DEMONSTRATION OF THE FEASIBILITY OF SAFE DISPOSAL OF RADIOACTIVE WASTES: THE SWISS APPROACH

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ABSTRACT

In Switzerland the further development of nuclear energy, and also the continuing use of current power plants, was made conditional upon the preparation of a project indicating the feasibility of safe disposal of nuclear wastes. The required scope of the project is wider than in other countries since it includes all wastes from reprocessing, from plant operation and from non-power-production sources. At the beginning of 1985, documentation on the work performed by Nagra in the last 6 years to produce appropriate projects was submitted for government review.

The concepts developed are (i) for a deep repository in crystalline bed-rock which will accomodate high-level vitrified wastes and possibly some actinide wastes from reprocessing, and (ii) for a horizontally accessed repository in marl for all other wastes including voluminous decommissioning wastes. Aspects documented include the characterization of all wastes, the engineering of both repository types and the long-term safety analyses. The results given are based on an extensive programme of laboratory work, field measurements and analyses. Geological data from Swiss site investigations are used, although no specific repository sites have been fixed at present.

The approach to the analysis of potential radiological consequences is primarily based on application of linked, deterministic models. Dose predictions for base-case scenarios, involving slow degradation of barriers leading to transport of radionuclides in groundwater, are very low at all future times. The technical and geological barriers both contribute to produce this result. Scenarios based on geological changes and on human intrusion have also been examined in order to ensure that no reasonable assumptions can lead to unacceptably high doses.

The projects have been designed primarily to meet the feasibility requirements mentioned. The documentation includes references to aspects where further investigations should be performed, either to clear up specific issues or to move to more optimized concepts before preparation of projects for the realization of waste repositories.

DEMONSTRATING THE FEASIBILITY OF SAFE DISPOSAL

The problem of demonstrating that safe disposal of radioactive wastes can be achieved has been much debated in recent years. Government requirements in this area have led to the preparation of specific projects in Sweden[1], Denmark[2], and Germany[3], and the results of the former study have been accepted as justifying commissioning of new nuclear plants. In international circles, thought has also been given to the meaning of a demonstration project[4]. Two components are normally judged necessary; one involves illustrating technical feasibility (by detailed engineering design work and perhaps even in-situ trials), the other is the preparation of a convincing case showing a high level of long-term safety. This latter aspect must be based on adequate modelling capabilities, a sufficient database, and convincing validation (through experiments or comparisons with analogue systems) of the analytical approaches used to quantify safety. Whilst most scientists in the field are convinced that repository safety is in principle possible, detailed projects and analyses are required for specific repository proposals.

In Switzerland planning of projects for the realisation of waste disposal projects has been underway for some time, with the appropriate intermediate and long-term timescales, according to the waste types involved. In 1979, however, it was legislated, following a popular referendum, that general demonstration projects should also be prepared before any further nuclear plant licenses were granted. The timescales for preparation of such projects became shorter when the licensing authorities decided that the same condition be applied to the renewal of operating permits for current plants beyond the year 1985. As a response to these requirements, Nagra (the National Cooperative for the Storage of Radioactive Waste) has coordinated the production of a warranty project ("Gewähr") which was submitted to the Swiss government at the beginning of 1985 to allow adequate time for review and assessment[5].

The definition of form and content of the project has been discussed repeatedly at technical, legal and political levels during recent years. A final consensus was indicated which includes the following important points:

- High, intermediate and low-level wastes (HLW, ILW, LLW) are included, but the main emphasis is on HLW consisting of vitrified residues from foreign reprocessors.

- Engineering projects showing technical feasibility are to be prepared.

- Real field data from geological investigations in potential siting regions are needed; but a specific site need not be named.

- The quantification of repository long-term safety is the central issue within the Gewähr project.

- The acceptable safety is specified by the guideline R-21[6] of the Swiss nuclear safety authorities, this is basically a deterministic individual dose limit of 10 mrem/y from a repository at any time in the future.

THE APPROACH ADOPTED IN SWITZERLAND

Based on the above requirements a large programme of technological investigations, geological field work, and analytical studies was developed and carried through during the past 6 years. A reference nuclear power programme of 6 GW(e) over 40 y was defined (this is twice the current installed capacity) and the total waste inventories arising were characterized in detail. Included are reprocessing, operational and decommissioning wastes from power stations, as well as waste from industrial, medicinal and research applications.

Nagra's earlier conceptual planning included basically 3 facility types[7]: a deep repository (Type C) for HLW, a geologic repository with less overburden (Type B) for ILW and LLW, and a near-surface largely engineered facility (Type A) for low-level wastes, primarily from decommissioning. Flexible allocation of wastes to appropriate disposal facilities is the goal of the concept. For project "Gewähr", a simplified procedure is used, in which the projected Type B repository includes capacity for all ILW and LLW so that no Type A facility is needed. Fairly detailed design work has been performed for a Type C repository and a Type B repository. For each repository the safety is analysed in two overview reports, the first of which reviews safety barrier behaviour, whereas the second contains the safety analysis results. The total structure of overview reports and of accompanying technical reports is summarized in Volume 1 of Ref. 5.

REFERENCE PROJECT FOR HIGH-LEVEL WASTE DISPOSAL

Repository Concept

Although a variety of engineering concepts have been reviewed, and a range of potential host rocks are available in Switzerland, one particular set of options has been chosen for the "Gewähr" project, in order that the data for safety analyses be as specific as possible. The repository system proposed is a mined facility around 1'200 m below the surface in the crystalline bedrock which is covered by some hundreds of metres of sediments. No definite site has been proposed but geological, hydrological and geochemical data are based on field data gathered during a regional geologic programme including a series of 6 deep drillings (1'500 - 2'500 m). The HLW to be disposed of in the repository consists of around 6'000 cylinders of borosilicate glass returned from foreign reprocessors following treatment of 7'860 t of spent fuel resulting from the reference power production programme of 240 MW(e)·a. A special feature of the planning is that flexibility in allocation of all nuclear wastes to an appropriate repository is ensured by allowing also for disposal of intermediate-level actinide wastes from reprocessing which may be unsuited for storage in the planned Swiss LLW/ILW repositories.

Engineering project studies have been performed to develop a reference repository design. The objectives were to assess the required technical expertise for engineering a repository system, and to provide a basis for safety analysis work. No technical optimization has been carried through. The repository consists of a series of tunnels 3.7 m in diameter lying in the interior of a tectonically stable block of crystalline bedrock. HLW canisters are delivered from an intermediate storage facility to the repository surface reception area where they are sealed into massive cast steel containers. The sealed packages are transferred in shielded containers down one of two 1'250 m shafts accessing the repository working level. They are then emplaced 5 m apart centrally in the tunnel axis surrounded by compacted bentonite blocks.

The filling operations take place simultaneously with drilling of further storage tunnels, with however complete spatial separation of constructional and operational activities. The storage area for non-HLW consists of 10 m diameter silos all of which are excavated before the start of disposal operations. The total building costs and times are estimated at 600 Mio SFr and 15 years. The conclusion of engineering studies carried out within the framework of the Swiss warranty project is that the required technology for construction, and operation of a deep HLW repository is already available today.

Analysing the Safety of the Type C Repository

A broad programme was aimed at understanding the behaviour of all components of the safety barrier system, and thus at improving our confidence in long-term predictions. The characteristics of the host rock and surrounding geosphere can be investigated only by extensive geological field work, which in the Swiss case is particularly complex and costly. The crystalline bedrock (granite and gneiss) is overlain by varied sediment sequences, in total some hundreds of metres thick. Mapping the surface topography of the bedrock, and understanding its tectonic, hydrologic and geochemical characteristics require a combination of advanced seismologic methods, deep drillings with complex test methodology, and surface observations and measurements over a large region.

These approaches have been employed over several years to allow a picture of representative deep geologic conditions to be built up; for the warranty project the data are gathered into a model data set upon which construction and safety studies are based. The assumed host rock is granitic with extensive small scale fracturing, almost all of which is, however, sealed by subsequent deposition of minerals so that the resultant hydraulic conductivity is low. Extensive borehole test sections have been shown with packer tests to have conductivities between 10^{-9} and 10^{-12} m/s. The small quantities of water which flow through such rocks (approx. 4 m^3/y for the whole repository area) are mainly confined to zones of relative weakness where tectonic movements have altered the rock structure. This has a huge impact upon system safety since the weak zones have a relatively high porosity (around 3%) and excellent sorption properties for radionuclides which diffuse out of the isolated water-carrying features within the altered zones.

The granite structure sketched here is found at considerable depths below the upper surface of the crystalline basement. The first few hundred metres of granite carry much more water and influence radionuclide release concentrations only by providing a significant dilution factor (around 10^4). Evidence for a qualitative difference between upper and lower granite is obtained not only from hydraulic testing but also from characterization of the chemistry of the rock itself and of the deep groundwaters. At depth reducing conditions are observed, which has an important influence on solubilities of compounds of radionuclides and hence on potential release rates. Even with very pessimistic assumptions for the important safety parameters, the geosphere conditions described ensure that radionuclides released from the near field of a repository can reach the biosphere only much later at greatly reduced concentrations.

Moreover, the technical barriers within the repository system themselves greatly restrict releases of radionuclides from the near field. Extensive work in various countries has been devoted to demonstrating the corrosion resistance of borosilicate waste glasses; based on this and on results of a current joint Japanese, Swedish, Swiss active glass leaching study, a reference lifetime for the vitrified waste of 150'000 years has been conservatively adopted. The massive steel pressure-vessel around the waste delays the start of glass corrosion at least 1'000 years. Equally important, however, is the chemical buffering effect of residual iron and corrosion products which remain after mechanical failure of the container occurs. The resulting low solubilities for important radionuclides ensure that releases occur only at very low levels. Finally the compacted bentonite, which in the reference design is over 1 m thick, provides a diffusion barrier which can delay releases for tens of thousands of years and thus allow decay of all nuclides which do not have very long half-lives.

Furthermore, even at steady-state conditions, radionuclides can be transported through the bentonite by diffusion only up to a maximum rate which is independent of the water flow in the adjacent host rock so that a degree of decoupling is present between technical and geological safety barriers. Figure 1 gives a schematic view of the total repository system modelled in the safety analyses.

Predicted Safety for HLW Repository Type C

The prime objective of the projects prepared for government review was to quantify the level of safety achievable for a repository system of the type described. Using appropriate calculational models the radiation doses which might arise due to releases of radionuclides from the HLW repository have been calculated. In choosing models and data, efforts were made to define a base case which should give a reasonably realistic picture of potential consequences, whilst ensuring that estimates remain on the high, i.e. conservative, side. For the chosen base case totally negligible doses were calculated (less than 10^{-7} mrem/year). Even when compounding pessimistic assumptions and data predicted doses remain very low (less than 10^{-2} mrem/year). It is clear that various issues remain to be further classified and that the predictions based on real, but limited, field data must be confirmed for a fully characterized site. However, the doses calculated are small, in absolute terms and relative to the low value of 10 mrem/y included in the Swiss safety authority guidelines, so that adequate safety is predicted for the high level waste repository.

REFERENCE PROJECT FOR L/ILW DISPOSAL

Repository Concept

Various host rocks have been considered for disposal of L/ILW in Switzerland. Currently Nagra is awaiting government decisions on applications submitted over a year ago for permission to conduct site investigations at 3 sites (in crystalline rock, anhydrite and marl). For project "Gewähr" the marl site was chosen as a model-dataset, since existing workings in the area have led to the availability of unusually large volumes of relevant geotechnical data. The choice of this model-dataset is not intended to prejudice the selection at a later date of an actual site for the Type B repository. The reference repository concept is a horizontally accessed tunnel system lying within a marl formation several hundred metres below the summit of the mountain Oberbauenstock near Lake Lucerne in central Switzerland. Up to 200'000 m^3 of mostly cement-solidified wastes from reprocessing, plant operation and decommissioning can be disposed of.

Repository Design

An access tunnel of cross section around 50 m^2 (partly in limestone, partly in marl) leads to the array of storage caverns approximately 170 m^2 in area and 200-400 m long, which are lined with thicknesses of concrete between 60 cm and 80 cm to allow for the increase in lithostatic pressure with overburden. In reception facilities near the entry of the access tunnel, all wastes in smaller packages are packed into 2 m x 2 m x 4 m concrete containers which are then filled with liquid cement. The large containers are transported into the repository and allocated to the appropriate storage tunnels. Wastes of varying radiotoxicity or of different chemical types are kept apart. The storage tunnels are backfilled in sections using a special cement mixture with suitable hydraulic and mechanical properties. Figure 2 gives a view of a section of partially filled storage tunnel. The total excavated volume is around 10^6 m^3 of marl; the estimated building costs and time are approximately 320 Mio SFr. and 7 years.

As for the case of the high-level waste repository Type C the conclusions drawn from the design studies are that although not yet optimized concepts are feasible under the technical and economic conditions of today.

Analysing the Safety of the Type B Repository

As mentioned above, no field work has as yet been able to be devoted to specific investigations of the Oberbauenstock site as a potential repository host formation. Desk studies have, however, been complemented by the data gathered during planning and construction of two major highway tunnels which pass through the marl some 600 m distant from the potential repository location. The intact marl is of low hydraulic conductivity ($\sim 10^{-12}$ m/s). Water moves predominantly in tectonically disturbed zones which have a conductivity of approximately 3×10^{-9} m/s and constitute around 3% of the host rock. Extensive two and three-dimensional hydrologic modelling of the study site has been carried out using differing assumptions for the as-yet unknown geological data.

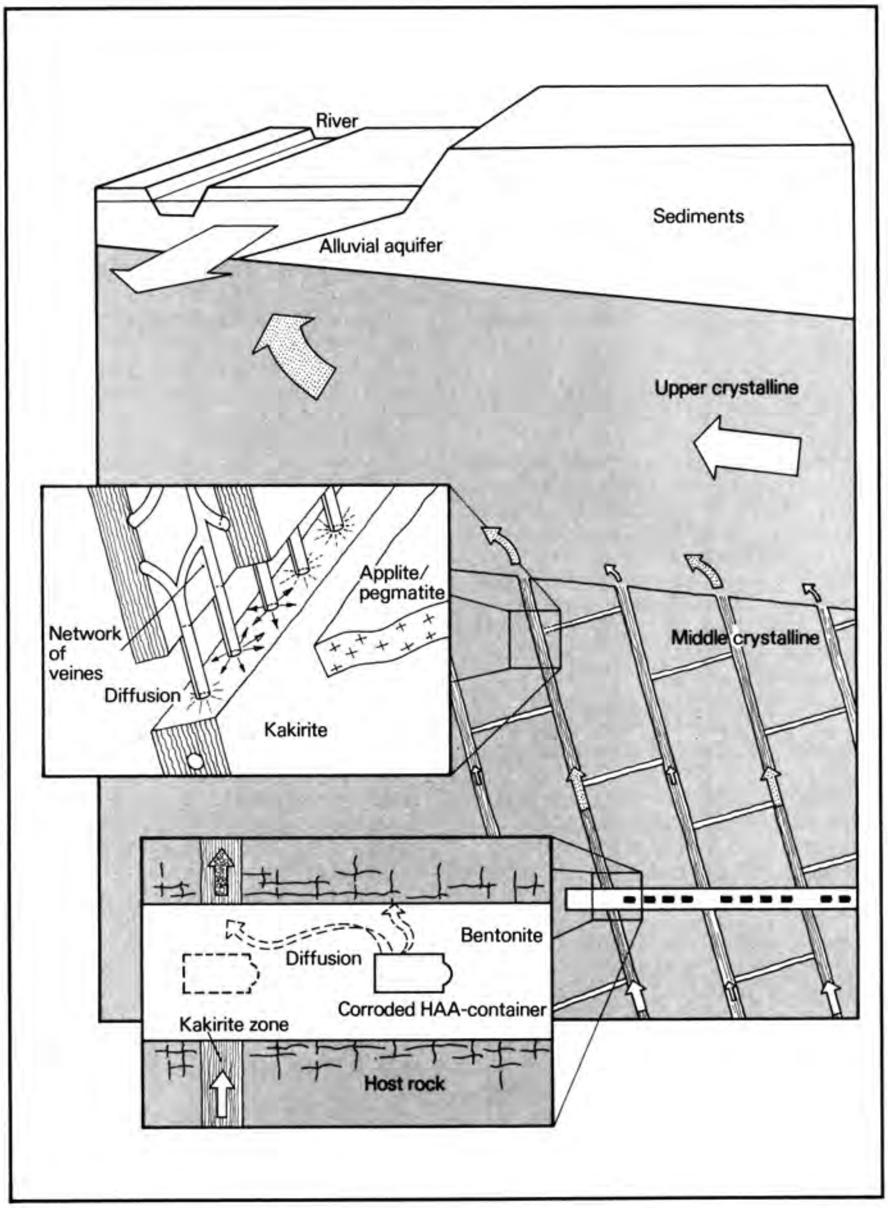

Fig. 1. This gives a schematic overview of those features of the total HLW disposal system which are explicitly modelled in the safety analyses.

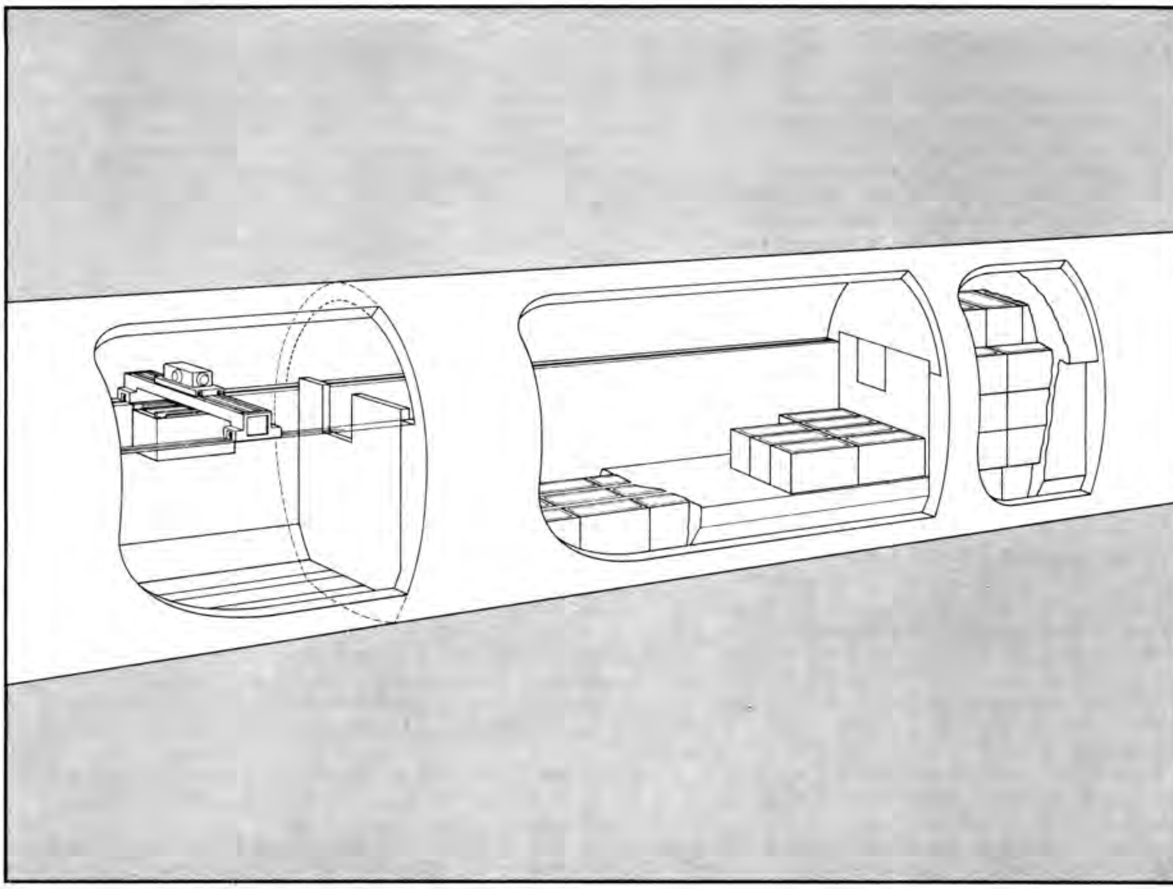

Figure 2: This illustrates the disposal of L/ILW in large diameter caverns in marl. Successive repository sections are filled with the monolithic waste containers and then backfilled with special cement.

Predicted water flow paths lead to the large lake or else to a decompressed zone around the existing tunnels which are assumed at some future date to have fallen into disuse and collapsed. Predicted water flow times are 600 to 1'600 years. Is is conceivable that the decompressed zone which will form around excavated tunnels might substantially influence the flow regime; calculations have been made with different conductivity estimates which can be firmed up only through site investigations.

The technical barriers containing the radioactive wastes are the cement matrix, the container, and the tunnel backfill and lining. It is assumed in the base-case analyses that nuclides can migrate to the groundwater by diffusion through the technical barriers. Appropriate diffusion and retardation coefficients are obtained by evaluation of available literature. Diffusivities are assumed to change as cement ages, with values increasing to those of compacted sand at 500 to 10'000 years. Alternative processes which can remove radionuclides from the repository near field are advection, in the case that barrier degradation leads to sufficiently high hydraulic conductivities, and gas pressure, if sufficient gas build-up can occur. Gases can be formed by corrosion, microbiological or radiolysis processes, whereby the first-mentioned is by far the most important.

A final process which can lead to far-future exposures is the total erosion of the host formation. This is estimated to be possible within around 500'000 y. Accordingly scenarios involving mixing of the traced quantities of long-lived radionuclides with agricultural land formed by erosion were also considered. The concentrations of alpha-emitters in the formed soil are as low as those of natural radionuclides in typical soils.

Predicted Safety for Repository Type B

Even using pessimistic data predicted doses in the far future are below the Swiss authority guidelines of 10 mrem/year/person. The predicted dose contributions are from mobile nuclides like ^{129}I and ^{135}Cs at shorter times (10^3 - 10^4 y) and ^{238}U-series nuclides at very long times (greater than 10^5 - 10^6 y). An exception is the erosion scenario where higher doses equivalent to those from natural radionuclides in soils can arise. The base-case calculations gave 13 mrem/y predominantly from ^{237}Np.

The predicted doses from a Type B repository are, therefore, as in the Type C case, predicted to be negligibly small. Confirmation of this prediction requires better site data as well as more detailed treatment of some technical issues such as the behaviour of chemical complexes in the repository environment.

CONCLUSIONS

Based upon the results of the projects summarized above, several conclusions have been drawn in the projects submitted to the government. For both HLW and ILW repositories it has been demonstrated that feasible engineering concepts have been developed. For assessing the safety of the repositories, appropriate methods have been developed and adequate data has been collected to allow quantitative predictions to be made. Adequate safety is predicted for both repositories; points remaining for further clarification are not expected to alter the principal conclusions drawn. The large efforts invested in project "Gewähr" have thus produced two main results: firstly evidence that the safety generally acknowledged to be achievable through geologic disposal can be attained also for specific Swiss conditions, secondly a valuable synthesis pointing the way ahead to realisation of repository projects.

The government and authorities in Switzerland have the task during 1985 of reviewing the "Gewähr" projects submitted by Nagra and judging the content before deciding upon licensing of future reactor operations. Meanwhile work will continue towards the realisation of repository projects for wastes currently arising. In the framework of Nagra activities this involves completion of the first phase geological studies on deep crystalline rock, further improvement of data and of models (including validation), and operation of the Grimsel underground rock laboratory. Most urgent, however, is the need to proceed with field investigation programmes which could lead to selection and development of a site for disposal of the low and intermediate level wastes for which no intermediate storage is necessary.

ACKNOWLEDGEMENTS

The paper presented here is an abbreviated summary of the results of intensive efforts invested over the previous 6 years by staff too numerous for individual listing within Nagra and within its subcontractor organizations.

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