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Äspö Hard Rock Laboratory

CROP – Cluster Repository Project

Final Technical Report
EC Contract Nº: FIR1-CT-2000-20023

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March 2004

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FINAL TECHNICAL REPORT

CONTRACT N° : FIR1-CT-2000-20023

PROJECT N° :

ACRONYM : CROP

TITLE : Cluster Repository Project

PROJECT CO-ORDINATOR: Svensk Kaernbraenslehantering AB (SKB), Sweden

PARTNERS :

Studiecentrum voor Kernenergie/ Centre détude de lÉnergie Nucleaire	SCK-CEN	Belgium
Posiva Oy	Posiva	Finland
Gesellschaft fuer Anlagen- und Reaktorsicherheit mbH	GRS	Germany
Empresa Nacional de Residuos Radiactivos, S.A	Enresa	Spain
Agence Nationale pour la gestion des Déchets Radioactifs	Andra	France
Nationale Genossenschaft fuer die Lagerung Radioaktiver Abfaelle	Nagra	Switzerland
Unite States Department of Energy Carlsbad Field Office	USDOE CBFO	USA
Ontario Power Generation	OPG	Canada
Geodevelopment AB	GEO	Sweden

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Contents

Part 1 Publishable Final Report

1 Executive publishable summary

In January 2001, the European Commission (EC) signed a contract with nine organizations with leading national responsibility for radioactive waste management for funding the development of a basis for evaluating and developing concepts for safe final repositories for long-lived radioactive waste by January 2004. The project is called the "Cluster Repository Project" and referred to in the project as either "CROP" or "the project". The nine Participants are in alphabetical order:

1. Agence Nationale pour la gestion des Déchets Radioactifs (Andra), France.
2. Empresa Nacional de Residuos Radiactivos S.A. (Enresa), Spain.
3. Gesellschaft fuer Anlagen- und Reaktorsicherheit mbH (GRS), Germany.
4. Nationale Genossenschaft fuer die Lagerung Radioaktiver Abfaelle (Nagra), Switzerland.
5. Ontario Power Generation Inc (OPG), Canada, supported by G.R. Simmons & Associates Consulting Services Ltd.
6. Posiva Oy, (Posiva), Finland.
7. Svensk Kaernbraenslehantering AB (SKB), Sweden, supported by Geodevelopment AB
8. Studiecentrum voor Kernenergie-Centre d'étude de l'Energie Nucléaire (SCK-CEN), Belgium.
9. United States Department of Energy Carlsbad Field Office (USDOE CBFO), USA, supported by GRAM, Inc. and Sandia National Laboratories (SNL).

Nagra, OPG and USDOE CBFO were self-funded Participants. Deutsche Gesellschaft zum Bau und Betrieb von Endlagern fuer Abfallstoffe mbH (DBE) joined CROP as a self-funded observer in 2002. SKB served as the project coordinator.

The project focused on design, construction and modeling of engineered barrier systems (EBSs) as well as on experimental procedures, and the cluster of Participants constituted a forum for exchange of information on these topics through correspondence and through seven meetings in different countries. Each meeting was combined with a visit to the underground research laboratory (URL) in the host country. The improved knowledge gained in this manner and documented in the CROP reports will be valuable in resolving issues in selecting repository designs, including engineered barrier components, systems to monitor *in-situ* test and repository system performance, and accurate theoretical models and numerical codes and for engineering designs and performance/safety assessment, and in describing the function of repositories to the scientific society and the public. It should be noted that the classification of radioactive waste differs among the countries participating in CROP and the term "long-lived radioactive waste", as used in CROP, covers spent nuclear fuel (SF) and other high-level radioactive wastes (HLW) as well as long-lived transuranic waste (TRUW), intermediate-level waste (ILW) and low-level radioactive/reactor waste (LLRW).

Several national URLs for studying the possibility of safe deep geological disposal of long-lived radioactive waste have been operated by the Participants for different periods of time in different geological media, such as bedded or domal salt rock in the United States of America (Waste Isolation Pilot Plant - WIPP) and Germany (Asse), crystalline rock in Sweden (Stripa and AEspoe), Finland (Olkiluoto), Switzerland (Grimsel), and Canada (URL, Pinawa), and clay rock in Belgium (Mol), France (Bure) and Switzerland (Mont Terri). The different site-specific geological conditions have led to different design and instrumentation of the aforementioned URLs. However, the engineered barriers tested and analyzed in the URLs have a similar function and, despite some obvious differences, many of the solutions and techniques summarized in the CROP documents are believed to be applicable to disposal concepts in a variety of different rock types. The results from tests conducted by the Participants in the many different geological media and involving a large number of EBS components are expected to be valuable to all organizations involved in repository development.

The project notes that all the repository concepts studied by the Participants fulfill very high demands of long-term safety, and summarizes lessons learned, remaining issues and areas of high potential for technical improvements of repository concepts and the testing of them. The conclusion is that improved technical solutions will evolve from the joint analyses conducted and documented by the Participants.

Sammanfattning

I januari 2001 tecknade Europeiska Unionen ett avtal med nio organisationer med ledande, nationellt ansvar för hantering av långlivat, radioaktivt avfall. Innebörden av avtalet var att Europeiska Unionen finansierade framtagandet av en bas för utvärdering och utveckling av koncept för säker slutförvaring av långlivat, radioaktivt avfall till januari 2004. Projektet benämndes ”Cluster Repository Project” och förkortades “CROP”. De nio deltagarna är i alfabetisk ordning:

1. Agence Nationale pour la gestion des Déchets Radioactifs (Andra), Frankrike.
2. Empresa Nacional de Residuos Radiactivos S.A. (Enresa), Spanien.
3. Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS), Tyskland.
4. Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (Nagra), Schweiz.
5. Ontario Power Generation Inc (OPG), Kanada, understött av G.R. Simmons & Associates Consulting Services Ltd.
6. Posiva Oy, (Posiva), Finland.
7. Svensk Kärnbränslehantering AB (SKB), Sverige, understött av Geodevelopment AB
8. Studiecentrum voor Kernenergie-Centre d′étude de l′Energie Nucléaire (SCK-CEN), Belgien.
9. United States Department of Energy Carlsbad Field Office (USDOE CBFO), USA, understött av GRAM, Inc. och Sandia National Laboratories (SNL).

Nagra, OPG och USDOE CBFO finansierade sitt deltagande själva. Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH (DBE) gick med i CROP 2002 som självfinansierad observatör. SKB var projektkoordinator.

Arbetet fokuserades på design, konstruktion och modellering av ingenjörsbarriärer för slutförvar av använt kärnbränsle och annat långlivat radioaktivt avfall liksom på experimentella tillvägagångssätt, och gruppen av deltagare har utväxlat information i dessa frågor i korrespondens och sju möten i olika länder med tillgång till ett besök till värdlandets berglaboratorium. Den förbättrade kunskapen kommer att bli värdefull vid val av förvarsdesign inklusive komponenter i ingenjörsbarriärerna, system för att registrera och övervaka fältförsök och förvarsfunktioner, noggranna, teoretiska modeller för ingenjörsutformning och säkerhetsfunktioner, och beskrivning av förvarsfunktioner till samhälle och allmänhet.

Olika nationella berglaboratorier för studier av möjligheten till säker geologisk deponering av radioaktivt avfall har varit i drift under olika lång tid. De representerar i projektet olika geologiska medier såsom kristallint berg i Sverige (Stripa och Äspö), Finland (Olkiluoto), Schweiz (Grimsel) och Kanada (URL i Pinawa), bergsalt i USA (WIPP) och Tyskland (Asse) samt lera och lerberg i Belgien (Mol), Frankrike (Bure)

och Schweiz (Mont Terri). De olika geologiska förhållandena har lett till olika utformningar och olika instrumenteringar i de nämnda berglaboratorierna. Men, ingenjörsbarriärerna har likartad funktion, och trots vissa uppenbara olikheter, bedöms många av lösningarna och metoderna vara applicerbara på deponeringskoncept i många, olika typer av bergmedier. Resultaten från tester i många olika geologiska medier, inkluderande ett stort antal olika komponenter i ingenjörsbarriärerna, förutskickas bli värdefulla för alla organisationer som är engagerade i utveckling av säkra geologiska slutförvarsmetoder för använt kärnbränsle och annat långlivat radioaktivt avfall. Det skall noteras att klassificeringen av radioaktiva material inte är enhetlig i alla länder och termen ”långlivat, radioaktivt avfall” avser i CROP att täcka alla långlivade radioaktiva material såsom använt kärnbränsle (SF), högaktivt, radioaktivt avfall (HLW), medelaktivt, radioaktivt avfall (ILW), lågaktivt, radioaktivt avfall/lågaktivt reaktoravfall (LLRW), och transuraniskt, radioaktive avfall (TRUW).

Projektet drar slutsatsen att alla studerade geologiska förvarskoncept uppfyller mycket högt ställda nationella säkerhetskrav, och rapporterar om lärda läxor, återstående frågor att studera och indikerar områden med hög potential till tekniska förbättringar av förvarskoncept och tester av dem. Slutsatsen är att förbättrade tekniska lösningar kommer att utvecklas med hjälp av resultaten från arbetet i CROP.

Part 2 Detailed Final Report

2 Objectives and strategic aspects

The main objective of the project was to collect and document information on how deep geological disposal of long-lived radioactive waste is planned and developed in countries involved in the project, for the purpose of identifying the current status, similarities and differences among the Participants. The purpose was to establish a common basis for the development of repositories for long-lived radioactive waste and to identify areas with a high potential for improvement. Three different groups of geological environment were evaluated by the Participants: *salt rock* (both bedded and domal salt rock), *crystalline rock*, and *clay rock* (both soft plastic clay and hard indurated clay).

The resulting CROP report Deliverable 6 “Comparison of repository concepts and recommendations for design and construction of future safe repositories” was expected to serve as an aid for future repository and URL design and construction in all countries utilizing nuclear power and hence be of value to national and international experts engaged in the handling and disposal of long-lived radioactive waste.

3 Scientific and technical description and assessment of results, and conclusions

3.1 Introduction

3.1.1 General

The project established early a forum for exchange of information among the Participants on repository design, construction and operation with the purpose of optimizing scientific networking among key experts in the involved countries. This was achieved by conducting a number of progress meetings at which pre-selected important issues were discussed, and by subsequently preparing individual Country Annexes (CAs) providing detailed technical information on the issues from each of the CROP Participants. As summarized below, each of the participating organizations has extensive experience in the siting, design, development, and operation of underground rock laboratories (URLs) supporting the design and development of deep geological repositories for safe disposal of long-lived radioactive waste in the considered geological media.

In addition, USDOE CBFO brought to the project the unique experience of having successfully developed, certified, and, since March 1999, safely operated a deep geological repository for safe disposal of long-lived transuranic radioactive waste (TRUW) in *bedded salt rock*.

A large number of issues of fundamental importance for designing, constructing, operating, monitoring and assessing the safe performance of repositories for long-lived radioactive waste and for designing, constructing and operating URLs have been addressed and described for each of the addressed geological media by the CROP Participants to assist in future planning of such facilities. The focus was on the following matters:

- Principles of siting, designing and constructing repositories and URLs.
- Objectives of activities in URLs with special respect to the relevance of experiments related to engineered barrier systems (EBS).
- Principles of designing, manufacturing and placing EBS.
- Selection of instruments and recording systems for measuring changes in temperature, groundwater and stress conditions in the far- and near-fields, and for monitoring the function and conditions of the EBS.
- Collection of data and description of the performance of the rock and EBS in URLs and repositories.
- Development and application of conceptual and theoretical models for predicting the performance of repositories and URLs with special respect to the EBS and its interaction with the near-field rock.
- Comparison of predicted and actual performance of URLs and repositories.

- Overall assessment of the repository concepts with respect to lessons learned, problems and potential solutions.

- Possible improvement of the repository concepts.

The work evolved systematically from the start and led to a successively improved knowledge that was continually presented in the planned Deliverables and summarized in the final Deliverable D6 “Comparison of repository concepts and recommendations for design and construction of future safe repositories”.

The assessment of the entire CROP is best made by considering the results described in the latest report, which therefore is in focus of this Final Technical Report.

3.1.2 Scientific achievements

The project’s nature, i.e., to compile information on applied testing methods and models, implied that no scientific development was expected. However, a number of valuable suggestions and conclusions on the applicability of various practical techniques and theoretical models were obtained, some of which have a scientific nature, particularly concerning creep and moisture migration. As to theoretical modeling of major processes of common interest, both similarities and differences between the selection of involved physical laws and related mathematics have been identified. A major question to further address is whether the conceptual models are truly relevant and whether the right processes are actually modeled.

3.1.3 Technological achievements

Suitable techniques for achieving effective isolation of radioactive waste disposed in underground repositories have proved to be applicable in practice as demonstrated by the testing conducted in national URLs. Different excavation methods have been used in the different geological media and the engineered barriers are significantly different: dense smectitic clay for repositories in crystalline rock and argillaceous clay, crushed salt in salt media, and clay or cement in plastic clay. A major technical achievement is the finding that certain clays fit well as engineered barriers in more than one geological medium and possibly in all of them, at least in certain parts of the repositories, for example sealing steep shafts that pass through sedimentary rock down to the salt host rock. Another experience concerns instrumentation, particularly with respect to their accuracy and sensitivity to conditions such as temperature and salinity.

It is obvious from the study that safe waste disposal can be obtained in any of the considered geological media but that the requested isolation capacity of engineered barriers ranges from moderate to very substantial. Thus, while the isolation potential of engineered barriers is very important and has led to the selection of very tight low-corrosive metal canisters for Posiva, SKB and OPG, the host rock is the most important barrier in the case of *salt* and *clay rock*, implying that less competent canisters fulfill long-term safety requirements in these rock types.

3.2 Results

3.2.1 General

The work was performed in a series of seven workshop sessions in different countries (AEspoe in Sweden, Braunschweig in Germany, Mol in Belgium, Murten in Switzerland, Winnipeg in Canada, Carlsbad in USA and Olkiluoto in Finland), where the Participants met and discussed pre-determined issues and exchanged information on the topics. Each meeting was combined with a visit to the URL in the host country. The workshops have stepwise addressed Work Packages (WP) in the following order:

WP1:	Design and construction of engineered barrier systems (EBS).
WP2:	Instruments and experimental procedures.
WP3:	Assessment of the function of EBS and the understanding of and capability to model the important processes.
WP4:	System improvement and development.

The start of the project was the compilation of the Project Work Plan.

The main results are summarized below.

3.2.2 WP 1 Design and construction of engineered barrier systems

Principles of siting repositories and URLs

Site selection and characterization for a repository for radioactive waste is a very demanding process which has to be based on national and international criteria and guidelines. The process includes on the one hand the selection of suitable host rocks, possible repository depth and an adequate tectonical setting and on the other hand direct field investigations to determine host rock geometry and geological features (e.g., faults and fractures zones) and to investigate the geological, hydrogeological, geochemical and rock mechanical characteristics of the host rock and the structural features.

One important issue in the evaluation of a site is the investigation of transport processes, as they significantly determine the repository performance. Transport in the host rock can either be dominated by advective flow in the intact rock or in geological features (e.g., in moderately fractured *crystalline rock*) or by diffusion (e.g., in *clay rock* and in sparsely fractured *crystalline rock*).

Groundwater flow is the major radionuclide transport mechanism in *crystalline rock* and the siting of a repository in such rock primarily has to be made with respect to the frequency and spacing of fracture zones, which are generally much more permeable than the rest of the rock mass. The need for deriving a reliable large-scale rock structure model is therefore very strong and considerable experience in identifying the major features of large rock volumes has been gained in the last 20 years using deep drillings and geophysical methods. Thus, cross-hole seismics and geoelectrical measurements have been developed for increasing the resolution power of structural investigations although further improvement would be beneficial particularly with respect to visualization of structural models. Structural and hydrological characterization of *crystalline rock* is essential for defining the hydraulic boundaries of the near-field, which determine the rate of water saturation of the buffer clay surrounding the canisters; the canister and the buffer together form the most important EBS components. The structural characterization with respect to rock mechanics and tectonic conditions is important for estimating the mechanical stability of drifts and rooms and for predicting possible impact by seismic events.

Site investigation for *clay rocks*, especially for quite homogeneous marine clay layers, is much easier than for fractured *crystalline rock*. The enormous experience from hydrocarbon exploration in such materials (cap rock investigation) using 2-D and 3-D seismic reflection measurements to delineate even small-scale structures can directly be used to investigate the geometry and the internal structure of such host rocks. Main issues for the characterization are detection of layer thickness and depth of the host rock as well as the detection of large-scale fracture systems. It should be noted that, under real repository conditions, fractures are more an issue from mechanical stability point of view rather than from hydrological considerations.

For *indurated* and *soft* *clay rock*, transport of radionuclides is dominated by diffusion rather than advection as shown by hydraulic testing and pore water chemistry (characteristic variation of isotopes in pore water) in Opalinus clay, Boom Clay and potential French clay host rock. Although natural fractures are observed in *clay rock*, especially in indurated clays, none of these natural fractures have shown increased hydraulic transmissivity compared to the investigated intact host rocks, as long as a certain effective normal stress on the fracture is assured (e.g., in Opalinus clay a burial depth larger than 200 m). Hydraulically important fracture zones and other permeable discontinuities have only been reported in highly indurated marls (e.g., Tournemire) or in *indurated clay rocks* at shallow depth. Induced, extensional fractures in excavation disturbed zones - EDZs - of drifts (Figure 3-1) may create continuous flow paths with high conductivity in *indurated clay rock* during the initial stage of the repository lifetime (construction and operational phase), but due to self-healing processes the transmissivity of the initial EDZ will be significantly reduced with time.

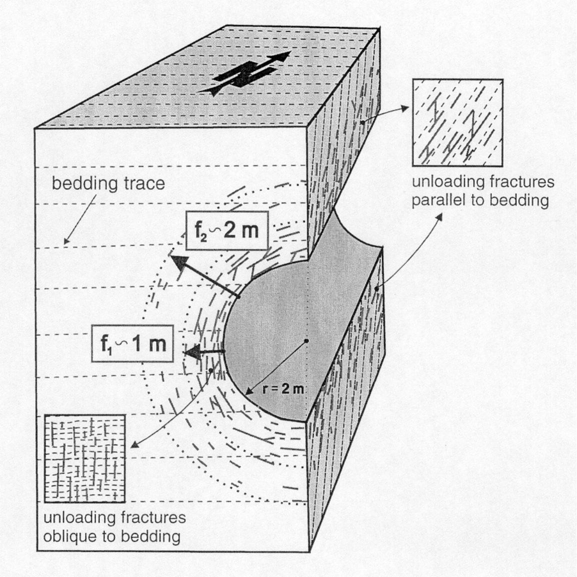

Figure 3-1. *Extension and nature of the EDZ in indurated clay rock. (Nagra)*

For *salt rock*, water flow is negligible except for possible inflow through shafts, which can cause considerable problems and make construction of strategically placed shaft seals necessary. Though very unlikely, safety analyses consider the existence of local brine pockets, which may cause leakage of high concentrated salt brines into construction areas.

Another major issue affecting the siting of a repository, i.e., the short- and long-term mechanical stability of underground excavations, is of greater importance to repository construction and operation in *salt* and *clay rock* than in common types of *crystalline rock.* Thus, while drifts and rooms in granite, for instance, can be stable and maintain their shape for extremely long periods of time, the physical parameters and the rheology of *clay* or *salt rock* can cause large strain possibly leading to failure or closure as early as during the construction phase and to significant changes in the near-field with time.

Short-term stability in weak rocks or soil may require support of the underground structures during the construction and operational phase of a repository. Depending on the state of stress and the material properties, support measures may include rock bolts and nets, (reinforced) shotcrete or even massive concrete liners (e.g., prefabricated wedge blocks). Such structures may influence the performance of the repository due to corrosion of steel and the associated gas production, high pH-plume for standard cements or hydraulically more conductive pathways along or through the concrete liners, especially when they degrade with time.

For normally or slightly over-consolidated *soft clay rock* both theoretical estimates and experience from the Hades URL, Mol in Boom Clay show that mechanical support in the form of a strong concrete or steel lining is needed in conjunction with the excavation (Figure 3-2). Rooms in *salt rock* will be totally closed by convergence in a few hundred years because of the inherent creep properties of the common salt rock types unless action is taken to keep them open (e.g., excavation of the perimeter to maintain the opening dimensions). Rock falls may take place where very large rooms in *salt rock* have been excavated and observations in the Waste Isolation Pilot Plant (WIPP) URL show that discontinuities like clay layers can also cause rock fall.

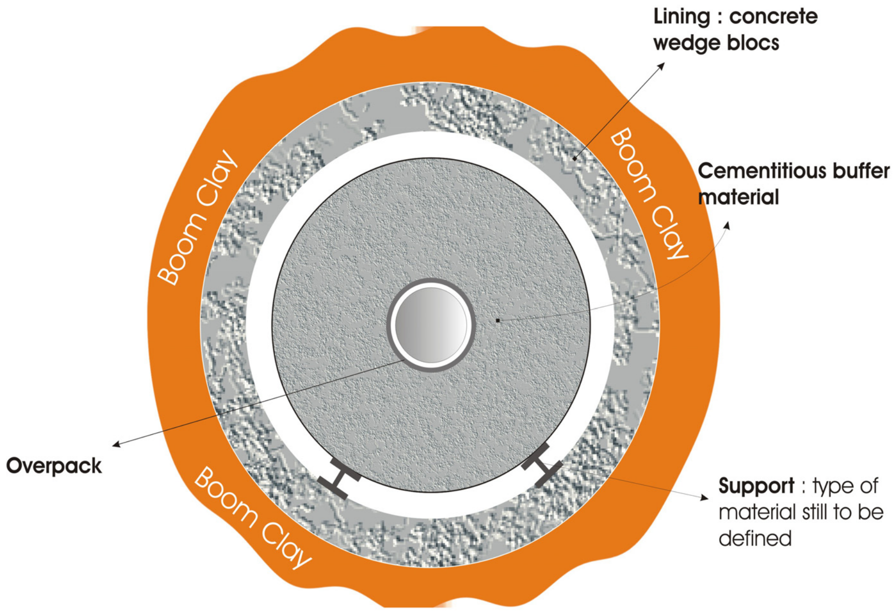

Figure 3-2. *Horizontal in-room emplacement alternative with "supercontainer" in soft clay rock. The lining consists of concrete wedge blocks. (SCK-CEN)*

In crystalline rock , which behaves as a brittle material that deforms very little under moderate pressure, but the strains associated with excavation can also be very significant. Thus, the principal stresses and their mutual ratios determine the potential of excavation-induced shearing of large zones as well as the mechanical stability of the near-field rock.

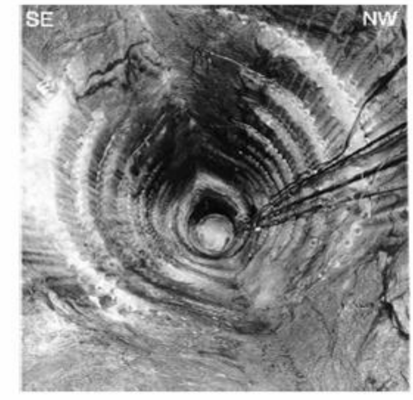

***Figure 3-3**. Planned excavation breakouts in the circular Mine-by Experiment drift caused by overstressing at the 420 m level of AECL´s URL. Primary principal stresses are: 60 MPa, sub-horizontal and normal to drift axis, 45 MPa sub-horizontal and parallel to drift axis, and 11 MPa sub-vertical. Rock boundary strength is approximately 120 MPa (granite) and approximately 150 MPa (granodiorite). Maximum hoop stress is 169 MPa. (OPG)*

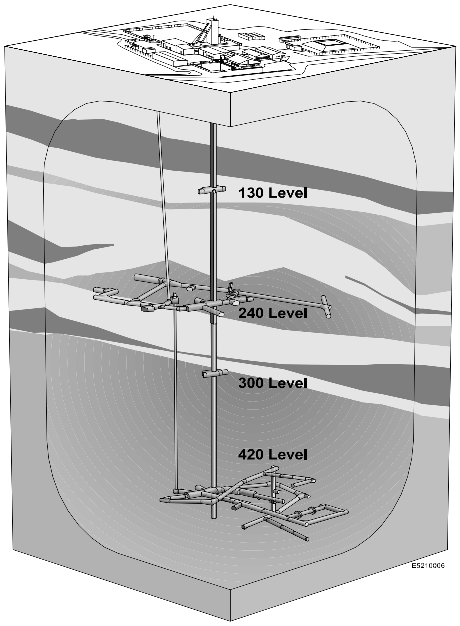

***Figure 3-4.** AECL´s URL at Pinaw. (OPG)*

This is exemplified by the conditions in some plutonic rock masses in the Canadian Shield where either spalling or significant localized failure on the excavation boundary can occur for some excavation shapes at depths below about 300 m (Figure 3-3). Further work at the AECL´s URL, Pinawa (Figure 3-4) has shown that stable openings of different cross-sectional shapes can be excavated in these stress conditions. High-stress conditions also prevail in other parts of the world and may limit the maximum depth at which a repository can be constructed at some locations.

For effective utilization of the rock mass one needs to take unsuitable rock features into consideration. This is more important for crystalline rock with its more frequent fracture zones than in salt and clay rocks, although unsuitable discontinuities like brine pockets in salt rock and large continuous silty layers in salt and clay rocks have to be avoided when selecting the exact emplacement location for waste canisters.

Having identified a potentially suitable site for repository construction, the repository design needs to be based on some knowledge of the local rock structure. For crystalline rock this is hard to achieve and detailed geotechnical information on where deposition rooms should be located and how they should be oriented cannot be obtained until after the excavation has started and reached the intended depth. Suitable adaptation of the repository geometry to the rock structure means that the degree of rock volume usability can be high while location of a repository in a region with frequent fracture zones can bring this degree down to a very low level (Figure 3-5). For salt and clay rocks the usually higher degree of structural homogeneity makes the planning of location of deposition rooms, waste canisters and plugs easier than in crystalline rock.

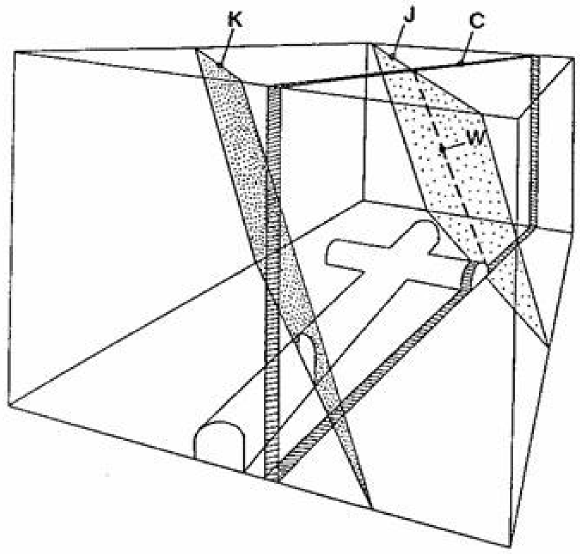

Figure 3-5. *Schematic picture of underground storage rooms interacting with typical systems of discontinuities. J and K represent minor fracture zones oriented NW/SE and C a major fracture zone oriented N/S (Stripa URL in granite). (SKB)*

Several national URLs for studying the possibility of safe deep geological disposal of long-lived radioactive waste have been operated by the Participants for different periods of time in different geological media, such as bedded or domal salt rock in the United States of America (WIPP) and Germany (Asse), crystalline rock in Sweden (Stripa and AEspoe), Finland (Olkiluoto), Switzerland (Grimsel), and Canada (URL, Pinawa), and clay rock in Belgium (Mol), France (Bure) and Switzerland (Mont Terri). The different site-specific geological conditions have led to different design and instrumentation of the aforementioned URLs. However, the engineered barriers tested and analyzed in the URLs have a similar function and, despite some obvious differences, many of the solutions and techniques summarized in the CROP documents are believed to be applicable to disposal concepts in a variety of different rock types.

“On-site” URLs are by definition located so that the rock resembles the general conditions in the type of geological medium intended for hosting the planned repository. This is the case for the Onkalo facility in Finland, which is planned to be a part of a future repository for spent fuel- SF (Figure 3-6). The WIPP URL in the US has already become a part of a repository (Figure 3-7). Some of the existing URL’s (e.g., Grimsel Test Site and the Mont Terri URL) are typical “off-site” laboratories, designed as pure research sites. These URLs are linked to existing underground infrastructures (e.g., highway tunnel) to limit infrastructural costs and their tectonical setting is different from that of potential repository sites.

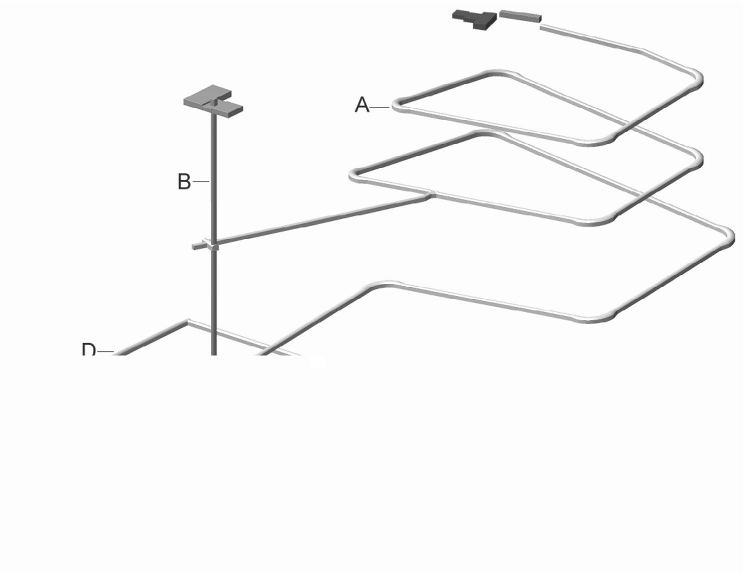

Figure 3-6. *Onkalo underground rock characterization facility at Olkiluoto. Preliminary plan; A) access tunnel, B) ventilation raise, C) upper characterization level, D) characterization tunnel, E) demonstration tunnels, F) lower characterization level. (Posiva)*

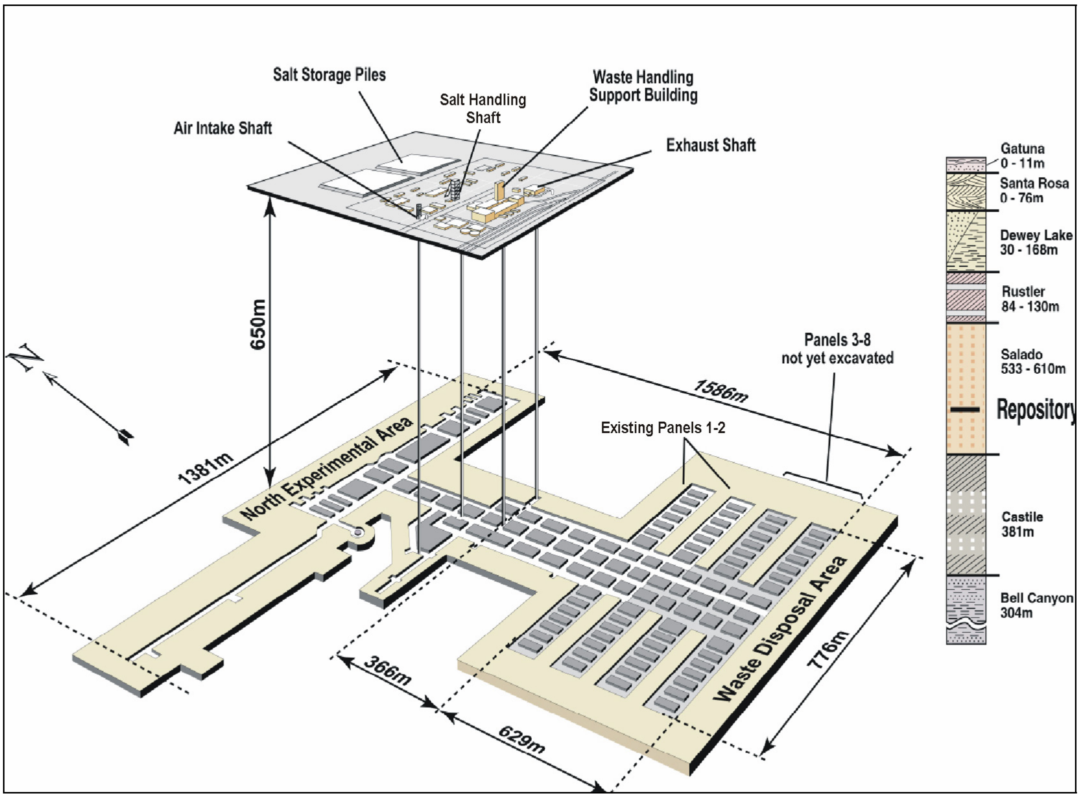

Figure 3-7*. Overview of the WIPP repository and the adjoining "on-site" URL, the North Experiment Area. (USDOE CBFO)*

Design and construction of repositories and URLs

A basic principle in repository design is the compartmentalization of the repositories on different levels, which means that separation exists between several waste types, disposal panels and units or even single canisters. This principle is outlined in Figure 3-8 and can be described in the following way:

- Main compartment (level I): includes the whole repository with seals of access shafts and ramps to limit the total flow through the repository.
- Sub-compartment (level II): separation of different waste types such as SF, high-level radioactive waste (HLW) and intermediate-level radioactive waste (ILW) to limit interaction (e.g., high pH plume from cementitious backfill in ILW and bentonite buffer in SF/HLW or to allow for retrieval of SF as possible resource).
- Sub-compartment (level III): separation of different disposal panels, which could be necessary because of major water conducting features (MWCF).
- Sub-compartment (level IV): disposal units such as drifts or deposition holes or drifts.
- Sub-compartment (level V): single canisters.

In an ideal, fully intact host rock with very low hydraulic conductivity, only compartments of level I and II would be required. The need for the smaller scale compartments (level III –V) comes from:

- Operational reasons (e.g., allow concurrent construction and emplacement).
- Necessity to isolate the repository from MWCF.
- Principle of increasing redundancy of the barriers.

It is obvious that for crystalline rock with its high number of potential MWCF a more intensive compartmentalization might be necessary than for salt or clay rocks.

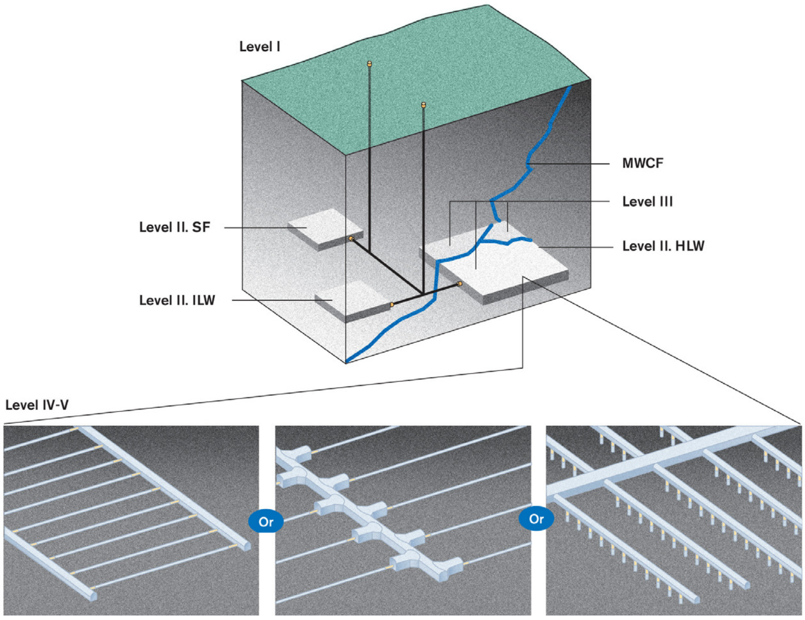

Figure 3-8. *The figure illustrates the compartmentalization principle. MWCF stands for "major water conducting feature". The Roman numbers refer to the compartment levels described in the text on the page above the figure. (Nagra)*

Most repository concepts involve construction of a number of parallel deposition drifts on one and the same level connected to transport drifts at the ends. This concept facilitates flexible rock characterization and excavation of the deposition drifts (Nagra concept), while blind construction deposition drifts are presently favored by SKB and Posiva since they may be advantageous from the viewpoint that the hydraulic regimes are local and separated. Repositories on two levels represent another design possibility. The distance between the drifts is chosen on the basis of temperature estimates, which depend on the amount and type of waste emplaced and on the thermal properties of the rock. In general, the rock temperature of concepts in *crystalline rock* will be held lower than 60-80°C while it may be considerably higher, i.e., up to and above 150°C in *salt* and *clay rock* concepts according to presently proposals, except at WIPP, where the maximum waste-induced temperature increase will be less than 6°C.

In principle, ordinary drift construction or mining methods are planned or used for construction of repositories; drill-and-blast, TBM boring, box-hole boring or use of road-headers. The selection of excavation/mining methods depends upon the type of host rock. For excavation of drifts in *crystalline rock*, drill-and-blast and mechanical-mining methods are commonly used. It is important to recognize that these mining methods have different impacts on the hydraulic performance of the near-field rock mass and on the rock stress situation and rock disturbance around the excavated openings, which turns out to be very important for assessing the structural and hydraulic function of the near-field. Thus, the EDZ has evolved as a major issue in the CROP project, within which many examples were given to illustrate its importance as a potential hydraulic conductor in all the geological media, especially for *indurated clay rock* and to some extent also for *crystalline rock*. For *salt rock,* the EDZ is of importance for the creep-dominated convergence of all underground openings.

For drill-and-blast excavation, it is currently understood that for conventional drill-and-blast methods in *crystalline rock* without any measures taken for smooth blasting the rock around the drift is damaged to an extent that substantially changes its mechanical and hydraulic properties. In the drift bottom may a zone as much as one meter deep be developed with an axial average hydraulic conductivity that is as much as 2-3 orders of magnitude higher than that of the undisturbed rock. Also beyond this distance can the axial conductivity of the rock be increased. On the other hand, the radial conductivity may be somewhat reduced in the near field because of circumferential stresses closing fractures ("skin-zone" effect). By applying proven smooth blasting technology is it possible to design an impact on the damaged zone, i.e., zone with new fractures that fulfills even very strict requirements on the EDZ properties. The bottom line is mechanical excavation by TBM, which develops an EDZ in *crystalline rock* that extends only to a depth of about a few tenth of millimeters and is only up to one order of magnitude more conductive than the undisturbed rock.

The performance of the near-field rock mass around a bored deposition is illustrated by Figure 3-9.

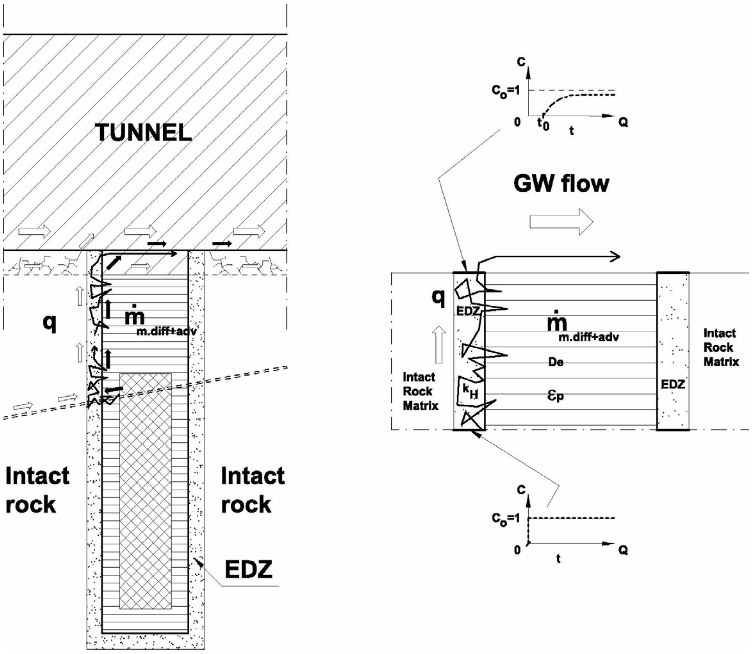

***Figure 3-9**. Conceptual model of transport of radionuclides through the excavation-damaged zone (damaged part of EDZ) by diffusion and advection. Denotes the path of a single radionuclide. (Posiva)*

In *indurated clay rock*, drifts will be constructed using mechanical excavation techniques. The initial local hydraulic conductivity in the EDZ will increase several orders of magnitude (6-7 orders of magnitude) compared to the intact rock during construction, but it has been shown that due to self-healing mechanisms (creep, swelling of rock and buffer, disintegration) of these rock types, the effective axial conductivity along the EDZ reduces significantly with time and load during resaturation of a backfilled drift (observations in Opalinus clay show reduction of about 4 orders of magnitude within 3 years and loads of 5 MPa). Therefore, it is expected that in the long-term phase, which is relevant for performance of the repository, the effective axial conductivity in the EDZ will again become similar to the intact rock or up to one order of magnitude higher. Similar behavior is for *salt rock* because of its favorable creep properties.

Objectives of activities in URLs with special respect to the relevance of experiments related to engineered barrier systems

URLs are currently used by the Participants to gather experience in the siting, construction and testing of the waste disposal concepts that will form the basis for future designs and establishments of long-lived radioactive waste repositories repositories. A common focus is on the performance of the EBS and scale-effects. More specifically, the purpose of the Participant's URLs can be assigned to one or more of the four categories in Table 3-1.

Table 3-1. Purpose of underground research laboratories.

URL	Organization	Rock	Purpose of URL			
			Development of concept	Confirmation of concept	Qualification of design	Qualification of site
Stripa BMT	SKB	Crystalline	X	X		
AEspoe HRL	SKB	Crystalline	X	X	X	
Grimsel Test Site(GTS)	Nagra	Crystalline	X	(X)	X	
VLJ Research Tunnel	Posiva	Crystalline	X	X	X	
Onkalo	Posiva	Crystalline				X
URL	AECL	Crystalline	X	X	X	
Asse mine	GRS	Salt	X	X	X	
WIPP	DOE	Salt	X	X	X	X
Mont Terri	Nagra	Clay (indurated)	X	X	X	
Hades	SCK-CEN	Clay (plastic)	X	X	X	

The main EBS-related activities in the URLs comprise:

1. Characterization and testing of near-field rock (coupled thermo-hydraulic-mechanical-THM).
2. Buffer material tests (coupled thermo-hydraulic-mechanical-chemical - THMC).
3. Borehole, shaft and drift plugging (THM).
4. Process modeling of the performance of clay buffers and backfills (THMC) and their interaction with the host rock.

In Sweden and Finland practical issues like sealing of fractured rock by grouting are being investigated as well and great efforts made to investigate manufacturing and emplacement of full-sized waste canisters (Figure 3-10), mega-sized buffer blocks and full-scale backfill. Nagra, Enresa, Andra and SKB have investigated feasible methods for emplacing canisters in a horizontal mode (Figure 3-11).

Figure 3-10*. Equipment for emplacement of experimental, electrically heated canisters in KBS-3Vertical emplacement mode*. (SKB)

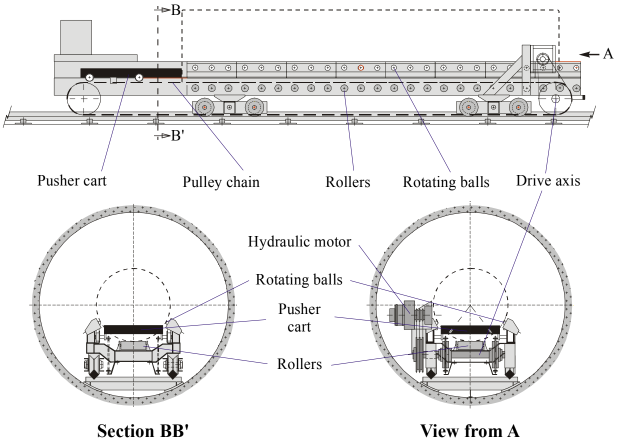

Figure 3-11. Emplacement equipment *for* the Febex "in-situ" test. (Enresa)

Principles of designing, manufacturing and emplacement of EBS

The design requirements for buffer material for SF and HLW are based on a design approach outlined at the Nuclear Energy Agency's design workshop. The hierarchy of the given requirements is the following:

- Fundamental (high-level) requirement.
- System requirement (total disposal system).
- Sub-system requirement (backfill around SF/HLW canisters).
- Design requirement.

Fundamental requirements

Repository designs are based on a multi-barrier system (natural and engineered barriers). The design has to be based on the robustness principle to account for long-term uncertainties and to some extend unknown or unexpected system behavior. The barriers include waste form, canister, host rock, seals and backfill (buffer).

System requirement

For the total system, acceptable consequences are required for the safety case for all scenarios. It should be noted that compartmentalization is one of the key elements for most of the concepts. The robustness provided by compartmentalization is related to ensuring acceptable consequences for all scenarios. In addition, operational safety requirements must be met.

Sub-system requirement

The physical/chemical conditions of the backfill/buffer must be such that other sub-system requirements are met:

- Chemical and flow conditions should ensure that a certain canister lifetime is met as well as slow dissolution of the waste form and low solubility and mobility of many radionuclides in the near-field (NF).
- Transport properties of the host rock in the EDZ around the drift should not be affected in an undesirable way.
- Erosion of the buffer material/colloidal transport should be avoided (especially during the re-saturation phase with enhanced hydraulic gradients).
- Gas-related properties of the backfill should avoid complex scenarios with expulsion of a lot of backfill pore water.

In addition to the requirements concerning long-term performance of the repository, operational safety during canister, buffer and backfill emplacement must be achieved.

One commonly distinguishes between three major phases in the performance of the EBS. The first phase (the first 100 to a few hundred years) comprises application and evolution of the buffer that includes water uptake and swelling under hydraulic and thermal gradients and high neutron and gamma radiation fields, leading to maturation; the second phase (up to 1 000 to a few thousand years) during which the matured buffer is exposed to a successively reduced thermal gradient and radiation field; and the third phase thereafter during which the repository may be affected by tectonics or glacial events under low temperature conditions but significant hydraulic gradients.

The first phase may involve complex physical/chemical processes during the maturation of the buffer, partly controlling its long-term performance. It is regarded as particularly important and has, therefore, been the focus for most of the international URL-related research, technical development and demonstration (RTD) work on buffers in crystalline rock and clay rock. For salt rock, with much less demand on the EBS, the buffer is equivalent to the host rock. The subsequent two phases, of which the second phase is also particularly important, have been far less studied. Although significant mineral changes in the buffer will not take place, according to most smectite conversion models, some cementation may take place that will affect the self-healing potential of clay buffers and this issue has not been fully analyzed. Gas penetration is also expected but the involved mechanisms and consequences are not fully understood. These issues are therefore still being studied by most of the Participants.

The major EBS components are:

- Canisters containing the waste.
- Buffer and backfill.
- Plugs and other stabilizing structures.

Grouting is used as a means of providing favorable conditions during construction, operation and closing periods.

In URLs, the heat production of the waste associated with the radioactive decay is simulated by electrical heaters. In some experiments, for example Enresa´s mock-up test, SCK-CEN´s CORALUS test and AEspoe´s LOT project, the release of radionuclides emanating from leaking canisters is simulated by placing small amounts of radioactive tracers in the buffer during installation of the experiment.

Canisters

Fractured *crystalline rock* is potentially the most hydraulically conductive of the geological media and requires the most effective EBS. Thus, SKB and Posiva are planning to use and OPG is proposing to use corrosion-resistant and very long-lasting metal (iron /copper) canisters for SF/HLW. In principle, the low hydraulic conductivity of the *salt* and *clay rocks* have less stringent requirements for the canisters but national requirements on effective isolation over long times and the demand for mechanical stability of the canisters in weak rock leads for clays to similar but less corrosive-resistant canister designs as for repositories in *crystalline rock* . The canisters proposed by the Participants will be made of materials with well-known and favorable properties and predictable performance that will provide the primary containment of the wastes and ensure their effective isolation in conjunction with the other engineered barriers over a pre-defined period of time.

Buffers and backfills

Smectitic materials are proposed as buffers and backfills in repositories in *crystalline rock* and *clay rock*, the requirements being:

- The hydraulic conductivity should be so low that diffusive transport of dissolved matter dominates as transporting process

- The buffer should have a sufficiently high expandability to maintain effective contact with the canisters and surrounding rock and have some self-healing ability if disturbance by shearing or dilatancy of the rock takes place

- The bearing capacity must be sufficiently high to prevent the canisters from sinking to the base of the deposition holes and drifts

- The long-term isolating capacity of the buffer to limit transport of radionuclides into the rock must be retained for the stipulated period of time, requiring that changes in mineral composition be at an acceptable level.

To fulfill these criteria, several conditions, which depend on the host rock and the water chemistry, have to be met. For *crystalline rock* and highly saline formation water, all these criteria are believed to be fulfilled if the density of the buffer in water-saturated form is at least 1 900 kg/m^3 and the temperature lower than about 100^{o}C. Nevertheless, at least certain parts of the buffer could bear significantly higher temperatures as long as a skin with defined thickness at the rock/buffer interface remains with acceptable alterations only. Ongoing research will show if higher temperatures can generally be accepted to maintain the performance of the buffer. For certain purposes, like backfilling of certain drifts and shafts or for very tight rocks (e.g., *clay rock*), the hydraulic conductivity does not have to be as low as for the buffer and mixtures of clay powder and natural sand/silt or crushed rock are being considered.

Practicality is an important matter and a number of methods for preparing and placing clay buffers have been tested. OPG has used techniques for layer-wise *in-situ* application of clay/sand mixtures in deposition holes in URL tests and, in one repository concept, propose to drill holes in the buffer for the vertical emplacement of canisters. SKB has manufactured ring-shaped highly compacted blocks of clay for emplacement in vertical deposition holes followed by installation of the canisters that fit very well in the column of stacked blocks (Figure 3-12). SKB, Enresa and SCK-CEN have manufactured smaller sector-shaped or rectangular dense blocks of smectite-rich clay powder or of mixtures of clay and coarser materials for surrounding horizontally oriented canisters and for plug construction. The technical/economic optimum size of clay blocks is currently being assessed, considering not only manufacturing costs but also material handling and time for emplacement.

Figure 3-12. *Application of a 2 Mg buffer block of bentonite in a deposition hole. (SKB)*

SCK-CEN is currently developing the "supercontainer" concept, in which the canister and cement buffer form one integrated package (Figure 3-13. See also Figure 3-2)

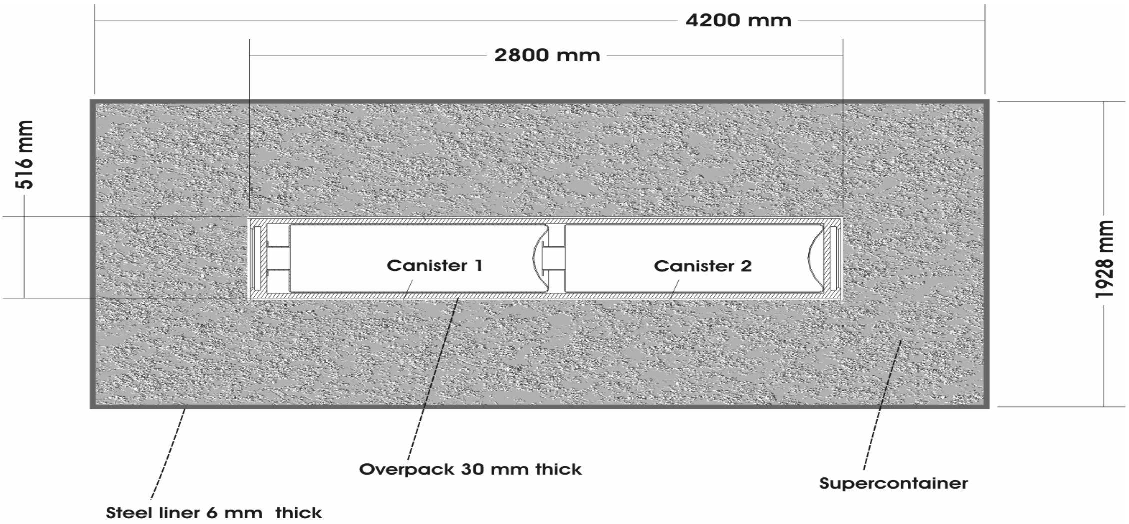

Figure 3-13. *Supercontainer design. (SCK-CEN)*

For *indurated clay rock*, Nagra's concept tested already in a first full-scale field test (Engineered Barrier experiment at Mont Terri) specifies that the canisters are placed on a foundation ("sarcophagus") of highly compacted smectite blocks so that they are initially located in the center of the cylindrical deposition drift with the remaining space being backfilled with highly compacted granular smectite material (Figure 3-14). The method, which is very well suited to disposal drifts in *indurated clay*, may be applicable also to *crystalline rock* although Nagra´s formal concept for *crystalline rock* is to use blocks of compacted clay like Enresa's although of larger size. Additional testing of this new emplacement concept is needed and will be carried out within the Integrated Project "ESDRED" (6th EC Framework Program).

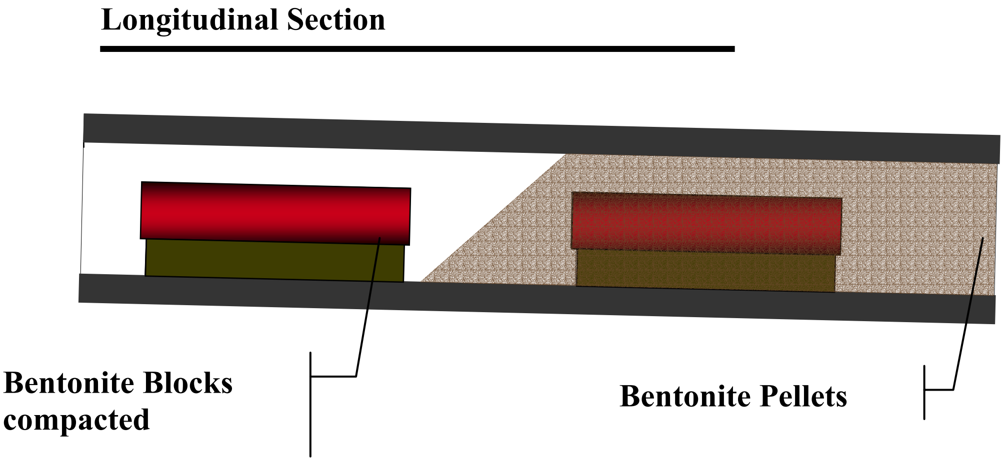

Figure 3-14. *Opalinus clay emplacement concept. (Nagra)*

For *salt rock* backfills placed in the voids around waste containers in boreholes, drifts and rooms can be crushed salt or magnesium chloride or magnesium oxide, the latter two being used in the WIPP URL. While the clay buffers and backfills in *crystalline rock* take up water and expand to eliminate any open space in the system, *salt rock* converges to yield the same effect and this process involves consolidation of the salt and magnesium-based buffers and backfills. In *clay rock* both processes, swelling of buffer and host rock as well as drift convergence due to creep processes, will exist and lead to closures of remaining gaps and reduction of EDZ transmissivity.

A remaining issue for buffers and backfills in *salt rock, crystalline rock* and *clay rock* is a better understanding of how gas, generated by the waste itself, can be released through them without affecting their long-term performance.

Plugs

Plugs are required for confining backfills in repository drifts and shafts in the waste emplacement phase and in the final phase of closing and sealing the repository. Temporary plugs that only need to provide support and tightness for weeks and months can be of simple type, for example shotcrete coatings. However, in practice, many temporary plugs may be required to be strong and tight even during their rather short operating lives.

A basic plug case for *crystalline rock* and *clay rock* is a bulkhead that can withstand the swelling and water pressures exerted by the contacting backfill. Concrete plugs are preferably keyed in recesses in rock for transferring the force to the rock and for cutting off the EDZ. Concrete plugs are also proposed for *salt rock* and the creep potential of the *salt rock* means that the contact with the plug will become increasingly tight. More complicated plugs or seals may consist of two mechanical abutments (e.g., constructed from low-pH cement and rock blocks) on either side of a sealing section to provide mechanical stability for the bentonite seal in between. Depending on the design of the drifts, the abutments may be keyed in recesses in rock to provide mechanical stability and to project through the EDZ. Seal sections may require the removal of liners and partial (slots) or full re-excavation of the EDZ in weak rocks to avoid preferential flow along or through the EDZ and/or engineered structures which will degrade with time.

After closure, the WIPP disposal system will include shaft seals/plugs and panel closures/concrete plugs. Shaft seals/plugs are an essential part of the repository/waste isolation design. The shaft seals are designed to prevent the movement of radionuclides toward the accessible environment through the shafts. The principal design criterion is that the seal elements must provide at least the same degree of radionuclide containment and isolation as the surrounding rock. The present design (Figure 3-15) consists of plugs of various engineered materials that together fill the entire shaft. The primary need for long-term sealing depends upon the reconsolidation of crushed salt, both by mechanical compaction and the creep of the salt shaft walls. Concrete, asphalt and clay are also used to optimize seal effectiveness. The design approach applies redundancy to functional elements and specifies multiple, common, low-permeability materials to reduce uncertainty in performance. The system comprises 13 elements/sections that completely fill the shafts with engineered materials possessing high density and low permeability. Laboratory and field measurements of component properties and performance provide the basis for the design and related evaluations. Hydrologic, mechanical, thermal, and physical features of the system are evaluated in a series of calculations. These evaluations indicate that the design guidance is addressed by effectively limiting transport of fluids within the shafts, thereby limiting transport of hazardous material to regulatory boundaries. Additionally, the use or adaptation of existing technologies for placement of the seal components combined with the use of available, common materials assures that the design can be constructed. This combination of engineered seal materials will effectively limit the permeability of the shaft seals to levels comparable with that of the undisturbed salt.

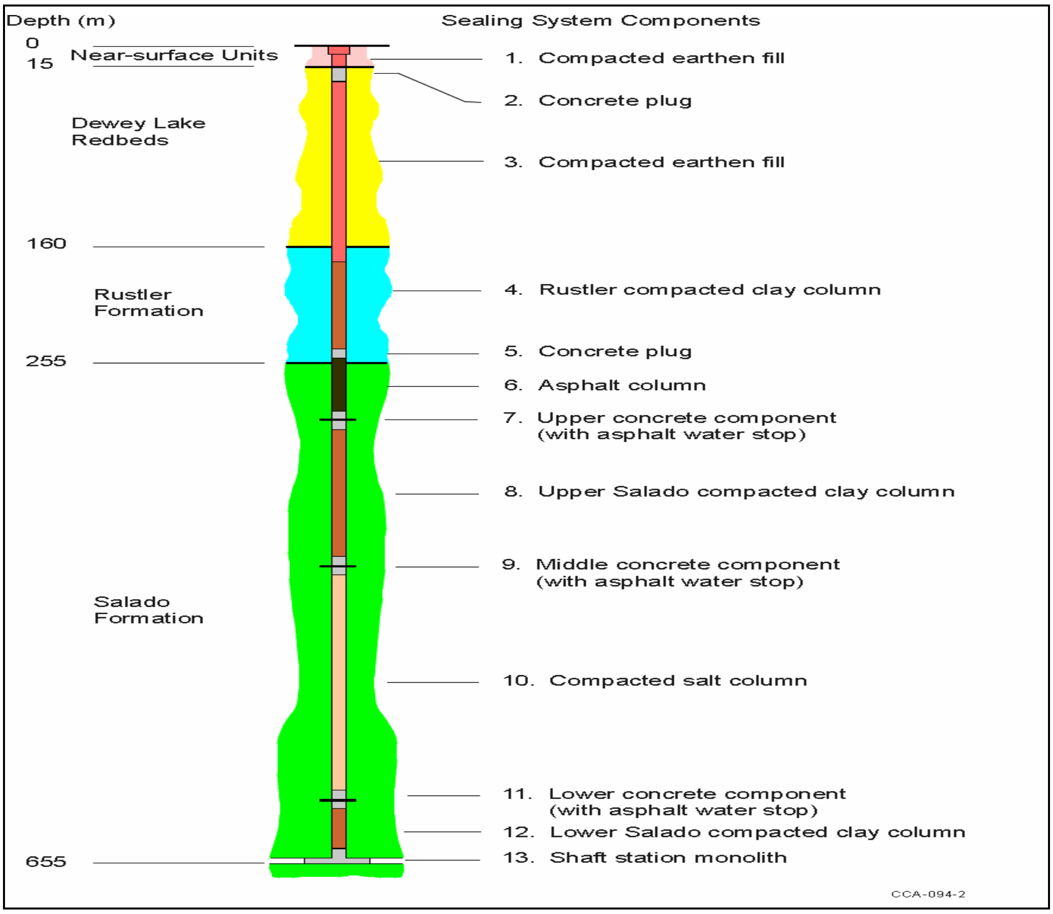

Figure 3-15. *Schematic illustration of shaft seals at WIPP. (USDOE CBFO)*

The German planning includes dismantling of the infrastructure in the repository upon completion/termination of the repository operation period followed by installation of shaft seals to close the repository. A concept for a shaft seal (Figure 3-16) has been developed. An *in-situ* experiment on the effectiveness and stability of a shaft seal consisting of bentonite pellets has been conducted successfully at the Salzdetfurth mine in Germany.

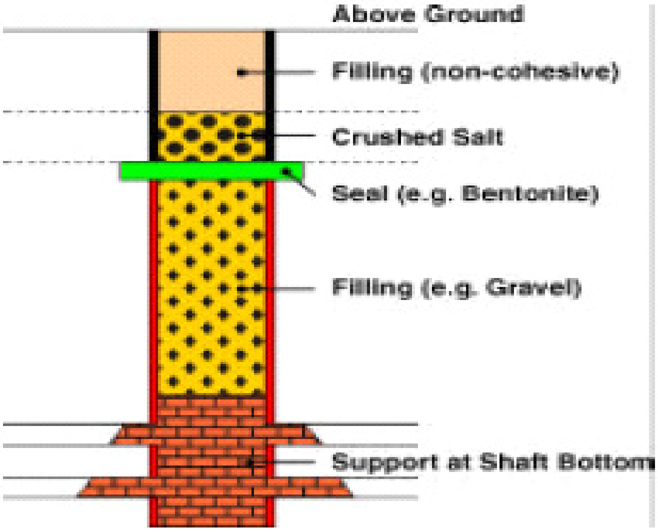

Figure 3-16*. Principal design of a shaft seal. (GRS)*

A comprehensive plug test has been performed in AECL's URL at Pinawa. It consists of two different plugs, one of highly compacted blocks of 70% bentonite/30% sand contacting a backfill wall of 10 % bentonite/90 % sand on one side and held in place by a structural steel restraint on the other side. The other plug consisted of structural concrete. The two plugs were separated by a sand-filled 12 m long chamber in the elliptically shaped drift (Figure 3-17). Both plugs were "keyed" into the rock. Grouting with bentonite clay was made around the clay plug and with cement into the interface and EDZ at the concrete plug. The drift had been excavated by careful blasting, yielding a relatively small EDZ, while the recesses were made by overlapping perimeter boreholes and the rock released by hydraulic splitters.

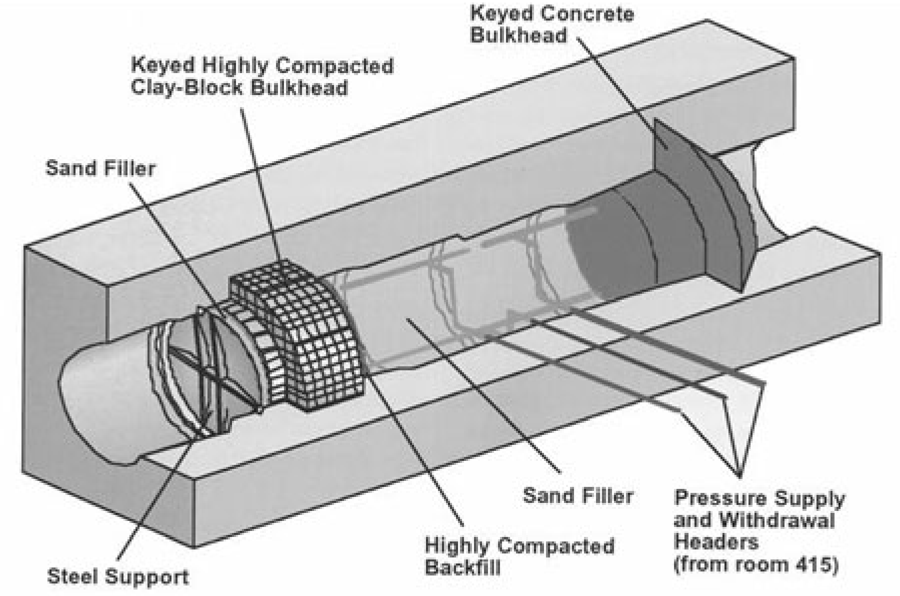

***Figure 3-17**. Configuration of the Tunnel Sealing Experiment at ACEL´s URL. (OPG)*

The plug test involved pressurizing water in the sand chamber. Various leakages along the rock/clay contacts and the joints between blocks caused rapid saturation of the 2 m thick clay bulkhead; which was largely saturated in about 3 years. After reaching almost steady state conditions at 4 MPa water pressure the amount of water passing from the pressurized sand chamber corresponded to an average hydraulic conductivity of 1.1E-11 m/s for the clay plug and E-10 m/s for the concrete plug. Most of the leakage, which amounted to less than 0.006 l/min, was concluded to take place along the rock/concrete and rock/clay interfaces, the latter being soft ("shotclay") placed at the interface.

Grouting (crystalline rock only)

A very important experience from rock grouting is that the penetration depth of even fluid grouts into natural fractures with a hydraulic aperture of a few hundred micrometers is small and the sealing effect rather limited if the rock is not confined or supported. Thus, grouting of the walls of a blasted drift from the interior is not effective while grouting around stiff plugs, supporting the rock, can give good results as demonstrated by two grout campaigns in the Stripa URL. It has been demonstrated by the Participants that the conductivity can be reduced by orders of magnitude by both clay and cement grouting if the initial average hydraulic conductivity of the rock is relatively high, i.e., on the order of E-7 to E-9 m/s. The conductivity of tighter rock than that cannot be appreciatively reduced by conventional cement grouting.

Rock support

Rock support by steel or non-metallic bolts and wire mesh in combination with shotcrete and/or cement grouting may be required in weak rocks at greater depth or in hard rock where drifts and shafts intersect unstable fracture zones. Although the iron in steel bolts and wire mesh may cause some chloritization and illitization of smectite buffer, and cement will yield minor dissolution of smectite clay and illitization, the small amounts of iron and cement involved will have very little impact on the long-term performance of the buffer. Alternative materials for rock support include non-metallic rock bolts cemented in place using epoxies, but these materials may provide nutrients for microbes. However, the matter is believed to require further attention.

3.2.3 WP2 Instruments in the near-field rock and EBS and experimental procedures

Selection of instruments and recording systems for measuring changes in groundwater and stress conditions in the far- and near-fields, and for monitoring the function of the EBS

Temperature evolution in buffers, backfills and near-field rock

Information on the temperature evolution is required for verification that the waste-induced temperatures and temperature gradients do not deviate unacceptably from the design criteria and hence validate the basis for the design of the EBS. Highly accurate of temperature data will be needed to correct for thermal expansion and thermal sensitivity of instruments such as pressure gauges and extensometers, and to use the temperature evolution as indirect information on the hydration rate.

A general conclusion is that thermal elements of the common types used in the URLs withstand the harsh conditions in maturing buffer and backfill, including high pressure and strain. However, their sensitivity to chemical attack by the pore water may quickly cause breakdown and special metal coatings must be used if the chemical environment is demanding.

Stress and strain measurements in the EBS and the near-field rock

Data from stress/strain measurements are required for testing the validity of theoretical models for predicting hydration of buffers and backfills, change in fracture apertures in the near-field rock, and displacement of canisters. Pressure measurements are made by a number of methods and sensor types, such as the vibrating wire principle and Gloetzl technique. Gloetzl cells, being the oldest and most extensively used pressure cells in rock construction, have proved to be long-lived and reliable in both *salt* and *clay rocks* while the accuracy depends on the pressure range. Strain is measured by the vibrating wire technique and by fiber optics as well as by conventional extensometers. For both stress and strain recording misinterpretations are made because of water leakage along tubes and cables, indicating faster water up-take than naturally occurring.

Hydration measurements

Psychrometers and other gauges for measuring the water content in maturing clay buffer are being used in most clay buffer experiments to supply information on the rate of wetting and drying required for calibrating and upgrading theoretical models. Many of the instruments operate accurately only up to a certain degree of fluid saturation or above a certain fluid content and the combination of two different types of gauges is recommended. However, obtaining information on the inhomogeneity of saturation in clay buffer requires a large number of gauges, which may cause practical spatial problems to the locating of gauges, cables and tubes.

A general conclusion is that sensors for recording saturation processes are the least reliable of all instruments and the first to fail according to the experience gained in several URLs. New types of sensors would hence be a major contribution to the understanding of on-going processes in experiments. As for thermal gauges, the risk for chemical degradation must be considered and suitable inert metals like titanium should be used. As with stress and strain measurement, there are difficulties in obtaining accurate data because of water leakage along tubes and cables. This has caused incorrect interpretations in URL experiments and wrong conclusions concerning the validity of certain numerical THM models for the maturation of buffers and backfills. Future development of remote sensing techniques and wireless transmission technology is encouraged.

Gas percolation, mineral changes, ion migration and microbial activities

For measurement of gas percolation, filters within the buffer, attached to tubes that reach out from the buffer, can be used in URLs. They have not been used extensively in field experiments but are known to work. 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 experiments have been terminated and samples taken.

Instrumental issues

A number of issues affect the possibility of successful instrumentation of URLs and future repositories. They are:

- The longevity of the portion of instrument systems that is not accessible during a particular application in a harsh geological environment, as with the sensors installed within an experiment, the connections from sensors, etc., are also uncertain.
- The thermal sensitivity of sensors and connections to accessible locations must be either minimized/eliminated or methods of gathering data to make accurate corrections must be developed.
- The instrumentation system must gather data that truly represent the processes being monitored and are not artifacts of the system, such as leakage along connecting tubes and cables that change local conditions, sensor size inappropriate for gathering data, or chemical interaction between the sensor and the local environment. This is illustrated by ongoing tests in SKB’s URL at AEspoe where the evolution of the swelling pressure was clearly misinterpreted because of water flow along cables to gauges that reacted much earlier than un-instrumented buffer clay at the same distance from the periphery of the deposition holes (Figure 3-18).

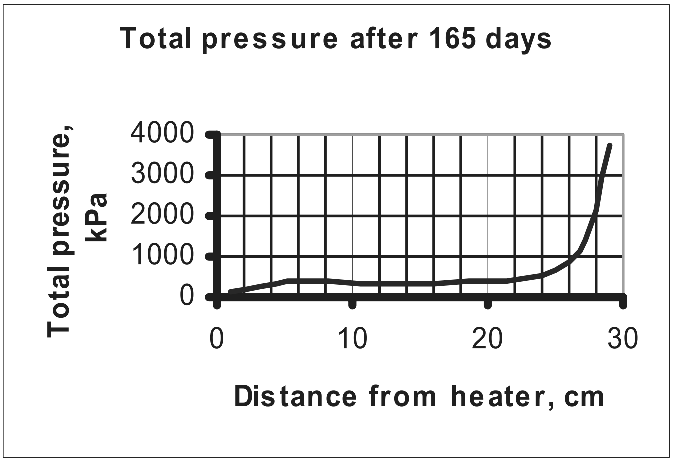

Figure 3-18. *Example of influence of cables on recording of hydration-controlled processes in typical buffer experiment (AEspoe URL). The wetting started at the outer "wet" boundary of the more than 30 cm thick buffer and the curve should be of diffusion type but water flowed along the cable to the pressure sensor and made the clay react much too early. (SKB)*

Monitoring and description of the performance of the rock and EBS in URLs and repositories

Data acquisition and processing have generally been very successful in the respective URLs. Safe backups and data transfer to data bases are standard procedures as well as automatic transmittal of data from certain sensors to local or remote data acquisition systems (DAS) on a regular basis for processing by the involved organizations, wherever their home base is situated.

A very important practical issue is to install "watch dogs" for automatic signaling if processes in the EBS yield values beyond present limits and to control the current and voltage, etc. of the power.

3.2.4 WP3 Assessment of the function of EBS and the understanding of and capability to model the most important processes

Development and application of conceptual and numerical models for predicting the performance of repositories and URL experiments with special respect to the EBS and its interaction with the near-field rock.

Performance of buffers and backfills

The URL experiments completed, in progress and planned normally run for no more than 20 years and hence cover only a very small part of the entire EBS operational period. A major question is therefore how relevant even careful examination of the initial performance really is for judging the long-term performance of the respective repository concepts.

For salt rock the situation is similar; a major part of the maturation process in the form of creep-induced encapsulation of waste containers, takes place in a few decades, while complete convergence into a homogeneous monolith takes longer time and estimation of associated mineral changes and impact of gas pressure build-up would require very long testing time. The important thing is that the fundamental physical/chemical processes can be identified and expressed in the form of numerical models that can be tested by applying them to natural analogues.

For *crystalline rock* with moderate hydraulic conductivity and the expected relatively quick maturation of the buffers and backfills – most of it takes place in the first 5-20 years and would normally be complete in about 100 years – the evaluation of data recorded during and sampling taken after termination of experiments will be valuable in assessing the validity of the conceptual and theoretical models of EBS performance with the exception of the chemical stability of the minerals, which would require much longer experiment durations for assessment.

For *clay rock* the situation is a bit different. The extremely low hydraulic conductivity of the *clay rock* means that buffers and backfills will not mature even to a very small extent in less than 50-100 years or even longer than that. This was realized early by Participants Enresa and SCK-CEN and led them to conduct mock-up tests on the ground surface. Still, the true maturation of the buffer under a considerable temperature gradient leading to desiccation of the buffer in conjunction with diffusive transport of electrolytes from the host rock may yield other physical/chemical effects in a long-term perspective than will a controlled mock-up test running for only a decade. Cementation and loss of spontaneous expandability of the smectite may be the result and more research is required on these issues for developing conceptual and theoretical models.

Conceptual models of EBS performance

The distinctive properties of the various host rocks led to different focuses for the conceptual models to evaluate the EBS performance. Naturally, modeling for *salt rock* has focused on the mechanical behavior of the host rock while the focus for *crystalline rock* has been on large-scale hydrology models and modeling of the evolution of buffers and backfills including the effects of an EDZ. For *clay rock* modeling has concentrated on the hydro-mechanically coupled processes in rock and buffer.

The evolution of the buffer in *crystalline rock* and *clay rock* involves the following processes irrespective of the detailed design concept (Figure 3-19):

- Redistribution of pore water contained initially in the buffer generated by the thermal gradient.
- Homogenization and subsequent consolidation of the initially heterogeneous buffer components.
- Uptake of water from the rock and backfill leading to hydration of the buffer.
- Expansion of the uppermost part of the buffer causing displacement of the overlying backfill (valid for KBS-3V concept only).
- Consolidation and shearing of the buffer caused by the canister load.
- Transport of chemical elements into and out of the buffer due to temperature gradients.
- Dissolution and alteration of minerals and precipitation of chemical compounds.
- Mechanical compaction of the buffer due to time-dependant rock deformation (in *clay rocks* only).

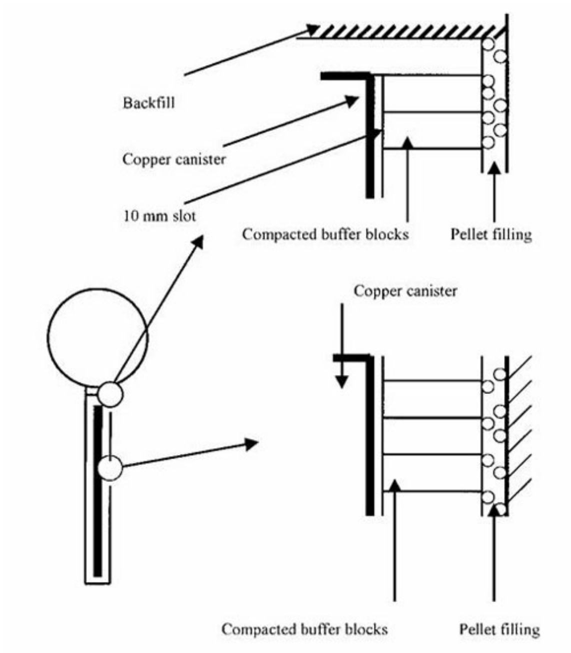

Figure 3-19. *Components of the Swedish repository concept, applicable also in principle for the other Participant's concepts in crystalline and clay rocks. (SKB)*

The most important mechanical processes are the water uptake and expansion of the buffer, which yield a swelling pressure on the surrounding rock and embedded canister as illustrated by Figure 3-20. The initial drying of the buffer near to the hot canister and subsequent wetting is obvious from Figure 3-21, which confirms that the major mechanisms in the evolution of the buffer are understood and can be modeled.

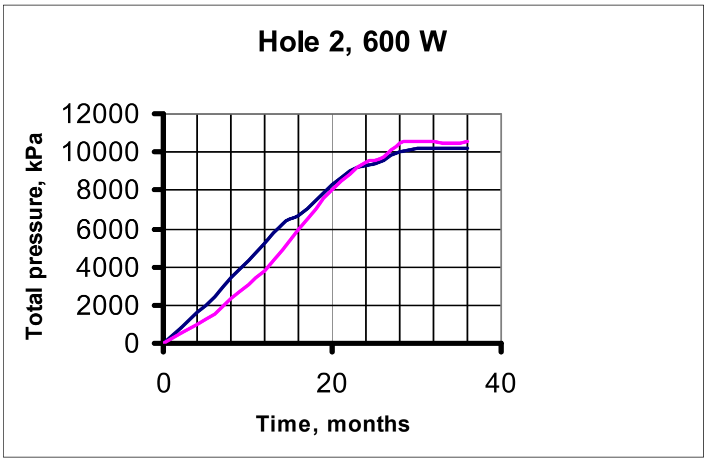

Figure 3-20. *Evolution of swelling pressure in the "wet" Stripa Buffer Mass Test Hole 2 (out of six holes), the two curves represent recordings on opposite sides of a canister. Notice that complete water saturation with build-up of full pressure occurred in about 3 years. (SKB)*

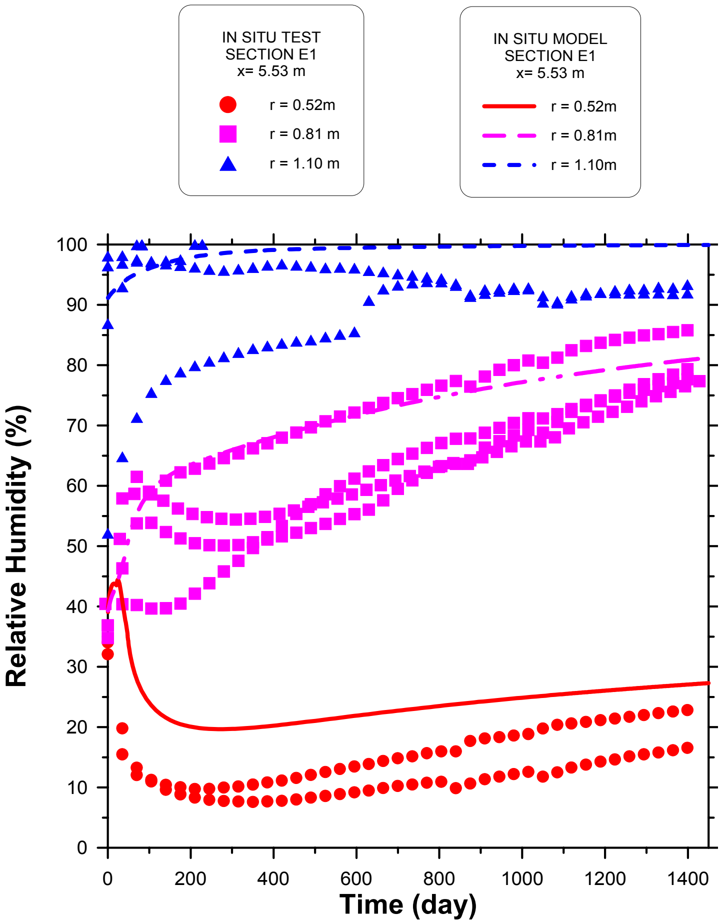

Figure 3-21. *Conceptual evolution of the degree of saturation at some selected points in a buffer around a heater in Febex (CODE_ BRIGHT). r denotes the distance from the center axis of the canister. Section E1 is located along canister #1 at 1.2 m from the end which in turn is located 4.33 m from the plug. (Enresa)*

Comparison of predicted and actual performance of EBS in URLs and repositories in crystalline rock

A number of well known numerical models have been used for predicting the major processes in the buffer, backfill and near-field crystalline rock and clay rock, i.e., temperature, buffer hydration and swelling pressure. A very good opportunity to compare predicted and actual data using such models is offered by the EU-supported Prototype Repository project (Figure 3-22). The codes used are:

- COMPASS developed and used by University of Wales Cardiff, UK
- CODE_BRIGHT, developed and used by CIMNE at the University of Barcelona, Spain.
- Rockflow/Rockmech (RF/RM) code developed and used by Bundesanstalt fuer Geowissenschaften und Rohstoffe (BGR), Hannover, Germany
- THAMES developed and used by Japan Nuclear Cycle Development Institute (JNC), Tokyo, Japan
- ABAQUS, developed by Habbitt, Karlsson and Soerensen at HKS Inc. of Pawtucket, RI, USA, and used by Clay Technology AB, Lund, Sweden.

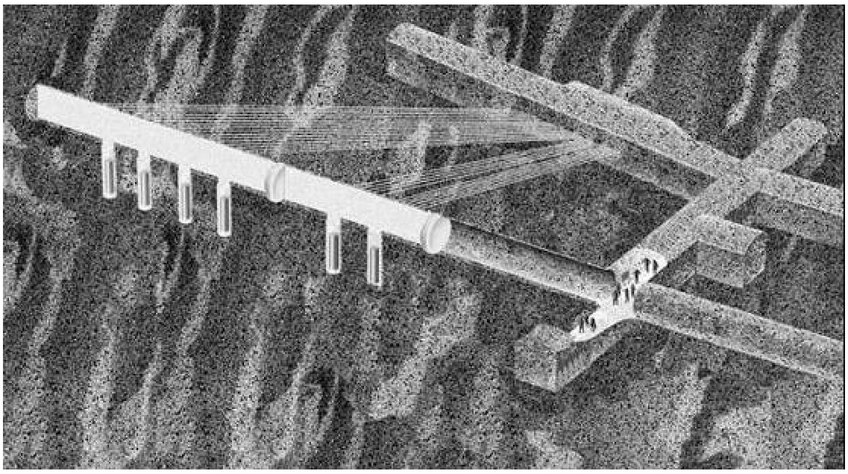

***Figure 3-22**. Layout of the Prototype Repository project. The hydraulic conditions are such that only one deposition hole, the innermost one(Hole No 1) is intersected by clearly water-bearing fractures yielding an inflow into the empty hole of 0.08 l/min, while the other five holes have an inflow of only 0.003 l/min or less. (SKB)*

Prediction of the THM evolution cannot be expected to yield perfectly adequate data because a number of assumptions have to be made that deviate from the true conditions, like neglecting the joints between the buffer blocks and the heterogeneity of the pellets fill. Taking also the limited accuracy of the recordings into consideration the comparison of predicted and experimental data is not expected to yield complete agreement. However, by comparing them one will be able to identify systematic misfits and such deviations that indicate inadequacy of the models. Naturally, a more definite assessment requires longer testing time.

The best defined and most important conditions for comparing predicted and experimental data are represented by the part of the buffer with the highest temperature in the hole with the highest water inflow for which representative recorded and predicted data are summarized in Tables 3-2, 3-3 and 3-4. The predicted and actual temperatures at the rock and the canister surfaces at mid-height canister level of the canister in "wet rock" represented by the innermost hole are shown in Table 3-2. One finds that two of the models give adequate data while one (THAMES) somewhat exaggerates the temperature. For the RF/RM modeling the canister temperature was pre-selected to be 100^{o}C, which hence controlled the heat evolution of the entire buffer. For ABAQUS the boundary conditions were set to yield maximum 83°C in the canister and the results not coupled to the wetting, which explains the high gradient in the buffer.

Table 3-2. Actual and expected temperature in degrees centigrade at the canister and rock surfaces at mid-height in the wettest hole after 1 and 2 years from start.

Location	Recorded	COMPASS (UWC)	CODE_BRIGHT (CIMNE, Enresa)	RF/RM (BGR)	THAMES (JNC)	ABAQUS (ClayTech, SKB)
Canister	1 y=69 2 y=72	1 y=70 2 y=72	1 y=70 2 y=72	1 y=100$^{1)}$ 2 y=100$^{1)}$	1 y=87 2 y=92	1 y=67$^{3)}$ 2 y=70$^{3)}$
Rock	1 y=56 2 y=60	1 y =56 2 y=59	1 y=57 2 y=60	1 y=92$^{2)}$ 2 y=96$^{2)}$	1 y=71 2 y=76	1 y=44 2 y=47

1) Set by modeler, 2) Controlled by 1), 3) No real prediction. Boundary conditions set to yield maximum 83°C in canister and results not coupled to the wetting.

The predicted and actual degrees of saturation are difficult to compare since the uncertainty in the recorded degree of saturation is significant. It should be noted that all the models gave quicker saturation than the *in-situ* measurements, which could be due to that the actual rock conditions deviate from the assumption of unlimited access to water.

Table 3-3. Actual and expected degree of saturation in percent at the canister and rock surfaces at mid-height in the wettest hole after 1 and 2 years from start.

Location	Recorded	COMPASS (UWC)	CODE_BRIGHT (CIMNE, Enresa)	RF/RM (BGR)	THAMES (JNC)	ABAQUS (ClayTech, SKB)
Canister	1 y=90-100 2 y=90-100	1 y=96 2 y=100	1 y=95 2 y=97	1 y=76 2 y=84	1 y=79 2 y=99	1 y=75 2 y=100
Rock	1 y=90-100 2 y=90-100	1 y=98 2 y=100	1 y=99 2 y=99	1 y=95 2 y=98	1 y=94 2 y=100	1 y=100 2 y=100

Table 3-4 shows the predicted total pressure, which deviates significantly from the actual data in most cases. ABAQUS predicts too rapid pressure build-up at the canister while the predicted and measured pressures at the rock agree well. COMPASS predicts too slow pressure increase at the rock interface.

Table 3-4. Actual and expected pressure in MPa at the canister and rock surfaces at mid-height in the wettest hole after 1 and 2 years from start.

Location	Recorded	COMPASS (UWC)	CODE_BRIGHT (CIMNE, Enresa)	RF/RMBGR)	THAMES (JNC)	ABAQUS (ClayTech, SKB)
Canister	1 y=1.0 2 y=4.0	1 y=0.8 2 y=3.2	1 y=3.0 2 y=5.1	1 y=3.5 2 y=4.8	1 y=4.7 2 y=6.2	1 y=5.3 2 y=6.8
Rock	1 y=6.0 2 y=6.7	1 y=2.8 2 y=3.9	1 y=5.0 2 y=7.2	1 y=3.5 2 y=4.8	1 y=6.4 2 y=7.2	1 y=5.3 2 y=6.8

The major conclusions drawn from the comparison of predicted and actual data are the following:

- The development of the temperature regime is captured well and the results illustrate that the temperature regime is well understood and represented within the models. It is clear, however, that the three-dimensional (3-D) configuration of the six deposition holes in the experiment is essential to correctly capture the variation in the thermal response in each of the boreholes.

- The simulated hydration rates in the buffer for the "wet" hole show reasonable agreement with the experimental results although some over-prediction of drying in the initial stages, (first 100 days), of the test is found. For the other "dry" holes it was found that the simulated hydration rates throughout the buffer also showed reasonable agreement with the experimental results measured by certain humidity sensors. The hydration is more difficult to predict than the temperature since the boundary conditions are poorly defined. Variations related to condensation and evaporation of pore water can be seen near the heater by close examination of recordings while such phenomena cannot be simulated because of the difficulty of combining water diffusivity and thermal diffusivity. Keeping in mind that the recorded hydration rate may have been too high due to water leakage along sensor cables it is possible that the deviation between predictions and actual data is even larger than shown by most model results reported in Table 3-3.

- One of the simulations of the mechanical behavior of the buffer in the "wet" hole captured the key features of the observed development of swelling pressures. Peak pressures close to the rock are under-predicted possibly due to an over-estimation of the compressibility of the pellet region. In the other holes there is very little swelling pressure developed in both the simulated and measured results due to the slow rate of hydration experienced in this hole. It is believed that a problem is caused by neglecting the gaps between the buffer blocks. For some models the initial stress in the simulation is therefore too large compared with the actual data.

Simulation over longer periods of time is naturally even more difficult, especially for those parts of a repository where only very little water is available for saturation of the buffer, as in some locations in *crystalline rock* and for all the buffer in *clay rock*. One example derived by the 3-D BGR model, based on two-phase flow, illustrates in Figure 3-23 the impact of the piezometric conditions and the presence of water-bearing fractures in deposition holes of the type represented by SKB's, Posiva's and OPG's concepts. The example shows that for one water-bearing fracture charged with water under 1 MPa pressure the degree of water saturation will still be below 80 % in some parts of the buffer after 30 years. For *clay rock*, which contains no discrete water bearing fracture, with an average hydraulic conductivity of about E-13 m/s and no discrete water bearing fractures the time to reach 100 % degree of saturation of the buffer may be more than 100 years. No experimental data are available and hence the predictions are uncertain.

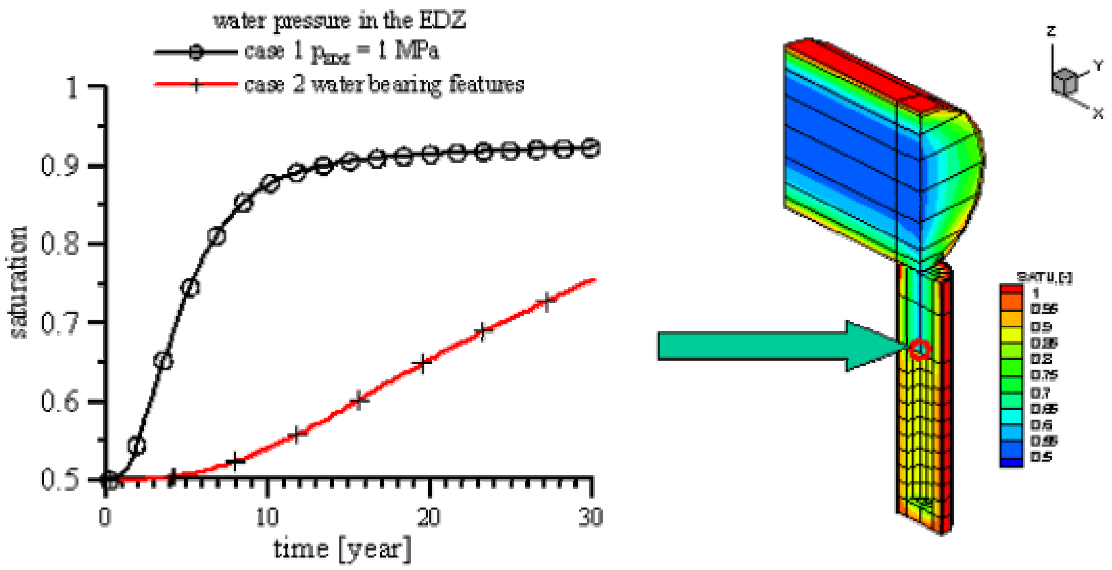

***Figure 3-23**. Water saturation versus time for two relevant cases, both with permeable EDZs. The upper curve shows hydration under 1MPa water pressure and the lower curve shows hydration under no water pressure. (BGR)*

Regarding the chemical evolution of the buffer clay in *crystalline rock*, there are large variations because of the evolutionary history of northern and central Europe and the Canadian Shield (glaciation/deglaciation and earth crust movements with associated changes in electrolyte and pH conditions). The groundwater salt content, usually with the Na/Ca ratio being higher than unity down to a depth of 500 m, can vary between slightly brackish to brine conditions. pH is usually in the interval of 6-8.

Predictive modeling calculations using codes like PHREEQC-2, WATEQ4F.DAT EQ3/6 compatible LLNL.DAT and NAGPSI_1.DAT for closed EBSs rely on constant near-field groundwater composition. The predictive modeling within buffer clay focuses on the major elements and certain solid phases, primarily montmorillonite, quartz, calcite, gypsum, pyrite, and goethite. The model computations follow the equilibrium thermodynamic assumptions and take into account the known cation exchange properties of the buffer.

The Febex project has investigated the evolution in the buffer under saturation and concluded that the processes occurring are closely linked together and may only be correctly captured by a coupled THC tool, which has been developed under the name “FADES-CORE”. This code suggests the major geochemical processes controlling the chemistry of the clay barrier during the hydration process be acid-base reactions, aqueous complexation, cation exchange, dissolution/ex-solution of CO_2 and dissolution/precipitation of highly soluble minerals such as calcite, dolomite, chalcedony, and gypsum/anhydrite. All these processes are assumed to take place under equilibrium conditions. Exchange experiments carried out indicate clearly that cation exchange is not affected by temperature. This is not the case for mineral dissolution-precipitation which shows a significant dependence on temperature.

The analysis and interpretation of various heating and hydration laboratory tests reveal that the following combinations of hydrochemical processes take place:

- At early times the thermal pulse causes calcite, gypsum and dolomite precipitation due to a decrease in their solubility with temperature.
- At intermediate times, hydration water which has less solute concentrations, causes a dilution which in turn induces the dissolution of all these minerals.
- At early and intermediate times, water evaporation near the heater causes a strong increase in solute concentrations which in turn causes precipitation of calcite, gypsum and to a less extent of chalcedony. Large concentrations near the heaters cause the solutes to diffuse away from the heater.
- At late times, as hydration progresses, the effect of dilution and mineral dissolution extends to most of the clay barrier. Once the hydration front reaches the vicinity of the heater, precipitated minerals re-dissolve.
- Changes in the cation exchange complex of the bentonite exchange in the mock-up test are mostly relevant near the heater. Anhydrite and calcite precipitation (due to evaporation) induce a depletion of dissolved calcium, which is compensated by calcium released from the exchange complex.
- As the buffer reaches near-saturation conditions, concentration gradients dissipate due to the effect of molecular diffusion.

The numerical model assumes that the porous media can be represented by a liquid phase (consisting of water, dissolved gaseous species and other aqueous species), a gaseous phase (which, in turn, is made of water vapor and "dry" air, i.e., a fictitious species which encompasses all the gaseous species except water vapor) and the bulk solid made up of different mineral phases.

Water moves through the porous media in liquid phase, responding to hydraulic gradients (Darcy's Law), and as water vapor (steam), in response to the moisture gradient (Fick's Law) and associated to air movement through the porous media (convection). The flows of liquid water and water vapor are mutually related through evaporation and condensation. When a liquid water front invades a zone having a very low moisture content, part of it will evaporate. On the other hand, if there is a drop in the temperature or pressure of the liquid, part of the water vapor will condense. The energy transfer due to the liquid water/steam phase transition is important due to the large evaporation/condensation enthalpy (585 cal/g, at 20 ºC) increment. This fact suggests that most of the energy transported through the medium must be transferred through both processes. Multiphase flow needs to take into account the following processes: a) the flow of liquid water (advection), b) the flow of water vapor (advection and diffusion), c) the flow of gaseous species different from steam (i.e., "dry" air) (advection and diffusion), d) the flow of air dissolved in the water (advection), e) the transport of heat through a the solid skeleton (conduction), f) the transport of heat through the liquid phase (convection) and g) the transport of heat in the gaseous phase (convection).

Regarding possible changes in minerals, especially the smectite constituents in buffer clay, most conversion models indicate only minor impact at temperatures lower than 90-100^{o}C. A safe margin with respect to temperature is not yet known but it is clear that temperatures on the order of 150^{o}C may locally cause very substantial mineral and property changes as indicated by Figure 3-24.

***Figure 3-24**. Appearance of FoCa-7 clay buffer after termination of an almost 4 year long test in the Stripa URL. The sector-shaped clay sample was almost 75 mm in radial direction and was in contact with an iron heater with 170°C surface temperature at the right end and with rock at the other. The dark part near the heater had converted into claystone and mineral changes had significantly changed the physical properties of the entire buffer. (SKB)*

Comparison of predicted and actual performance of EBS in URLs and repositories in salt rock

The most important properties of *salt rock* and salt backfill are the rate of strain since it determines the rate convergence and possible critical stress states. The basic creep model is of Arrhenius type implying that an activation energy has to be derived. Several comparisons have been made in Germany of measured and predicted data for the convergence with special respect to the impact of temperature. Figures 3-25 and 3-26 show examples of measured and predicted borehole strain, illustrating the significant strain rate and its dependence on temperature. An important conclusion from this work was that 3-D modeling is needed to satisfactorily simulate the conditions in the drift of limited length and thus to obtain satisfactory agreement between experimental and numerical results. Observed quantitative deviations and inconsistencies regarding the prediction of stresses indicate shortcomings in the material models that need to be reconciled.

For WIPP similar, largely empirical creep models have been used for predicting time-dependent strain and for back-calculation of creep parameters like the activation energy.

The model used for predicting creep strain is of the form:

$$\dot{\varepsilon}_s = A \cdot exp\left(\frac{-Q}{RT}\right) \cdot \left(\frac{\sigma}{\sigma^*}\right)^n \qquad (2)$$

where:

A = constant factor in MPa · s^{-1}
n = 5
Q = activation energy in J · mol^{-1}
σ^* = 1 MPa
R = universal gas constant: 8.314 J · $mole^{-1}$ K^{-1}

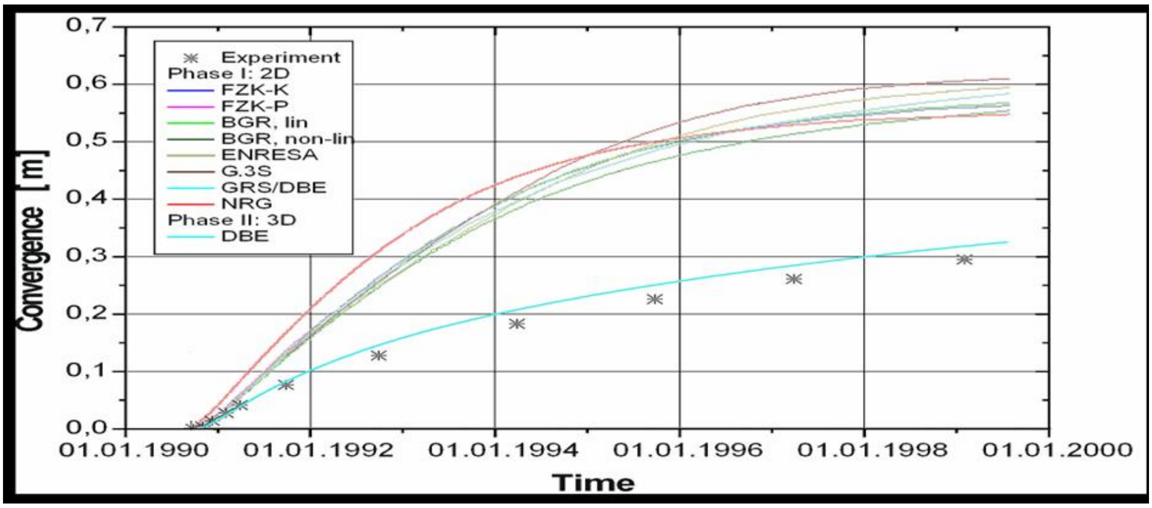

Figure 3-25. *Comparison of modeled and measured data for convergence in the central cross section of the Thermal Simulation of Drift Emplacement (TSDE) based on 2-D (BAMBUS I) and 3-D (BAMBUS II) calculations. (GRS)*

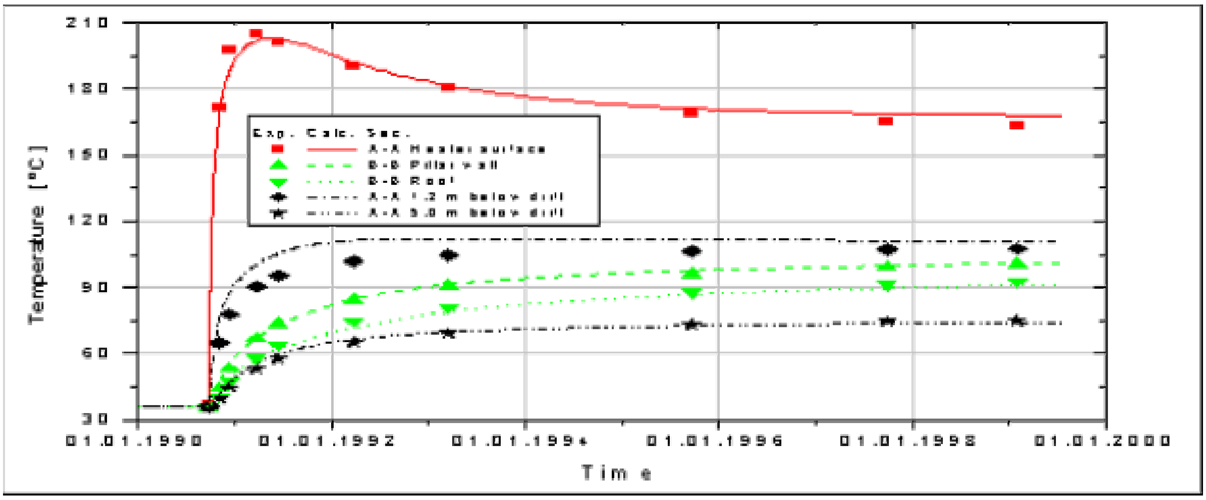

Figure 3-26. *Temperature at selected points of two central cross sections from 3-D calculations. (GRS)*

The DEBORA-2 experiment in the Asse mine/URL simulated the maturation of a seal between the drift and the top of a canister stack in a deposition hole with a 0.6 m diameter and 15 m depth located at the 800-m level. The test was conducted over a period of 14 months and modeled as in the previous experiment (i.e., BAMBUS I and II), using a 3-D quasi 3-D finite element (FEM) model. The agreement between predictions and measured results of *salt rock* porosity was considered to be acceptable (Figure 3-27.) This experiment illustrates the consolidation of crushed salt as backfill, the process being affected both by creep-induced convergence of the surrounding rock and by compression of the backfill under its own weight.

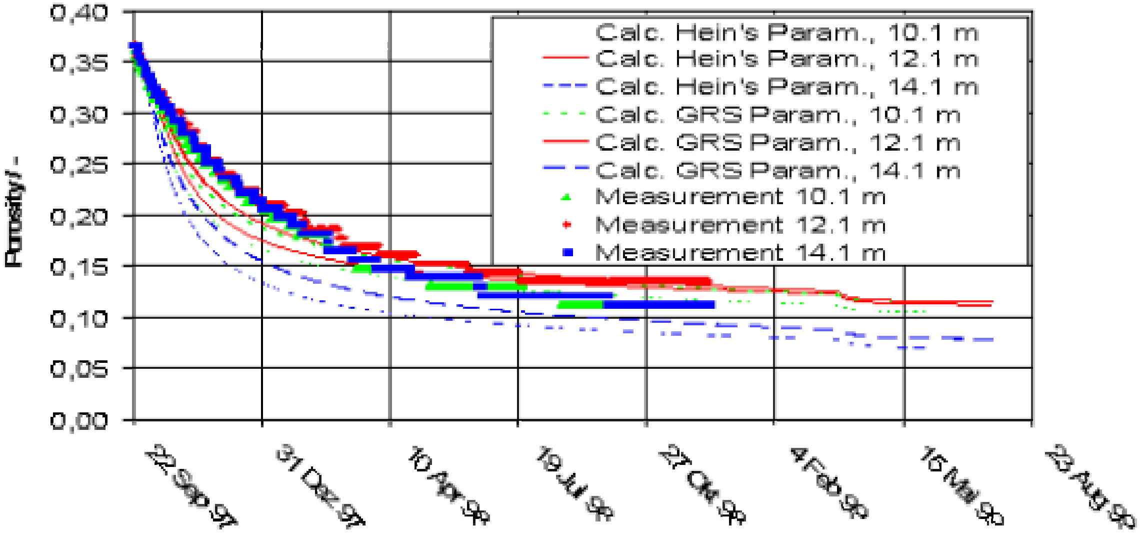

Figure 3-27*. Porosity decrease in the DEBORA borehole backfill. Very considerable reduction in porosity was obtained in about 2 years but complete disappearance of voids may take several decades. (GRS)*

One concludes from the field experiments at the Asse and the WIPP URLs that the conceptual model of convergence of any opening in salt rock implying complete closure after sufficiently long time is valid. The time dependence of the closure is not known with great certainty, but the majority of observations indicate that the process is slower than estimated.

Comparison of predicted and actual performance of EBS in URLs and repositories in clay rock

Modeling of *indurated clay rock* and engineered barriers has been performed using CODE_BRIGHT. A three-phase porous medium is considered composed of solid grains, water and gas. THM aspects are taken into account, including coupling between them in all possible directions. Darcy's law is assumed for advective fluxes of liquids and gas, Fick's law for non-advective fluxes in vapor and air, and Fourier's law for conductive heat flux. The degree of saturation of the liquid phase is given by appropriate retention curves, like for the buffers and backfills in *crystalline rock*, while mechanical constitutive laws were used for the mechanical calculations.

The results from a small-scale heater test with artificial wetting of the buffer show that the temperature development can be adequately modeled, while attempts to model the saturation of the buffer in a full scale isothermal buffer mass experiments using artificial supplies of water to the buffer are still showing problems because of the complications arising from the combined use of bentonite blocks and highly compacted granular bentonite The analysis of these forced-saturation buffer mass experiments remains to be finished and the final evaluation of the modeling will have to be postponed. Long-term tests under repository-like conditions, i.e., with no artificial wetting, would have to run for centuries to give representative data for model assessment.

A number of issues related to *indurated clay* (e.g., Opalinus clay) and similar strata have been identified, the major ones being:

- The conceptual and numerical models might be very accurate in terms of physical processes but effects due to heterogeneity of the materials at large scale (e.g., due to the buffer emplacement or natural variability in the strongly anisotropic host rock) can lead to significant deviation between prediction and reality.
- The parameter evaluation determined on small-scale samples might not be adequate (scale effects), which could be significantly influenced due to sample disturbance during unloading in the sampling process, leading to an underestimation of strength.
- The rheology of the rock has to be determined to understand long-term deformation processes, especially the hydro-mechanical interaction between rock and buffer (long-term convergence of disposal drift and self-healing of EDZ).
- As the HM and THM processes are very complex, their modeling requires a large number of parameters (THMC parameters and initial state conditions with respect to stress and hydrology. A significant uncertainty in these parameters and state conditions must be taken into account in predictive modeling.
- Significant effort is needed to obtain a relevant database for the “calibration” of the models. This in turn competes with the need for “least-possible disturbance” of the test environments and could lead to data bias.
- Several projects address the question of simplifying assumptions when HM and THM processes are modeled by using different modeling approaches of increasing complexity. The question “what degree of complexity” is required in modeling to obtain a reasonably good simulation of the THM processes is still open.

Chemical processes to be considered for any host rock type but particularly for *clay rock*, with its greater content of physical/chemically active and less stable minerals than in most *crystalline rocks*, include the evolution of the chemical environment (e.g., redox processes, dissolution- precipitation, cation exchange), chemical coupled (reactive) transport (e.g., alkaline plume) and transport of radionuclides (e.g., advection, diffusion, sorption). Different modeling codes are available to account for the evolution of geochemical conditions (e.g., PHREEQE or EQ3/6) and for chemically coupled transport (e.g., Hydrus + PHREEQE) and have been used for preliminary predictions by the Participants.

Coupled THM(C) models are good and adequate tools to investigate processes to understand system behavior. Most models for the different, partly non-linear processes employ a combination of pure physical and empirical laws. However, empirical laws should be used with care for time scales that are significantly longer than the experiments used for calibration. Together with uncertainties in parameters and heterogeneities in the host rock this can lead to large discrepancies between observations and model results especially over long periods of time. In addition, the use of some of these codes is very time consuming, especially if the time steps are not updated during the calculations, which may require undesirable long calculation times. Therefore, simplified coupled THM(C) models, using conservative assumptions, should be used to determine robust bounding cases and investigate the final stage in maturation of the system rather than details of the development in the transient phase.

3.2.5 WP4 System improvement and development

Overall assessment of the repository concepts with respect to problems and solutions

The respective repository concepts have undergone peer review and assessment by national authorities and international experts and have been judged to guarantee safe long-term isolation of long-lived radioactive wastes. The concepts cannot be directly compared since they are based on local geological conditions, combined with suitable EBS on one hand and the specific waste inventories from the different countries on the other hand. The performance of the repositories is analyzed in comprehensive safety assessment studies to ensure that national and international guidelines (e.g., dose rates) and regulations are met for the assumed base cases and alternative scenarios. The necessary robustness of these assessments is demonstrated by evaluating possible alternative and even very conservative (what-if?) cases. This analysis includes the performance of the whole system including waste types, waste forms, and engineered and natural barriers.

For *salt rock*, the only important transport mechanism is diffusion of contaminants from possibly leaking canisters that takes place uniformly in the largely homogeneous *salt rock* mass at a rate that is so low that radioactive contamination of the biosphere is not expected to occur unless the natural environment is breached by human intrusion. The natural problems that may occur are related to low-probability events such as unexpected inflow of water from the ground surface or sediments covering the salt dome or bed, or creation of transport pathways within the *salt rock* by high gas pressure or inadvertent human intrusions such as e.g., drillings. To solve the first mentioned problem a system of very tight plugs must be constructed in the access shafts or ramps both above the *salt rock* and in it. For eliminating the risk of gas-generated pathways in the *salt rock*, in addition to minimizing the inflow of water that could stimulate gas-generating breakdown of any organics, the canisters have to be highly corrosion resistant with a very low probability of manufacturing defects and in-service failure, or the disposal rooms have to be closed with seals providing the required gas permeability.

For *crystalline rock* the potential for frequent water-bearing fractures or EDZs interacting with very permeable fracture zones means that released radionuclides into these systems could be quickly moved by flowing water. The solution to this problem is to use an EBS with excellent isolating and retardation properties as exemplified by repository concepts described in this report.

Transport in potential host rocks consisting of *indurated and soft clays* are dominated by diffusion. Advective transport could be important in *indurated clay* if a continuous, hydraulically conductive EDZ will be formed along drifts during construction that provide effective flow paths. On-site and laboratory tests have shown that the self-healing potential of the candidate rocks will lead to a substantial reduction of the induced EDZ transmissivity with time.

In addition, the robustness of the system can be increased by cutting of this potential flow path in specific seal sections by partial or full removal of the EDZ immediately before the emplacement of the sealing material.

For *plastic clay rock* a short-term problem is providing adequate mechanical stability during the construction phase. The solution is to apply strong concrete or steel supports immediately after the advancing excavation machine. During the heat pulse in the transient phase of the repository, significant pore water pressure and total stress changes will occur which could lead to variations in effective stress. A reduction of the effective stress could cause a further extension of the EDZ and creation of additional induced fractures. As the drifts are already back-filled at this time, no major problems are expected from this process. In addition, heating will accelerate creep of the rock and therefore enhance the self-healing capacity of both *soft* and *indurated clays*. A chemical problem might arise from the fact that the high pH of the concrete liner may partially degrade the smectite clay buffer at the buffer/liner interface. This problem can be reduced by using low-pH cement in the concrete liner.

Possible improvement of the repository concepts

Design and construction

Underground construction in *salt rock* may be based on a long-time, extensive experience gained in salt mines and in oil and gas storages in salt rock. The safe, successful design and construction of the WIPP URL and repository in *domal salt rock* made use of the know-how from potash mines in the WIPP region. Conventional excavation methods in salt rock cover both drill-and-blast techniques and mechanical methods like road header excavation or full-face boring with TBM. The excellent creep properties of rock salt provide for stable rooms during the operational period of a repository, but in special cases when high stress concentrations occur or the room geometry is unfavorable rock bolting is needed to prevent e.g., roof spalling. The salt rock has very low water content and the underground environment in e.g., salt mines is exceptionally dry.

The construction of URLs and repositories in *crystalline rock* presents no great difficulties and the huge experience of underground mining in *crystalline rock* in most countries certifies that a repository with stable rooms can be prepared even in rather poor quality rock and in highly stressed rock. However, very high rock stresses may have an impact on the selection of the depth of a repository for some designs. The orientation of the principal stresses and certain rock structural features need to be considered in selecting the design and geometry of the rooms for optimal utilization of the host rock mass. A significant problem may be caused by high water inflow into drifts and shafts during the backfilling stage. New techniques for backfilling are being considered but they need to be tested at full scale to ensure that these concepts are applicable without reservations or changes.

Repositories in *indurated clay rock* can as well be constructed using standard tunneling and mining techniques. Mechanical excavation is the preferential tunneling method in these weak rocks. Depending on the size and shape of the underground openings, full-face boring machines (TBM) or road headers will be used. The choice of an appropriate support system is essential in such materials and, depending on rock stability and stress situation, light support measures like rock bolts and meshes or heavy support (e.g., massive steel or concrete liners) could be the solutions to this problem. Due to the hydraulic properties of the host rock no water inflow from the rock is expected but care has to be taken, that no water from overlaying formations will flow into the repository along shafts and ramps. In addition, no water should be used for construction purpose or be introduced by ventilation.

Instruments

Practical instrumentation of URLs has been more difficult than initially assumed in the planning stage, primarily because the sensors are sensitive to the harsh conditions prevailing in the near-field, i.e., high temperatures, high crushing loads and high concentration of groundwater electrolytes, and because cable and tube connections can serve as artificial groundwater flow paths. The problem with avoiding the latter defect is not yet solved and it is the main reason why instrumentation of the near-field of real repositories can not be designed at present. A possible solution could be the use of wireless transmission techniques which were tested in a few cases so far. Considerable development of instruments is needed and steps must be taken for avoiding their disturbing impact on the evolution and performance of rock and the EBS, and to ensure that they have the durability and accuracy required for reliable long-term monitoring. In Belgium an attempt in this direction is being made by introducing "supercontainers".

Experimental procedures

The experiments in the URLs turn out to be fairly similar and focusing on rock testing with special emphasis self-healing properties of *salt rock*, on groundwater flow and radionuclide migration in the near- and far-field in *crystalline rock*, and on stability, deformation processes and radionuclide diffusion in *clay rock*. In addition, experiments have been conducted to investigate the interaction of the near-field *crystalline* and *clay rocks* and the buffer and backfill during saturation and heating. Experiments can only be conducted for a limited period of the very long repository lifetime and they only provide indications on the short- and medium-term performance of a repository. Typically, experiments and tests performed to date essentially provide data on the very first phase of the evolution of the EBS and the function of buffers and backfills, which would likely undergo additional hydrothermal changes for thousands of years. The long-term evaluation of the system can only be inferred from adequate natural analogues and performance assessment studies have to use simplified and robust models with conservative assumptions to demonstrate the long-term safety of the system.

Among processes that are considered to be of importance from safety points of view but that have not yet been fully considered are effect of brine intrusion into crushed salt backfill and gas channeling in bedded *salt rock*, temperature impact on processes taking place at lower temperature in *domal salt rock*, gas channeling in the buffer, release of colloidal clay particles from buffer in *crystalline rock*, and microbial processes affecting EBS components.

It is both an important and attainable task to design and conduct experiments identifying possible changes of clay buffers in *crystalline rock* in both short- and long-term perspectives. Among the most important experiments are gas penetration experiments, sampling and analyzing the content of colloids in water-bearing fractures that intersect deposition holes and drifts in future experiments, and bacterial existence and microbial processes. These issues are in common for all Participants, but with different impacts in different host rocks, and consequently with different weights of importance in the work. One example is *crystalline rock* and bacteria, of which sulphate-reducing ones are a particular threat to the integrity of the canisters, and spores may stay alive and multiply in smectite clay. Although ongoing research indicates that bacteria are not active in highly compacted clay and therefore irrelevant for most concepts, their potential occurrence, survival and performance should be further investigated in *in-situ* field experiments.

Conceptual and mathematical models

Conceptual and theoretical understanding of coupled processes (THMCB) and means of modeling most important processes in a coupled mode appear to be sufficiently good for general use in planning and running experiments in URLs.

Maturation of salt buffer in *salt rock* and of clay buffer in *crystalline rock* and *clay rock* is intimately connected to the rheology of the surrounding host medium. With the exception of the already certified and operating WIPP repository, the development of the rate of convergence in the final codes and models the rate of convergence of *salt rock* and *clay rock* will need further site-specific study. The understanding of creep processes in salt buffer and salt rock as well as in stiff and plastic clay rock should benefit from additional study of the mechanisms on the micro-structural scale.

The development of models for describing and predicting maturation of clay and salt buffers under varying thermal conditions has been extensive among the Participants. Numerical THMCB modeling based on the current conceptual models cannot, however, be made with any accuracy if the knowledge of the structural and hydrological properties of the near-field rock is not improved (*crystalline rock*)**.** Thus, a potential area for improvement is modeling of the structure and associated flow properties of the near-field rock, including the EDZ. They can, especially in very tight rock, determine the rate of hydration of the buffer and thereby some of the chemical and mineralogical evolutions in it that affect both the short- and long-term physical performance.

Gas release from canisters and gas migration through the EBS and the rock requires more attention in HLW repositories although the conceptual understanding of processes involved has been developed.

Modeling of chemical processes in especially clay buffer is an issue that requires more work, especially in the areas of complexation and cementation. A remaining task is to develop more accurate theoretical models and numerical codes for cementation by mineral precipitation, and conversion of smectite to non-expandable minerals. Prediction of mineral changes can be made with some confidence but validating field tests with the temperature conditions implied by the repository concepts would require many hundreds of years and can therefore not be made.

However, it has been noted that safety assessment relies on the long-term properties of the EBS and rock rather than their properties during the complicated transient phase dominated by high driving forces and gradients. Therefore, it has to be ensured that during the transient phase these materials are not affected by negative, irreversible alterations. The detailed process understanding is advantageous and can lead to optimization but is not always necessary to demonstrate the safety of the system.

3.3 Lessons learned and potential areas for improvements

The most important lessons learned with respect to *salt rock* can be summarized as follows:

- Retrieval of canisters is expected to be very difficult without re-mining or overcoring after some tens of years following canister emplacement.
- Continuous maintenance must be made to retain the design geometry of drifts and shafts.
- The tightness of the rock mass is very good and would require only simple canisters but there is a risk that production of gas under very high pressure may cause problems by forming pathways for radionuclides.
- The risk of post-closure production of gas with very high pressure that may cause problems by forming pathways in the host rock must be mitigated.

For *crystalline rock* the following important experience has been gained:

- High rock stresses may cause unstable excavation openings in certain parts of a repository and localized rock failure may be triggered when heat-generated stresses develop.
- The size and flow capacity of the EDZ can be very significantly reduced by suitable location and orientation of drifts, ramps, shafts and seals. The use of TBM excavation has been shown to result in smaller zones of the excavation-induced damage in the excavation perimeter when compared to the EDZ associated with drill-and-blast excavation methods.
- Water inflow into drifts, shafts and deposition holes has the potential to cause very significant problems with the physical stability of buffers and backfills, particularly during emplacement when specific properties must be achieved.
- The quality and performance of the EBS components is more important to long-term safety in most *crystalline rock* conditions than in the other geological media.

For *clay* the lessons learned are:

- Transport in the host rock and even in natural fractures under sufficient normal load is diffusion dominated in the candidate rocks. Therefore, the host rock is a very efficient and reliable barrier, which reduces the requirements on the engineered barriers.
- The rock mass stability around drifts and rooms can be sufficient depending upon the depth but adequate drift support measures have to be used. The choice of an appropriate drift shape and the orientation of drifts with respect to the stress field direction can be very advantageous.
- The rock is very sensitive to water and environmental conditions (e.g., relative humidity). Water flow from overlaying formations along shafts and ramps has to be avoided and no water should be used for construction purpose.

- The EDZ in indurated clay may form a flow path along deposition drifts during construction and the operational phase. For the evaluation of the long-term properties of buffer and rock, time dependent processes have to be considered (drift convergence, swelling etc.). Self-healing processes will significantly reduce the transmissivity of such path ways. Depending on rock properties and the hydrogeological regime effective plugs may be required for cutting off these flow paths.

- The hydration rate of buffers and backfills is very low and the impact of desiccation may lead to some loss of clay-expansion capacity.

4 Acknowledgements

The European Commission is gratefully acknowledged for providing financial support to most of the Participants and for being deeply interested in promoting the project. The Participants are especially grateful to the EC representatives Bertus Haijtink, Michel Raynal and Christophe Davies for their devoted engagement in and valuable contributions to the project. Partial financial support of the Swiss project partner by the federal Office for Education and Science, and the full financial support by OPG and USDOE of the respective Canadian and US project partner are gratefully acknowledged. Thanks are also extended to the Participants and in particular to their representatives in the Task Forces that provided the large bulk of the project information through the Country Annexes and to the members of the CROP Steering Committee.

The project co-coordinator would also like to express a special gratitude to Roland Pusch, Peter Bluemling, Gary Simmons and Leif Eriksson who assisted effectively to the preparation of the present, Final Technical Report.

5 References

Deliverable 1. Project Work Plan

Deliverable 6. Comparison of repository concepts and recommendations for design and construction of future safe repositories

Country Annexes

All are available through respective originator.

Project Participant	**Country Annex**
Agence Nationale pour la gestion des Déchets Radioactifs (Andra) Parc de la Croix Blanche 1-7 rue Jean Monnet 92298 Chatenay-Malabry FRANCE Phone: +33 1 46 11 80 00 Representative: Frédéric Plas E-mail: frederic.plas@andra.fr	WP1 and WP2, Design and construction of engineered barriers (EBS), and Instruments and experimental procedures. Two Appendices. WP3, Conceptual and Mathematical models predicting THMC performance of the Engineered Barrier system. One Appendix. WP4, Preliminary assessment of performance of underground laboratories and repository concepts.
Empresa Nacional de Residuos Radiactivos S.A. (Enresa) Emilio Vargas 7 28043 Madrid SPAIN Phone: +34 91 5 66 81 32 Representative: Fernando Huertas E-mail: fhui@enresa.es	WP1, Design and construction of engineered barriers. Case a) APG – Granite and Case b) APG–Clay. WP2, Instruments and Experimental Procedures. Case a) Granite and Case b) Clay. WP3, Assessment of the function of EBS and the understanding of and capability to model the important properties. WP4, Preliminary assessment of performance of underground laboratories and repository concept.
Gesellschaft fuer Anlagen- und Reaktorsicherheit mbH (GRS) Theodor-Heuss Strasse 4 D-38122 Braunschweig GERMANY Phone: +49 531 8012 226 Representative: Tilmann Rothfuchs E-mail: rot@grs.de	WP1, Design and construction of engineered barriers WP2, Instruments and experimental procedures WP3, Assessment of the function of EBS and the understanding of and capability to model the important processes. WP3, Application of conceptual & mathematical models for predicting THMCB performance. WP4, Preliminary Assessment of Performance of Underground Laboratories & Repository Concepts. GRS-201. ISBN-3-931995-68-2
Nationale Genossenschaft fuer die Lagerung Radioaktiver Abfaelle (Nagra) Hardstarsse 73 5430 Wettingen SWITZERLAND Phone: +41 56 437 11 11 Representative: Peter Bluemling E-mail: blumling@nagra.ch	WP1 Design and construction of engineered barriers. WP2 Instruments and experimental procedures. WP3 Assessment of the function of EBS and the understanding of and capability to model the important properties and application of conceptual & mathematical models for predicting THMCB performance. WP4, Preliminary Assessment of Performance of Underground Laboratories & Repository Concepts.

Project Participant	**Country Annex**
Ontario Power Generation Inc. (OPG) 700 University Avenue Toronto, Ontario, M5G 1X6 CANADA Phone: +1 416 592-2555 Representative: Gary Simmons E-mail: simmonsg@granite.mb.ca	WP1-WP4, Ontario Power generation's input to the European Commission's Cluster Repository Project – A basis for evaluating and developing concepts of final repositories for high-level radioactive waste. 06819-REP-01200-10115-R00
Posiva Oy (Posiva) 271 60 Olkiluoto FINLAND Phone: +358 2 8372 31 Representative: Jukka-Pekka Salo E-mail: jukka-pekka.salo@posiva.fi	WP1, Design and construction of engineered barriers. WP 2, Instruments and experimental procedures. WP3, Assessment of the function of EBS and the understanding of and capability to model the important properties. Mathematical models and parameters needed for applying them. WP4, Preliminary assessment of performance of underground laboratories & repository concepts.
Studiecentrum voor Kernenergie-Centre d′étude de l′Energie Nucléaire (SCK-CEN) Boeretang 200, 2400 Mol BELGIUM Phone: +32 14 33 21 11 Representative: Jan Verstricht E-mail: jverstri@sckcen.be	WP1, Design and construction of engineered barriers. WP2, Instruments and experimental procedures. WP3, Assessment of the function of EBS and the understanding of and capability to model the important properties, Combined annex for "Mathematical models and parameters needed for applying them" and "Application of conceptual & mathematical models for predicting THMCB performance". WP4, Preliminary assessment of performance of underground Laboratories and Repository concepts.
Svensk Kaernbraenslehantering AB (SKB) Box 5864 102 40 Stockholm Sweden Phone:+ 46 459 8400 Representative: Christer Svemar E-mail: christer.svemar@skb.se	WP1, Design and construction of engineered barriers. WP2, Instruments and experimental procedures. WP3, Assessment of the function of EBS and the understanding of and capability to model the important processes. WP4, Preliminary assessment of the performance of underground laboratories and repository.
U.S. Department of Energy Carlsbad Field Office (USDOE CBFO) PO Box 3090 4021 National Parks Highway Carlsbad New Mexico, 88220 USA Phone:+001 505 234-7467 Representative: Mark Matthews E-mail: mark.matthews@wipp.ws	WP1, Design and construction of engineered barriers at the Waste Isolation Pilot Plant (WIPP) salt rock repository site. WP2, Instruments and experimental procedures. WP3, Assessment of the function of the engineered barrier systems and the understanding of and capability to model the important properties at the Waste Isolation Pilot Plant (WIPP) salt rock repository site. WP3, Results from application of models for evaluation and prediction of important near-field repository processes at the Waste Isolation Pilot Plant (WIPP) salt rock repository site. WP4, Preliminary assessment of the performance of underground laboratories and repository concepts at the Waste Isolation Pilot Plant (WIPP) salt rock repository site. WP4. Final assessment of performance of the underground laboratory and repository concepts at the Waste Isolation Pilot Plant (WIPP) salt rock site and recommendations for the design and construction of future safe repositories.

Part 3 Management Final Report

6 List of deliverables

D1	Project Work Plan
D2	Repository Concepts & Testing of EBS in facilities
D3	Conceptual & mathematical models for predicting THMCB performance
D4	Application of THMCB models to lab & field tests for verification/validation
D5	Preliminary assessment of performance of underground laboratories & repository concepts
D6	Comparison of repository concepts & recommendations for design & construction of future safe repositories

7 Comparison of initially planned activities and work actually accomplished

The two main objectives of the project, were to: a) form a forum for exchange of information on repository technology with focus on engineered barriers, and b) compile a document that may serve as an aid for future repository design and construction in countries utilizing nuclear power.

More precisely the work was broken down into the following three successively addressed objectives:

- Establish the CROP network
- Planning of meetings so that site visits and detailed technical discussions could take place at all the Participant's URL facilities
- Preparing the compilation of Country Annexes so that the intended information would be timely available for the last project deliverable (D6).

In practice the work was performed and documented stepwise in the following four Work Packages (WPs) focusing on design and construction of EBSs with special respect to their interaction with the considered host rocks, which in the case of CROP were *salt rock, crystalline rock* and *clay rock*.

- WP1: Design and construction of EBS.
- WP2: Instruments and experimental procedures
- WP3: Assessment of the function of the EBS and the understanding of and capability to model the important processes
- WP4: System improvement and development of practically applicable concept, which summarizes the results and contains the final reports

When analyzing the project results, the work accomplished supports the conclusion that the two objectives were met. A forum for information exchange was created and the knowledge of the CROP team has increased in the course of project meetings and visits to the Participant's URLs. All Country Annexes and project Deliverables have been produced, and are in a final form.

Seven project meetings were held during the course of the project at the following locations:

- AEspoe (AEspoe Hard Rock Laboratory)
- Braunschweig (Asse URL)
- Mol (Mol URL)
- Munchenwiler (Mont Terri)
- Winnipeg (AECL´s URL)
- Carlsbad (WIPP)
- Olkiluoto (VLJ Research Tunnel)

In addition one writers meeting was held in Paris and combined with a visit to the Bure site.

8 Management and co-ordinating aspects

The Participants had a long experience of working together on joint RTD issues prior to the CROP, although basically on issues that concerning only one type of host rocks. A productive working climate was therefore quickly established and maintained throughout the whole project.

One coordinating lesson learned was that the correctness of the presentation of results produced and reported was judged to be of utmost importance to the Participants, and because of this the internal reviews of the final project documents took much longer time than initially anticipated in the Project Plan.

Project contacts for the future are in alphabetical order, see details in Appendix 1.

ANDRA, Bertrand Vignal

ENRESA, Fernando Huertas

Geodevelopment AB, Roland Pusch

GRS, Tilmann Rothfuchs

Nagra, Peter Bluemling

OPG, Sean Russell or Gary Simmons

Posiva, Jukka-Pekka Salo

SCK-CEN, Jan Verstricht

SKB, Christer Svemar

USDOE CBFO, Mark Matthews

The EC officers were Christophe Davies and Michel Raynal.

Part 4 Summary of Final Report

9 Objectives

The aim of CROP was to provide a forum for exchange of information on repository design, construction and operation, and on testing and modeling of EBS in different repository host rocks with the purpose of optimizing scientific networking among key experts in the involved countries as well as improving testing and modeling procedures.

The result is a document that may serve as an aid for future repository design and construction in countries utilizing nuclear power and hence be of value to national and international agencies engaged or interested in the safe handling and disposal of long-lived radioactive waste.

10 Brief description of the research performed and methods/approach adopted

The work has been performed in a series of workshop sessions, which stepwise have addressed Work Packages dealing with the following issues/topics:

- WP1: Design and construction of engineered barrier systems EBS.
- WP2: Instruments and experimental procedures.
- WP3:Assessment of the function of EBS and the understanding of and capability to model the important processes.
- WP4: System improvement and development

The start of the project was the compilation of the Project Work Plan (Deliverable 1) and the main results are compiled in Deliverable 6, and summarized in this Final Technical Report.

11 Main achievements (absolute and relative to expectations)

11.1 WP1 - Design and construction of engineered barrier system (EBS)

For each of the geological media considered by the Participants the principles for repository design have been described with special emphasis on the EBS performance. The URL/repository location with respect to depth is in the interval 200 to 1 200 m below ground surface and all concepts are basically of the one-level type. Nevertheless, some concepts take the potential use of several levels into account. Access to the repositories is through shafts for *salt rock* and *plastic clay* and both ramps and shafts for *crystalline rock* and *indurated clay rock.*

The major repository-design principle is to use a redundant multi-barrier system of natural and engineered barriers to ensure the effective isolation of the waste for a defined period of time and to limit the transport of radionuclides in such a way that applicable regulations and guidelines can be met. Among other constraints, this requires the prediction of the evolution and performance repository system, including degradation of the EBS, which appears to have been modeled very conservatively by the Participants. The temperature in the near field during the heat pulse is shown to be an important factor since it could strongly affect the chemical processes, pore water pressure, total stress, groundwater flow and longevity of the EBS components.

As to the canisters, SKB, Posiva and OPG are designing very corrosion-resistant canisters for the spent fuel in *crystalline rock*, while less durable canisters represent an option for several of the other organizations for their disposal concept in *salt* and *clay rocks*. The projected lifetime of canisters for a repository in *crystalline rock* is 100 000 years, while for other concepts lifetimes of about one to tens of thousands of years are assumed. For long-lived transuranic waste (TRUW) being disposed of in the WIPP, a licensed American repository in *bedded salt*, no barrier function is ascribed to the steel containers, and a canister lifetime of only up to a thousand years is assumed for several other concepts (although actual canister lifetimes are expected to be much longer in the repository).

Buffers and backfills considered by the Participants are of different types. For the two concepts related to *salt rock* , magnesium chloride, magnesium oxide and crushed salt will be used. For those related to *crystalline rock* and *clay sediments*, smectitic clay is relied upon as buffer and backfill, either alone or mixed with other materials. Cementitious seals and concrete are options for Andra's concept intended for either *crystalline rock* or *indurated clay rock* and for the Belgian repository concept in *soft clay rock*. Nagra favors multi-component seals formed by adequate abutments to provide the mechanical stability on both sides of a sealed section containing highly compacted bentonite.

All Participants recognize the importance of effective plugs. The isolation provided by a plug is closely related to the extent and properties of the EDZ in all the geological media, and the capability of the plug to seal or cut off the EDZ in a long-term perspective.

11.2 WP2 - Instruments and experimental procedures.

The work on instrumentation and experimental procedures has been very successful, giving both the background for selection and the evaluation of performance in the field. An important finding is that the instruments themselves and the tubes and cables that transfer signals to the monitoring units may have a significant adverse effect on the performance of the buffer and backfills in URL demonstrations. The experiments with complete systems of heat-producing canisters, clay buffer and surrounding rock have provided an extensive data base on the various short-term processes that would affect maturation of the EBS in real repositories. These data are being used for comparison with numerical predictions.

The selection, application and performance of the various instruments in the URLs have been described in detail in the Country Annexes supporting WP2. The major findings are described below.

11.2.1 Temperature evolution in buffers, backfills and near-field rock.

Temperature data are required for repository design and for validating codes. High accuracy (e.g., +/- 0.1°C) may be needed to correct for thermal expansion and thermal sensitivity of instruments. The sensitivity to chemical attack by the pore water may cause rapid breakdown of the sensors hence necessitating special metal coatings, such as titanium, in demanding chemical environment.

11.2.2 Stress and strain measurements in the EBS and the near-field rock.

Stress/strain data are needed for validating theoretical models for predicting hydration of buffers and backfills, impact on rock and displacement of canisters. However, there are difficulties in obtaining accurate data, the major problem being water leakage along tubing and cables connecting instruments and monitoring/recording devices.

A general drawback is the size of these stress and strain gauges, which limit the special resolution and allow only detection of average conditions in a rather large part of the rock and soil. The risk of chemical degradation requires that corrosion-resistant metals be used for instrument construction or shielding.

11.2.3 Hydration measurements.

Moisture gauges like psychrometers are used for recording the rate of wetting and drying in buffers and backfills. They serve accurately only up to a certain degree of fluid saturation and combination of two different types of gauges covering the full range of conditions expected is recommended. The number of gauges that can be used is limited by the space they require.

A general conclusion is that sensors for recording wetting processes are the least reliable of all instruments and the first to fail according to the experience gained in several URLs. Hence, new types of more durable/robust sensors would be beneficial to future experiments.

11.2.4 Gas percolation, mineral changes, ion migration and microbial activities

Filters in buffers have been successfully used for recording gas flow. For evaluation of ion migration and determination of microbial activities, cups can be installed for sampling at the termination of the test. Mineral changes and microbial populations can only be evaluated using samples taken after the experiments have terminated.

11.3 WP3 - Assessment of the function of EBS and the understanding of and capability to model the important processes

The development of conceptual and numerical models for describing and predicting maturation of clay and salt backfill under varying thermal conditions has been extensive. However, the conditions for hydration of clay buffers are not well known and, in particular, more could be known about the role of the rock structure, including the EDZ, in providing water to support buffer maturation. The detailed movement of water associated with condensation/evaporation and film transport also needs more attention. A further question in *crystalline rock* that also deals with inflow of water is how to reduce or stop excessive water inflow into deposition holes or drifts in the construction and waste emplacement phases, particularly during the emplacement of clay buffers and backfills.

Re-composition of a salt backfill in *salt rock* and of a clay buffer in *plastic clay rock* is intimately connected to the rheology of the host medium. Whereas the rheology of the *bedded salt* repository host rock formation at the WIPP site has been established to the satisfaction of the cognizant regulator, the rate of open convergence in *domal salt rock* will need further study on a site-specific basis for developing complete models. The understanding of time-dependent deformation processes in stiff and plastic *clay rock* as well as in a *salt rock* should benefit from additional study of the deformation mechanisms on the micro-structural scale.

Gas release from canisters and migration through the buffer requires more attention in long-lived radioactive waste repositories although conceptual understanding of processes involved has been adequately developed.

Modeling 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 cementation by mineral precipitation, and conversion of smectite to nonexpandable minerals.

11.4 Discussion, conclusions and lessons learned (WP4)

The inter-media comparison is a new issue brought up during this project and lengthy discussions on this subject have been conducted throughout the whole project. Some general conclusions derived from these discussions follow.

Salt rock

- Crushed salt rock makes a good backfill as stress and creep-induced room closure (convergence) ultimately leads to consolidation of crushed-salt backfill and ultimately the complete encapsulation of the waste canisters.
- With the given weight and size of waste packages, the repository design is a country- and site-specific issue, of which the WIPP repository in bedded salt rock is an operating/functioning proof-of-principle example. The designs of seals and plugs, which are the main engineered barriers in salt rock, are also site-specific.
- For the German domal salt rock repository, work remains to be conducted for verification/optimization of design details.
- Good capability exists of modeling excavation-induced effects, e.g., the rate and extent of EDZ generation, but adequate prediction of EDZ healing needs further research.
- 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 (SF) into 300 m deep boreholes, is pending.
- *In-situ* testing of the suggested drift seal design under representative conditions is pending.
- The THM behavior of crushed salt rock backfill is largely understood. With the exception of the MgO used at WIPP, the effectiveness of including geochemical additives in the EBS to increase sorption of special radionuclides in the near-field has not been tested adequately.

Crystalline rock

- Crystalline rock has brittle characteristics and contains fractures, which may form patterns of groundwater transport pathways from a repository to the ground surface. The existence of fracture systems and their transport characteristics are the major factors that influence both the construction conditions and the long-term safety case.
- Canister design and manufacturing, as well as the performance of different materials, have been investigated in detail.
- The most important single parameter for the design of the repository is the maximum temperature allowed in the near-field.
- The selection of excavation method needs consideration with respect to the repository design and operation and the consequences of the presence and extent of the EDZ.
- Grouting as a means for sealing drift walls against inflowing water needs to be developed as current experience shows limited success in grouting unsupported rock surfaces, and low-alkali (low pH) cements should be used because ordinary cementitious materials (high pH) are potentially detrimental to the properties of the clay-based EBS.

- Swelling clay alone or mixed with other materials is an outstanding material for use in buffer, backfill and plugs and has been thoroughly investigated for more than 20 years. Manufacturing of highly compacted blocks of various sizes has been verified.
- Emplacement and deposition methods have been tested on a full scale for vertical in-hole emplacement, but other emplacement configurations must be demonstrated at full scale.
- Backfilling of deposition drifts in the KBS-3V (vertical in-hole emplacement method) has been tested on a full scale for low-electrolyte-water but is not verified for salt water.

Clay rock

- The disposal concepts in both soft/plastic and hard/indurated *clay rocks* (clay shale, clay stone or argillite) are governed by the fact that the clay layers exhibit limited thickness and homogeneity. This favors in-room emplacement of canisters rather than in-hole emplacement in vertical holes. The alternative is several tens of meter long horizontal large diameter boreholes or micro-drifts.
- Excavation is typically more complex in clay rock than in salt rock or crystalline rock, but proven technology can be applied. Major verification of optimum techniques has been made in soft clay in the Hades URL, Mol where the rock promptly needs permanent support of liners to prevent/alleviate the inherent plastic deformation/closure of the excavated openings.
- The clay rock 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 man-made damage or disturbance due to the construction of the repository does not jeopardize long-term safety.
- Drift convergence, EDZ creation and de-saturation of clay rock may be minimized by concurrent excavation and operation (waste emplacement) of underground openings because it would keep the emplacement cells open for a minimum of time.
- Repository components such as large waste packages, buffer, backfill, seals and plugs are being investigated and the work exhibits many similarities with the work going on in crystalline rock.

General

- The application of the "observational method" that is based on design with probabilistic techniques (First Order Reliability Method) as identified by the Eurocode 7 would be advantageous in order to plan for flexibility that allows for necessary changes caused by new information from site characterization or under ground excavation work on the existence of unexpected structural elements/discontinuities in the rock. Such discontinuities can occur especially in crystalline rock and stiff clay rock and could result in e.g., local drift instabilities.

11.5 Concluding remarks

From the successful development and 1999 opening of the WIPP repository and from all other programs advancing towards the licensing of deep geological repositories for long-lived radioactive waste, it is clear that authorities issuing future permits for repository development will recognize the importance of a sound safety case, good science and engineering, and public acceptance.

The CROP project has further clarified that there exist geological disposal concepts for long-lived radioactive waste that have been verified to perform in accordance with the respective nation's safety requirements as well as international standards and that have been checked and found safe by international peer review teams.

The basis for the performance/safety analysis has been existing data bases built up, with among other things, full-scale testing in URLs of the combined and complex processes that are expected to take place in geological repositories.

As the objective is to identify, verify and develop methods for simulating processes, important for the design and the safety case, i.e., that is operative in a repository for long-lived radioactive waste, the Participants concluded that some full-scale verification tests, with extensive process coupling, remain to be done. These tests would be different for different geological media and in each country depending among other things upon the country's state of progress.

The existing URLs have performed according to plans and the ones in operation and under planning/construction represent a large enough variety of geological conditions in order to have the capability to provide credible generic information on repository concepts in all geological media of consideration in the world today (except tuff). However, they are neither capable of providing the site-specific information that every disposal program requires for final verification and fine-tuning of the safety case nor the detailed construction/operation parameters.

The different geological situations have led to different design and instrumentation of the respective Participant's URL. However, the EBSs have a similar function and, despite some obvious differences, many of the solutions and techniques documented by the Participants are believed to be applicable to disposal concepts in several other rock types. The results from tests conducted in the many different geological media and involving a large number of EBS components are expected to be valuable to all organizations involved in repository development, and it is thus expected that improved technical solutions and repository and URL designs will evolve from the joint analyses conducted and documented in the CROP reports by the Participants.

12 Exploitation and dissemination

The main dissemination activity of CROP is the publication of the Deliverable D6.

Other important means are papers submitted to international conferences. No magazine articles are planned.

The following papers, having information on CROP, have been presented:

Simmons G.R., Bluemling P., Huertas F., Merceron T., Salo J-P., Svemar C., 2003. Repository concepts for nuclear waste disposal in crystalline rock. In Proc. FMGM 2003, 6th International Symposium on Field Measurements in Geomechanics, , Frank Myrvoll (ed.), pp. 789 – 798. Rotterdam: Balkema.

Svemar C., 2003. The role and limitation of URLs to foster development of expertise, information exchange, transfer of knowledge, and confidence building through international co-operation. Stockholm International Conference on Geological Repositories: Political and technical Progress. Stockholm – Sweden, December 7-10, 2003.

Svemar C., 2004. CROP – a networking for guidance in development of deep geological repositories for safe disposal of long-lived radioactive waste. DisTec2004 – International Conference on Radioactive Waste Disposal, Berlin-Germany, April 26-28, 2004.

Verstricht J., Bluemling P., and Merceron T., 2003. Repository concepts for nuclear waste disposal in clay formations. In Proc. FMGM 2003, 6th International Symposium on Field Measurements in Geomechanics, , Frank Myrvoll (ed.), pp. 387-392. Rotterdam: Balkema.

Annex 1

List of CROP Project Participants

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