

**GERMAN PARTICIPATION IN THE EU PROJECT NET.EXCEL
STATUS AND PROSPECTS OF WASTE DISPOSAL RESEARCH IN ROCK SALT -**

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ABSTRACT

In the forefront of the 6th EU frame program the NET.Excel project was launched by the end of 2002 in order to establish the present state-of-the-art in radioactive waste disposal and to provide thorough information concerning the needs in research and development. The basic objective is to elaborate a guideline for future joint RTD activities in the field of long-lived and highly radioactive waste. So far, the work performed in various underground rock laboratories in EU countries has led to substantial know-how concerning repository design and construction as well as waste encapsulation and disposal. The idea of a 'co-operation of expertise' is to get those organisations and research establishments together which are committed to the concept of underground waste disposal and which are interested in making stronger use of networking in order to meet the commission's overall objectives with respects to greater integration and greater common benefit of the know-how achieved. It is expected that a comparison of the different national programmes will reveal research and development areas, issues and projects, which would gain in efficiency and quality if they were planned and carried out in co-operation.

The NET.Exel project covers a wide range of national programs in Europe which are bound to rock salt, crystalline rocks and clay formations. Focus areas are waste, canisters, buffer, backfill, plug and host rock as well as phenomena and processes which can take place in the repository in the short and in the long run.

INTRODUCTION

With respect to the salt option considerable know-how has been achieved in Germany in the last 30 years and to a certain extent also in the Netherlands. Other countries like Spain showed some interest before focussing research on hard rock formations. The great potential of rock salt for the long term isolation of radioactive waste has been established by various activities:

- Operation of the Asse mine as research and demonstration facility
- Operation of the underground LLW repository Morsleben
- Investigation of the Gorleben salt dome for its feasibility for all kinds of radioactive waste
- Applied research and development program for the disposal of hazardous waste in deep geological formations

Research for the disposal of heat-producing HLW from reprocessing of spent fuel was already started in the mid sixties and concentrated in the first stage on the investigation of thermal and coupled thermo-mechanical as well as hydraulic and radiolytic effects in the nearfield of HLW. In the second stage several full-scale simulation tests were performed focussing on development, testing and improvement of disposal techniques and on backfilling and sealing of HLW repositories.

After the successful demonstration of disposal techniques for LLW and ILW in 200 l drums and shielded concrete casks in the Asse mine three full-scale in situ experiments were planned with respect to transport

and emplacement of high and intermediate-level waste in a salt repository. The so-called Brine-Migration-Test was successfully terminated in 1985. In the HAW-project the system for handling of HLW canisters was constructed and tested, and in the MAW-project a similar system for handling of ILW and HTR fuel elements was developed. Both systems were designed to meet the requirements of a real nuclear repository. Because of licensing uncertainties both projects were prematurely terminated by the end of 1992 before the emplacement of radioactive waste casks in the Asse mine. The testing of a full scale multi-component sealing dam was stopped after complete installation in 1994 for financial problems and for some uncertainty with respect to the Gorleben planning.

The only large scale demonstration test performed in the Asse mine was the so called TSDE (Thermal Simulation of Drift Emplacement) - experiment representing the drift disposal concept. It was run over a period of almost 10 years showing good results on backfill compaction, container corrosion and rock mass deformation. All data achieved were used for checking on the efficiency of the constitutive numerical models for salt creep and backfill compaction.

The Federal Minister of Economics and Labour (BMWA) is responsible for applied basic research. In 2001 the r&d program was updated identifying the BAMBUS II project on the thermo-mechanical behaviour of rock salt and backfill as a most important for the German program, since the underground rock laboratory will be no more available after 2005. Other research and development tasks concern the sealing capacity of improved backfill materials and the hydraulic properties of anhydrite seams in rock salt strata. A specific challenge is the development and testing of plugs and seals for shafts and underground galleries in order to prevent groundwater intrusion into the disposal sections. The information exchange and co-operation with the Carlsbad Field Office of US DoE, operating the Waste Isolation Pilot Plant, are focused at fracture-flow and transport, near-field geochemistry, rock mechanics, disposal room processes, seals and monitoring.

The sub-group 'Ver- und Entsorgung' of the German Reactor Safety Commission (RSK), advisory board to the Federal Minister for the Environment, Nature Conservation and Reactor Safety (BMU) has reviewed the German r&d program in several sessions in 2000/2001. The overall conclusion was that all aspects which govern the long-term safety of underground repositories and which are non site specific are covered by the program. In 2002 this group discussed specific safety issues with respect to waste disposal in rock salt and stressed the importance of basic research in view of a better understanding of geochemical processes in the near field and the generation of gases from different waste forms. It also suggested to look deeper into the consequences of human intrusion scenarios and to increase confidence in the safety case by natural analogs.

At present some basic questions raised by the German Government concerning the feasibility of rock salt as a host formation for heat generating radioactive waste are being pursued by the Federal Office for Radiation Protection (BfS). Only if they are answered satisfactorily the moratorium on the Gorleben project will be lifted.

WASTE MANAGEMENT SITUATION IN GERMANY AFTER THE DECISION TO PHASE OUT NUCLEAR ENERGY

In July 2000 the German Government reached agreement with the German Power Utilities to phase out nuclear Power. On this basis the Atomic Act was amended, which came into force on April 27, 2002. In accordance the 19 German nuclear power plants are entitled to generate altogether another 2600 TWh, from 2000 on. This figure corresponds to a mean full load over a lifetime of about 32 years. It is assumed that the last nuclear power plant will be shut down in the year 2022.

It was also implemented in the Atomic Act that after June 2005 no more spent fuel will be sent for reprocessing to France and Great Britain. This decision is based on a policy change in waste management away from reprocessing and for direct disposal of spent fuel.

Until a final underground repository for all kinds of waste is operational in app. 2030 two centralized storages (Ahaus and Gorleben) and 12 decentralized storages at the individual NPPs will be maintained. After interim storage the casks will be transported to the spent fuel conditioning plant. In this plant the spent fuel will be taken out of the storage/transport casks, prepared for final disposal and inserted into the specific disposal casks. The total amount of heat generating waste to be disposed of may run up to 9000 t of SNF and to about 5500 t HLW (Tab. I).

Table I Amount of heat generating waste in Germany (including stocks and prognoses until year 2030)

	Amount		Total Inventory [Bq]	Specific Activity [Bq/t _{hm}] (after recharge)	Specific Heat generation [W/t _{hm}] (after 10 ys)
	[m ³]	[t _{hm}]			
HAW	908	5 550	4.14·10 ¹⁹	7.45·10 ¹⁵	1747
Spent Fuel	18 258	8 947	1.38·10 ²⁰	1.54·10 ¹⁶	1440
HTR	1 890	10	2.22·10 ¹⁷	2.2·10 ¹⁶	3425

DISPOSAL CONCEPT FOR HEAT-GENERATING WASTE IN ROCK SALT

Several disposal concepts have been investigated and developed in Germany as a combination of technical variants and waste type ratios as well as for long-term isolation of the waste in the host rock. These are:

- borehole emplacement of vitrified HLW,
- drift emplacement of SNF in Pollux casks, and
- combined drift and borehole emplacement of Pollux casks and HLW, respectively.

According to the concepts considered in Germany, the HLW stemming from reprocessing will be vitrified in steel canisters. The steel canisters will then be disposed in between 300-m to 600-m-deep, 0.6-m-wide, vertical boreholes extending down from a disposal drift located at a depth of some 880 meters below ground (Fig. 1). About 200 canisters will be lowered into each borehole. The annulus between the canisters and the borehole wall will be backfilled with crushed salt to transfer the weight load of the canister stack to the surrounding rock mass. The inherent rheological characteristics of the salt rock surrounding the boreholes will then gradually compact the crushed salt and, thereby, completely encapsulating the HLW cans in very short time.

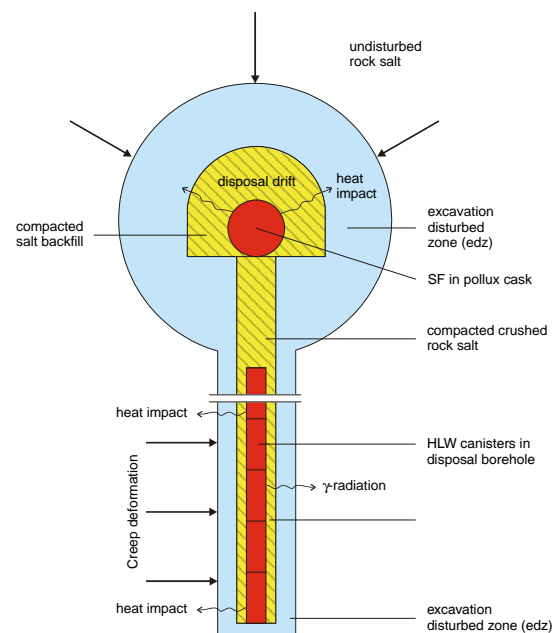


Fig.1 Disposal drift with HLW borehole

A different concept has been developed for direct disposal of SNF (Hartje et al, 1989). In this concept, large, self-shielding Pollux casks containing Light-Water Reactor (LWR) SNF elements will be emplaced

in horizontal drifts about 200-m length, 4.5-m width, and 3.5-m height. Following the emplacement of a Pollux cask, the remaining voids in the drift will be backfilled with crushed salt. Similar to the borehole emplacement concept for HLW canisters, the creep of the surrounding rock mass will compact the initially loose, crushed-salt backfill and, thereby, effectively seal the emplaced Pollux casks from the biosphere.

CONCLUSION

Several research teams have analyzed these concepts and the results are reported in SAM (Bechthold, W. et al, 1993). The most promising concept appears to be the combined drift and borehole emplacement of Pollux casks and HLW-canisters. Quite recently a strategy was developed to use, comparable to HLW cans, CSD-C containers for disposal of compacted head / bottom end pieces in boreholes. The uncut fuel elements will be inserted into BSK-3 containers which are about 5 m long. This concept has still to be checked for its technical feasibility and safety performance.

WASTE FORMS AND CANISTERS

For the disposal of the different types of heat generating and long-lived radioactive waste several types of containers have been designed and developed (Tab. II). In rock salt – more distinctly than in any other concept – one has to differentiate between canisters for borehole and drift disposal. Main reasons for this are the rheological and technical features of rock salt as well as the big volume of diapirs which provide most favourable conditions for deep implacement borholes.

Due to the great isolation potential of rock salt canisters and casks are mainly designed for handling and radiation shielding purposes. With respect to SNF disposal the Pollux casks serve both radiation shielding and long-term mechanical stability in order to withstand the mechanical load of the rock mass.

Table II Types of containers and casks with their calculated waste masses

	Waste-matrix	Container	Content [t _{hm}]	Emplacement Concept
HLW	glass	steel can	1.15	borehole
		Pollux – cask for HLW cans	6.9	drift
Spent Fuel	UO ₂	Pollux - can	1.602	borehole
		Pollux - cask	4.72	drift
THTR / AVR	graphite	400 l drum	0.02	borehole
		Pollux - cask	0.09	drift

The ILW drums have no particular barrier function. Main aspect is the handling of the drums in the repository. For better logistics in the disposal drift large concrete containers are planned which can take up to four 400 l drums.

The HLW steel cans are handled in transport casks. With respect to borehole disposal the steel cans have no special function since the boreholes are sealed shortly after emplacement. The CSD-C and BSK-3 containers fit into the same disposal boreholes. However, different to HLW cans, they have greater mechanical strength in order to take the stacking load in the borehole.

For the drift disposal of SNF the Pollux casks serve as transport as well as disposal container. They differ in their internal set-up depending on the type of fuel they are designed for. With a total weight of about 65

Mg they can take the full load of the rock mass at the envisaged depth of the underground repository. As basis for an preliminary integrated performance assessment study on the disposal of heat generating waste (SAM) representative types of canisters were considered (Tab. II). The CSD-C and the BSK-3 containers have not yet been incorporated in this concept.

Since 1985, important scientific and technical questions have been discussed in detail by the High-Level Waste Review Panel. So far nine recommendations have been issued which formed the basis for some regulatory and licensing decisions (Tab. III).

Table III Recommendations issued by the High-Level Waste Review Panel (acc. to Kienzler, B. Loida, A., 2001)

No.	Title of Recommendation	Application
1	R&D work needed for the characterization of HLW glass product	R&D planning of the involved research centers and institutes
2	Diameter of HLW canisters	BMU approval for the COGÉMA glass product to be returned to Germany, granted in 1988
3	Corrosion experiments on vitrified radioactive waste - brines and S/V-ratio	Involved research centers and institutes, mainly BGR and FZK
4	Interval between the central temperature of HLW products and the transformation temperature T_g	Thermal lay-out of interim storage facilities (including flasks) and final disposal concepts
5	BNFL Vitrified Residue Specification, assessment of properties relevant for final disposal	BMU approval for the BNFL glass product to be returned to Germany, granted in 1994
6	Properties and characteristic values of HLW glass products relevant for final disposal	Issuing of the Process Qualification Handbooks for the vitrification plants PAMELA, R7/T7, WVP and VEK and the assessment by PKS
7	Properties and characteristic values of compacted heat generating waste (CSD-C) relevant for final disposal	Issuing of the Process Qualification Handbooks for the ACC compaction facility (in progress for waste to be returned to Germany)
8	Properties and characteristic values of conditioned LWR spent fuel relevant for final disposal (POLLUX + BSK-3 package)	Pilot conditioning plant (PKA) license granted by NMU, issuing of the PKA Process Qualification Handbook (in preparation)
9	Radiation stability of HLW glass products	Used for public acceptance issues

CONCLUSION

From various PA studies it became obvious that there is a fairly good understanding of those processes which concern the physical waste parameters and the source term for near field mobilization and migration models. Further research is still needed in the field of the waste chemistry, specifically with respect to radiolysis inside the Pollux casks in case of a brine intrusion. An important issue is the generation of oxidizing species directly at the surface of the waste matrix, especially of burned nuclear fuel.

In case of brine intrusion the stability of the geochemical milieu in the repository is to some extent an issue. There are some considerations to use specific additives in the backfill in order to control stable geochemical conditions. With respect to the long-term performance of disposal containers more data are needed for the CSD-C container manufactured by COGÉMA as well as for the BSK-3 container. As a special issue the possibility of critical masses in boreholes loaded with BSK-3 containers has to be investigated.

BACKFILL AND SEALS

The host rock represents the most important barrier within the multiple-barrier concept of a waste repository in rock salt. According to the German concept, the engineered barrier system (EBS), which is to be implemented in addition to the geological barrier, consists of borehole seals, drift seals (dams), and shaft seals. In addition to these seals, access and transport drifts will be backfilled with crushed salt in order to minimize remaining voids in the repository and to assure rock stability as soon as possible after termination of the disposal operation. The EBS comprises the following main components:

- an approximately 30-m-long seal consisting of crushed salt to be filled into the top section of each HLW-disposal borehole,
- backfill of the disposal drifts for SNF in Pollux casks with crushed salt concurrent with the cask emplacement,
- drift seals (dams) will be installed between the shaft area and the disposal sections after termination of the disposal operation.
- shaft seals will be installed in order to prevent any water intrusion from overlying strata into the repository.

The permeability of the backfill material is of special importance to the long-term safety of the very near field including the waste canisters. It reduces the open space in the repository and, in the event of a brine intrusion from the overburden or from an undetected brine pocket in the rock mass, limits the availability of water for corrosion and mobilization processes. In addition the backfill material will become gradually compacted by the creeping rock mass and even faster by heat impact on the convergence and drift-closure. As the compaction proceeds backfill porosity decreases and heat conductivity /dissipation in the backfill increases. No other backfill material than crushed salt is considered necessary in the repository concept. The crushed salt in the HLW boreholes will be adequately compacted by the creeping host rock within about 10 years. Additional borehole seals are not required.

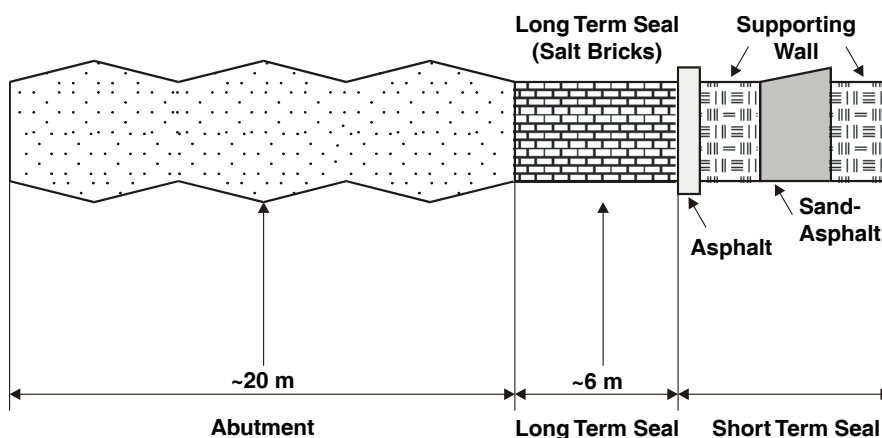


Fig. 2 Principle design of a long-term sealing dam

No specific design criteria is needed for the use of crushed salt as sealing material in HLW disposal boreholes and drifts. However, the grain distribution of the backfill is to be controlled in order to avoid emplacement problems, especially in the narrow annulus between the waste canister and the host rock in deep boreholes. In the

DEBORA borehole experiment, the largest grain size filled into the borehole annulus was 10 mm.

Drift seals (dams) between the shaft area and the disposal sections are constructed after the disposal operation. A prototype drift seal was developed by Stockmann et al. (1994). The proposed design (Fig. 2)

is made up by a sand-asphalt seal for short-term tightness in the early stage and by pre-compacted salt bricks for long-term sealing. A static abutment of salt concrete provides the necessary stability against brine pressure in case of complete mine-flooding. Long-term sealing is generated in time by the progressing drift convergence and successive material compaction.

A concept for shaft stabilization and sealing was developed by GSF together with industrial enterprises. An in-situ experiment on the efficiency and stability of such a seal was conducted successfully at the Salzdetfurth mine in Germany (Breidung, 2001) by using bentonite pellets as sealing material.

CONCLUSION

The THM behaviour of crushed salt backfill is largely understood. Adding of geochemical additives to increase sorption of specific radionuclides has been discussed but was not tested so far.

Since the large-scale dam experiment was not carried out as planned in the Asse mine there is a great need for thorough investigations concerning the system properties and system behavior under mechanical and hydraulic load. The experience gained so far with similar experiments have shown that there are great differences between laboratory and in situ tests. Important is the application of the full hydraulic pressure to be expected in a real repository in order to prove the functioning of the individual and interacting dam components. A decision has to be taken how to run these tests, either up to the failure point or to prove parameter values which, according to performance assessment calculations, are sufficient for maintaining the required long-term safety. In the second case it is expected that such experiments will take considerable time in order to get representative results.

Concerning the long-term efficiency of shaft seals it became quite clear that there is a strong dependence on the site specific situation. Case studies reflecting the various hydrogeological and geotechnical possibilities are required for the identification of additional research work which should be aimed at the reduction of parameter uncertainties.

GEOSPHERE AND BIOSPHERE

In the northern part of Germany evaporites of the Zechstein (Upper Permian) are widely deposited. There are up to seven evaporation and sedimentation cycles which consist of argillaceous rocks, carbonates, sulfates (anhydrite, gypsum) and chlorides (halite, potash and magnesium rich salt). In a secondary process the Permian salt formations have accumulated in large pockets, anticlines and big diapirs with a volume of up to several 100 km³ each. There are about 400 salt diapirs known in Germany. Several studies have been performed for the pre-selection of those which are presumably suited best for site characterization and the construction of a deep geological repository. The design of an underground repository depends strongly on the geological, structural and stratigraphical aspects of the selected salt formation. Salt domes show a rather complicated geological structure, while the properties of bedded salt with vertically stratified layers are assumed to be much simpler.

The second cycle, the Stassfurt Series, is the biggest with an original thickness of about 600 m. Its petro-physical properties such as its relatively high ductility and its tightness as well as the large rock volumes available are particularly favorable for the disposal of radioactive and heat generating waste. The ductility of rock salt is characterised by its creep, which is predominantly carried by dislocations in the crystal lattice. The creep depends mainly on stress and temperature. The steady state creep rate is an exponential function of the deviatoric stress with an exponent of 5 to 7, without a lower stress limit. An increase of temperature of 10 K causes an increase of the creep rate by about a factor of two, due to thermally activated micro-mechanical mechanisms. Creep of salt is also dependent on air humidity, but only under low mean stresses. The creep is enhanced by a factor of about 20 when the relative air humidity is

increased from 10% to 65%. In fact, different types of rock salt exhibit differences of more than a factor of 100 in creep rate, due to a different distribution of microscopic impurities within the grains. The creep behaviour of salt can be well represented by material laws based on micro-mechanisms, such as the so-called composite model developed by BGR. The physically-based creep laws allow reliable prediction of the mechanical long-term evolution of a repository in rock salt.

For the dimensioning of disposal rooms and safety pillars as well as for an integrated geomechanical performance model dilatancy, damage, and failure of the host rock are the most important processes to be considered. They essentially dependent on the mean rock stress and stress geometry of the site as well as on the loading rate and temperature of the waste. The dilatancy boundary is a direct safety boundary for permeability and integrity of the rock. An increase in volume during deformation due to micro-cracking causes damage and produces a number of consequences: increasing permeability, accelerating creep rupture, mechanical weakening and failure (Hunsche and Schulze, 2000). Rock mass damage resulting from mining operation (excavation disturbed zone, EDZ) is one of the current research topics.

The basic concept of waste disposal in rock salt is aimed at complete and long term isolation of the waste in the host rock formation. For this reason the biosphere does not play a specific role beyond the general safety consideration of the repository and its operation. With respect to long term performance there will be no groundwater intrusion into the repository under normal conditions. In PA studies so-called altered evolution scenarios have been considered. An important process is the main anhydrite seam becoming permeable due to stress overload . However, this can be prevented most likely by thorough mapping of the salt formation and a well tuned disposal concept. This leaves the biosphere as subject for normal site characterization with the collection of environmental data and with the investigation of the groundwater regime according to the Governmental Regulation (AVV). In case of groundwater being in contact with the salt dome the groundwater salinity and the formation of a caprock are of great interest for the better understanding of the recent geological evolution.

During the Quaternary the northern part of Germany was exposed to three glacial advances from the north. Detailed investigation of all remnants of the ice sheets may help better to assess the impact a future ice age could have on the hydrogeological system and the upper part of the salt dome. Since there is a strong tendency in the German waste management strategy to expand the time boundary for long term safety modeling from 10^4 years to 10^6 years this matter is gaining importance.

CONCLUSION

Under undisturbed conditions, rock salt is practically impermeable due to the tightness of the salt structure and the absence of open natural joints and fissures known from many other types of rocks. The permeability of rock salt is a non-linear function of dilatancy. Owing to its pronounced viscoplastic behavior, salt has a high self-healing capacity under suitable conditions. However, the residual permeability of rock salt became a subject of interest in view of gas generating waste and the eventual over-pressurization of the sealed repository. In this context research and development on the evolution and healing of the excavation damage zone has to be intensified and, if possible geotechnical analoga in operating salt mines have to be investigated.

Although the rock mechanical behavior is fairly well understood there is a need to get a more specific data base on the primary creep of rock salt. Since the Gorleben site has not been confirmed yet as a repository the different types and facies of rock salt have to be investigated for the impact the different parameters can have on the creep rates.

REPOSITORY CONSTRUCTION AND OPERATION

The large-scale demonstration tests in the Asse mine have proved that detailed monitoring of the THM and geochemical properties of the host rock is required in order to qualify a mine section for the disposal of heat-generating waste. To some extent these parameters have a direct impact on the lay-out of the disposal sections with drifts and boreholes and the system of safety pillars. Present technology requires the application of advanced computer models in order to simulate the thermo-mechanical near-field processes. These models are indispensable for licensing.

Most of the demonstration tests in the Asse mine were conducted at a depth of 750 m to 900 m in the center of the salt anticline where Halite of the Stassfurth Na₂B is developed. These conditions correspond in some way with the envisaged concept for the candidate site Gorleben. Furthermore, the experiments were designed, as far as possible, at full-scale to avoid scaling effects and to test the handling and disposal system for HLW in an almost representative manner.



Fig. 3 Testing of a HLW disposal system / concept in the Asse mine / URL.

In the years 1984 to 1993 all mine installations were set up in the Asse mine for the conduction of a full-scale HLW disposal experiment in boreholes (Fig. 3). The entire system for transport, handling and

emplacement of 30 highly-radioactive radiation sources in Cogéma canisters was designed, manufactured and successfully tested as well as technically approved by the responsible mining authority. In 1993, the project was prematurely terminated for several non technical reasons. Thus, the testing of the system under real conditions is still pending. This applies also to the emplacement of Cogéma canisters and of alternative canisters for SNF into 300-m-deep boreholes.

With respect to Pollux casks, weighing 65 Mg each, the shaft transport is the most crucial issue. In order to prove safe loading on to the hoisting cage / platform and unloading a testing facility was set up for the simulation of real loads. As a result an efficient locking device was developed in order to hold the loaded cage in position at the 800 m or 900 m level for unloading. With this difficult problem solved there are all technical components at hand to operate SNF disposal in heavy duty casks. In the Asse mine six dummy Pollux canisters were assembled and fitted with electrical heaters for the TSDE heating experiment. Despite the backfilling behavior the corrosion rates of the cast iron and some coating materials were investigated.

Unlike in any other underground laboratories the mining techniques for waste disposal have been steadily developed further. Dimensioning of safe disposal drifts, adaptation of smooth blasting and continuous mining, and high quality backfilling of mine workings and disposal rooms have been the main points of interest. Most important for HLW disposal was the development of a drilling technique for deep boreholes (300 m to 600m) with diameters of 0,6 m to 1,0 m and a minimum of deviation.

Conclusion

Despite the advanced technology developed for HLW and SNF disposal in rock salt there is need for a detailed comparison of the different concepts in order to optimize both the waste management and

disposal strategy as well as the safety approach. In this very context all partners involved identified an extended non-closure stage of heated disposal sections as an important safety issue. This applies in particular to the emplacement of BSK 3 and THTR containers in boreholes. There could be some good arguments for borehole liners in order to hold convergence and to maintain retrievability for some time. Such liners would prevent also gamma radiolysis in the neighbouring rock salt. So far, the subject of monitoring was not a high ranking issue. However, in several countries decision has been taken for the development of adequate strategies and tools. With the concept changing from sole HLW to mixed HLW - SNF disposal monitoring becomes in issue also in the salt option.

PERFORMANCE ASSESSMENT

In view of the long-term safety of underground waste repositories in rock salt several PA studies have been performed in the last 20 years. The PAGIS project, organized in the framework of the EU research and development program, focused mainly on the comparison of the different disposal options. With respect to rock salt the first data from the Gorleben exploration were used in order to assess the radiological consequences which might result from brine intrusion into a HLW repository as well as from a subsidence scenario. This study contributed to a better understanding of the main parameters and processes which govern the post operational safety of a waste repository in rock salt.

In the so called PSAG exercise a NEA working group checked on the implementation of a probabilistic approach in performance assessment and developed numerical tools for an analysis of the different uncertainties bound to the complex system of geological and engineered barriers.

In the EU projects EVEREST and SPA processes and parameters were investigated in greater detail which may have a distinct impact on the dose rates to be expected in the far future. Based on the latest improvements made in the technical and scientific field the SPA project focused on the disposal of SNF. The near field source term, engineered barrier behavior and possible effects of the excavation damaged zone were of particular concern.

Most important from the German perspective is the national project SAM / SEK (Bechtold, W. et al, 1993) which dealt with the overall safety of the different repository concepts envisaged for the salt dome at Gorleben.

Mobilization and transport of radionuclides as a possible consequence of a brine intrusion scenario were modeled for a conceptual disposal system incorporating both the host rock as well as the covering rock formation. Due to the groundwater travel time in the Quaternary which is greater than 1000 years the first appearance of dose rates above 10^{-9} Sv/y were calculated for the year 5500 after closure of the repository. The peak dose rate appears at 45000 years after closure. The peak value of 10^{-5} Sv/y is about one order of magnitude below the limit set by the German radiation ordinance (Fig. 4).

In this case study I-129 mainly contributes to the dose rate because of its low retardation and long half-life. Additionally Se-79 and Cs-135 play a role in the first 10^5 years. Actinides are more strongly retarded. In the time frame beyond 10^5 years long-living Np-237 still contributes significantly to the total dose rate. Thus, it is a suitable indicator for the very long-term performance of the system under non-base-case conditions.

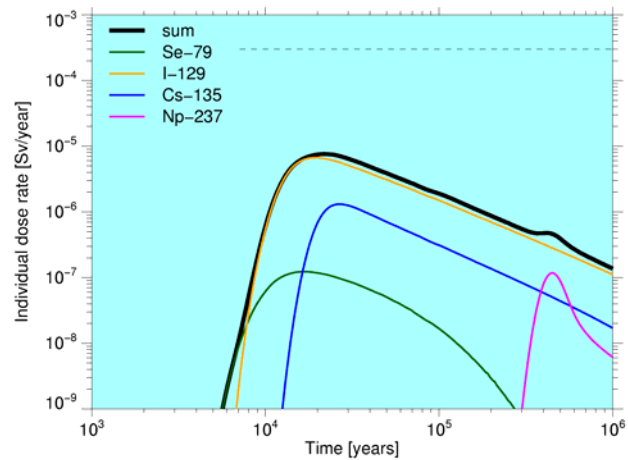


Fig. 4: Individual doses calculated for brine intrusion into a SNF repository in rock salt.

It was also proved that radionuclide release into the covering strata and the biosphere will not occur if the HLW disposal sections, i.e. the heated sections, are located closer to the shafts than the non-heated sections. Due to the heat-induced acceleration of the convergence potential pathways for radionuclide migration will close in relatively short time. Concurrently the backfill in the drifts gets compacted faster, and with the convergence rate slowing down the possibility of contaminated brine reaching the shafts will distinctly be reduced. In this case the connecting drifts between the central area of the repository and the HLW-section will be closed after about 155 years, whereas the brine coming from the shaft will reach this drift only after 233 years. The drifts in the HLW-disposal section will be closed after 70 to 80 years, preventing the brine from getting into the boreholes.

Conclusion

Integrated PA-models comprising the near field, far field and biosphere have revealed radionuclide migration and residence times in the geological formations as crucial processes/parameters for altered evolution scenarios. Despite the importance of the solubility of all relevant radionuclides, it is essential to gain greater knowledge of the solubility levels as a function of the geochemical characteristics of the geological medium through which they travel. This includes the engineered barriers protecting the waste packages against groundwater or brine intrusion, and their role in delaying the migration of radionuclides. In this respect the determination of the sorption properties of potential backfill additives has been identified as an important research task. On the other hand, because the covering formations are not considered as an indispensable long-term barrier the investigation of those sorption properties is classified as more or less site specific.

In a repository with all types of radioactive waste a considerable gas generation is being expected by conditioned LLW and ILW. The effects of gas pressure on the barrier integrity as well as on the fluid transport are being discussed. There is a need for a better integration of long-term effects in PA models. Despite the efforts for getting a more consistent geochemical data base there were some additional and, for the salt option far reaching issues identified for further research. In view of the envisaged isolation time in the host rock of up to 1 million years there is a need for the development of a set of safety indicators which could help to support the established performance analysis. In this context the questions about climate changes and the impact of future ice ages may become more important. In the same line the use of natural analogues appears which may lead to a better understanding of slow geological processes on specific aspects of long-term isolation of long-lived waste.

RÉSUMÉ

The NET.Exel project gives a very good overview on the status of the various national research programs. The scientific and technical information underline the basic safety strategies and objectives and confirm the great potential of underground waste disposal in general.

Structure and content of the formalized report offer the possibility to compare in detail the disposal options and the techniques to be applied. However, with respect to RTD needs the basic differences between the individual options have to be taken into consideration.

Referring to the salt option it becomes evident that some issues require further research work. This applies in particular to

- chemical interaction of waste, SNF and canisters with brines (corrosion, gas generation),
- permeability of rock salt and backfill against fluids, self - healing processes (EDZ),

- migration and sorption of radionuclides in the near-field (retention by additives in backfill),
- qualification of underground sealing dams and shaft plugs in view of their long-term properties,
- monitoring systems and adaptation of emplacement technologies to advanced disposal concepts,
- PA strategies and methodologies (isolation time of 1 million years).

The retrieval of emplaced HLW and SNF is no part of the German disposal concept. Due to the dry host rock it is planned to backfill and seal the emplacement vaults as soon as possible. Any other concept leaving these vaults open for an extended period of time makes the entire system more complicated. However, some provisional considerations have been made in Netherlands on this issue. Concerning the disposal of SNF the problem of 'safeguards' has to be tackled, even for a deep geological repository in rock salt.

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