are directly related to specific activities within Member States. The Member State profile will include information on the current inventory of waste volumes, waste volume projections, policy and regulatory developments, organizations responsible for waste management activities, national strategies, waste management research and development programmes, operational activities, and significant milestones.

The initial objective will be the development of waste management profiles for the 31 Member States that operate and/or have nuclear power plants under construction. After this goal is achieved, efforts will be directed toward developing and placing into the database system profiles for Member States that generate radioactive waste only from nuclear energy applications. It is expected that the WMDB will be operational in late 1990, although some parts of the system should be available sooner.

The database will be used by the Agency to enhance the waste management programme by providing ready access to information on Member States activities in the field. The information it contains will be used to provide reports on the international status of radioactive waste management and to assist the Agency in the planning and development of its waste management programme. All Member States are encouraged to participate in the database's development and operation and to make use of it in the planning and implementation of national waste management programmes.

Conclusions

Radioactive waste management is an ever changing activity, as Member States adjust to both the technical and public acceptance aspects of the issues involved. In recognition of this, the Agency's waste management programme must be flexible to respond to Member States needs with activities that are both beneficial and timely. The new initiatives described here represent the results of a continual assessment process to develop services which are useful to Member States regardless of the status of their waste management programmes. This assessment process will continue as the Agency strives to ensure that resources are directed to activities that are of direct interest and importance to Member States.

State-of-the-art report on radioactive waste disposal

Different types of radioactive wastes can be, and are being, stored and disposed of safely

by Alf Larsson

In view of the considerable work required to develop repositories for radioactive waste, an extensive international co-operation has evolved within the area. The work has also engaged the IAEA to a great extent. The Agency has published a number of reports, covering different aspects of waste disposal. Following a recommendation by its Technical Review Committee on Underground Disposal (TRCUD) the Agency will publish a "state-of-the-art" report on radioactive waste disposal. The report is still in the preparation stage. In this article the principal subjects of the future report are discussed.

Radioactive waste and the nuclear fuel cycle

In the nuclear fuel cycle, radioactive waste arises in the mining and milling of uranium ores, the enrichment process, the fuel fabrication plants, the operation of nuclear reactors, the reprocessing of spent fuel, and the decommissioning of nuclear facilities. Safe management and disposal of nuclear waste is of primary importance for countries with nuclear power programmes. Also other countries making use of radioactive substances in hospitals and research institutions are faced with similar problems, although on a smaller scale.

Several alternatives have been proposed for radioactive waste disposal. Excluding the more exotic proposals which do not seem feasible with existing tech-

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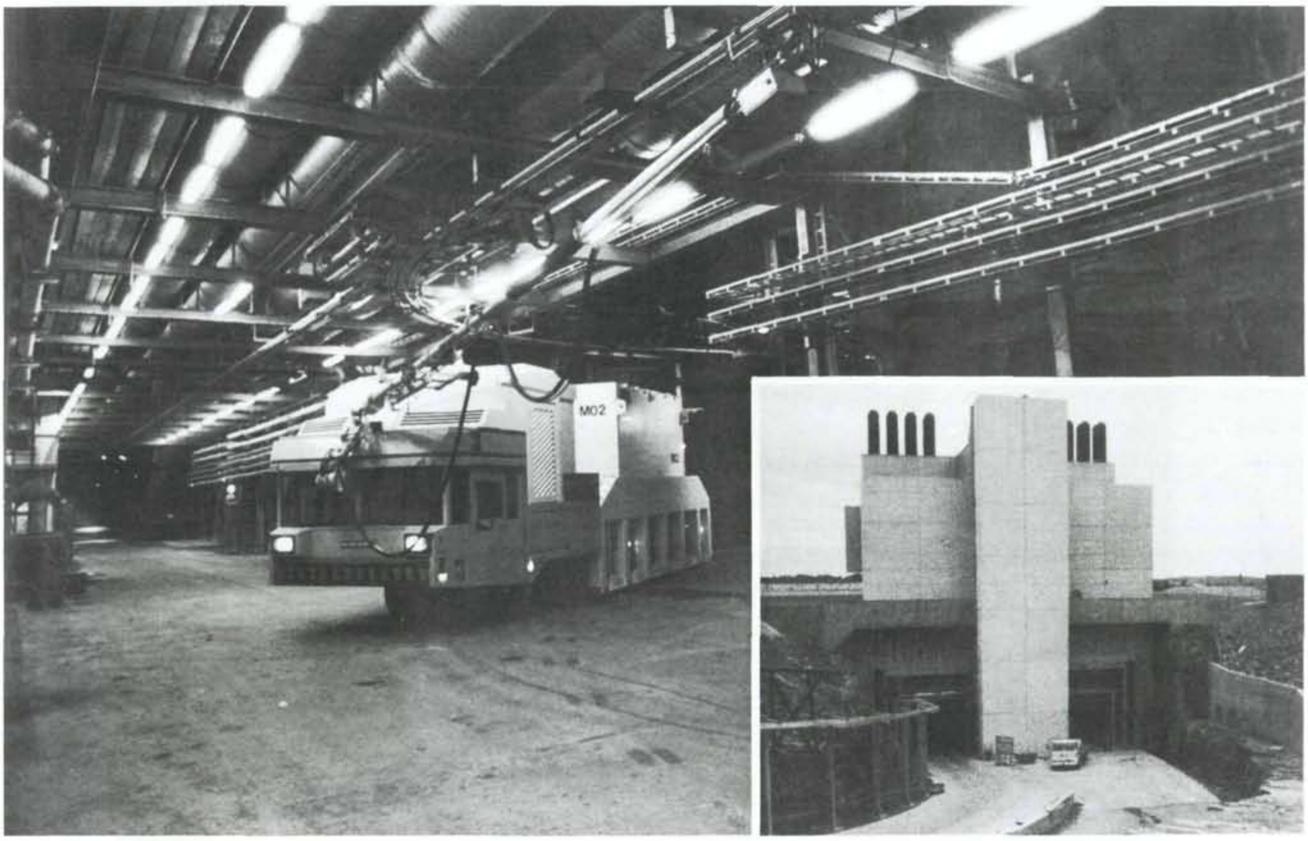

Sweden's repository for low- and intermediate-level radioactive wastes is located at the Forsmark nuclear power station. The repository, built in a mined rock cave, started operation in 1988. *(Credit: SKB)*

nology, e.g., sending the waste to the sun or outer space or using transmutation in high-flux neutron reactors, there are two basically different principles for the management of radioactive wastes — dispersal and confinement.

Dispersal means the release of radionuclides into the environment, in the normal case in a controlled manner in order not to have any detrimental impact on humans and the nature.

Confinement implies the segregation of radionuclides from the human environment and the restriction of their release into that environment in unacceptable quantities or concentrations.

Dispersal can only be used for limited amounts and low concentrations of radionuclides in order to adhere to the principles of recommendations of the International Commission on Radiological Protection (ICRP). Very low-level radioactive liquid wastes from waste treatment plants of nuclear reactors and reprocessing facilities are today discharged to rivers and to the sea. For many years, dispersal has also been employed for solid waste in the form of sea dumping of low-level radioactive material. This practice has recently been abandoned, at least temporarily, due to wide public opposition.

For the main amounts of the radioactive waste, it is necessary to use confinement of the material for periods of time which depend on the characteristics of the waste, above all its nuclear composition. Waste containing nuclides with short half-lives need confinement only for a fairly short time, up to a few hundred years, while long-lived nuclides may require confinement for tens of thousands of years or more. It is being realized that after long periods of time, in some instances millions of years, any confined radioactive waste may be released and dispersed into the environment. However, the radioactivity will have decreased to very low levels and be below acceptable international dose standards.

The basic safety principle for confinement is "defence in depth". This principle implies that it is customary to use several, ordinarily independent "barriers" to delay or prevent radionuclide migration from the waste or the repository into the surroundings. Natural barriers are, in the case of deep geological repositories, represented by the host rock and the surrounding geological formation. An engineered barrier is a feature made by or altered by man; it may be part of the waste package or part of the repository.

Repositories for radioactive wastes can broadly be categorized into three groups: near-surface disposal facilities, disposal facilities at intermediate depths, and deep geological disposal. Considerable experience has been developed from disposal of low-level wastes in near-surface disposal facilities. Disposal at intermediate depth is being practised in a more limited scale, whereas deep geological repositories are generally not yet in operation.

Repositories for high-level waste and spent fuel are, with some exceptions, in the research and planning stage. Considerable work is still needed to develop an appropriate siting methodology and to find suitable sites for this type of waste. Many countries have instituted an extensive research and development programme for high-level waste.

Natural barriers

The natural barriers provided by the host rock are the main justification for geological disposal. A barrier is defined as a feature which delays or prevents radionuclide migration from the waste and/or repository into its surroundings.

To evaluate the effectiveness of natural barriers, as well as engineered barriers, aspects of physical isolation, hydrogeology, and geochemistry have to be considered. Furthermore, the behaviour of the radionuclides in the biosphere must be included, e.g., dilution and dispersion in soil, shallow aquifers and surface water, atmosphere, and the food chain.

Emplacement of waste below the surface utilizes the overlying rock as a physical barrier to invasive processes which could cause releases to the environment, e.g., deliberate or inadvertent human intrusion, fires, airplane crashes, floods, and hurricanes. Subsurface structures are also less subject to damage by earthquakes, and the rock acts as a radiation shield and a sink for radiogenic heat.

In general, the effectiveness of the isolation of the waste, and also the suitability of hydrogeological and geochemical regimes, increases with increasing depth. This has to be balanced, however, against constraints set by temperature, engineering practicality, operational safety, and costs. The criteria for selection of a defined depth of a repository vary greatly with waste type, disposal concept, and host rock. This implies that the criteria have to be established for each individual site.

Near-surface repositories tend to have a higher risk of loss of isolation from natural events, such as storms and earthquakes. Often these repositories rely only on engineered barriers for the isolation and not at all on the geosphere. This implies that as soon as the engineered barriers fail, the waste is directly released into the biosphere. For short-lived waste, this situation may be totally acceptable, while for long-lived waste this may not be the case.

Hydrology. The most likely mechanism causing release of radionuclides from a repository involves ingress of groundwater. For deep repositories the hydrologic characteristics of the host rock are thus of key importance. Primary parameters required to characterize the hydrology are water fluxes, velocities, and flow paths. They are dependent on regional hydraulic gradients and on properties of the host rock and surrounding formations, such as porosity and permeability. The hydrologic characteristics are needed for the development of a mathematical model of the system.

Salt and anhydrite deposits are being considered as possible host formations for high-level waste repositories of the dry rock type. Although all rocks contain some water, rocks such as salt or anhydrite contain no apparent connected water-filled pores which would provide a pathway for transport of dissolved radionuclides. However, mechanical disturbance during repository construction or radiogenic temperature fields may cause some migration of any fluid inclusions. In the normal evolution scenario, no releases would occur from such a repository as long as the host rock remains intact. The WIPP facility in the United States is an example of a repository in a bedded salt deposit. The Gorleben facility in the Federal Republic of Germany is an example of a site being investigated for a repository in a salt dome.

Certain near-surface disposal sites and deep disposal sites in arid climates may be located above the water table. The host rock is thus unsaturated, indicating that the connected pores of the rock are not entirely water-filled. The degree of unsaturation varies between different systems and may, indeed, change seasonally. The dryness and the very low rates of water movement often found in such rocks make them attractive candidates for waste disposal. Any water transport which did occur would be through a microporous system which provides a great potential for radionuclide retardation due to sorption processes and which could also act as a filter for colloidal species. The Yucca Mountain at the Nevada test site in the United States is an example of a repository site in the unsaturated zone. The rock consists of densely welded rhyolitic tuff.

Most effort worldwide is today focused on disposal in saturated rocks, as such rocks are common in most countries with nuclear programmes. Saturated rocks are often classified as either porous or fractured.

Ideally, porous rocks should have no major structural discontinuities; water flow (or nuclide diffusion in the case where flows are negligible) should occur uniformly throughout the bulk of the rock. The water velocities through such rocks should be very small and the entire rock matrix should be available for sorption. In practice, porous rocks are enclosed by strata having quite different properties from the host rock, making the hydrology much more complicated.

In many rocks, flow occurs predominantly in distinct, isolated features, generally classified as "fractures". These include a wide range of geological discontinuities. The bulk hydrologic properties of such rocks, e.g., granites and clays, can be quite attractive, as they have low water fluxes and velocities. However, the characterization of their hydrological properties presents many problems.

Several countries, e.g., Canada, Sweden and Switzerland, have large development programmes on deep repositories for high-level waste in saturated rock, including site investigations and underground testing laboratories. The Swedish SFR underground repository for low- and intermediate-level waste serves as an example of an operating facility in saturated rock.

Geochemical. The geochemical properties of the host rock cause it to serve as a barrier by providing an environment which slows down or prevents the degradation of engineered barriers and, in the event of loss of complete containment in the repository, limits the rate of mobilization and transport of radionuclides. The properties of a particular geochemical system are also very dependent on the waste type and the repository design.

Site selection. Selection and characterization of a site for disposal of radioactive waste proceeds through several stages. Generally, a survey is performed in order to identify suitable general areas according to the criteria set up for the repository. A few areas are then selected for further study. Field studies have to be made, and in case of underground disposal sites, boreholes have to be drilled to characterize the sites. Modelling the hydrology is a major part of this characterization.

While siting the repository away from volcanic features is obviously advantageous, the positioning with respect to major faults is not so clear. Although it is obviously desirable that a major fault does not penetrate the repository, since such a feature is a potential transport pathway, it also represents a weakness along which movement will occur in response to build-up of tectonic stress, thus decreasing the chances of new fissures occurring within the repository area. Furthermore, predominant faults surrounding a repository tend to isolate the repository from the groundwater flow. Examples of this kind of reasoning can be found in the Swedish KBS-3 study.*

For all repository types, but particularly those near the surface, human intrusion scenarios must be carefully considered. Careful siting away from natural resources can minimize such risks.

Prediction of the temporal evolution of the disposal system is a key problem area and this is as applicable to the geosphere as it is to the biosphere. As far as physical isolation is concerned, the process of most interest is usually erosion. Such erosion is inherently dependent on the tectonic processes and the climate, which affect the hydrology and hence the geochemistry.

Engineered barriers

An engineered barrier is defined as a feature made by or altered by man; it may be a part of the waste package and/or part of the repository. The engineered structures in a repository perform a number of roles which may differ in significance for different waste types and repository concepts.

In France, the La Manche disposal site incorporates elaborate engineered barriers to prevent the radioactive waste from coming into contact with groundwater. (Credit: ANDRA)

The prime role of the waste matrix is to constrain the release rate of contained radionuclides to a value set by its slow degradation. When stability over long periods of time is required, mechanistic understanding of matrix degradation is required to support more empirical modelling approaches. For high-level waste, the matrix in the case of disposed spent fuel is usually the uranium dioxide itself; for reprocessing waste it is usually borosilicate glass, although a number of alternative waste forms, for example Synroc and ceramics, are also being studied. Cement and bitumen are often employed as waste matrices for intermediate-level waste. In the case of low-level waste, generally no matrix is needed.

The container is a means of providing complete isolation of the waste matrix for a certain period of time. The time required for keeping the integrity of the container varies according to the type of waste, the site characteristics, and the legislation in a specific country. In the United States, for example, a minimum isolation time of 1000 years is required for high-level waste. The Swedish KBS-3 study indicated isolation times as long as one million years for a copper canister. The requirements for low- and intermediate-level waste are not as stringent. The main purpose of the container in this case is often to prevent contamination, ease the handling of the waste, and act as a radiation shield during emplacement. Metals are normally selected as container

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* *Final Storage of Spent Nuclear Fuel — KBS 3*, 4 vols, Swedish Nuclear Supply Co. SKBF/KBS Sweden (1983).

materials for high-level waste because of the requirement for mechanical strength. Standard metal drums are ordinarily used for low-level waste as well as for intermediate-level waste, although for this latter category concrete containers are also utilized.

The purpose of a flow barrier is to ensure that groundwater mainly flows around, rather than through, the engineered barriers of the repository. This occurs when the near-field has a lower permeability than the host rock. In practice, this can be achieved by using a low permeability backfill, e.g., bentonite and special cements. In many cases, the flow barrier will also have the additional function of retarding the transport of radionuclides leached from the waste matrix by serving as a complexing geochemical medium.

In the case of heat-emitting wastes, it is important to ensure that the engineered barriers are designed so that unacceptably high temperatures are not reached in the repository or its surroundings.

One factor which has come to the fore in the last few years is the potential role of gas formation in a waste repository and its influence on the performance of engineered barriers.

As the complete system of engineered barriers consists of a number of components, some performing several roles, the interaction between the different barriers must be evaluated. For deep repositories, interfaces, particularly between engineered structures and the host rock, are of particular concern in the area of backfilling and sealing, as a range of openings, including tunnels, shafts and boreholes, have to be filled and sealed during final closure of the repository.

Repository design concepts

Considerable experience exists from shallow ground disposal of low-level waste. Many facilities of this type are being operated, e.g., in Canada, France, the United Kingdom, and the United States, and the technique for shallow ground disposal is well established. Existing facilities vary in design, depending on local circumstances, such as waste packaging and site characteristics. Sometimes, as in the French disposal site at La Manche (La Hague), elaborate engineering facilities are used to prevent contact with groundwater. In other instances, as in the United States, use is made of the arid climate at the site, which makes it possible to use simple trenches and backfilling techniques. The tendency today is to construct much more well-designed facilities than was the case previously. Also, the licensing authorities normally require a thorough safety analysis to be performed and approved, before any shallow ground repository is allowed to go into operation.

Until recently, near-surface disposal has been the most prevalent practice for the disposal of low-level radioactive wastes. This technique now includes certain alternatives, such as earth-mounded concrete bunkers, below-ground vaults, and mined cavities. An example of a repository for low- and intermediate-level waste in a mined rock cave is the Swedish SFR repository, taken into operation in 1988. Another example is the Konrad facility in the Federal Republic of Germany, which is almost completed but has not yet been approved for operation. Konrad utilizes an essentially dry disused iron ore mine for disposal.

It is generally recognized that the necessary degree of long-term isolation for wastes containing large amounts of long-lived radionuclides can only be obtained in deep geological repositories. Programmes for the development of deep geological systems for disposal of high-level waste have been initiated in a number of countries. Conceptual designs have been developed as a part of the development programmes. While designs are and must be specific to the site and host rock, all are based upon the concept of multiple barriers — natural and engineered — to assure the necessary containment and isolation.

Although no repository for high-level waste is yet in operation, since the WIPP facility in the United States is still waiting for its operating permit, advanced plans exist in many countries. Illustrating examples can be found in the construction studies for the German Gorleben site, the designs for the Swedish KBS-3 study, and designs for the Swiss study Project Gewähr.*

Performance assessment of a disposal system

One of the most important areas of research and development related to radioactive waste management is the analysis of environmental impacts and performance assessment of radioactive waste disposal systems. There are various approaches to these tasks, but all have one common goal — to extract pertinent information from field and laboratory studies in order to assess the performance of a disposal facility in relation to safety and acceptability criteria. These criteria are being developed and refined by the appropriate national and international authorities.

It is recognized that the long-term performance of a disposal facility cannot be demonstrated directly, as we are dealing with time periods covering thousands or sometimes tens of thousands of years. We have to revert to indirect methods, using predictive analysis based on a detailed knowledge of the disposal arrangement and processes acting on the structure.

Many countries are spending substantial efforts in the development of methods for the assessment of the performance of repositories over long time scales. Safety analyses for waste repositories require the development of models which can describe real disposal systems and quantify the processes that occur within them. In order

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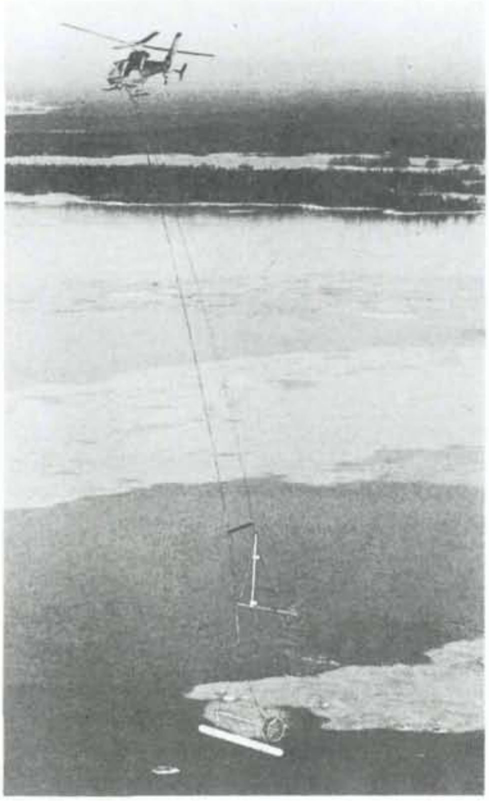
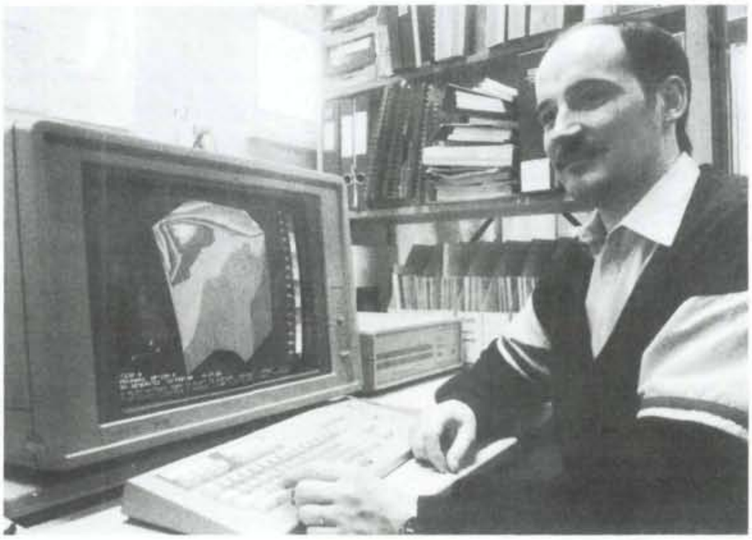
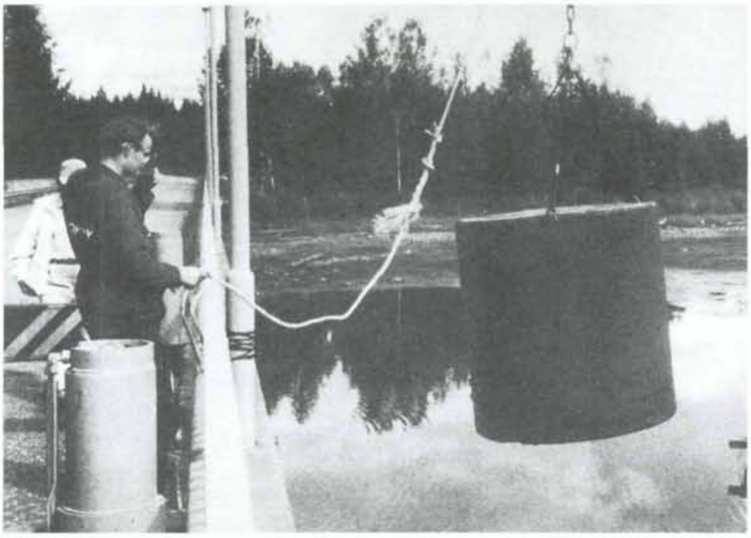
* "Site investigations and conceptual designs for the repository in the nuclear 'Entsorgungszentrum' of the FRG," Röthemeyer, H., IAEA-SM-242, Vol. 1 (1980) 297-30. Also, *Project Gewähr,* 8 vols, NAGRA NGB-89-09, NAGRA, Baden, Switzerland (1985).







In Finland, extensive research has been conducted for nuclear waste disposal. As part of site investigation studies, a geophysical airborne survey was done. Computer codes are used for studies of groundwater movement. Additionally, full-scale concrete waste containers were submerged in a river for 5 years to test their properties. (Credit: YJT, Finland)

to achieve the predictive capacity required to carry out such analyses, it is essential to develop a thorough understanding of the processes involved, fully characterize the system being modelled, and establish a complete database.

With respect to analysis of biosphere performance, the current patterns of radionuclide transport through the biosphere over fairly short time periods are quite well understood. The major problems arise, however, regarding the evolution of the biosphere far into the future and the possible changing patterns of human eating and living habits.

In general, the techniques for safety analysis can be divided into two large groups, probabilistic and deterministic analyses. An event might have a certain probability of occurring within a certain time period, or the event may be certain to occur within the same period. It is important to recognize that probabilistic analysis and deterministic analysis are complementary techniques, and that both should be used in a comprehensive safety analysis.

Safety assessment aims at demonstrating compliance with performance objectives, most often expressed as acceptability criteria. The assessments are of two general types, generic and site-specific; both types of assessments are usually performed in an iterative manner, until the system is thoroughly understood and conclusions can be drawn.

Generic assessments are useful for making decisions regarding a concept or choice between concepts. They are also helpful for gaining acceptance from the authorities and from the general public for the geological disposal concept itself. Site-specific assessments are an integral part of the decision-making process during siting, design, construction, operation, shutdown, and sealing of a radioactive waste disposal facility.

The technique generally applied in performance assessment is to make mathematical models, representing physical and chemical processes of importance for predicting the behaviour of the repository over long time periods. The question then arises, how well the model can describe the real events. The process carried out by comparing results of predictive analysis (modelling) with field and laboratory observations and measurements is usually called validation. Properly conducted and carefully designed laboratory and field experiments are crucial for model validation. Also natural analogues, such as analyses of uranium ore bodies can be used for validation purposes. However, in the framework of complete confirmation of future behaviour of a disposal facility, a "full validation" can never be achieved. International studies within the field of safety analysis and performance assessment are being conducted by a number of organizations, e.g., the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (NEA/OECD), Commission of the European Communities (CEC), and Swedish Nuclear Power Inspectorate (INTRAVAL).*

Institutional aspects

Disposal of radioactive waste involves a number of issues which must be addressed through a reasoned decision-making process. Most countries with programmes for waste disposal regulate these programmes through licensing actions by means of a body whose purpose it is to review, certify, and ensure all of the stages of the disposal programme. The regulatory body may either be one single national authority or a system of authorities designated by the government. The key to such regulation is a set of procedures for the actions of the implementing organization, the review by the regulatory body, and the involvement of other parties.

In some countries, e.g. in the United States, the government may undertake both the implementing and the regulatory functions. Nevertheless, also in these countries, the implementing functions for waste disposal are, as a rule, effectively separated from regulatory functions.

Several countries with nuclear power, e.g. Finland, Sweden, and the United States, require that the power-producing companies set aside money for the funding of waste disposal. Ordinarily, they pay an amount based on the kilowatt-hours produced. The sums collected are generally being used for research and development in the waste disposal field and will also suffice for construction and operation of necessary disposal facilities. In some countries, as in the case of Sweden, the funds will also cover decommissioning of nuclear facilities and disposal of decommissioning waste.

It seems to have become increasingly difficult with time to obtain public acceptance of nuclear facilities, including waste disposal facilities. Information appears to be a key word. How to inform the public on the safety matters in the nuclear field is an issue of considerable interest today, both among the nuclear power producers, politicians, and safety authorities. The IAEA has devoted much time and convened several symposia covering the aspects of public acceptance. One difficulty is that a solution for one country is seldom directly applicable to another country.

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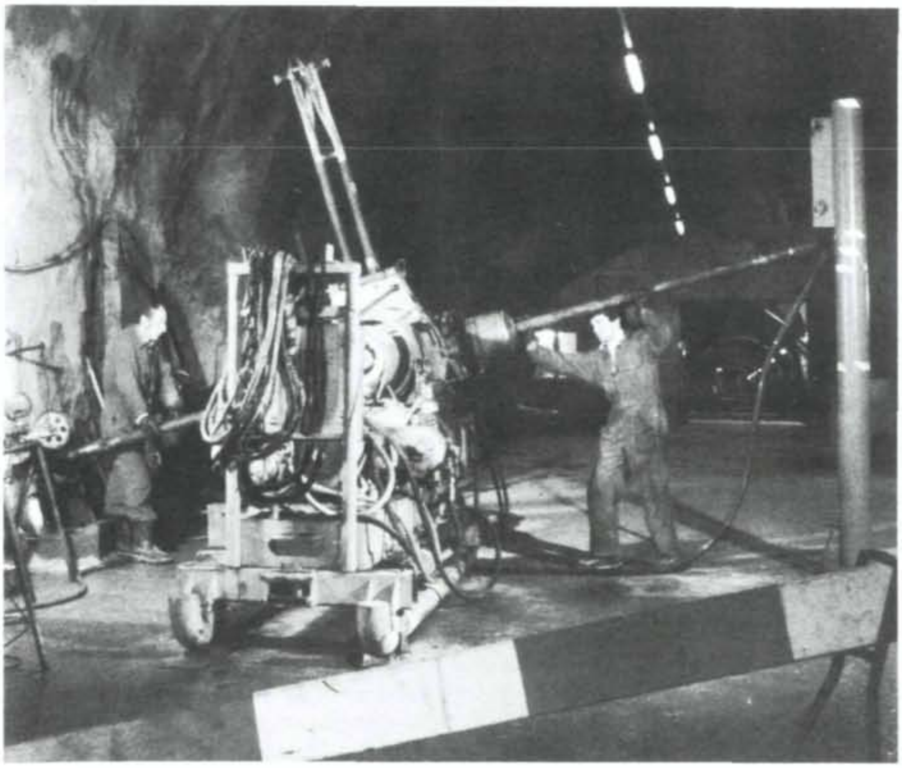
* *Safety assessment of radioactive waste repositories*, Proceedings of the CEC/IAEA/NEA Symposium, Paris, France, 9-13 October 1989 (to be published by NEA).



In a number of countries, nuclear waste research is being carried out at underground facilities, such as the Mol facility in Belgium. (Credit: UNIPEDE)

Over the years, an extensive international co-operation has emerged in the radioactive waste management field. This co-operation includes not only the international bodies, such as IAEA, NEA/OECD, CEC, ICRP, and the United Nations Environment Programme (UNEP), but also other constellations, bilateral or multilateral. This co-operation has proved to be of utmost importance and the results of collaborative work are being utilized by all organizations dealing with waste disposal.

Concluding remarks

The future development of nuclear energy is dependent on our ability to handle and dispose of radioactive waste in a safe and acceptable manner.

It seems that we now can master the means for disposal of low- and intermediate-level waste. Site-specific solutions have to be found for individual repositories, but no main difficulties should be encountered, maybe with the exception of achieving public consent.

The situation for high-level waste is partially different. The technique for disposal exists, but the methods for assuring the safety still need more development. Again this question is closely linked to public acceptance. It has resulted in safety authorities requiring a considerable database and a thorough safety analysis for a proposed repository.

In view of the substantial research and development work in making field measurements — for example, in the underground laboratories in Canada, Sweden, and Switzerland, complemented by laboratory work in chemistry and geochemistry, and theoretical work in mathematical modelling — there is no reason why there should be a delay in designing, constructing, and operating high-level waste repositories. Apparently, there will not be any operating high-level waste repositories in Europe before the year 2000. In the United States, the plans are to have a disposal facility for high-level waste around the year 2000. It has to be remembered, though, that an early disposal of high-level waste is not technically or radiologically necessary: experience has proven that these wastes can be safely stored in engineered surface facilities for many decades.