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The long-term safety of underground waste repositories – A key issue for research and development –

Felszínalatti hulladéktárolók hosszútávú biztonsága – kutatás és fejlesztés

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(3 figures)

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Kulcsszavak: radioaktív hulladék, tárolók, biztonsági tervek, hosszútávú biztonságbecslés

Abstract

Concepts for the final disposal of radioactive waste include, among others, disposal in underground cavities and, in specific cases, disposal in deep geological formations. In several countries provisions have been made in the national regulatory framework for the adoption of such waste disposal concepts. The basic idea is to isolate waste from ground surface and meteoric water as long as required for the sustainable preservation of the environment. The time-frame depends on the toxicity of the radioactive materials as well as on durability of the waste containers. Both are essential parameters for the selection of appropriate underground cavities or deep geological strata for the construction of such repositories. One of the most challenging tasks for scientists and engineers is to forecast the long-term behaviour of the repository and the assessment of potential adverse conditions on the basis of sound geological data and realistic evolution models (scenarios).

For very good reasons many countries are pursueing radioactive waste disposal in deep geological formations. The principal advantage is that deep repositories are covered by thick geological barriers, in many cases with separated aquifers and without effective hydraulic pathways which could be potential travelling ways for toxic substances. That means that under normal conditions the isolation capacity of deep repositories should be in the range of geological time-frames. Potential host rocks are granite, rock salt, argillaceous rocks and others, depending on favourable site-specific conditions.

With respect to the operational safety rock mechanic aspects are the most important factors. This is why various parameters, such as rock stresses and tensile strength, have to be investigated. In addition, field measurements may help to characterise the rock mass stability and the changes which may be induced by the repository. For post-operational safety hydrogeological and geochemical research is mainly needed in order to produce data on radionuclide mobilisation and groundwater-transport. These are input parameters for generic as well as site-related performance assessment models. An engineering task is the development of adequate backfilling and sealing measures for the underground cavities and the access shafts. In Germany a comprehensive R&D programme has been devised to cover these issues. The main objective is to improve both the data-base and methodology for the long-term safety assessment of underground waste repositories.

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Összefoglalás

A radioaktív hulladékok végső elhelyezésére irányuló tervek között – egyéb megoldások mellett – földalatti üregek, és különleges esetekben mélységi földtani képződmények is szerepelnek. A nemzeti jogszabályozás keretében több országban ilyen hulladékelhelyezési koncepciót fogadtak el. Az alapgondolat az, hogy a hulladékot mindaddig elszigeteljék a felszíntől és a csapadéktól, amíg azt a környezet védelme megköveteli. A szükséges idő hossza a radioaktív anyagok mérgező tulajdonságától és a hulladéktartályok tartósságától függ. Mindkettő fontos tényező a tároló építéséhez megfelelő földalatti üregek vagy felszínalatti földtani képződmények kiválasztásában. A tudósok és a mérnökök számára az egyik legnagyobb kihívás a tároló hosszútávú viselkedésének előrejelzése és a lehetséges kedvezőtlen események becslése a földtani adatok és a fejlődési modellek alapján.

Jól érthető okokból számos ország törekszik a radioaktív hulladékok mélyen fekvő földtani képződményekben való elhelyezésére. Lényeges előny, hogy a mélységi tárolókat vastag földtani gát fedi, sok esetben elkülönülő vízadó réteggel, és nincsenek hatékony áramlási pályák, amik egyben a mérgező anyagok lehetséges szállítási útvonalai lehetnének. Ez azt is jelenti, hogy normális körülmények között a felszínalatti tárolók szigetelő hatása földtani időkben mérhető. A lehetséges befogadó kőzetek között van a gránit, a kősó, az agyagok és a telephely sajátos körülményeitől függően más kőzetek.

A biztonságos üzemeltetés szempontjából a kőzetmechanikai jellegek a legfontosabbak, ezért meg kell határozni a kőzetfeszültséget és a húzószilárdságot. A terepi mérések hozzásegíthetnek a kőzet stabilitásának, és a tervezett tároló által létrehozott változásoknak a jellemzéséhez. Az üzemeltetés utáni biztonságossághoz a hidrogeológiai és a geokémiai kutatás a legszükségesebb, mivel ezekből a radioaktív elemvándorlásról és a talajvízmozgásról nyerünk adatokat, amik az általános és a telephelyközeli modellek bemenő adatai. Mérnöki feladat a földalatti üregek és az aknák megfelelő tömedékelése és a záró́rétegek kiépítése. Németországban átfogó K&F (Kutatási és Fejlesztési) program készül ezeknek a problémáknak a megoldására. A fő cél a felszínalatti tárolók hosszútávú biztonsági becslésének alapjául szolgáló adatbázis és a módszertan fejlesztése.

Introduction

The final disposal of radioactive waste arising from nuclear research centres and operating nuclear power plants is an increasingly important issue in most countries which use nuclear power as a major energy source. In Germany the problem was already being tackled in the mid-sixties when the disused salt mine ASSE was converted into a R&D-facility for underground waste disposal. In the late seventies and beginning of the eighties the disused iron ore mine KONRAD was investigated for its feasibility as a non-heat generating site and for the decommissioning of waste disposal. On the basis of a favourable result the licensing procedure was started in 1982. This required detailed site characterisation and an advanced technical disposal concept. However, an operating licence has still not been granted. In the former East Germany an underground repository was being developed from 1971 onwards and this later operated in the disused potash mine MORSLEBEN. The operation was re-started for LLW-disposal in 1994 but stopped in 1998. The GORLEBEN salt dome is at present being investigated for its feasibility as a repository for all categories of radioactive waste, in particular high level heat generating waste but also intermediate and low level material. In Germany the new government has decided to reconsider both the disposal strategy as well as the disposal options. A group of experts – most of them geologists – has started working on advanced criteria for site selection.

In other countries there have been different approaches (DECAMPS 1996). In Sweden and Finland, for instance, underground repositories for low and intermediate level waste have been mined and constructed in granitic rocks (POSIVA OY 1996; VIRA 1994). These geological repositories have been operated successfully for several years. France has pre-selected claystone and granite as a host rock formation for high level waste, and the USA is planning a final repository for spent fuel in welded tuff (WITHERSPOON 1996). German scientists are participating in some underground laboratories in the various countries.

Despite some politically motivated disputes, in a number of countries there are no basic problems to be solved for low and intermediate level waste disposal in deep geological repositories. For high level waste repositories specific issues – such as coupled processes in the repository near the field and the retention of long living radionuclides in the geosphere – still have to be investigated in order to gain sufficient data sets for performance assessment. The long-term safety of such repositories depends very much on geological and site specific parameters as well as on the technical concepts used for backfilling and the sealing of disposal vaults and shafts. It also has to be acknowledged that for large and spacious waste repositories some damage to the geological barrier, caused by mining and/or specific site conditions, may require special technical solutions in order to achieve the necessary safety for extended periods of time. This again might require advanced experimental and performance assessment methodologies.

Safety concepts for underground waste repositories

Safety concepts for underground repositories have to be based primarily on the parameters of the radioactive waste to be disposed of – e.g. radiotoxicity, decay time, amount of α-bearing waste, waste form and waste volume. The operational safety for HLW/ILW requires (in comparison with LLW) specific shielding for transportation, handling and disposal. For construction and post-operational safety the selection of 'dry' or 'wet' host rocks is crucial importance (IAEA 1991). The ultimate objective of site-specific R&D is to provide technical concepts for the safe operation and long-term safety of such a repository. With respect to operational safety, this concept has to comply with the relevant mining regulations and the actual radiation protection regulations. The long-term safety has to be proved for the required periods of time (10 000 years and more). The entire repository system with its different technical, geotechnical and geological barriers has to be analysed in detail; by modelling the most relevant mobilisation and migration processes it has to be demonstrated that there will be no radioactivity release resulting in unacceptable individual doses to the public. This task requires specific geological and geotechnical investigations as well as specific methodologies for performance and long-term safety assessment.

Today considerable know-how is available, not only through the individuals working on some national projects but also on an international level. Safety criteria for radioactive waste disposal have been internationally agreed upon and published by the IAEA and frequent exchange of the latest achievements is being organised by OECD/NEA (BALTES 1995; RÖTHEMEYER 1994). The main objective of ongoing R&D-activities in several countries is the envisaged disposal of HLW and spent fuel in deep geological formations. In particular the development of adequate backfilling and sealing strategies and the further development and application of advanced PA-methodologies are important tasks, given the more demanding licensing procedures in a very conscious public environment.

R&D Aspects in Rock Salt Formations

In Germany rock salt was selected as a 'dry' disposal formation for all categories of radioactive waste at a very early stage of the German waste management programme. The first experiences with LLW/ILW-disposal were made in the ASSE salt mine in 1972 – 1977 (GSF 1982). For ILW a special disposal technique for 200 l drums without over-packs was developed and tested. A total of about 1300 drums containing an inventory of 5 000 TBq, mainly of short-lived radionuclides, was emplaced in rock salt in a small chamber of about 9000 m^3 and permanently sealed off from the mine workings. The maximum surface dose rate of the drums was about 30 Sv per hour and was mainly caused by Cobalt 60. This radiation level required transport and handling techniques to be carried out under permanent radiation shielding. The LLW/ILW-disposal operation in the ASSE-mine was terminated in 1977. With respect to operational safety, the following results can be given:

- the ILW-drums were safely emplaced by routine operations while a permanent radiation shield was maintained,
- the radiation exposure of the staff was very low compared with that of the emplacement of unshielded LLW-Drums,
- within 20 years of permanent emplacement the concentration of hazardous components in the chamber's atmosphere remained far below any set safety limit,
- the radiation level decreased as expected from the half-lives of the radionuclide inventory.

With respect to the post operational safety of radioactive waste disposal in rock salt several case studies were performed within the scope of national and international R&D-projects (BUHMANN et al. 1995; BUHMANN 1996; HIRSEKORN et al. 1991; STORCK et al. 1988). In the PAGIS-project (co-funded by the EU) different host rock formations were evaluated for their isolation potential for HLW (STORCK et al. 1988). In the PACOMA project the long-term effects of conceptual underground repositories for intermediate-level and α-contaminated wastes were compared with those of HLW-repositories (HIRSEKORN et al. 1991). The calculated radionuclide release into the biosphere, as a consequence of a brine intrusion scenario, resulted in a dose rate of about 10^{-7} Sv/year and no release for HLW repositories. If, shortly after operation, a considerable number of disposal chambers and drifts is affected by brine intrusion the total dose rates for both will be in the range of 10^{-4} to 10^{-6} Sv/year. With reference to the long-term consequences of HLW and spent fuel disposal in rock salt a number of sensitivity analyses were performed in the framework of the German R&D-programme. Based on the findings the key parameters for research and development for HLW disposal in rock salt were identified:

- convergence of underground cavities and disposal rooms,
- volume of brine pockets to be expected,
- permeability and porosity of geo-barriers,
- permeability of underground sealing dams,
- time span to be considered for brine intrusions,
- k_d-values of parts/sections of the geosphere,
- groundwater flow in overlaying strata.

Additional studies were performed with a view to creating a central repository in a salt dome for the disposal of all radioactive waste categories (BUHMANN et al. 1991). Among other things dissolver sludges, decommissioning waste as well as structural parts and secondary wastes from the conditioning of spent fuel elements were considered as ILW. It was presumed that HLW would be emplaced in boreholes, spent fuel in drifts, and ILW in galleries or in boreholes in special disposal sections, apart from heat-producing wastes (see *Fig. 1*). Due to the great amount of heat-producing HLW, the rock salt will be effected in such a way that the volume convergence of the underground cavities will increase and open voids near HLW disposal sections will close more rapidly. If the design of a radioactive waste repository in rock salt takes advantage of these rock mechanical aspects brine is unlikely to reach the HLW disposal sections. In this case the possibility of radionuclide releases from HLW will be limited and so, too, will unlikely events such as an early and large brine intrusion. This applies in particular if all waste categories are emplaced commonly in disposal drifts and the inventory of ILW is mobilised first due to of the limited quality of the technical barriers.

ILW-Disposal in Argillaceous Formations

A number of countries have pre-selected argillaceous formations for the construction of LLW and ILW repositories. In France such rock formations are also being investigated for HLW disposal. In Germany the 'to be licensed' repository KONRAD for non-heat generating waste will be constructed in the Oxford formation of the Upper Jurassic at a depth of 800 to 1300 m. The geological barrier is formed almost entirely by claystones and is up to 900 m thick. Due to these site conditions the mine is extremely dry. Because of the mechanical properties of the rock mass and the great depth, disposal drifts can only be of a limited size. This is – besides waste-specific and waste management arguments – a site-specific reason why this repository was planned for self-shielding waste only. The size of the various loading stations and travelling ways are not wide enough to accommodate the necessary shielding devices for the handling and disposal of large waste volumes. In order to comply with the occupational dose limits of the German radiation protection regulations various types of concrete,

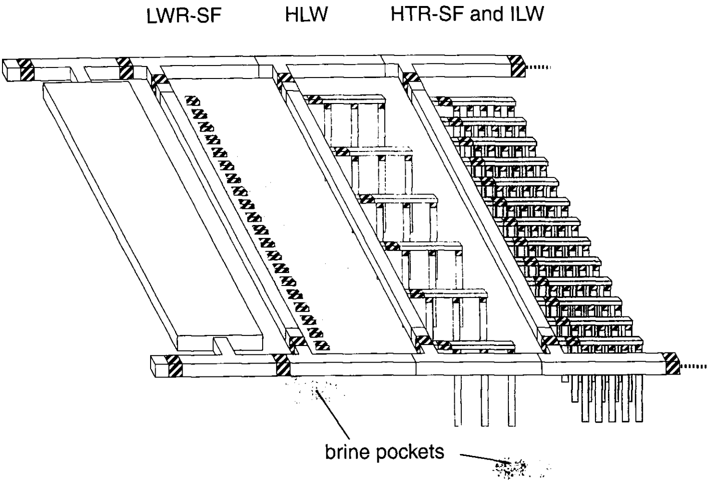

Fig. 1 Schematic concept of a repository for HLW, spent fuel and ILW in salt formations

1. ábra. A nagyaktivitású radioaktív hulladék, az elhasznált fűtőelemek és a közepes aktivitású radiokatív hulladék só formációkban történő elhelyezésének elvi modellje

cast iron and normal 5 ft and 10 ft containers have been selected for LLW and ILW. The containers will be emplaced in 40 m^2 wide drifts by means of the stacking technique. The remaining open space will be backfilled before the drifts are sealed off.

The long-term safety assessment of the repository is based on a hydrogeological model covering an area of 40 km from north to south and 14 km from east to west (STORCK 1988). The hydraulic rock parameters and, in particular, the rock mass conductivity were either directly measured or determined from geological analogues. From the experiences gained in the KONRAD mine itself and in the entire mining district of Salzgitter, it was concluded that a considerable water intrusion will not occur during the operational phase. After shutdown the repository will slowly be filled with high saline, deep groundwater and this will take up to several thousand years. Only then will the regional groundwater flow become effective again, but at a greater depth. Due to the uniform geological structure and the absence of deep cutting tectonic faults only three possible pathways were identified for radionuclide transport (these are shown in *Fig. 2*). After shutdown of the repository the total radionuclide inventory will amount to 10^6 TBq, of which 97% will be beta/gamma- and 3% alpha-emitters. Iodine-129 amounts to 0.15 TBq. Although the density of the high saline groundwater was not taken into account, the calculated groundwater travelling times ranged from 0.3 to 1.1 million years. The calculation of individual doses as a function of time

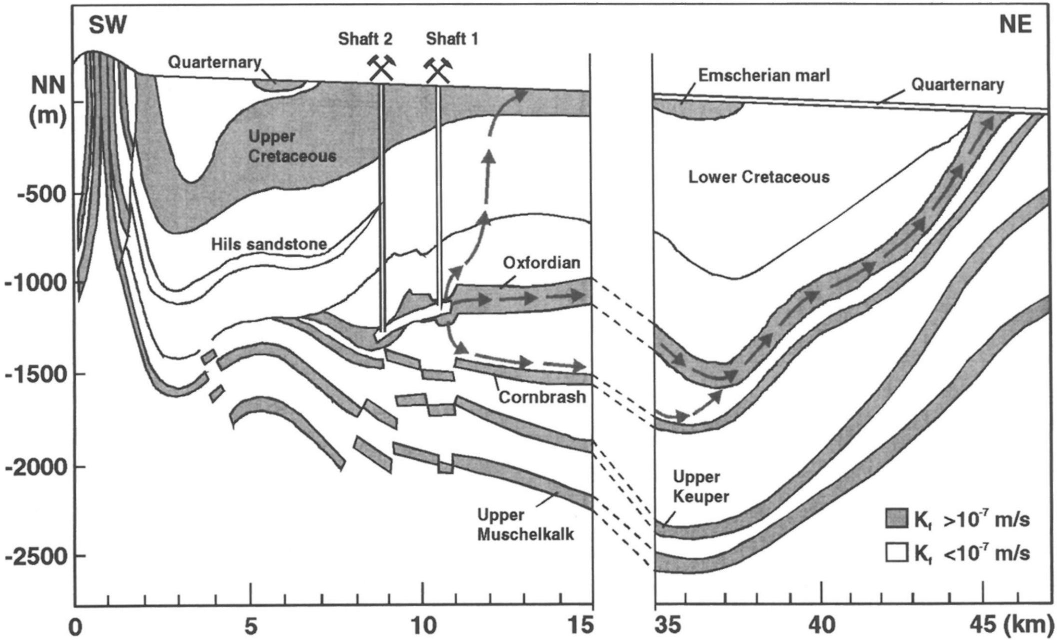

Fig. 2 Konrad site: Geological cross section and identified travel pathways

2. ábra. Konrad telephely: földtani szelvény és áramlási útvonalak proved that for up to 10 000 years and more there will be no contamination of the biosphere. Hypothetical calculations for individual radionuclides revealed that after more than 300 000 years Iodine–129 could cause some minor exposure in a range which is a natural level of exposure to man.

It has to be stressed that due to the most favourable site conditions, the great depth and the almost complete lack of groundwater in the mine, major side effects will not occur. In particular, the corrosion of containers and waste is of no great importance in the operational phase of the repository. In the post-operational phase corrosion gases (which may be generated as a consequence of water seepage into the disposal drifts) can migrate along the excavation damage zone so that no gas pressure build up has to be considered. This may be completely different at other sites with larger volumes of groundwater present or freely available from adjacent rock masses. However, for a repository taking advantage of the 'dry' site conditions, adequate backfilling and sealing measures in drifts and shafts are of utmost importance in order to preserve these conditions for as long as required.

Waste disposal in granitic formations

In many European countries granite is the preferred host rock formation for the disposal of HLW and this has been explored in great detail. In Germany granitic formations have not been explored to any great extent. However, Germany (BGR, GRS) has been participating in underground repositories at Grimsel and Äspö since 1983 and 1995, respectively. In addition a study was performed (GEISHA) in order to compare the most relevant data and processes of the two disposal concepts (rock salt, granite) from the view point of PA (PAPP 1997). In this context the following aspects were considered:

- site investigation,
- backfilling and sealing,
- repository design,
- geochemistry,
- long-term safety.

On these basis and an understanding of various systems, first conceptional models and numerical tools for a long-term safety assessment of an HLW repository in granitic formations have been developed in Germany. In the EC-funded project „Spent fuel performance assessment (SPA)", a long-term safety assessment study for a repository in a granitic formation (based on the above mentioned preliminary concept) has been performed (LÜHRMANN et al. 2000). For the repository design, engineered barriers and the geological situation assumed to demonstrate the long-term safety of the repository system. As shown in *Fig. 3* the highest release and dose rates have been caused by the limited non-solubility and weakly absorption capacity of the radionuclides C-14, Cl-36, I-129, Cs-135 and Se-79 (but these rates remained well below the regulatory limits).

The study has shown that the near-field barrier is of significant importance for the long- term safety of the repository. Moreover, geotechnical barriers also

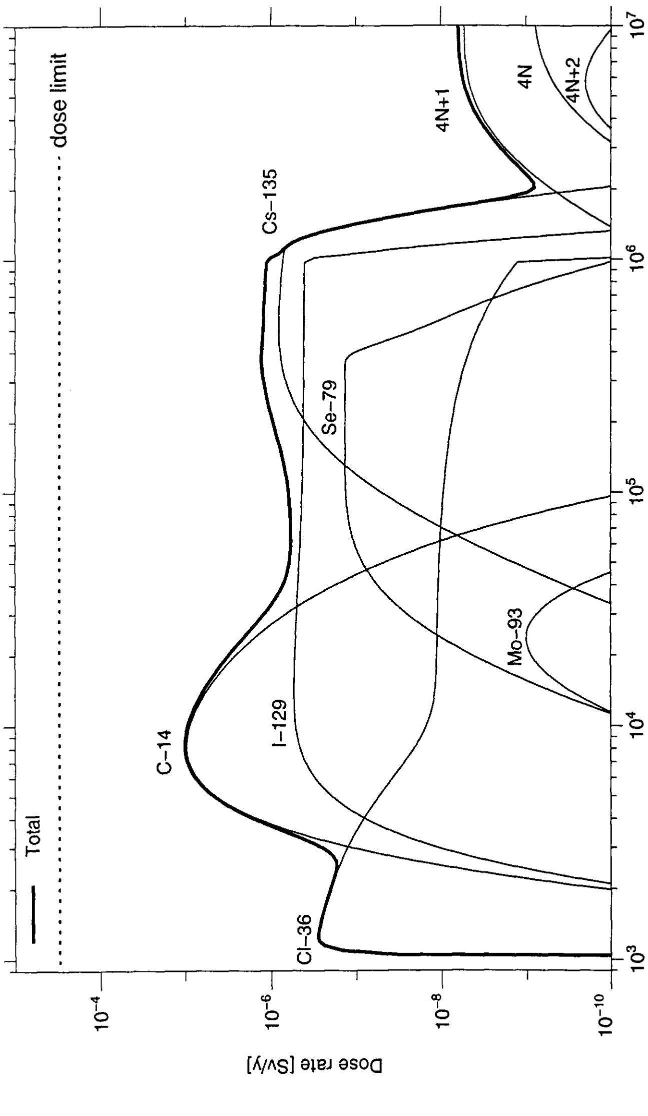

Fig. 3 Dose rates calculated for a reference scenario for a generic repository in a granite formation in Germany

3. ábra Radioaktív hulladékoknak gránitokban történő elhelyezése céljából referencia helyzetekre számított dózis–ráta időbeli eloszlása require high financial inputs for development and construction. So a more detailed investigation of all processes which might influence the barrier function of the near-field barrier is necessary, it is intended that this investigation will be performed on the European level. The overall aim of the planned project is to enhance the modelling of the near-field barriers in order to reach a close-to-reality-level and to investigate the optimisation potential of the geotechnical barrier.

German scientists are participating in in-situ projects in granitic formations. With respect to the ongoing experimental work at Grimsel and Äspö respectively the following experiments should be mentioned:

- two-phase flow,
- geoelectrical measurements in the zone disturbed by excavation (EDZ),
- gas migration in geotechnical barriers (e.g. buffer, seals).

The main emphasis at the moment is on the development, characterisation and long-term performance of geo-barriers since, given the findings of from our projects GEISHA and SPA, it is apparent that these are the most important issues.

Backfilling and sealing concepts for underground waste repositories

As outlined above, backfilling and sealing measures contribute substantially to the long-term safety of the underground waste repositories. For this very reason considerable R&D efforts are being made in various national waste-management programmes. In Germany several projects are in progress in both the site investigation programs of BfS and the basic R&D-programme of BMBF. For repositories in rock salt crushed salt is being investigated for its use as backfilling material in disposal drifts and boreholes. Although most of these experiments are run under a heat load, some results will also be achieved with respect to unheated disposal sections. The main concern is the compaction behaviour of such materials. The sooner high compaction is reached, the smaller the chance for intruding brines to come into contact with the waste. This mechanical process is mainly governed by the creep behaviour of rock salt (and upon which depth and heat have an accelerating effect). In a specially mined repository for all waste categories the arrangement of heated and unheated disposal sections may have a highly positive effect on the long-term safety.

This favourable situation may differ due to site-specific geological features. For the LLW-repository MORSLEBEN (BfS 1995; Brennecke et al. 1997; Ebel 1991) – which is sited in a disused potash mine – a concept for backfilling and sealing is presently being developed. The mine has a total cavity volume of 7.6 million m^3 of which the southern part Bartensleben, with the disposal sections, makes up about 70%. In addition to 14 000 m^3 from former disposal operations about 40 000 m^3 of LLW will be disposed of by the end of the year 2000. For the various disposal sections with access drifts, adjacent travelling ways, internal shafts and boreholes the following alternatives are being investigated:

– isolation of the disposal sections from mine workings using dams made from highly compacted bentonite and placed at specific locations in the access drifts,

– enclosure of disposal chambers by backfilling of all the access drifts with qualified sand-bentonite mixtures,

– deceleration of brine extrusion by the backfilling of all drifts with porous sand gravel mixtures.

What is common for all three concepts is that some parts of the old mine will also be backfilled in order to stabilise the mine workings where necessary. By means of system analysis and performance assessment they have been evaluated for their effectiveness, advantages and disadvantages (STORCK & PREUSS 1997). It was shown that in principle each concept can ensure the long-term safety of the repository. However, some of the data sets used in the models need to be confirmed by laboratory and/or in situ experiments. This applies in particular to the use of highly compacted bentonite for dam constructions in a highly saline environment. Such experiments have already been started and will last for about three years.

With respect to the backfilling of shafts the BMBF together with the German potash mining company KALI + SALZ has just started a large scale field experiment in the disused potash mine SALZDETFURTH. The concept is to backfill a 770 m deep shaft with stabilising material in the bottom part and with a 40 m thick bentonite plug in the transition section to the covering rock strata. After construction the mechanic and hydraulic performance of the seal plug will be measured using direct and indirect methods. Without explaining in detail the various technical and scientific challenges, it has to be stated that this R&D project is of great importance for any kind of underground waste repository.

Summary

The final disposal of low- and intermediate-level radioactive waste in deep geological formations has been tested and is being applied in some countries. Both the operational and post-operational safety concepts have been approved by the respective national licensing authorities. However, it has to be acknowledged that these repositories are either small in volume and activity, having an enlarged system of technical barriers, or they are situated in exceptionally dry rock formations. For a large-volume repository – and especially if the underground environment is basically wet – the disposal strategy might be different. Interactions of waste and waste containers with groundwater, as well as the generation and migration of gases, may be of particular concern. In such a case appropriate technical and geotechnical barriers have to be developed which take into consideration the barrier potential of the geological formations and the possible effects upon geochemical site conditions. These are very important issues, not only with respect to the long-term safety, but also for the construction and operating costs of an underground waste repository. This applies in particular to the design and construction of HLW- and SF-repositories.

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