CROP: A European Thematic Network Project for Evaluating and Developing Concepts of Final Repositories for High Level Radioactive Waste

Main Results and their Importance for the German Final Repository Research Programme

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Abstract:
On initiative of the European Commission (EC) the Cluster Repository Project (CROP) was performed to provide a forum for discussion and appraisal of repository concepts and achievements of related research in underground research laboratories (URL). The focus was on engineered barrier systems and actual capabilities to model their long-term behaviour in interaction with the surrounding host rock formation. On basis of country annexes provided by the project partners the achievements in the national research programmes and different host rock media were discussed and compared. A conclusion was that a comparison on a general level has merits. A comparison on detailed level, however, was found directly misleading since site and formation as well as host rock differences make such an approach extremely difficult. In addition, all studied concepts have proved the safety case, and have a potential for providing a long term isolation of the nuclear waste with a major margin to the safety requirements. The discussions also revealed commonalities which should be used to integrate research and development activities in future European research programmes. For each of the host rock media considered proposals were compiled for continuative R&D-work in view of concept improvement and/or optimisation, respectively.

1 INTRODUCTION

Several underground research and development projects, which deal with disposal of radioactive waste in crystalline rock, salt and clay formations, have been supported by the European Commission. By constituting a forum (the Cluster Repository Project (CROP)) for synthesising construction experience and results from testing engineered barrier systems (EBS) in underground laboratories, and correlation of theoretical predictions with the outcome of performed experiments) an appraisal of the status achieved in Underground Research Laboratories (URL) with a view towards future design and construction as well as technical/economical improvement of concepts of future European repositories for highly radioactive waste was to be performed within a European Thematic Network. Nine end-user organisations took part representing Europe as well as North America. The participants are in alphabetical order:

1. Agence National pour la gestion des Dechets Radioactifs (Andra), France.
2. Empresa Nacional de Residuos Radiactivos SA (Enresa), Spain.
3. Gesellschaft für Anlagen- und Reaktorsicherheit GmbH (GRS), Germany.
4. Nationale Genossenschaft für die Lagerung radioactiver Abfälle (Nagra), Switzerland.

5. Ontario Power Generation Inc (OPG), Canada, supported by G.R. Simmons & Associates Consulting Services LTD.
6. Posiva Oy, (Posiva), Finland.
7. SKB (Svensk Kärnbränslehantering AB), Sweden, supported by Geodevelopment AB
8. Studiecentrum voor Kernenergie-Centre d'Etude de l`energie Nucleare (SCK-CEN), Belgium.
9. United States (U.S.) Department of Energy Carlsbad Field Office (CBFO), USA, supported by GRAM, Inc. and Sandia National Laboratories (SNL).

Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe (DBE) has participated as an observer since 2002. SKB serves as the project co-ordinator, i.e. project manager.

The aforementioned CROP participants represent underground rock laboratories (URLs) in several different geological media, such as crystalline rock in Sweden (Äspö), Finland (Olkiluoto), Switzerland (Grimsel), and Canada (URL, Pinawa), bedded salt in the United States of America (WIPP) and salt domes in Germany (Asse), and sedimentary clay formations in Belgium (Mol), France (Bure) and Switzerland (Mt Terri).

2 OBJECTIVE AND WORKPLAN

2.1 Objective

The aim of CROP is to provide a forum for exchange of information on repository design, construction and operation, and on testing and modelling of engineered barriers in host rock with the purpose of optimising scientific networking among key experts in the involved countries as well as improving testing and modelling procedures. The related information gained through the development of and testing in URLs constitute the basis for the current information exchange.

The result of the CROP collaboration is a document that can serve as an aid for future repository design and construction in all European and other countries utilising nuclear power and hence be of value to national and international agencies engaged in handling and disposal of highly radioactive waste.

It also provides an appraisal of the actual achievements in URL research and gives hints for potential concept optimization as well as for further research needs.

2.2 Work plan (Pusch and Svemar, 2001)

CROP was organized in form of two primary instruments which were

- desk studies with the outcome of country annexes describing the actual status of repository concepts, research in underground laboratories (URL), and modelling capabilities to predict repository behaviour
- project meetings for discussion of country annexes with the aim to find out commonalities of existing concepts in different geological media allowing cost reduction by sharing r&d work and the development of common safety standards

The participants contributed in the following way.

- Crystalline rock (Andra, Enresa, Nagra, OPG, Posiva, and SKB)
- Clay (and/or argillaceous) rock (Andra, Enresa, Nagra and SCK-CEN)
- Salt rock (USDOE CBFO, GRS and DBE)

The desk studies to be performed aimed at the following for work packages

WP 1: Design and construction of engineered barriers
WP 2 Instruments and experimental procedures
WP 3 Assessment of the function of EBS and the understanding of and capability to model the important processes as well as application of conceptual & mathematical models for predicting THMBC performance
WP 4 System optimization and the development of practically applicable concepts

3 MAIN RESULTS

The forum for discussion has developed as planned and meetings at each of the sites for URLs engaged in the project have provided up-to-date information on results achieved and information on plans ahead. Fruitful discussions on technical matters have followed and enhanced the knowledge among the participants of the state of progress in the other programmes, especially the programmes on other media than the one in focus in the organisation's own programme. A summary project report (Pusch et al., 2004), the most important results of which being described this chapter 3, will be published soon.

3.1 Repository design and construction of engineered barriers

For each of the geological media considered in CROP the principles for repository design have been described with special emphasis on EBS performance. Most of the concepts consider one-level repository layout. A major difference is the access to the repository which in case of salt is via a shaft while in granite and clay formation via ramp or shaft. While in salt the geological formation is considered the most important barrier the concepts developed for crystalline rock and clay formation rely more on EBSs hermetically encapsulating the waste packages. However, in all concepts credit is taken from both the geological formation and the EBS.

Hence, the long-term behaviour of the EBS represents a major issue in all repository design studies. Besides investigation of chemical stability the impact of temperature increase and decrease, the heat pulse generated by high-level waste (HLW) plays an important role.

Regarding the design of waste containers there are differences between the concepts. While some (e. g. granite) require very corrosion resistant long lasting canisters others (e. g. salt) rely on the barrier function of the host rock and thus do not ask for long-lasting containers.

Buffer and backfill concepts are different as well. In salt, for instance, magnesium oxide (at WIPP) and crushed rock (German concept) compacting in consequence of disposal room convergence with time until reaching similar properties as the host rock are considered most suited. In clay and crystalline rock, where formation waters may intrude into the repository self sealing smectitic clay barriers are favoured.

Plugs needed to seal off completed parts of a repository have not yet been tested in all concepts to a satisfactory degree. Hence, this area, among others, needs further R&D.

3.2 Instruments and experimental procedures

Application of instruments and experimental procedures have been very successful in all URLs. The analysis of the work done so far provided very useful information with regard to successful instrument installation and improvement of experimental procedures. One item found important was that instruments may have an adverse effect on EBS performance so that adequate optimization of measuring and performance requirements is required.

A general conclusion is that ***temperature sensors*** of common types are known to survive the harsh conditions in maturing buffer and backfill. However, their sensitivity to chemical attack by the pore water or brines in salt may cause quick breakdown, and special metal coatings, like titanium, should be considered to ensure adequate functioning.

Multipoint extensometers are of high accuracy (+/- 1-10 μm) and are thus even suitable in crystalline rock. Leakage of formation waters along multiwire cables, however, is a point of concern. Single cables are more appropriate in very moist environments. In addition, rod extensometers are sensitive to greater deformations in buffers and backfills and may thus remain operative for a short period of time only.

Absolute stress measurements in elasto-viscoplastic rocks like salt suffer of very long times needed to reach adequate coupling of the stress gauges to the rock. It is that, why commonly only stress changes are measured. Instruments in this regard are available and provide the required accuracy.

Sensors for recording wetting processes (e. g. psychrometers) are found to represent the least reliable of all instruments. Hence, new types being more robust and of higher accuracy would be beneficial to future experiments.

For ***measurement of gas concentration***, filters attached to tubing that reach out from clay or salt buffers have been used with good result. They have, however, not been used extensively in the URLs. For evaluation of ion migration and determination of microbial activities, cups can be installed for sampling at the termination of the test. Mineral changes can only be evaluated after the heating experiments have terminated.

3.3 Assessment of the function of EBS and the understanding of and capability to model the important processes

The work shows that the development of conceptual and theoretical models has been comprehensive and relevant concerning the maturation of clay buffer and salt backfill under the thermal conditions caused by the heat-producing waste canisters. However, certain conditions of great importance for the maturation of *clay buffers,* as for instance the importance of the near-field rock structure on providing water for buffer maturation have not been fully investigated. The nature and function of the excavation disturbed zone (EDZ) in this context is not fully clear, the matter being of fundamental importance to the understanding and modelling of chemical processes like accumulation of salt and long-term impact of hot water vapour on the clay buffer. The movement of water vapour that is associated with condensation/evaporation and film transport needs more attention to be properly implemented in the modelling.

The ***coupled THM behaviour of salt backfill*** compaction and drift convergence was investigated at Asse mine/Germany (Bechthold et al., 1999). Although the results show reasonable agreement between predictions and measurements it was concluded that modelling improvements may be achievable by both ongoing material parameter value determination and application of 3D-models. Also the modelling of the thermal behaviour of

backfill and rock shows some shortcomings which are to be overcome by further research on the material models.

The ***effect of high pore water pressures*** induced by the heat pulse on the stability of *plastic clay rock* may require further attention. The understanding of creep processes in *stiff and plastic clay rock* as well as in *salt backfill and rock* should benefit from additional study of the mechanisms on the micro-structural scale.

Gas release from canisters and migration through the buffer and backfill requires more attention in HLW repositories. Work has been done and conceptual understanding of processes involved has been developed. Still, modelling of gas migration through buffer, backfill, and rock should be further addressed. For WIPP the modelling result has been examined and accepted by peer reviews as well as the regulator.

Modelling of chemical processes in clay buffer is an issue that requires more work, especially concerning complexation and cementation. A remaining task is to develop more accurate theoretical models for conversion of smectite to nonexpendable minerals and associated release of elements that can cause precipitation, cementation and brittleness. The conceptual models need to be upgraded with respect to the possible formation of chlorite in the presence of iron sources, and reference to natural analogues could be made for back-calculation of activation energies.

Issues with ***THMC modelling*** concern the saturation ***of clay buffer*** which is driven by the negative pore pressure and controlled by the transient hydraulic conductivity on the microscopic scale, which in turn is controlled by the micro-structural evolution. However, the macroscopic averaging Darcy law is applied in the modelling and it may not be valid. The wetting can be described as a number of diffusion processes if no external water pressure acts on the buffer and this is the case also when thermal gradients exist. If an external water pressure is built up early the counteracting thermal gradient will yield wetting of the “advancing wetting front” type, which has been observed in field tests.

The impact of external water pressure on the ***wetting process*** is included in the buffer saturation models but its important practical role needs to be demonstrated by considering the hydraulic conditions of the near field. This highlights the need for modelling the piezometric state with respect to the hydraulic conditions in the rock structure and its interface with the EBS.

The state-of-art is that THMC models are partly uncoupled especially with respect to coupling of C and THM processes. Hence, the development of the models with respect to chemically induced changes in buffer, backfill and sealing material properties needs attention.

In the analyses ***of mechanical performance of clay-based materials in the maturation phase*** non-linear “Porous Elastic Models” and Drucker-Prager or Cam Clay plasticity models and the effective stress theory as defined by Bishop are adapted to unsaturated conditions. This implies use of empirically derived relations between the void ratio and the average effective stress, and empirically derived Drucker Prager parameters for the friction angle, the cohesion, the dilation angle and the yield function. Application of these models and laboratory derived relationships between suction and degree of fluid saturation, and introducing pore fluid conditions give the rate of wetting and time-dependent development of swelling pressure. The models appear to describe the theoretical performance for different stress paths well but it is not clear if the relationships are applicable to highplastic clays that undergo large micro-structural changes in the water saturation process.

THM models for describing the mechanical performance of clay-based materials after maturation can be used for predicting practically important processes like canister

movement and pore pressure evolution in saturated clay-based materials in the course of tectonic shearing. Still, their validity has not yet been proven.

4 RECOMMENDATIONS FOR CONTINUATIVE R&D

4.1 Clay and clay sediments

The disposal concepts in both soft and hard clays (clay shale, clay stone or argillite) are dependent on the fact that the clay layers generally have a limited thickness. This favours in-room emplacement in several hundred meter long horizontal to sub-horizontal drifts. The canister and waste package designs vary and improvements of large packages even including the buffer around the canister are being developed and tested. In all cases, the clay is the main barrier in the multi-barrier system, but the near field of the repository has to be designed and constructed in a way that defects do not jeopardise the long-term safety. Similar to the crystalline rock repositories buffer around the canister is part of almost every concept in clay. Backfilling, sealing and plugging are other repository components that have many similarities with those in crystalline rock and with salt repositories.

Ongoing work on improvement/optimisation addresses several items as for instance:

- Country-, waste- and site-specific layouts including the EBS (buffers, backfill and plugs)
- Emplacement strategies for different waste types
- Optimization of execution and operation for keeping the emplacement cells open for a minimum of time.
- “Active design” to provide for flexibility that allows for necessary changes
- Waste packages, buffer, backfill, seals and plugs which exhibit many similarities with the work going on in crystalline rock.

4.2 Crystalline rock

Crystalline rock has brittle characteristics and contains fractures, which form patterns of groundwater transport pathways from a repository to the ground surface. The existence of these fracture systems and their transport characteristics are the major factors that may influence the long-term safety case. The application of the multibarrier principle, however, puts the main burden for radionuclide containment and isolation on the EBS, in contrast to the repositories in salt and clay host rocks that essentially rely on the natural barriers. Still the near-field chemical environment and the natural radionuclide retardation properties of the host rock are important, although credit in the safety assessment can be taken only for verified conditions.

Ongoing work on improvement/optimisation addresses several issues as for instance:

- Canister design and manufacturing, as well as the performance in interaction with the buffer/backfill/plugs and the surrounding rock mass
- Maximum temperature allowed on the surface of the canister and design (shape and size) and the orientation of drifts at depth under consideration of the prevailing state of stress and conditions for groundwater flow

- Excavation method with respect to the creation of EDZ
- Grouting as a means for sealing drift walls against inflowing water
- Swelling clay alone or mixed with other materials for use in buffer, backfill and plugs.
- Emplacement and deposition methods of horizontal emplacement in addition to well tested emplacement in vertical boreholes, also with large waste packages containing both canister and surrounding buffer.

4.3 Salt

Two main disposal concepts have been considered in Germany for vitrified waste and spent nuclear fuel. The canister design has been identified (among existing types and sizes). In USA, the WIPP repository for long-lived nuclear waste was certified in 1998 and opened in 1999. A variety of waste packages are handled. In both Germany and USA, the host rock – the salt – is the main barrier against radionuclide releases to the biosphere, but backfill and EBS are required to ensure repository stabilization and sealing. Crushed salt makes a good backfill as stress and creep-induced room closure (convergence) ultimately leads to consolidation of crushed-salt backfill and the complete encapsulation of waste containers. With given weight and size of waste packages, the repository design including the designs of seals and plugs which in salt are the main engineered barriers is a country and site-specific issue, of which WIPP is an example in a bedded salt formation.

The experience and lessons learned at WIPP include both an operating repository and an on-site URL situated approximately 650-m below the ground surface in a 225-250-million-year-old, 600-m-thick bedded salt formation. The major basis for the successful certification and opening of the WIPP repository is equal advances in both repository-science-related issues (site conditions, disposal concept, and performance requirements), and social science- and demographic-related issues (local acceptance, political will, and organizational leadership). Although the WIPP repository already is operating, the development of the WIPP repository is phased and, by law, the safety of the WIPP disposal concept/system has to be recertified at least every five years.

Performance of different designs of plugs and seals as well as backfill in drifts has been investigated but an overall sealing strategy for the whole repository remains to be made in all concepts.

5 IMPORTANCE OF CROP RESULTS FOR THE GERMAN FINAL REPOSITORY RESEARCH PROGRAMME

The discussions held in CROP yielded enhanced knowledge among the participants, especially on the running programmes on other media. The inter-media comparison made in CROP was e new approach and lengthy discussions were held on the following issues:

- Can the three media be compared on a general level?
- If so, can the three geological media be compared on a detailed level?

The conclusion is that a comparison on a general level has merits. A comparison on detailed level is, however, directly misleading, because each of the studied concepts have proved the safety case, and have all a potential for providing a long term isolation of the nuclear waste with a major margin to the requested safety requirements. Each medium exhibit pros and cons, which, however, are to a major extent affected by the design and application of

appropriate EBS, i.e. the safety case is the result of the combined properties of the natural and the engineered barriers.

Following this unanimous conclusion medium-specific presentations were made with special emphasis on lessons learned and means of improving/optimizing the present concepts.

Regarding the German research programme the following conclusions can be drawn from the results of the CROP project:

5.1 Clay formations

Currently, clay formations in Germany are geologically assessed on their suitability to host a repository for HLW. So far, no site has been selected or recommended to be investigated in more detail. That is why, for the time being, research in Germany on the clay option can only be of generic character. Participation in foreign research programmes in the Opalinus clay formation at Mt. Terri in Switzerland and the plastic Boom clay formation in Belgium should therefore concentrate on issues which are of common importance for all kinds of clay formations. According to the findings of the CROP project such issues are for instance:

- design of buffer, backfill, and seal systems and their functioning under the impact of heat load, formation waters, stress and deformation fields, and the prevailing geochemical milieu
- effectiveness of seal systems in interaction with disturbed host rock, e. g. EDZ and de-saturated rock in consequence of repository ventilation during operation
- THM properties and behaviour of host rock, especially creep behaviour and diffusion
- model improvement with regard to coupled THM processes
- model validation by appropriate experiments in surface and underground laboratories

5.2 Crystalline rock

In Germany, crystalline formations like granite, are considered a back-up option for radioactive waste disposal. It is therefore why German research institutions participate in foreign programmes in the Grimsel Rock Laboratory since many years and since a couple of years also in the Äspö Hard Rock Laboratory in Sweden. A URL is not available in Germany and thus, as in the case of clay formations, research is limited to generic aspects only.

As pointed out above, crystalline rock formations are often characterized by fracture systems representing preferential pathways from the repository to the biosphere. Thus, practically all concepts rely on near field EBS which are therefore besides the transport characteristics of the fracture systems in the focus of all foreign research programmes. Generic issues that have been found worth in CROP for ongoing research and which should thus be of interest for the German research programme are the experimental investigation and modelling of:

- Saturation behaviour of bentonite buffer
- Gas generation by canister corrosion as well as resulting gas pressure build-up and migration/release through buffer
- Chemical processes in the buffer that influence its long-term stability
- Transport properties/characteristics of fracture systems

5.3 Salt

In Germany, the final disposal of radioactive waste in salt formations represented the first option from the mid sixties until the late nineties of the last century. Because of a change in the Federal Energy Policy, specially in regard to the use of nuclear power, in 1998 the German government expressed certain doubts with respect to the suitability of salt as host rock in general and of the Gorleben site in particular. All exploration activities were halted by the end of 2000 and a moratorium was imposed for three to ten years. During this time all pending issues shall be looked into, and new formation-independent site selection criteria are to be developed in order to identify alternative sites with favourable geological settings.

Recognizing this and by analyzing the R&D programme performed in the Asse mine/URL during the past 35 years within CROP (Rothfuchs et al., 2004), the items listed below were found to represent topical areas deemed to embody significant potential for improvement on the German research programme on repository research in salt:

- Compaction behaviour of crushed salt backfill in case of brine intrusion

  In the safety analyses, an intrusion of limited amounts of brine into backfilled disposal boreholes and drifts is being considered possible. Laboratory investigations have shown that adding of 1wt.% of brine leads to a reduction of the compaction resistance by one order of magnitude (DBE, 2001). Further investigations have been conducted in this area but the results have been not yet published. The data published by BGR have been used by the DBE to analyse compaction of moist backfill in large disposal rooms. In (DBE, 2001) it is stated that the BGR data are the only ones available, so far. Further investigation is, therefore, considered necessary to confirm the BGR data and could be accomplished by using Asse reference backfill material.

- sorption of special radionuclides in the near-field

  The THM behaviour of crushed salt backfill is largely understood. Adding of geochemical additives to increase sorption of special radionuclides in the near-field is under discussion and has not yet been tested adequately.

- EDZ generation and healing

  Detailed research on EDZ evolution in salt formations started about a decade ago in order to enable the assessment of its importance for the long-term safety analysis of radioactive waste repositories. Constitutive models to predict damage, dilatancy and permeability distribution around excavated drifts have been developed recently. The results of the first numerical simulations of underground experiments/analogues are very promising. However, the extent and degree of healing of the EDZ around the backfilled and over nine years heated TSDE experiment at Asse were significantly underestimated in model calculations. To enable satisfactory simulation of the long-term reduction/healing of the EDZ, adequate model improvement is considered indispensable.

- Hydraulic modelling

  Hydraulic modelling has so far only been performed with rather simple models or poorly validated material/parameter data. One reason limiting this effort was that the experiments conducted in the Asse mine/URL yielded brine-release data that were considered acceptable with regard to the repository safety issues then at hand. However, if very unlikely altered repository conditions were to be considered, fluid flow in a backfilled repository would be of high, possibly critical, importance and would require the determination of two-phase flow parameters for both the EDZ and the crushed salt rock backfill. First modelling results for altered evolution scenarios show a very complicated flow behaviour, even if only the basic two-phase flow effects are considered. Additional effects like a non-isothermal temperature distribution or a time-dependent porosity are

therefore to be included for more realistic predictions. This leaves a vast open field for the investigation of material behaviour as well as for code-developing even if it is not clear if a fully coupled THM approach is necessary.

The issue of fracturing of the host rock in case of gas generation in disposal rooms has not yet been addressed in the German research programme to a satisfactory degree. Respective R&D-work is thus recommended since high gas pressure may evolve due to corrosion and microbial degredation of waste forms if the disposal rooms are sealed gas tight. The corresponding improvement of existing coupled H and M models is considered very important, too.

- Drift seal

  In section 2 information is presented on drift seals (plugs) between the shaft area and the disposal fields that will be installed after the repository-operations period. However, the possible drift seal design presented by Stockmann et al., (1994) was never tested in situ under representative conditions and is still pending.

- HLW emplacement techniques

  Between 1984 and 1993, preparations were undertaken to conduct a full-scale experiment simulating the disposal of HLW in boreholes at the Asse mine (Rothfuchs et al., 1995). This experiment would have involved the retrievable emplacement of 30 highly-radioactive radiation sources in six 15-m-deep disposal boreholes on the 800-m level of the Asse mine. During the preparation phase, a complete transport and emplacement system was developed, successfully tested, and technically approved by the responsible mining authority. In 1993, the project was prematurely terminated because direct disposal of SNF became an alternative disposal option in Germany. Thus, the emplacement system was never tested with highly radioactive material. Hence, final confirmation of the technical emplacement system for Cogéma canisters, as well as the testing of the feasibility of the emplacement of alternative canisters for SNF into 300-m-deep boreholes, is still pending.

In the year 2000, a national expert group (named AkEnd) was asked by the German government to develop new, formation-independent, site-selection criteria for the identification of repository sites with favourable geological settings. The final report of this group was published in December 2002 (AkEnd, 2002). According to this report, the geological formation the repository is built in must meet the following requirements:

- The thickness of the host rock must be at least 100 m;
- The disposal level shall not be closer than 300 m to and not deeper than 1500 m below the ground surface;
- The potential disposal area at the disposal level must be at least 3 km^2
- The hydraulic conductivity of the host rock must be smaller than 1E-10 m/s; and
- The aforementioned properties must be assured for 1 million years.

In the light of these requirements, it is necessary to reconsider the conclusions drawn from the research work done to date. For instance, the importance of slow migration processes, such as diffusion of carrier fluids like brines and gases in the whole repository system, including the EBS, the EDZ in the early as well as in the late (healed) repository stages, in the undisturbed host rock, and in the overburden rock strata, increases significantly.

6 SUMMARY AND CONCLUSIONS

The CROP project represented a forum for synthesising repository construction experiences and results from testing of engineered barrier systems in underground research laboratories.

The new approach of inter-media comparison of repository concepts and related research provided an enhancement of knowledge about work conducted and envisaged in other media than the one in focus in the own country and thus a valuable basis for the assessment of achievements in the own research programme. It was found, however, that a comparison on a general level may be advantageous, but comparisons in detail were found to be not recommendable because of significant differences between the various concepts which are due to differences in local geology and specific properties of the different host rocks. It was concluded that all media exhibit pros and cons and prove the safety case with adequate margins with regard to the safety requirements.

The major conclusions regarding the German research programme in salt comprise the following:

- Good capability exists of modelling backfill behaviour and excavation-induced effects, e. g., EDZ generation, but the adequate prediction of EDZ healing needs further research.
- The THM behaviour of crushed salt backfill is largely understood. The behaviour of moist backfill in case of brine intrusion, however, has not yet been studied to a satisfactory degree. Also adding of geochemical additives to increase sorption of special radionuclides in the near-field has not been tested adequately.
- The host rock integrity in case of high gas pressures in disposal rooms has not yet been addressed in the German research programme to a satisfactory degree. Respective R&D-work is thus recommended in combination with the necessary improvement of existing coupled H and M models.
- In situ testing of suggested drift seal design under representative conditions is pending.
- Final confirmation of the technical emplacement system for Cogéma canisters, as well as the testing of the feasibility of the emplacement of alternative canisters for spent nuclear fuel into 300 m deep boreholes, is pending.

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