the long-term safety is based on a design independent of human supervision or corrective measures.

A number of different options for protecting man from radioactive residues could be envisaged. The waste could be removed from the earth, could be transmuted into other substances with much shorter hazard time, or could be buried deep into the earth to be well separated from man.

Today the ejection into space and a complete transmutation are not technically, economically or otherwise mature enough to be regarded as feasible options.

The only system on earth known to have inertia and hence predictability enough to cope with the timespans involved in nuclear waste disposal is the geologic system. Thus from the very beginning the development work has worldwide been directed mainly towards repositories in stable deep geologic formations. An impressive body of practical experience and fundamental data is now available.

The purpose of a repository is to protect human beings from unacceptable radiological impact. This can be achieved in two ways, either by containment or by dilution. In all schemes proposed for the disposal of spent fuel or high-level waste both principles are used in combination as is shown schematically in figure 3. During the first phase, when the activity is high, safety is based on the containment principle. To achieve this the waste is encapsulated in a corrosion-resistant container. However, absolute containment cannot be guaranteed over the very long time periods the waste remains toxic, and the safety will be dependent upon the rate of release from the containment and the decay and dilution of the radionuclides during the transport through the geosphere, factors that are depending on the geologic host medium.

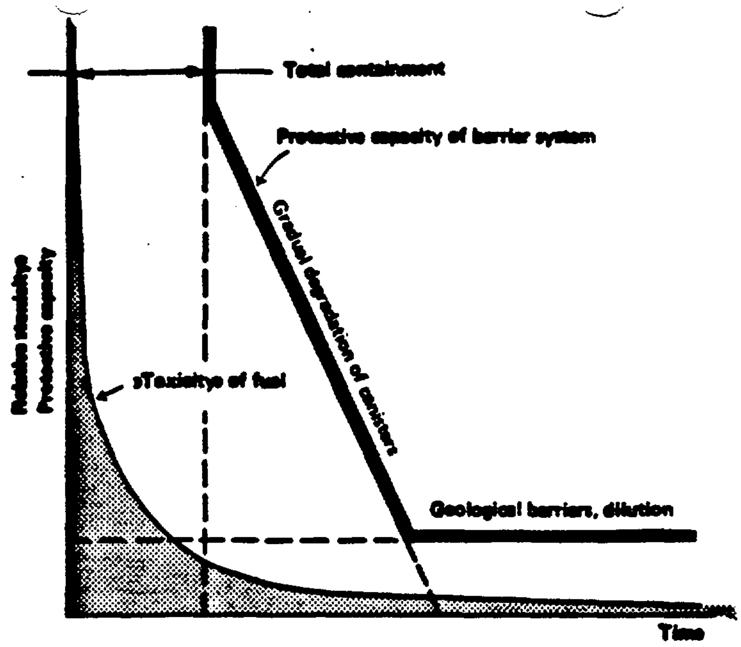

Figure 3 Schematic description of the function of the barrier system

Major geologic host media for repositories for high-level and long-lived wastes now investigated are rock salt, clay and crystalline rock. Different geological media are considered in the different countries, depending on the natural conditions.

On an international basis (OECD/NEA) also disposal of spent fuel or high-level waste into the thick sediments of the deep seabed is evaluated.

Most concepts for disposal utilize the principle of multiple barriers, i.e. the safety of the repository is not based on the assumed performance of only one barrier but a system of relatively independent barriers.

By use of models the behaviour of the various subsystems, interactions between them, the decrease in radioactivity with time and the long-term performance can be predicted. In this way the safety of several waste isolation concepts for various kinds of host media has been assessed. The results of these assessments indicate that with proper choice of engineered barriers, host media and siting the waste can be finally disposed of without causing a noticeable increase of dose to man.

The time-schedule for the development of repositories for spent fuel and high-level waste is dependant on the time needed to select and evaluate a suitable site and also takes into account the heat decay of the waste. In the US and in the FRG a disposal facility is expected to be in operation around the year 2000. Other countries have adopted a longer time-schedule, around year 2020.

Management of spent fuel in Sweden

Sweden has chosen the direct disposal option for the management of spent fuel. This choice has been judged to be the most rational and cost-effective solution under the prevailing conditions in Sweden, with a plan to phase out all nuclear power plants no later than 2010. It is also the politically preferred option.

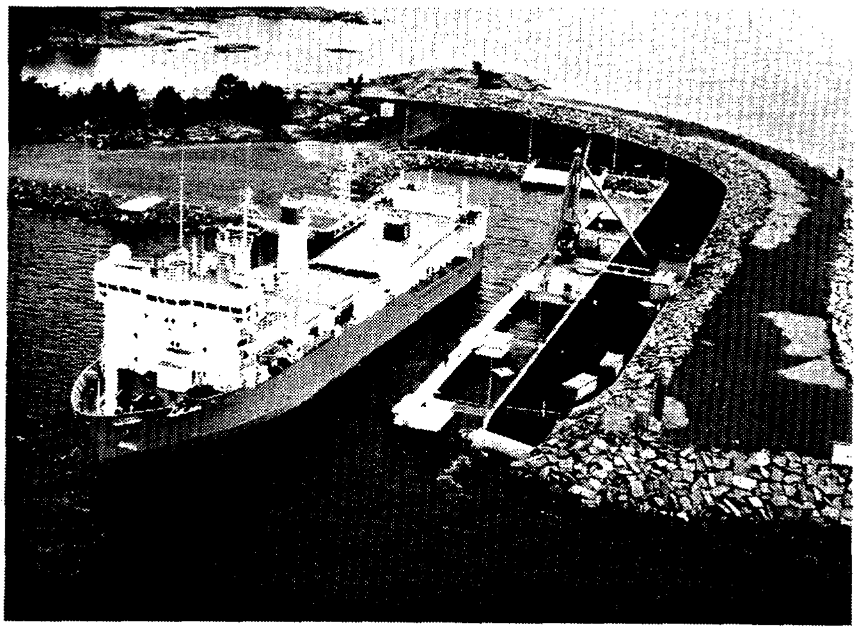

Figure 4 Spent fuel transports in Sweden are made by M/S Sigyn

The main features of the Swedish "once-through" scheme for direct disposal are briefly as follows.

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

CLAB

In CLAB, which was taken into operation in July of 1985, the principle of wet storage in pools is applied. The CLAB facility is situated on the east coast of Sweden adjacent to the Oskarshamn power plant (2).

The CLAB facility constitutes a fundamental strategic element in the Swedish spent fuel management scheme. It will ensure uninterrupted nuclear power production and it will provide ample time for R&D work, site selection, system design and optimization for the development of a permanent repository.

The facility consists of underground storage pools in a rock cavern and a receiving building on the surface. When fully expanded CLAB will have a capacity to store all the spent fuel generated at the 12 Swedish reactors, about 8,000 tonnes.

Transport system

All the Swedish nuclear power stations, as well as the storage facilities, are located on the coast. It has therefore been deemed expedient to develop a sea transportation system for the nuclear waste, consisting of a ship, transport casks and containers and terminal vehicles.

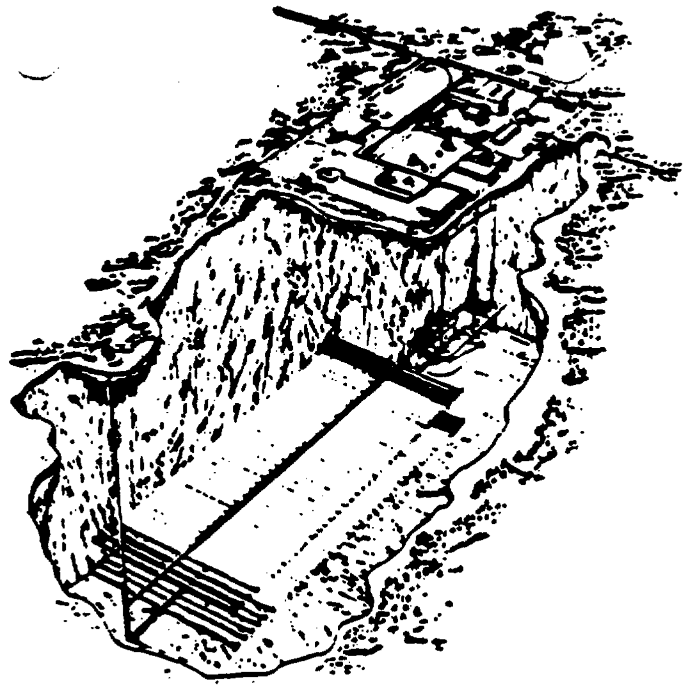

Figure 5 Final disposal of spent fuel according to KBS-3

Final repository for spent fuel

In accordance with present plans, facilities for the final disposal of spent fuel and long-lived waste will not be required until the year 2020. Consequently, construction work has not yet commenced on these facilities.

Extensive research has, however, been performed in Sweden since the mid70s. It has resulted in concepts for final disposal of waste from reprocessed fuel (KBS-1) as well as for direct disposal of spent fuel without reprocessing (KBS-3) (3,4). These concepts have been evaluated by the government and have been found to be acceptable with regard to safety and radiation protection.

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

The KBS-3 concept

In principle, final disposal according to KBS-3 is technically fairly simple; the spent nuclear fuel is encapsulated in thick copper canisters that are deposited 500 m down the crystalline bedrock, figure 5.

The safety of the repository is based on the fact that the degradation of the canisters and subsequent transport of the radioactive substances will take such a long time that the radioactive substances will decay and be diluted to such a degree that they reach the biosphere only in harmless quantities. The waste is isolated from the environment by a number of mutually redundant barriers such as the rock mass, a bentonite buffer, highly corrosion resistant, copper canisters, and the low solubility of the spent fuel.

Research and Development

In KBS-3 one feasible method has been demonstrated. Considerable work remains to be done in order to develop the optimal method, however. The future work comprises (5):

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

An application for licensing of a repository is foreseen around the year 2000.

MANAGEMENT OF SHORT-LIVED WASTES

The majority of the short-lived wastes, ie waste that are harmless in less than a few hundred years, comes from the operation of the nuclear power plants. Also some waste from the reprocessing and from research facilities fall into this cathegory.

For these wastes there is no technical advantage of delaying their disposal and there is a tendency worldwide to develop and operate disposal facilities as quickly as possible.

The safe management of short-lived low and intermediate level waste is generally not considered to be a big problem, although it can contain certain technically complicated steps.

Treatment and conditioning

Many methods have been developed for the treatment and conditioning of the short-lived waste. The purpose of the treatment is normally to concentrate the waste thereby reducing the volume, or to render it chemically inert. The residues are then conditioned by incorporating them into a suitable matrix or simply to package them.

Example of treatment methods are coprecipitation, ion-exchange or evaporation for liquid waste and compaction or incineration for solid waste. These are conventional methods that are used in other industries and that have been succesfully transfered to the nuclear application.

The most common method for solidification is encapsulation in cement or concrete. This method is being used worldwide and has the advantage of being relatively simple and cheap. Other methods that are frequently in use are bituminization and incorporation into different plastics.

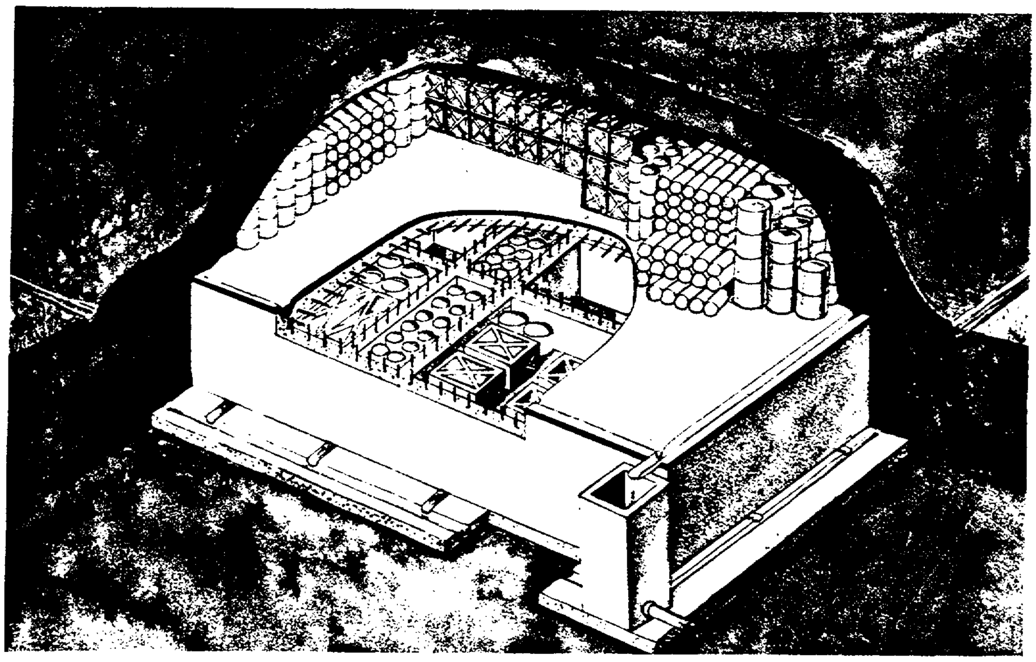

Figure 6 Near-surface disposal of short-lived waste at the Centre de La Manche

Transport

The transports of low-and intermediate level waste has to follow the IAEA transport regulations or similar national regulations. For the intermediate-level waste special radiation-shielding containers must be used, while for low-level waste standard shipping containers can be used.

A large number of transports of these wastes have been performed worldwide, and the safety record have been very good.

Disposal

For the disposal of short-lived low- and intermediate level waste three different practices have been used,

sea disposal
near surface disposal
geological disposal

Sea disposal has been practiced by many countries earlier. At present, however, there is practically a moratorium on sea disposal, awaiting a renewed evaluation of the safety.

Near surface disposal is the most commonly utilized method for disposal of short-lived wastes. It has been practiced in the US, France and the UK for many years. Normally the waste is disposed of in an engineered trench, that is lined with concrete. The trench is normally above the ground water surface. After emplacement of the waste, the trench is backfilled and covered. In the French system used at the Centre de La Manche for instance the backfilling is concrete, so that the waste is fully surrounded by concrete. At La Manche also some low-level waste is stored in earth-covered tumuli above ground.

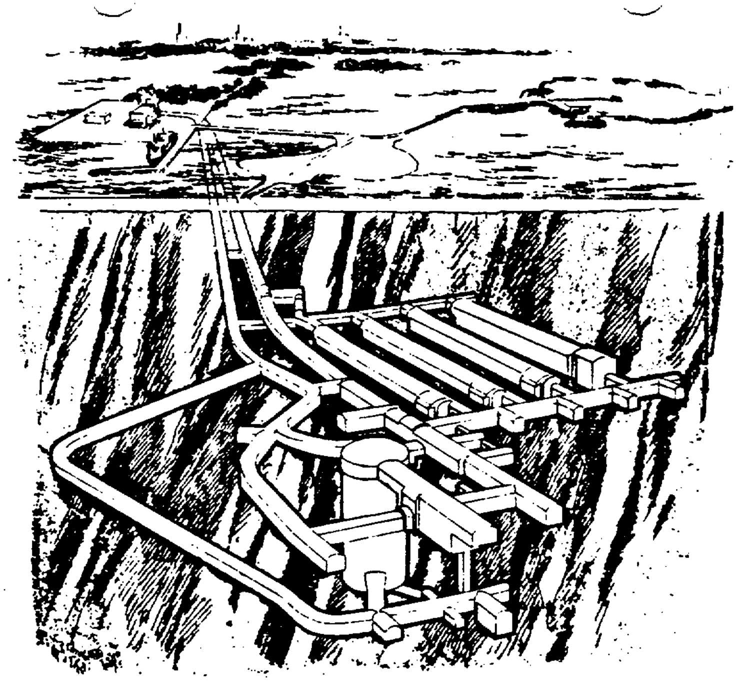

Figure 7 SFR - Swedish disposal facility for short-lived wastes

When a near surface facility is closed it has to be safeguarded for a few hundred years to protect it from inadvertent intruders and to check the integrity of the barriers.

In some countries near surface disposal is not accepted unless for very low-level waste. In these countries **geological disposal** facilities are developed, eg in the Federal Republic of Germany and in Sweden.

Management of short-lived waste in Sweden

The operating waste from the nuclear power plants is encapsulated in concrete or bitumen and is at present being stored in specially built facilities at the reactor sites. It will, from 1988 onwards, be transported to the central repository for final disposal of low and medium level reactor waste, the so called SFR, which is currently under construction near the Forsmark nuclear power plant.

The entire repository is situated in rock 50 metres below the seabed about 1 km outside the Forsmark harbour. The repository consists of rock caverns of various designs depending of the type of waste to be disposed of, Figure 2. The intermediate level waste, which contains most of the activity, will be deposited in a silo-like concrete structure cast inside a cylindrical rock cavern and the waste will be isolated from the surrounding rock by concrete walls and a layer of clay backfill (bentonite) between the silo and the rock. The low level waste will be deposited without extra barriers in the rock caverns designed for the particular type of containers being used for such waste.

When the repository is filled, the facility will be sealed with concrete plugs in the rock caverns and in the access tunnels to prevent future access. After sealing of the repository no further surveillance will be needed.

SFR will accomodate all the of low and medium level operating waste generated in Sweden. Later, when the reactors have been decommissioned, an extension will be made to accomodate also the decommissioning waste.

DECOMMISSIONING OF NUCLEAR INSTALLATIONS

When a reactor or another nuclear installation is finally shut down, parts of the facility is radioactive and special measures has to be taken in order to decommission and dismantle it in such a way that the health and safety of the decommissioning workers, the public and the environment is protected.

So far no large nuclear power plant has been decommissioned. Experience has, however, been obtained from the decommissioning of small test and power demonstration reactors. Several major projects are also underway around the world, that will demonstrate the decommissioning of larger reactors, eg the Shippingport reactor in the US, the JPDR reactor in Japan and the Winfrith AGR in the UK.

Although it is generally considered that the technology already exists for decommissioning of large power reactors, all these projects will yield valuable experiences for improvement of the technology, with aim to minimize doses to the personnel and costs.

The wastes generated during dismantling are similar to the wastes from operation and can thus be disposed of in a similar way.

CONCLUDING REMARKS

In the introduction of this paper I posed the question

Can radioactive waste be handled and disposed of in a safe way?

With the overview given in this paper I have tried to show that the answer is yes.

Good progress is being made worldwide to implement the different steps involved in the safe management of the radioactive waste.

Handling and storage of spent fuel and radioactive waste is done on a routine basis at the reactor stations and at reprocessing plants.

The transport of the material is also routine in many countries, and shows an excellent safety record.

Disposal facilities for low- and intermediate level short-lived wastes are in operation in a few countries and are under construction in some others.

For the disposal of the spent nuclear fuel or the high-level waste from reprocessing different concepts have been proposed and evaluated. In a recent report by an Expert Group within the OECD/NEA member countries have concluded (1).

"Extensive study and research in OECD countries have provided a high level of confidence that both waste disposal options, direct disposal of spent fuel and disposal of high level reprocessing waste, are technically feasible. Safety assessments for possible repositories indicate that they would present no greater long term risk to man and the environment than allowed by current radiation protection standards or from radioactive materials occuring naturally in the earth's crust. Studies are continuing to further improve the already significant level of knowledge about long term behaviour of geologic repositories to facilitate selection of suitable disposal sites and to optimize reporsitory designs."

They also concluded

"The cost of either back-end option, direct disposal or reprocessing, will be a small fraction of the total cost of electricity generation. The economics of the two options are sufficiently similar that a compelling argument cannot be made for one over the other on economic grounds alone."

The waste management issue is an issue of great public concern all over the world.

For Sweden, as well as for most other countries with nuclear power, broad and open international cooperation in the field of radioactive waste management plays an important role not only because of obvious gains in technical efficiency, but also from the point of view of public understanding and acceptance. It is particularly important that the international work include long term radiation protection objectives as well as principles for evaluation and performance of various disposal systems.

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