CHAPTER 11

GEOSCIENTIFIC AND ROCK MECHANICAL ACTIVITIES FOR THE RADIOACTIVE WASTE REPOSITORIES IN GERMANY: KEY ISSUES, STATUS AND FUTURE PLANS

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Abstract. The engineering geological and rock mechanics activities for radioactive waste repositories are strongly linked to the safety concepts for the repository projects. Key issues are: proper site characterization, proof of geotechnical safety and quantitative description of geochemical processes and of geological scenarios for long-term safety assessment calculations. Astatus report of the German repository projects Gorleben and Konrad based on this concept will be presented. While these projects are still being pursued the former Morsleben salt mine in Sachsen-Anhalt, which was used as a repository for short-lived low and intermediate level waste from 1981 until 1991 has resumed its operation in 1994. In the paper some issues are demonstrated by an example: site characterisation work for a salt dome, geotechnical measurements and calculations to proof the stability of a mine, and considerations of geomechmical natural analog for calibration of constitutive laws. For the future the role and contributions of geoscientific and rock mechanics work within the safety assessment issues (e.g. geomechanical safety indicators) must be identified in greater detail.

11.1 INTRODUCTION

Since the early sixties, the radioactive waste disposal policy in the Federal Republic of Germany has been based on the decision that all kinds of radioactive waste are to be disposed of in deep geological formations. The basic aspects which must be taken into account to achieve this objective of disposal are compiled in the "RSK-Sicherheitskriterien für die Endlagerung radioaktiver Abfälle" (Safety Criteria for the Disposal of Radioactive Waste in a Mine). The following criteria are considered to be the most important ones:

The required safety of a repository constructed in a geological formation must be demonstrated by a site-specific safety assessment which includes the respective geological situation, the technical concept of the repository including its scheduled mode of operation, and the waste packages intended to be disposed of.

In the post-closure phase, the radionuclides which might reach the biosphere via the water path as a result of transport processes not completely excludable must not lead to individual dose rates which exceed the limiting values specified in section 45 of the German Radiation Protection Ordinance (0.3 mSv/a concept).

11.2 GEOTECHNICAL SAFETY

Natural geological and geotechnical barriers are an important part of a multiple-barrier system. Thus, the loadbearing capacity of the rock (expressed, for example, through subsidence or cavern stability), its geological and tectonic stability (e.g. mass movement or earthquakes), and its geochemical and hydrogeological development (e.g. groundwater movement and the potential for dissolution of the rock) are important aspects of the safety analysis. Therefore safety cannot be assessed from a purely engineering point of view, but must include geological factors. A site-specific modelling of geotechnical and geomechanical features and processes is needed.

The safety analysis must be based on a safety concept that includes the possibilities of failure (failure scenarios) that could occur during the excavation, operation and post operation phases, as well as measures to avoid such failures. Monitoring is also a part of the safety concept.

11.2.1 Geotechnical safety plan

The site specific geotechnical safety plan has to include the individual dose/risk scenarios and possible contingencies for which again measures and/or verifications are required. The safety plan has to be updated as new experience becomes available (e.g. during the construction or during the operation of the plant) The safety plan for an underground disposal plant (disposal mine) should, inter alia, describe the following (Langer et at 1993):

- measures to avoid or reduce risks;
- possible actions to enhance stability of the plant-based on monitoring systems; and
- acceptable residual risks.

The potential risks define the limiting situations which are to be avoided. These could be for example:

- local fractures in mine openings;
- failure of pillars and roofs;
- rock burst;
- rock mass loosening due to large cavity or shaft convergence, leading to a loss of integrity of the rock mass; and
- loss of functionality of seal structures(e.g. dams).

The safety plan should assess the following:

- system failure of load bearing structures;
- long term integrity of geological barriers; and
- seal functions of seal structures.

To this end the following measurements and/or calculations are available:

- the short term and long term convergence of cavities;
- large scale deformations in rock mass and neighbouring rock and overburden; and
- stress states in rock mass.

11.2.2 Numerical proof of geotechnical safety

The potential risks as described in section 11.2.1 which generally represents states of a hypothetical character and are hence not covered by the in situ measurements are to be checked mathematically. Relevant models have to be developed for each situation, and are to comprise the following component sections:

- presentation of the dose/risk scenario under investigation;
- effects such as primary state of rock mass, temperature, cavity convergence, effects of waste, earthquake, etc;
- calculation model which must cover rock mass formations, cavities and their changes as realistically as possible;
- material models for rock mass and overburden, and possibly also waste and backfill;
- calculation of safety relevant status variables such as deformations, stresses, and possibly permeability of liquids (and gases);
- checking and assessing calculation results; and
- safety concept which provides statements as to threshold values for risks.

The informative value of the theoretical proofs is decisively influenced by the expressions introduced into the calculation model. For this reason it is necessary to be aware of these influences when assessing safety matters. These include, inter alia:

- show sources of errors e.g. in the structural description of the disposal facility, in the material laws, in the numerical calculations methods; and
- show the sensitivity of the results to changes in the input parameters by calculating with parameters variations (e.g. also to identify natural scatter).

In the practical performance of the proofs it may be useful to initially work with assumptions which are unequivocally conservative which produce simple verification methods and then move on to more complex expressions in places where the conservative calculations indicate possible critical states. When using this procedure of simplified verification the conservativeness of the expressions must be thoroughly evaluated.

Uncertainties are for example:

- variation of material properties with respect to space and time;
- uncertainties in the determination of the load;
- inexactness of the model (simulation of the physical and geological conditions); and
- efforts of unexpected and/or possibly omitted events.

Geological and geotechnical uncertainties can be mastered by a method of calculated risk (“Geoengineering

Confidence Building", see Fig. 11.1). The main part of this method is the handling and validation of models (Langer, 1994).

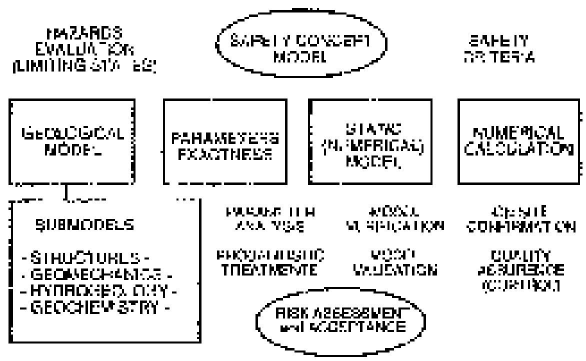

Figure 11.1. Geo-engineering safety confidence building.

11.3 GORLEBEN REPOSITORY PROJECT

11.3.1 Site investigation and planning

The Gorleben salt dome has been under scrutiny since 1979 to host a repository at depths between 840 and 1200 m, mainly for high level and/or alpha bearing wastes and spent fuel. Site investigations and planning are at present based on a nuclear capacity of 2500 GWa, leading to a total activity of about 10^{21} Bq and an alpha activity of about 10^{19} Bq (Brennecke et al., 1994). The following work from above ground was carried out between 1979 and 1985 to investigate the geology and hydrogeology of the Gorleben site:

- 4 boreholes, each about 2000 m deep, for investigation of the salt dome;
- 44 boreholes for investigation of the cap rock and the underlying salt beds;
- 2 preliminary boreholes for the shafts Gorleben I and Gorleben 2;
- 156 km of seismic profiles;
- 145 investigation drillings into the Cenozoic cover;
- 326 drillings for the installation of piezometers;
- 4 long time pumping tests (pumping time about 3 weeks for each test); and
- 1 borehole for investigations of the Palaeogene in the rim syncline.

Other investigations which were carried out include geoelectrical and geothermal studies, gravimetry, seismology, geochemistry, isotope geochemistry, and micropalaeontology.

The objective of the exploration from underground is to acquire all information needed to evaluate the operational and long-term safety of the planned repository. This has to be achieved while keeping disadvantages of potential damage to the geological barriers as low as reasonably achievable. Two shafts have been erected. Subsequently two pairs of exploratory drifts, connected by eight cross-cuts, will be driven to the northeast and southwest in a depths of 840 m. From there, numerous exploratory wells (in total about 60 km) will be drilled horizontally and vertically up to about the outer boundary of the prospective repository fields.

The stratigraphy and structure of the salt dome will be investigated by geological, geophysical and petrographic methods in such detail that it will be possible to identify rock salt sufficiently large and otherwise suitable for the different types of radioactive waste. Also, the positions of the more problematic layers, such as the main anhydrite and the Stassfurt potash seam, as well as brine pockets and gas-bearing salt bodies, will have to be determined exactly for proper risk assessment.

11.3.2 Results

In agreement with the international approach (IAEA, 1994), remarkable results were recently achieved in the use of safety indicators for the barrier performance of rock salt in general, and of the Gorleben salt dome in particular:

- An empirically tested exponential mass change model predicts isolation potential of repositories in rock salt of millions of years. The results from the site investigations in Gorleben are in agreement with these predictions (Röthemeyer, 1991).
- This evidence is supported by site-specific natural analogues. The analysis of fluid inclusions gave evidence of the depth down to which the glacially influenced subrosion processes effected the salt dome, and proved a past isolation period of 2.5×10^8 years at the depths of 860 to 1360 m envisaged for waste disposal.
- Regarding the halokinetic process of the Gorleben salt dome, the average rate of uprise of salt in the top part of the salt diapir has been calculated. The diagram (Fig. 11.2) shows a rapid increase in the rate of uprise from the beginning of piercement to a culmi-

nation in the Cretaceous, and a gradual decrease in the rate up to the present day. Jaritz (1991) plotted curves of the variation in the rate of uprise with time using Zirngast's figures. He obtained values of 0.07 to 0.08 mm/a (Fig. 11.2) for the maximum rate of uprise of the salt, using different time scales. This is slightly lower than the other salt diapirs in NW Germany, for which Jaritz gives values between 0.1 and 0.5 mm/a. Both curves agree as to the present rate of uprise (0.01 mm/a). In the light of the more or less constant dynamic conditions, on which the supply of fresh salt from below depends, it is possible to predict that in the future the rate of salt uprise will not change significantly for at least one million years. Thus, assuming a rate of uprise of about 0.01 mm/a, uprise over the next 10,000 years will amount to 10 cm and over the next 1 million years, about 10 m.

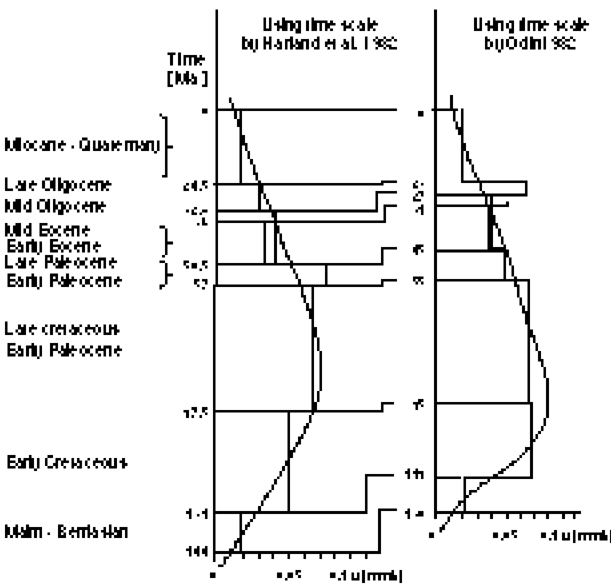

Figure 11.2. Mean rate (v) of uprise of the salt at the top of the salt diapir, after ZIRNGAST in aJARITZ, 1991.

- The effect of future geological processes have been considered with probalistic modelling of structural response. As an example, impact of a temperature decrease during glacial age on the integrity of the salt barrier above a repository has been analysed. A sensitivity study showed that besides the depth of the salt dome, also the shape of the dome and the stiffness of the adjacent rock have a significant influence on the development of tensile stress at the top of the salt dome. However, creep capacity of rock salt enables the salt formation to significantly reduce the total amount of tensile stress. Even under very conservative assumptions, thermally induced fractures will only develop as far as about 100 metres depth, and therefore will not endanger the barrier function. With respect to the computational procedure, it has to be mentioned that the linear approach to the system response surface is valid for the case in question but can be insufficient for other evaluations. A nonlinear approach would be recommended. Respective development is under progress (Wallner and Eickemeier, 1994).

- Regarding the rock mechanical properties of the rock salt from Gorleben dome, the creep behaviour has especially been investigated. The application of improved experimental techniques, as well as examination of our extensive data base, show that the specific textural characteristics of the various types of rock salt cause significant differences in creep behaviour. In spite of the same experimental stress and temperature conditions, samples yield steady state creep rates that vary from each other by a factor of more than 10. Differences of up to a factor of 100 have even been recorded from rather pure rock salt (greater than 95% halite). Figure 11.3 illustrates a summary of the experimental results for steady state creep rates at room temperature, which were obtained on rock salt samples from the Gorleben salt dome. These suggest that there is a large range of creep characteristics. The “locally” large differences (factor of 100) are rarely taken into consideration during modelling calculations, and consequently the results are not particulary reliable. The results shown in Figure 11.3 also confirm the “miners law” in that the “older halite” (z2) on average creeps faster than the “younger halite” (z3). Two formulae for steady state creep (BGR2 and BGRb) have been determined. In Figure 11.3 the BGRa law is located in the upper domain for the creep rates, and the BGRb law in the lower domain. Both formulae yield a stress exponent n= 5 for the stress sensitivity. Miroscopic impurities are the main reason for the large differences in creep. It is known from material science that it is not the overall mass-proportion of impurities but the number, distribution and type of particles that affects the ductility. This is easy to comprehend, since every defect in the crystal lattice is an obstacle to the moving dislocations (Hunsche and Schulze

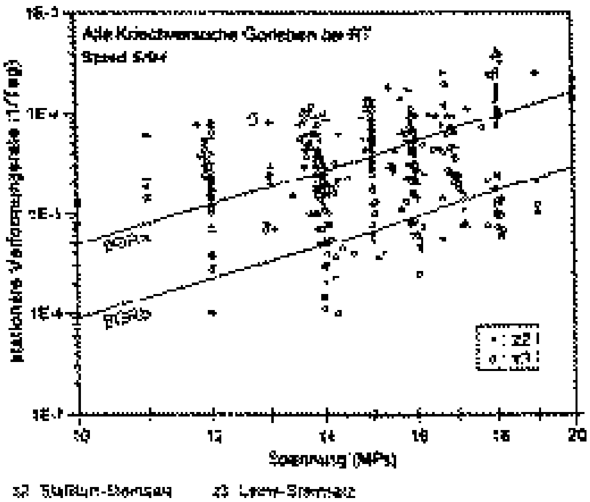

Figure 11.3. Stationary creep rates of salt cores from Gorleben.

1994).

11.4 KONRAD REPOSITORY PROJECT

11.4.1 Safety assessment and planning

It is intended to emplace into the Konrad repository - an abandoned iron ore mine in the southeast of Niedersachsen - radioactive wastes which exert a negligible thermal influence on the host rock (total activity 5 x 10^{18} Bq, alpha activity 1.5 x 10^{17} Bq). The application for the initiation of a licensing procedure for the Konrad repository project was filed in 1982. A decision on the project is expected for the near future.

New cavities of about 10^6 m^3 volume will be driven at depths between 800 and 1300 m for the emplacement of the waste. Atime of operation of at least about 40 years is expected, depending on the amount of waste to be disposed of annually.

Because of the licensing autbority's opinion on long-term safety, limitations will arise to 7.0 x 10^{11} Bq for ^{129}I and 1.9 x 10^{12} Bq for ^{238}U. Due to the long travel times from the repository to the biosphere, a potential radiation exposure of the biosphere will only result in the case of long-lived radionuclides like ^{129}I and ^{238}U with its decay products, and only after hundreds of thousands of years and several million years, respectively. These results are taken from model calculations for radionuclide migration in the repository's near and far field. Since the potential radiation exposure will occur far beyond a time limit for which it may be assumed with sufficient reliability that the marginal conditions like the present geological and hydrogeological situation at the site underlaying the calculations are still valid, the results obtained for individual doses only have the purpose to judge the isolation potential of the site. This opinion of the applicant was discussed controversially within the licensing process. More details were presented by Röthemeyer (1993).

11.4.2 Rock mechanics work

Among others, the following types of measurements have been carried out:

- measurement of subsidence at ground level using leveling;
- measurement of the drop in roof level in the main levels;
- measurement of the convergence in the main levels and exploratory drifts;
- measurement of rock mass deformation above a former working field (flushing field); and
- measurement of rock stresses.

Subsidence was measured using precision levelling on a fixed network of 390 points distributed over approximately 40 km^2. The results of these measurements may be summarized as follows:

- The first subsidence occurred approximately one year after the start of mining.
- The maximum subsidence of the trough is in the area above the flushing field. In May 1985, 20 years after the start of mining, the subsidence here totaled 264 mm. The subsidence trough had a limiting angle of between 35 and 39°.
- During ore extraction the maximum rate of subsidence over the southern field was 2.8 mm/month; in 1985 this had reduced to only 3 mm/year.

The development over time of the subsidence of levelling points does not indicate any irregulatrities. The trough is subsiding uniformly.

Overall, the subsidence may be considered as small. This is confirmed by the fact that no damage has been observed at the surface. The measurement results allow the assumption to be made that subsidence is close to its final value. A large number of convergence measurement stations were set up on the main levels and exploratory drifts. It proved in part possible to carry out initial measurements very soon after cavity excavation.

The evaluation of the convergence measurements has provided the following results:

1. The convergence processes observed in the Konrad mine are not based on creep processes, as in rock salt, for example. They are rather related to microfissuring processes in the nearby surrounding rock, which lead to deconsolidation of the rock mass.
2. The convergence of the drifts over time may be described using a logarithmic function (Fig. 11.4).
3. The convergence behaviour of the drifts is dependent upon the degree of excavation; the higher the degree of excavation the higher the convergence.
4. The floors of the drifts frequently show greater convergence than the roofs.
5. In drifts which pass through old mine sections the effects of stress redistribution in the area of the old workings are continuing.

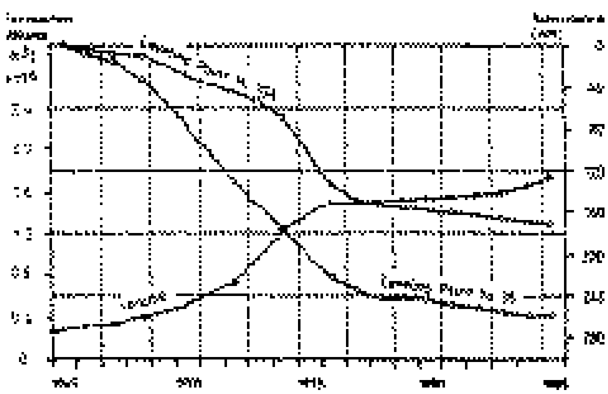

Figure 11.4. Subsidence and excavation volume versus time, Konrad mine.

In addition, numerical calculations were executed to assess the rock mechanical processes in the overburden and the stability of the repository. The calculations were carried out using the Finite Flement Program System ADINA.

Primary stress measurements were carried out in two boreholes at borehole depths of approx. 15 m to 25 m. The results are plotted in Figure 11.5. The maximum and minimum stresses are shown as functions of depth of the borehole under study. The measurements allow maximum values of between approx. -18.0 and -24.5 MPa to be read, and minimum values of between approx. -12.0 and -17.6 MPa. The overall averages are -21.0 MPa (maximum values) and -14.8 MPa (minimum values). The maximum stresses are generally subvertical (±20° to ±30°) in orientation.

Typical results measured for secondary stresses normal to plane of bedding me given in Figure 11.6 for measurement section MQ4 in the pillar between chamber 231S and chamber 241S. Here the measured stress changes were raised by the amount of the theoretical primary stress. The measured values show a marked drop as distance from wall increases. At approx. 10 m distance stress changes have fallen to minor levels.

As a comparison the results of the numerical model calculations are shown. These model calculations are reported in detail in Dickmmn et al. (1991). As Figure 11.6 shows, there is good agreement between measured and theoretical secondary stresses.

Generally, the rock mechanics tests undertaken at the Konrad drift system in field 5/1 have as their most important result that the construction of storage chambers in middle Jurassic coal oolite for radioactive wastes generating low levels of heat with cross sectional areas of 40 m^2 and chamber separations of approx. 35 m can be safely carried out from a rock mechanical point of view. The results of the geotechnical measurements performed in test field 5/1 do not indicate my risk to stability of the hard rock and the drifts.

With respect to the test techniques under the difficult *in-situ* conditions in the underground, the instrumentation proved itself for the most part very well and produced reliable results. The test concept of overlapping and complementary test methods has proved itself to be constructive and expeditious.

11.5 MORSLEBEN REPOSITORY

Short-lived low and intermediate level radioactive waste from the operation of nuclear power plants and the application of radionuclides in research, medicine and industry in the former Geman Democratic Republic was disposed of in the Endlagerung für radioaktiver Abfälle Morsleben (ERAM, Morsleben repository for radioactive waste) an abandoned salt mine located near the village of Morsleben (now in the state of Sachsen-Anhalt).

Until 1969, this mine had produced potash and rock salt. The salt was excavated in room and pillar mining down

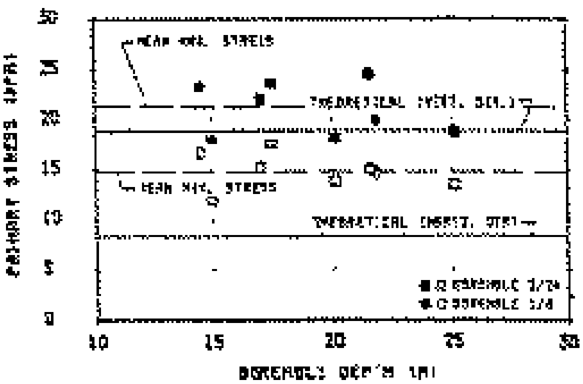

Figure 11.5: Primary stresses in test field 5/1.

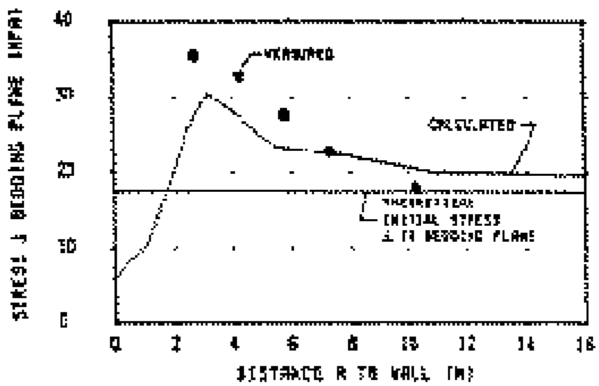

Figure 11.6. Secondary stresses normal to plane of bedding.

to a depth of about 500 m so that mine openings resulted with a maximum length of about 150 m and a maximum width and height of about 30 m, respectively. In total, a volume of about 7.6 x 10^6 m^3 was excavated and partly backfilled (2.1 x 10^6 m^3,). Since the first operational license was granted in 1981, the repository has been used for the emplacement of short-lived low and intermediate level waste without the intention of retrieval. Spent radiation sources were also disposed of in this facility.

Until 1991, radioactive waste with a total emplacement volume of approximately 14,500 m^3 and about 6,200 radiation sources were disposed of. In total, an activity of 1.8 x 10^{14} Bq was emplaced. The activity of alpha emitters amount to 1.6 x 10^{11} Bq, and the activity of beta/gamma emitters, to 1.8 x 10^{14} Bq. The waste was mainly delivered by combined rail-and-road transports using standardized freight containers. About 2,900 such containers were delivered until 1991.

Since the German Unity in October 1990, the Morsleben facility has the status of a federal repository. The operating license is limited by law until June 30, 2000. Emplacement of waste has been resumed in January 1994. Until the end of the year 1995, 5,691 m^3 of waste with the total activity of 2.6 x 10^{13} Bq [(α: 1.4 x 10^{10} Bq] has been disposed of.

11.6 FUTURE RESEARCH WORK

The European Commission has recently performed a review study on the status of understanding of thermal, mechanical, hydrogeological and geochemical properties of host rock formations (Balz, 1995). In general, it was concluded that the large number of heating experiments which have been performed, both in laboratory and in the field, have provided sufficient knowledge about the nature of the purely thermal aspects and existing models seem to be adequate for predicting the resulting temperature field and its evolution with time.

It becomes more difficult when one has to consider the influence of temperature increase on the mechanical, hydrogeological and geochemical properties and in particular to understand and perform predictive modelling of coupled effects.

Table 11.1. Recommendations for research

Priority 1
• Further development of investigation and interpretation methods for coupled geochemistry/geomechanical/brine migration models. • Further studies of geomechanical properties with gas and brine related parameters as variables. • Development of consistent thermomechanical models and relevant codes for backfill material. • Scientifically based engineering studies to develop performance criteria for backfilling and sealing techniques. • *In-situ* studies of the gas problem.
Priority 2
• Comparison of stress measurements methods and interpretation procedures, taking salt creep into account. • Development of a freshwater/brine groundwater flow model, and validation under *in-situ* conditions. • Development of models for generation and transport of gases and brines. • Optimization of “geoprospective” natural analogue, scenarios and palaeohydrological methods. • Testing of backfilling techniques in a URL.

Therfore, it has also been recognised that the couplings of chemistry with thermo-hydromechanical (THM) processes of the various host rocks is a crucial issue which has to be further investigated.

Another subject which has gained attention in recent years is the issue of gas generation and transport and possible impact on operational and long term safety. In any repository for radioactive wastes, gases will be formed due to corrosion of metals, microbial degradation of organic matter and to a lesser extent from radiolytic decomposition of water and organic compounds. As a consequence, gas pressure will build up in the near field until it is released through the system of engineered barriers into the geosphere at a rate equivalent to the production rate. Research efforts have been undertaken to assess the rate of production for various waste forms, disposed of in various host rocks. Moreover, models have been developed for describing gas transport and/or two phase flow through the geologic formations. However, more research is needed for a better understanding of basic mechanisms of gas and/or two phase flow through the host rock or along preferential pathways, fractures and faults. Site specific data are necessary for the assessment of the possible impact of gas generation on repository safety. Technical measures are available or further being developed to cope with these issues by appropriate repository design.

Reflecting these results and considering the following key questions:

- can a candidate respository site be adequately characterised (availability of site characterisation techniques and methodology)?
- are thermal, hydrogeological and mechanical properties and processes of salt formations well enough understood (long-term efficiency of the geological barrier)?
- will it be possible to build, operate, backfill and seal a repository in salt rock in a safe and economic way (repository design aspects)?

Conclusions for further scientific work have been given (Langer, 1995). Regarding rock salt as host rock the recommendations listed in Table 11.1 can be given. The aim of this research work is to assure that appropriate use of safety assessment methods, coupled with sufficient information from proposed disposal sites, can provide the technical basis to decide whether specific disposal systems would offer to society a satisfactory level of safety for both current and future generations.

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