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The use of scientific and technical results from underground research laboratory investigations for the geological disposal of radioactive waste

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THE USE OF SCIENTIFIC AND TECHNICAL RESULTS FROM UNDERGROUND RESEARCH LABORATORY INVESTIGATIONS FOR THE GEOLOGICAL DISPOSAL OF RADIOACTIVE WASTE

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FOREWORD

Underground research laboratories (URLs) play an important role in the development of deep geological repository systems for the disposal of long lived and high level radioactive waste, both from a scientific and technological point of view and for building public confidence. Several IAEA Member States have been conducting extended experimental and demonstration programmes in such facilities, both generic and site specific, for more than two decades.

The results produced by carrying out investigations in URLs have proved to be valuable both in generic terms, i.e. developing and assessing the disposal concept and building confidence in it, and in specific terms, as an essential means for detailed characterization, design and assessment of potential repository systems.

The objective of this publication is to provide information on the use of results obtained from URL investigations for the development of deep geological repository systems. This Technical Document is intended for decision makers, programme managers, research institutions and other stakeholders in the radioactive waste management community. Specifically, it also provides Member States that intend to start a geological disposal programme with an overview of existing facilities and of the sort and quality of results that have already been acquired.

This publication supersedes IAEA-TECDOC-446 published in 1987. It was produced as a result of a number of consultants meetings attended by experts from Member States involved in underground research programmes for the purpose of geological disposal of radioactive waste. A list of those who attended is provided at the end of the report. The IAEA officers responsible for this publication were J. Heinonen and M. Raynal of the Division of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

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1. INTRODUCTION

1.1. Background

The preferred, and internationally recommended, option for the long term management of long lived and/or high level radioactive wastes (including spent fuel when considered as radioactive waste) consists in their disposal in deep geological repositories [1–3]. Such option is based on a multibarrier concept consisting of natural and engineered barriers. The natural barriers include the host rock and surrounding geological formations, with their structural, hydrogeological and geochemical characteristics. The engineered barrier system (EBS) includes among others the conditioned waste form, the waste package and its potential overpack, the backfill, buffer and seal materials. As an integrated system these natural and engineered barriers are expected to provide, over very long period of time, adequate containment and isolation of waste, subsequent retardation of any released radionuclides and ultimately, dilution of any remaining radionuclide concentrations.

Characterization work performed in subsurface and, in particular, underground research laboratories (URLs) play an important role in the development of deep geological repository systems [4–6]. The first URLs were already developed in the sixties and seventies in order to assess the suitability of rock salt as repository host formation (Lyons and Asse salt mines) [7]. Several IAEA Member States have been conducting extended experimental and demonstration programmes in such facilities for more than two decades. The results produced have proved to be valuable both in generic terms, i.e. developing and assessing the disposal concept and building confidence in it, and in specific terms as an essential means for detailed characterization, design and assessment of potential repository systems.

The abbreviation 'URL' was initially used when referring to any underground research facilities, and in particular when referring to the Canadian and Belgian facilities. The denotation of 'rock laboratory' is also becoming more common when describing a facility in hard rock (e.g. Äspö Hard Rock Laboratory or Mont Terri Underground Rock Laboratory). It should be noted that despite the use of the acronym URLs, the purposes of many of such facilities might be focused on more applied objectives rather than research (e.g. site characterization and assessment, demonstration). Such evolution in terminology and in URLs' purposes can be confusing in different contexts but, for practical reasons, it was decided to refer in this report to URLs in the broad sense of the word, i.e. any underground facilities (purposely built or existing) used in the development of a deep repository system. Section 2.2 further clarifies the various types of URLs.

1.2. Objective

The objective of the report is to provide information on the use of results obtained from underground research laboratory investigations for the development of a deep geological repository system for long lived and/or high level radioactive waste, including spent fuel. This publication is intended for decision makers, programme managers, research institutions and other stakeholders in the radioactive waste management community. Specifically, it should also provide Member States that intend to start development of a geological disposal system with an overview of existing facilities and of the sorts and quality of results that have already been acquired.

1.3. Scope and limitations

The report addresses some of the topical investigations that have been carried out in underground laboratories, and reviews their use as support to repository development. In this context it complements and updates the information provided in a previous IAEA publication [8].

The present report is not intended to provide a comprehensive catalogue of all in situ experiments, testing and demonstration activities that have ever been performed in URLs. It is aimed at discussing, on a selective basis, some of the major achievements and lessons learned from those activities from different perspectives such as host rock characterization, barrier performance, demonstration, international co-operation and confidence building.

The report is directed to deep geological repository systems; however, appropriate experience gained in designing, constructing and operating subsurface repositories for low and intermediate level waste has been considered.

The report is based on information available as of early 2001. Its content has been defined taking into account a parallel initiative under the auspices of the OECD/Nuclear Energy Agency (NEA) aimed at defining the role and place of URLs in the development of a repository in geological formations [9].

1.4. Structure

After this introductory section, the report outlines the overall deep repository system with emphasis on its various components, their interaction and integrated assessment, in the context of the different host rocks generally considered with respect to geological disposal. A classification is then proposed for the types and roles of URLs on the basis of existing and planned facilities, depending on their location, purposes and timing (Section 2).

Uses of the results of underground investigations are then detailed according to six main themes, even if it is clearly recognised that most underground activities cover more than one theme:

- Rock characterization methodologies and testing (Section 3);
- Assessment of the geological barrier (Section 4);
- Assessment of the engineered barrier system (Section 5);
- Repository construction techniques (Section 6);
- Demonstration of repository operations (Section 7);
- Confidence building and international co-operation (Section 8).

Based on the concluding remarks of each section key conclusions are highlighted and general recommendations are proposed in the final section.

Main URLs where in situ experiments have been or are still carried out are listed in Table I. Additional information (status, key experimental work) on some of the URLs in operation is provided in Annexes A–G.

2. UNDERGROUND INVESTIGATIONS IN THE CONTEXT OF DEEP GEOLOGICAL REPOSITORY DEVELOPMENT

2.1. Overall description of the disposal system and its assessment

The goal of radioactive waste disposal is passive isolation of waste so that it does not result in undue radiation exposure to humans or the environment, now or in the future. This objective can be achieved by isolating radioactive materials in a repository system that is located, designed, constructed, operated and closed such that any potential hazard to human health is kept acceptably low over the required period of time.

Deep disposal, several hundred metres below the surface in stable geological formations, is generally recognised to be an appropriate solution for radioactive waste arising from nuclear power generation, high level waste from reprocessing operations, spent fuel elements (when considered as waste) and alpha bearing waste [1–3, 6, 10].

Overall, deep repository systems rely on the multibarrier concept. In the multibarrier concept, natural and man-made (engineered barriers systems – EBS) components are used to prevent (isolation) and delay (retardation) radionuclide migration into the surrounding environment. A third function (dilution) may take place in the geosphere during the migration of radionuclides toward the biosphere.

The main natural and engineered components of a repository system are:

- Host rock (e.g. clay/shale, granite, salt, tuff);
- Backfill, buffer and seal materials (e.g. crushed salt, bentonite, cement, grout), that are used to fill the voids in the repository facility and close the disposal system;
- Waste container materials and its potential overpack (e.g. stainless steel, copper, titanium);
- Waste matrix (e.g. glass, bitumen, concrete).

The main safety functions of a repository system can be described as follows:

Isolation is the primary function of the repository system. It is obtained through the conjunction of the waste matrix, the container, the backfill and the geological barrier. Good isolation is often possible with minimal groundwater flow to the waste container. For salt and clay stone(s), isolation is provided by the non-fractured, impermeable nature of the geological medium itself while in fractured crystalline rock, the isolation effect may have to rely on low fracture permeability or the engineered barriers.

Retardation of radionuclides dissolved in groundwater is the second important barrier function of the repository. Retardation is provided by the physical and chemical processes (e.g., sorption, complexation and precipitation) which occur in the repository and the geosphere. The major emphasis in the safety assessment calculations may therefore be put on the weakly retarded nuclides even though they may not be the dominant constituents in the waste inventory.

Dilution, the process of reducing the concentration of radionuclides in the rock volume surrounding the repository, is the third important barrier function. Its magnitude is very much depending on site specific conditions.

The long term safety of repository systems is evaluated through the use of performance assessment, which identifies possible scenarios that might lead to radiological hazard. This is done notably by analysing the consequences of the most relevant scenarios and by comparing these consequences (e.g. dose, risk) with regulatory criteria. Other indicators of long term safety can also be used in the assessment [11]. The site characterization activities, the design of the repository concept and the assessment of its long term safety are performed in an iterative and integrated way.

2.2. Types and roles of underground research laboratories

Since the mid sixties, several IAEA Member States have been conducting extended experimental programmes in underground facilities that have been purposely built or created from existing mines and galleries. Based on the existing, but rather confusing terminology, an attempt is made in this report to classify all past and current URLs in a simple and comprehensive way.

The proposed classification is applied to the underground facilities discussed in the framework of the present report and in Table I, which summarises the main past and operating URLs. A list of the most common acronyms used in relation with URLs is given as Table II.

2.2.1. Generic URLs

Generic URLs are constructed or developed in a location that is not considered as a potential site for disposal of radioactive waste. Generic laboratories can be developed from:

- existing underground facilities such as mines (e.g. Stripa, Asse, Amélie, Tono, Kamaishi, and Fanay), and tunnels such as for railways, dams or highways (e.g. GTS, Tournemire Research Tunnel, G-Tunnel, Climax and Mont-Terri URL);
- undeveloped sites (e.g. Äspö HRL, Lac du Bonnet URL).

Subsurface repository facilities for low and intermediate level radioactive waste can also be used for performing generic-type experiments of interest to deep disposal (e.g. VLJ Research Tunnel).

Generic URLs can be developed in a potential repository host rock (e.g. Mont Terri URL in Opalinus Clay) or in a geological media that is representative of potential host rocks. In some cases, generic laboratories that are located within potential host formations may provide opportunities for later development as geological repositories. However, adverse geological, and/or the societal context may clearly exclude them from ever being considered as a candidate repository site.

Generic URLs can also be developed by nuclear regulatory authorities (or their scientific advisors) in order to build their own expertise concerning in situ experimental work. This is especially the case for the Tournemire Research Tunnel in France [12].

2.2.2. Site specific URLs

Site specific URLs are by definition located in a specific (but not necessarily candidate) site for deep repository system considering a potential host formation (e.g. HADES-URF, Gorleben, Konrad, WIPP, Yucca Mountain-ESF and Bure URL).

Table I. Main past and operating URLs

COUNTRY	LOCATION	USUAL NAME	FACILITY TYPE[1]	HOST ROCK/ FORMATION	NATURE OF EXPERIMENTS[2]	PERIOD
Belgium	Mol	HADES-URF PRACLAY	S (purpose-built)	Soft clay	TCHMR+D	Since 1980
Canada	Pinawa, Manitoba	Lac du Bonnet URL	G (purpose-built)	Granite	TCHM	Since 1984
Czech Republic	Príbam	Shaft 16	G (galleries in U mine)	Granite	Characterization work	Late 90's
Finland	Olkiluoto	Research Tunnel	G (in VLJ repository)	Granite	HM+D	Since 1993
France	Fanay Augères/Tenelles	Fanay	G (galleries in U mine)	Granite	TCHM	1980–1990
	Amelie	Amélie	G (galleries in K mine)	Bedded salt	TM+D	1986–1994
	Tournemire	Tournemire Research Tunnel	G (railway and test galleries)	Shale	CHM	Since 1990
	Bure	Bure URL	S (purpose built)	Shale	Under construction	Since 2000
Germany	Asse	Asse Forschungsberg-werk – Asse Salt Mine	G (test galleries in K/salt mine)	Domed salt	TCHMR + D	1977–1995 Now in sealing phase
	Gorleben	Gorleben	S (purpose built)	Domed salt	Characterization	Since 1997
	Konrad	Konrad	S (test galleries in Fe mine)	Shale	CHM	Since 1980
	Morsleben	ERAM	S (test galleries in K/salt mine and repository for L/ILW)	Domed salt	D	Since 1981
Hungary	Pécs	Pécs	G (galleries in U mine)	Shale	Characterization work	1995–1999
Japan	Tono	Tono	G (galleries in U mine)	Sandstone	CHM	Since 1986
	Kamaishi	Kamaishi	G (galleries in Fe–Cu mine)	Granite	Characterization work	1988–1998
	Mizunami	MIU	G (purpose built)	Granite	Under development	
	Honorobe	Honorobe	G (purpose built)	Sedimentary rocks	Under development	
Sweden	Stripa	Stripa	G (galleries in Fe mine)	Granite	TCHM	1976–1992
	Äspö	HRL	G (purpose built)	Granite	TCHM + D	Since 1990
Switzerland	Grimsel	GTS	G (dam tunnel)	Granite	TCHM	Since 1983
	Mont Terri	Mont Terri URL	G (highway and test galleries)	Shale	TCHM	Since 1995
UK	Sellafield	RCF	S	Tuff	Characterization	Project stopped in 1997
USA	Nevada Test Site	Climax	G (galleries in mine)	Granite	D	1978–1983
	Nevada Test Site	G-Tunnel	G (tunnel)	Tuff	THM	1979–1990
	Lyons, Kansas	Project Salt Vault	G (galleries in mine)	Bedded salt	TM	1965–1968
	Carlsbad, New Mexico	WIPP	S (TRU repository)	Bedded salt	TCHMR+D	Since 1982
	Yucca Mountain, Nevada	ESF	S (purpose built)	Tuff	TCHM+D	Since 1993
	Yucca Mountain, Nevada	Busted Butte	G (purpose built)	Tuffs	CHM	Since 1997

[1] S = site specific URL; G = generic URL.
[2] T – Thermal, C – Chemical, H – Hydrogeological, M – Mechanical, R – Radiation, D = Demonstration tests.

Table II. Frequently used URL acronyms

ERAM	Low and intermediate level radioactive waste repository, Morsleben, Germany
ESF	*E*xploratory *S*tudies *F*acility, Yucca Mountain, Nevada, USA
GTS	*G*rimsel *T*est *S*ite, Switzerland
HADES	*H*igh *A*ctivity *D*isposal *E*xperimental *S*ite, Belgium
HRL	*H*ard *R*ock *L*aboratory (used to define the Äspö URL, Sweden)
MIU	URL in Mizunami, Japan
RCF	*R*ock *C*haracterization *F*acility, Sellafield, United Kingdom (project abandoned)
URF	*U*nderground *R*esearch *F*acility (used to define the HADES and PRACLAY facilities, Mol, Belgium)
URL	*U*nderground *R*esearch *L*aboratory (used to define the Lac du Bonnet URL, Manitoba, Canada)
	*U*nderground *R*ock *L*aboratory (used to define the Mont Terri URL, Switzerland)
VLJ	Low and intermediate level radioactive waste repository, Olkiluoto, Finland (operating)
WIPP	*W*aste *I*solation *P*ilot *P*lant, Carlsbad, New Mexico, USA (operating repository in bedded salt for transuranic, defence waste)

If nominated as a potential repository site, it should be stressed that the suitability of any such site for deep repository development must still be assessed by comprehensive underground experimentation, testing and validation — which is precisely the main purpose of site specific URLs and by complete evaluation of its performances. On the other hand, the aim of site specific URLs can be restricted in a first phase to the assessment and confirmation of the suitability of a potential host formation in adequate repository conditions, and geological context.

In some cases, e.g. Yucca Mountain-ESF and WIPP, site specific underground facilities are designed and developed in a way that they constitute a first step in the process of potential repository construction. This step requires appropriate designing and dimensioning of the openings such that the initial development does not compromise or add significant remedial expenses to the ultimate repository facility.

The nature of a particular URL can obviously evolve with time. Additionally, an URL can be defined as site specific from the point of view of its main operator and developer, but as generic from the point of view of some other partners. This is especially the case in the framework of multi-lateral or international co-operation, which is often implemented within URL activities (see Section 8).

2.2.3. Main roles of generic and site specific URLs

The current designations used at a national level — e.g. rock characterization facility, underground research laboratory, prototype repository, exploration study facility, test site – are reflecting the broad range of roles and aims of underground facilities, their evolution with time and, to some extent, the requirements of the licensing process.

In this framework, the various roles currently assigned to generic and/or site specific underground facilities can be briefly outlined as follows [5, 8, 9, 13]:

- To develop the technology and methodology needed for underground experimentation;
- To develop and improve methodologies for rock characterization and testing;
- To better understand, model and test relevant processes (and their coupling) in the geosphere;
- To better understand, model and test the behaviour of the various component of the engineering barrier system (and their coupling and interaction with the geosphere) in relevant repository conditions, e.g. in the presence of thermal loading and radiation;
- To provide quantitative data for safety assessment calculations;
- To test and optimize full-size repository components and operating procedures (demonstration);
- To optimize repository construction techniques and their impact in terms of disturbance to the host rock;
- To orient and train national and international multidisciplinary teams promoting benchmarking;
- To train staff in managing multidisciplinary projects;
- To promote international co-operation;
- To build confidence in the scientific and technical community that the understanding and modelling of important processes governing repository performance is adequate;
- To contribute to public trust and confidence.

Following more than 20 to 30 years of work on specific scientific issues, there is a trend towards focusing future underground investigations on large scale, integrated experiments and demonstration activities rather than on R&D and methodological development [5, 9, 14, 15].

Attention has to be drawn to the fact that a sequencing approach is generally referred to within the general context of repository development (step by step approach). This does not mean that a generic URL stage would be a pre-requisite to the development of a site specific one. All existing URLs worldwide can and should be used as generic laboratories for many other countries wishing to develop practical experience in realistic conditions regarding both geological and disposal contexts.

2.3. Time related issues

Assessing the suitability of a site and of the components of a repository system should be based on investigations conducted not only at different spatial (i.e. regional to local) but also temporal scales (long term extrapolation). Time periods of several ten of years are necessary to develop the required actions planned before the operation of a repository, from preliminary reconnaissance works to site characterization, selection and confirmation. Some national geological disposal projects have been running their own URL for more than 15 years (e.g. Belgium, Canada and Germany). The time perspective with regard to start operating a repository could be of similar magnitude.

Besides the need for a complete and reliable set of tools and experimental methods to gain representative input data for performance and safety assessment, the organizations responsible for radioactive waste management must also develop their own expertise and that of their subcontractors. This training, which is time intensive, could be best carried out, at least partly, in the numerous URLs worldwide before the data collection itself may start at an organization specific URL.

However, it should be stressed that the kinetics of many processes taking place in the geological medium is very slow and imposes long lasting experiments. This is especially true for large scale in situ experiments that are often the key purposes of URLs development. In these conditions, even radionuclide migration tests using non-sorbing elements are very time consuming.

Once the research has progressed so far that the necessity of such in situ R&D activities becomes of less importance, other requirements and opportunities might arise for addressing new scientific questions and focusing on demonstration tests. Issues such as waste emplacement, retrievability and monitoring may become a significant focus for additional effort. Some of these issues could be best dealt with through international co-operative demonstration projects. During the implementation of such a demonstration project in a laboratory located in a potential repository site, efficient use of time is mandatory.

Setting up an URL, especially a site specific one, also requires stakeholder acceptance, which could take long to acquire and vanish or be more demanding with time.

3. USE OF URLs FOR IMPROVING CHARACTERIZATION METHODOLOGIES

3.1. Introduction

As already stressed in the previous section, the procedures related to siting URLs usually are very time consuming so there is a significant time between the selection of a potential geological medium or site and the availability of an URLs at that site. In addition, equipment and methods required to collect site data are often not available off the shelf and must be developed from the beginning or, more often, derived/adapted from related fields and industries [16]. It should be noted that the unavailability of equipment and methods tends to decrease progressively as lessons from URLs activities are drawn and shared.

It is therefore recommended that waste management organizations that do not have an URL start the technological developments, and multidisciplinary team building necessary to support their site characterization programme in available underground facilities, especially if the latter are not specifically tied to a designated repository programme. This could be done in generic URL or within parts of site specific URLs that could be devoted to generic experiments. As mentioned earlier, numerous of such facilities exist worldwide and many of them are open to international co-operation, as stressed in Section 8.

3.2. Activities in methodology development and testing

Several examples of methodology development and equipment improvements at existing URLs are presented hereafter. It should be noted that the process to make technology ready for an underground laboratory starts with a market survey followed by testing of available products. In addition, attention needs to be paid to possible time dependent instrument error. Most of the devices embedded in the host rock, lining or buffer material cannot always be checked regularly, making maintenance and re-calibration impossible. In this context, redundancy is required, provided that the installation of all these devices does not compromise the representativeness of the measurements by disturbing, to an unacceptable extent, the host medium.

Regarding instrumentation, several developments were noticed in many current programmes.

In Canada, the improvement of a limited number of geomechanical instrumentation devices was required to make them suitable for the conditions of a granite site [17], in particular for determining the in situ stresses in rock at depth. Hydraulic fracturing and overcoring stress determination methods have been tested extensively and produce acceptable data under low and intermediate stress conditions. These conventional methods, however, cannot be used in regions of high horizontal stressed as encountered at greater depth in the Canadian URL. Among the various tested methods, research efforts were focused on investigating a technique for determining such high horizontal stressed by overcoring doorstopper strain gauges in a deep sub-vertical borehole [18]. Overcoring and hydraulic fracturing methods for stress measurements were also refined at the GTS, also in a granitic environment [19].

Among other methods developed or adapted for the characterization of granitic host rocks, it is worth mentioning the fine tuning and testing of the ground penetrating radar device that was possible in the framework of the Stripa project [20] and of the seismic tomography at the GTS [21, 22]. The latter case is aimed at evaluating and testing the possibility of using seismic tomography to explore large areas of underground rocks, as needed for detail design of repositories in potentially fractured media. Other devices, initially designed for borehole testing, have been successfully adapted and used in URL conditions, as e.g. new flowmeter techniques (difference flow and transverse flow methods) that have been used to measure hydraulic parameters in fractured granitic environment at the Äspö HRL and the Lac du Bonnet URL [23].

For low permeability clays, nothing reliable was available for porewater pressure measurement or collection. A new type of piezometer, and a convenient emplacement procedure was developed and tested for plastic clays at depth at the HADES-URF. Such a prototype – using sintered metal filter with no/little dead volume – was adapted several times, in combination with other measurements (total pressure, humidity). The same principle was upgraded for carrying out migration experiments [24]. Participation in the Mont Terri project allowed the adaptation of this measuring device to more indurated clays with lower water content. To compensate for the lack of convergence of the clay around the filter in the access hole, the measuring chamber was isolated by packers. The new prototype device was tested successfully in the Mont Terri URL [25]. The artificial hydration of backfill and sealing material also takes benefit of such technological developments.

Understanding the coupled processes of water movement, mechanical disturbance and chemical changes in unsaturated media when influenced by heat cannot rely on any one method or instrument. Consequently, a combination of techniques and instruments must be used. At Yucca Mountain, in the Drift Scale Test, a combination of several instrumentation techniques such as electrical resistivity, ground penetrating radar, acoustic emission monitoring, neutron logging as well as isotopic sampling of gas and water are being used. This made possible a better understanding of how water flows and how the natural barrier changes under the influence of heat [26].

Such a multidisciplinary approach was also followed for the characterization of fracture zones at the GTS, especially by attempting to relate seismological parameters to mechanical and hydrogeological properties of fractures [27].

Not only experimental hardware, but also methods can be fine tuned in URLs, especially the generic ones. Of particular interest is the building of confidence of each organization in its capacity to plan, implement and control experiments with as little disturbance as possible of in situ conditions in the rock mass.

As an example, experimentation in any underground laboratory needs a great number of good quality boreholes drilled. Basic requirements are great accuracy in direction, minimum contamination of the geological medium, and stability of the borehole walls. In large scale thermal and radionuclide transport testing, the accuracy of instrumentation sensor location is essential for understanding the physical processes associated with thermal and transport influences. This makes subsequent investigations more effective since you can mine or drill directly to the area of importance. To assure minimal disturbance of the unsaturated rock mass at Yucca Mountain considerable time and budget was expended to develop dry air drilling techniques to depths in excess of 750 m [28].

Still in the scope of drilling, overcoring can be a suitable technique to recover the tested host rock after a small-scale experiment is completed. This has been performed several times in most of the URLs. As already mentioned, under and overcoring methods are used to derive the in situ stress state from deformation measurements, even though the interpretation of results is not always as straightforward in argillaceous rocks as in granitic ones. In the context of the Mont Terri URL, an extensive rock mechanics test programme is under way, aiming to assess many of the available measuring techniques in this field including borehole slotter and hydrofracturing.

In argillaceous settings, the combination of these techniques with down-hole techniques such as video and geophysical surveys can also be useful in assessing disturbance of recovered cores. The quality of core samples can also be investigated by performing X-ray Computerized Tomography Scanning where the occurrence of cracks or pyrite nodules and the porosity variation can be highlighted before cutting laboratory samples from the core.

In the framework of the early investigations into the use of the Konrad oolitic iron ore mine as a final repository for non-heat emitting waste, one of the key objectives was to analyze and predict the overall stability of the mine and its overburden during the mining and disposal operations and after the sealing of the repository. In the absence of tested and proven techniques or procedures able to meet this objective, a new method for rock mechanical surveys was developed in which practical mining knowledge and experience are integrated with newly developed in situ measurements and numerical calculations [29].

In bedded and domed rock salt, characterization works are notably focused on the identification and geometry of anhydrite layers and potash seams, as well as brine pockets and gas-bearing salt bodies, as these geological features may have significant impact on operational and long term safety and on the final design of the repository [30, 31].

As early mentioned, URLs often serve as testbed for new measuring devices or for demonstrating the applicability of a method in repository relevant conditions. Not all of these tests have been successful. For instance, one attempt to measure response of rock salt on pressure changes in order to derive constitutive parameters to describe the thermo-mechanical behaviour of rock salt failed at the Asse salt mine. The device (variable pressure device – VPD) was installed in a deep borehole drilled from one of the mine galleries [32].

3.3. Concluding remarks

Characterization work at URLs is essential for experiencing methodologies, understanding processes, developing drilling technologies and installation procedures but also for testing prototype devices that are not commercially available for conditions prevailing at the site.

It is important to stress that the development of any new URL activity should ensure considering the benefit and lessons learnt from more than two decades of development and adaptation of in situ experimental methods and devices to repository-relevant conditions.

Some examples were provided here for different host rocks regarding rock mechanics, hydraulics, geophysics and drilling. This list of practical illustrations is everything except exhaustive but is intended to support and point out the importance of assuring quality and representativeness in characterization activities with a view toward confidence building. This should make the implementation of an underground experimental programme more effective.

4. USE OF URLs FOR ASSESSING THE GEOLOGICAL BARRIER

4.1. Introduction

The geological barrier has to provide an adequate environment to assure (i) the longevity of the engineered barrier system and (ii) a sufficient retention of eventually released radionuclides for hundreds of thousands of years. The requirements for the geological environment of a repository system for high level and long lived waste are described in [1]; the main ones being:

- Erosion and tectonic movements should not unduly affect the performance of the barriers of the repository or lead to fast groundwater flow paths from the repository to the biosphere;
- A host rock should have a low hydraulic conductivity and/or low hydraulic gradients to allow for a small flux of contaminated groundwater;
- A host rock should have sorbing minerals and reducing conditions that may significantly enhance retention of radionuclides in the repository.

The first of these three requirements can be evaluated by surface based regional and site specific investigation programmes. The second and third requirements can be investigated from URLs.

The contribution of the geological barrier to the safety of a repository will be assessed first by the study of its natural characteristics and the main processes influencing radionuclide transport. Then an understanding of the impacts of disturbance induced by the excavation of the underground facilities and, as appropriate, by the installation of testing equipment is needed. Finally, studies of the consequences of the emplacement of heat emitting waste and its associated container, buffer, backfill and concrete on the characteristics of the geological barrier will further support the assessment of the long term safety of the whole disposal system.

4.2. Characterization and modelling of the host rock as geological barrier

4.2.1. Geosphere models

For the evaluation of the barrier function of the geosphere, a series of models can be developed, describing the geological or the hydrogeological context. Key parameters and their spatial distribution, specific features and relevant processes are implemented in these models. They are based on observations and experiments carried out in surface or underground laboratories. The models are iteratively improved, as results from experiments and further understanding become available [33].

Characterization of the geosphere around an URL starts usually by an a priori initial geological model which is progressively refined and tested with the systematic addition of information derived from surface based surveys and then from excavation activities and in situ testing. The latter include e.g. careful mapping of all excavated galleries and of all cores of the drilled boreholes, complemented by laboratory analyses of rock samples. The geological model usually consists of a detailed description of the different lithological units, the rock discontinuities, e.g. fissures and fracture zones, and their geometrical layout.

The mechanical properties of the different lithologic units and discontinuities and the in situ stress field are described in a rock-mechanical model. Many relevant parameters of this model are obtained with laboratory analyses. Field measurements are carried out to obtain e.g. seismic velocities and in situ stresses.

The thermal model describes the thermal conductivity and the heat capacity of the rock and is the basis for the calculation of the heat flow and the evaluation of a reasonable distribution of heat emitted by waste containers in a repository. Thermal conductivity parameters are determined on rock samples. Heater experiments, carried out in many URLs as described in Section 4.4, give significant input to simulate heat flow processes taking place during the thermal phase of the repository operation.

Another important model to consider is the hydrogeological model. It is of key importance for the evaluation of the transport and retention of radionuclides in the geological barrier. It describes the permeability distributions in the different lithological units and discontinuities and, taking into account hydraulic gradients, it allows for a qualitative and quantitative assessment of groundwater (and gas) transport in the rock. In fractured media, input to this model is obtained by mapping in detail all groundwater inflow zones, if any, in the URL gallery system.

The hydrogeological models for practically impermeable rock salt, or for plastic clays where groundwater is assumed to circulate through the rock pores only (and not on discrete discontinuities) are not too complex. Those models describing the groundwater movement through indurated clays are in preparation to help answer key questions related to the possible occurrence of advective groundwater flow through discontinuities and the expected impact with regard to the groundwater flux. The models for hard rocks, like granite or tuff, where groundwater flows through an interconnected system of discontinuities referred as the water conducting features with very heterogeneous transmissivity distributions, are much more complex.

The hydrochemical model describes the physico-chemical and isotopic composition of the groundwater in the rock pores and the discontinuities, and their possible evolution with time. The above mentioned information regarding geological and hydrogeological models together with physico-chemical and isotopic analyses from water samples (collected from the water-conducting features or extracted from the pore) are the main input for this model. Hydrochemical conditions and their evolution are of major importance for the behaviour of the engineered barrier system (e.g. corrosion resistance of canisters, solubility of radionuclides eventually released into the geosphere). For clay formations, this model may also help improve the understanding of diffusion processes that have occurred in the past.

Last but not least, the radionuclide transport model, which has to describe the radionuclide movements in the rock mass, needs to be elaborated. It is based on all the above mentioned models and requires integration of hydrogeological, geochemical and transport processes.

Among the advantages of a phased approach to URL development (siting, surface-based characterization, excavation and testing) is the possibility to iteratively develop, test and further refine all the above mentioned models, notably through comparison of 'blind' modelling predictions with observations.

4.2.2. Tracer testing

As previously mentioned, understanding, testing and modelling radionuclide transport through the geosphere encompass the whole set of site data. URLs considering either radionuclides or surrogates to perform in situ tracer experiments in close to real conditions are of course essential for the development of models with regard to radionuclide transport. This is the reason why it has been chosen to focus the examples given in this section on tracer transport experiments (see [34] for a more comprehensive overview of in situ tracer experiments).

It should be stressed that, in fractured media, in situ tracer experiments requires a detailed hydrogeological and mineralogical characterization of the water conducting feature that is being tested. Therefore, many major experiments have been carried out in the last twenty years in different URLs in fractured rocks in order to characterize such features [35].

Migration tests are carried out at Mol to study the diffusion of actinides and fission products in the Boom Clay Formation. The results of these large scale tests, some of which being carried out for several years, confirm the fact that transport in Boom Clay is diffusion-controlled [24]. The role of organic matter on the migration of radionuclides is under investigation using ^{14}C labelled organic matter in a large-scale 3D experiment, quite similar to those in progress for tritiated water or ^{14}C labelled bicarbonate [36]. At Mont Terri adiffusion experiment started in a packed off borehole in 1998 with tritium and iodine.k by overcoring, the tracer distribution in the core will be analysed.

A series of multiphase tracer tests were conducted in the granitic rock that intersected a drift on the 360 m level of the Stripa mine [37]. At the Canadian URL, in situ programmes to study the migration of radioisotopes in highly fractured rock and in moderately fractured rock were also undertaken [18, 38]. These experiments provide, on the one hand, estimates of the physical solute transport properties of natural fracture zones and, on the other hand, a test of the suitability of the porous media equivalent method for modelling solute transport in moderately fractured rock.

At Äspö HRL, a programme has been defined for tracer testing at different experimental scales, the *T*racer *R*etention *U*nderstanding *E*xperiments (TRUE) [39]. The overall objective of the experiments is to increase the understanding of the processes that govern retention of radionuclides transported in crystalline rock and to increase the credibility in the computer models for radionuclide transport which will be used in licensing of a repository.

The migration experiment (with non-sorbing and reactive radionuclides) in a shear zone at the GTS allowed notably to increase significantly the confidence in the validity of solute transport models used in safety assessment and to demonstrate the existence of a significant diffusive component in the transport (i.e. 'matrix diffusion') [21, 40]. For the purpose of this experiment, a method of sampling of the shear zone based on resin injection had also been successfully developed.

At Olkiluoto, tracer tests have been performed between boreholes and pilot full-scale deposition holes drilled from the Research Tunnel. These tests, coupled with hydraulic characterization, give indications of flow in sparse and narrow channels and transport processes where the dispersion is time-dependent [41].

At Busted Butte near Yucca Mountain where it is of particular importance to understand radionuclide transport in bedded tuffs, the use of radioactive tracers was not allowed because of local regulations. As an alternative, several non-radioactive tracers were selected for use as surrogates after comparative testing in conventional laboratory environment [42]. These tests have contributed to refining the site scale unsaturated zone transport model for Yucca Mountain [43].

To study the dominant transport processes occurring at different spatial and temporal scales in the tight, low porosity and very low water content argilites at the Tournemire Research Tunnel, naturally present isotopic tracers (both from the solid matrix and from the interstitial fluid phase) have been used. These studies, supported by a comprehensive hydro-mechanical (e.g. swelling) and mineralogical characterization of the rock have highlighted the key parameters, and their couplings, that govern fluid transfer processes and demonstrated that diffusion is the main one [44].

Another series of in situ experiments relate to transport properties of the geosphere, and in particular to the geochemical buffering capacity of the rock, even if tracers are not directly used. Among these is the block scale redox experiment that was carried out in a fracture zone at 70 m depth in the entrance tunnel at Äspö HRL. In spite of massive surface water input, the fracture zone remained persistently anoxic. The main conclusion from that study was that the increased inflow of relatively organic-rich shallow groundwater, instead of adding dissolved oxygen, added organic compounds that acted as reducing agents in the deeper part of the fracture zone. These conclusions are specific to this particular fracture zone, experimental conditions and the time scale (3 years) of the experiment, but are probably also relevant for other conductive fracture zones [45]. The detailed scale *R*edox *EX*periment (REX) also at Äspö HRL is focusing on the question of oxygen that is trapped in the tunnels when the repository is closed [46].

4.3. Characterization of the host rock disturbed by excavation and testing

The characteristics of the geological barrier may change in the immediate vicinity of the repository, often called near field, caused by the excavation of underground facilities and even the access boreholes required for the installation of testing and/or monitoring equipment.

During and after excavation of an underground facility, the rock, due to stress release, expands into the cavity, resulting in the formation of a so-called excavation disturbed zone (EDZ); that may create, under certain conditions, an interconnected fracture system. This zone may have a significantly enhanced hydraulic conductivity that may lead to groundwater flow along the tunnel wall. As EDZ has been recognised in most types of host rock, its characterization, understanding, modelling and minimization have been key aims addressed by many major experimental programmes in URLs. The excavation of underground facilities often leads to a groundwater gradient towards the openings, which disturbs the natural groundwater flow field. Groundwater from overlying formations with a different chemical composition may potentially flow into the openings. During the long time period of repository operation, this groundwater may even influence by mineral dissolution the transmissivity of water conducting features. Therefore, in many URLs the hydrochemical evolution of the inflowing groundwater has been monitored. It was also noticed that not only chemical but also mechanical factors could explain the existence of tight fractures at repository depth, especially in argillaceous settings [47]. For these lithologies, it has further been noticed that, when the hydraulic conductivity in the EDZ is significantly enhanced, the presence of swelling clay minerals and/or creep may lead to a self-healing of the fracture system with time, through resaturation after repository closure. The on-going EDZ self-healing experiments address this question for indurated clays at Mont Terri URL. Such self-healing behaviour was also noticed around the HADES-URF in soft clays.

An overview of most important EDZ experiments in hard rocks is given in [48]. Some typical examples are given below. A discussion concerning EDZ minimization is given in Section 6.2.

In the Olkiluoto Research Tunnel, an evaluation of the quality of the full-scale pilot deposition holes, and in particular the EDZ, was carried out using two novel methods, the He-gas method (for diffusion measurements) and the ^{14}C-polymethylmethacrylate method (for porosity measurements) [49, 50]. It was found that the porosity of the rock in the disturbed zone was clearly greater than the one of undisturbed rock to a depth of about 11 mm. The values of permeability and effective diffusion coefficient in the EDZ were found to be approximately one order of magnitude higher than those of undisturbed rock. The perturbation caused by the drill and blast excavation of the research tunnel itself is also being analysed [50].

In the Canadian URL, a mine-by experiment was conducted to study progressive brittle failure and the development of an EDZ around a tunnel mechanically excavated in high compressive stress regions. V-shaped notches developed in the tunnel with intense fracturing and crushing of the rock over some tens of centimetres [51]. As these zones would be the locations with the greatest potential to contribute to contaminant transport, their hydraulic connectivity and their transport properties were also tested. The hydraulic connectivity of the EDZ created by blasting was compared to the EDZ resulting from stress redistribution around the mechanically excavated tunnel. The latter showed a small zone of hydraulically connected fractures that potentially extended over the entire length of the excavation and demonstrated the necessity to interrupt such hydraulic pathway by keying a low permeability bulkhead through the EDZ [18].

At the GTS, the EDZ around a tunnel excavated by blasting has also been intensively investigated. To facilitate interpretation, the tested area was selected in a relatively homogeneous and weakly naturally fractured part of the granitic massif. To cope with the potential anisotropy of the EDZ, a series of boreholes with various orientations were used. Among the methods performed, at a metric scale, are the analyses of shear seismic wave and, at the milimetric scale, the direct observation of microfissures with the help of resin injection. A new modular mini-packer system (MMPS) was developed for the hydraulic testing of the EDZ. This system, which can be performed in small diametre borehole, allows multiple configuration of testing of small portion of the rock [21]. A significant effort has also been made in Äspö to understand and minimize the EDZ in granitic settings in the framework of the ZEDEX experiment (see also Section 6.2).

Mine-by tests [52] were not only performed to allow for a qualitative and quantitative assessment of the EDZ in various media, but they are also the basis for the elaboration of coupled hydro-mechanical models. In particular, this type of test allows a comparison of blind model predictions with in situ observations [53].

Experiments were also required to test and confirm geomechanical models, especially concerning the creep behaviour of some sedimentary rocks. In particular, salt exhibits creep which are sensitive to climate change (moisture, temperature) and induces stress redistribution around openings [54]. As a result, an apparent transient phase can last several years or decades and the frequency of data acquisition for ambient air parameters has to be high.

It could be concluded that the intensive experimental programmes carried out in URLs have significantly help understand the mechanisms and processes responsible for the creation of an EDZ (especially from a mechanical point of view) and allowed to optimize excavation techniques.

4.4. Characterization of the host rock disturbed by waste emplacement

When the disposal facility becomes operational, new processes are taking place. We are not considering here the potential impact of the ventilation of galleries and their associated hydraulic transfer that will be dealt with in Section 6. We are here addressing the impact of:

(1) Temperature of heat-emitting waste or spent fuel;
(2) Radiation, depending on the waste/spent fuel package design;
(3) Gas produced by the anaerobic corrosion of metals, radiolysis or microbial activity;
(4) The introduction of materials (construction, backfill, buffer, seals) likely to affect the alkalinity of the host rock and its retention properties.

4.4.1. Heater tests

Heat emitting waste may change locally the properties of the rock. Especially in clay formations with a rather high water content (5 to 25 weight %) or in permeable fracture zones in crystalline rocks, heat may drive significantly groundwater and gas flows and consecutively also change the thermal and mechanical properties of the rock.

In many URLs heating experiments have been or are being carried out to allow for process understanding, parameter evaluation and model testing. Such type of experiments was performed in Stripa, Asse, GTS, Yucca Mountain ESF, WIPP, Canadian URL, HADES-URF etc. In general, such tests pointed out a good understanding of the phenomena, the suitability of most of the instrumentation and the site specific response of the rocks. The thermal coupling magnifies the transient phase and the discrepancies with models because of the uncertainty concerning the parameters. In crystalline rocks, an evaluation of aperture change of fractures and the subsequent modification of hydraulic behaviour induced by the thermal dilation of the rock mass is needed for safety assessment purposes. The importance of the effects is related to the size and characteristics of the fracture pattern and the magnitude of the heat release. A pertinent experiment should involve enough fractures to be representative of the applied thermal load.

In situ heater tests have been performed at the Canadian URL [55] as well as extensive monitoring of the geomechanical and hydrological response in granite under thermal load in the framework of an integrated near field experiment [56]. These tests also allowed demonstrating the minimal effect of thermal loads on the extension of the EDZ in highly stressed rock (see Section 4.3) [18]. Also in a granitic environment, the heater test performed at the GTS showed that the reactions of the crystalline rock remain locally confined and that thermo-induced hydraulic effects are of short duration [57].

At Yucca Mountain, fully coupled thermal-mechanical-hydrologic-chemical drift scale heater experiments are carried out in a comprehensive programme that considers the concept of start small and then move to larger experiments. The same consideration is used regarding complexity; start simple, learn, and then get into the more complicated experiments that may reveal the effect of coupled processes. The large scale drift scale test was started after core and small blocks had been thermally tested in the laboratory, a large 3 × 4 m free standing block was tested and a single heater test in the Yucca Mountain/ESF was conducted [58].

Several of these heater tests also considered buffer/backfill materials in the framework of large scale integrated experiments (e.g. BACCHUS, BAMBUS, Buffer/Container Experiment), as discussed in Section 5.4.

In this framework, it is worth mentioning the ongoing international modelling exercise known as DECOVALEX (*DE*velopment of *CO*upled models and their *VAL*idation against *EX*periments in nuclear waste isolation), considering thermo-hydro-mechanical – THM – coupled process models in hard rocks [59].

4.4.2. Radiation effect

With regard to radiation effects, one of the few tests ever performed with radioactivity is the CERBERUS test at the HADES-URF [60]. This test, installed in 1988, simulated the near field effects in an argillaceous environment of a vitrified HLW canister after 50 years cooling time. The gamma activity of this canister was simulated during 5 years using a ^{60}Co source. Two heaters were dissipating each 365 W. The total absorbed dose at the canister wall reached 17 MGy and temperatures up to 120^{o}C were recorded. Some conclusions could be drawn from this test:

- The behaviour of microcracks confirms the self-healing behaviour of the Boom Clay;
- The physico-chemical conditions have not yet evolved after the 5 year duration to strongly oxidizing conditions (pH neutral, Eh still reducing);
- Oxidation of pyrites is affecting water composition.

Species relevant for the integrity of near field were detected (e.g. thiosulphates for corrosion of metals, small organic anions for radionuclide complexation, boron or silicate chemistry for glass matrix corrosion).

Radiation effects in rock salt (e.g. defects in the NaCl lattice, decomposition of fluid inclusions) have been mostly studied in surface laboratories. An in situ irradiation experiment was planned in the Asses salt mine but canceled due to licensing uncertainties [61].

4.4.3. Generation and migration of gas

The disposed of waste and its containers may produce significant amounts of gas by various processes (radiolysis, corrosion and alpha decay). The produced gas has, if generated in sufficient amounts, to escape from the repository area. In very low permeable formations as rock salt and clays, a free gas phase may form in the repository and may lead, in case of overpressurization, to rock fracturing and the potential formation of new groundwater flow paths. A recent report gives a very comprehensive overview of the experimental evidences and current understanding of gas generation, accumulation and migration in repository conditions [62]. Only some examples of results of in situ experiments are given here.

In the context of the low permeability Boom Clay, an experiment (MEGAS) has addressed this question in the HADES-URF. A long-term in situ gas injection test followed by a tracer (tritiated water) injection showed that when a preferential gas pathway is created, it heals very rapidly and does not constitute a preferential path of migration once radionuclides are released. The geomechanical control on gas pathway formation was also investigated [63]. The results of this experiment may also be transferred to gas flow in bentonite-based backfill and buffer materials.

The GAM experiment at the Grimsel GTS is aimed at investigating solute and gas migration processes in a single fracture (shear zone in a granitic environment), which is characterized by a heterogeneous internal structure [64]. The GAM experiment should allow the development and testing of consistent conceptual/numerical models for single-phase solute transport and two-phase flow gas transport. It consists of four components:

- Solute, particle and gas tracer tests in the shear zone;
- Visualization of in situ tracer experiments using high frequency, ground-penetrating radar techniques;
- Laboratory experiments with core samples;
- Integrated interpretation of laboratory and field results.

4.4.4. Chemical effects

The waste forms and the engineered barriers may react with the groundwater and change its composition. High alkaline waters from cement leaching and/or concrete backfill may lead to leaching of minerals, precipitation of new ones, porosity and permeability changes, etc. But oxidizing waters may also change the solubility of radionuclides and the speciation of some critical elements. Radionuclides may sorb on organic acids leached from bitumen waste and then be transported with the mobile fraction without significant retardation. Such questions are currently addressed in URLs programmes when designing in situ migration experiments.

In the radiation controlled zone of the GTS a high-pH plume (HPF) experiment is currently being performed. The HPF is aimed at assessing the effect of high-pH leachates (from cement-based materials) on the fractured granitic rock and on the retardation behaviour of radionuclides under realistic, in situ conditions [65]. This test should also provide a link between existing laboratory data and natural analogue data.

Some examples of in situ experiments related to the potential effects of change in the redox conditions were given in Section 4.2.2.

4.5. Concluding remarks

Experiments in URLs allow an understanding of the characteristics and processes affecting radionuclide transport through the geosphere. They also enhance the ability to evaluate the role of a formation as a geological barrier. Not only the undisturbed geological barrier, but also the changes induced in it by the construction and operation of the underground facility have been assessed by many different and integrated experiments. In an URL, boundary and experimental conditions can be representative of repository construction and operation and are then suitable to properly observe such disturbances and their evolution with time.

From the point of view of the overall assessment of the perturbations induced by excavating an underground facility and emplacing waste in it, recent or planned URLs programmes (e.g. Äspö HRL and Sellafield RCF) have put strong emphasis on the establishment of the initial geological conditions prior to any excavation work and on the prediction of host rock behaviour during and after excavation and (dummy) waste emplacement. Comparison of model predictions with in situ observations constitutes a key aspect of confidence building in the models used [66, 67].

Many of the current experiments are in a long term monitoring phase and relevant results normally will be available only after several years. The long term duration necessary for these typical time-consuming, tests should be carefully considered before planning any new major URL testing programme.

The URL becomes more and more a catalyst for initiating the iterative interactions between those responsible for collecting site data and developing geoscientific models, and those responsible for abstracting and integrating this information into the safety assessment. Experimenters and analysts must continue collectively to refine the models and parameters that will be used in the safety analysis. Some parameters required by safety assessment specialists, to properly exercise their models, may not still be directly measured in URLs because of limitations in technology or because of dependence with other measurements. For example, a groundwater flux must be inferred from measurements of hydraulic head and hydraulic conductivity, usually through the application of a groundwater model. Regardless, the development of the conceptual models and their representation in mathematical models for safety assessment calculations require first a cohesive team that ensures the essential elements of the detailed process models are embedded within this assessment.

5. USE OF URLs FOR ASSESSING THE ENGINEERED BARRIER SYSTEM

5.1. Introduction

In many geological repository investigations, the URL, either generic or site specific, is used as a test bed for the emplacement of the engineered barrier system (EBS) and the study of its various components. The most important processes studied include the degradation of isolation and containment properties due to interaction with water, and the evolution of chemical properties linked to the behaviour of the different components of the disposal system. Critical factors include waste form alteration, canister corrosion, backfill, seal and buffer materials performance.

Testing EBS in an URL is often quite advantageous as one can integrate several types of studies at a relevant scale and in repository relevant conditions. For instance, a dummy canister with enclosed heating elements, to simulate the heat of radioactive decay, can be placed within the proposed buffer, to integrate in a real environment, canister corrosion and buffer performance studies. The engineered barrier system and the natural barrier system can then all be instrumented and monitored. Such tests are often preliminary to larger, full-scale demonstration tests as discussed in Section 7.

Increasingly in situ testing of EBS or of specific EBS components is focused towards acquiring parameters that are of direct use for safety assessment. These tests contribute to better system understanding as well as to confidence building in the processes considered and the numerical models used. Inversely, safety assessments, and in particular, sensibility studies, can reveal the key processes and/or parameters to be tested in priority. The EU-funded safety assessments EVEREST and SPA have for instance allowed defining further in situ data and basic research requirements. These requirements constituted one of the rationales for designing some current experimental and demonstration projects like FEBEX (demonstration of canister emplacement in granite — see Section 7.3), RESEAL (sealing of shaft in clays — see Section 5.4) and BAMBUS (backfilling of drift and galleries in rock salt — see Section 5.4) [68].

5.2. Waste form alteration

Determining the compatibility of the waste forms with the disposal environment must notably consider the generation of gas, the swelling of the waste forms due to interaction with water and leaching, the release of chemicals likely to affect the near field, the corrosion rate of the container material and waste matrix and the soluble fraction and speciation of the radionuclides that may be released. Due to frequent restrictions on testing radioactive materials in situ, matrix-leaching experiments are generally, but not exclusively confined to above ground, strictly controlled access, laboratories. Likewise, experiments that require carefully controlled boundary conditions are less suited to underground laboratories and should be performed in a surface laboratory setting. At some stages of research however, tests can be conducted underground in accordance with local regulations.

In Belgium, for instance, a new test array using an alpha-active glass is being implemented in the HADES-URF. The overall objective of the CORALUS test [69] is to study the performance of active glass specimens in direct contact with backfill materials from different compositions, under conditions as representative as possible for those expected to prevail in a geological repository in the Boom Clay formation.

5.3. Corrosion

Corrosion of canister (and/or overpack), material can be initiated by several processes to include irradiation, bacterial activity, and the physical chemical conditions created by the host rock. Perhaps the most corrosive host rock environment is salt. Corrosive tests of canister materials in salt formations have been carried out in the Asse mine and at WIPP.

It is commonly known that irradiation can affect the material properties [70]. Mechanical and metallurgical properties of stainless steel can be affected by embrittlement that is caused by intergranular attack that depletes chromium at grain boundaries. The environment chemistry also may have a detrimental effect on the corrosion behaviour of the metal. In this context, in situ corrosion tests are only part of a larger programme supported by surface laboratory tests.

Tests were previously conducted at the HADES-URF on carbon steel up to 7.5 years indicating e.g. that corrosion proceeds mainly by pitting attack in the aerobic phase and congruent corrosion in the anaerobic phase. This supports further the importance of well-controlled boundary conditions.

Testing of a combined canister-buffer system in fractured crystalline rock has been performed at the Stripa URL. In that case, pre-fabricated blocks of compacted bentonite were used to fill the void between the canister and the rock. In order to simulate the conditions of the repository properly, the canister was heated [20]. A continuation of canister-buffer system tests of the type conducted at the Stripa project has been undertaken at Äspö [71]. The test is aimed at:

- Decreasing the uncertainties regarding time needed for buffer re-saturation;
- Validating models concerning buffer performance and degradation processes;
- Studying bacteria activity;
- Determining nature and extent of possible copper corrosion;
- Determining gas breakthrough pressure and gas conductivity;
- Being used as a pilot for a planned full scale test.

5.4. Backfill, buffer and seal materials

Regarding backfill, buffer and seal materials, in situ investigations started in the 1980s with the *B*uffer *M*ass *T*est (BMT) in the Stripa mine. This test was developed to examine experimentally the phenomena and processes related to plugging with clay materials the excavated volume remaining around the heat-generating waste containers. Once the feasibility was demonstrated, the BMT was expected to contribute to improving repository design and understanding of ongoing processes. The highly compacted bentonite used as buffer in the BMT was prepared by isostatic compaction of MX-80 bentonite to a rather high dry density. Mixtures of sand and bentonite were foreseen to backfill access tunnels. The buffer material surrounding the container can exert ultimate pressures as high as 10 MPa [72, 73].

In clay formations where the retention role of backfill is less critical than for hard rocks, similar clay-based materials are also considered as buffer around the canister or to fill in sections of galleries. Swelling pressures as high as those of the commercial MX-80 bentonites in hard rocks may not be required because of the geological context and, therefore, the re-use of clay cuttings from the excavation of the underground facilities, could be considered providing no oxidation takes place during the re-conditioning phases. For the time being, running tests at different scales are using well-characterized clay materials. In HADES-URF, the BACCHUS 2 test was developed to test a mixture of high-density pellets and powder, first in a vertical configuration [74, 75]. The installation procedure, materials and techniques used are close to realistic industrial processes and capabilities. The detailed follow-up of the hydration process will be used to gain confidence in the application of the hydro-mechanical model for unsaturated clay-based materials. After full saturation, the experimental set-up is used for further testing, like the in situ measurement of hydraulic conductivity and gas migration. In a similar context and at a larger but not full scale, a more recent project on repository sealing is carried out in the same URL (RESEAL project). It consists of installing, using semi-industrial techniques, a seal plug from an exploratory shaft, 2 m in diametre, and of demonstrating the gas and water tightness of this seal. Its mechanical stability will also be checked under accidental overpressure conditions. The material used in this context is quite similar to the granular material used in the BACCHUS 2 experiment [76].

At the Yucca Mountain ESF, the drift scale test made an initial step in the direction of EBS testing. Although the simulated waste canister was constructed of conventional materials (the current disposal concept does not include buffers or backfill), the canister dimensions and spacing approximated a possible repository system scenario. Additionally, typical rock support systems to include rock bolts and mesh, and a cast-in-place concrete lined section were included in the drift [77]. Sample coupons of a variety of potential waste package materials were included in the heated drift. The primary objective of the drift scale test is the understanding of the coupled processes of heat, hydrology, chemistry and mechanical changes. However, the ability to add some engineered barrier realism to the test may often provide valuable information at minimal cost to the test programme.

The BAMBUS project (*Ba*ckfill and *M*aterial *B*ehaviour in *U*nderground *S*alt Repositories) in the Asse salt mine, was aimed at improving the understanding of the behaviour of backfill and seals in a repository in rock salt [78, 79]. The test was performed between 1996 and 1998 and supported by surface laboratory experiments on crushed salt backfill and further development of process and numerical models. Another essential aspect of this test is the determination of gas generation and release from the backfill (gases primarily present in the rock salt and newly formed gases generated by thermally induced processed). It comprised 3 large scale underground experiments under near reference disposal conditions:

1. The TDSE (*T*hermal *S*imulation of *D*rift *E*mplacement) focused on the thermomechanical response to drift emplacement of spent fuel assemblies. In this concept, disposal casks (Pollux) are to be emplaced on the floor of drifts backfilled with crushed salt. For the TDSE, 1/1 scale electrically heated mock up were used [80];

2. The DEBORA 1 and 2 experiments (*De*velopment of *Bo*rehole Seals for High-Level *Ra*dioactive Waste) were conducted to investigate the performance of crushed salt as backfill and seal in a borehole to be used to dispose of reprocessed waste canister.

Significant improvements were achieved in the understanding of the processes to be expected in an underground repository for heat generating waste in rock salt. By performing in situ experiments as well as laboratory tests, the database on important phenomena in crushed salt backfill was increased and relationships between significant parameters were obtained. The material laws and computer codes for predicting the repository performance were developed further to a status that allows predicting some of the processes with high accuracy and others with a high degree of confidence [81].

The influence of the presence or absence of crushed salt as backfill material around reprocessed HLW emplaced in disposal borehole in rock salt was also studied in the Amelie mine [82]. This test demonstrated notably that the presence of an empty annular space in the disposal borehole severely complicates the heat transfer situation. A space filled by a granular material such as crushed salt appears to be a favourable solution, since the thermal properties of the backfill material increasingly improve with compaction, the latter being assured by the convergence of the borehole walls.

In the German repository concept, dam construction used for sealing waste emplacement drift represents an essential component of the multibarrier EBS. Among the dam component the seal is responsible for the long term tightness of the system. The DAM project was aimed at testing and improving the technical feasibility and material behaviour under the influence of gas or brine. For these purposes, a 1:1 scaled test was planned in the Asse salt mine with a dam consisting of concrete abutments and of a salt briquette seal. This test was stopped before implementation. However, despite this cancellation, the DAM project allowed to better characterize (laboratory investigations) potential materials to be used in dams and seals [83, 84].

5.5. Concluding remarks

The components of the engineered barrier system and some of the processes important for isolation can be tested in either generic or site specific URLs.

Increasingly in situ testing of EBS or of specific EBS components is focused towards acquiring parameters that are of direct use for safety assessment. These tests contribute to better system understanding as well as to confidence building in the process considered and the numerical models used.

The given examples demonstrate the complexity of the processes governing the behaviour of engineered materials in natural conditions. Even if most of the presented tests concern a limited number of materials/interactions, they clearly show the importance of the interactions between the various components of the EBS and between the EBS and the host formation. To minimize artefacts and help data interpretation and process modelling, such tests should be undertaken prior to larger full scale demonstration tests.

6. USE OF URLs FOR OPTIMIZING REPOSITORY CONSTRUCTION TECHNIQUES

6.1. Introduction

Because URLs, both generic and site specific, often involve major underground excavation, lining, ventilation and operation, they can be used to optimize future repository construction techniques. Retrievability requirements addressed for waste disposal by some countries further enhanced the need of such investigations.

The construction of an URL can be considered, in itself, as a major integrated experiment. The shafts, ramps, galleries, drifts and other excavated openings allow an examination of the vertical and horizontal variability of the geological formations, a testbed for major in situ experiments and a first observation of the large scale impact of the excavation on stability conditions. In most cases, the impact of the excavated disturbed zone (EDZ) requires special attention with regard to the nature and thickness of the host formation, the reference concept and/or the safety/performance assessment studies (see also Section 4.3).

6.2. Excavation

Before building important and costly underground facilities, the systematic development of reconnaissance galleries should be considered in order to evaluate geotechnical conditions such as rock stability or convergence or swelling in case of clay formations and to verify design calculations. Understanding the stability of underground openings is not only important for the testing and development programmes but also the long term operation and possible pre-closure periods. These periods may extend for decades until a regulatory requirement is met or a point in time when society decides it is safe to close and seal an operating and/or monitored repository.

During excavation of URLs, typical layouts and dimensions for waste disposal vaults and galleries can be tested. These openings can be used for testing the site specific geological, hydrogeological and mechanical conditions as well as for assessing the impact of excavation techniques on the rock. In current practice in existing URLs, several excavation techniques have been tested and optimized. These include drill and blast, smooth face blasting, full face tunnel boring machine, road header, pneumatic hammer-based machine, and the raise boring technique. Some examples of the use of these techniques in an URL context are provided below.

In the ZEDEX experiment in Äspö, two parallel drifts have been excavated, one with a tunnel boring machine, the other one using blasting. The effect of the different excavation methods on the disturbance of the rock and the extent of the EDZ has been evaluated [85]. The research gallery and niches at Mont Terri were excavated with different excavation techniques (blasting, road header, pneumatic hammer) and the benefits of each method are currently being assessed [86].

When shaft sinking of the HADES-URF started in 1980, it was not certain at all that excavation of galleries in deep clay was feasible. After testing various techniques including freezing at increasing scales, it became apparent that the feasibility of excavating a large diametre gallery in virgin, soft clay was feasible and practical. The extension of the HADES-URF for the PRACLAY project has provided the opportunity to develop a mine-by test in relation to these new excavation works, the CLIPEX project [87]. These results can be extrapolated to other similar deep clays in such a way that the need for other mine-by tests could be reduced in the future.

Successful demonstration of the possibility to bore full scale deposition holes for spent fuel in granitic environment was achieved in the Research Tunnel in Olkiluoto (VLJ repository) using a novel dry blind boring method [49, 88].

6.3. Lining and ventilation

Most underground excavations, regardless of their ultimate purpose, i.e. testing, transportation tunnels, mines or nuclear waste repositories generally require certain degrees of rock support to maintain the stability of the opening. This support can range from very limited rock anchor approaches in massive stable granites or other hard rock to complete lining of excavation walls in less mechanically stable formations, especially the ones presenting significant convergence just after excavation.

In conventional i.e. non-radioactive waste related facilities, the installation of support measures is often a matter of cost or convenience. Maintenance, repairs, and replacement can often be reasonably accommodated. In radioactive waste repositories however, additional considerations must be addressed. Before closing and sealing a repository, at least a part of the gallery system may be open for many decades. This period may be much longer than the normal life of typical support and lining systems. Additionally, the very nature of the support and lining materials such as concrete cements and iron based metals may strongly influence the long term performance of the whole repository system. This occurs as the initially isolated waste form comes into contact with the surrounding environment once the waste packages deteriorate and excavated openings degrade [89].

At HADES-URF, the interaction between the lining and the clay host was extensively investigated, depending on the construction technique. The knowledge gained regarding the stress field through convergence/confinement surveys in the different construction phases of the URL allowed a change from very stiff cast-iron segments to other alternatives. A 1.2 m thick concrete lining designed in the preliminary phase, evolved to a 45 cm thick concrete lining. In some well-defined conditions even sliding steel ribs or shotcrete can be used as primary lining [90].

At Mont Terri, all galleries and niches are lined with shotcrete, reinforced with steel fibres. According to the Swiss waste emplacement concept in hard clays, it is foreseen to line the disposal galleries with steel grids only (to avoid the use of concrete and resulting high pH waters). It is planned to test this alternative lining technique in a full-scale experiment.

Ground support in underground openings provides the necessary stability for worker's and user's health and safety. Companion to the ground support is the ventilation system that provides the clean, fresh air. In radioactive waste repositories ventilation may take on an additional role, helping to keep the temperature of the underground facilities at such a level that openings remain stable and the performance characteristics of the natural environment are not altered. Additionally, heat build-up can be detrimental to waste package materials, buffers, backfill and spent fuel cladding which often forms the first line of defence against radionuclide release to the environment. At Yucca Mountain ESF the ventilation of the underground facilities has been considered as part of the near-term performance of the repository system [91].

An indirect consequence of ventilation is the possible desaturation of the host rock and associated desiccation features, especially in argillaceous formations, through hydraulic transfer with the ventilated underground excavation. In this context, recent results of URL experiments show that the main effect of ventilation on the near field is the contamination by oxygen of the host rock and its geochemical consequences. Change in the mechanical behaviour of clay due to the strong hydro-mechanical coupling was the purpose of the PHEBUS experiment developed at HADES-URF. This 'ventilation' test also gave a good estimate of the macro-permeability of the surrounding rock, which is usually a rather difficult measurement in such argillaceous settings [92]. Similar developments are running at Tournemire and Mont Terri URLs.

6.4. Concluding remarks

Excavation, lining and ventilation techniques can all be tested and developed in either generic or site specific URLs with results that may have broader implications than initially expected in the whole development of geological repositories. These results can be applied to:

- Optimize the design and the layout of the gallery system of a repository;
- Optimize the excavation programmes, techniques and time schedules;
- Assess the stability of the gallery system of a repository over the very long times of operation, monitoring and retrievability, required for regulatory purposes;
- Assess the potential deleterious effect of introduced lining materials on the long term performance of the repository system;
- Assess the various effects of ventilation, removing heat such that the performance of natural barriers is not adversely effected;
- Assess the effects of desaturation of rock by ventilation.

As previously mentioned in Section 4.3, the excavation experiments carried out in URLs have significantly help reduce the extension and consequence of the excavation disturbed zone.

7. USE OF URLs FOR DEMONSTRATING REPOSITORY OPERATIONS

7.1. Introduction

As it is the case for many industrial facilities and processes, repository systems need to be tested under realistic conditions. This often starts with the testing of individual components (see Sections 3–5), and preferably evolves to testing operation of an integrated repository system. This is very important because the entire integrated system will need to function correctly underground. As part of any waste disposal research and development programme, an URL can be used to demonstrate that waste can in fact be emplaced, backfilled in situ and retrieved if necessary. We need to show that the repository as planned could be constructed and operated in the deep geological environment and that it meets the required performance safety standards and any requirements with regard to retrievability based on individual national programme regulation and policy.

The purpose of a repository in a deep geological formation must be for disposal, not for intermediate storage. The IAEA Working Group on Principles and Criteria for Radioactive Waste Disposal noted in its second report [68]: "A geological repository is designed to provide long term safety without the need for retrieval of the wastes. However, provisions to ease any future retrieval are not precluded, providing that they do not impair the safety of the repository". Nevertheless, public reassurance could be achieved by demonstrating that hazards during disposal operations have been considered and that retrieval remains feasible.

Several URLs include demonstration projects as part of their R&D programmes. These range from simple single component demonstration of waste emplacement, backfilling or retrievability to large scale demonstration of an entire repository system. This section is mostly restricted to past, present and firmly planned full scale demonstration projects. These include Climax, FEBEX, PRACLAY, WIPP and Prototype Repository. WIPP is a site-specific programme (and currently an operating repository). Climax was located at a generic URL in granite. FEBEX is currently being carried out in granite at GTS. PRACLAY is still in a preparatory stage and will be located in the extension of the HADES-URF. The Prototype Repository is being carried out in granitic settings at the Äspö HRL.

7.2. Objectives of demonstration projects

A demonstration project should consider a broad range of topics that will include all major operational aspects of a proposed repository concept. These topics should include waste emplacement, backfilling/buffer and sealing, and retrievability; all fully integrated and suited to construction and operation in the deep geological environment. A major objective, however, is to "have a sufficient level of confidence that the repository system will satisfactorily perform its intended function of long-term isolation of the waste, and therefore final closure operations may begin" [94].

Waste emplacement: Usually in a generic URL it is not the intent to demonstrate the feasibility of the total waste package transfer sequence from the surface to the disposal level. The shafts and drifts are generally not tailored for that purpose. However, such a test is planned at Äspö HRL and was partly carried out at the Asses salt mine.

Waste emplacement operations in the proposed underground excavation, are a complicated operation and should be tested as part of a full scale demonstration. The test plan should be based on an actual repository disposal concept, including a selected host rock, i.e. Climax in granite, FEBEX in granite, PRACLAY in clay and WIPP in bedded salt. For country specific safety standards and legal management reasons the waste packages should be simulated by dummy-packages with the same size and weight. Depending on local regulations, sealed radioactive sources could also be considered. These packages, dummy or sealed source containers, should be handled by a prototype of the equipment intended for use in the repository.

Backfilling, buffer and sealing: In most repository concepts, the geological barrier will fully perform its function when backfilling/buffering of disposal galleries and sealing of shafts and drifts are well designed and efficiently constructed (see Section 5.4). It should however be noted that requirements allocated to backfilling, buffer and sealing materials may vary significantly from one repository concept to another. Demonstration experiments on backfilling, buffer and sealing are to show that:

1. The requirements could be achieved with materials and technology available today;
2. There is confidence in the long-term performance of the chosen materials.

The geological barrier will fully perform its function when sealing of shafts and drifts is well designed and efficiently constructed (e.g. with hydraulic, swelling and chemical properties required by the performance assessment). In many cases the geological survey from both surface and URL will give relevant information to performance assessment so that sealing zones would be appropriately located in the repository layout. Whatever the considered country, such a repository will not likely be closed for many decades. Experiments on sealing are to demonstrate that requirements could be achieved with materials and technology available today. The main points to consider are:

- Develop and demonstrate emplacement technology to ensure a good contact of the seal material with the host rock;
- Installation of lining in host rock formations to avoid instability during the seal emplacement;
- Seal material isolation properties that provide geochemical compatibility with the host rock with good ageing behaviour.

Retrievability: Retrieval of packages during the operating phase simply stated is how to handle and to get the waste packages out of the disposal facility. The same kind of testing as used for waste emplacement could be the answer. However, retrievability must also address other questions [95, 96] for example on:

- Which criteria the retrieval could be decided; which measurable parameters are relevant to retrieval, and how might these parameters be measured without impairing the safety condition with a good degree of confidence?
- What safety indicators might be observed that would warrant operational changes or require reinforcement of support/lining or even make the decision to backfill a disposal vault or gallery?

7.3. Full scale demonstration projects

One of the earliest examples of a full scale concept specific multicomponent demonstration project at a generic URL was the Spent Fuel Test – Climax. This project to demonstrate the technical feasibility of placing spent nuclear fuel in granite was located 420 m below the surface in the Climax stock granite at the Nevada Test Site. Facilities were constructed between June 1978 and April 1980. Spent fuel was emplaced until May 1980, and retrieved between March and April 1983. Post-test characterization followed retrieval of the spent fuel and the project as planned was successfully completed during 1985 [97].

At the GTS in Switzerland, the FEBEX (*F*ull-scale *E*ngineered *B*arrier *Ex*periment for a Deep Geological Repository for High-Level Radioactive Waste in Crystalline Host Rock) experiment was started in 1995. The main aim of the FEBEX experiment is to control the performances of the EBS in a realistic natural and repository environment. Two heater elements in full size dummy-packages where placed in a drift surrounded by blocks of compacted bentonite. The heat was turned on and the impact on the bentonite and rock is currently monitored by several hundreds of sensors [98]. The in situ FEBEX experiment is run in parallel with a mock-up surface experiment consisting of a fully instrumented cylindrical steel body with hydration and heating systems. The observations that are being made at the mock-up help notably improve in situ monitoring devices, understand measurements and support modelling exercises. In late 1999, DECOVALEX III selected FEBEX as one of the modelling tasks to be undertaken by several participating national waste management agencies.

The PRACLAY project is a demonstration experiment simulating the thermal output of a 30 m long high level reprocessed waste disposal gallery, 2 m in diametre, according to the reference repository concept in Belgium. The experiment will be installed from an extension of the existing HADES-URF, presently in the construction phase. It is a thermal-hydrological-mechanical experiment intended to demonstrate the feasibility of the disposal of heat-emitting waste in clay. A preliminary surface experiment consisting in a full scale mock-up representing a 5 m long disposal gallery is currently running and has already provided valuable feedback on the installation procedure, the backfill hydration and the sensors' performance in close to real conditions [99].

Another example of a full scale concept specific multicomponent demonstration project at a site specific URL was the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico. Development of this project began during the 1980's and included an extensive testing and demonstration programme in bedded salt 660 m below the surface in the Salado Formation [31, 100]. On March 26, 1999, it became the United States of America's first operating underground repository for defence-generated transuranic radioactive waste.

The rationale for the Prototype Repository at Äspö HRL is the need to test and demonstrate the execution and function of a deposition sequence of spent fuel with state-of-the-art technology (the sequence starts from detailed characterization of the host rock and ends with resaturation of the backfilled deposition holes and tunnel according to the KBS3 disposal concept). The test will as much as possible simulate a part of the disposal tunnel in the real deep repository. The objectives are to [101]:

- Demonstrate the integrated function of the repository components under realistic conditions;
- Provide a full scale reference for comparison with models and assumptions;
- Develop and test appropriate engineering standards, quality criteria and quality systems.

In addition, the methodology and equipment for encapsulation of spent nuclear fuel will also be tested as well as the possibility to retrieve a spent fuel canister.

It is also worth mentioning in this section the plans that were developed for a full scale testing of a disposal facility at the Asse salt mine in preparation of the construction and operation of a HLW repository in rock salt in Germany. The major objectives of this demonstration project were [102]:

- The development and testing of a handling system for the transport and emplacement of HLW canisters;
- The study of the thermomechanical response of the host rock to the emplacement of heat emitting waste;
- The study of the release of fluids from the salt by radiolysis and heating up.

In this framework, a handling system for the transport and emplacement of HLW canisters was successfully developed and tested before the demonstration project was stopped in 1992 due to licensing uncertainties. Also two non-radioactive heater tests were conducted during five years.

7.4. Concluding remarks

The importance of demonstrating that deep geological repository operational components (waste emplacement, backfilling, sealing and retrievability) are performing as an integrated system is a prerequisite to gain public acceptance and to meet required performance standards. Public acceptance may be further enhanced by incorporating concepts of reversibility and retrievability into national repository programmes to increase flexibility and be in accord with emerging ethical issues.

Demonstration projects are by definition time consuming and tend to be very costly at generic as well as site specific URLs. Many demonstration-type experiments do not have to be absolutely repeated at potential repository sites for their benefit to be realised. Consequently, experience from the URLs mentioned in this section may benefit the international community.

Such demonstration tests also greatly benefit (experimental set up, monitoring, modelling, artefacts, etc.) from mock-up tests that are carried out in surface laboratories under well-controlled conditions.

8. USE OF URLs FOR BUILDING CONFIDENCE AND FOSTERING INTERNATIONAL CO-OPERATION

8.1. Introduction

Among the roles generally dedicated to a URL, several were considered in the information provided by the previous sections:

- Tool for site characterization studies in a stepwise approach;
- Development of multidisciplinary research for demonstration and validation purposes;
- Demonstration and optimization of construction techniques.

A URL is also a ‘public relation’ facility allowing not only for visitors to gather visual information but also to get the opportunity for discussions with technicians and managers. This role of enhancing public confidence through involvement and even partnership is becoming more important with time to help the decision making process.

Furthermore, an URL is a framework and a unique opportunity to develop and stimulate beneficial international co-operative efforts. This international approach, developed accordingly to national policies and/or regulatory framework, has already been stressed in the previous sections.

8.2. Confidence building

Confidence building in the disposal option and the safety of a proposed repository system is a critical issue for the scientists, managers, stakeholders, regulatory authorities, decision makers and the public. A repository programme, to be successful, will require public acceptance. The role of the public in siting processes and more particularly in assessing the need for a URL will vary depending on the:

(1) Type and role of the facility being considered;
(2) Its location and timing;
(3) The socio-economic conditions within the host municipality;
(4) Existing regulatory statutes;
(5) The overall objectives of the scientific programme.

When the URL is being developed in a previously existing underground infrastructure (e.g. Stripa, Asse) where regulatory statutes preclude the continued development of a repository facility, strong public support is often present. The URL is viewed by the public as a R&D facility that provides employment, revenue, and training to the community without concern over the long term development of a permanent repository. A well-run URL facility adds to public trust and confidence and can facilitate the future development of the repository programme at other sites.

When the URL site selection process is proceeding in a manner similar to siting a repository but providing that regulatory statutes preclude repository development, public support is also generally strong (e.g. Äspö HRL, and the Lac du Bonnet URL). URLs of this type become a vehicle for building public trust and confidence in the technology and capabilities available to safely construct and manage a repository facility without the potentially adverse effects associated with a repository being constructed within the immediate vicinity.

When the URL is being developed at a potential repository site, the public response can be highly variable. As an example, in the USA, public support is significantly different at the two proposed deep geological repository locations containing URL facilities. At the WIPP, the Carlsbad community has been proactive in furthering the development of WIPP and the technologies associated with transuranic waste management. The community is actively involved in providing input to the project and assuring that all issues associated with long term health and safety considerations are properly addressed. The facility is recognised by those in the community as contributing to the socio-economic basis of the area and as a significant contributor to a technology base for training and employing local residents. At Yucca Mountain, the state of Nevada is strongly opposed to the long term repository project and continuously strives to stop all studies including those affiliated with the ESF. Trust between the community and the applicant is minimal and any socio-economic benefits are considered to be detrimental.

To develop an URL requires teaming between the applicant and all the stakeholders, including the public. The applicant must be open and candid with the community and involve them in decisions that are likely to impact the area for generations to come. This is essential at URL locations that could be intended (if ever found suitable) to become repositories. The applicant must seek to understand the public concerns and actively pursue activities to address their concerns. At Yucca Mountain, one of the goals of the strategic information programme is to "enable Nevada citizens to make informed decisions about the repository project", not to persuade them to take a particular position [103]. Large scale demonstrations of waste handling, emplacement and retrievability within an URL can often contribute to the confidence of the community. Without this confidence, a very suitable technical site may never be acceptable for further repository development.

In any case, it should be stressed that most, if not all, URLs in operation have an important 'public relation' programme (information, visits, etc.) and that they often constitute a significant 'show case' for the waste management organizations.

Furthermore, URLs constitute a unique tool to build confidence:

(1) In a national or international R&D multidisciplinary team;
(2) In the ability of a waste management organization to:
    - Run a major project;
    - Develop the techniques and methods that are necessary to dispose of the waste;
    - Assess the performances and safety of a particular disposal concept.

New scientific questions are addressed by many experiments in URLs and the results, which in many cases are published as open literature, are of high interest for the scientific and academic communities at large. Furthermore, URLs represent rather unique scientific and technical tools. Open scientific discussion of the methods used, and results gained, in URLs also contributes significantly to confidence building both within the waste disposal programme (peer reviews) and outside (fostering collaborative works, using URL for non disposal purposes, etc.).

8.3. International co-operation

In many URLs, some experiments may be carried out jointly by several organizations of different nations. Additional underground testing facilities can be built based on the needs of multiple individual initiatives combined together in an international project. This international co-operation may be very beneficial, not only for the involved scientists, but also for strengthening the contacts and discussions among the management of the involved organizations. For those countries which are starting to address the issue of radioactive waste disposal in geological formations, the joint participation in running experiments at existing URLs may be a unique opportunity to launch or resume close contacts with organizations which have been involved for many decades, and learn from the past successes, attempts and failures.

Most URLs have been initiated and are managed by national organizations that are or will be responsible on a national level for implementing and operating repositories for radioactive waste. These organizations plan and carry out the research programmes with the support of contracted national research institutes, universities and private companies. Most of these organizations have bilateral co-operation agreements with sister organizations of other countries and in this framework, co-operative experiments can easily be carried out. Some of the co-operative projects have a very large base like INTRAVAL [104] and DECOVALEX (see Section 4.3). Seal emplacement and demonstration projects also constitute co-operative activities to enhance worldwide expertise by establishing partnerships with several waste management organizations in USA, Canada, France, Germany and Japan [105].

The European Commission (EC) also significantly promotes international co-operation in URLs by co-financing experiments which are co-operatively carried out by organizations of different EU countries [14, 106]. Germany and Belgium are some examples of countries operating URLs that have had long term in situ experimental programmes in co-operation with the EC and EU partners.

In Switzerland, the Mont Terri URL is somewhat different in concept from other European URLs in that it is not managed by one national organization that is responsible for implementing repositories for radioactive waste. It is an international project, developed under the patronage of the Swiss National Hydrological and Geological Survey (SNHGS), where nine organizations of six nations jointly plan, steer and finance the entire research programme. According to the international co-operation agreement of this project, other organizations may join the project. Similar co-operative developments are expected at PRACLAY (Belgium).

8.4. Concluding remarks

URLs play a substantial role in developing and demonstrating advanced radioactive waste disposal technologies and are a significant step to the ultimate construction and operation of full scale geological repositories.

As discussed in the previous sections, confidence building and international co-operation are closely linked. Joint demonstration projects can therefore be further promoted by facilitating international co-operation, e.g. under the IAEA’s aegis. Collaborative R&D and demonstration projects on technologies for the disposal of high level and long lived radioactive waste could contribute to:

- Helping Member States achieve strategic objectives and make progress in implementing state-of-the-art technologies in their waste management programmes;
- Advancing knowledge on radioactive waste disposal and integrate worldwide expertise in a cost-effective way;
- Enhancing public acceptance for waste disposal and building international consensus.

International co-operation efforts should further contribute to making the transfer of knowledge and technology for geological disposal easier to Member States not having direct access to URLs. Good identification and integration of key areas for this co-operation will make the Agency's guidance more effective.

9. CONCLUSIONS AND RECOMMENDATIONS

9.1. Conclusions

Since the late sixties and the seventies, several IAEA Member States have been conducting extended experimental programmes in underground facilities (here named Underground Research Laboratories – URLs), both generic and site specific. Overall, generic URLs address key questions concerning a type of host rock and typical components of a disposal concept whereas site specific URLs allow to characterize and evaluate the geological barrier at a potential site as well as the interaction of the planned disposal system with the host rock.

Therefore a site specific URL (or a similar facility like a pilot gallery) is an integral part of the development of a geological disposal system for radioactive waste, including low and intermediate level waste and non-exothermic waste. It is also usually considered to be included as a phase of the detailed site investigation programme

In this report it is recognised that:

- URLs play a broad range of purposes allowing responsible organizations and stakeholders to achieve their goals in implementing a national programme for radioactive waste disposal;
- In URLs, equipments and methods for in situ characterization of different host rocks can be tested and improved. Numerous generic URLs have proved the usefulness for researchers and implementing disposal organizations to develop techniques and methodologies before going on site, and for regulatory authorities to develop their own experimental expertise;
- The host rock as geological barrier and its disturbance by excavation, thermal loading, gas generation and chemical interactions can be characterized in URL;
- Engineered barrier systems can also be tested in URLs. For the demonstration and assessment of performance of different repository components, URLs have proven to be a very valuable tool;
- The construction of a URL offers an excellent opportunity to test and optimize different excavation methods and lining systems, a prerequisite for the planning, design and development of a repository.

Therefore, URLs constitute an essential step towards the performance and safety assessment of the disposal system.

Since repository site investigations are very extensive undertakings, requiring substantial time and resources, both financial and personnel, a meaningful site investigation strategy is necessary for the achievement of the objective and utilization of resources. The experience gained from investigations in existing URLs is noteworthy for the development of site investigations and planning of programmes as well as for developing new URLs. This is important both in terms of experimental arrangements and model studies, as well as in adapting and further developing investigation methods.

URLs offer unique possibilities to demonstrate to the involved public the scientific and technical work which is carried out to assess the safety of a repository and therefore significantly contributes to building public confidence in radioactive waste disposal in geological formations.

Last but not least, URLs offer opportunities for international co-operation, resulting in close contacts among involved scientists and managers of radioactive waste management organizations of different nations, but also among other scientific communities which may take advantage of the pole of research and excellency created by an URL.

9.2. Recommendations

These recommendations are meant to be useful at any stage of a national waste disposal programme. Several countries have had operational URLs for many years or even decades or may be in a position very close to building an URL and/or a repository. For these countries the recommendations are not as useful as they might be for the countries which have just recently started their waste disposal programme.

- A national waste disposal programme can get started with the focus on host rock and site selection. The fundamental principles and understanding is well established on the basis of previous and ongoing experiments in existing URLs.
- A site specific URL should be considered as an integral part of the siting process - not a parallel activity, but a step toward the repository.
- Coupling of experimental and performance assessment programmes at the beginning of the URL process, planning experiments and design of the URL is a prerequisite for the elaboration and adaptation of a research programme which addresses safety-relevant key questions. Therefore, it is of utmost importance to keep together experimentalists, analysts and safety assessment specialists through the entire URL developments. As those developments have extended, and will continue to extend, over long periods of time (several decades), a system ensuring knowledge management and traceability of all data, concepts, models and decisions should be implemented.
- Countries which have recently started their waste disposal programme should try to participate in experiments in existing URLs. In that sense, all existing and planned URLs could be considered by those countries as generic URLs, where they are usually welcome.
- International co-operation, sharing of experience and technology in URLs should continue to be promoted because it is significant for building confidence with public and the scientific community.
- URLs significantly contribute to local, national and international public acceptance. Well organized visits and tours are recommended. They allow for personal contacts between scientists and managers of the responsible organizations and politicians, journalists and citizens, which often has more positive impact than perfect brochures.

The importance of URLs, both for the scientific and technological development of a geological repository programme and for building public confidence in radioactive waste deep disposal, is nowadays clearly acknowledged outside expert forums. This is evidenced by the specific session devoted to URLs that was set up in the framework of the International Conference on Geologic Repositories held 31 October to 3 November 1999 in Denver, Colorado, organized by the US Department of Energy and co-sponsored by the IAEA [107, 108].

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ANNEX A

THE HADES UNDERGROUND RESEARCH FACILITY (URF), MOL, BELGIUM

- Reference geological formation: Boom Clay (Rupelian, Lower Oligocene).
- Location: Campine Bassin, North-Eastern Belgium, under Nuclear Energy Research Centre, SCK•CEN.
- Facility layout: galleries (>100 m) at a depth: of 223 m, with one access shaft. A second shaft was dug in 1997–1999 and a connecting gallery between this shaft and the existing facilities will be excavated in 2001.

Belgian framework

- Well-rounded fuel cycle capability, including fuel fabrication.
- ONDRAF/NIRAS is the waste management agency, a public body in charge of the different aspects of waste management including the implementation of a disposal system.
- SCK•CEN is the Nuclear Energy Research Centre, undertaking research in the field of nuclear science including reactor safety, radio-protection and waste management.
- Economic Interest Grouping (EIG) PRACLAY was a joint venture between ONDRAF/NIRAS and SCK•CEN aimed at managing the construction of the HADES URF until 2001, now replaced by EIG EURIDICE.

Disposal issues

- Only argillaceous formations are available for geological disposal in Belgium.
- Disposal of reprocessed high-level and long-lived waste, possibly of spent fuel.
- Expected total volume of waste to be disposed of ranges from 10.000 to 15.000 m^3.
- Final disposal, likely to include reversibility to some extent.
- Repository with horizontal disposal galleries (in order to minimize host rock disturbance)
- High-level and long-lived waste disposed in independent galleries.

Boom Clay Formation

- Sedimentation in an open marine shelf environment (50/150 m), in a subtropical climate.
- Rather constant chemical and mineralogical composition (55 to 65% clay minerals).
- Typical layering as a result of variations in grain size, organic matter and carbonate content.

Milestones (URF)

- 1974: research on geological disposal is launched in Belgium.
- 1980: construction of the underground laboratory is started.
- 1985: the HADES URF is operational and first in situ tests are installed.
- 1987: construction of the first extension (Test Drift).
- 1995: the Economic Interest Grouping (EIG) PRACLAY is created.
- 1997–2000: construction of the second shaft in the frame of EIG PRACLAY.
- 2001: EIG EURIDICE to replace EIG PRACLAY with the extension of HADES facility.

Main in situ experiments

It should be noted that all the experiments referred to in this annex are cost-sharing contracts with the EC.

- BACCHUS II

Second phase of the previous Bacchus test (1988) for the study of backfill performance and demonstrate the in situ application of an industrial clay-based backfill material.

Specificity: use of a granular backfill material (mixture high density pellets/ powder).

- CACTUS

"*C*haracterization of *C*lay under *T*hermal loading for *U*nderground *S*torage": study of the thermo-hydro-mechanical behaviour of a clay massif in the near-field of a heater.

Specificity: the overall instrumentation is providing a rather unique database to support modelling work.

- MEGAS

"*M*odelling and *E*xperiments on *GAS* migration in repository host rocks": understanding of the consequences of a gas generation in a clay host rock.

Specificity: validation of a gas migration model through an in situ 3-D large scale experiment.

- CLIPEX

"*Cl*ay *I*nstrumentation *P*rogramme for the *Ex*tension of an underground research laboratory": study of the hydro-mechanical response of clay during excavation of a gallery.

Specificity: characterization programme associated to the mine-by test as a support to blind predictions.

- PHEBUS

"*P*henomenology of *H*ydrical *E*xchanges *B*etween *U*nderground atmosphere and *S*torage host": study of the hydro-mechanical behaviour of deep clay when submitted to desaturation.

Specificity: in situ 'ventilation' test developed in parallel with a surface mock-up (macro-permeability).

- RESEAL

"*Seal*ing of a *re*pository for radioactive waste in an argillaceous host rock" to demonstrate the feasibility of making an effective seal in semi-industrial conditions.

Specificity: small- and large scale in situ tests supported by laboratory and modelling work.

- CERBERUS

"*C*ontrol *E*xperiment with *R*adiation of the *Be*lgian *R*epository for *U*nderground *S*torage": demonstration test to study the near-field effects of a HLW-canister in a clay formation.

Specificity: HLW canister simulated by a heater for heat emission but also with ^{60}Co source for radiation.

- CORALUS

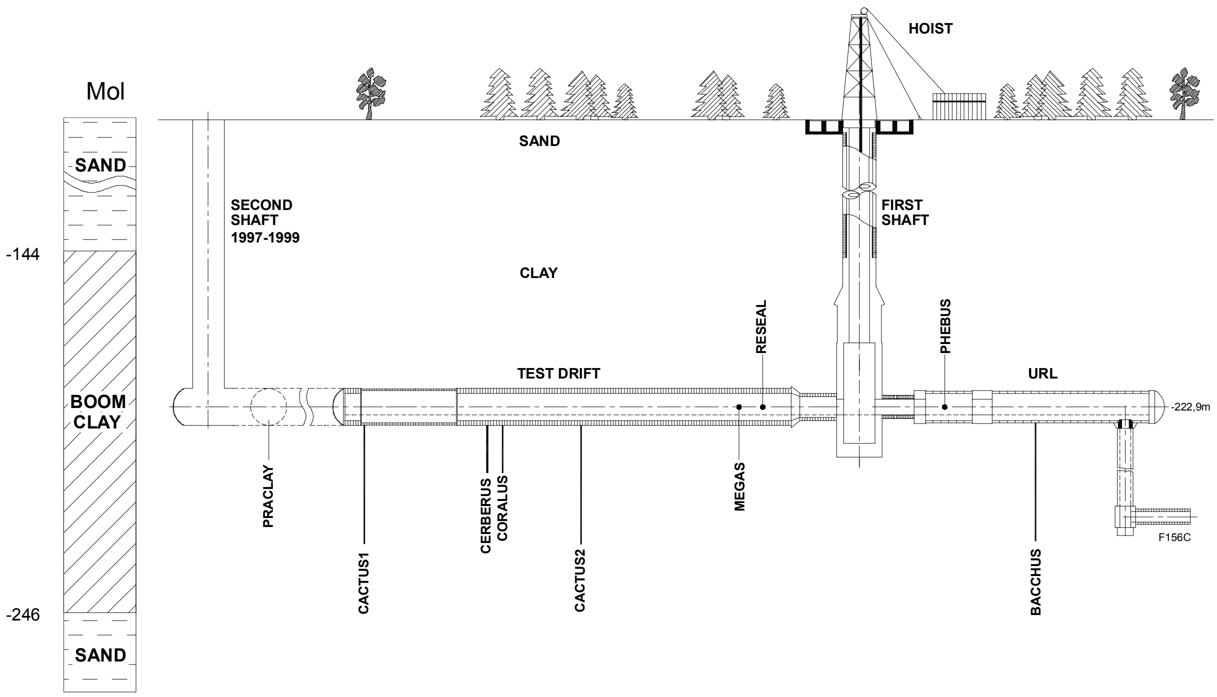
"*Cor*rosion of alpha-*A*ctive G*l*ass *U*nder *S*torage conditions": study of the dissolution of glass in disposal conditions (clay/bentonite).

Specificity: integrated in situ test using an alpha-active glass and ^{60}Co sources for the gamma field.

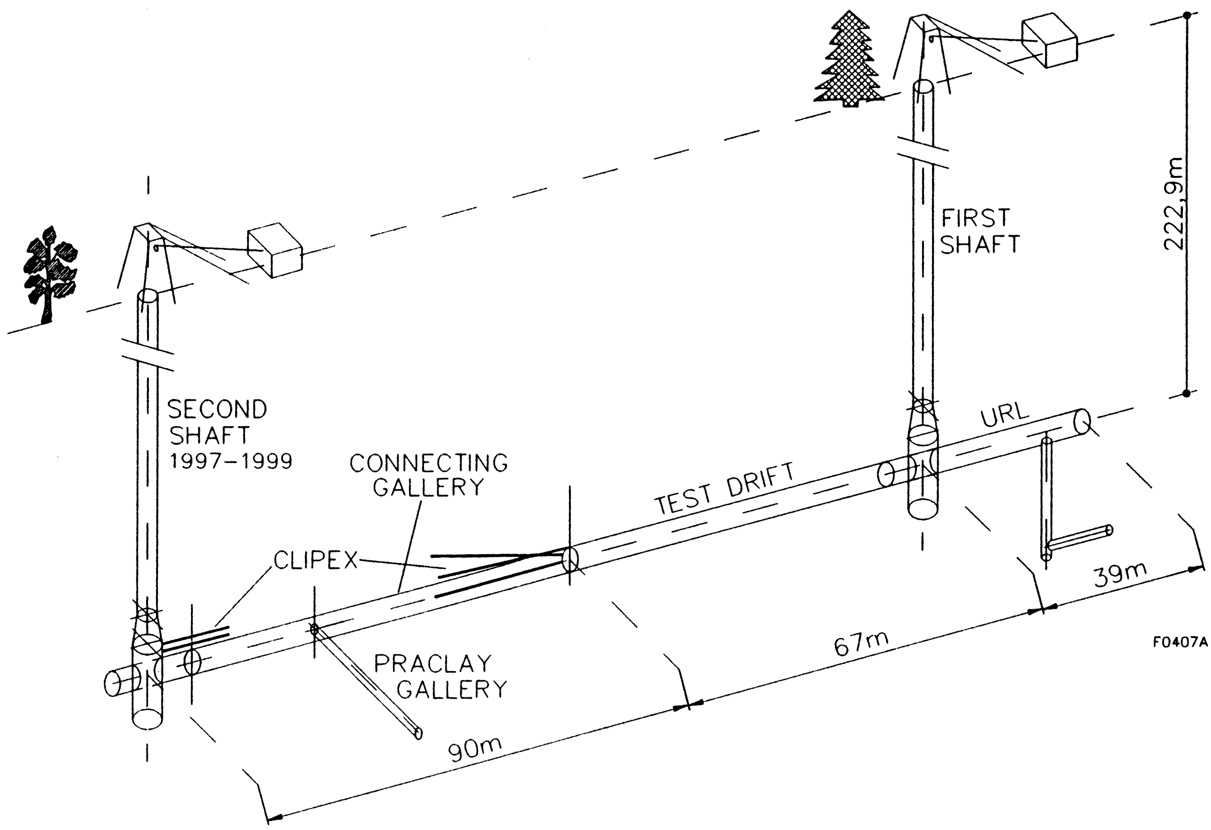
- PRACLAY

Preliminary demonstration test for clay disposal of high-level radioactive waste: demonstration of the feasibility of the Belgian reference concept developed for HLW.

Specificity: construction of a 30 m long "dummy" disposal gallery and study of THM behaviour and EDZ.



Location of main experiments in HADES URF (in dotted lines: extension to be completed in 2002).



Extension of the HADES URF within the EIG EURIDICE (running).
Location of the PRACLAY gallery and CLIPEX instrumentation holes.

ANNEX B

THE LAC DU BONNET UNDERGROUND RESEARCH LABORATORY (URL), PINAWA, MANITOBA, CANADA

- Reference geological formation: granitic pluton; Lac Du Bonnet Batholith.
- Location: western edge of the Canadian shield in southeastern Manitoba, Canada.
- Facility layout: several hundred metres (m) of tunnels and test rooms located on two major testing levels at depths of 240 m and 420 m. The complex is centered on a vertical access shaft that extends to a depth of 443 m with an additional ventilation raise that connects all levels to the surface.

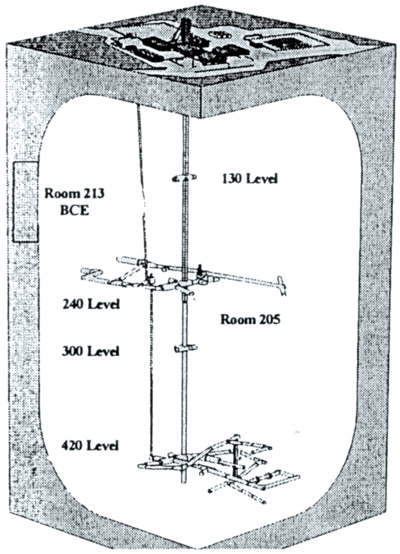


Fig. 1. Layout of the Canadian URL.

Canadian framework

- The Government of Canada has responded to the Recommendations of the Nuclear Fuel Waste Management and Disposal Concept Environmental Assessment Panel.
- Producers and owners of nuclear fuel waste responsible for its management.
- The URL of Lac du Bonnet, Manitoba, will serve as an International Training and Demonstration Facility for nuclear fuel waste management and disposal, announced the Canadian Government in June 2000.
- In April 2001 the Government of Canada took an important step forward in the announcement of an Act Respecting the Long Term Management of Nuclear Waste Fuel. The legislation calls for nuclear utilities to form a Waste Management Organization that would report regularly to the Government of Canada on long term management of waste including its disposal.

Disposal issues

- Comparison of risks, costs and benefits of practicable long-term options for managing nuclear fuel wastes to be undertaken and Government of Canada to make informed choice that reflects public preference.

- Technology has been developed to a conceptual level to meet the requirements of the Environmental Impact Statement; further work to support siting of the disposal project.

Milestones (URL)

- 1980: approval of lease for the URL from the Province of Manitoba.
- 1983: shaft sinking started upon completion of initial site evaluation.
- 1990: underground assess to 240 and 420 m levels completed.
- 1990: operating phases experiments begun.
- 1993: lease for site extended to 2011.

The URL is now in the operating phase until 2011. The specific areas of research, development, and demonstration include:

- URL CHARACTERIZATION PROGRAMME

Develop integrated methodology for underground characterization of a disposal vault, provide information for siting experiments at the URL, common data needed for the URL experimental programme, geotechnical information for use in the regional geologic siting studies of the Lac du bonnet Batholith.

- IN SITU STRESS PROGRAMME

Improving the ability to measure and understand in situ stress in hard rock.

- STUDY OF SOLUTE TRANSPORT IN HIGHLY FRACTURED ROCK

Develop and demonstrate methods for determining the solute transport properties of zones of highly fractured rock.

- STUDY OF SOLUTE TRANSPORT IN MODERATELY FRACTURED ROCK

To improve the understanding of solute transport in moderately fractured rock defined as volumes of rock with intersecting fracture sets having one to five fractures per metre of linear core sample.

- MINE-BY EXPERIMENT

The specific objectives are to improve the fundamental understanding of in situ rock mass behaviour and failure mechanisms.

- BUFFER/CONTAINER EXPERIMENT

Examine the performance of the reference buffer material in a geological setting and in situ moisture conditions, with and without heating.

- GROUTING EXPERIMENT

Demonstrate the ability to permanently seal high-permeability water-bearing zones when intersected by tunnels and shafts using super-plasticized grouts capable of penetrating fine fissures and fractures.

- TUNNEL SEALING EXPERIMENT

Assess the applicability of technologies for construction of practicable concrete and clay bulkheads, to evaluate the performance of each bulkhead; and to identify and document the parameters that affect the performance.

- MICROBIOLOGY PROGRAMME

To assess the impact of microbial activity on all aspects of the disposal concept.

- IN SITU DIFFUSION EXPERIMENT

Confirmation of the laboratory and literature date for diffusion parameters, mainly porosity and tortuosity.

ANNEX C

THE GRIMSEL TEST SITE (GTS), BERN CANTON, SWITZERLAND

Type of laboratory:	Generic
Investigated formation:	Central Aar Granite
Location:	Bernese Alps, Canton Bern, 1750 m above sea level, overburden 450 m
Facility layout/key features:	1983–1984 construction, extensions in 1995 and 1999, TBM drilled tunnel system, diametre 3.5 and 2.3 m, total length approx. 1 km, blasted caverns, horizontal access

Swiss framework

- Nagra (the Swiss Cooperative for the Disposal of Radioactive Waste) was set up in 1972 by the utilities and the Federal Government (responsible for waste from medicine, industry and research) to discharge their legal obligation to ensure safe management and disposal of all the categories of radioactive waste which they produce.
- 2 deep geological repositories envisaged, one at the proposed Wellenberg site for L/ILW (marl host rock) and one in Northern Switzerland (sedimentary or crystalline host rock) for HLW/TRU. A recently inaugurated central interim storage facility (Zwilag) removes some of the time pressure on repository projects.
- Two underground test facilities are currently operational in Switzerland; Grimsel and Mt. Terri, both of which are characterized by extensive international collaboration.

Grimsel Test Site GTS – Milestones and main experimental programmes

1984–1986	Basic site characterization
1994–1996	Geophysical investigations
1986–1997	Radionuclide migration and retardation
1990–1993	Far-Field programme
1994–1996	Near-Field programme
1997–2003	Ongoing GTS Phase V
1997–2002	Model testing/’validation’ experiments
2003–?	Future Phase (GTS–VI) under consideration

Main programmes GTS Phase V, 1997–2003

Key issues:

(i) gas transport processes in the engineered barrier system and the geosphere;

(ii) radionuclide retardation processes, taking into consideration geochemical alteration of the host rock by high-pH leachates and the effect of colloids generated in the near-field;

(iii) determination of effective parameter values describing a representative volume of potential host rock (up-scaling).

The FEBEX experiment was initiated to investigate the capability of coupled thermo-hydro-mechanical codes and the basic feasibility of the high-level waste disposal concept.

GAS MIGRATION TEST IN SHEAR ZONES (GAM)

- Investigation of solute and gas migration processes in a single, heterogeneous fracture (shear zone).

GAS MIGRATION TEST IN THE EBS AND THE GEOSPHERE (GMT)

- Construction of a silo as an advanced engineered barrier system for L-ILW/TRU under realistic conditions to study gas transport through the EDZ and the immediately surrounding host rock.

FEBEX: FULL-SCALE ENGINEERED BARRIER EXPERIMENT FOR HLW

1:1 scale experiment simulating the conditions in an emplacement tunnel of a HLW repository (spent fuel) with massive engineered barriers (project initiated by ENRESA and supported by EC) and aimed at testing and improving the predictive capability of coupled thermo-hydraulic-mechanical (THM) or thermo-hydraulic-chemical (THC) models.

The FEBEX project consists of four major components:

- The in situ experiment at the Grimsel Test Site.
- A mock-up experiment (about 2/3 scale) in Madrid (Spain).
- A series of laboratory tests to complement the information from the two large-scale experiments.
- Development and testing of THM and THC models.

In 2001 the partial dismantling of the EBS, including the first heater, followed by back-plugging of the tunnel is foreseen.

PROCESSES IN THE GEOLOGICAL BARRIER-RADIONUCLIDE RETARDATION

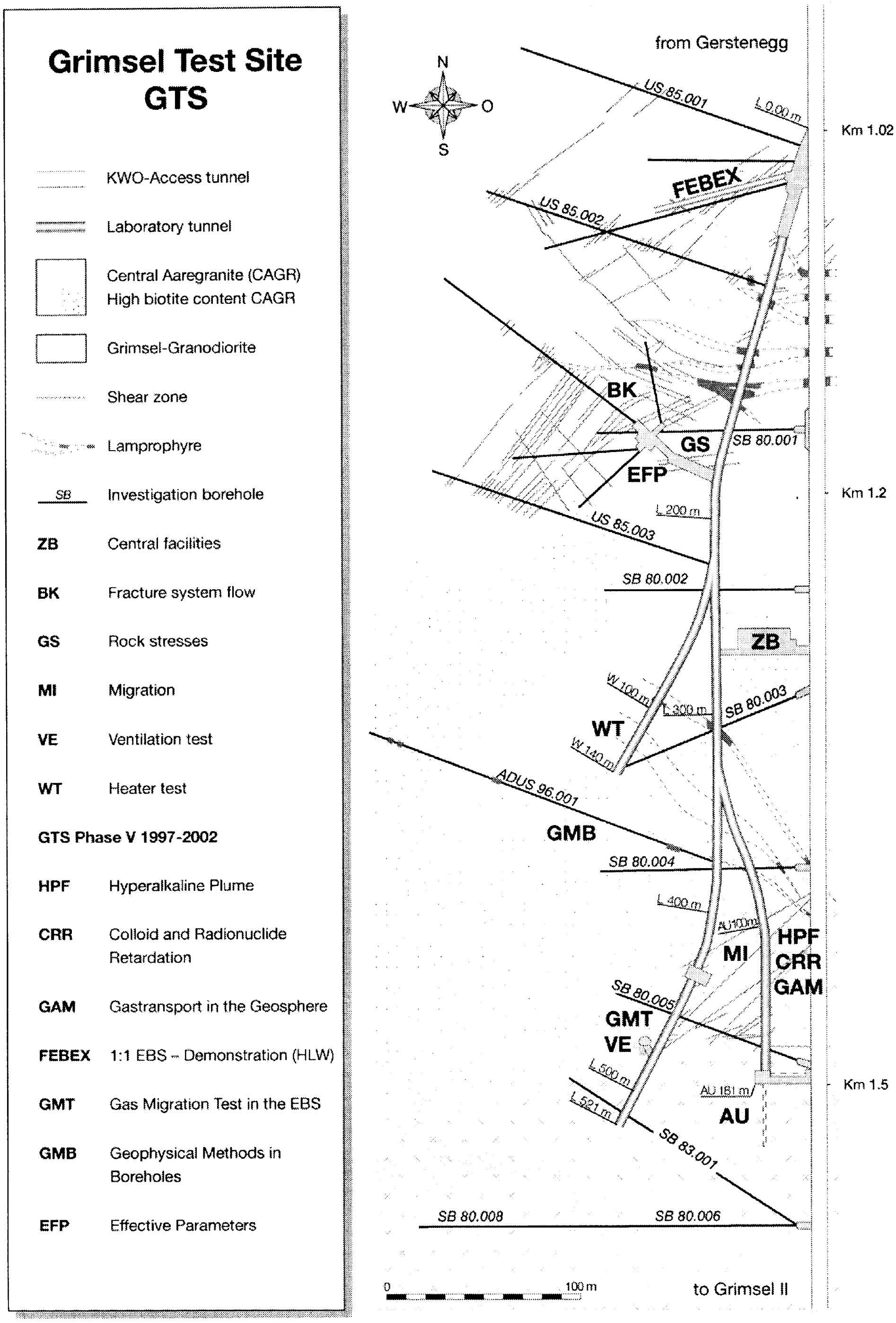
Two experimental programmes are being performed in the radiation-controlled zone of the GTS:

- HIGH-PH PLUME (HPF) in fractured rock aimed at assessing the effect of high-pH leachates (from cement-based materials) on the host rock and the retardation behaviour of radionuclides.

- COLLOID AND RADIONUCLIDE RETARDATION (CRR) experiment to address the retardation behaviour of safety-relevant nuclides in the presence of near-field colloids.

EFFECTIVE PARAMETERS (EFP)

"Validation" of groundwater flow and solute transport models using in situ data from large-scale tracer experiments at the GTS.



Grimsel test site – plan view.

ANNEX D

THE MONT TERRI ROCK LABORATORY, JURA CANTON, SWITZERLAND

- Generic laboratory
- Investigated geological formation: Shale, Opalinus Clay (Lower Aalenian, Dogger)
- Location: Northwestern Switzerland, Jura Canton, St-Ursanne

Layout and geological setting (see Figs 1 and 2):

- Horizontal access through escape gallery (reconnaissance gallery) of the Mont Terri motorway tunnel.
- Eight niches in the escape gallery and a new research gallery with lateral niches of a total length of 230 m (Fig. 1).
- Overburden: 300 m.
- Opalinus Clay, thickness: 160 m.
- typical mineralogical composition: 65% clay minerals (10% illite-smectite mixed layers), 20% quartz, 7% calcite, 7% dolomite/ankerite, siderite, feldspars, pyrite. Porosity 15%. Pore water highly mineralized (Na-Cl water, up to 20 g/l).
- Tectonic setting: folding during late alpine orogeny, dipping of formation 45°, a series of minor faults, one main fault zone (Fig. 2).

Concept of the Project and Project Partners

The Mont Terri Project is an international research project and has three main aims:

- Hydrogeological, geochemical and rock mechanical characterization of an argillaceous formation.
- Analysis of the changes of the formation induced by the excavation of galleries, heat and high-pH cement waters.
- Evaluation and improvement of appropriate investigation techniques in an argillaceous formation containing swelling clay minerals.

The research programme consists of a series of individual experiments, each carried out by on or several Project Partners together. New experiments may be added as required.

The Project Partners are (status end of 2000):

SNHGS (Swiss National Hydrological and Geological Survey, patronage and holder of the authorizations), NAGRA (Switzerland), ANDRA and IPSN (France), ENRESA (Spain), BGR (Germany), SCK-CEN (Belgium), JNC and OBAYASHI (Japan).

Further organizations may join the project as Project Partners.

Milestones

1996 Excavation of eight niches and start of experiments
1997/98 Excavation of a research gallery
1998 Start of large scale experiments
Programme until 2004 at least.

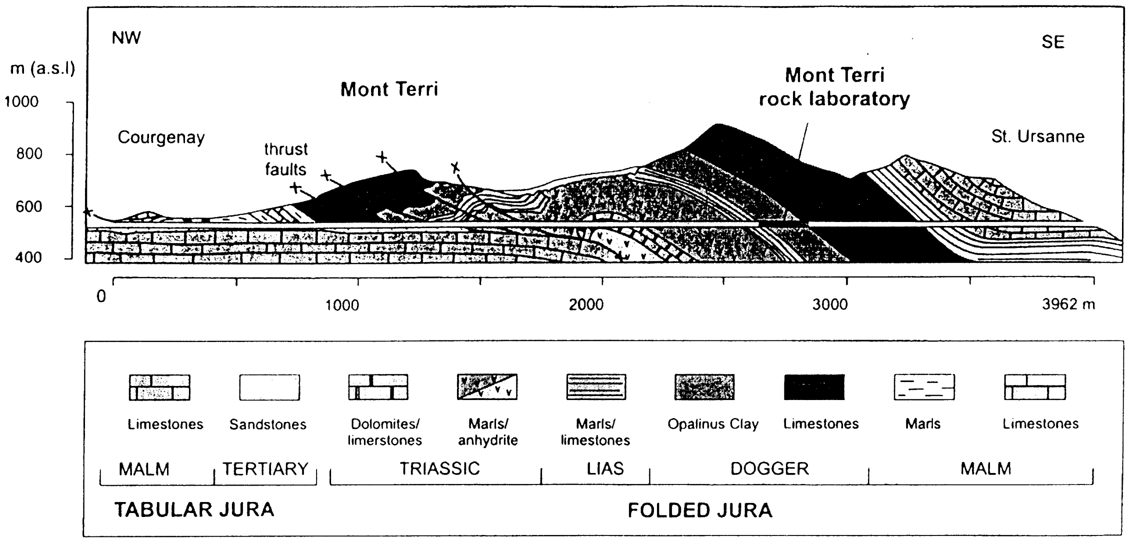


Fig. 1. Geological profile along the Mont Terri motorway tunnel.

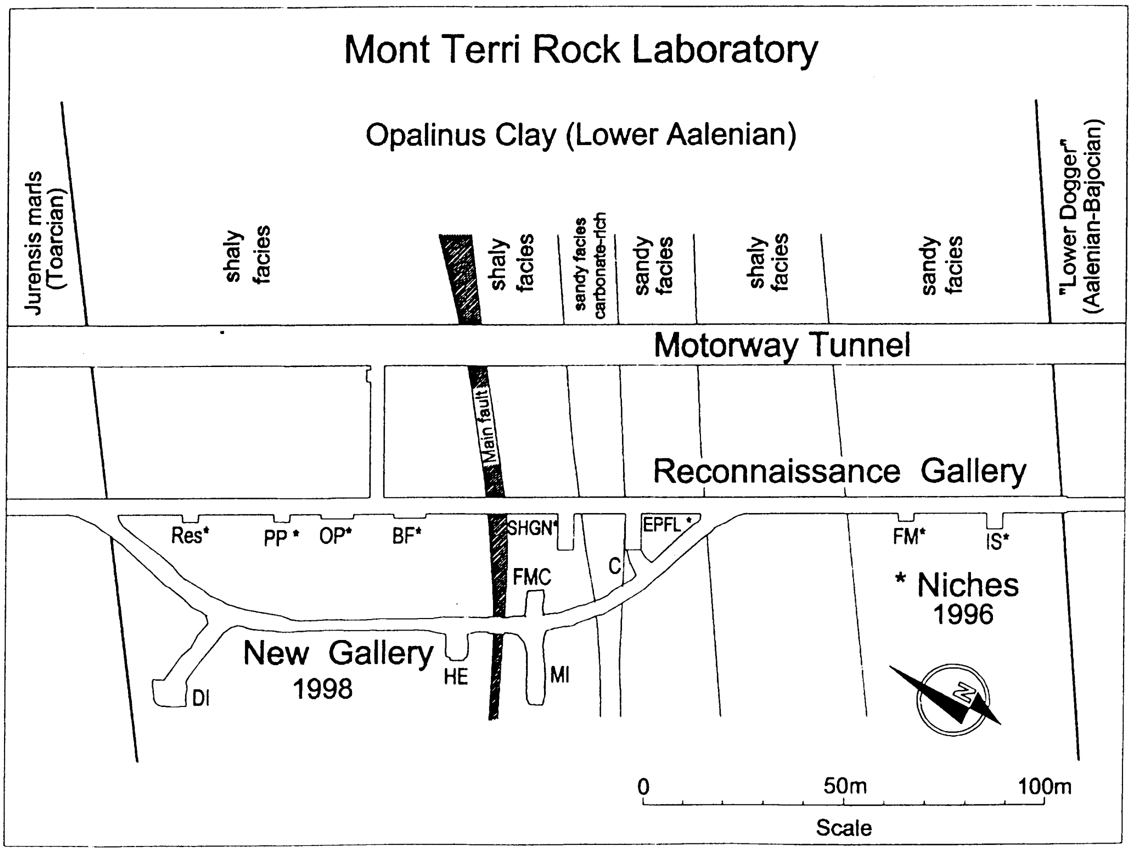


Fig. 2. Layout of the Mont Terri Rock Laboratory.

Main in situ experiments

HYDRAULIC AND GAS PERMEABILITY EXPERIMENT (GP)

- Objective: evaluation of the hydraulic and gas permeabilities of the undisturbed rock and the discontinuities (minor faults, main fault zone).
- Specificity: a series of packer tests.

DIFFUSION EXPERIMENT (DI)

- Objective: evaluation of solute transport parameters of Opalinus Clay.
- Specificity: in packed off sections of boreholes add traced water, overcore after one or several years and analyse the tracer distribution in the overcored section.

EVOLUTION OF EXCAVATION DISTURBED ZONE EDZ (ED-B)

- Objective: evaluation of changes (e.g. convergence, porewater pressure, formation of fracture network) induced by excavations.
- Specificity: drill and instrument boreholes in the area of the planned gallery, dig the gallery and monitor the changes in the EDZ.

EDZ SELF-HEALING EXPERIMENT (EH)

- Objective: evaluate the self-healing capacity of the interconnected fracture network by creep and swelling of the rock.
- Specificity: characterize the hydraulic conductivity of the fracture network, inject water and observe the expected reduction of the hydraulic conductivity.

IN SITU STRESS MEASUREMENTS (IS)

- Objective: evaluate the in situ stress field in the rock.
- Specificity: test different techniques (e.g. overcoring/undercoring, borehole slotter) and compare the results.

HIGH-PH CEMENT WATER EXPERIMENT (CW)

- Objective: evaluation of the changes in the rock induced by hyper-alcaline waters.
- Specificity: in packed off sections of boreholes add hyper-alcaline water, overcore after several years and analyse the changes.

HEATER EXPERIMENT (HE)

- Objective: study of the thermo-hydro mechanical behaviour of the clay under thermal load.
- Specificity: install a heater, heat over several years and observe the behaviour of the clay.

ANNEX E

THE ÄSPÖ HARD ROCK LABORATORY (HRL), SWEDEN

- Generic laboratory.
- Investigated geological formation: Småland granite (Precambrian).
- Location: Southern Sweden, in the vicinity of Oskarsham, Baltic coast.

Swedish framework

- Svensk Kärnbränslehantering AG (SKB), the Swedish Nuclear Fuel and Waste Management Company is responsible for the disposal of all Swedish radioactive waste from nuclear power, medical care, industry and research.
- Operational waste from NPPs is disposed of in the Forsmark repository for low and intermediate radioactive waste, operated since 1988. Spent fuel is not reprocessed but stored in an interim storage facility (CLAB facility) until the radioactivity and heat output will have decreased by 90% and disposal operation could start.
- The Äspö Hard Rock Laboratory was built in the 1990s to develop research, technical development and demonstration in a realistic setting before a deep repository could be built.

Disposal issues

- Prior to deposition spent fuel will be encapsulated in copper canisters with inner steel containers.
- Canisters will be disposed of in a tunnel system in the granitic bedrock following the KBS-3 method (a multibarrier concept) which was accepted by the Swedish Government in 1984. Canisters will be embedded with surrounding compacted clay in disposition holes dug in galleries.

Äspö HRL milestones

- 1986: geological investigations of the bedrock in Äspö and nearby islands
- 1988: Äspö selected as the site for the underground laboratory
- 1990: tunnel construction started in the autumn
- 1995: the nominal depth of 450 m was reached and the construction phase completed
- 1995–2005: major scientific experiments being carried out (movement and chemical composition of water)
- 1999–2008: major demonstration experiments (Deposition technology, Prototype repository, Retrieval Test, etc.)
- 2002: start of site investigations on at least two sites
- 2009: starting construction of a geological repository

Layout of Äspö *HRL* (*see Figure 1)*

A 5 m diametre tunnel goes in a double spiral down to a depth of 450 m below the sea level. The total length of the tunnel is approximately 3600 m. The first part was excavated by conventional drill and blast methods while the second part of the spiral from 340 to 450 m level, was excavated by a 5 m full face Tunnel Boring Machine (TBM). One shaft (3.8 m in diametre) is for the personnel and 2 small shafts (1.5 m in diametre) are for ventilation.

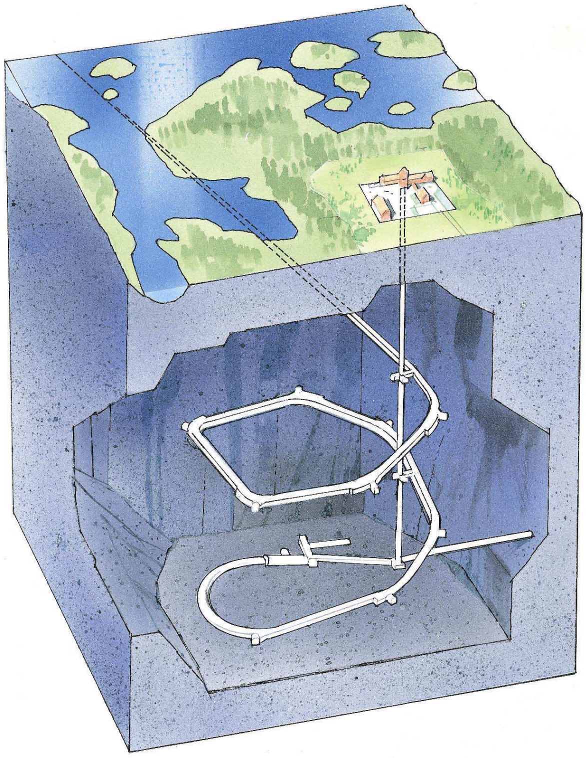


Fig. 1. Layout of the Äspö *Hard Rock Laboratory, Sweden.*

Main in situ experiments

- SKB's ROCK VISUALIZATION SYSTEM (RVS)

RVS is an application built on top of MicroStation to generate 3D models.

- UNDERGROUND HYDRAULIC TESTING SYSTEM (UHT)

UHT cope with hydraulic conditions in boreholes drilled underground. All equipments are assembled in modules installed in a container to measure flow and pressure from test sections.

- THE TRACER RETENTION UNDERSTANDING EXPERIMENTS (TRUE)

These experiments are carried out to improve the understanding of radionuclide transport and retention processes by the means of a set of hydraulic and tracer tests in a single fracture. Several modelling teams have been engaged to perform blind predictions of experimental results (breakthrough curves). This has been the basis for scientific tests of different conceptual models of retention processes in single fractures.

- THE TRUE BLOCK PROJECT

This experiment focusses on flow and transport in a fracture network on a 50-100 m scale (repository scale).

- LONG TERM DIFFUSION EXPERIMENT

The objective of this experiment is to study diffusion into matrix rock from a natural fracture and to obtain data on sorption properties and processes.

- THE RADIONUCLIDE RETENTION PROJECT (RNR)

The objective is to validate the radionuclide retardation data measured in laboratories with data from in situ experiments by the means of the CHEMLAB borehole laboratory probe.

- THE REDOX EXPERIMENTATION OR DETAILED SCALE (REX)

REX project is developed to answer on how does oxygen trapped in the closed repository react with the rock minerals and in the water conducting fractures, i.e. how fast will free oxygen be removed from the repository.

- MATRIX FLUID CHEMISTRY

The objective of this experiment is to determine the origin and age of matrix fluids.

- MICROBE

This project comprises a set of microbiology research tasks of importance for the performance assessment of high level nuclear waste (HLW) disposal. The programme includes studies on microbial influence on radionuclide migration, microbial corrosion of copper, and microbial production and consumption of gases.

- THE EXCAVATION DISTURBED ZONE EXPERIMENT (ZEDEX)

The ZEDEX project which objective was to understand the mechanical behaviour of the Excavation Disturbed Zone (EDZ) contributed to the knowledge base for selecting/optimizing the construction method (TBM).

- THE PROTOTYPE REPOSITORY

The Prototype Repository will as much as possible simulate a part of the disposal tunnel in the real deep repository. The objective is to demonstrate the integrated function of the repository components under realistic conditions and to compare results with models and assumptions.

- DEMONSTRATION OF DEPOSITION TECHNOLOGY

The objective is to develop and test methodology and equipment for encapsulation and deposition of spent nuclear fuel.

- CANISTER RETRIEVAL TEST

The objective is to develop and test methodology and equipment for loosening of the canister from the grip of the swolen bentonite. It will show in an illustrative manner that a canister can be retrieved in an underground environment.

- BACKFILL AND PLUG TEST

The objective is to develop and test different materials and compaction techniques for backfilling of tunnels excavated by blasting and to test the function of the backfill and its interaction with the surrounding rockmass.

- LONG TERM OF BUFFER MATERIAL (LOT PROJECT)

Test to produce data for validation of models concerning buffer performance under steady state conditions after water saturation.

- THE TWO-PHASE FLOW EXPERIMENT

The objective is to create from in situ tests results a database for the simulation of two-phase flow in fractured rock. (2D and 3D models to calculate gas and particle migration around underground excavation).

- PROTOTYPE REPOSITORY

The objective is to test and demonstrate the integrated function of repository components under realistic conditions on a full scale and to compare results with models and assumptions.

ANNEX F

THE WASTE ISOLATION PILOT PLANT (WIPP), CARLSBAD, NEW MEXICO, USA

- Reference geological formation: The Permian Salado Formation (~214 million years old) of the Delaware Basin in southeast New Mexico, USA. An extensive bedded salt, predominantly halite with occasional interbeds of anhydrite, polyhalite, and claystone.
- Location: approximately 30 miles east of Carlsbad, New Mexico, USA.
- Facility layout: The WIPP facility consists of four vertical shafts (a salt handling shaft, an air intake shaft, an exhaust shaft, and a waste-handling shaft) extending approximately 655 m to the repository horizon. The single repository horizon will consist of eight panels, each consisting of seven waste disposal rooms, each about 91 m (300 feet) long, 10 m (33 feet) wide, and 4 m (13 feet) high. Pillars between rooms will be 30 m (100 feet) wide. Only one panel has been excavated to date.
- Mine layout diagram, see Figure 1.

United States transuranic waste framework

- The WIPP is regulated by the Environmental Protection Agency (EPA) under 40 CFR 191 (Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High Level and Transuranic Radioactive Wastes) and 40 CFR 194 (Criteria for the Certification and Re-Certification of the Waste Isolation Pilot Plant's Compliance with the 40 CFR Part 191 Disposal Regulations).
- The WIPP was designed by DOE to receive, handle and dispose of transuranic (TRU) and transuranic-mixed waste. TRU waste is defined as alpha-emitting radioactive waste containing radionuclides with atomic numbers greater than 92 with half-lives longer than 20 years, and in concentrations greater than 100 nanocuries per gram of waste. TRU-mixed waste is a TRU waste also contaminated with any listed or characteristically hazardous (e.g. toxic, corrosive, ignitable, etc) contaminants as provide in 40 CFR 261.
- The WIPP is managed by the DOE Carlsbad Area Office. The Managing and Operating Contractor is Westinghouse, the Scientific Advisor is Sandia National Laboratories.

Disposal issues

- The WIPP is authorized to dispose of 175,600 cubic metres of transuranic waste resulting from atomic energy defence (i.e. non-commercial) activities. Only a small portion of the total volume is authorized for remote-handled waste (7080 cubic metres).
- WIPP is currently expected to have a 35 year operations phase.
- Approximately 62,000 cubic metres currently exist in storage at several government defence installations across the USA. Additional waste is anticipated primarily from future decommissioning and environmental restoration activities.
- Waste is shipped by truck in specially designed shipping casks. First waste receipt was in March of 1999.

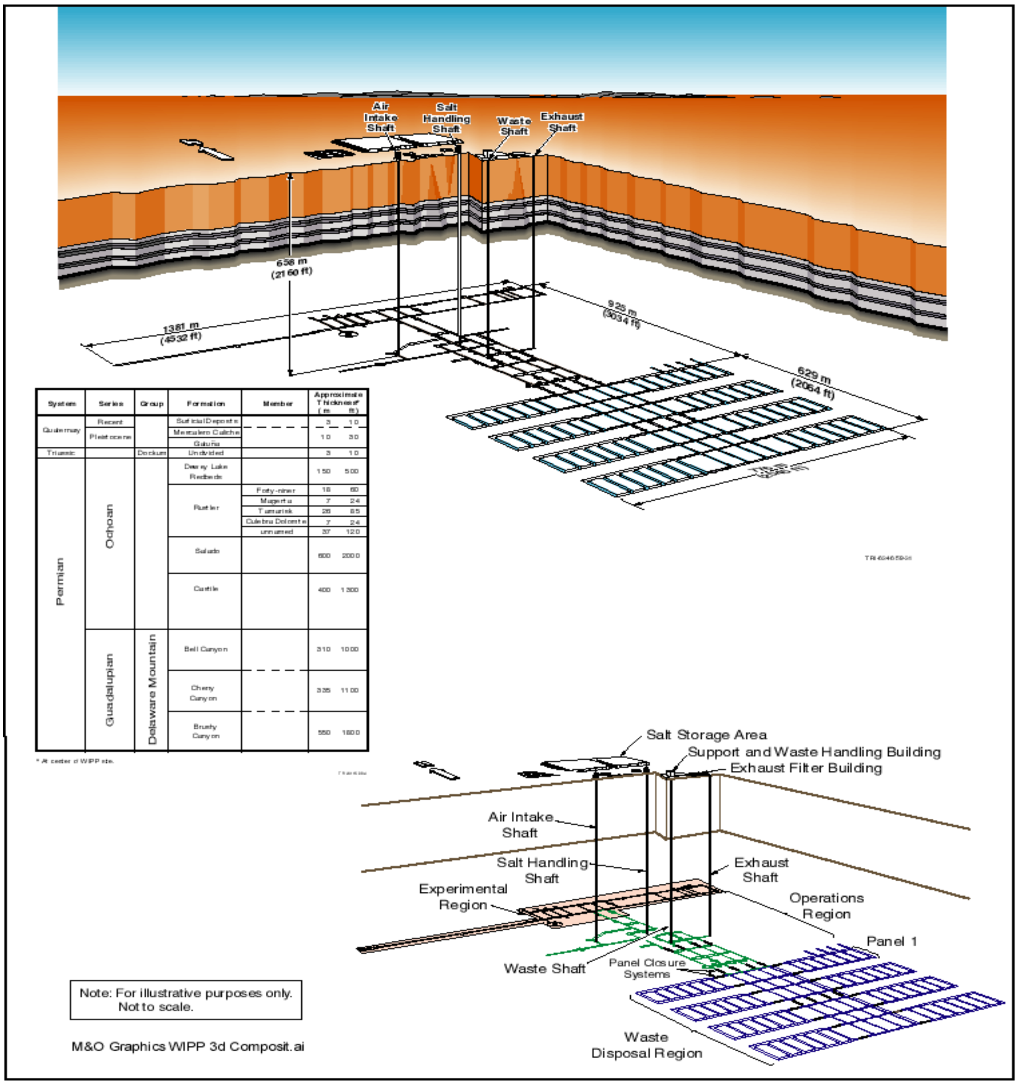


Fig. 1. Layout of WIPP facility.

Milestones

- 1955: US Atomic Energy Commission (AEC, predecessor of the US Department of Energy (DOE) asks the National Academy of Sciences to study permanent disposal of radioactive wastes.
- 1956: National Academy of Sciences recommends disposal in salt deposits.
- 1970: The AEC selects a salt mine near Lyons, Kansas, as the potential site for a radioactive waste repository.
- 1972: After gathering input from public hearings, the Kansas Geological Survey and the AEC determine the Lyons site unacceptable because of the area's geology, hydrology, and previously undiscovered drill holes that could lead to extensive dissolution of salt.
- 1974: The AEC chooses a site 30 miles east of Carlsbad, New Mexico, for exploratory work.
- 1979: Congress authorizes WIPP (Waste Isolation Pilot Plant) for research and development of safe methods of disposal of radioactive wastes generated by defence facilities.

- 1981: First exploratory shaft is drilled.
- 1982: Underground excavation begins.
- 1983: DOE decides to proceed with full facility construction of the WIPP.
- 1984: First underground experiments begin.
- 1985: EPA establishes radioactive waste disposal regulations specifically addressing transuranic waste and applicable to the WIPP.
- 1989: DOE issues its five-year test plan for the WIPP. DOE concludes underground facility construction by completion of the air intake shaft.
- 1990: Construction officially complete.
- 1992: Congress passes the WIPP Land Withdrawal Act.
- 1995: DOE initiates the engineering and planning process for the deactivation of the experimental area of the mine and the majority of underground experiments.
- 1996: DOE sends WIPP Compliance Certification Application to EPA. The deactivation of the experimental area of the underground is completed.
- 1997: EPA decrees DOE WIPP Compliance Certification Application is complete.
- 1998: EPA certifies WIPP.
- 1999: Disposal phase operations begins with first waste receipt.

Main experiments referred to in this report include numerous in situ experiments in the areas of:

- rock mechanics of a heated axisymetrical salt pillar (Room H).
- seal system performance tests for various seal materials (Room M).
- disposal room interactions to determine degradation mechanisms of glass and waste package materials (Room J).
- fluid flow and transport permeability measurements throughout the underground area.

It should be noted that with the demonstration of compliance and the beginning of waste disposal operations, nearly all in situ experimental operations have concluded.

ANNEX G

THE YUCCA MOUNTAIN – EXPLORATORY STUDIES FACILITY (ESF), NEVADA, USA

- Reference geological formation: welded tuff of the Topopah Spring Tuff Formation (Tertiary-Mid to Late Miocene; 15 million to 7.5 million years old).
- Location: On the western boundary of the Nevada Test Site approximately 100 miles northwest of Las Vegas, Nevada.
- Facility layout: synoptic description with Figure 1.

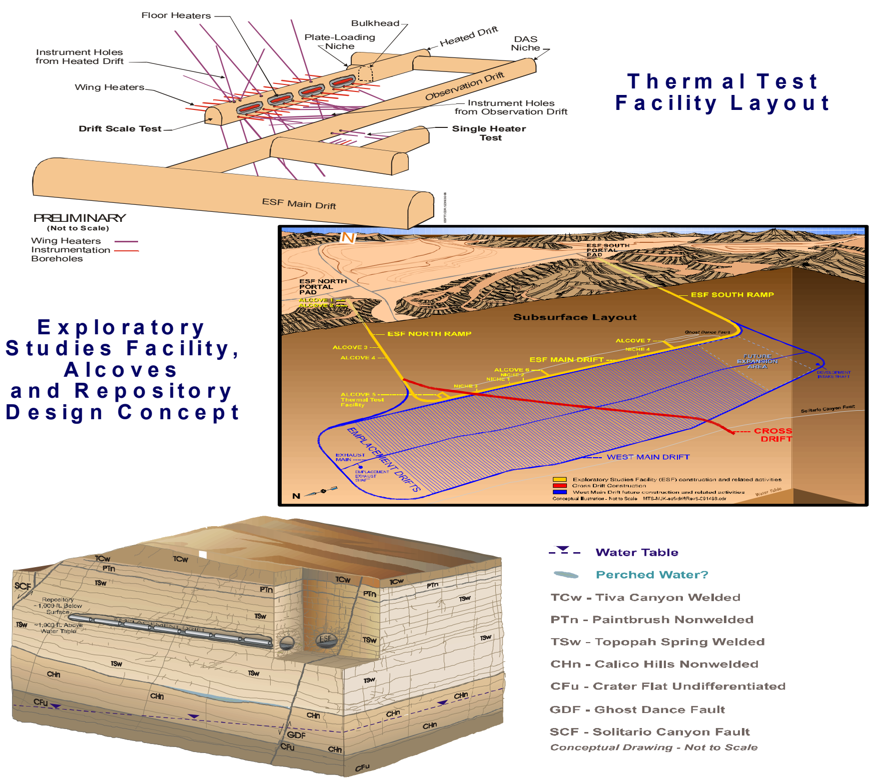


Fig. 1. General layout of ESF.

US high level nuclear waste framework

- Geologic disposal of spent nuclear fuel and high level nuclear waste is the stated policy of the US government.
- The Office of Civilian Radioactive Waste Management (OCRWM), part of the Department of Energy (DOE) is the nuclear waste management authority.
- The Yucca Mountain Site Characterization Office is responsible for the characterization, design and submittal of a license application (LA) to the Nuclear Regulatory Commission, an independent government agency responsible for the licensing of nuclear facilities in the USA.

- Several US national laboratories and contractor organizations assist OCRWM with the characterization and development of a LA for the Yucca Mountain site.

Disposal issues

- The welded tuff at the Yucca Mountain site is the only geologic formation and the only site in the USA currently designated for characterization.
- Disposal of spent nuclear fuel and high level waste.
- Total volume of material designated for the first repository, 70,000 MTHM.
- Final disposal, although long term monitoring before closure likely, retrievability prior to closure required if necessary, demonstration of retrievability required by regulation.
- Repository with horizontal emplacement galleries to be ready in 2010.

Milestones (Yucca Mountain)

- 1982: Nuclear Waste Policy Act codified the concept of geologic disposal in the USA and mandated a search for an appropriate repository(s).
- 1987: The Act as amended specified Yucca Mountain, Nevada as the only site to be characterized as a potential repository.
- 1994: ESF construction started to provide an underground research laboratory for large scale in situ testing of the anticipated host rock at the proposed repository site.
- 1997: Drift scale thermal test started in alcove five of the ESF with four year heating and four year cool down periods planned. Busted Butte facility constructed and testing started in early 1998.
- 1998: Viability Assessment published which indicated the Yucca Mountain Project should continue.
- 1999: Draft Environmental Impact Statement published.
- 2001: If the site is found to be suited for repository development, a Site Recommendation will be forwarded to the President of the USA.
- 2002: If found suitable and approved, a licence application will be forwarded to the Nuclear Regulatory Commission (NRC).
- 2005: If licensed, a construction authorization will be issued by the NRC and construction will commence.
- 2010: If a licence to receive and possess waste is granted by the NRC, emplacement of waste can begin.

Main in situ experiments referenced in this report

- DRIFT SCALE THERMAL TEST

Project: Exploratory Studies Facility (ESF)-Alcove 5-Large Scale Heater Test (Figure 1).

Objective: To develop an understanding of T-H-M-C processes in approximately 10,000 m^3 of fractured rock mass from an extensively instrumented facility that includes observation drifts and a full size drift heated with simulated waste canisters (Figure 1).

Specificity: Nine heated canisters with associated wing heaters intended to raise rock wall temperature from 23ºC ambient to 200ºC over a four year monitored heating period followed by a monitored four year cool down period. Pre-test calculations developed to compare against actual test measurements to assess confidence in the understanding of coupled process modelling for a full scale thermal test.

- BUSTED BUTTE-UNSATURATED ZONE TRANSPORT TEST

Project: Underground Facility excavated at Busted Butte site approximately 5 km southeast of Yucca Mountain (Figure 2).

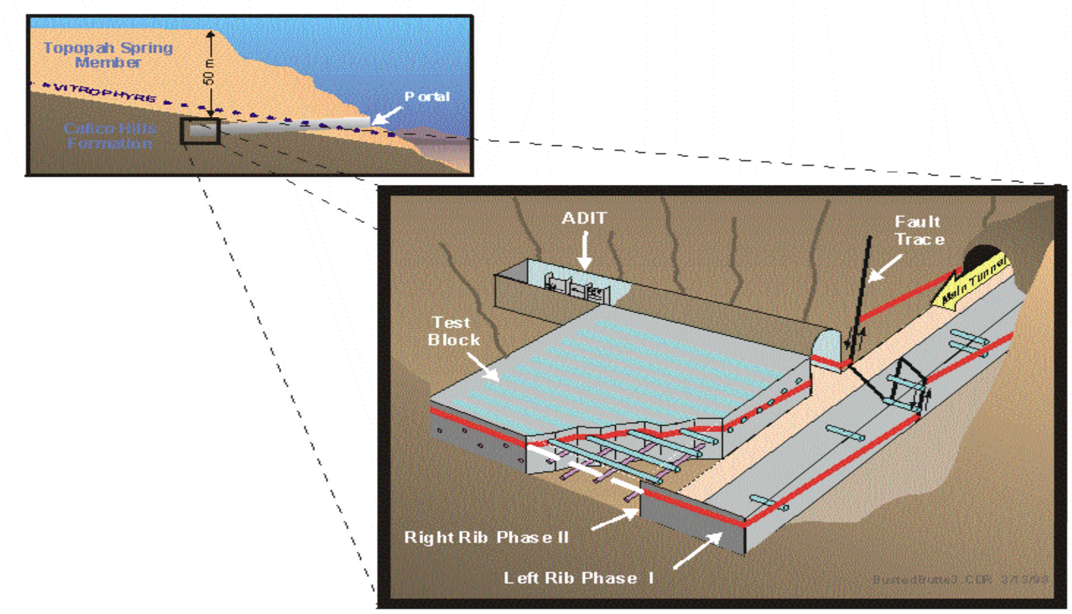


Fig. 2. Underground excavated facility at Busted Butte.

Objective: To develop an understanding of flow and transport in the unsaturated zone below the proposed repository horizon. The stratigraphic location is at the contact of the Topopah Springs tuff and the underlying Calico Hills formation.

Specificity: The presence of both fractured and unfractured rock and various minerals including zeolites will allow testing and evaluation of controls on transport processes below the proposed repository horizon.

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Consultants Meetings

Vienna, Austria: 14–18 April 1997, 15–19 March 1999,
30 August–3 September 1999, 10–14 April 2000

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