EUROPEAN COMMISSION

Community Research

ESDRED

(Contract Number: FI6W-CT-2004-508851)

Module 6 (Integration activities)

Final summary report and global evaluation of the project

Author(s):	**IPC with contribution of all Contractors**	
Approved and Validated:	**W.K.SEIDLER**	

Date of issue of this report: **30 January 2009**

Start date of project: **01 February 2004** Duration: **60** Months

Project co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	Yes
RE	restricted to a group specified by the partners of the ESDRED project	No
CO	confidential, only for partners of the ESDRED project	No

TABLE OF CONTENTS

List of Figures

Publishable Executive Summary

The Integrated Project known as ESDRED (Engineering Studies and Demonstrations of Repository Designs) has been a joint research and development effort by major national radioactive waste management agencies (or subsidiaries of those agencies) and by research organisations. ESDRED was co-ordinated by the French National Radioactive Waste Management Agency (ANDRA) and was part of the European Commission's 6th Euratom Framework Programme for Nuclear Research and Training. The five year Project started with a total budget of EURO 18.4 million, of which 7.3 million was provided by the EC's Framework Programme. Many of the participants elected to do more, or more elaborate, work than originally envisaged so that a conservative estimate of the total final expenditure (including other increased costs) is 23 million €.

The 13 participants (Contractors) in this project, from 9 European countries, were:

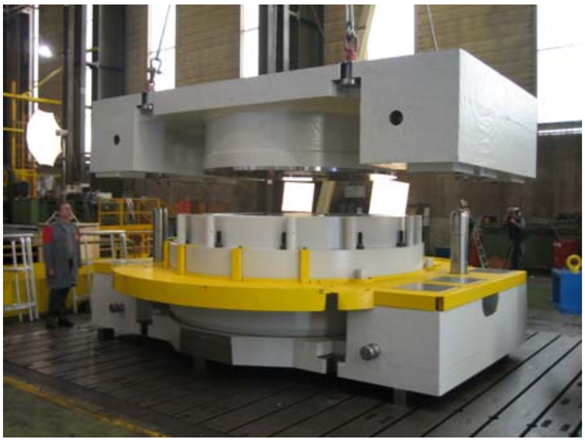
Radioactive Waste Management Agencies:
ANDRA, France
ENRESA, Spain
NAGRA, Switzerland
NDA (Originally NIREX), United Kingdom
ONDRAF/NIRAS, Belgium
POSIVA, Finland
SKB, Sweden

Technological R&D Organisations:
AITEMIN, Spain
CSIC, Spain
DBE TECHNOLOGY, Germany
ESV EURIDICE EIG, Belgium
GRS, Germany
NRG, the Netherlands

ESDRED has been focused on technology and has had three main objectives. The **FIRST OBJECTIVE** was to demonstrate, at an industrial scale, the technical feasibility of some very specific activities related to the construction, operation and closure of a deep geological repository for high level radioactive waste. This part of the work was organised inside four (4) Technical Modules (and numerous work packages) and essentially involved the conception, design, fabrication and demonstration of equipment or products for which relevant proven industrial counterparts (mainly in the nuclear and mining industry) do not exist today. Execution of the work was often by third party sub-contractors (especially the detailed design, fabrication and testing of new equipment) although, depending on the participant, more or less of the work was done in-house.

Each of the four technical Modules involved from 3 to 7 participants thus ensuring that the know-how and experience from several different national disposal concepts could be integrated into the work. The programmes within these Modules are provided on the following pages.

Within **Module # 1, Buffer Construction Technologies for Horizontal Disposal Concepts,** certain participants were able to successfully design the necessary formulation and thereafter produce 4 tonne bentonite rings to be used as an engineered barrier. Other participants demonstrated backfilling of the annular gap between a waste canister and the disposal drift wall using a variety of wet and dry products. Still others developed the product and the technique for backfilling disposal drifts with granular bentonite. The evolution over time and the performance of bentonite based seals, particularly in relation to gas permeability, was also assessed and is in fact on-going beyond ESDRED. Aspects of seal construction and the interaction between the swelling seal material and the host rock were the focus of another participant. In situ underground construction of such a seal is foreseen for Q2 2009.



100 Tonne Mould for Pressing Sand/bentonite Rings

Double Auger (green) Placement of Granular Bentonite around a Canister

Finally non- intrusive monitoring techniques based on seismic tomography were also developed and demonstrated.
The various reports produced, most of which are available to the public, will enable interested parties:

- To design a sand/bentonite mixture which, when compressed into a ring or produced as pellets, is suitable to be used as an engineered barrier around waste canisters with appropriate physio-chemical characteristics
- To design and fabricate a mould for producing large EBS rings as well as all the related stripping and handling equipment
- To formulate various wet and dry materials for use as a backfill and to evaluate different related placement options
- To design and construct a seal in a disposal drift with a prior understanding of the potential interaction between the swelling seal material and a clay host rock
- To formulate a borehole seal made of moderately compacted sand/bentonite mixtures and to have an understanding of the gas/water permeability of such a seal over time and with increasing water saturation
- To evaluate whether non-intrusive monitoring based on seismic tomography is suitable to this particular application and to understand the scope and limits of the technique

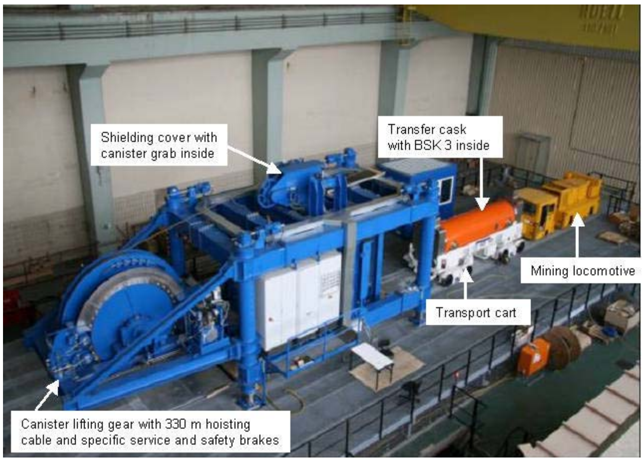
4 Tonne, 2.25m Diameter Sand/bentonite Ring After 45 000 tonnes of Pressure & Stripping from Mould

Granular Materials Backfill Test Configuration (June-Oct. 2006)

Back-end side of the mockup after removal of the lid

Borehole seal tests and non-intrusive monitoring tests were all conducted underground however the EBS rings and the backfilling tests (with the exception of the O/N Praclay Plug Construction) were conducted on surface, but at full scale.

In **Module # 2** the two main participants were able to design, fabricate and demonstrate the equipment needed for the **Transfer and Emplacement of Waste Canisters** weighing between 2 and 5.2 tonnes. The equipment is designed for emplacement in both horizontal and vertical disposal boreholes with very small annular clearances between the canister and the wall of the disposal boreholes. A desk study related to retrievability was also produced.



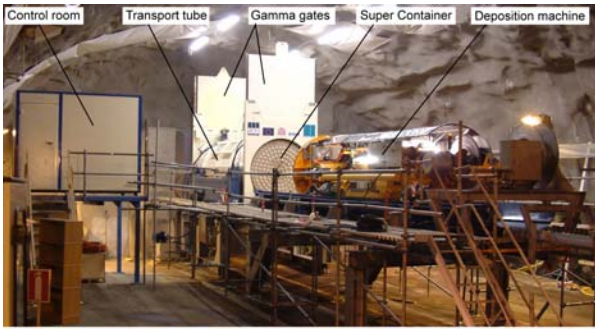
Vertical Emplacement Device

Horizontal Emplacement Demonstrator

The horizontal emplacement equipment which was produced (photo on left) can be seen by the public at ANDRA's Technology Centre (CTe) in Saudron, near the Bure URL. Likewise the vertical emplacement equipment (photo above) can, for the short term at least, still be seen at the Kraftwerk Robert Frank facility at Landesbergen Germany. The vertical equipment was designed and fabricated in compliance with German atomic and mining regulations.

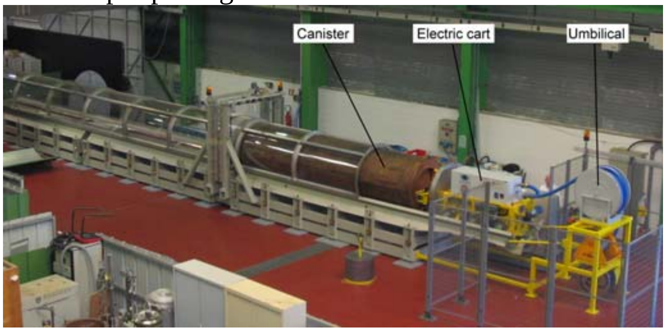
Both emplacement systems were demonstrated in surface facilities using inert waste canisters that were otherwise accurate geometrically and with regard to mass.

Heavy Load Emplacement Technology for horizontal disposal concepts was the only focus of **Module # 3.** The two participants active in this work each successfully produced a machine for emplacing 45 tonne waste canisters in bored disposal tunnels while maintaining only a very small annular gap between the canister and the walls of the tunnel. One machine was based on water cushion technology while the other used air cushions.



Water Cushion Emplacement Machine with 45 Tonne Super Container in Background

The latter machine was subsequently adapted to demonstrate the emplacement of packages of 4 bentonite rings produced in Module 1, weighing 17 tonnes per package.



Demonstration of emplacement of 45 tonne canister using Air Cushion Emplacement Equipment

The air cushion machine is also on public display at ANDRA's Technology Centre in Saudron, near the Bure URL. At time of writing the water cushion machine is set up underground on the -220m level at the Äspö URL. Design details, test results, as well as recommendations for future enhancements are available in the various project reports which have been designated for public access.

The work in **Module # 4, Temporary Sealing (using low-pH cement) Technology,** consisted first of designing low-pH cement formulations and then of preparing several concrete designs suitable for the construction of sealing plugs and for rock support. In both cases shotcreting was used as the construction method. A short plug and a long plug were subsequently constructed in 2 different URL's. The short plug was loaded to failure, (i.e. slippage), very quickly and monitored during the entire process. The full scale longer plug is still being loaded using the swelling pressure created by bentonite blocks which are being artificially hydrated. This is a much slower loading process more closely related to what would happen in reality (albeit still on a much faster time scale).

At time of writing the swelling pressure of the bentonite had not reached the nominal value, thus the plug has not started to slip.

Short Plug Construction at Äspö

A variety of project reports, available to the public, describe in detail the process used to develop low-pH cements which would meet the project needs. Other reports describe the test plan and the execution related to the construction of the 2 plugs noted above.

Long Plug in Background with Monitoring Equipment

The short plug constructed at Äspö has been tested and demolished. However the full scale long plug at the Grimsel test site in Switzerland is still intact. The desired water saturation and the maximum swelling pressure are not expected to be reached until well after the end of the ESDRED Project. As the saturation of the bentonite is taking longer than expected the partners involved agreed to continue with the saturation of the bentonite blocks and the related data monitoring. The Grimsel Test Site is managed by NAGRA and can be visited at any time by making appropriate arrangements in advance. The evolution of the long plug test will be followed and interpreted under the planned EURATOM 7th Framework Programme, MoDeRn Project.

This plug has also been employed for a further programme of cross-hole seismic tomography and wireless monitoring (TEM Project) organised by some of the ESDRED partners outside of the ESDRED programme.

A **SECOND** and equally important ESDRED **OBJECTIVE** was to promote a shared European vision in the field of radioactive waste disposal technology. This was accomplished through the INTEGRATION process, which is one of the key objectives that identify EURATOM's 6th Framework Programme. Among other things integration resulted from working together, sharing information, comparing input data and functional requirements, learning from one another's difficulties, developing common or similar tender documents and bidder lists, jointly developing courses and workshops and coordinating demonstration activities whenever possible.

Clearly objectives such as designing a common European Repository or even designing European Repositories that are all based on common technology did not fall within the ESDRED mandate. In the end the legal framework, the national waste management programs, the existing and the perceived constraints, the stakeholder expectations and the physical settings are different in each country. On the other hand by working together the participants were able to observe first hand that they were all facing the same basic challenges and that they all shared a concern for the same fundamental issues that are key to the design of a safe geological HLW repository. In other words it quickly became clear that there already existed a common European view regarding deep geological disposal of high level radioactive waste, which was simply reinforced by the ESDRED experience. For example all national waste management agencies are concerned with (among many others) most of the issues listed below:

- Having a stable geological media with well know characteristics and behaviour
- A need to ensure operational and long term safety
- Having multi-barrier systems for isolating the waste
- Having safe and effective handling and emplacement methods
- Having reliable and proven transport and emplacement equipment
- A need for effective backfill and sealing materials, placement methods and related equipment
- A need for reversibility, retrievability and monitoring

Except for the first 2 bullets all of the other items in the list relate somehow, either directly or indirectly, to the ESDRED Project and everyone has learned from the solutions being developed by the others.

Some of the positive results from the ESDRED integration experience are somewhat intangible while others may not manifest themselves for some time. On the other hand some very obvious things did occur. For example emplacement systems and equipment were designed for handling different types of canisters in different settings. This equipment did not exist before ESDRED. Although it would be unrealistic to expect that suddenly this new equipment would become "*off the shelf*" it remains however that all the participants had, and continue to have, access to the designs and various related reports and more importantly that they had an opportunity to see the equipment operate, that they know who the engineers/fabricators were and most importantly that they know where they can see the equipment on display. In the course of the past 5 years a significant confidence building phenomenon has taken place. The same is true regarding all the work related to engineered barriers and to backfilling.

In the course of the project other positive things, with potentially long term benefits, happened as well. For example, the participants had the opportunity to visit each of the underground laboratories associated with the ESDRED partners. In the course of these visits there was the usual transfer of knowledge and experience as expected but also, and of equal importance, a network of contacts for the future exchange of information was established.

Demonstrations were arranged at the workshops of the Contractors hired to design and fabricate various equipments. Thus a network of competent contractors that might be considered for future work was developed. Because of the variety and complexity of some of the work that was put out to tender the ESDRED participants helped each other establish different international bidders' lists. Also, for the same reasons, some work was awarded to smaller firms which had never before operated in the nuclear field.

A team of "*technical experts*" was assembled specifically to review certain aspects of the early work and to witness some of the technical demonstrations. This covered the broad spectrum of the ESDRED work and as these *technical experts* became familiar with the work being undertaken they critiqued the work and provided valuable comment. They have subsequently been available to any of the partners for other or related projects.

The **THIRD OBJECTIVE** focused on training and communication. Over the life of the project the participants wrote articles, presented technical papers at international conferences, produced videos, held workshops, developed and presented university lectures, and finished up by organising an international conference on the operational aspects of deep geological disposal. Also a web site (www.esdred.info) was created and maintained over the life of the project. This site will be kept on line until about March 2010.

Once again the ESDRED participants were called upon to work very closely together in order to get the job done. Joint papers were written by representatives from several different national agencies. Seventeen (17) Masters level lectures were developed by 8 of the 13 ESDRED participants and presented to the students of the University Polytehnica of Bucharest, Romania. Three workshops were organised. Two workshops entitled *"R&D on low-pH Cement for a Geological Repository"* were organised by the concerned ESDRED partners and attracted an international audience and authors. A third training workshop organised by DBE TECHNOLOGY focused on "*Transport and Emplacement Technologies for Radioactive Waste Packages*". ESDRED representatives also participated world wide in workshops organised by others. Broad dissemination of ESDRED results undoubtedly helped to build confidence in the types of disposal concepts being considered in the European nuclear area as well as to bring the representatives of the national agencies closer together. As a minimum a better understanding of the issues was shared and a broader knowledge of the available solutions was imparted. Informal networks of engineers, contractors, suppliers and experts were established.

The crowning highlight of the Project came in June of 2008 when an *"International Technical Conference on Practical Aspects of Deep Radioactive Waste Disposal"* was organised by ESDRED in conjunction with the Czech Technical University of Prague (CTU) and RAWRA the Czech national waste management agency. This Conference was held in the facilities of the CTU. Nineteen of the 37 papers and posters related directly to ESDRED, to the national agencies represented in ESDRED or to the contractors that had been engaged by

ESDRED participants. Eleven of the 13 ESDRED partners worked together to make this important event happen. The results were much appreciated by the more than 120 participants hailing from 19 different countries. The proceedings have been posted on the ESDRED website and bear the following ISBN # 2-916162-05-4.

The last major communication and confidence building activity undertaken by the ESDRED partners occurred in October of 2008 at the EURADWASTE ’08 Conference. ESDRED contributed 5 papers and 3 posters to this event. Four of the 5 papers were in fact presented as part of the associated field trip to Bure, the site of the French URL. On this occasion, heavily attended by local, regional and national French politicians, as well as by many representatives from various European NWM agencies, ANDRA’s demonstrators (including those produced within ESDRED) were all on display and operational in the new showroom of the Technology Centre (Cte) located next to the URL. Meanwhile in Luxembourg, at the entrance to the main meeting room 2 large TV screens were showing ESDRED produced videos on a continuous basis.

1 Introduction

1.1 Summary of ESDRED Project

The Integrated Project known as ESDRED (Engineering Studies and Demonstrations of Repository Designs) has been a joint research and development effort by major national radioactive waste management agencies (or subsidiaries of those agencies) and by research organisations. ESDRED was co-ordinated by the French National Radioactive Waste Management Agency (ANDRA) and was part of the European Commission's 6th Euratom Framework Programme for Nuclear Research and Training. The five year Project started with a total budget of EURO 18.4 million, of which 7.3 million was provided by the EC's Framework Programme. Many of the participants elected to do more, or more elaborate, work than originally envisaged so that a conservative estimate of the total final expenditure (including other increased costs) is 23 million euros.

The 13 participants (Contractors) in this project, from 9 European countries, were:

Radioactive Waste Management Agencies:
ANDRA, France
ENRESA, Spain
NAGRA, Switzerland
NDA (Originally NIREX), United Kingdom
ONDRAF/NIRAS, Belgium
POSIVA, Finland
SKB, Sweden

Technological R&D Organisations:
AITEMIN, Spain
CSIC, Spain
DBE TECHNOLOGY, Germany
ESV EURIDICE EIG, Belgium
GRS, Germany
NRG, the Netherlands

ESDRED was mainly focused on technology issues and had **THREE MAIN OBJECTIVES**.

The **FIRST ESDRED OBJECTIVE** was to demonstrate, at an industrial scale, the technical feasibility of some very specific activities related to the construction, operation and closure of a deep geological repository for high level radioactive waste. This part of the work was organised inside four (4) Technical Modules (and numerous work packages) and essentially involved the conception, design, fabrication and demonstration (and further evaluation) of specific equipment or products for which relevant proven industrial counterparts (mainly in the nuclear and mining industry) do not exist today. Execution of the work was often by third party sub-contractors (especially the detailed design, fabrication and testing of new equipment) although, depending on the participant, some of the work was done in-house. Each of the four technical Modules involved from 3 to 7 participants thus always bringing the know-how and experience from several different national disposal concepts to the work. The programmes within these Technical Modules are provided below.

- Within **Module # 1, Buffer Construction Technologies for Horizontal Disposal Concepts,** certain participants were able to successfully design the necessary formulation and thereafter produce 4 tonne bentonite rings to be used as an engineered barrier. Other participants demonstrated backfilling of the annular gap between a waste canister and the disposal drift wall using a variety of wet and dry products. Still others developed the product and the technique for backfilling disposal drifts with granular bentonite. The evolution over time and the performance of bentonite based seals, particularly in relation to gas permeability, was also assessed and is in fact on-going beyond ESDRED. Finally non- intrusive monitoring techniques based on seismic tomography were also developed and demonstrated paving the way for additional experiments and cooperation between some of the partners beyond the end of the ESDRED Project.

- In **Module # 2**, the 2 main participants were able to design, fabricate and demonstrate the equipment needed for the **Transfer and Emplacement of Waste Canisters** weighing between 2 and 5.2 tonne, in both horizontal and vertical disposal boreholes. A critical review type desk study related to retrievability of emplaced canisters was produced by a third partner.

- **Heavy Load Emplacement Technology** for horizontal disposal concepts was the only focus of **Module # 3.** In this Module two machines were successfully produced, each capable of emplacing 43 to 45 tonne waste canisters in bored disposal tunnels while maintaining only a very small annular gap between the canister and the walls of the tunnel. One machine was based on water cushion technology while the other used air cushions. The latter machine was subsequently adapted to demonstrate the emplacement of sets of 4 pre-assembled bentonite rings (produced in Module 1), weighing 17 tonnes.

- The work in **Module # 4, Temporary Sealing (using low-pH cement) Technology,** consisted first of designing a low-pH cement formulation and then of preparing several concrete designs suitable for the construction of sealing plugs and for rock support using shotcrete techniques. A short plug was constructed at Äspö in Sweden and it was very quickly loaded to failure i.e. slippage by applying water pressure to one face. A second, much longer full scale plug was subsequently constructed at Grimsel test site in Switzerland. It was loaded using the swelling pressure created by bentonite blocks which were artificially hydrated. At time of writing the long plug had not started to slip. As the saturation of the bentonite is taking longer than expected the partners involved agreed to continue with the saturation of the bentonite blocks and the related data monitoring. It is planned that the results of the test will be followed under the EURATOM's 7^{th} Framework Programme, **MoDeRn** Project.

A **SECOND** and equally important **ESDRED OBJECTIVE** was to promote a shared European vision in the field of radioactive waste disposal technology. This was accomplished through the **INTEGRATION** process, which is the essence of **Module 6** and which is one of the key objectives that identify EURATOM's 6th Framework Programme. Among other things **INTEGRATION** resulted from working together, from sharing information, from comparing input data and functional requirements, from learning about one another's difficulties, from developing common or similar tender documents and bidder lists, from jointly developing courses and workshops and from coordinating demonstration activities whenever possible.

Generally at least two **INTEGRATION** meetings were convened annually so that all ESDRED participants were updated on the progress of the work in all the Modules. Whenever practical these meetings were combined with the demonstration of a particular piece of new equipment, process or construction.

The **THIRD ESDRED OBJECTIVE** was entirely focused on training and communication which is the essence of the work in **Module 5** of the Project. Over the life of the project the participants wrote articles, presented technical papers at international conferences, held workshops, produced videos, developed and presented university lectures. The Project finished up by organising an international conference on the operational aspects of deep geological disposal in June 2008 and by contributing significantly to the EURADWASTE '08 Conference in Luxembourg/Bure in October 2008. A web site (www.esdred.info) was created and maintained over the life of the project with more than 16 000 visitors by Q3 2008. This site will be kept on line until 2010.

1.2 Scope of application of ESDRED Work

The objective of this section is to highlight that, in spite of all the commonality between the different European national reference concepts for high level and long lived waste disposal, there are nevertheless many important differences in the details. When faced with the technical and scientific challenge associated with the disposal of highly active and long lived radioactive waste all European National Waste Management Agencies involved in ESDRED (and probably all those not involved as well) have all come up with a common solution i.e. deep geological disposal. Nevertheless, as shown in the subsections below, there are many differences in the approach and/or the conditions. The reader should be aware that in a few instances the technical concept that was studied within ESDRED was in fact an alternative to the corresponding national reference concept. To give just a couple of examples: low-pH cement for rock support was studied by NAGRA as an alternative to their reference concept; SKB developed a horizontal emplacement system to complement their reference concept which is vertical disposal and DBE-TEC have designed, fabricated and demonstrated a vertical disposal system using BSK-3 canisters for the disposal of spent fuel whereas the German reference case is the horizontal disposal of POLLUX casks.

The benefits of having so much different know-how and experience readily available within the four common ESDRED technical themes are significant but at the same time they are difficult to evaluate.

1.2.1 Different Host Rocks

It is a given fact that the ESDRED partner organizations have been developing repository design(s) within the context of their own national programs, thereby focussing on the host rocks available within their own countries. In terms of general characteristics, three basic types of host rock can be discerned, i.e. salt, crystalline and clay host rocks. The latter host rocks can be further subdivided according to their level of induration.

The basic host rock type is a determining factor in the development of a disposal concept and has an impact on many other aspects of the repository design. In a host rock with important water movements, such as a crystalline host rock, it is necessary to surround the waste with a hydraulically sealing engineered barrier (the “buffer”), and to protect this barrier from degradation processes. Hence, the importance of using low-pH cement in disposal concepts for these host rocks to avoid the unfavourable impact of high pH cement on the buffer. In a host rock that is susceptible to alteration at high temperatures, it is necessary, during the thermal phase, to reduce the peak temperature by encapsulating the waste in a watertight engineered barrier or “overpack” having a higher thermal conductivity. In a plastic host rock such as clay (salt on the other hand is an elasto-plastic rock typically with good unsupported stability), it will be necessary to provide the disposal drifts with a rigid lining capable of withstanding the host rock lithostatic pressure. In those host rocks, for economical reasons, there will be a strong tendency to limit the dimensions and the extent of excavations to a minimum, which has consequences on many operational aspects of the repository.

The partner organizations that have been involved in Module 1 (“Buffer Construction”) have based their work on a repository design in a clay host rock. Nevertheless, the disposal concepts belonging to those designs are not transportable from one host rock to the other. The host rocks envisaged by ANDRA and NAGRA, respectively Callovo-Oxfordian and Opalinus Clay, are both indurated clays, but the Swiss Opalinus Clay is more capable of sustaining high temperature excursions, for reasons of geological history. Consequently, the overpack temperature limit, which represents an important boundary condition for the design of the engineered barriers, is much higher in the NAGRA concept (150°C versus 100°C). The host rock envisaged by ONDRAF/NIRAS (O/N) is poorly indurated plastic clay, with excellent self-sealing qualities, but also one which is relatively corrosive, so that in the disposal concept much emphasis has been put on the protection of the overpack and less on any hydraulic buffer component. Hence O/N have adopted the use of high pH cement, which at first glance would seem contradictory in relation to the importance of using low-pH cement in crystalline rock disposal concepts, e.g. the SKB and POSIVA situation.

In some countries, such as in Germany and the USA, rock salt has been selected as the host rock. In Germany, rock salt was selected in the early 1960s as the preferred host rock for a repository for heat-generating waste because of its unique hydrogeological, thermal, and geomechanical properties which make it a self-healing impermeable rock. In comparison to other host rock formations the heat conductivity of rock salt is twice as high. Thus the temperature limit at the contact between waste container and salt can be as high as 200° C. On the other hand the mechanical stability of rock salt makes it possible to excavate and operate (over decades) rooms and drifts in a mine that may be 800m to 1000m below surface, without needing any ground support structures. This is evidenced by the salt mining industry over more than 100 years. Furthermore the creep behaviour of rock salt, over time, ensures the entire enclosure of waste packages by the host rock itself. Thus, from a safety point of view the salt host rock is the most important barrier. Engineered barriers such as the waste container and the buffer materials are less important.

A number of repository design aspects are not directly host-rock related and thus these are relatively transportable, e.g. monitoring, sealing, handling and transportation, safety measures, etc. The work by Module 1 partner GRS, on the performance of seals, primarily developed within the context of a clay host rock repository, would be directly applicable also to salt and crystalline host rocks. The work by Module 1 partner NDA, on non-intrusive monitoring by use of micro-seismic technology, performed in Opalinus Clay, is also easily adapted to other host rocks. As a matter of fact, a similar program of non-intrusive monitoring experiments (outside of the ESDRED scope) has been set up by some of the partners at Grimsel, a crystalline host rock URL.

1.2.2 Different Transport Systems to Underground Disposal Unit

Designs for getting packaged radioactive waste from surface to underground were not specifically included in the ESDRED Scope of Work. Nevertheless the emplacement systems designed as part of ESDRED needed to take into account the technical specifications of the canister/overpack/transport cask which were to be delivered to the underground working level, and eventually to the disposal cell/drift excavated for the final disposal, and the method by which these were taken below surface.

Some partners in the project came from national designs based on shaft transport, others from ramp transport and still others from a mix of ramp and shaft underground access. It is interesting to note that the ESDRED partners represent 5 active European URL's and one under construction. The various underground accesses for these URL's include shaft only, shaft and ramp, and adit only access. None are ramp only at the present time although 2 partners are cooperating (as a direct result of working together on ESDRED) on a shaft versus ramp access study. These two have already shared information and undertaken a joint site visit to an intermediate level radioactive waste repository which is based on ramp access only.

On the underground disposal levels ESDRED partners were familiar with rail and with rubber tyre transport, sometimes having adopted a combination of the two. After working together for 5 years some partners were encouraged to look at alternate transport systems to the ones incorporated inside their national reference concepts – for example replacing shaft transport with ramp transport.

1.2.3 Different Disposal Configurations

According to the host rock(s) available in a country and the type and amount of radioactive waste to be disposed of specific technical repository designs have been developed for deep geological disposal. This task includes the development of an appropriate disposal concept comprising also the configuration of emplacement cells (drifts and boreholes either vertical or horizontal) in the repository.

The two Scandinavian ESDRED partners have developed repository concepts in crystalline rock. Their repository will be constructed at a level of some 500m below surface and be accessible via a shaft and ramps. Two concepts for direct disposal of spent nuclear fuel canisters were separately designed based on the multi barrier system called the “KBS-3”. The “KBS-3V” concept (reference case) deals with vertical emplacement of spent fuel canisters (25 tonnes) in 10m deep vertical disposal holes lined with buffer material on the floor and the walls. The “KBS-3H” concept (alternative case) deals with an alternative method, i.e. horizontal emplacement in drilled disposal drifts with a diameter of 1.85 m. In this case spent fuel canisters are surrounded by buffer material inside a Super Container (45 tonnes) and emplaced in a horizontal tunnel thus dispensing with the need for separate emplacement of buffer material and fuel canister. Within the ESDRED Project the KBS-3H concept was the subject of investigations including an in situ demonstration programme.

In Germany the reference concept for the disposal of heat-generating radioactive waste anticipates the emplacement of canisters containing vitrified waste in deep vertical boreholes, whereas spent fuel is to be disposed of in self-shielding POLLUX® casks in horizontal drifts inside a salt repository. The POLLUX® carbon steel casks weighing 65 tonnes each, are laid down on the floor of a horizontal drift at a depth of 840 m. The spaces between the casks and the drift walls are back-filled with crushed salt. The transport, handling, and emplacement techniques related to the POLLUX® cask were subjected to successful demonstration and in situ tests performed in the 1990s. As a result of these tests the atomic energy act was amended in 1994. In the vertical disposal concept, unshielded canisters with vitrified high-level radioactive waste (HLW) are emplaced in boreholes with a depth of up to 300 and a diameter of 60 cm. In order to facilitate the fast encapsulation of the waste by the host rock (rock salt) the boreholes are not lined. The maximum temperature at the contact surface between waste canister and host rock is maximum 200 °C.

In order to align and optimise the emplacement technologies for both categories of waste (vitrified waste and spent fuel), an alternative technical approach was investigated. Therefore the borehole emplacement concept already foreseen for the disposal of high-level reprocessing waste was now considered for consolidated spent fuel as well. Consequently a fuel rod canister (called BSK 3, capable of holding 3 PWR or 9 BWR fuel rod assemblies) was designed by the German nuclear industry. The design, fabrication and demonstration of a reliable transport and emplacement technology for BSK 3 canisters (5.2 tonnes) were an important component of the ESDRED Project.

In France, clay (Argillite) was selected as the host rock suitable for a geological repository for heat-generating waste (long-lived high activity), in the Bure area. The reference concept developed in the “Dossier 2005” for the emplacement and storage of C type (vitrified waste) canisters in horizontal disposal cells comprises a 40-m-long horizontal disposal cell lined with a carbon steel casing to support the clay formation wall and to facilitate any future retrieval operation of the C type package (2 tonnes). The access gallery at a level of approx. 500m below surface enables the transport shuttle to reach the cell mouth for docking operations and the subsequent emplacement of the canisters. The main difference between this reference concept and the technical programme developed in ESDRED is the length of the disposal cell which has been increased from 40 m to 100 m. The original plan to develop further disposal concepts for spent fuel was postponed on the basis of a new law enacted in June 2006.

Opalinus clay in the northern part of Switzerland has been chosen as the favoured host rock for the reference disposal concept for vitrified HLW and for spent fuel. The emplacement level will be 650m below surface and accessible via a shaft (for transport of personnel and materials) and a ramp (for transport of waste packages). The waste packages will be emplaced in inclined (4 to 6 %) 800m long galleries with a diameter 2.5 m. The waste packages and the compacted bentonite blocks which they are meant to sit on will be emplaced by remote controlled equipment. The empty space between the waste package and the drift wall will be backfilled with granular bentonite. All the emplacement and backfill equipment is rail mounted and powered by electric drives and winches. Within the ESDRED Project the backfilling of the granular buffer material was investigated and demonstrated.

In Belgium, Boom clay has been selected to host radioactive waste from NPPs and from reprocessing. The reference disposal concept comprises the emplacement of Super Containers (30 tonnes for HLW canisters and 60 tonnes for spent fuel assemblies) in horizontal galleries at a depth of approximately 300m below surface, accessible via shafts only. The Super Containers consist of a thick Portland concrete buffer enclosing a 50cm diameter cylindrical carbon steel overpack with 30mm walls. The overpack contains either two vitrified HLW canisters or four UOx assemblies. The Super Containers are emplaced in 1km long and 3m diameter disposal galleries which are lined with concrete. Once a 30m long section of a disposal gallery is filled, the remaining empty space between the canister and the gallery wall will be backfilled either by injection of a cement based material (grout) as the reference solution or, as a potential alternative, by pneumatic projection of a granular material. Within the ESDRED Project the backfilling techniques (grout and granular) were the subject of intensive investigations and demonstration programmes.

1.2.4 Different Emplacement Systems

Experience related to the transport and handling of radioactive waste packages has been accumulated over a long time period within EC. For example, in France, the “Centre de La Manche” facility was operated from 1969 to 1994 and that facility is now replaced by the “Centre de l’Aube” which started operation in 1994. In Spain similar experiences are collected at the El Cabril facility and in Sweden at the SFR facility, the final repository for low level operational waste. The waste packages arrive at these repositories sites in shielded containers that meet the IAEA Transport Regulations. The unloading of the waste packages and their emplacement in the disposal cells at these facilities is mainly done with overhead cranes.

However, canisters with spent nuclear fuel or vitrified waste have, up to now, not been transported or disposed of in a deep geological repository. It is nevertheless foreseen that the transportation will also be done in shielded casks that will meet the IAEA Transport Regulations. The size and weight of the transport casks will depend on the size and radiation level of the waste packages. For spent fuel canisters the weight will be in the range of 50 – 90 tonnes.

The transport from surface to the repository level will be done either in a shaft or a ramp. The transfer of the cask down to the repository level has not been included in the ESDRED project. Nevertheless in the early 1990’s there was a successful 1:1 scale demonstration in Germany when a 65 tonne cask sitting on a 20 tonne transport wagon were transported in a simulated shaft set up on surface.

However, within the ESDRED project three different emplacement systems for waste packages have been developed and tested.

In Module 2 both horizontal and vertical emplacement systems have been demonstrated for the Transfer and Emplacement of Waste Canisters weighing between 2 and 5.2 tonnes. In the horizontal emplacement system (developed by ANDRA) a vitrified waste container, placed in an over-pack fitted with ceramic runners on the outer shell, is emplaced in clay in a drift up to 100 m long by a pushing robot.

In the vertical emplacement system (developed by DBE TECHNOLOGY) the system developed within ESDRED is designed to emplace spent fuel canisters (BSK 3) in 60 cm diameter vertical boreholes in salt with a depth of up to 300 m.

In Module 3 emplacement systems based on the use of a fluid (water or air) cushions for the transportation of heavy loads in narrow drifts were developed by SKB/Posiva and ANDRA respectively. The deposition machine developed by SKB/Posiva uses a cradle fitted with water cushions for emplacing 45 tonne waste containers in bored disposal drifts with only a very small annular gap between the container and the walls of the drift. The waste container, normally called a “Super Container”, consists of a copper canister with encapsulated spent fuel, surrounded by buffer material and assembled in a container with a perforated outer shell to which short 50 mm feet are attached.

In the ANDRA case the deposition machine has a cradle fitted with air cushions for the emplacement of 43 tonne canisters containing spent nuclear fuel. ANDRA also demonstrated that the same technology can also be used for the emplacement of packages of 4 bentonite buffer rings with a total weight of 17 tonnes per package.

The choice of water or air cushions is related primarily to the type of host rock in the deep geological repositories. Water, for obvious reasons, is not suitable for a disposal horizon composed of clay rocks whereas it is very suitable for disposal in crystalline rock. There are also operational advantages whenever water can be used. These are explained in more detail in Chapter 2.3.

1.2.5 Different Materials for Underground Construction and Backfilling

Ordinary construction or mining methods, which vary somewhat depending on the type of host rock, are used or planned to be used for the construction of repositories and therefore for the excavation of drifts/tunnels designed for the disposal of radioactive waste. Rock support by steel arches, concrete rings, cast in place concrete, steel or non-metallic rock bolts and wire mesh in combination with shotcrete and/or cement grouting, may be required in weak rocks or in hard rock where drifts and shafts intersect unstable fracture zones. In soft clays, the disposal drift lining is typically based on precast, non-reinforced concrete ring elements, which are placed against the excavated drift wall with special mechanical equipment. In indurated clays the disposal drift lining is often based on shotcrete. Concrete will also be used for construction of various auxiliary structures needed for the normal operation of the repository. In a repository in rock salt the openings will remain stable for decades without the need for any artificial ground support. Periodic scaling to remove loose rock from tunnel roof and walls is normally sufficient.

The major components of the Engineered Barrier System (EBS) are: the canisters containing the radioactive waste, the buffer to isolate the canisters and the backfill and plugs to seal and stabilize the structures. The canisters currently being proposed by the various National Waste Management Agencies are made of materials with well-known properties and predictable performance: copper, cast iron, cast steel, carbon steel or stainless steel. The buffer could be made of smectite clay (e.g. bentonite without the addition of any sand or other material), although some programs propose bentonites mixed with aggregates in different proportions (e.g. sand/bentonite or crushed rock/bentonite mixtures) to increase the thermal conductivity, to improve the mechanical resistance and to reduce the cost. The envisaged buffer material for the emplacement of long-lived ILW in clay rock is typically cement (Ordinary Portland Cement or Blast Furnace Slag). Backfills for repositories in salt rock can be made of crushed salt, magnesium chloride or magnesium oxide (the later two are being used in the WIPP URL). For crystalline rock the envisaged backfill materials are different mixtures of clay and ballast, crushed rock or sand. For clayey rock the proposed backfill materials are typically crushed host rock from the excavation or bentonite/sand mixtures. Seals or plugs are needed to confine backfills in repository drifts and shafts. A basic seal/plug consists of a hydraulic sealing element made, for example, with bentonite and one or two bounding support elements (bulkheads or plugs) that guarantee the mechanical stability of the hydraulic seal. Other concepts look for alternative ways to provide the required mechanical stability of the seals. These include frictional gravel supports and specially designed rock blocks.

Therefore it can be seen that in most repository concepts significant masses of concrete will be in contact with the repository host rock and with the engineered barrier materials. Over time, concretes based on Ordinary Portland Cement (OPC), leached by the ground waters, will give rise to the release of significant quantities of ions, mainly OH-, K+, Na+ and Ca2+. The resulting leachate could have a pH as high as 13.5. This leaching water can potentially perturb the bentonite buffer, the backfill material and the near-field host rock (a phenomenon known as the hyper alkaline plume or plume effect). Hence this interaction and the potentially deleterious effects have to be addressed. For preventing the development of the hyper alkaline plume effect it has been proposed to develop low-pH cement pastes as an alternative to OPC for concrete formulation. The definition of these special materials and their suitability for the construction of shotcrete plugs and for rock support is the subject investigated in the Module 4 of ESDRED.

1.3 Elements of a Common European View of Geological Disposal Management

The previous sections in this Chapter 1 have served to summarise the ESDRED Project and to demonstrate that the participants in the project, by virtue of their individual national concepts and constraints, covered almost the entire spectrum of existing conditions, legislative requirements, stakeholder aspirations and other fundamental elements that might be encountered in the field of radioactive waste management. Thus those previous sections were intended to be a precursor to addressing the overriding question – did the ESDRED Project contribute to an enhancement of the *Common European View* in these matters? The authors believe the answer is YES!

Is there really such a thing as a common European view regarding the disposal of long lived HLW? This is a question that was not intended either to be asked or to be answered by the Scope of Work undertaken within ESDRED. On the other hand it was hoped at the outset that the work would help to "- - *underpin the development of a Common European View on the main issues related to the management and disposal of waste"*. After 5 years of working together there is no doubt that the overall experience, the sharing of information, the very close cooperation for certain parts of the work, the common presentations at international training and/or communication activities, etc, have all helped not so much to shape a Common European View as to confirm that a common view exists. The authors believe that the common view of the essential elements of waste management was strengthened, maybe even expanded, but in the end that will be for others to evaluate.

As a minimum it can be said that the 13 participants in the project witnessed first hand the validity of the statement that is sometimes used in this field "A Common Objective, a Variety of Paths". In our view the most important result of the work undertaken within ESDRED is that it will have increased the number of available solutions to the various needs or requirements (i.e. elements of a *Common European View)* of the different national waste disposal concepts and in particular that it will have increased the level of confidence in those solutions. The technical results of the ESDRED Project which give rise to the available solutions mentioned above are detailed in Chapter 2 of this report. What follows below is a summary discussion of the various features or elements of a *Common European View* and their link, if any to the ESDRED work. Those elements which have been identified are shown in bold in the following paragraphs.

As in any other industrial venture the **need for operational safety** is always the appropriate starting point. The notion of having a "fail safe" design was common to all demonstrators built by the partners. This of course applies primarily to SKB's water cushion emplacement equipment, to DBE TECHNOLOGY's vertical borehole equipment and to ANDRA's air cushion and pushing robot emplacement equipment; including reduced scale prototypes as well as the full size industrial versions of these. In conjunction with the fail safe design this type of mechanical equipment also incorporated the usual safety related interlocks, cameras, TV screens etc. Because the ultimate purpose of this equipment was for public demonstration the designs included the usual guards, shields, barriers and, where appropriate, full EC certification. Although the work related to shotcrete rock support, referred to in the next paragraph, has a strong operational safety element the actual development of the mixes and the methodology for applying the shotcrete was focused on a different common element of European design. This will be discussed briefly in a subsequent paragraph.

Other activities such as the backfilling work by ONDRAF/NIRAS (O/N) and NAGRA, the plug construction by AITEMIN/ENRESA or the shotcrete rock support work by SKB and NAGRA focused on appropriate dust control issues as well as the **need for radiation shielding coupled with remote control capabilities**. Remote control of course is also integral to the demonstrators mentioned in the previous paragraph.

The need for radioprotection was certainly a common thread throughout all of the work. It was taken into account in the design of the various demonstrator pieces of emplacement equipment and/or special handling equipment. Although real radioprotection features were not always actually incorporated in the demonstrators every effort was made to ensure that the mass and geometrical dimensions of the prototype equipment would be identical to the equipment (with full radioprotection) which would some day operate in a real repository.

The need for a well characterized and stable geologic media is also common to the view of all the waste management agencies that participated in ESDRED. Although this was a common assumption it did not enter any formal part of the work. The same can be said regarding **the need for a safe and stable access to the disposal area(s)** although here again the shotcrete for rock support work package contributed to this element.

Whereas all of the elements highlighted in the preceding paragraphs are related to operational safety in one way or another there is also a **need for long term safety** that is common to all European concepts. This too did not enter directly into the work undertaken by the ESDRED partners. On the other hand a number of other elements, all of which could be described as common to a European View of waste disposal, were directly or indirectly a part of ESDRED and these do in fact relate to the need for long term safety. They include the **need for multiple safety functions based on natural and engineered barriers.** In this regard ANDRA developed the formulations and eventually fabricated 4 tonne sand/bentonite donut shaped buffer rings designed to surround the waste canisters within the disposal tunnels. NAGRA proved that it could achieve similar results using granular bentonite with different sand/bentonite ratios. The **need to ensure the compatibility between engineered materials and between engineered materials and natural barriers** also relates to the common need for long term safety and was a part of the ESDRED Work, i.e. Module 4, managed by ENRESA. This included the design of different low-pH cement/concrete/shotcrete formulations. The actual design work was largely undertaken by CSIC and the actual construction and demonstrations were organised by AITEMIN, NAGRA and SKB. The underlying objective of having low-pH cement was to reduce the alkaline plume effect i.e. the impact of construction or backfill concrete on clayey barriers and to a lesser extent on the glass in vitrified waste canisters. Other partners such as O/N took a different approach preferring to use cements/concretes with a higher pH in the HLW overpack environment, based on the argumentation that: (1) the trade-off between the enhancement of the overpack integrity in the pyrite-rich Boom Clay host rock and the virtually negligible plume effect on the latter results in an overall gain in long-term safety, (2) the glass leaching has a negligible effect on safety performance in the envisaged long-term evolution scenario. Related to all of the above, with some overlap, is the **need to have effective backfill materials, the need for effective backfill placement equipment and methods,** the **need for effective sealing materials** and **the need for effective seal/plug construction methods and equipment**. The ESDRED work in Module 1 which is focused on Buffer/Backfill construction materials, and all of the ESDRED work in Module 4 which is focused on the development of low-pH cements, is related to the needs expressed in the previous sentence, in one way or another.

In spite of everyone's best efforts to design short, medium and long term safety into their repository concepts there will always be a **need for safe handling and emplacement methods** and a **need for proven and reliable transport and emplacement equipment.** These two elements are of course not separable from each other. Much, if not most, of the equipment that is needed to meet these requirements does not exist today in a ready to use off the shelf variety. Therein lies the "raison d'être" for ESDRED, and yet this is also its biggest challenge. Because of all the tangible evidence, there can be no doubt that from a technical perspective the project (all 4 Modules) was a success. Thus ESDRED was able to fill a very critical and important gap in repository concept design. This can be viewed as a major contribution to the back end of the nuclear fuel cycle and to the commonality between, not just the European Waste Management Agencies but, agencies world wide. The design, fabrication and demonstration of this equipment and the special products/processes developed gives agencies the option of considering concepts that may be different from the ones they are currently contemplating and the ability to do so with confidence. What better way is there to develop a common European view?

Another, but not totally common, element of the European View of radioactive waste disposal relates to the **need for flexibility** in view of the long time periods of operation, which are expected to span many decades. Different agencies, for a variety of reasons that are national by nature, have a different view regarding this need. In some national programs flexibility includes the need for **reversibility and/or retrieval methods & equipment**. For example, the ESDRED equipment designed for horizontal emplacement (ANDRA) included retrieval as one of its important functional requirements. Similarly SKB's horizontal emplacement equipment also has some retrievability capability although this is not a national requirement.

A final and incontestable element of the *Common European View* is the **need to communicate effectively with the public at large and to build confidence.** A specific Work Package called "Confidence Building" was included in ESDRED. The work involved participating in another EC FP6 funded project called COWAM which stands for **COmmunity WAste Management.** Over the course of 3 years this involved attending all of the WP4 meetings of this project and making numerous presentations regarding the objectives and the advance of the ESDRED technical work.

There is another aspect of confidence building that is not directly related to communicating with the public at large and that is **monitoring**. Once again national requirements vary from "must have" to "don't need" to "not yet decided". The main driver behind **monitoring** is the desire/need to provide confidence in a solution once it has been implemented. Within ESDRED, the state-of-the-art of non-intrusive monitoring has been advanced by a number of experiments at the Mont Terri URL using micro-seismic technology. Non-intrusive monitoring is characterized by the fact that the sensors are located outside of the engineered barrier system in order to avoid an effect on the safety performance of the disposal system. The fact that several European waste management agencies have cooperated on this subject within ESDRED and that it has found succession in similar cooperative projects going forward, is a good example of how ESDRED has contributed to the underpinning of a Common European view.

1.4 Common Elements Addressed Within ESDRED

As has already been stated a number of times in this report, in different ways, the ESDRED mandate was to develop technology, the need for which had been established **PRIOR** to the signature of the Contract with the EC. Hence those elements that might constitute a "*Common European View*" of radioactive waste management, and which are discussed and shown in bold in the previous section, were not specified within the Scope of Work of the ESDRED project. On the other hand, while working closely together, the partners came to realize more and more that they all shared essentially the same concerns and therefore had similar needs. This served to reinforce the notion that a "*Common European View*" already exists. The results of the ESDRED work therefore served to strengthen this notion by providing additional solutions to common needs that could be adopted with a higher degree of confidence than ever before.

A poster headline from a recent conference on nuclear waste management put this issue so succinctly, as follows: *"A common objective, a variety of paths"*. Over the course of the past 5 years the ESDRED partners have seen by virtue of real examples, over and over again, that they shared the same challenges but that the road to the solution was often different and at other times not as different as people had imagined.

Some of the common elements raised in Section 1.3 above are, except in a very indirect way, totally unrelated to any of the ESDRED Work Packages. The list below nevertheless serves as a reminder of those subjects that have been the focus of people's attention either by way of comparison or by a need/desire to know more about what others are doing. These include:

- Need for operational safety
- Need for multiple safety functions based on natural and engineered barriers
- Need for safe handling and emplacement methods
- Need for effective backfill materials
- Need for effective backfill methods and equipment
- Need for sealing materials
- Need for seal/plug construction methods and equipment
- Need for flexibility which in some national programs included reversibility and/or retrieval methods & equipment
- Need for radioprotection including radiation shielding and remote control
- Need to communicate effectively with the public at large and to build confidence
- Need for monitoring including the non-intrusive variety

2 Program Implementation

2.1 Buffer Construction Technology (Module 1)

2.1.1 State of the art and brief discussion of differences between national concepts

Module 1 is principally dedicated to the construction and/or emplacement, in a horizontal configuration, of the buffer around a disposed HLW package. In addition, Module 1 aimed to test the performance of seals (saturation rate and gas permeability) and certain seal installation aspects, and to advance the state-of-the-art of the application of non-intrusive monitoring techniques in geological repositories. The scope of Module 1 and the involved partners are summarized in **Figure 1**.

R&D projects, before ESDRED, had already studied several bentonite materials and their conditioning with the aim to investigate their application as key materials in buffers, backfill or seals in geological repositories (e.g. RESEAL in Mol or BOS in Grimsel). Most of these projects had been performed on a small or intermediate scale, and only a few addressed the emplacement techniques related to these components. The demonstration testing at full scale was essentially limited to the vertical disposal configuration. However, the horizontal configuration was getting increased consideration in the disposal concepts of several EU countries and it was also becoming clear that the horizontal configuration would pose specific challenges that had not been sufficiently addressed before. Module 1 was therefore in the first place set up to advance the technological know-how related to the construction of the buffer/backfill around a horizontally disposed HLW package. The investigation of this subject by the partners ANDRA, ONDRAF/NIRAS and NAGRA was motivated by the R&D needs within these organizations at the time ESDRED was set up. Three different configurations were considered because these organizations have developed different conceptual designs, for reasons that have been addressed in Section 1.2.3. Nevertheless, this work on different configurations is fully in line with the ESDRED objective to deliver “off-the-shelf” solutions.

In contrast to highly compacted buffers, lightly compacted clay-sand mixtures exhibit a high permeability to gas in the unsaturated state and a comparably low gas entry/break-through pressure in the saturated state in combination with an adequate self-sealing potential due to swelling of the clay minerals after water uptake from the host rock. By using optimized material mixtures, the potential development of a high gas pressure in the repository near-field is avoided and at the same time any possible migration of radionuclides from the waste matrix in the liquid phase through the buffer is diffusion-dominated, just like in the clay host rock. At the onset of ESDRED, the GRS had already been investigating the sealing properties of clay-sand within the projects “**2-Phase Flow**” [1] and **KENTON [2].** The objective within ESDRED was to develop the acquired knowledge further and to apply it in actual in situ conditions.

Seal construction in clay host rocks is a subject which, certainly at the onset of ESDRED, had only a relatively small knowledge basis; some theoretical studies had been performed, but in situ testing and/or seal construction were rare. There was e.g. **RESEAL** [3], but this was primarily focused on the sealing of shafts and access galleries and not disposal galleries.

Non-intrusive monitoring, which can incorporate borehole-based, surface-based or airborne techniques allows monitoring of the repository to be carried out remotely from the waste emplacement location. Non-intrusive monitoring avoids any potential consequences to the passive safety provided by the EBS. At the onset of ESDRED, the application of non-intrusive monitoring had already been considered by several waste management organisations (e.g. **the EC Thematic Network study [6]**). The objective within ESDRED was to select one particular technology that could be used for non-intrusive monitoring, considering the potential usefulness to other waste management organisations and the available time frame, and to develop it further while testing it under real in situ conditions. In the initial phase of ESDRED, seismic tomography was selected.

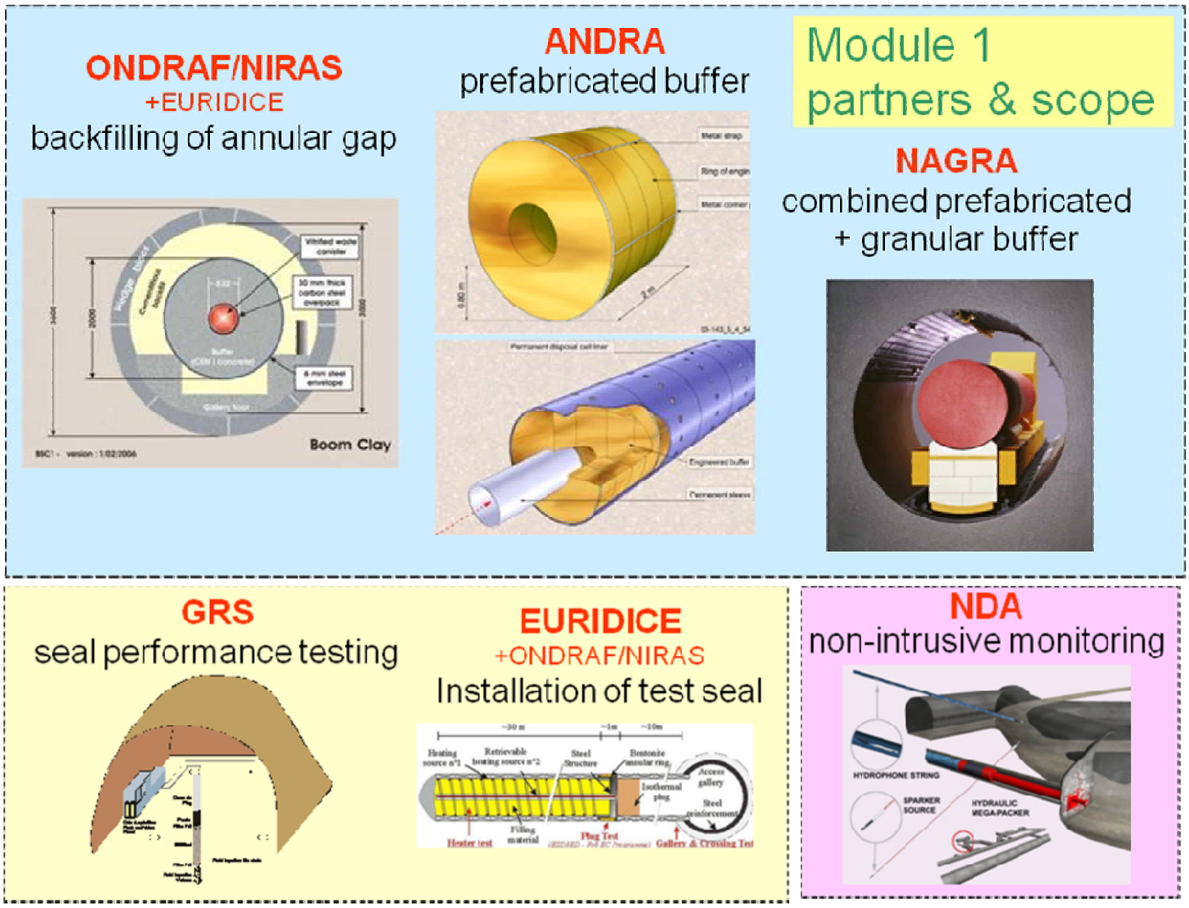


Figure 1: Overview of the Module 1 partners and scope

2.1.2 Technology issues addressed within ESDRED Module 1

The technology issues regarding buffer/backfill construction that were addressed within each of the three configurations investigated in ESDRED Module 1 are described below.

- Backfilling of horizontal annular gap:

  The combined requirements of being able to backfill at an industrial rate, while at the same time addressing all the long-tem phenomenological requirements related to the disposal of a HLW container in a high pH environment, represented a unique challenge. The adoption of the high pH Super Container disposal concept by O/N in 2003 meant that previous R&D work on the buffer/backfill had to be re-evaluated for its relevance. In fact, within ESDRED it meant a start from scratch. Two basic backfill techniques were tested: (1) grout injection, (2) projection of dry granular material. The main technological issue addressed was the demonstration of the industrial performance capability of the considered backfill technique, i.e. the demonstration that, within a given set of boundary conditions, the required volumes of backfill material could be emplaced within a certain time and with a limited risk of technological malfunctions.

- Prefabricated buffer configuration:

  The main technological issue involved was the scale-up of the existing know-how for prefabricating rings of buffer material through cold compaction, to dimensions in the range of 2 m in diameter. At the beginning of ESDRED, buffer rings with a diameter in the range of 1 to 1.5 m had already been produced successfully (**e.g. testing by Ishikawajima-Harima Heavy Industries [4]**).

- Combination of granular buffer and prefabricated blocks:

  Building on the results of the **EB project [5]**, the basic technological issue addressed within ESDRED was the achievement of a specific dry density of the buffer material when emplaced around a waste canister using auger technology.

The technology issues regarding the low pressure gas break-through seal were related to verifying whether certain clay-sand mixture seals would perform under in situ conditions as predicted from small-scale laboratory tests. More specifically, the main technological challenges were the installation techniques for achieving a specific installation density, the artificial saturation of the seals, the continuous monitoring of water uptake and the evolution of the swelling pressure and finally their subjection to a gas pressure, first on full scale vertical mock-ups and then in situ in boreholes in the Mont Terri URL.

The main technological issues involved with the installation of the PRACLAY seal were the integration of the steel support structure within the gallery lining and the insertion of the swelling material into the annular void between the steel structure and the host rock.

The technology main issues involved with the non-intrusive monitoring testing were the establishment of good testing conditions (types and location of sensors) and the derivation of useful information out of the seismic echoes.

2.1.3 Objectives of the Work within ESDRED Module 1

The work involved the following more specific targets given here below.

- Backfilling of horizontal annular gap:
  1. Grout backfilling: to test, first on a 2/3rd scale mockup and then on a 30 m long full scale mockup, whether the annular gap can be filled within a time frame during which the fluidity of the grout can normally be guaranteed (i.e. about 5 hours) and to achieve a quasi complete filling of the void with homogeneous backfill material. The composition of the specific grout is predominantly determined by long-term phenomenological requirements.
  2. Dry granular materials: to test on a 2/3rd scale mockup whether the annular gap can be filled, using the dry-gun technique, at a linear pace that would allow application in an actual repository (i.e. faster than 1 linear m/h) and to achieve a quasi complete filling of the void with homogeneous backfill material. The work involved a pre-selection of the most promising dry granular materials, while focusing on the technological aspects. Robust projection equipment was designed specifically for operating in the disposal gallery under mechanically harsh conditions encountered in the annular gap environment when using the dry-gun technique.

- Prefabricated buffer configuration:

  The specific objective was to fabricate 10 rings and 2 discs of 2.3 m outer diameter, with 0.8 m inner diameter and of 0.5 m thickness. All of the equipment needed for handling; for assembly in sets of 4; for packing; and for transportation and for storage of the rings once they had been pressed in a mould also needed to be designed, fabricated and tested.

- Combination of granular buffer and prefabricated blocks:

  The objective was to select and test a number of mixtures of different granule size of MX-80 bentonite derived by computer modeling, to fabricate these mixtures and to use these to perform backfill testing on a 2/3rd scale mockup using auger emplacement technology, with the operational target of obtaining a dry density of 1500 kg/m^3.

The specific targets related to the low pressure gas entry/break-through seal testing were to see whether the borehole seals would behave as predicted from laboratory experiments and the mockup testing. The final objective was to see whether the gas entry/break-through pressure during gas injection would be below 2 MPa (a Mont Terri specific value).

Specific operational targets are less relevant to the PRACLAY seal or the seismic tomography testing.

2.1.4 The Partners within Module 1

The participants in this work and their respective roles are pictorially indicated in **Figure 1** and in more detail in Section 2.1.5 below.

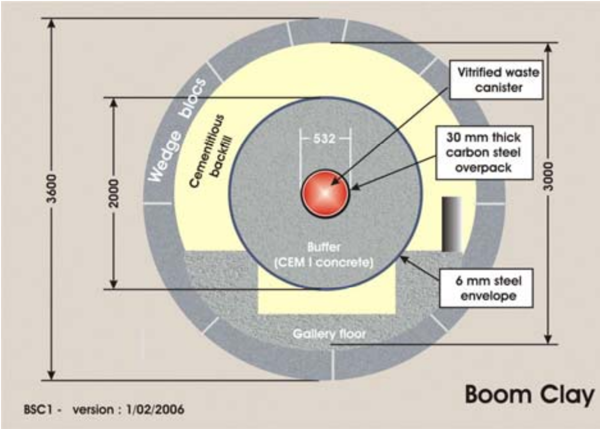
2.1.5 Execution of the works

In general, the work within ESDRED Module 1 passed through the following sequence: (1) definition of requirements and gathering of input data, (2) computer modeling and/or laboratory testing, (3) mock-up and/or in situ testing. For monitoring, it was first assessed that the work should be devoted to non-intrusive monitoring, instead of wireless monitoring, mainly because of the more general interest to all partners. Then, it was decided that seismic tomography offered the best opportunity and Mont Terri was identified as the URL in which testing could begin without delay. After that, the work on monitoring followed the sequence described in the preceding paragraph.

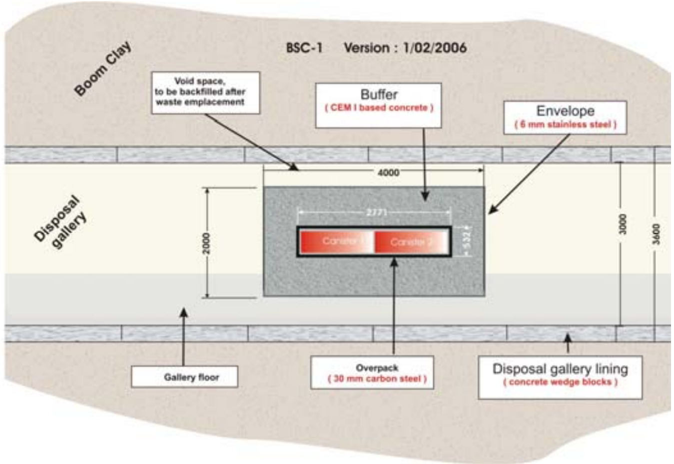
Backfilling of annular gap (by ONDRAF/NIRAS and EURIDICE)

In the O/N disposal concept for HLW, illustrated in **Figure 2**, the primary function of the backfill component is to prevent a cave in of the disposal drift, which might damage the Super Container or distort the host rock surrounding the drift. The requirements for the backfill are further determined by a number of constraints, relating to long-term safety as well as to operational feasibility and performance capacity.

Because of its straightforward chemical compatibility with the disposal concept and the perceived better opportunities for achieving the industrial performance, the grout injection technique is considered by O/N to be the reference solution for backfilling disposal galleries. The development of a specific grout fulfilling the requirements was a key process that was entrusted to BASF Construction Chemical Belgium. It resulted in a dry premix, composed of clinker cement, calcium carbonate powder, fine sand and a limited addition of a polycarboxylate ether-based superplasticizer. To obtain the desired grout only water, according to a pre-determined water/cement ratio, needed to be added.



(a)



(b)

Figure 2: Schematic representation of Super Container concept - radial (a) and axial (b) cross-section

On June 30th 2006, the grout injection backfill technique was tested on a 5 m long, reduced scale (2/3rd scale) mockup of a disposal cell. In mockup, the Super Container was represented by a steel tube, filled with sand to simulate the thermal inertia of the high pH concrete "buffer". In the centre was a heater, to simulate the heat generation by the waste. The initial average temperature of the steel tube surface was a stable 40°C. **Figure 3** shows the set-up of the experiment. It took about 100 minutes, at a target rate of 5 m^3/h, to fill up the annular void. After the setting of the grout, the result was investigated by means of borehole samples and slice cutting of the mockup (**Figure 4**). It was noticed that a 100% void filling with a homogeneous backfill had been achieved. Based on the above, it was concluded that the test had been a complete success and a promising basis for full scale successor test within ESDRED.

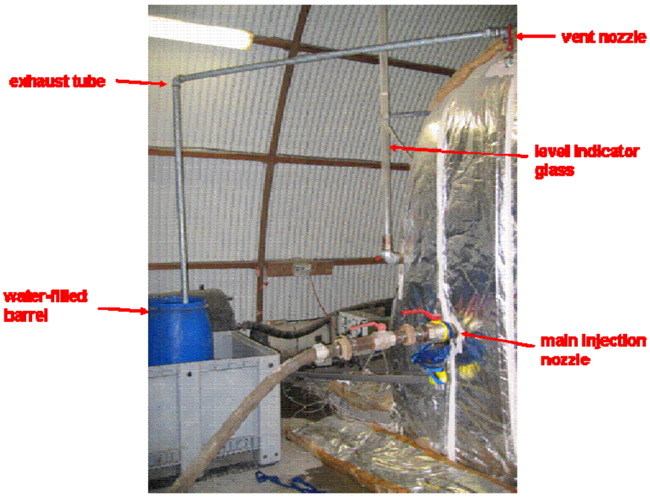


Figure 3: Experimental set-up of the reduced-scale mock-up for grout backfill testing

Figure 4: Reduced-scale mock-up for grout backfill testing, after slice-cut (Nov. 2006)

For this full scale test, a 1/1 scale mockup representing a 30 m long section of disposal gallery was built. Like the reduced scale mockup, it was constructed on the EURIDICE site in Mol (Belgium). The construction was done by the same contractor, an international tunneling company located in the vicinity. The mockup was extensively equipped with sensors measuring temperature, grout level and strain. The heater inside the sand filled tube was controlled to obtain an initial average tube surface temperature of 60°C.

The grout injection test was performed on April 8th 2008. It took about 6 hours, at an average rate of 15 m^3/h, to fill up the annular void. **Figure 5** shows the front end of the mock-up during the test with the vent and injection lines clearly visible.

Even though from an operational performance viewpoint, the test could be called a success, the grout did ultimately fail to become hard, even after a curing period of several months. This important difference with the reduced scale test has been explained by the fact that the 1.3 to 1.35 water/cement ratio (W/C) in the grout is a critical value. Above this value, there is too much water, so that the cement granules reacting with water are not able to join and create a rigid spatial network. In the reduced-scale test, a certain quantity of water was absorbed by the concrete of the standard pipes used to simulate the gallery wall and thus the critical W/C was undershot. In the full scale test, because of the inner steel wall of the concrete jacking pipes, no water was able to escape and the W/C remained above the critical value. In the real life repository, the gallery lining will also be saturated up to a certain degree and thus unlikely to be able to absorb much water. Therefore it can be said that the full scale test has treated this phenomenon in a conservative way. **Figure 6** shows the back end of the mockup after the lid was removed, resulting in a hard backfill face (of about 20 cm thickness).

In any case, the test did succeed in demonstrating the feasibility of the backfill technique by grout injection and a broad knowledge basis was established which can be used for the next phases in the development of the grout backfill technology. It has been suggested to use a W/C of maximum 1.25, accompanied by a small increase in the superplasticizer content, as a starting basis for this future work.

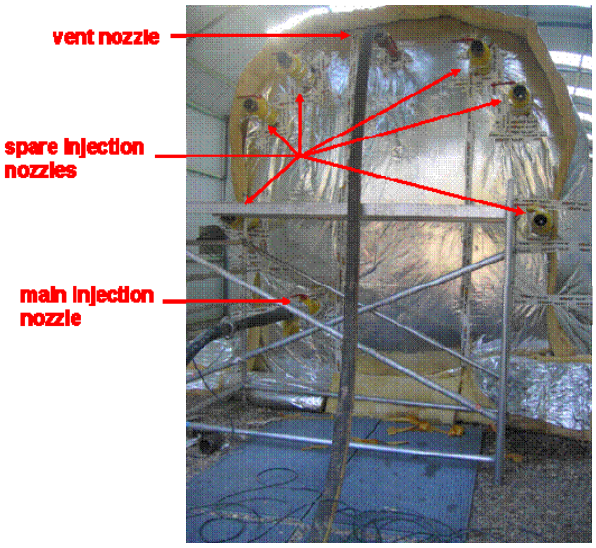


Figure 5: Front-end side of the full scale mock-up during the test

Figure 6: Back-end side of the mockup after removal of the lid (picture taken December 2nd 2008)

Alternative backfill solutions are still being considered by O/N. A materials survey, accompanied by pre-testing using the dry-gun projection technique in August 2005, rendered the following list of granular material for possible use as backfill: pure sand (SiO_2), pure bentonite (MX-80), sand-bentonite mixture (25/75), sand-cement mixture (90/10), and bentonite-cement mixture (85/15).

The projection of granular materials with a dry-gun was tested on a 5 m long, reduced scale mockup similar to the one used for grout testing, but without a central heater. The projection nozzle was mounted on a vehicle, running on rails, specially designed for mechanical robustness (**Figure 7**). All selected backfill materials were tested between June and October 2006. Borehole samples were taken from the resulting backfill. It was observed that the machine operated without failure under mechanically very harsh conditions and achieved a linear pace of about 2 to 3 m/h. No problems with dust generation or water runback were encountered. The annular void was 100% filled with a backfill which was relatively homogeneous in terms of density and water content and which exhibited a relatively steep and regular slope, although generally the result was more positive for the bentonite based materials than for the sand based materials. Based on the above, it was concluded that the test had been a success. The thermal conductivity is relatively low for some cases and probably on the edge of what would be acceptable. The tests did not address the issue of chemical compatibility with the Super Container concept.

(a)

(b)

Figure 7: Granular materials backfill test configuration (a) and nozzle in operation (b)

Prefabrication of buffer rings (by ANDRA)

The buffer material used was a bentonite/sand mixture (70/30). For the bentonite, MX-80 was chosen since it is well characterized. Furthermore, it offers high plasticity and is forecast to be available on the market over the long term. The buffer mixture was characterized in the laboratory (bench scale testing of different samples with variable water content and different compaction pressure values) in order to optimize the fabrication process and to check the compatibility of the cold compacted material with the required swelling pressure and conductivity.

At ANDRA it was decided to produce 10 rings and 2 discs with an outer diameter of 2.25 to 2.30 m, an inner void (rings only) of 80 cm, and a thickness of 50 cm. The weight of one ring would be in the order of 4 tonnes. The compacting pressure deemed optimum (80 MPa) and the size of the rings led to the selection a press capable of exerting a compacting force of at least 45 000 tons. The only suitable press available in Europe turned out to be the Aubert & Duval press at Issoire in France (**Figure 8**).

The mould, for fabricating the rings and discs, was designed to cope with the required pressure and to suit the geometrical dimensions and functional limitations of the selected press. The fabrication of the various pieces of the mould involved some very demanding casting and machining. **Figure 9** shows the mould when assembled. A consortium of French engineering companies was contracted to design and produce the mould, thus broadening the experience of the conventional industry with waste disposal technology.

The fabrication took place in three pressing campaigns between June and December 2006. Stripping of the rings and discs turned out to be a technical challenge. Nevertheless, during the last pressing campaign, the 10 rings and 2 discs were produced in less than 16 hours, including mobilization and demobilization of personnel and equipment. The final product turned out to be of very good quality. The rings complied with the geometrical requirements and had a smooth surface. Samples taken from one of several extra rings fabricated during the two first campaigns confirmed the homogeneity of the compacted material. **Figure 10** shows a ring just after stripping from the mould. **Figure 11** shows a detail of the upper side of a ring, displaying the sharp edge and smooth surface as a visible feature of the good geometrical quality of the end product.

Figure 8: Press at Issoire

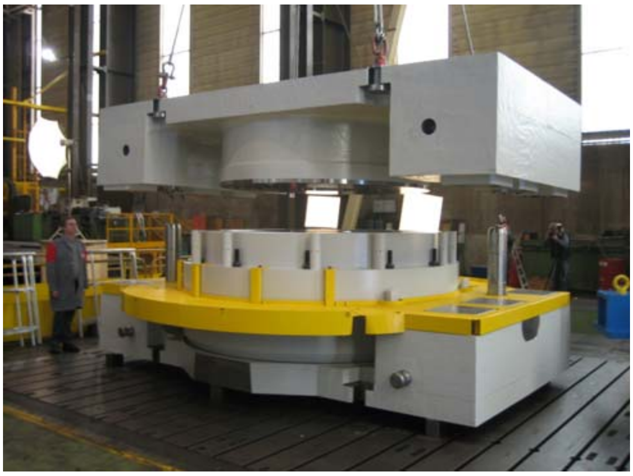


Figure 9: Assembled mould

Figure 10: Ring just after stripping from mould

Figure 11: Detail of the upper side of a ring

Also the assembly, packaging and transportation of the rings in sets of 4 were tested. Lifting of a ring or disc from a horizontal position to a vertical one was carried out with a suction cup device (**Figure 12**) in conjunction with a tilting frame, while the final lifting and transportation (inside a special container) was assured by a special yoke (**Figure 13**).

Additional testing related to handling involved lifting a ring by means of a mandrill inserted through the central hole (**Figure 14**). Also a destructive shear strength test, the so-called "Brazilian test" was executed (**Figure 15**).

Figure 12: Lifting of disc by suction cup handling device

Figure 13: Deposition of 4 pre-assembled rings on transport container lower part

Figure 14: Lifting with a mandrill

Figure 15: "Brazilian" shear strength test

Emplacement of granular buffer material in an annular void in combination with prefabricated blocks (by NAGRA)

Sodium-bentonite MX-80 was delivered to the test site in a conditioned, slightly granulated state to improve the pourability and the granulation. The production of the granulated material had been done in a specialized facility in Germany (Rettenmaier in Holzmühle). During the granulation of the bentonite, an increase of the bulk grain dry density from 1.17 g/cm^3 to 2.10 g/cm^3, with simultaneous halving of porosity, was achieved.

A twin auger system was designed and built to emplace the granulated buffer material. The length of the two auger casings is 7.0 m, and the diameter of the tubes is 0.2 m (see **Figure 16**). The feed rate can be controlled via the auger turning speed. The rotating screwing motion of the auger moves the materials to the end of the outer casing tube where the material either falls off the end of the auger freely or pushes the material out into the existing bentonite mass. The maximum feed rate of the system is 7 m^3/h of granular bentonite material (±10 t/h), which results in a steel cylinder (the disposal drift mockup) being filled, in about one hour.

As part of the testing, a comprehensive laboratory program was executed to investigate the performance of the overall emplacement system. Bentonite samples were taken from each "big bag" before pouring into the auger hopper for grain size distribution, water content and bulk density. After every backfilling operation of the disposal drift mockup, the following parameters were determined:

- global bulk wet density

- particle size distribution of the granular bentonite material before emplacement (out of the "big bags") and after emplacement (sampled at selected points at the outer surface of the steel cylinder)
- water content of the granular bentonite material before and after emplacement

Other properties of the granular bentonite such as mineralogy, swelling pressure and thermal conductivity were determined in the laboratory of the ETH Zürich (Switzerland) and Clay Technology in Lund (Sweden).

After each emplacement test, the bulk wet density of all the bentonite material in the steel cylinder was measured. The bulk density is the net weight of the emplaced buffer material divided by the total volume. The bulk densities of the granular bentonite material show only small changes for different admixtures of fine granular bentonite and/or coarse granular bentonite material. The water content increased only slightly during the tests (5.0 to 5.8 %). The results are very promising as the required densities could be reached reliably.

Figure 16: Experimental setup (left) and emplacement of bentonite granulate with twin auger system (right)

Seal saturation rate and gas permeability testing in the SB experiment (by GRS)

In the GRS laboratory in Braunschweig, different clay/sand mixtures with mixing ratios between 35/65 and 70/30 were investigated with regard to their sealing performance. These investigations have shown that the functional requirements are best met by 35/65 and 50/50 clay/sand mixtures. These were therefore selected for further testing.

Before going in situ, both the installation techniques and the required saturation time for the material mixtures being considered were first investigated and optimized in mockup tests in the GRS laboratory. The mockup tests were performed in vertically arranged steel tubes (**Figure 17**) designed as a full scale replica of the envisaged in situ experiments (**Figure 18**).

Scoping calculations were performed with the computer code CODE_BRIGHT, on the basis of the material data determined in the laboratory investigations and data taken from the literature, to assess the time needed to reach full saturation in the mock up and in situ experiments. According to the results of these scoping calculations, for a seal length of 1 m and a water injection pressure of 1 MPa, the saturation time for the 35/65 clay/sand mixture would amount to about 170 days for the mockup tests and 300 days for the in situ experiment. For the 50/50 clay/sand mixture, 570 days for the mockup and 1050 days for the in situ experiment were calculated.

The first mockup test was performed from October 2004 until November 2005 by using a 35/65 clay/sand mixture. Due to the problems at the beginning of saturation, the hydraulic sealing and the swelling properties were possibly influenced by the effect of water flow (by-pass) along the inner surface of the tube. The sealing potential of the 35/65 mixture could nevertheless be successfully demonstrated in this test.

Mockup 2 was initiated with the improved injection procedure developed following the Mockup 1 experience. The first water break-through, indicating a situation close to full seal saturation, was only observed in September 2007, after about 870 days of testing. Further research is needed to clarify this discrepancy in relation to the predicted 170 day saturation period and to enhance the respective process understanding for further model improvement. The hydraulic data measured at the time of break-through indicated a water permeability value of about 3E-18 m^2, which is in very good agreement with the data determined from the small samples used in the laboratory. The remaining gas injection test was started on 7 January 2009. The current actual data shows a clear start of the gas entry at a pressure of about 3.5 bars, a value that is consistent with the values observed on small lab samples before. Both the water permeability as well as the gas entry pressure measured at full saturation in Mockup 2 confirm the expected optimized sealing properties of the 35/65 clay sand mixture. These results confirm that the required sealing functions were fulfilled in this test and serve to support the other in situ experiments ongoing at the Mont Terri URL.

Figure 17: Mockup test in the GRS laboratory

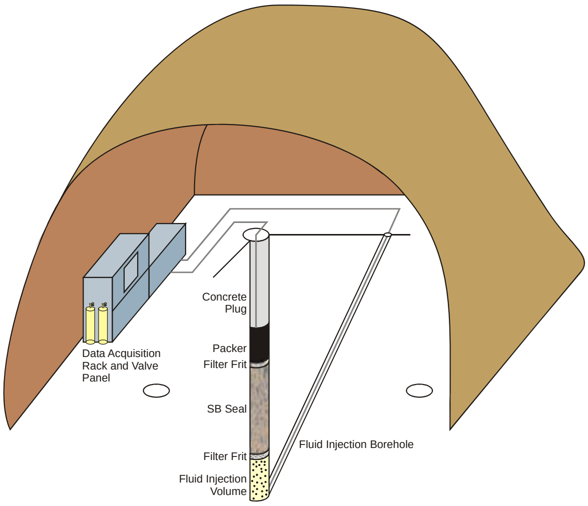
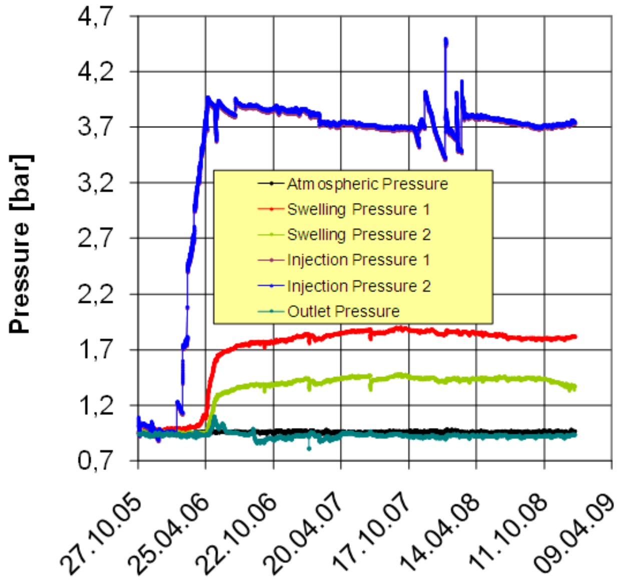


Figure 18: Design of the SB experiment in a test niche at the Mont Terri URL

The first in situ experiment at Mont Terri (in borehole BSB2), using also a 35/65 clay-sand seal, was started in October 2005 and has so far been operated without disturbances. The swelling pressure measured at the top of the seal (**Figure 19**) is quite constant since about two years. The pressure is in the same order of magnitude as those values determined on small laboratory test samples and thus, similar sealing properties can be expected in this in situ experiment. At the end of 2008, the swelling pressure seems to have started to redistribute. A similar behaviour was observed in the Mockup2 shortly before the water breakthrough which is therefore expected to occur in this test borehole within a reasonable period of time.



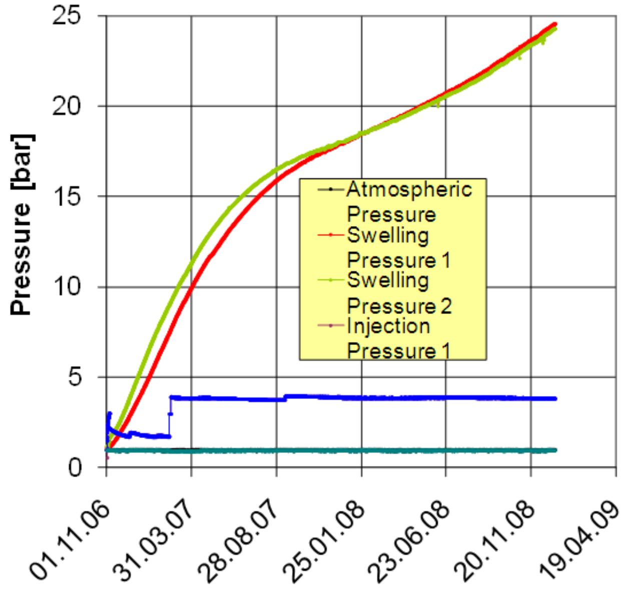


Figure 19: Pressure evolution in test borehole BSB2 sealed with a 35clay/65sand mixture

Figure 20: Pressure evolution in test borehole BSB13 sealed with pure bentonite granulate (NAGRA material)

The other three in situ experiments with clay/sand mixtures with ratios of 35/65, 50/50 and 100/0 were taken into operation in November 2006.

The test with pure bentonite in borehole BSB13 is running without disturbances and had reached a swelling pressure of about 24 bars by December 2008 (**Figure 20**). The excellent conditions of this test and of that in borehole BSB2 provide a very good basis for the envisaged comparison of the sealing behaviour of the different sealing materials, which, according to the test program, is to be demonstrated at the end of the saturation phase by gas injection tests in all boreholes.

The two experiments with clay/sand mixtures with ratios of 35/65 in Borehole BSB1 and 50/50 in borehole BSB15 showed the expected evolution of swelling pressure in the early saturation phase. The seal length in BSB15 was however reduced to 0.5 m in order to reduce saturation time. After increasing the injection pressure, these two experiments showed water bypassing to the upper water collection filter. This behaviour is most likely due to a distinct excavation disturbed zone along the borehole wall. Thus, the seal in these two boreholes will be saturated not only through the lower injection volume but very likely to some extent also along the borehole wall.

Testing will be continued in the forthcoming months including the determination of the gas entry/break-through pressure of the saturated seal and the remaining gas permeability after gas break-through. Based on predictions for borehole BSB2, the gas injection following seal saturation, could be done in the first half of 2009. It will have to be decided on the basis of actual experimental data how to proceed with the other borehole experiments.

PRACLAY seal construction (by EURIDICE)

EURIDICE is currently preparing for the installation of the different components for the PRACLAY In situ Test, in the Mol URL. The PRACLAY gallery was constructed in late 2007. In the In situ Test, the thermal behaviour of a disposal gallery will be simulated at approximately full scale. To obtain the initial undrained boundary conditions, an annular seal will be installed between the heated zone and the access gallery. The swelling material in this seal will consist of pre-compacted bentonite blocks replacing the concrete gallery lining over a length of 1 m. A stainless steel confining structure encases the bentonite ring. The central section will be closed with a steel plate and is equipped with several flanged holes to allow the feed through of the instrumentation and heater wiring and tubes. Currently, there is a temporary or “alternative” wooden lining where the PRACLAY seal will be installed. **Figure 21** displays a photograph of this temporary lining. **Figure 22** shows the basic structure of the seal.

Figure 21: Lining in the zone where the hydraulic seal will be placed

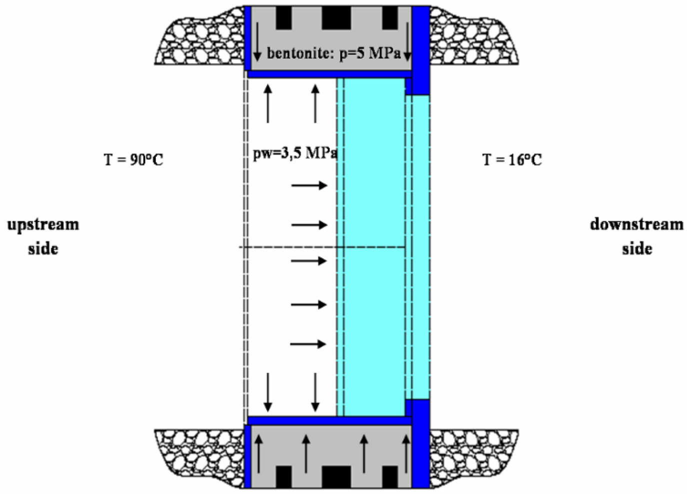


Figure 22: Steel structure: nominal operating conditions and location

Currently, the design of the seal steel support structure and the selection of MX-80 as the swelling material have been achieved. The latter selection has involved a literature study, a series of scoping calculations by aid of a computer code and laboratory testing (e.g. at the CERMES institute) focusing on a number of specific aspects related to the interaction of the swelling material and the Boom Clay host rock.

The actual in situ installation of the seal in the PRACLAY gallery remains to be done. Due to a rescheduling of works, this activity will fall outside of the contractual time framework of ESDRED; it is now foreseen for the second quarter of 2009.

Non-intrusive monitoring testing (by NDA)

In the initial phases of ESDRED, the NDA, together with the Module 1 partners considered the available technical options for developing and testing non-intrusive monitoring techniques within the project, and considered what was feasible given the time constraints of the project. Taking consideration of repository concepts, monitoring objectives and potential non-intrusive techniques, the partners concluded that seismic tomography was the most promising technique to pursue. It was also decided that the most pragmatic approach would be to monitor the phases of the already planned HG-A experiment at Mont Terri.

The HG-A experiment is set up around a horizontal micro-tunnel with a diameter of about 1 m, located 11 m from Gallery 04 of the URL. A niche was excavated to allow for the positioning of drilling equipment. To facilitate non-intrusive monitoring by seismic tomography, two additional boreholes, approximately 27 m long, were drilled, one above and one below the micro-tunnel, and stabilized with a concrete liner. The experiment layout is illustrated in **Figure 23** and **Figure 24**. In addition to the boreholes drilled for the experiment, the main components of the set-up are a seismic source (high frequency sparker), which is inserted into the lower inclined borehole and a 24-channel hydrophone chain (receiver), which is inserted into the upper inclined borehole. To operate these requires the boreholes to be filled with liquid (fluid coupled). Therefore, a special purpose sealing cap was required for the upper inclined borehole.

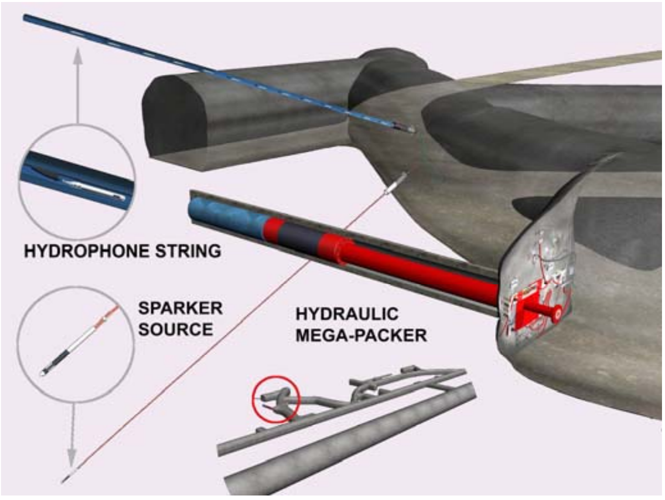


Figure 23: Layout of the non-intrusive monitoring experiments around the HG-A micro-tunnel in the Mont Terri URL

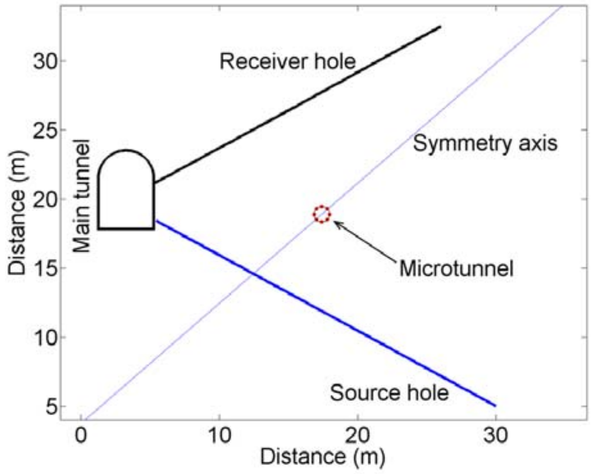


Figure 24: Schematic representation of the non-intrusive monitoring experimental set-up

A number of non-intrusive measurement campaigns were set up, to try to monitor the effects of the key phases of the HG-A experiment, being:

- measurement of the empty micro-tunnel
- measurement after sand emplacement in micro-tunnel
- measurement after saturation of backfill material with water
- measurement prior to and after gas injection

Six measurement campaigns have so far been performed during the period March 2006 to June 2008. Measurement campaigns prior to and after gas injection are now planned for mid-2009.

For the interpretation of the measured data, a computer model of the anisotropic host rock environment of the HG-A tunnel was developed and a full waveform inversion code is in the process of being developed. The technical components of the activities, including field measurement, research and full waveform inversion of tomographic data have been undertaken by the Swiss Federal Institute of Technology, Zurich (ETH), in the framework of a 4-year PhD thesis sponsored by the NDA and undertaken by Edgar Manukyan under the supervision of Dr. Hansruedi Maurer and Professor Alan Green at ETH.

To conclude, it is noted that about a year ago, an ESDRED spin-off collaboration project between NDA, NAGRA and ANDRA has been started at the Grimsel URL, involving the use of non-intrusive monitoring to follow the changes induced by the swelling of the bentonite in the in situ large plug test of Module 4.

2.1.6 Main results and critical analysis thereof and perspectives for the future

Main results and critical analysis thereof

To summarise, at the end of the contractual project time frame, ESDRED Module 1 has achieved all of its objectives. There is, however, one experiment (PRACLAY seal) that is awaiting mid-2009 for work to be finalized and there are two experiments (SB seals and non-intrusive monitoring) that can expect an interesting contribution from additional work that will be performed in 2009 independent of the ESDRED Project. Results regarding the non-intrusive monitoring work will be fully reported and made available on completion as part of the MoDeRn (EC funded) Project while the SB experiment will generate a stand alone public document. Eventually there will be documents that address all of the work that is continuing outside the ESDRED Project.

More specifically:

- ANDRA has succeeded in the cold compaction of a MX-80 bentonite / quartz sand mixture prepared as a powder, to obtain the prefabricated buffer rings described in their *Dossier 2005* report to the French Government. ANDRA has also successfully tested the handling of these buffer rings and their rigidity.
- ONDRAF/NIRAS has demonstrated the feasibility of two different emplacement techniques for backfilling the annular void around a horizontally disposed high level waste package: (1) projection of a dry granular material, for which sand, cement, bentonite and mixtures thereof were used, (2) injection of a custom made high pH grout designed to have the required thermal, chemical and physical characteristics. Both emplacement techniques have been tested successfully on $2/3^{rd}$-scale mock-ups. The grout injection technique was also tested on a full scale mockup of 30 m in length. Again, the feasibility of the injection technique was demonstrated, but it was also concluded that the W/C ratio of the specific grout will need to be reduced in the next phases of the development process, to ensure that the grout becomes hard after injection. In general, the backfill tests within ESDRED have provided a broad knowledge basis for this further development process.
- NAGRA, using auger technology and a reduced-scale steel model of a horizontal disposal drift with a waste container disposed on a cradle of prefabricated bentonite blocks, has tested the emplacement of a range of bimodal mixtures of granular bentonite. NAGRA succeeded in achieving the desired dry density of the emplaced buffer material.
- GRS has until now been satisfactorily running performance tests on four seals of different clay/sand composition in boreholes at the Mont Terri URL. The results of these in situ tests, and also the preceding laboratory mockup tests, appear to confirm the advantageous sealing properties of moderately compacted clay/sand mixtures which were previously determined on small samples under ideal conditions in the laboratory. It should nevertheless be noted that the seal saturation rates are much lower than predicted by computer models. Hence the break-through gas injection tests will now most probably be executed around mid 2009. Since the initial stages of ESDRED a continuation beyond the contractual end date has never been excluded. The work already performed, together with the anticipated gas injection tests, will have considerably advanced the knowledge base on moderately compacted bentonite/sand seals in clay host rocks.
- NDA has been successfully conducting a development program to advance the knowledge basis of non-intrusive monitoring based on seismic tomography. A series of measurement campaigns performed around the HG-A tunnel in the Mont Terri URL have been performed. To interpret the information provided by the seismic echoes, an anisotropic model of the clay test environment has been developed and an associated full wave inversion code is being developed, in cooperation with the Swiss Federal Institute of Technology (ETH Zurich). Due to a rescheduling of the HG-A experiment the last campaigns are now anticipated to commence mid-2009. The performance of this final test campaign, and the finalization of the wave inversion code, will contribute to the already gathered knowledge base.
- EURIDICE have prepared the design of the PRACLAY seal steel support structure and have selected MX-80 as the swelling material to be used. The latter selection has involved a literature study, a series of scoping calculations by aid of a computer code and laboratory testing (e.g. at the CERMES institute) focusing on a number of specific aspects related to the interaction of the swelling material and the

Boom Clay host rock. The actual in situ installation of the seal in the PRACLAY gallery remains to be done. Due to a rescheduling of works, the in situ installation of the PRACLAY seal will fall beyond the contractual end date of ESDRED. The installation is now foreseen for the second quarter of 2009. The work by EURIDICE, especially the actual in situ implementation, will have advanced the phenomenological and technical knowledge base related to the construction of a hydraulic seal in a disposal gallery.

Recommendations / perspectives for the future

The work performed by ANDRA on the prefabricated buffer rings has delivered a complete product. In view of the fact that in the meantime the French HLW disposal concept has been changed and no longer includes these rings, it would not be justified to state that further development is now required. The work by ANDRA has nevertheless resulted in an off-the-shelf solution that is still useful for other disposal programs, outside of France, as well as for the hypothetical French direct disposal program for spent fuel. Furthermore it provides a better basis for comparing this technical option with other alternatives. The acquired technological know-how could also be used for the fabrication of large dimension sealing blocks.

Regarding the non-prefabricated options to emplace the buffer/backfill, the work by O/N and NAGRA should be followed by a further fine-tuning of the composition of the material. An important boundary condition, which has until now been neglected in many programs is the understanding of the logistical needs behind the buffer/backfill emplacement. It is therefore strongly recommended to reserve an important part of future development efforts to the study of these logistical needs and the development of equipment to satisfy these.

Regarding the design and construction of seals, it is clear that a lot of R&D work still needs to be done especially regarding the installation techniques. The understanding of the saturation process as well as the applicable computational models both need to be improved in order to achieve better predictions of saturation times. Thanks to its sand content the SB sealing material shows a higher thermal conductivity in addition to its advantageous hydraulic properties. Favourable near-field conditions will therefore take place in a HLW repository in a clay formation when using the SB sealing material rather than the highly compacted 100% bentonite buffers considered in many other disposal concepts. The continuation of R&D regarding the suitability of the SB sealing material as an alternative will therefore remain the focus of future GRS geotechnical R&D related to the clay option. Working at full scale and in close collaboration with industrial companies which master the state-of-the-art in underground construction technologies, will enable waste management organisations to get a better understanding of the technological challenges involved.

Regarding non-intrusive monitoring, it is recommended that more R&D should be devoted to further improving the usefulness of seismic tomography. Particularly the linking of the tomogram and waveform data to specific processes should receive dedicated attention. Moreover, to guide technology development, further work should be undertaken to identify monitoring objectives, strategies and decision making processes in order to improve the understanding of requirements on monitoring techniques.

2.1.7 Contribution to "Common European View"

Regarding the construction of the buffer/backfill around the disposed HLW, within ESDRED a number of off-the-shelf solutions have been developed up to a certain level of completeness. These solutions or certain technological aspects thereof, are ready to be shared among partner countries whenever the need might arise.

Regarding the realization of seals in a clay based repository, the phenomenological and technological knowledge base has been advanced by two different experiments (SB and PRACLAY seal) and will be more so in the future as these experiments will be continued beyond ESDRED. The contribution by ESDRED is however only a first step forward and many more steps will have to be taken in the development of repository sealing techniques.

Regarding non-intrusive monitoring, seismic tomography and the analysis of data has been developed up to a certain level as a useful technique that can be shared among partner countries. So far, the development has focused on application in a clay repository, but the technology is expandable to other host rocks.

In the course of the project, the partners within Module 1 have developed a better understanding of each other's solutions and the technical challenges involved. This in turn has lead to a better self critical analysis and understanding of each organisation's own solutions. Most of all however, five years of collaboration have led to the formation of a network for cooperation between technological experts within the partner organisations. This has generated collaborative spin-off projects, of which the non-intrusive monitoring experiment at Grimsel URL is a good example. It has also provided the foundation for cross-organizational initiatives, of which some have been accepted for the 7th EC Framework Programme, like the MoDeRn Project on monitoring. It is this kind of collaboration, more than anything else, which contributes significantly to European integration. To have achieved this is the greatest merit of ESDRED and it has certainly also been the case within Module 1.

2.2 Waste Canister Transfer & Emplacement Technology (Module 2)

2.2.1 State of the art in Germany and in France

According to most of the national waste management programmes, the feasibility of reliable and safe transportation/emplacement of remote handled waste canisters has to be demonstrated prior to repository industrial implementation. Both the transport and the emplacement systems are strongly dependant on the amount and type of waste packages to be disposed and on the selected host rock. However there are a lot of commonalities regarding the approach to designing and testing an entire transport and emplacement system. In this context Module 2 considered the emplacement of small canisters for spent fuel into deep vertical boreholes (DBE-TECHNOLOGY was in charge of the German concept) and small canisters for vitrified waste in specially prepared horizontal disposal cells (ANDRA was in charge of the French concept).

In Germany a reference emplacement concept has been developed and demonstrated in a 1:1 scale in the past. It consists of the emplacement of spent fuel elements in shielded POLLUX®-casks in horizontal drifts in a repository in rock salt and the emplacement of HLW canisters in deep vertical boreholes. The appropriate transport and emplacement components for the POLLUX®-system have been developed and successfully tested on surface in a 1:1 scale in the early 1990s. The POLLUX®-cask and a pilot conditioning plant have been realized. In comparison the technology for the HLW canister transport and emplacement was still lagging behind. However, there is comprehensive experience available from the oil- and gas industry as well as from the salt mining industry in drilling vertical boreholes.

In order to develop one common emplacement technology for both categories of waste (vitrified waste and spent fuel), an alternative technical approach was investigated. This emplacement concept which was the subject of the ESDRED Project Module 2 pursues the safety/technical and economic optimization of direct disposal of canisters in salt, through joint disposal (in open deep boreholes) of canisters containing:

- complete fuel rods from spent fuel assemblies,
- vitrified high level wastes from reprocessing, and
- compressed medium level wastes (cut cladding and structural parts arising from reprocessing).

These various canisters come with identical outer diameters and grapple heads, but different lengths, depending on types of waste to be disposed of.

In France ANDRA produced and issued the “Dossier 2005”, which served as an official support document (the Repository concept) and which underpins the new “Planning Act of 28 June 2006 Concerning the Sustainable Management of Radioactive Materials and Waste” which is now governing ANDRA’s activities. The appropriate repository concept comprises the disposal of heat generating radioactive waste at a level of approx. 500m below surface in an argillite formation (a type of clay rock). The connection between the surface and the underground will be provided by large diameter shafts (8 to 12 m) and one ramp. No transport and emplacement system for the variety of disposal packages for spent fuel and vitrified waste had been fabricated and demonstrated before the ESDRED Project Module 2 was launched.

In ANDRA’s case a disposal package essentially consists of a metal envelope that holds one or more primary packages of the same type. Two types of waste packages (CU2 for Spent Fuel and C for vitrified waste) were originally considered for the demonstration test within the ESDRED Project Module 2. On the basis of a reconsideration of the repository concept at the end of 2006, it was decided to concentrate the activities in the coming years on the repository concept for C type waste only and to stop most activities concerning the spent fuel disposal packages (which in any case were the main focus of the work in Module 3). Consequently Module 2 dealt only with the transport and emplacement technologies for C type waste packages. This waste package is transferred underground, inside a metal radiation shielding cask via a waste shaft and horizontal drifts to a disposal zone. The waste package is emplaced into horizontal disposal cells, which are permanently lined with a carbon steel casing.

2.2.2 Technology issues addressed within ESDRED

The main objective of the entire ESDRED project was the demonstration of the technical feasibility at an industrial scale of the transport and handling of different types of waste packages in terms of dimensions and content of radioactive material for their application in different host rock environments.

Waste Canister Transfer & Emplacement Technology was the subject of **Module 2** of the project. In this context two different emplacement systems capable to handle and emplace waste packages with a weight of either 2 or 5.2 tons were developed, fabricated and successfully tested in 1:1 scale demonstration facilities. One concept was dealing with the safe and reliable emplacement of vitrified waste packages into horizontal emplacement cells in argillite formations whereas the other concept did consider the emplacement of spent fuel assemblies into deep vertical boreholes in rock salt. In both concepts the issue of retrievability and reversibility was investigated in case studies. More details about this special issue (and its impact on the disposal architecture design) are presented in section 2.4 of this report.

The BSK 3 concept in Germany

In Germany a common transport and emplacement technology for both categories of heat-generating radioactive waste (vitrified waste and spent fuel) was sought as an alternative technical approach to the reference concept which considers separate transport and handling systems for spent fuel and vitrified waste. In this context, the vertical borehole emplacement technique for spent fuel assemblies, as already foreseen for high-level reprocessing waste, was reconsidered. A new fuel rod canister (called BSK 3, weight 5.2 tonnes) was designed by the German nuclear industry. It can be filled with 3 PWR or 9 BWR fuel rod assemblies. The BSK 3 concept offers the following optimization possibilities:

- The new steel canister has nearly the same diameter as the standardized canisters for HLW and compacted technological waste, as delivered from reprocessing abroad.
- The standardized canister diameter provides the possibility to apply the same transfer and handling technology for both categories of waste (vitrified HLW and spent fuel) and thus to reduce costs.
- The new BSK 3 canister is tightly closed by welding and designed to withstand the lithostatic pressure at the emplacement level.
- Thermal calculations verified that the residual heat generation of a canister loaded with fuel rods burned up to 50 GWd/tHM will enable its emplacement in a salt repository after only about 3 to 7 years following reactor unloading of the fuel assemblies.
- Compared with the emplacement of POLLUX® casks the creeping process of the host rock (rock salt) will be accelerated, resulting in a faster (earlier) encapsulation of the entire waste canister. This may reduce the requirements for geotechnical barriers.

The BSK 3 concept, therefore, provides a common solution for the emplacement of all types of heat-generating radioactive waste in Germany, thus considerably reducing the necessary effort in terms of time and costs. Within the ESDRED Project Module 2, the investigation of the reliability of individual components and their interaction with the others of the entire system was the subject of a demonstration programme with more than 500 emplacement cycles.

The Pushing Robot system in France:

The reference concept developed in the "Dossier 2005" for the disposal of C type (vitrified waste) canisters comprises the emplacement and storage of waste packages into horizontal disposal cells excavated in argillite formations. The 40-m-long horizontal disposal cell is lined with a carbon steel casing to support the clay formation wall and to facilitate any future retrieval operation. The access gallery enables the transport shuttle to reach the cell mouth for docking operations and the subsequent emplacement of the canisters. The C type package consists of a primary package (Cogema CSD-V), contained in an overpack of 55-mm-thick carbon steel. It is equipped with 12 ceramic sliding runners which reduce the friction force exerted and at a later stage prevent corrosion sticking (to facilitate any future retrieval operations). The C type waste package weighs approximately 2 tons and has a length of 1.6 m and an outer diameter of about 60 cm. The emplacement of the waste package into the horizontal cell will be managed by a so called "Pushing Robot" system, a device installed in the shielding cask together with the waste canister and capable of pushing the canister in a stepwise approach into the disposal cell. If required this system is capable as well to retrieve a waste canister out of the emplacement cell.

The main difference between this reference concept and the technical programme developed in ESDRED is the length of the horizontal disposal cell which has been increased from 40 m to 100 m. The functioning of the pushing robot system at an industrial scale was the subject of a series of demonstration tests (prototype and later full scale tests) within the ESDRED Project Module 2.

2.2.3 Objectives of the Work within ESDRED Module 2

The overall objectives of ESDRED Module 2 were:

- Identification of a clear set of shielding cask requirements based on European nuclear regulations and safety objectives of the implementers,
- Demonstration of the technical feasibility at an industrial scale of the transportation and emplacement of remote handled waste canisters in horizontal disposal cells and in vertical boreholes,
- Demonstration of the compliance of the development equipment with reversibility requirements.

In addition concept specific objectives were formulated for both the BSK 3 and the Pushing Robot concepts.

The following objectives for the BSK 3 research and development project were set:

General objective:

- to develop and test the emplacement technology for BSK 3 canisters on a 1:1 scale,

Detailed objectives:

- to prove the technical feasibility of constructing the individual components as well as of the entire emplacement system for BSK 3 canisters,
- to prove the operational safety by corresponding demonstration tests,
- to derive safety measures for the operation in a repository,
- to investigate the approvability (i.e. possibility of licensing) of the emplacement system.

The following objectives for the Pushing Robot research and development project were set:

- to develop and test the emplacement technology for the Pushing Robot on a 1:1 scale,
- to prove the technical feasibility of constructing the entire emplacement system for the C type canisters and the individual components,
- to investigate the robustness of the emplacement system,
- to display the Pushing Robot Demonstrator in operating mode in the Bure – Saudron Technology Centre (called the Cte), located in the vicinity of the French URL, at mid-2009.

A successful execution of the demonstration tests would deliver in the case of the German BSK 3 concept the necessary data to enter into a licensing process for a repository for heat generating waste. In the case of the Pushing Robot the success would provide the basic data for repository specific design of an emplacement system for vitrified waste packages.

2.2.4 The Partners within ESDRED Module 2

The partners within Module 2 were DBE TECHNOLOGY (Germany) acting also as Module 2 leader, ANDRA (France) and NRG (Netherlands) dealing specifically with Retrievability issues.

2.2.5 Execution of the works

The common interest of the participating organisations ANDRA, DBE TECHNOLOGY and NRG was to develop technologies, manufacture equipment and demonstrate the use of appropriate shielded transportation casks and emplacement devices, matching the European nuclear (and their own corporate) regulations as well as the specific nuclear safety objectives of the implementers. The development of these technologies also addressed retrievability issues. The engineering process applied to Module 2 was developed in a classical plan for applied research, broken-down into main tasks as listed below:

- Collection of Input Data and Definition of Functional Requirements,
- Development of Conceptual Design,
- Testing of a Preliminary Prototype to check the feasibility of a sensitive technical issue
- Development of the Basic Design,
- Development of the Detailed Design,
- Building and testing of a full-scale Demonstrator for each of the 2 applications,
- Critical evaluation of the performance of the 2 concepts developed

The BSK 3 concept (DBE TECHNOLOGY)

Background

Obtaining a license to construct a repository in Germany requires previous demonstration to the competent authority that the level of protection (with regards to exposition to radiation or risk) can be met with a high level of confidence. For waste canister transport and handling systems, the proof of compliance with the regulatory requirements can be provided by means of full-scale demonstration and reliability tests. The transport, handling, and emplacement techniques of the POLLUX® cask were subjected to successful demonstration and in situ tests performed in the 1990s. As a result, the atomic energy act was amended in 1994.

In the reference disposal concept for a repository in rock salt, which allows a maximum temperature of 200 °C at the contact surfaces between waste canisters and host rock, unshielded canisters with vitrified high-level radioactive waste (HLW) are emplaced in vertical boreholes with a depth of up to 300m and a diameter of 60 cm. In order to facilitate the fast encapsulation of the waste by the host rock (rock salt), the boreholes are not lined. The proof of the compliance with the regulatory requirements for high-level reprocessing waste canisters was pending and needed to be developed.

Consequently a research programme was set up in order to develop, fabricate and test the necessary technical components for the transport and handling of the BSK 3 canister. This programme was launched with the start-up of the ESDRED project. The main objective was to develop the components for demonstrating the functionality and reliability of a suitable emplacement technology. In addition, the results of the tests and investigations should provide all information required for the licensing of this new back-end technology, thus meeting the legal requirements for a German HLW repository.

Data and requirements

The main functional requirement was that the emplacement system should be able to safely transport and emplace BSK 3 canisters into deep vertical boreholes (diameter 60cm) in a repository in salt.

A second functional requirement was to provide proof of the compliance of each individual component with the regulatory requirements by means of full-scale demonstration and reliability tests.

The waste container considered, a so-called BSK 3 canister, is a cylindrical container with a welded base plate of fine grained construction steel. The top end of the BSK 3 canister is closed by a system of covers, comprising a threaded primary cover and a welded secondary cover. A grab attachment integrated in the secondary cover is used for handling. On the underside of the primary cover an enclosed moderator plate is installed.

The main dimensions and weight of a BSK 3 canister are as follows:

- Outer diameter 430 mm,
- Outer diameter at the collar 440 mm,
- Wall thickness (without collar) 40 mm,
- Height (including grab attachment) 4 980 mm,
- Weight approx 5.2 tonnes.

Design

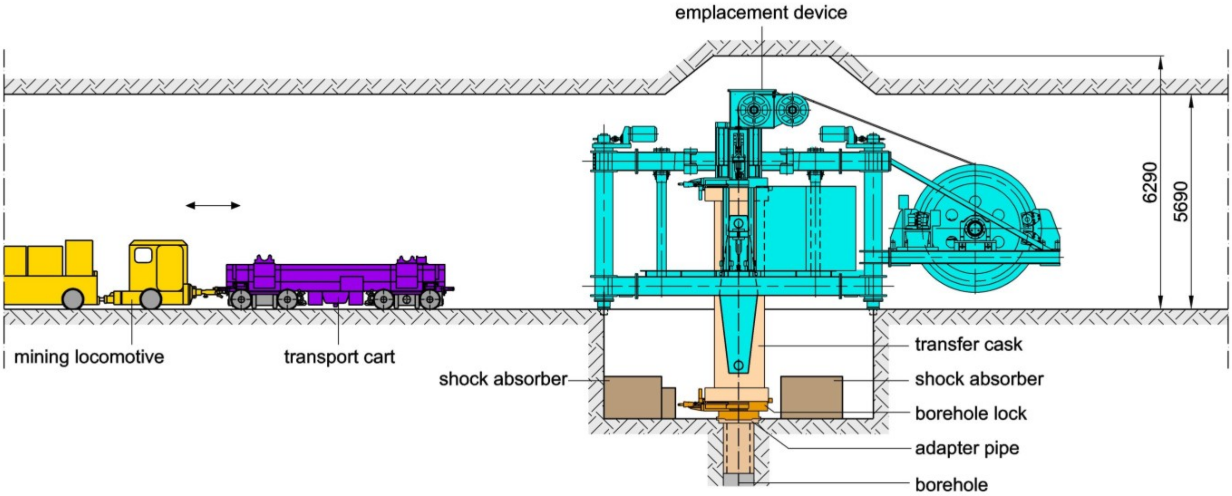
The engineering process was performed in a very classical plan for applied research, i. e.: collecting input data, defining functional requirements, elaborating basic and conceptual designs (and formulations), doing the detailed design and fabrication of the components and eventually testing at full scale a prototype and evaluating the performance of the system. The conceptual design of each individual component was done by DBE TECHNOLOGY staff from July 2004 to summer 2005 whereas the basic and detailed design was performed simultaneously by several specialised German companies (under the supervision of DBE TECHNOLOGY) from mid-2005 to mid-2007.

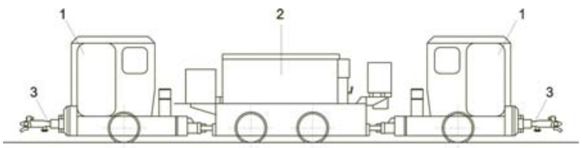
As a result, an emplacement system was developed and designed for the handling and disposal of BSK 3 canisters that comprises:

- a BSK 3 canister capable to safely holding either 3 PWR or 9 BWR fuel rod assemblies; for the demonstration tests a BSK 3 canister dummy was fabricated only,
- a transfer cask for the safe enclosure and transport of BSK 3 canisters,
- an emplacement device for automatic acceptance and handling of the transfer cask and the BSK 3 canister,
- a borehole lock which seals the emplacement borehole and thus provides radiation protection during the operational phase,
- a transport unit consisting of a transport cart and a battery driven mining locomotive for rail-bound transport of the transfer cask from surface to underground and inside the repository drifts.

An early idea to reuse the transport cart, which had been initially successfully used during the demonstration tests with POLLUX® casks in the 1990s, had to be discarded. From an economical point of view it was less expensive to build a new one than to modify the existing one. However, the battery-operated mining locomotive was used again.

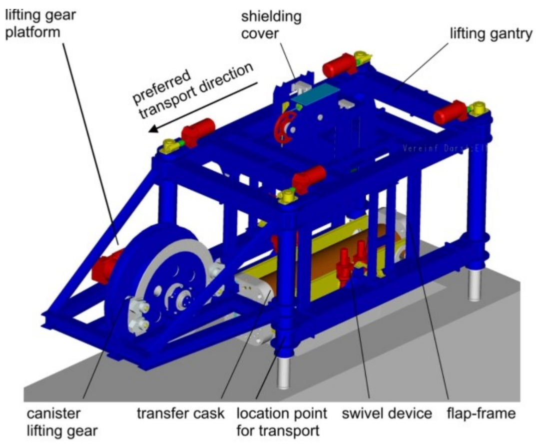
The BSK 3 transport and emplacement system displayed in **Figure 25** was selected, out of two different options, on the basis of a set of technical and safety criteria and designed accordingly. A combination of a separate transfer cask and emplacement device did show a few more benefits from a handling and technical point of view than a transfer system integrated in the emplacement device. Accordingly the transport and emplacement process starts above ground in a hot cell in a conditioning plant. Here the BSK 3 canister is inserted into the transfer cask. After shipment to the repository, the transfer cask (which is also a transport cask) is moved by the transport cart (pushed by the mining locomotive) through the repository access shaft down to the emplacement drift underground. The mining locomotive drives the transport cart with the transfer cask to the emplacement device. The emplacement device, previously positioned on top of the previously excavated emplacement borehole, lifts the transfer cask from the transport cart, tilts the cask into an upright position and lowers it down onto the top of the borehole lock which is fixed on top of a 4m long adapter pipe inside the borehole. The borehole lock and the lock of the transfer cask are then opened simultaneously, and the BSK 3 canister is lowered down by means of a rope and canister grab.

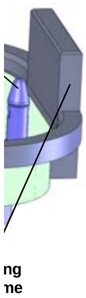




1 Control cabin
2 Power unit
3 Active coupling

Battery locomotive for rail bound transport **Transport cart with transfer cask**





Borehole lock for sealing emplacement borehole **Emplacement device for handling transfer cask**

Figure 25: The BSK 3 emplacement system with its main components

Full scale tests

Due to the lack of an underground laboratory in salt rock in Germany it was decided to perform the demonstration tests in a surface facility. For this purpose, a former turbine hall of a power station owned by E.ON in the village of Landesbergen in the vicinity of Hanover, Federal State of Lower-Saxony has been rented. This building provides the possibility to simulate the emplacement process of a BSK 3 canister in a vertical borehole over a total height of approximately 10m.

In spring 2008 the platform for the demonstration tests was erected, followed by the delivery of the components of the emplacement system in the summer of that same year. All the components were assembled at a level of 10 m above ground floor (**Figure 26**), while a 10-m-long vertical steel metal casing was erected to simulate the emplacement borehole. The BSK 3 canister is lowered down by the grab of the emplacement device and - unlike industrial operations in a real repository - removed again for further tests.

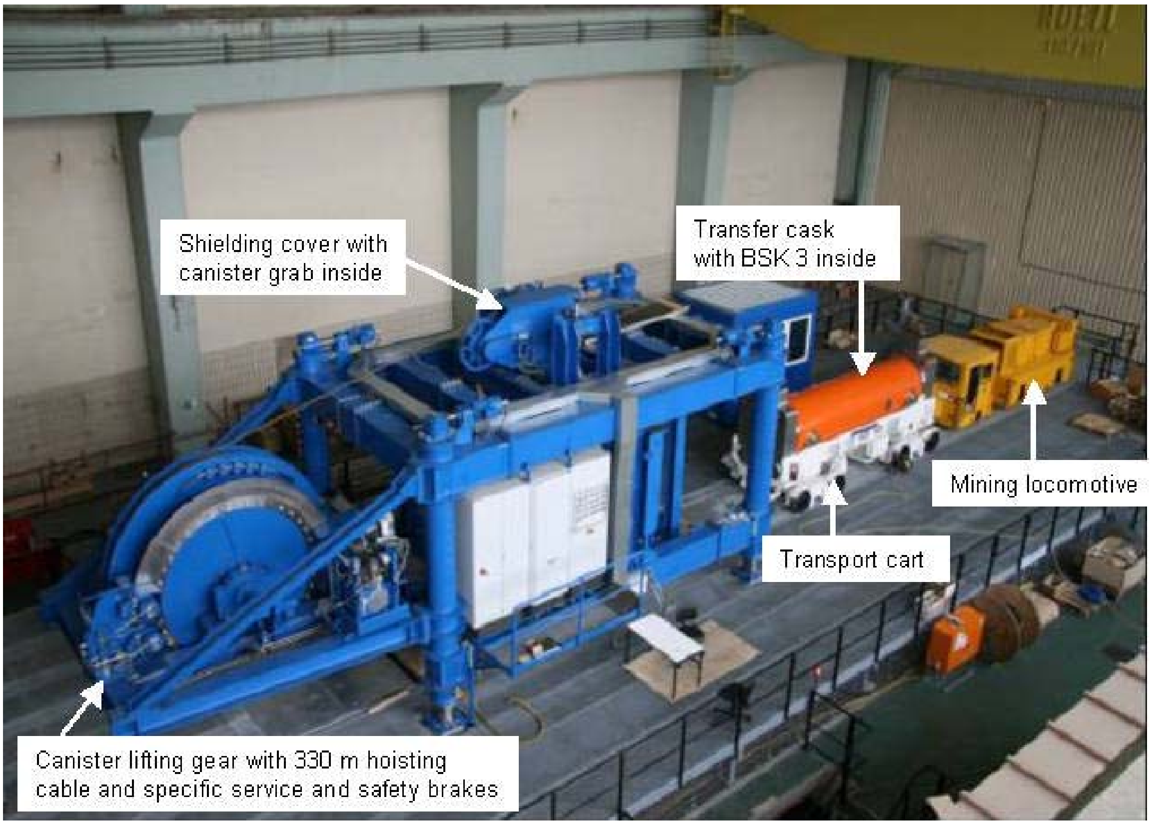


Figure 26: Photo of the Vertical Emplacement test facility in a former power station in Landesbergen

In a series of demonstration tests, the handling and sequences planned for the underground emplacement process were successfully demonstrated from September 2008 to the end of the Project. All the components which are relevant to the system function and control were taken into account. In combination with a specific test programme, experimental data on the reliability of the underground emplacement process were obtained during several hundred emplacement cycles.

Possible disturbances of operation were simulated and analysed with regard to their effects in order to plan corrective actions systematically. In this regard it was shown that for instance the entire system can be safely operated manually in case of malfunction of the automatic steering system. And it was confirmed that the failure of a position switch is compensated by a safety switch.

As an example, during the tests, the failure of one of the four spindle driven legs of the emplacement device was simulated. It could be shown that the system remains in a safe and operable situation and that the design of the construction fulfils even this requirement. In addition the undue loading of the emplacement device was simulated by performing 10 times the amount of emplacement processes than are necessary in a real repository. The system remained stable and worked properly.

The Pushing Robot system (ANDRA)

Background

Within the framework of the European IP ESDRED Project Module 2, a research & development programme was launched in order to design, manufacture and test the necessary technical components for the transport and emplacement of C type canisters into horizontal disposal cells in Argillite. The main objective was to develop a system for demonstrating the functionality and reliability of a suitable emplacement technology, called the Pushing Robot system. In addition, the results of the tests and investigations should later provide to the Public at large valuable information on practical, down-to-earth operations likely to be encountered in the future industrial disposal of radioactive waste. After testing, the demonstration model was planned to be moved and re-erected in the CTe (ANDRA's Technology Centre now under construction in Saudron, near the Bure URL site) for presentation purposes to a general public.

Data and requirements

The main functional requirement was that the emplacement system should be able to safely transport and emplace C type canisters into horizontal disposal cells (inner diameter 70cm) excavated in the host formation (Argillites) of the repository. This system should be representative of a real industrial application underground.

A second functional requirement was to check the compliance of each individual component with the predefined performance and geometrical requirements by means of full-scale demonstration and reliability (endurance) tests.

The third functional requirement was to design a system that should also be capable to be later installed and operated for demonstration in ANDRA's showroom, in Bure to satisfy the need to provide information to the general public on technical issues and for public confidence building.

The C type package, as conditioned for reversible emplacement in the repository disposal cell and the emplacement disposal concept architecture are respectively illustrated in **Figure 27** and **Figure 28** below.

The C type package is a 2 tonne, 1.6 m long and 0.60 m OD canister consisting of:

- A primary vitrified matrix containing the waste,
- A stainless steel primary envelope,
- A 50 mm thick carbon secondary envelope called the "overpack",
- This over pack is equipped with 12 (6 at each end) ceramic sliding runners, installed i) to reduce the friction coefficient (hence the pushing force) when the package is emplaced inside the disposal cell steel liner by the Pushing Robot and ii) to prevent at a later stage "corrosion sticking" at the interface of the package outer wall and liner inner wall, which would be detrimental to retrievability (should such operations be implemented).

The disposal cell is excavated in the Argillites by means of a TBM (Tunnel Boring Machine) at a diameter of approximately 0.70 m and lined with a carbon steel casing approximately 25 mm thick. Its length is about 40 m.

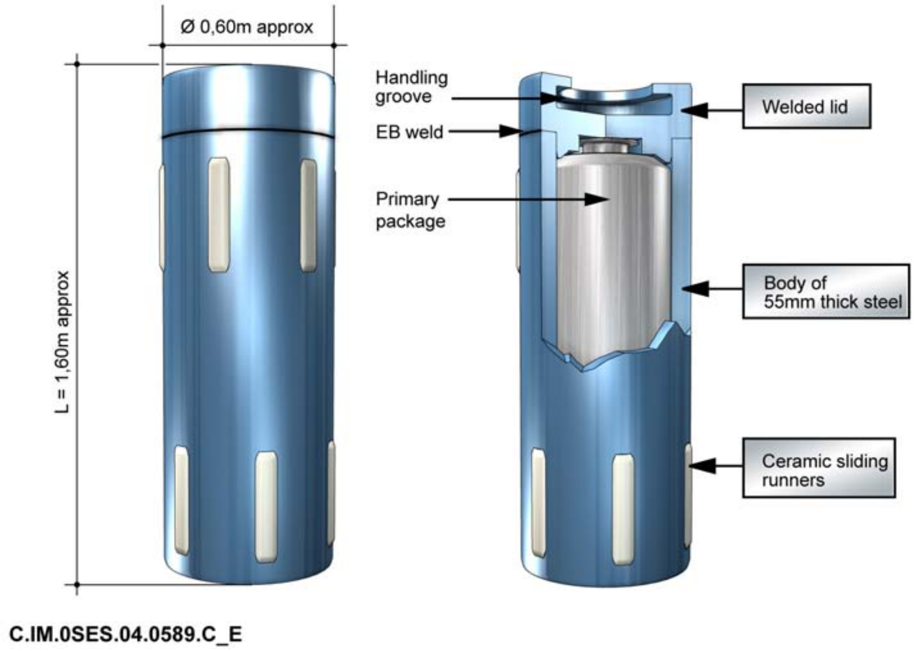


Figure 27: Construction principle of a C waste overpack

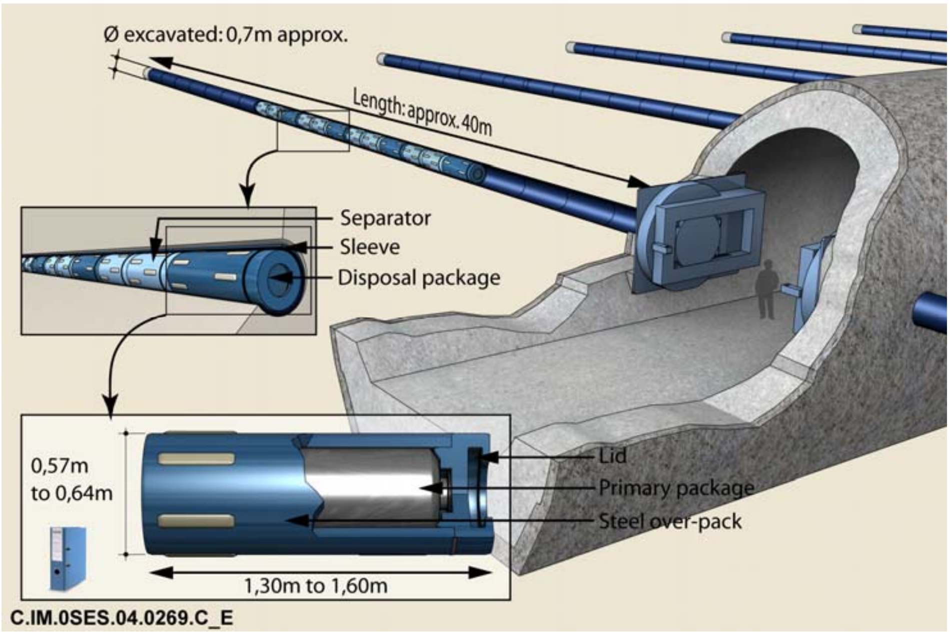
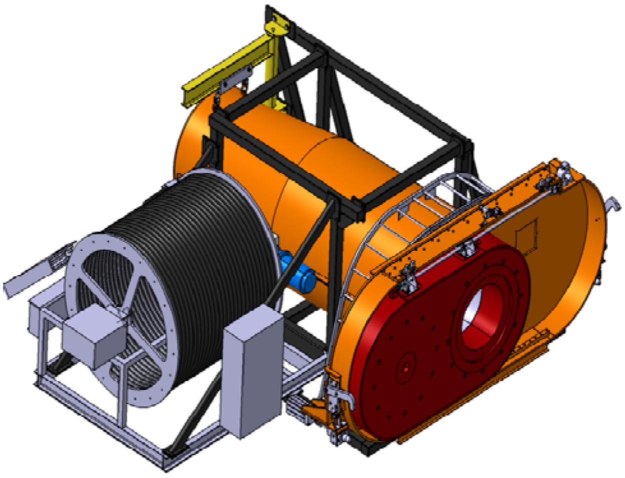


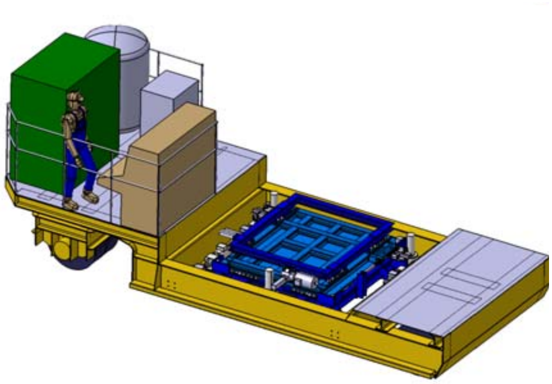
Figure 28: C type disposal concept architecture

Design

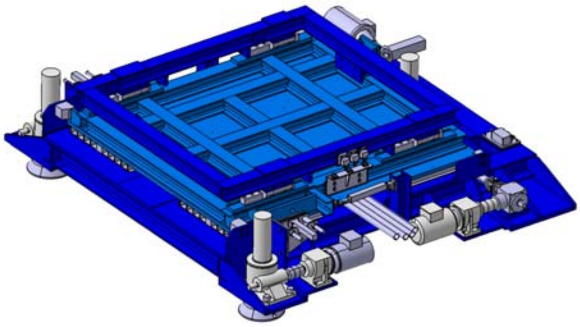
The engineering process was performed in a very classical plan for applied research, i.e.: collecting input data, defining functional requirements, elaborating basic and conceptual designs (and formulations), doing the detailed design and fabrication of the components and eventually testing at full scale a prototype and evaluating the performance of the system. These tasks were subcontracted by ANDRA to an Industrial Integrator. The Prototype phase lasted from May 2004 to March 2006, while the full scale design phase lasted from July 2007 to April 2008. The full scale emplacement system design comprised the following main components:



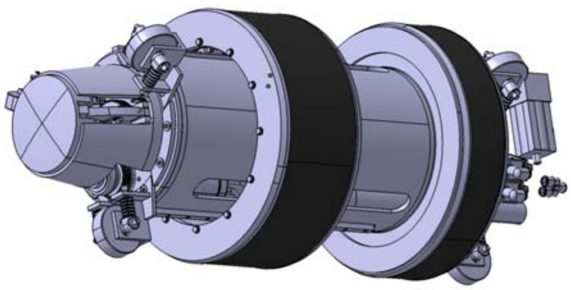
a transfer cask, which provides appropriate shielding during the transport and emplacement process



a transport unit consisting of a shuttle with hydraulic drive motors



a docking table for connecting the transfer cask to the cell mouth



a Pushing Robot to move the canister into the disposal cell

Figure 29 below shows the arrangement of the transport and emplacement system after erection, as set up in an underground emplacement drift mock-up. The general layout is designed to incorporate the various technical requirements and demonstration objectives. It shows the limited space available around the emplacement system, with the transport cask in a docking position.

This installation was essential for checking and testing in particular the relevancy and effective-ness of the various contingency remedial devices developed. Finally **Figure 30** shows more precisely the Demonstrator in its endurance testing configuration, for which 100m of liner were installed (instead of only 40 m as initially planned and presented in the Dossier 2005) to assess the potential for an extension of the Disposal Cell and also in order to assess more thoroughly the real operating time for a canister emplacement cycle.

Furthermore, this full length 100m liner provided an opportunity to check how reliable the winch and its spooling system are and whether the anticipated air pressure loss is detrimental or not to the effective functioning of the Pushing Robot (motorized by a pneumatic motor).

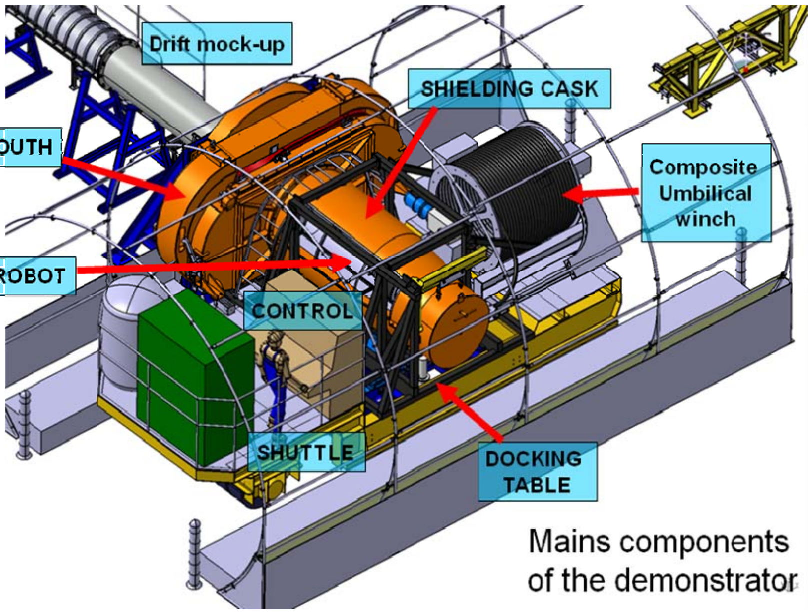


Figure 29: Conceptual view of the shuttle in a docking position inside the access drift mock-up

Full scale tests

Due to the lack of space available in the Bure URL, it was decided to perform the demonstration tests in a surface facility. For this purpose, a former workshop in Saint-Chamond, in the vicinity of Saint-Etienne (Loire Department) was rented and partially revamped. This building provided the necessary lifting means and length to simulate the emplacement process of a C type canister into a 100m long horizontal disposal cell mock-up. The components of the emplacement system were locally assembled (**Figure 30)**. After erection of the full test bench, the test campaign per se could take place.

The test programme comprised performance tests and other tests to evaluate and resolve operational challenges and breakdowns so that contingency plans were developed and implemented. Once all the test configurations were positively passed and solved, a total of approx. 500 hours of operations was carried out in order to obtain information on the reliability and robustness of the entire system and of each component.

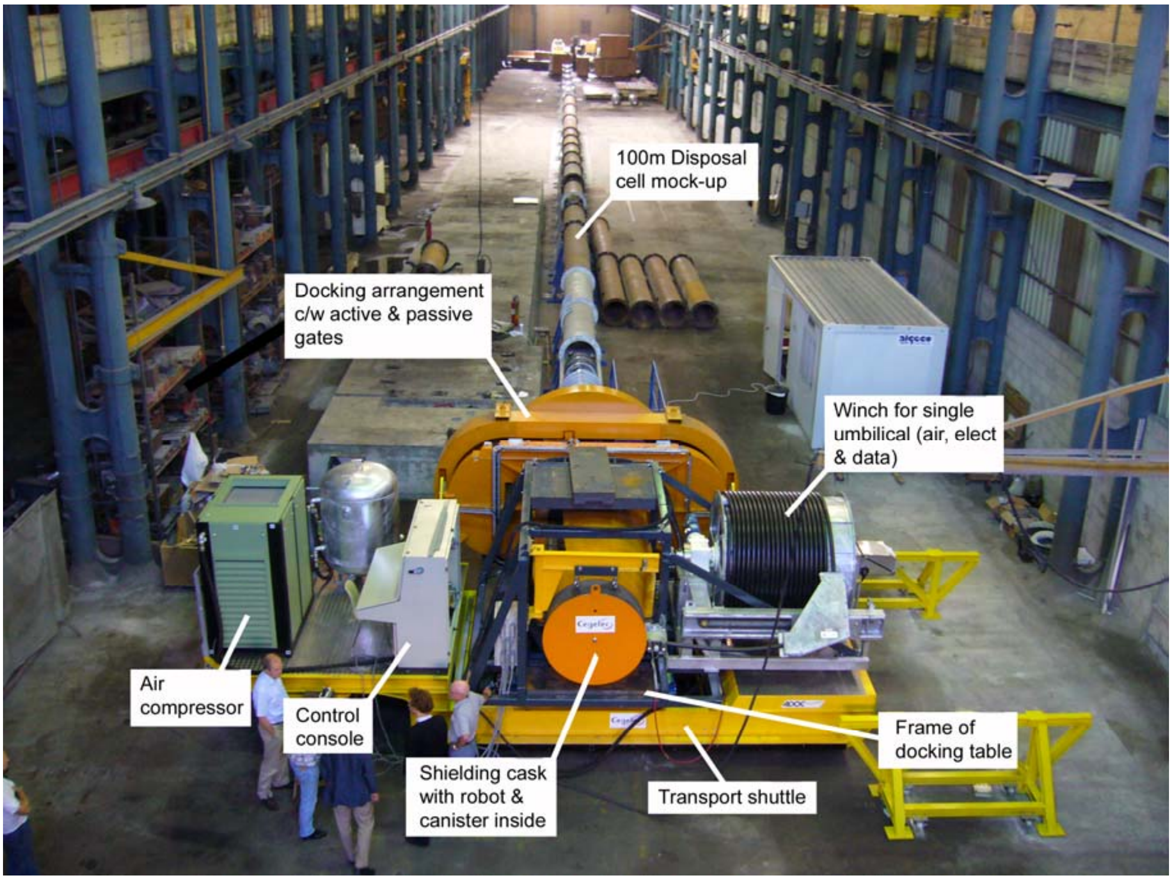


Figure 30: General View of the Horizontal Emplacement Demonstrator as set in St-Chamond

2.2.6 Main results and critical analysis thereof and perspectives for the future

The BSK 3 concept (DBE TECHNOLOGY)

It can be stated that the development, the fabrication and the performance of demonstration tests of the BSK 3 emplacement system was a success. All the components have been designed in detail, the drawings and reports evaluated by external experts confirming the compliance with the requirements of the German mining law and atomic energy act. The components were fabricated on a full-scale basis between summer 2007 and spring 2008. The construction work to prepare a suitable test platform was successfully completed in April 2008. The individual components (mining locomotive, transport cart, BSK 3 dummy, transfer cask, emplacement device and borehole lock) were delivered to the test site between April and June 2008. After the individual components had been accepted on site (SAT), the demonstration programme - performed in two shifts because of unforeseen delays in fabrication and installation of the emplacement device - was started in August 2008 and lasted until the end of the project. In the mean time the reliability of the emplacement system was confirmed by means of a large number of demonstration tests (several hundreds of cycles) and conclusions and recommendations were drawn for the industrial application in a real repository.

The successful demonstration programme led to the decision not to dismantle the entire transport and emplacement system after the end of the ESDRED project but to use the system for a second type of waste canisters. The idea is to investigate as well its reliability for handling and emplacing a so-called “triple-pack” of HLW canisters instead of a BSK 3 canister. Accordingly additional demonstration tests will be performed in the spring of 2009 outside the scope of the ESDRED Project. In this case three canister dummies will be encapsulated by a thin wall steel envelop by this providing geometry and mass similar to the BSK 3 canister.

This encapsulation is the prerequisite for the emplacement process with the same transport and emplacement system already successfully tested for the BSK 3 canister.

One lesson learned during the fabrication process of the different components of the BSK 3 emplacement system was that there is always a need to continuously control all steps of a component fabrication in spite of having very precisely formulated technical specifications and exact drawings.

The Pushing Robot system (ANDRA)

It can be stated that the development, the fabrication and the performance of demonstration tests of the Pushing Robot system was also a success. All the components have been designed in detail. The fabrication of all the system components was completed as planned. The components were delivered to the test site between June and mid August 2008.

After the individual main components had been accepted during the FAT (Factory Acceptance Tests) during the months of April and May 2008, the complete test bench was progressively assembled and erected in Saint-Chamond (near Saint-Etienne). The erection was completed in September 2008. Then the Site Acceptance tests (SAT), which lasted from October to November 2008, were started. The demonstration programme was prolonged by an endurance test campaign which lasted until the end of 2008.

The whole system turned out to be very rugged and reliable. No mechanical failures or design flaws could be identified. All the performance requirements were met, including the pushing of 3 canisters at a time instead of one as initially programmed at the start-up of ESDRED Module 2. Only one piece of equipment (the upper part of the electrical screw jacks used for elevating the docking table) showed an abnormal wear (but no breakage occurred) when a dismantling of all the moving pieces took place for inspection and evaluation of the “wear factor”. This weak point (which does not put the disposal system in question) is still undergoing investigation at time of writing.

One lesson learned is that the weak points of a machine are quite seldom those expected (in the present case the wear was anticipated on the Pushing Robot components, which showed virtually no wear at all) and that endurance testing is mandatory.

Outside the ESDRED programme, ANDRA decided to run in January 2009 an additional test configuration called the “S type curve” test, in which an exaggerated theoretical shape of a TBM (Tunnel Boring Machine) trajectory is simulated, that is an axis of the excavated (drilled) hole which is not straight but curved. This additional test is illustrated below in **Figure 31**. The results obtained were also quite satisfactory and show that the system has a strong compliance with the potential geometrical defect of a constructed disposal cell (the defects can be created at time of excavation of after that time because of geotechnical phenomena somehow bending the cell steel casing/ liner inside which the canisters are later emplaced). The only phenomena noticed was an increase of the pushing force necessary to move the canisters forward, but this increase was not detrimental to an effective and smooth emplacement process.

An additional improvement (also outside of ESDRED) is also envisaged. In the year to come, i.e. after erection and start-up of the test bench at the Cte (showroom), a new type of ceramic sliding runners will be tested (their shape has been slightly modified, with a lower rugosity coefficient). The new ceramic runners would be made of zircon instead of alumina, which should result in a reduction of the friction coefficient (hence the pushing force exerted on the canister by the Pushing Robot) by at least 20%.

Figure 31: View the Horizontal Emplacement Demonstrator in the S type configuration

2.2.7 Contribution to "Common European View"

The two emplacement systems were successfully developed and tested for respectively 1) the transport and 2) the emplacement of packages into horizontal disposal cells and of spent fuel rod canisters into deep vertical boreholes. The work clearly showed that the Pushing Robot system and the BSK 3 system provide a safe and reliable means for the transport and emplacement of HLW and SF canisters at an industrial scale. Both emplacement systems were effectively tested in the second half of 2008 by virtue of demonstrators fabricated for this purpose.

In the case of DBE TECHNOLOGY the demonstration of the transport and emplacement of BSK 3 canisters into 300m deep open boreholes was successfully shown in a 1:1 scale test facility. The technology which was designed for its application in a repository in rock salt might be applied in other host rocks as well. In this regard the results contribute to a common European view on how to safely handle high level waste in a repository, when a vertical disposal configuration is preferred.

In the ANDRA case, the equipment developed shows that it is technically feasible to emplace HLW Canisters (C) into 100m long steel lined horizontal emplacement cells using a Pushing Robot system. An Endurance Test campaign was started in December 2008 following the completion of the Site Acceptance Tests. The subsequent installation of this emplacement equipment in the Technology Centre near the Bure URL will contribute to a better understanding of the use of the technology that has been developed within Module 2 and more generally to the confidence building process. In this regard the results contribute to a common European view on how to safely handle high level waste in a repository, when a horizontal disposal configuration is preferred.

2.3 Heavy Load Emplacement Technology (Module 3)

2.3.1 State of the art and brief discussion of differences between national concepts

In industry, air and water cushion systems for lifting and handling heavy loads (up to several hundred tonnes) are being used world wide. The application of such a technology is however generally limited to situations where the air or water cushions are acting on flat and smooth "sliding" surfaces. Applications where the air/water cushions act on cylindrical surfaces (i.e. either on the surface of the load to be moved or on the surface on which the cushions "slide") are not so common. The specific applications considered within the scope of the ESDRED work are without precedent, since the emplacement concepts relate to moving and placing cylindrical waste canisters inside horizontally bored disposal drifts (cells) whose cylindrical walls have a rough surface. At the same time the annular gap between the outside diameter (OD) of the canister and the inside diameter (ID) of the disposal drift wall is limited to a few centimetres. Working underground with radioprotection constraints, requiring remote control (i.e. no direct access or vision of the moving load) adds a further level of complexity.

In the case of SKB/Posiva they have selected the use of water cushion technology for the transport of 45 tonne spent fuel waste containers in horizontal bored drifts up to 300m long. The reason for selecting water cushions instead of air cushions is that it is impractical to supply air in a 300 m hose due to the pressure drop in the hose. It would have been possible to install an air compressor on the deposition machine but the power consumption for the compressor would have created undesirable heating inside the drift during emplacement. By using water (which is recycled at the emplacement machine with very little loss) instead of air the total power consumption is reduced to about 1/10. Finally the use of water is not a problem in a granitic host rock.

In the case of ANDRA whose base case concept involves short (about ± 40m) drifts in a clay host rock the supply of air in a hose is not a problem and, because of the water soluble clay, the use of water must be avoided at all cost.

Typically the surface of the disposal drift invert, even when bored, will be too uneven for the proper operation of either the air or the water cushions. Therefore a very smooth slide plate (on which the cushions will blow either air or water) must be incorporated into the system and therefore the emplacement process occurs in incremental steps where the length of each step depends on the length of the slide plate and the design of the emplacement vehicle.

It should also be noted that ONDRAF/NIRAS also propose to use air cushions for moving heavy waste packages (Super Containers with vitrified waste) in their planned future repository. The work done by ONDRAF/NIRAS has been done outside ESDRED but some exchange of technical information took place in the early part their work.

2.3.2 Technology issues addressed within ESDRED Module 3

One ESDRED objective was to demonstrate, at an industrial scale, the technical feasibility of some very specific activities related to the construction, operation and closure of a deep geological repository for high level radioactive waste.

Heavy Load Emplacement Technology for horizontal disposal concepts was the focus of the work carried out in **Module 3** of the project. In this Module two machines were successfully produced, each capable of emplacing 43 to 45 tonne waste canisters in bored disposal tunnels. One machine, based on water cushion technology, was designed for the KBS-3H system in Sweden and Finland, while the other machine, designed for the Spent Fuel (CU1) Canister Emplacement System (ANDRA), used air cushions. The air cushion deposition machine was also adapted to demonstrate the emplacement of sets of four pre-assembled bentonite rings (produced in Module 1), weighing 17 tonnes.

The KBS-3H system in Sweden and Finland
In Sweden and Finland two concepts for direct disposal, in granite type formations, of spent nuclear fuel canisters are being separately investigated, based on the multi barrier system called the “KBS-3”. The “KBS-3V” concept deals with vertical emplacement of spent fuel canisters in disposal holes lined with buffer material on the floor and the walls. The “KBS 3H” concept deals with the alternate method, i.e. horizontal emplacement of the spent fuel canisters placed inside a prefabricated Super Container, which also includes the buffer material as part of the package to be emplaced.

The KBS-3V disposal method is currently the reference case, both in Sweden and Finland, but the KBS-3H concept has a high potential, being more cost effective and environmentally advantageous. The KBS-3H concept is still under development. It also presents a number of specific technical challenges. Some of them have been demonstrated within Module 3 in the ESDRED programme.

Outside the ESDRED programme SKB and Posiva have also demonstrated that it is possible, in hard rock, to bore long horizontal disposal drifts with a diameter of 1.85 m and with very stringent geometrical mining requirements.

Direct disposal of spent nuclear fuel canisters in France
At the time of the ESDRED Project start-up (February 2004), the disposal of spent fuel canisters was considered to be highly probable in France and the technically related emplacement system was subsequently developed. The emplacement of a pre-fabricated engineered barrier around the spent fuel canisters was also considered as scientifically relevant, both around spent fuel canisters and around vitrified waste canisters.

In France the reference scenario being developed today (i.e. since the passing of the Law of June 2006) by ANDRA is focused on the development of disposal concepts for vitrified waste canisters only. In this new reference scenario an engineered barrier no longer surrounds the vitrified waste canisters. However, direct disposal of spent fuel canisters in horizontal cells (excavated in clay) is still an option that may be reconsidered in the future, e.g. for fuel not suitable for reprocessing. In all cases, in the management system for high level long-lived waste in France, it is necessary to also show that direct disposal of spent fuel canisters is a feasible option. It is also important to demonstrate the capability to fabricate large compressed donut shaped rings of buffer material and to demonstrate the ability to emplace these rings in a confined space where they will eventually surround the waste canisters, after these have been emplaced in the sleeve that is inserted in the central hollow part of the rings.

Therefore what has been successfully demonstrated by ANDRA within the ESDRED project will remain as a worthy reference for the European nuclear community, and in particular for ANDRA, should the concept of emplacing a pre-fabricated engineered barrier ever evolve again in France.

2.3.3 Objectives of the Work within ESDRED Module 3

The objectives for Module 3 were, starting from conceptual designs which were pre- existing at the time of start-up of the ESDRED Project, to develop three specific **demonstrators** capable of transporting and emplacing the following types of cylindrical shaped heavy loads:

- For the Swedish/Finish concept a 5.5m long, 45 tonne Super Container with an OD of 1.76m. This canister is to be positioned inside a long 1.85m diameter bored drift, in a granitic type host rock,
- For the French concept a set of four pre-assembled buffer rings weighing 17 tonnes and with a diameter of 2.3m. These are to be placed inside a horizontal disposal drift supported by a perforated liner.
- For the French concept a 5.4m long Spent Fuel or CU1 type Canister, with a weight of 43 tonnes and with a diameter of only 1.25 m. This canister is to be placed inside a metallic sleeve which is itself

placed inside the central open part of the pre-fabricated bentonite rings, adapted for a clay type host rock.

The objective was also to:

- Test the reliability and availability, over a sustained period, of the three developed machines and of their ancillary pieces of equipment, and to
- Identify the necessary and/or desirable improvements for a potential future industrial application.

The success of the demonstration of these machines would then pave the way for additional work on the disposal concept for SKB/Posiva and would remain as a positive case story for ANDRA. In all cases it would contribute to a much needed and continuous Public Confidence Building process.

2.3.4 The Partners within Module 3

The partners within Module 3 were SKB (Svensk Kärnbränslehantering AB), acting as the Module Leader, POSIVA and ANDRA (Agence nationale pour la gestion des déchets radioactifs).

The contractor selected by SKB /Posiva for the deposition equipment using water cushions was CNIM, located at La Seyne-sur-Mer, in France,

The contractor selected by ANDRA for the deposition equipment using air cushions was MECACHIMIE located in Beaumont- Hague in France.

2.3.5 Execution of the works

2.3.5.1 KBS-3H Deposition Concept (SKB / Posiva)

Background
The conceptual design phase for the KBS-3H deposition system was carried out during the year 2003, i.e. before the start-up of the ESDRED Project.

The main objectives of the conceptual design were:

- The elaboration of a functional description of such equipment, complete enough for ordering the design and fabrication of the equipment.
- The verification that the fluid cushions lifting principle was feasible for the horizontal emplacement of a Super Container. Therefore, some prototype testing of the air/water cushion technology was performed at the 1:1 scale (for the diameter), while the length of the test rig was reduced to 1⁄4 of the length of the real Super Container.

The workshop tests were satisfactorily performed in April and July 2003. Then the decision was taken to effectively incorporate the development of the KBS-3H within the framework of the ESDRED general technical programme, in Module 3. During March 2004, at the very beginning of the ESDRED programme, some additional tests were performed in order to better evaluate the appropriate lifting height of the water cushions.

The basic design phase resulted in drawings and mechanical analyses of the different functioning parts of the deposition equipment as well as in the specifications of the electrical and control systems. This information was incorporated in the general technical specifications contained in the Request for Proposal documents.

The equipment to be fabricated consisted of the following main components:

- Deposition Machine,

- Start Tube for Deposition Machine with Transport Support,
- Transport Tube for Super Container with Transport Support.

For test purposes a 95 m long drift was excavated in granite with a special tunnel boring machine, early in 2004, at the Äspö Hard Rock Laboratory (HRL). The excavation of the demonstration drift was outside the ESDRED project programme and financing, even if such work was mandatory for the effective development and testing of the KBS-3H system. The excavation of the test drift was an important precursor to the development of the KBS-3H deposition equipment concept.

Data and Requirements

The main Functional Requirement was that the Deposition Machine should be able to transport Super Containers and Distance Blocks (Spacers) inside a horizontal drift with a diameter of 1.85 m using the water cushion technology.

A second Functional Requirement was that the machine developed had to be compatible with the pre-defined geometrical weight and dimensions of the Super Container and the pre-defined dimensions and slope of the disposal drift.

The so-called Super Container contains the copper canister with encapsulated spent nuclear fuel, the compacted buffer material and the external perforated steel shell. The Super Container is provided with feet to allow it to be transported by the deposition machine inside the drift.

The Super Container has the following dimensions and weight:
- Steel shell outer diameter 1765 mm,
- Steel shell overall length 5550 mm,
- Height of feet 45 mm,
- Weight approx 45 tonnes.

The Distance Blocks (or spacers) are circular blocks made of compacted bentonite. The feet necessary for their transport are fixed directly to the bentonite blocks. The Distance Blocks have the following dimensions and weight:
- Diameter 1765 mm,
- Length 900 mm,
- Height of feet 45 mm,
- Weight approx 4.6 tonnes.

The Deposition Machine was also designed to meet the following **Functional Requirements** to be verified during the tests:
- The machine should be able to position Super Containers and Distance Blocks in contact with each other inside the deposition drift.
- The machine should be designed to prevent water from coming into contact with the buffer material contained in the Super Container.

Design

The equipment needed for the deposition of Super Containers and Distance Blocks was developed and fabricated during 2005 by CNIM, France.

The main components of the deposition machine design are shown in **Figure 32** below. The machine is wheel driven with electrical gear motors on all four wheels.

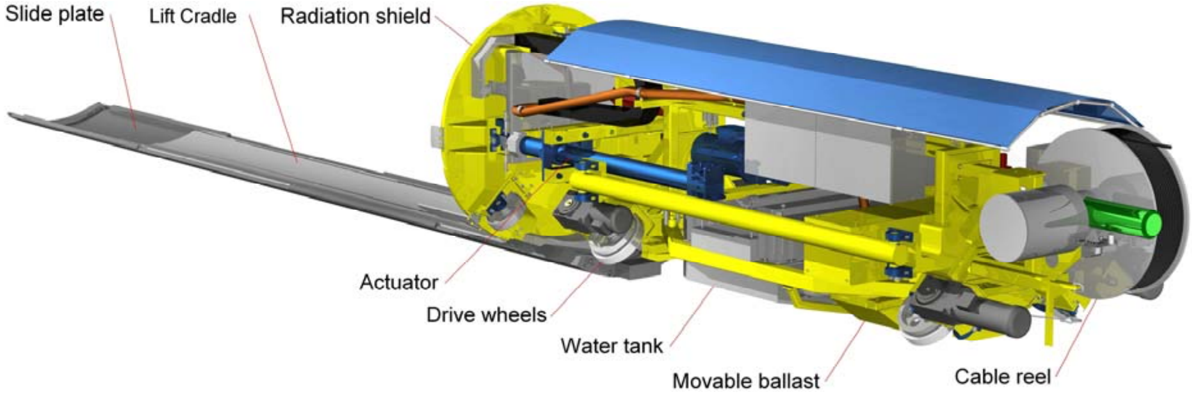


Figure 32: 3-D Illustration of the Deposition machine, view from back left side.

The slide plate, on which the lift cradle is sliding, is made of stainless steel and is attached to the main machine frame. The lift cradle, provided with 24 water cushions, is attached to the radiation shield, which is connected to the machine frame via three synchronized actuators allowing for the stepwise movement.

Full Scale Tests

Figure 33 shows the emplacement equipment and the control room as set up in the chamber in front of the test disposal drift at the Äspö HRL, on the -220 m level.

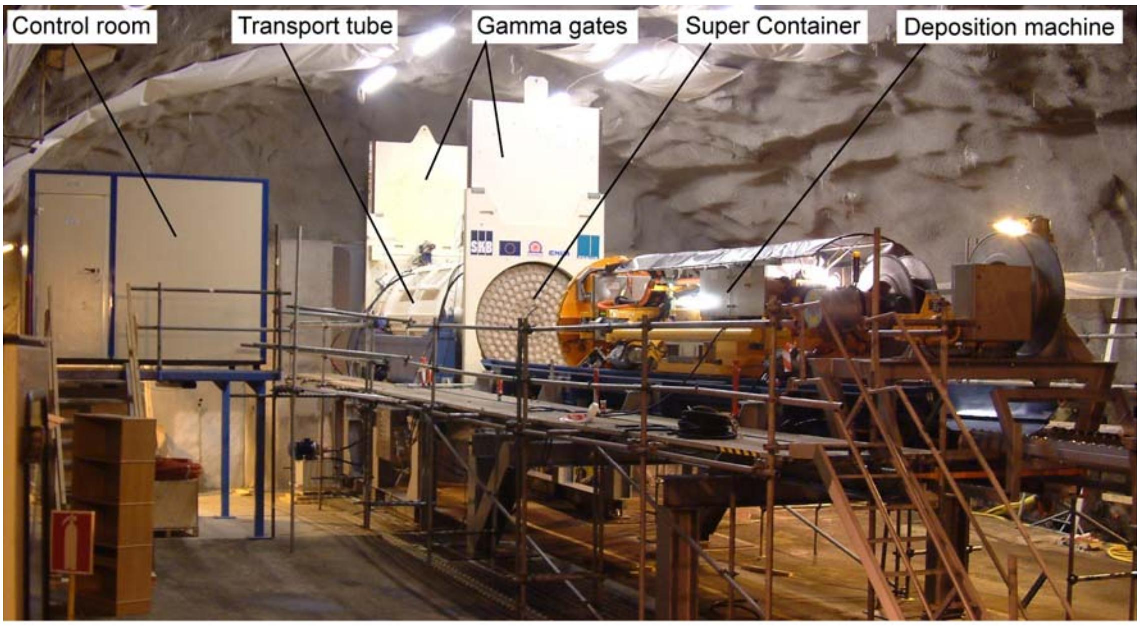


Figure 33: Set-up of equipment at the test site at Äspö HRL, level -220 m. The Super Container is inside the transport tube with the two shielding gamma gates open.

One of the early results during the pre-tests performed at Äspö showed that it was impossible to properly handle an unbalanced Super Container. Unbalance occurs if not all fuel positions in the canister are filled. Therefore all the tests were performed with a properly balanced Super Container.

It was also observed that the mobile ballast (used as a balancing means) on the machine was only capable of balancing the Super Container in a static situation and not when the container was moving forwards/backwards.

As soon as the container was moved, it and the lift cradle started to rotate clockwise or counter clockwise. The only way to keep the Super Container and the lift cradle from rotating during transport was to guide the lift cradle along the slide plate edge by installing longitudinal rails acting as a guide system.

The tests also showed that this rotation phenomenon could be offset thanks to the ballast system if the correction was done as soon as an unbalanced condition was detected. Therefore, the ballast system was made automatic.

It was also observed that if the Super Container together with the lift cradle and the slide plate were (cumulatively) rotated more than 3.5 - 4 degrees, then this movement could create problems for the proper functioning of the water cushions. The reason for this was that with rotation the water cushions are no longer equally loaded and the cushions with the heaviest load are no longer capable of lifting the container. It was therefore considered impossible to properly handle an unbalanced Super Container with the present water cushion system.

Another observed problem was that the lifting height (between cradle and slide plate) was very sensitive to pressure variations or load changes. One crucial point with the installed guiding system was the need to accurately control the lifting height. Too much lift would result in derailment. It was therefore decided to perform additional tests on the water cushions to verify the actual lifting height in a separate workshop test. This led to the decision to replace the water cushions with a newly designed model that was less sensitive to pressure variations and/or load changes.

The performance requirement for the average deposition speed of 20 mm/s (1.2 meter per minute) was finally reached after correction/adjustment of the water cushion control valves. According to the test programme the goal was to make, as a minimum, one deposition and one subsequent recovery of the Super Container per day. The transportation and endurance tests were performed during the period from April 2007 to September 2007 however the operation of the deposition machine has continued. The cumulative total distance travelled by the Deposition Machine, between the Site Acceptance Tests in February 2007 and mid 2008, is approximately 45 km.

2.3.5.2 SF (CU1) Canister Emplacement System (ANDRA)

Background

In 2003 ANDRA, in France, selected the concept of air cushion transportation technology as the most appropriate means for the emplacement of SF (Spent Fuel) canisters (also called CU1 canisters) inside a disposal cell, as well as for the transport and emplacement of sets of four pre-assembled buffer rings when constructing the disposal cell. In the ANDRA case the sets of four pre-assembled buffer rings and the SF canisters are handled separately (unlike SKB’s integrated Super Container), due in particular to a) the need for assuring the retrievability of the SF canisters and b) the limitations related to the maximum allowable weight during transfer in a shaft cage.

The two ANDRA emplacement systems were totally developed within the framework of the ESDRED Project, as of early 2004. The main components in the ANDRA disposal system for the emplacement of CU1 type SF canisters were developed first and were subsequently adapted for the emplacement of sets of four pre-assembled bentonite rings. Each set of rings has a weight of 17 tonnes, with an OD of 2.25 m and a length of 2 m.

Air was selected as the appropriate lifting medium for two main reasons: i) it is a medium compatible with the clay host formation , ii) the pressure loss experienced over a 40 m long umbilical is still compatible with the proper functioning of the air cushions, without having to put an air compressor on board the emplacement machine.

The air cushion cradle enables: i) lifting of heavy loads and minimum effort to achieve forward movement, ii) minimizing the clearance (annular gap) between the outside diameter of the load (canister or buffer rings) and the inside diameter of the cell wall. This geometrical optimization results in lower construction costs as there is less material to be excavated and also in lower operating costs as less material is needed to backfill the disposal cell and because there is no need to fill the small annular gaps.

Data and Requirements

The weight of the SF canister is 43 tonnes and it has an OD of 1.25 m and a length of 5.39 m.

The disposal cell is excavated in clay rocks. It has a length of approximately 40 m from mouth to cell dead end. The annular clearances for a spent fuel canister installed inside a bentonite buffer ring are presented below in **Figure 34**. The clearances shown were selected as being the best compromise between the minimum gaps needed for operational reasons and the confinement (long term safety) requirements. For practical reasons the bentonite rings actually fabricated as part of Module 1 of the Project, and transported as part of this Module 3, were the smaller (2.3m OD) rings that were to have been used with the smaller vitrified waste canisters (Module 2 of the ESDRED Project) when this was still part of the ANDRA concept.

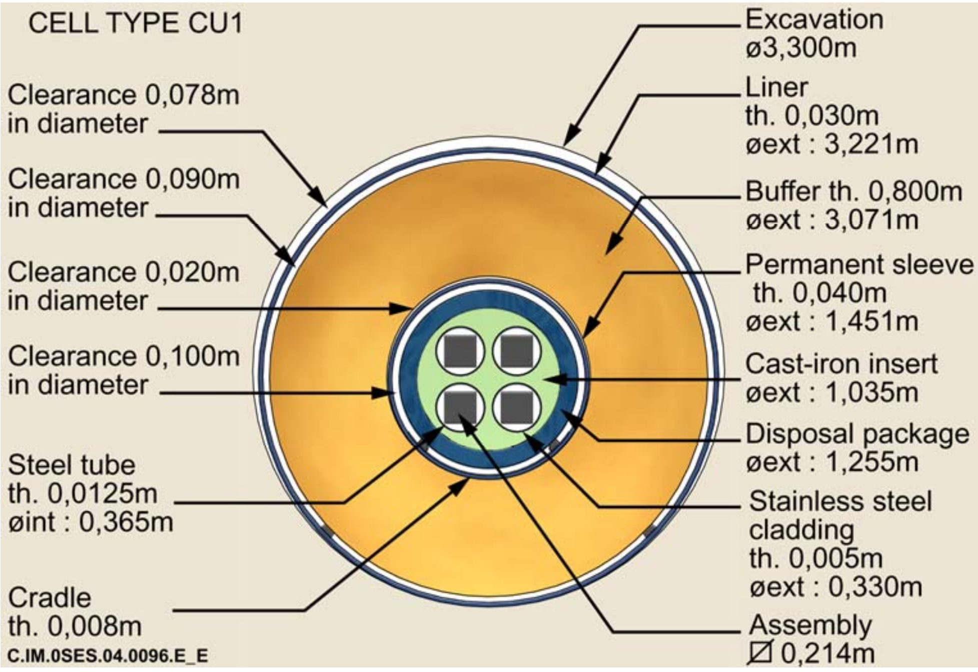


Figure 34: Main components of ANDRA's emplacement concept for a spent fuel canister disposal cell c/w annular clearances

Prototype Test Programme

The CU1 spent fuel canister considered in the French concept has a smaller diameter, only 1.25 m, but almost the same weight (43tonnes) as the SKB/Posiva Super Container.

As the radius of curvature of the cushions on the lifting cradle is significantly smaller than in the SKB/Posiva case, it was considered necessary to first carry out a preliminary prototype testing with an air cushion cradle specifically designed for the CU1 spent fuel canister application.

The objectives of the prototype test programme were as follows:

- to verify that the overall air cushion lifting system functioned correctly,
- to assess the required power needs for the proper operation of the overall system,
- to validate particularly the following data: the number and characteristics of the proposed air cushion modules, the air flow rate and the working pressure, the required annular clearance and the operational height of the cushions,

- to determine the required thrust and pulling force,
- to characterise the capability of the overall system to tolerate operational "anomalies",
- to determine the capability of the system to deal with geometric irregularities, such as bumps or steps along the emplacement track, misalignment of guide rails and package rebalancing, excessive grade of the travel path, etc,
- to assess the achievable speed (movement in 1m increments) with the identified acceptable defects and to extrapolate from them an average advance speed of the canister in the disposal cell.

A Prototype Test Bench was erected at the BERTIN premises near ANDRA's head office. The design of the bench was full scale regarding the radius of curvature of the canister, and at a reduced scale (1 to 3) regarding the length of the canister. This work was successfully carried out in November/December 2004. The test bench is now installed in ANDRA's Technology Centre (CTe) near the Bure URL site.

Full Scale Tests
Following the successful implementation of the Prototype Test Programme, it was decided to proceed with the development of a full scale demonstrator.

The erection, testing and demonstration were carried out in a surface workshop.

The equipment designed during 2005 by Mécachimie for the emplacement of CU1 (SF) canisters consisted of the following main components:

- Deposition Machine complete with slide plate, air cushion cradle, electric emplacement cart, control & monitoring system, motorized winches for steel cable/air umbilical/electrical wire,
- Simple mock-up of shielding cask with a motorized shielding gate,
- Mock-up of disposal cell section (first 10m) with a passive shielding gate at mouth,
- A supporting frame.

The test campaign related to the testing of the machine designed for the emplacement of CU1 Spent Nuclear Fuel Canisters took place from May 2006 to September 2006 in Mécachimie's premises in Beaumont-Hague, near Cherbourg, France. This campaign started with the erection of a complete test bench in the configuration shown below in **Figure 35**.

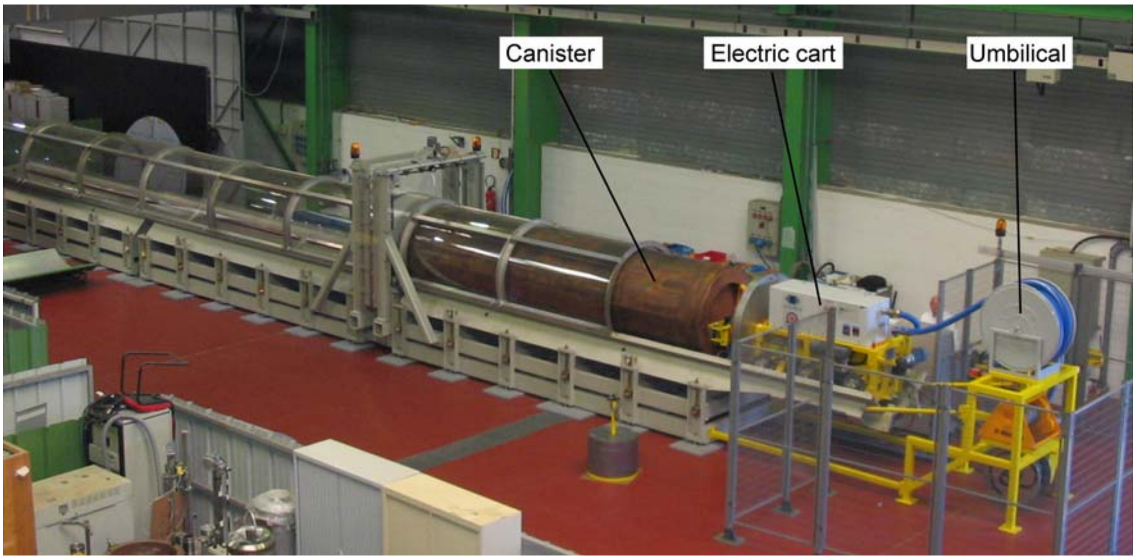


Figure 35: ANDRA - Set-up of the CU1 canister emplacement system at Mécachimie's premises. This equipment is now also installed at the TC at Bure URL site.

After completion of the tests with the CU1 canister the test bench was then modified for testing of the emplacement of the bentonite buffer ring packages and these tests were performed between October 2006 and January 2007.

The primary objectives and challenges of the test programme for emplacement of CU1 canisters were as follows:

- to show that the emplacement equipment could meet or exceed all the specified technical performances, including the successive emplacement (and subsequent retrieval) of the dummy canister in automatic mode, the automatic closing and opening of the gamma gates and finally the specified average travel speed over a complete emplacement cycle;
- to demonstrate that the emplacement equipment could pass over obstacles such as the recesses in the door frames created by the shielding gates or over the discontinuities between two consecutive sections of guide rails. For this purpose, the use of a sliding plate could not be avoided;
- to evaluate the sensitivity of the system to the various possible construction defaults (steps, misalignments, etc) likely to be encountered underground and to any off-centre (radial or longitudinal) location of the centre of gravity of the dummy canister;
- to identify the weak points of the system likely to require some re-engineering and/or retrofitting in the real industrial application;
- to identify some potential improvements (mainly in terms of ruggedness and performance).

And for the emplacement of bentonite buffer ring packages these were:

- to check the behaviour of the rings, the air cushion cradle, and their stability under the various conditions during the emplacement operations,
- to check the relevance of the pre-defined operating parameters since no Preliminary Testing had been performed.

During the test work it was noted that the emplacement of ring packages (no radioactivity in the disposal drift) could be simplified by replacing the slide plate with just a fiber glass carpet (sheet) on the bottom of the disposal drift mock up. The transfer of the bentonite rings into the disposal drift could then be performed in a single continuous operation instead of the stepwise procedure needed for emplacing canisters. In the absence of any radioactivity the fiber glass carpet can later be removed manually once all the bentonite rings are emplaced in a disposal drift.

2.3.6 Main results and critical analysis thereof and perspectives for the future

KBS-3H Deposition Concept (SKB / Posiva)

The tests performed in situ demonstrated that the emplacement equipment can operate effectively for the transport and deposition of Super Containers and that the specified performances are effectively reached.

The main technical points observed during the test campaigns are listed below:

- The water cushion technique used is sensitive to load variations. This means that the Super Containers to be transported must be well balanced.
- The operation of the emplacement system is sensitive to the alignment in the set-up between the Super Container transport tube, the deposition machine start tube and the deposition drift.
- Further tests are required to verify the availability and the reliability of the equipment over a longer period of time. Further tests are also required for the transportation of Distance Blocks and also to demonstrate that the machine is capable of placing the Distance Blocks in direct contact with the Super Container.
- A number of issues regarding the Programmable Logic Controller (PLC) programme were observed which also need to be improved before further testing.

- The tests have also shown that the integrity of the Super Container is not jeopardised during the handling/transport phases, but the fixation of the feet to the Distance Blocks must be improved in order not to jeopardize the integrity of the Blocks.

It should be noted that management of SKB and Posiva have decided to continue the test operation of the KBS-3H deposition equipment at the Äspö HRL at least during 2009 and 2010.

Spent Fuel Canister, (CU1), Emplacement System (ANDRA)

What follows is a condensed overview of the results with reference to the main functional requirements as well as other observations noted during the tests.

The commissioning of the emplacement system took place during the months of May and June 2006. PLC programming was a large part of the work during that period. The main difficulties encountered during this commissioning period (and their solutions) are listed below:

- The friction coefficient between the lower face of the slide plate and the steel invert (sliding track) of the disposal drift mock up tube turned out to be bigger than anticipated. Consequently, the pushing force, which had to be exerted by the electrical cart's pushing jack, exceeded the capacity of that jack. This problem was solved by attaching a Teflon sheet onto the lower face of the slide plate.
- At the end of each 1 m stroke of the pushing jack, the air cushions had to be deflated to lower and place the canister on the sliding track rails. Subsequently, the sliding plate was advanced by another 1m. The time needed for deflating and purging the air from the air cushion system turned out to be too long. Consequently, the cycle time specified could not be achieved. This problem was solved by the installation of a quick relief (purge) valve.
- The compressed air feeding the air cushions carried considerable moisture. This resulted in the formation of condensation within the air cushions following the quick pressure drop. As a result, the rubber part of the air cushion tended to separate from its steel supporting plate. Replacement cushions were glued with a water resistant compound and the problem was solved.
- The presence of moisture in the air also impacted the operation of the flow control system. A regular purging of the electro-valves turned out to be necessary on a regular basis, i.e. at the end of every emplacement cycle. Later, a desiccator (air dryer) was added to the air system.
- As originally designed, the air cushions could raise the air cushion cradle higher than the top of the guide rails inducing a tendency for derailing the system. This problem was solved by increasing the height of the guide rails by adding a 5 mm band spacer underneath the rail.
- The air cushions also turned out to be quite sensitive to individual load variations. This phenomenon appeared mainly when simulating the longitudinal imbalance of the SF canister. In the most critical simulation tested, the canister could not be moved.

The results concerning the emplacement of bentonite ring packages can be summarized as follows.

- No particular difficulties were encountered during the test programme, which turned out to be a complete success.
- The specified emplacement performances were easily met.
- The emplacement of the set of rings was very smooth, without shocks. Thus, the lateral stability of the rings was not affected.
- A compressor equipped with a desiccator (air dryer) was used and no troubles, such as those encountered with the CU1 system, appeared.
- The air cushions turned out to be also quite sensitive to voids (gaps, rough surfaces), which is why a temporary layer of fibre glass carpet was installed on the disposal drift invert.

2.3.7 Contribution to “Common European View”

The work done within Module 3 of ESDRED has clearly demonstrated that water/air cushion technology can be used for the emplacement of heavy waste containers, bentonite buffer ring packages as well as distance bocks (spacers) in small diameter disposal drifts. The deposition machine installed at the Äspö HRL in Sweden has been successfully operated since the completion of the Site Acceptance Test in April 2007. Up to mid 2008 the total accumulated distance travelled by the emplacement machine exceeds 45 km. This indicates that the equipment is quite reliable however SKB/Posiva have decided to continue the operation of the equipment during 2009 and 2010. During that period it is also foreseen that the equipment will be modified and improved based on the additional operating experiences gained.

In the ANDRA case the equipment developed shows that it will be possible to emplace buffer ring packages and Spent Fuel Canisters (CU1) using a deposition machine utilising an air cushion cradle. This equipment has not been operated (except for very brief and infrequent demonstrations) after the completion of the Site Acceptance Test in September 2006. However, the equipment is now installed and operational in ANDRA’s Technology Centre (CTe) at the Bure URL. The mock up for the prototype tests for the CU1 emplacement is also installed at the Technology Centre at the Bure URL.

The installation of the emplacement equipment in the Technology Centre at the Bure URL will contribute to a better understanding of the use of the technology that has been developed by ANDRA within Module 3. In the case of SKB/Posiva it will be possible to witness demonstrations of the emplacement of the Super Container in the bored hard rock tunnel located on the -220 meter level at the Äspö HRL in Sweden. This too will contribute to confidence building and public acceptance of this new technology as the Äspö HRL has for a long time had more then 12 000 visitors per year.

2.4 Retrievability (Module 2)

2.4.1 State of the art and brief discussion of differences between national concepts

The emplacement of radioactive waste in a geological disposal facility is generally considered without any intent for retrieval. However, the issue of retrievability[1] is increasingly looked upon as important for enhancing confidence amongst stakeholder groups as well as to increase the level of flexibility and, thus, the ability to respond to changes in technical information and policy factors. Besides the normal control and surveillance of the disposal operation, the concept of retrievability requires the possibility for reversal of operational steps if desired. Such reversal of operational steps can only be ensured if specific technological measures (e.g. the construction of disposal cells from which waste packages can safely be recovered) are already implemented in the design of the repository.

Potential design measures that enhance retrievability of waste prior to repository closure are primarily aimed at providing easier accessibility to the waste packages (1), particularly in clay and salt host environments, and/or providing an improved capability to retrieve the waste packages (2). Potential design measures in the first category include enhancing the stability of openings (e.g. by incorporating concrete or steel liners) and, in the second category, provision of easily removable buffer materials (e.g. in the form of pre-fabricated bentonite blocks).

In most disposal concepts relevant to ESDRED these issues are still under consideration and definite positions may not be reached until countries are much closer to starting the development phase. Likewise, operational and monitoring strategies are still under development. For some disposal concepts, this may mean that access ways will remain open for perhaps several decades whilst greater levels of confidence in the disposal concept are achieved, e.g. as a result of ongoing monitoring of the disposal system. For other concepts, it is likely that intensive monitoring activities will be focused on a special facility with closure of accesses to the main facility taking place relatively sooner, on the basis that the risk of neglect or even from deliberate intrusion is thereby significantly reduced.

2.4.2 Technology issues addressed within ESDRED Module 2 Retrievability

A desk study was carried out within ESDRED concerning retrievability of (high-level) radioactive waste. Since the retrieval of radioactive waste from a geological repository includes many aspects, the objectives of the desk study had to be defined more explicitly. Based on the objectives of ESDRED it was decided to exclude non-technical issues like political, economical, social and ethical aspects. In addition, the desk study should comply with the time frame of the ESDRED project. Hence, it was decided to confine the review to the operational phase of the repository in which possibly some design base accidents (as a result of earthquakes, water intrusion, etc.) might be taken into account.

The potential retrievability measures in the studied disposal concepts have been evaluated along the three basic conditions, which determine the extent of retrievability provided by a particular disposal system, being:

- Accessibility of waste packages;
- Confinement of the waste in the waste packages; and
- Technical feasibility of retrieving the waste packages.

On this basis the ESDRED retrievability desk study has focused on the retrieval of waste packages (accessibility) as well as on the availability of equipment and the constraints for retrieval induced by the ambient environment (technical feasibility). In view of the small time window to be considered within ESDRED

[1] Retrievability is the ability provided by the repository system to retrieve the waste packages for whatever reason retrieval might be wanted for (EUR 19145).

(only the operational phase) confinement of the waste (i.e. the integrity of the waste packages) is not likely to be a relevant issue, so this aspect got less attention in the study.

2.4.3 Objectives of the Work within ESDRED Module 2 Retrievability

The detailed work programme for Work Package 4 ("Retrievability Desk Study") of Module 2 was established at the third technical module meeting. It was agreed between the three module partners that the assessment phase of this task should focus on two predetermined case studies, representing the two main disposal concepts considered in Module 2 of ESDRED. These case studies have been agreed in close consultation with the module partners, viz.:

a. Peer review of the French horizontal disposal concept based on C type waste;
b. Investigating of the possibilities of and/or obstacles for retrieving BSK 3 canisters in the German vertical borehole concept.

Furthermore, it was decided that this desk study would also contain a review of the current disposal concepts of the countries participating in the ESDRED project from the perspective of retrievability.

Hence the "Retrievability Desk Study" comprised the following two tasks:

Task 1: A review of retrievability measures in the current disposal concepts of the countries participating in ESDRED;

Task 2: Two specific retrievability case studies that represent the two main disposal concepts within ESDRED Module 2: the German vertical (borehole) concept and the French horizontal (disposal cell) concept.

2.4.4 The Partners within Module 2 Retrievability

WP4 of Module 2 had three project partners, viz. DBE TECHNOLOGY (Module leader), ANDRA and NRG (responsible for WP4).

2.4.5 Execution of the works

NRG, as the organisation responsible for WP4 of Module 2, performed the Retrievability Desk Study. Of course the precise definition of the work was a concerted action of the three organisations involved. This applies especially to the description of the two specific retrievability case studies i.e. the German vertical borehole concept and the French horizontal emplacement technique, of which the prime developers are DBE TECHNOLOGY and ANDRA, respectively.

Task 1: Review of the current disposal concepts

The approach to Task 1 of the review was to seek information from each of the partner organisations on their current national disposal concepts from the perspective of retrievability. Rather than doing this by means of a questionnaire, NRG had documented, as a first step, its understanding of the different national positions, using the information provided for each country in the European Commission Reports EUR 19145 ("*Concerted action on the retrievability of long-lived radioactive waste in deep underground repositories*") and EUR 21025 ("*Thematic network on the role of monitoring in a phased approach to geological disposal of radioactive waste*"). The NRG summary document was then provided to each of the participants.

Each participating organisation was requested:

1. to update or correct the information for their own country in terms of current policy and the current national strategy concerning retrievability;
2. to add any pertinent comments; and

3. to provide references to relevant published documents setting out the national policy and strategy.

The findings of the review were recorded in a public ESDRED Memorandum published on 30 May 2005 and subsequently put on the ESDRED web site (www.esdred.info).

Task 2: Specific retrievability case studies

Because of the advanced status of the French horizontal disposal design with respect to the incorporation of the concept of retrievability, it was decided that the retrievability desk study for the French disposal technique would take the form of a peer review. The safety concept of the German vertical disposal concept is based upon a rapid and permanent isolation of the emplaced waste by the host rock itself. Hence, it was decided that the retrievability desk study for the German disposal technique would focus on generating potentially technically feasible ideas for retrieval of what are effectively considered to be non–retrievable waste packages once they are emplaced.

The results of both case studies were published as two internal ESDRED memoranda in the spring of 2007. Both documents have a dissemination level restricted to a group specified by the ESDRED partners.

2.4.6 Main results and critical analysis thereof and perspectives for the future

A comparison of the disposal concepts relevant to ESDRED (performed as Task 1 of the Retrievability Desk Study) showed that there exists today a wide range of national requirements concerning the extent to which the development of a waste disposal facility should be reversible prior to closure. For example, France now has a law which says that a repository must be shown to be reversible for at least 100 years before an operating licence can be granted. By way of contrast, Germany currently has no requirement concerning reversibility or waste retrievability in the context of any future geological disposal. Within this broad spectrum, most national disposal concepts aim to show that waste could be retrieved during the operational period of a repository, if so desired in the future for whatever reason, though only limited provisions are intentionally incorporated in the design to facilitate easy retrieval of the waste.

The peer review conducted for the French design of a repository for retrievable disposal of radioactive waste (denoted as Task 2 of the retrievability desk study) has shown that in general the design agrees quite well with the present state of the art concerning the retrievability concept. In all stages of repository development the three basic retrievability conditions (noted in Section 2.4.2) have been observed extensively. The review led also to a number of very specific comments that can be dealt with in due course without serious implications.

The assessment conducted for the German repository design for disposal of radioactive waste in deep vertical boreholes (also part of Task 2 of the retrievability desk study) has shown that in general the design agrees well with the present state of the art concerning geological disposal. This assessment also led to some very specific comments with respect to the construction of a deep geological repository in rock salt, the emplacement operations, and the topic of retrievability of waste packages. Here too most of the comments on this design can be dealt with in due course without serious implications for the German borehole concept.

2.4.7 Contribution to “Common European View”

Deep geological disposal remains the only feasible long-term option that provides a safe and ethically sound method for managing long-lived radioactive waste. However, deep geological disposal is a long-lasting process in which the key drivers are acceptance and confidence. In addition, there is a natural reluctance on behalf of decision makers to make irreversible decisions on complex matters such as deep geological disposal. The adoption of a stepwise approach could avoid difficulties due to disquiet over irreversible decisions. In such a staged-decision-making process the need for large, more difficult to reverse decisions, is avoided by introducing smaller, possibly reversible intermediate decisions (steps) that each have to be accepted before progressing to the next phase. One element of this approach is the concept of the possible retrieval of the waste.

From the assessment of existing geological disposal concepts with respect to retrievability and reversibility, it can be concluded that most national disposal concepts aim to show that waste could be retrieved during the operational phase of the repository, if so desired for whatever reason, though only limited provisions are intentionally incorporated in the design to facilitate easy retrieval of the waste.

This outcome can be seen as a contribution to a common European view with regard to the vision report EUR 22842; a document that prepares the launch of the European Technology Platform on Sustainable Nuclear Energy. The proposed roadmaps contribute to the European Commission’s Strategic Energy Technology Plan towards Europe’s transition to a low-carbon energy mix by 2050. A realistic assessment of the potential of nuclear energy cannot ignore the essential question of public acceptance and perception in which the (safe) management of radioactive waste must be addressed properly and satisfactorily. It is most likely that facilitating retrievability in geological disposal concepts will positively influence the general public’s perception of nuclear as a viable energy source that fits into a strategy for sustainable development, and will therefore support the EC’s Strategic Energy Technology Plan.

2.5 Temporary Sealing Technology (Module 4)

2.5.1 State of the art and brief discussion of differences between national concepts

Except in salt, the construction of underground repositories for the disposal of high activity wastes (high level vitrified waste and spent fuel) will require the use of large amounts (up to thousands of tonnes) of cementitious materials for ground structural support and for the construction of auxiliary structures needed for the operation of the repositories. Besides other applications, most underground repository concepts consider the use of cementitious materials for the construction of temporary or permanent seals and plugs.

Plugs are required for confining backfills and seals in repository tunnels and shafts during the waste emplacement phase and in the final phase of closing the repository. Temporary seals/plugs that only need to provide support and/or tightness for a period of weeks or months can be quite simple and in the extreme may consist only of a shotcrete coating. However, in practice, many of the temporary seals/plugs will be required to be strong and tight even for rather short periods of time. The principal design criterion is that the seal elements must provide at least the same degree of radionuclide containment and isolation as the surrounding rock.

Concrete is not considered to be chemically stable because of the dissolution of the cement and, in reinforced concrete, the dissolution of some types of reinforcement. The hydrogen gas production associated with this dissolution can cause piping within adjacent seals, backfills and plugs. The operational lifetime of plugs is estimated to be on the order of one to a few hundred years. Furthermore, since concrete elements may have a degrading effect on other EBS components they may have to be removed (temporary) and replaced by backfills/seals or masonries of compacted clay blocks in conjunction with permanent closure of the repository.

The construction material for the seals/plugs differs in the national concepts. Most concepts favour the use of concrete for plugs but in some cases (e.g. Switzerland) alternative materials are under discussion for the final plugs to ensure that the degradation of the cement with time does not influence the function of the seal. For example frictional gravel supports or constructions including specially designed rock blocks are being considered.

Concrete plugs are also proposed for salt rock where the creep potential of the salt rock means that the contact with the plug will become increasingly tight. More complicated plugs may consist of two mechanical abutments (e.g., constructed from low-pH cement and rock blocks) on either side of a sealing section to provide mechanical stability for the bentonite seal in between. Depending on the design of the drifts, the abutments may be keyed in recesses in rock to provide mechanical stability and to project through the EDZ. Seal sections may require the removal of liners and partial (slots) or full re-excavation of the EDZ in weak rocks to avoid preferential flow along or through the EDZ and/or engineered structures which will degrade with time.

2.5.2 Technology issues addressed within ESDRED Module 4

For some repository plugs the concrete will be in contact with the bentonite buffer materials and the host rock and therefore, the interaction and any potentially deleterious effects have to be addressed. Over time, concretes based on Ordinary Portland Cement (OPC), leached by the ground waters, will give rise to the release of significant quantities of ions, mainly OH^-, K^+, Na^+ and Ca^{2+}. The resulting leachate could have a pH as high as 13.5. This leaching water might perturb other repository materials such as the engineered barriers (bentonite buffer and backfill material) and the near-field host rock. In literature this phenomenon is known as the hyper alkaline plume or plume effect.

From the point of view of creating a solid safety case for a nuclear repository, it is currently impossible to predict how fast and where cement pore waters may travel during the long periods of time involved. Furthermore the hyper alkaline plume can last for a very long time (up to thousands of years) and therefore cause physiochemical transformations that could modify the radionuclide confinement properties of the disposal components.

Several studies have been performed on the reactivity of cement pore waters towards minerals, and bentonite in particular (**ECOCLAY II**). In several experimental and modelling studies it has been shown that compacted bentonite is not stable in contact with cement pore waters but the maximum expected alteration will be at the cm scale. It has also been shown that cement pore waters of low-alkali cement with pH ≈ 11 are much less reactive towards compacted bentonite. In addition, models of spent fuel leaching are uncertain in the high pH range, but the intrinsic solubility of spent fuel is believed to increase drastically above pH ≈ 11 (**SFS Project**).

Within ESDRED it was proposed to develop low-pH cements as an alternative to standard OPC based ones for concrete formulation and plug construction, so as to prevent the development of the hyper alkaline plume effect. On the other hand, although the utilization and performance of standard shotcrete in conventional construction works is well known, there is no experience with either the workability or the performance of shotcrete formulated to obtain a final low-pH product and, therefore, testing of this specific material under realistic conditions was needed. Also the bearing capacity and the hydraulic properties of a plug constructed with low-pH shotcrete needed to be demonstrated to determine the eventual possibilities.

2.5.3 Objectives of the Work within ESDRED Module 4

The specific objectives of the research carried out for the development of low-pH shotcrete for the construction of sealing plugs for repository disposal tunnels/drifts were:

- Definition of the design criteria applicable for the construction of low-pH shotcrete plugs in underground repositories.
- Development of low-pH cement formulations for industrial shotcrete application in repository construction.
- Design of low-pH shotcretes, compliant with some pre-established functional requirements, to be used in the construction of repository plugs
- Adaptation and optimization of the shotcrete technique to the construction of concrete plugs in real underground drifts using the low-pH concrete formulation designed
- Full scale demonstration of a low-pH shotcrete plug.

2.5.4 The Partners within Module 4

The work performed for the construction of low-pH plugs was developed by ENRESA, IETcc-CSIC and AITEMIN. IETcc-CSIC focused its efforts on the laboratory work and the development of suitable cement/concrete formulations whereas ENRESA and AITEMIN were mostly involved with the planning, execution and evaluation of the construction work. SKB, POSIVA and NAGRA focused their work on adapting the formulations developed by IETcc-CSIC to make them suitable for use in rock support shotcrete. This work is described in Section 2.6.

2.5.5 Execution of the works

The first step of the project was focused on the definition of the design criteria applicable for the construction of low-pH shotcrete plugs in underground repositories, with the collaboration of ANDRA, NAGRA, SKB & POSIVA.

The next step involved the design of low-pH cement formulations, which are responsible for the pH of the system, and the design of concrete mixes (basic mix) that would be placed using the wet-mix shotcrete technique. Concrete mix design involved the optimisation of aggregates grading and the selection of suitable chemical admixtures.

Before proceeding with the demonstration activities, the elaborated low-pH concrete designs were tested and verified in realistic field spraying tests, regarding their compliance with the specific functional requirements. The industrial production of the low-pH concretes in combination with the selected shotcreting equipment and application techniques were evaluated in conditions similar to those expected in the underground repository.

For determining the feasibility of the obtained solution and the bearing capacity of a plug of this type, which is needed for the design of the demonstrator, a short low-pH shotcrete plug was constructed and tested up to failure in a horizontal gallery in the ÄSPÖ underground research laboratory (Sweden).

Finally, using the results from the short plug test, a full scale (long) low-pH shotcrete plug was designed and constructed in the Grimsel underground research laboratory (Switzerland), to be tested under realistic conditions for demonstration purposes.

2.5.6 Main results and critical analysis thereof and perspectives for the future

The main results from the work performed for the construction of low-pH plugs are as follows:

- The design criteria applicable for low-pH concrete plugs were established at the beginning of the project by the major national radioactive waste management agencies participating in this Module: ENRESA, NAGRA, SKB, and POSIVA and ANDRA.
- Different low-pH cement formulations were developed using conventional cement components and their key properties were characterized. According to the characterisation results, the most suitable low-pH cements were selected to design the basic concrete composition for shotcreting.
- Results from preliminary field tests confirmed that the concrete materials selected and the proportions used were suitable to fulfil the design criteria, and that conventional wet-stream shotcreting technique would be appropriate for the construction of plugs with the selected low-pH concrete.
- Results from a short low-pH shotcrete plug constructed in an horizontal gallery in the ÄSPÖ underground research laboratory (Sweden), that was tested up to failure and thereafter dismantled and analysed, confirmed the feasibility of the selected solution and helped to determine the key parameters of the bearing capacity of a plug of this type.
- Finally, a full scale (long) low-pH shotcrete plug demonstrator was designed and constructed in the Grimsel underground research laboratory (Switzerland), which is being tested under realistic conditions. The hydration rate of the bentonite is so small that the performance of the plug must be studied beyond the end of the ESDRED schedule. This will be done within the EURATOM's 7^{th} Framework Programme, **MoDeRn** Project.

Therefore all the objectives of the planned research were fulfilled. In particular a solution for minimising the effects of the hyper alkaline plume potentially created when OPC cements are used for constructing concrete plugs in a repository, is now available at an industrial scale.

2.5.7 Contribution to "Common European View"

The results of the research carried out contributed mainly to the following aspects of the "Common European View":

- Potential increase of the long term safety due to a more stable multiple barrier systems (natural and engineered) thanks to the reduction of the hyper alkaline plume effect.
- Better compatibility of engineered materials and natural barriers due to an improved plug construction material: the low-pH concrete.

- Potential improvement of seal/plug design because the concrete plugs could be built with no reinforcement and without any recesses excavated in the rock when the repository is located in competent formations such as granite.
- Improvement of seal/plug construction methods because the concrete plugs could be built using the shotcreting emplacement method, which is much faster than cast in place concrete construction, could be easily automated and could be executed almost on a continuous basis due to the low heat release of the low-pH concrete during hardening.

2.6 Rock Support Technology (Module 4)

2.6.1 State of the art and brief discussion of differences between national concepts

The need for using cementitious materials in the construction of a deep geological repository and the background supporting the development of low-pH shotcrete for ground structure (rock) support and plug construction is presented in Section 2.5.1. The main reason for developing low-pH shotcrete is that ordinary cementitious material such as shotcrete may have a detrimental effect on the bentonite buffer and the long term safety of the repository. The pH value in cementitious material can be lowered to around 11 by the substitution of cement with about 40 % silica fume.

The most common shotcrete method is the wet method. By this method a wet concrete mix is fed into the shotcrete gun and sprayed onto the rock or other surface using compressed air. A normal concrete will flow easily, however substitution of cement with silica fume in the low-pH concrete makes the concrete more viscous. Experiences related to the use of low-pH shotcrete in an industrial scale are limited or almost not existent. Also the use of superplasticizers and accelerators in low-pH shotcrete is almost without precedent. It was therefore necessary to develop cement/concrete formulations that could meet the functional specifications and which could be used and emplaced in deep geological repositories.

2.6.2 Technology issues addressed within ESDRED Module 4 Rock Support

Important issues with regard the development of shotcrete formulae for rock support are for e.g. compressive strength, workability, durability, adherence, permeability, shrinkage, fibre corrosion etc. The focus in this part of ESDRED was to demonstrate the feasibility of using low-pH shotcrete for rock support. This also included the selection of superplasticizers and accelerators.

The utilization and performance of standard shotcrete in conventional construction works is well known, however there is almost no experience with either the workability or the performance of shotcrete formulated to obtain a final low-pH product and, therefore, testing of this specific material under realistic conditions was needed. Furthermore, shotcrete with low-pH values will not give the same corrosion protection as cementitious material with high pH values and therefore the lifetime of any reinforcement steel fibres in the shotcrete could be affected.

However, with pH values of 11 or less, glass fibres will presumably be stable for a long time and could therefore be an alternative to the steel fibres which are normally used. Glass fibres have the same density as the concrete matrix and they will not corrode. The selection and testing of the most suitable reinforcement material was outside the scope of this project but requires investigation.

The main technological issues related to the use of low-pH concrete, with large amounts of silica fume as part of the binder, are the following:

1. The concrete has a low yield stress but a high plastic viscosity compared to normal shotcrete.
2. It is not understood how the set accelerator works in the binder matrix.
3. The development of the compressive strength will take longer than with normal shotcrete.
4. A low-pH concrete normally has large autogeneous shrinkage and when used as shotcrete it may have even larger shrinkage.

2.6.3 Objectives of the Work within ESDRED Module 4 Rock Support

The main objective for this subsection of Module 4 has been to demonstrate the feasibility of using low-pH shotcrete for rock support. The low-pH shotcrete formulation for the rock support was based on the development work for low-pH shotcrete for plug construction within Module 4.

The specific objectives of the research carried out for the development of low-pH shotcrete for rock support in a deep geological repository were all related to finding a formula for a workable shotcrete. The work included:

- The development of suitable low-pH shotcrete formulae including the selection of superplasticizers and accelerators for industrial shotcrete applications.
- Pilot testing of these low-pH shotcrete formulae for rock support.
- Full scale field testing of these low-pH shotcrete formulae for rock support.
- Demonstrations to prove the feasibility of using low-pH shotcrete for rock support in both crystalline and clayey rock.

2.6.4 The Partners within Module 4 Rock Support

SKB, Posiva and NAGRA have been involved in this sub-project with low-pH shotcrete for rock support. SKB has had the responsibility for development of the low-pH formula for shotcrete for rock support for Swedish conditions based on the formula developed for the plug, as well as for pilot and full scale field tests in Sweden. NAGRA had similar responsibilities for Swiss conditions.

SKB has also had the overall responsibility for the reporting to the EC for this subsection of Module 4.

2.6.5 Execution of the works

On behalf of SKB, the Swedish Cement and Concrete Research Institute (CBI) in Stockholm and shotcrete experts at the Royal Institute of Technology (KTH) in Stockholm performed the work related to the development of the formulation. They also managed the pilot test demonstration of the application of this shotcrete at Älvkarleby and the full scale field tests at the Äspö HRL. Both sites are in Sweden.

Based on the formulation developed by CBI/KTH in Sweden, NAGRA then developed their own formulations using materials available in Switzerland. NAGRA subsequently performed pilot tests at the Hagerbach Test Facility in Switzerland by spraying Mont Terri clay rock samples (fixed onto standard test panels) with the NAGRA designed low-pH shotcrete.

Posiva has followed and reviewed the work and the documentation related to the development of the low-pH shotcrete for rock support including the results from the pilot and field tests.

The general time schedule for the work within this sub-section was:

- The work started in Sweden in September 2005 after ENRESA had completed their design work with the formula for the low-pH shotcrete for plug construction. The laboratory work at CBI was completed in January 2006.
- The pilot tests at Älvkarleby in Sweden were performed in February 2006
- The field tests at Äspö HRL were performed at the end of April 2006
- During August and September 2006 NAGRA started modification of the formulations used in Sweden by incorporating materials available in Switzerland
- Then the low-pH shotcrete was applied (and tested) onto test panels prepared with approximately 4.7 m^2 of Opalinus clay rock samples. This was done in September 2006

- Finally a large-scale field test was performed mid November 2006 by spraying 6 m^3 of wet mix onto approximately 20 m^2 of previously unsupported rock.

Figure 36 below shows the field test at Äspö HRL in Sweden and pilot tests at the Hagerbach Test Facility in Switzerland.

Figure 36: Shotcrete tests at Äspö HRL in Sweden and Hagerbach Test Facility in Switzerland.

2.6.6 Main results and critical analysis thereof and perspectives for the future

The functional requirements established at the start of the project for the shotcrete for rock support had to be revised mainly due to the slow increase of the compressive strength of the shotcrete. Consequently a 90-day value had to be added. The various mechanical properties of the final shotcrete product were also measured including pumpability, compressive strength, Young's modulus, shrinkage, and bonding to the rock wall. The formula used for the tests contained 350 kg of binder (60% OPC and 40% silica fume) and the actual compressive strength after 90 days exceeded the specified compressive strength by about 50% and was in the range of about 70 MPa.

The general conclusions from the work done with low-pH shotcrete for rock support are:

- The development of formulations for the low-pH shotcrete for rock support has been successful.
- The tests in Sweden (Äspö) and in Switzerland (Hagerbach) show that the mixture was pumpable, could be sprayed and could meet the functional requirements.
- The wet mix can include common local components such as aggregates and Portland cement.
- The tests demonstrated that, in the short term at least, the low-pH shotcrete developed in Sweden is suitable for supporting hard rock while the shotcrete developed by NAGRA is suitable for supporting the Opalinus clay sedimentary rock.
- However, further development work including demonstrations in laboratories, in pilot scale and in situ in the field is recommended.

As the work completed so far is preliminary, additional work will be needed before this low-pH shotcrete can be approved for use as ground support in a future deep repository in Sweden, Finland or Switzerland.

Based on the experiences made during the tests at Älvkarleby and at the Äspö HRL in Sweden it is recommended that:

- Further investigations are conducted regarding the selection of suitable superplasticizers and accelerators with regard to the long-term safety of deep repositories.

- The shotcrete used in the laboratory and in the field tests did not include any kind of reinforcement. In order to enhance the applicability of low-pH shotcrete for rock support, the corrosion rate of wire mesh and steel fibres within the sprayed concrete structures should be tested and compared with the corrosion rates in common shotcrete. The possibility to use other materials for reinforcement should also be investigated.
- The low-pH concrete requires good mixing. Different mixers and pumping equipment should be investigated, compared and tested in underground conditions.
- Large-scale tests under real conditions are also recommended in order to demonstrate the competitiveness of low-pH shotcrete as compared to common shotcrete when used for rock support in deep geological repositories in hard rock in Sweden, Finland and elsewhere.

Based on the experiences made during the tests at Hagerbach in Switzerland it is also recommended that:

- The pH of hardened low-pH shotcrete should be determined on cores taken from sprayed linings to ascertain the actual low-pH. This exercise needs to take into consideration that, due to rebound, the proportion of the admixtures differs between sprayed shotcrete linings and the basic wet mix before spraying.
- Reliable data should be collected regarding the durability of low-pH shotcrete for instance by determining pore volumes, freezing tests and examining the microstructure of the concrete.
- Large-scale in situ tests under real construction work conditions (e.g. in Opalinus Clay at the rock laboratory at Mont Terri) should be conducted in order to demonstrate the competitiveness of low-pH shotcrete as compared to common shotcrete.
- Techniques for improving the mixing of the shotcrete and in particular the precise control of the addition of predetermined amounts of admixtures such as superplasticizers and set accelerators should be developed.
- The long term behaviour of low-pH shotcrete reinforced with steel fibres and/or wire mesh should be investigated.
- The shrinkage of the low-pH shotcrete is a problem - this issue needs to be investigated.
- The applicability and the performance of a dry-mix shotcrete should be investigated.

In general the tests have also indicated that the aggregate used must be reasonably well controlled for gradation and roundness. Thus the mixes developed will need to be modified based on aggregate source to ensure that the shotcrete meets the specifications. The tests have also highlighted the importance of having skilled operating personal who understand that the mix should not be revised just to improve the application at the operational level, e.g. adding water to improve pumpability. Finally good communication and strict quality control have been identified as issues that are key to producing low-pH rock support shotcrete that meets all of the pre-determined specifications.

2.6.7 Contribution to “Common European View”

The general contribution to the “Common European View” resulting from the low-pH shotcrete research carried out in Module 4 has already been well presented in Section 2.5.7. With regard to low-pH shotcrete used for ground support it is clear that a lot more work needs to be done and that this presents a good opportunity for various European countries to work together to advance the level of knowledge. In particular the selection and behaviour of superplasticizers and set accelerators needs to be better understood as this very important in relation to the long-term safety assessment of a final repository. Furthermore in Sweden and Finland where the deep geological repositories are located in granitic host rock there is typically only a very small amount of buffer material between the spent nuclear fuel canister and the shotcrete used in rock support. Hence the use of low-pH cementitious material is very important in this type of host rock.

2.7 Monitoring (Module 1)

2.7.1 State of the art and brief discussion of differences between national concepts

Repository monitoring is a fundamental component of national disposal programmes, and is an important constituent of the ESDRED project. Monitoring has a role to play through all phases of repository development, from the establishment of baseline conditions, through construction and operation of a repository (to ensure operational safety), through to closure and post-closure. Parameters such as temperature, groundwater inflow, humidity and radioactivity might be monitored.

A key principle identified by the European Union Thematic Network Study **[6]** on the role of monitoring states that "monitoring must be implemented in such a way as not to be detrimental to long term safety". The development of effective non-intrusive techniques for repository monitoring would provide methods for monitoring without affecting the passive safety of intact repository barriers. Non-intrusive, remote monitoring also avoids problems associated with the failure of monitoring sensors located within the EBS, which can only be repaired or replaced by disturbing the near-field of the repository system.

A programme of monitoring will be carried out throughout the all phases of repository development and might employ a variety of techniques, as appropriate, which are intrusive to varying degrees. For example, conventional, direct monitoring might incorporate sensors emplaced within the repository excavations (and perhaps within the EBS). The output from these sensors would be transmitted through wires to observation points (most likely at the surface). Whilst such approaches are commonplace in a variety of industrial applications and would be applicable during the construction and operation phases of the repository, both data collection and data transmission activities would have the potential to compromise the passive safety of the repository and the EBS, and therefore, would not be applied post-emplacement.

A less intrusive approach would employ wireless data transmission, sometimes referred to as through-the-earth, (TTE) transmission. This approach might make use of conventional and/or novel monitoring sensors, but, importantly, the integrity of engineered and natural repository barriers is maintained by transmitting the data remotely using, for example, radio frequency signals. Research in this area is ongoing by a number of waste management organisations. Key challenges include the reliability and lifetime of wireless data transmitters, particularly their power supply. These factors, which include the continued integrity of the monitoring sensors and the data transmitters, sustaining the power supply for wireless transmission of data and the ability to transmit data through many hundreds of metres of solid rock, may limit the scope of monitoring by this method.

In most disposal concepts relevant to ESDRED, the development of monitoring programmes is still under consideration. However, these programmes will differ in response to the national context, which includes the wastes to be disposed of, the design of the repository and the nature of the geological environment.

2.7.2 Technology issues addressed within ESDRED Module 1 Monitoring

The work conducted in the ESDRED Project focused on development of non-intrusive monitoring techniques, specifically cross-hole seismic tomography. Cross-hole seismic tomography is a sonic method that allows for the production of an image of the space or plane between two boreholes. An energy source (such as a high-frequency sparking unit) is installed in one borehole and a receiver string (a number of sensors linked in a chain) is deployed in a second borehole. Images in terms of seismic velocity or attenuation can be obtained through travel time inversion (frequency only) or full waveform inversion (taking account of the frequency, amplitude and phase of the seismic data) and interpreted in terms of engineered and geological structures. The technique is sensitive to physical characteristics such as the density of the medium, the degree of saturation, gas storage and gas pressure build-up and is therefore potentially invaluable in observing the performance and evolution of a repository environment following emplacement of the waste.

Development of the seismic tomography technique was undertaken by applying and developing seismic tomography through monitoring of the phases of the NAGRA HG-A experiment at Mont Terri, which is related to gas flow through the near-field host rock (the Opalinus Clay Formation of northern Switzerland) and along seals in the Excavation Damaged Zone (EDZ) of a repository.

The specific issues addressed in ESDRED were:
- To develop methods for acquiring seismic tomograms in repository environments.
- To develop approaches to analysing the data.
- To consider the application of seismic tomography for monitoring repositories.

2.7.3 Objectives of the Work within ESDRED Module 1 Monitoring

The principal objectives of activities under ESDRED Module 1, Work Package 5 are as follows:

- To further evaluate and develop cross-hole seismic tomography techniques for non-intrusive monitoring of repository systems, by investigating the potential of the technique to monitor the performance of the EBS and the near-field host rock at Mont Terri.

- To provide recommendations for designing repository monitoring programmes incorporating non-intrusive techniques.

2.7.4 The Partners within Module 1 Monitoring

Work on monitoring in ESDRED was led by NDA RWMD, with collaboration from NAGRA and ETH Zurich.

2.7.5 Execution of the works

The HG-A experiment (which was initiated in Phase 11 of activities at Mont Terri) consists of a horizontal micro-tunnel with a diameter of ~1 m, together with several observation boreholes. The micro-tunnel is located 11 m from Gallery 04 of the Mont Terri URL. A niche has been excavated to allow for the positioning of drilling equipment. To facilitate non-intrusive monitoring by cross-hole seismic tomography, two additional boreholes, approximately 27 m long were drilled above and below the micro-tunnel and stabilised with a concrete liner.

The micro-tunnel was filled with sand and closed by a hydraulic mega-packer. This “backfill” was then saturated with water before being injected with nitrogen to cause desaturation. Four measurement campaigns were carried out to determine the influence of the degree of saturation, gas storage and gas pressure build-up on the geophysical data obtained through seismic tomography. The seismic measurements provide the basis for a comparison with direct observations from sensors in the backfill and in the near-field host rock.

To gain additional insight about the effects of the different micro-tunnel infill materials on the seismic waveforms, eight vertical-component geophones were installed directly in the micro-tunnel. Such wired measuring devices would be not an option for an actual repository, but should the tunnel geophones produce useful data, one may consider the possibility of developing wireless and self-sustaining seismic sensors.

Analysis of the data from the HG-A experiment has focused on the following aspects:
- Appraisal of the quality of the seismic waveform.
- Inversion of the signal travel times.
- Analysis of the micro-tunnel geophones.

- Modelling of the tomograms.
- Development of methods for waveform analysis.

The technical components of the activities, including field measurements, research and analysis of the tomographic data, have been undertaken by the Swiss Federal Institute of Technology, Zurich (ETH), in the framework of a four year PhD thesis sponsored by the NDA. The PhD project incorporates the following components:

1) Development of an anisotropic visco-elastic modelling algorithm for deconvoluting seismic tomography signals. The algorithm can be applied in finite element modelling implemented in the frequency domain.
2) Numerical modelling of realistic scenarios of the Mont Terri monitoring experiment. Through this study, the sensitivity of the seismic data with respect to the varying physical parameters has been evaluated.
3) Development of a full-waveform inversion code that considers anisotropy. The resolution power of the method has been extensively tested using synthetic data.
4) Development of assumptions and boundary conditions to improve the efficiency of the inversion algorithm. For example, large parts of the area between the boreholes are not affected by the saturation and injection experiments and may therefore be kept constant throughout the analysis.
5) Extension of the inversion algorithm for monitoring purposes. This work attempts to invert directly for differential changes of the seismograms between individual experiments. Such an approach may reduce systematic errors caused by the finite resolution of the tomographic inversions.
6) Application of the methodology to the data sets collected in the Mont Terri rock laboratory.

2.7.6 Main results and critical analysis thereof and perspectives for the future

Several seismic tomography campaigns were conducted during the project. Enhancements to the experimental approach have been developed, including an understanding of source and receiver spacings, and methods for coupling sources and receivers to improve signal transmission.

Analysis of the seismic tomograms has required consideration of the characteristics of the host rock. In particular, the Opalinus Clay has a high seismic anisotropy, and methods have been developed and successfully applied to the tomograms to compute travel time tomograms. The method development has included use of new schemes for inversion of travel time parameters.

Analysis of data from the geophones installed in the micro-tunnel identified differences that could be attributed to the saturation of the tunnel. Analysis of the tomograms indicated that there were no seismic impacts on the EDZ as a result of saturation.

Work on analysing the seismic tomograms is ongoing and will be completed as part of the associated PhD studies. In particular, the PhD work will focus on full waveform inversion of the data set collected during the ESDRED Project.

2.7.7 Contribution to “Common European View”

The work on monitoring undertaken as part of ESDRED has allowed an evaluation of the use of seismic tomography in repository environments, and has highlighted the extent to which the host rock must be characterised for monitoring using seismic tomography.

The following conclusions can be made from the work:

a) Seismic tomography is generally a useful option for non-intrusive monitoring, but more research needs to be performed on several key instrumental and methodological issues.

b) Consistent repeatability of the seismic measurements is a critical issue. In particular, receiver coupling seems to be an important factor that needs to be markedly improved. This would be achieved by installing permanent sensors in boreholes surrounding a repository. They should be firmly grouted, such that coupling conditions will remain constant.

c) Seismic sensors emplaced within the micro-tunnel proved to be critical for delineating changes in the experimental conditions. As a consequence, it is highly desirable to have seismic sensors installed along the walls of a nuclear repository. This would require substantial (unforeseen) progress in the technical development of wireless seismic sensors.

d) Monitoring temporal changes via seismic waveform tomography requires precise knowledge of the background medium in which the repository will be embedded. Accordingly, seismic tomography experiments should be performed prior, during and after excavation of the repository. Identical experimental configurations should then be used for the subsequent monitoring phases.

In collaboration with NAGRA the NDA initiated a separate non-intrusive monitoring programme; project **TEM** (Test and Evaluation of Monitoring techniques) at the Grimsel URL in Switzerland. This programme integrated with the ESDRED Module 4 low-pH full-size shotcrete plug experiment and provided the opportunity for non-intrusive seismic tomography monitoring to be carried out alongside "wireless" monitoring and conventional hard-wired monitoring techniques; providing a robust opportunity to test and evaluate the three monitoring methods and to gain experience in applying the technique in a granitic environment. This programme of work will be continued and further developed through the EC 7th Framework programme under Project **MoDeRn.**

2.8 Training & Communication (Module 5)

2.8.1 Methodologies employed

The partners involved carried out training and communication activities by using all of the typical tools available. These included:

- News releases to kick off the project
- Organising an International Conference around ESDRED technology issues
- Creating and maintaining an up to date web site
- Organising university lectures for Masters level students & young graduates
- Organising international workshops and contributing to international workshops organised by others
- Preparing videos of the work for industrial and general public consumption
- Participating at International Conferences by presenting ESDRED papers and/or posters and at times chairing sessions
- Publication of articles in technical journals
- Preparing leaflets for the professional and the general public on specific parts of the project
- Ensuring coverage of ESDRED activities within in house publications/newsletters at the national agency and the research institute level as well as with some of the ESDRED sub-contractors
- Organising media events and related news releases around some of the demonstrators fabricated within ESDRED
- Organising demonstrations of the equipment produced, to which various stakeholders are invited
- Encouraging a secondment to an ESDRED related fabrication project
- Participating in other FP6 projects (COWAM2) for increased exposure to other stakeholders and for confidence building

Much of the material referred to in this Section 2.8, including proceedings from Conferences and Workshops, is currently available on the ESDRED web site at www.esdred.info

2.8.2 Technology issues addressed within ESDRED Module 5

The training and communication activities undertaken by various ESDRED partners related to all of the technological issues addressed by the 4 Technical Modules that are the basis of the Project. These include:

- Buffer Construction Technology (Module 1)
- Waste Canister Transfer & Emplacement Technology (Module 2)
- Heavy Load Emplacement Technology (Module 3)
- Retrievability (Module 2)
- Temporary Sealing Technology (Module 4)
- Rock Support Technology (Module 4)
- Non-Intrusive Monitoring (Module 1)

The details regarding the work within those Technical Modules (Module 1 to Module 4) are provided in the previous Sections 2.1 to 2.7 of this report, and will not be repeated here.

2.8.3 Objectives of the Work within ESDRED Module 5

Separate objectives were developed for Training and for Communication. In the case of Training there were 3 main objectives:

- Training of students and young engineers
- Training of personnel from RWM agencies and R & D organisations

- Focusing on individuals coming from New Member States

In the case of Communication the main objectives were:

- Dissemination of ESDRED results to the professional community directly and indirectly related to nuclear waste management
- Dissemination of results to the public at large
- Motivation of students towards an interest in RW programs
- Confidence building

2.8.4 The Partners within Module 5

Although there are 13 partners or participants in ESDRED, not all partners were involved in each of the 4 Technical Modules. In fact the participation varied between 3 and 7 partners per Module. The same was true for Module 5 – except that here the participation was further sub-divided between *Training* and *Communication*. The leader for Module 5 was ANDRA. For the *training* portion ANDRA was assisted by NAGRA and the 4 Technical Module Leaders i.e. DBE TECHNOLOGY, ENRESA, ONDRAF/NIRAS and SKB. However the responsibility for *communication* was left to ANDRA and the 4 Technical Module Leaders only.

It should be noted however that many of the other ESDRED partners did participate in both training and communication activities, even though this was not a contractual obligation for them. In fact over the life of the project all of the 13 partners at one time or another reported some activity in this area.

2.8.5 Execution of the works

The Project began with the distribution of a Press Release in 6 languages outlining the general terms of the ESDRED Project and describing what was to be achieved over the course of the following 5 years. Also within the first few months of 2004 a “PROJECT PRESENTATION BOOKLET” was prepared in French and English for general distribution and it was so used from time to time over the life of the project. Thereafter the work in this module was broken down into the 2 main topics indicated in the name of the Module i.e. *Training* and *Communication.*

By the end of Month 6 a *Training Plan* had been developed which served as a guideline for the remainder of the Project. The plan focused on 3 main training activities. This was to include two training workshops and one training session in an existing facility such as a University or College.

Two training workshops both entitled “*R&D on low-pH Cement for a Geological Repository*” were held in Madrid June 15-16, 2005 and in Paris June 13-14, 2007. Both workshops attracted in excess of 30 participants from between 8 and 10 countries. There had been an earlier workshop on low-pH cement is 2003 which was not a part of ESDRED. The interest in the subject is so strong that there is a possibility that a fourth low-pH workshop will be held somewhere in the coming years.

A third training workshop was organised late in the ESDRED Project. Following the successful demonstration of its vertical emplacement system DBE TECHNOLOGY held a training workshop at its head office in Peine, Germany on November 4, 2008. This effort was supported by the 4 Technical Module Leaders as well as NAGRA. This workshop focused on “*Transport and Emplacement Technologies for Radioactive Waste Packages*” and in all some 23 young professionals (mainly from WMO’s) from 10 countries attended.

The training in an existing facility was carried out at the University Politehnica, in Bucharest Romania, November 8-9, 2006. It consisted of 17 lectures prepared and delivered by ESDRED representatives to 32 students enrolled in a Masters’ Programme in the Faculty of Power, Department of Nuclear Engineering and young professionals working for Romanian State Agencies or for private industry. The themes of the presentations focused almost entirely on the technical work within ESDRED. Teaching assistants and lecturers from the University also attended the lectures.

One of the minor training objectives was to secure a staff or student secondment into one part of the EDRED work. This occurred in the final year of the project when a young engineering student was engaged by one of ANDRA's sub-contractors. He was integrated into the team responsible for preparing ANDRA's horizontal system for transport and emplacement of vitrified waste, for final testing, for demonstration and for transfer to the newly constructed Technology Centre (CTe) at Bure in France.

In the area of *Communication* an internal Draft Communication Action Plan was developed at the beginning of the Project and then revised and finalised a few months later. This plan, which served as a guide and a reference over the life of the project, focused on 5 main activities:

1. Publications & international conferences
2. Leaflets and videos
3. Confidence building
4. The media
5. The web site portal
6. An ESDRED International Event

Various ESDRED partners, at different times, contributed papers to international as well as to local and in-house publications. A number of videos and leaflets were produced.

ESDRED work in and of itself (presentation of demonstrators) contributed to Confidence Building in the public at large however a more direct activity was also planned. The Integrated Project Coordinator (IPC) participated in WP4 of the COWAM2 Project. The theme of this work package was "Long Term Governance for Radioactive Waste Management". ESDRED was one of 26 Stakeholder Reference Group Representatives. Over the course of 2.5 years the IPC made one introductory presentation covering the ESDRED programme and objectives, following by 3 other presentations showing the progress of the work.

Only a few of the partners actually managed to hold media events and these were generally organised around the demonstrators that they had built. One of the most significant events (with local, regional and national politicians in attendance) was held at Bure, in October 2008, in conjunction with ANDRA, the EC and the Euradwaste '08 Conference. Prior to that, on September 9, 2008, DBE TECHNOLOGY organised a very successful demonstration of its vertical emplacement system, temporarily installed in a demonstration hall at Landesbergen Germany. More than 100 people representing most of the NWM stakeholders participated at this very successful event. Before that SKB had organised a media event related to the KBS-3H horizontal water cushion emplacement system, at Äspö in June 2007. The last such activity took place in Saint Chamond France, on January 21, 2009, when ANDRA's pushing robot emplacement system for vitrified waste canisters was shown to about 35 people including representatives from all of the main French waste producers in particular.

An ESDRED web site (www.esdred.info) was set up by the IPC and first put on line in September of 2004. Thereafter it was updated and/or modified at least 15 times. There have been more than 16 000 visitors to date. The intention is to keep the web site on line for approximately one year after the end of the ESDRED Project i.e. to about March 2010. Most of the material reference directly or indirectly in this Section 2.8 of the report can be found on the web site.

Finally the crowning highlight of the Project came in June of 2008 when an "*International Technical Conference on Practical Aspects of Deep Radioactive Waste Disposal*" was organised by the ESDRED partners, ANDRA and GRS, in conjunction with the Czech Technical University in Prague (CTU) and RAWRA the Czech national waste management agency. This very successful event, which also included a special Student Session, was held in the facilities of the CTU, Faculty of Civil Engineering, Centre of Experimental Geotechnics, June 16-18, 2008. Nineteen of the 38 papers and posters were related directly to ESDRED, to the national agencies represented in ESDRED or to the sub-contractors that had been engaged by the ESDRED participants. Papers and posters reflected the work being carried out in/by 13 countries while the conference registrants came from 19 different countries. Total registration (over 120 attendees) exceeded the objective fixed 2 years earlier.

2.8.6 Main results and critical analysis thereof and perspectives for the future

The main results of ESDRED activities in the areas of *Training* and *Communication* have already been highlighted in the previous section and to a lesser extent in the first section on methodologies. All of the readily available tools were utilised. With one exception ESDRED representatives responded to each and every request to make a presentation or participate in some relevant activity. Ultimately it is important to note that in relation to the Contract with the EC, to the agreed budget and to the agreed effort (man-months) the ESDRED partners greatly exceeded their budget and manpower commitments!

Will there be any long term benefits accruing to the training and communication efforts made within the framework of the Project? This is always difficult to evaluate. Suffice it to say that ESDRED has made direct contact with a fair number of students and young professionals in Romania and in the Czech Republic. Via the web site some contact was also made with students around the world based on the correspondence that was initiated during the run up to the Prague Conference. Also, a work placement position was secured, for an engineering student, with one of the sub-contractors who was designing and fabricating an important demonstrator.

Furthermore there is a possibility that another low-pH Cement Work shop will be organised in the future. Also a related theme (measurement of pH in concrete) has already evolved into a new project involving some former ESDRED participants and some former workshop participants.

Finally it can be noted that the general consensus after the end of the International Conference in Prague seemed to be that this type of event, with a strong focus on technology, should be repeated in the future but not necessarily every year and more likely as a workshop.

As a result of working together on the ESDRED Project several of the partners, have joined together (with new partners as well) to carry on with at least 4 related cooperation projects beyond the end of ESDRED, some outside of FP7. These are:

- Ramp transport cooperation SKB & ANDRA,
- pH Measurement protocol for concrete – led by SKB,
- TEM Multi method monitoring project led by NAGRA & NDA,
- MoDeRn monitoring project (FP7) – led by ANDRA.

2.8.7 Contribution to “Common European View”

The efforts made in the areas of *Training* and *Communication* played an important, but probably subtle, role in enhancing the notion of a “Common European View. These are areas where the participants were often called upon to work very closely together in order to get the job done. For example joint papers were often written by representatives from several different national agencies for presentation at workshops and at international conferences. The preparation of the material for the Masters course in Bucharest was also very much a collective effort even if the lectures were presented by individuals. The same was true for the preparation of the papers for the conference in Prague where several joint papers were presented.

Broad dissemination of ESDRED results undoubtedly helped to build confidence in the disposal concepts being considered in the European nuclear area. Internal dissemination of information amongst the ESDRED partners helped to bring the representatives of the national agencies closer together. As a minimum each one developed a better understanding of the shared issues and a broader knowledge of the available solutions. Furthermore an informal network of engineers, contractors, suppliers and experts was established on a European Scale.

2.9 Other Outcomes (Across all Modules)

The preceding eight sections, organised per specific themes rather than strictly according to the 4 Technical Modules, have served to provide an overview of the work executed by the members of the ESDRED Consortium. This work was outlined in the "*Description of Work*" or D.O.W. which is an attachment to the Contract between the Consortium and the European Commission. Among other things, each section highlighted the main results of the work including a critical analysis thereof. Each section also provided a perspective for the future and evaluated the contribution to a "Common European View".

Over the course of 5 years of work, as a direct or indirect result of the ESDRED Project, other positive outcomes happened that were not specifically outlined in the D.O.W. What follows is a brief description of some of these outcomes that were not planned and that were not necessarily even foreseeable. No attempt has been made to present them in any order of importance.

The ESDRED Project did not procreate an **ESDRED 2** Project although this possibility was raised on a number of occasions. The reasons for this are outside the scope of this report. HOWEVER the ESDRED work did result in giving birth to new projects and to new co-operations between various members of the Consortium. At this point only one such project is included in the EC's 7th Framework Program (FP7); the rest have been organised independently of the EC. New activities include:

- SKB, CSIC, NAGRA and NUMO and others have initiated a work programme aimed primarily at defining a common protocol for measuring the pH of concrete samples. The lack of an existing reference protocol and the urgent need for such a tool were recognized as a result of the 2 low-pH Workshops organised as a part of ESDRED. Furthermore at least one more low-pH Workshop may be organised in the future outside of any EC funded project.

- As a result of working closely together in Module 3 of the ESDRED Project, SKB and ANDRA have decided to continue working together in the area of Ramp/Shaft transport. This was not a topic within ESDRED and is therefore not a natural continuation of something started in ESDRED. Rather it is the direct result of people working closely together and developing a mutual appreciation of one another's work.

- Within FP7 ANDRA is leading the **MoDeRn** Project which aims to provide a " - - *reference framework for the development and possible implementation of monitoring activities and associated stakeholder engagement during relevant phases of the radioactive waste disposal process* - - ". The monitoring work described in Section 2.7 led to some additional monitoring work at Grimsel in Switzerland (**TEM** Project) that was concurrent with, but mostly outside of ESDRED. The results of this cooperation reinforced an earlier decision to present a proposal to the EC for partial funding of the **MoDeRn** Project within FP7. The **MoDeRn** Project includes 9 of the original ESDRED partners as well 2 non-EU national waste management agencies (Japan and USA) and some universities and R&D organisations.

Another interesting outcome of the ESDRED Project, not directly related to any specific objective exposed in the D.O.W., relates to the vast number of contractors retained by the different ESDRED partners to carry out important parts of the work. The bulk of the physical work was executed in 6 different countries and involved in excess of 40 different contractors. Some of these Contractors (it is difficult to know with certainty how many but it could easily be up to 25%) had never or seldom before been involved with any nuclear related projects. The bottom line is that as a result of ESDRED there are today more companies available to undertake work in the nuclear field in Europe than there were 5 years ago.

Another apparent outcome of the ESDRED work is an increased confidence on the part of many stakeholders in the competence and expertise of WMO's and research organisations, in particular after the latter have demonstrated that they are capable of designing, fabricating and demonstrating completely new transport and emplacement equipment which in some cases already comply with mining and nuclear regulations. This is one additional brick in the wall of confidence building, not only for the public at large but for the entire community involved in waste management including NPP operators, WMO's, licensing authorities, external experts and decision makers (local and other politicians).

As a result of the International Conference in Prague, organised by ESDRED, with representatives from 19 countries attending, it is clear that the technological side of European research in NWM was given a significant boost and exposure. The same can be said for exposure in the new member states of the European Union (NMS) as there was an important participation by representatives from these countries as well. The long term impact, if any, cannot be evaluated at this time. Furthermore the long term impact of the 17 lectures provided by ESDRED members as part of the Masters course on NWM at the University Politehnica in Bucharest Romania in 2006, for the benefit of young professionals and future graduates, is equally difficult to evaluate at this time.

Finally it is obvious that during 5 years of cooperation within the ESDRED Project the partners had the opportunity (and most took some advantage of this) to obtain details about the other partners' National Waste Management Programmes in areas other than those covered within ESDRED. Some have described this as getting insider information. By so doing they learned more about one another's designs and in particular about the associated challenges and solutions (actual or anticipated). They also got an overview of the approach being used by others to solve technical/engineering problems, either in-house with their own staff, or by involving outside contractors.

3 Summary and Conclusions

3.1 Summary of the main ESDRED Technical Achievements

The main ESDRED technical achievements are fully described in Sections 2.1 to 2.7. The paragraphs below aim to provide a brief summary of these achievements and follow the same order. The same applies to Section 3.2 and 3.3 below with regard to the "Potential impact on a Common European View" and the "Recommendations for Future Related Integrated Work".

At the end of the contractual project time frame, ESDRED **Module 1** has achieved essentially all of its objectives, although there is one experiment (PRACLAY seal) that is awaiting mid-2009 for minor contractual work to be finalized and there are two experiments (SB seals and non-intrusive monitoring) that can expect an interesting contribution from additional work that will be performed in 2009 independent of the ESDRED Project. The main achievements, per partner, are:

- ANDRA has succeeded in the cold compaction of an MX-80 bentonite / quartz sand mixture prepared as a powder, to obtain the prefabricated buffer rings described in their *Dossier 2005* report to the French Government. ANDRA has also successfully tested the handling of these buffer rings and their rigidity.
- ONDRAF/NIRAS has demonstrated the feasibility of two different emplacement techniques for backfilling the annular voids around a horizontally disposed high level waste package: (1) projection of a dry granular material, for which sand, cement, bentonite and mixtures thereof were used, (2) injection of a custom made high pH grout designed to have the required thermal, chemical and physical characteristics. Both emplacement techniques have been tested successfully on 2/3rd-scale mockups. The grout injection technique was also tested on a full scale mockup of 30 m in length. Again, the feasibility of the injection technique was demonstrated, but it was also concluded that the W/C ratio of the specific grout will need to be reduced in the next phases of the development process, to ensure that the grout becomes hard after injection. In general, the backfill tests within ESDRED have provided a broad knowledge basis for this further development process
- NAGRA, using auger technology and a reduced-scale steel model of a horizontal disposal drift with a waste container disposed on a cradle of prefabricated bentonite blocks, has tested the emplacement of a range of bimodal mixtures of granular bentonite. NAGRA succeeded in achieving the desired dry density of the emplaced buffer material.
- GRS has until now been satisfactorily running performance tests on four seals of different clay/sand composition in boreholes at the Mont Terri URL. The results of these in situ tests, and also the preceding laboratory mockup tests, confirm the advantageous sealing properties of moderately compacted clay/sand mixtures which were previously determined on small samples under ideal conditions in the laboratory. It should nevertheless be noted that the seal saturation rates are much slower than predicted by computer models. Hence the gas entry/break-through gas injection tests will now most probably be executed around mid-2009. Since the initial stages of ESDRED a continuation beyond the contractual end date has never been excluded. The work already performed, together with the anticipated gas injection tests, will have considerably advanced the knowledge base on moderately compacted bentonite/sand seals in clay host rocks.
- NDA has been successfully conducting a development program to advance the knowledge base of non-intrusive monitoring based on seismic tomography. A series of measurement campaigns performed around the HG-A tunnel in the Mont Terri URL have been performed. To interpret the information provided by the seismic echoes, an anisotropic model of the clay test environment has been developed and an associated full wave inversion code is being developed, in cooperation with the Swiss Federal Institute of Technology (ETH Zurich) as part of an ongoing PhD programme. Due to a rescheduling of the HG-A experiment the last campaigns are now anticipated to commence mid-2009. The performance of this final test campaign, and the finalization of the wave inversion code, will contribute to the already gathered knowledge base.

- EURIDICE have prepared the design of the PRACLAY seal steel support structure and have selected MX-80 as the swelling material to be used. The latter selection has involved a literature study, a series of scoping calculations by aid of a computer code and laboratory testing (e.g. at the CERMES institute) focusing on a number of specific aspects related to the interaction of the swelling material and the Boom Clay host rock. The actual in situ installation of the seal in the PRACLAY gallery remains to be done. Due to a rescheduling of works, the in situ installation of the PRACLAY seal will fall beyond the contractual end date of ESDRED. The installation is now foreseen for the second quarter of 2009. The work by EURIDICE, especially the actual in situ implementation, will have advanced the phenomenological and technical knowledge base related to the construction of a hydraulic seal in a disposal gallery.

Within **Module 2** transport and emplacement systems for two different waste canister types (for vitrified waste: weight 2 tonnes and for spent fuel rods: weight 5.2 tonnes) were developed, fabricated and successfully tested in surface facilities in the second half of 2008. The technical solution for the emplacement of vitrified waste packages into horizontal disposal cells is based on a Pushing Robot system capable of pushing up to three waste packages into a lined horizontal disposal cell with a length up to 100m. The transport and emplacement of spent fuel rod canisters (BSK 3) into deep (up to 300m) boreholes can be managed by a specific emplacement device which is capable of accepting a transfer cask , turning it into an upright position and then lowering the BSK 3 canister through a borehole lock (completely radiation protected) into the emplacement borehole. Both systems clearly showed that the safe and reliable transport and emplacement of HLW and SF canisters is technically feasible.

The work completed within **Module 3** has demonstrated that either air or water cushion technology can be used for the emplacement of long (more than 5m), heavy (up to 45 tonnes) waste containers that have a relatively small diameter (as small as 1.25m) in disposal drifts with a diameter only marginally bigger than the canisters. The same equipment is also capable of emplacing 17 tonne bentonite buffer ring packages (2.3m diameter) again with only minimal annular gap between the rings and the disposal drift wall. The water cushion technology was demonstrated underground in a 95m long disposal drift (up to 300m is assumed possible) whereas the air cushion system was proven for a 40m long disposal distance.

A Retrievability Desk Study was included as part of the work completed in **Module 2**. The study showed that there exists today a wide range of national requirements concerning the extent to which the development of a waste disposal facility should be reversible, and the waste retrievable, during the operational period prior to closure. A peer review of the French design for retrievable disposal of C type (vitrified) radioactive waste, which by law must be shown to be reversible for at least 100 years, has shown that in general the design agrees quite well with the present state of the art concerning the retrievability concept. A similar review of the German repository design for disposal of radioactive waste in vertical boreholes in salt was also performed. Even though waste disposal in Germany is not subject to any legal requirement concerning reversibility or waste retrievability, this too did not highlight any serious technical issues.

The ESDRED work related to temporary sealing technology (**Module 4**) has shown that shotcrete with a pH equal to or below 11, which is compatible with engineered barriers such as bentonite, can be formulated and used for the construction of plugs/seals in underground repositories. Furthermore it has been shown that such shotcrete is compatible with the use of standard wet-shotcrete equipment.

Other work confirmed that low-pH shotcrete could also be used for on rock support linings. This was demonstrated on crystalline rock in Sweden and on Opalinus clay sedimentary rock in Switzerland. In both cases the pre-determined functional requirements were achieved.

There was no precedent for the application of cross-hole seismic tomography as a non-intrusive monitoring tool in deep geological radioactive waste disposal. Consequently the experimental set up and procedures, including source and receiver spacings, methods for coupling sources and enhancements of signal transmission all needed to be developed and evaluated. Seismic tomograms analysis procedures, as well as new schemes for inversion of travel time parameters, were also developed. Among other things the completed work has shown that in Opalinus Clay, which is characterised by high seismic anisotropy, saturation level differences have minimal effect on the travel times from source to receiver. In contrast, changes to EDZ within the micro-tunnel, resulting from saturation and recorded by geophones directly installed in the tunnel, are very pronounced. As this work is part of a comprehensive PhD program, and is continuing beyond ESDRED, much more remains to be learned and/or confirmed.

3.2 Potential impact on “Common European View”

Regarding the construction of the buffer/backfill around the disposed HLW, within ESDRED a number of off-the-shelve solutions have been developed up to a certain level of completeness. These solutions or certain technological aspects thereof, are ready to be shared among partner countries whenever the need might arise.

Regarding the realization of seals in a clay-based repository, the phenomenological and technological knowledge base has been advanced by two different experiments (SB and PRACLAY seal) and will be advanced even more so in the future as these experiments will be continued beyond ESDRED. The contribution by ESDRED is however only a first step forward and many more steps will have to be taken in this still relatively new domain.

Regarding non-intrusive monitoring, seismic tomography has been developed up to a certain level as a useful technique that can be shared among partner countries. So far, the development has focused on application in a clay repository, but the technology is expandable to other host rocks. The ESDRED work on monitoring has allowed an evaluation of the use of seismic tomography in representative repository environments, and has highlighted the extent to which the host rock must be characterised before monitoring based on seismic tomography can be used. The ESDRED work has already fathered 2 related collaborative monitoring programmes that will carry on beyond the end of ESDRED i.e. the project TEM (Test and Evaluation of Monitoring techniques) at the Grimsel URL in Switzerland, in a granitic environment, and the MoDeRn programme which is part of the EC 7th Framework programme.

Safe transport and emplacement of waste packages is a prerequisite for the operation of a deep geological repository for high activity waste. The BSK 3 emplacement system which was designed and successfully tested for application in a repository in rock salt is in principle adaptable to other host rocks as well. Hence this technical achievement contributes to a Common European View on how to safely dispose of high level waste packages in geological repositories. The same is true for the Pushing Robot system which was developed and successfully tested to emplace HLW Canisters (C) in horizontal disposal cells of a repository in clay but which is equally adaptable to other types of host rock.

The development and demonstration of the application of fluid cushion technology (air & water) has provided the European nuclear community (the international community in fact) with a practical means of emplacing heavy loads in horizontal disposal drifts while maintaining only a very small annular gap between the external wall of the canister and the wall of the drift. This technology was not available before ESDRED and was in fact deemed improbable by some. In the meantime at least 4 European waste management agencies have integrated this technology into their concepts for horizontal disposal. Furthermore it has also been shown that fluid cushion disposal systems are adaptable for the emplacement of heavy pre-fabricated bentonite buffer ring packages as well as for spacers to be located between consecutive Super Containers.

The assessment done within ESDRED indicates that most national disposal concepts aim to show that waste could be retrieved from a repository, if so desired in the future for whatever reason, though only limited provisions are intentionally incorporated in the design to facilitate easy retrieval of the waste. This outcome can be seen as a contribution to a common European view with regard to the vision report EUR 22842; a document that prepares the launch of the European Technology Platform on Sustainable Nuclear Energy. A realistic assessment of the potential of nuclear energy cannot ignore the essential question of public acceptance and perception in which the (safe) management of radioactive waste must be addressed properly and satisfactorily. It is most likely that facilitating retrievability in geological disposal concepts will positively influence the general public's perception of nuclear as a viable energy source that fits into a strategy for sustainable development, and will therefore support the EC's Strategic Energy Technology Plan.

Performance assessment (PA) is an important issue for all radioactive waste management organisations. The use of a concrete (for construction, rock support and sealing purposes) with a pH equal to or below to 11 is more compatible with certain clay rocks and particularly with engineered barriers, such as bentonite, than standard concrete. Hence the ESDRED work in this area has provided the European Nuclear Community with an important tool for minimizing the potential plume effect and for ensuring a positive PA for their designs.

With regard to low-pH shotcrete used for ground support it is clear that more work needs to be done and this therefore presents a good opportunity for various European countries to work together to advance the level of knowledge in this area. The participants in this sub-module are of the opinion that the work completed so far is preliminary and that additional work will be needed before low-pH shotcrete can be approved for use as ground support in a future deep repository. This future work should focus on the long-term effects of the low-pH shotcrete chemistry on the repository environment. Another issue that should be studied relates to the corrosion of steel reinforcement.

3.3 Recommendations for Future Related Integrated Work

Regarding the non-prefabricated options to emplace the buffer/backfill material, an important boundary condition in repositories in clay and granite, which has until now been neglected in many programs, is the understanding of the logistical needs behind the buffer/backfill emplacement. It is therefore strongly recommended to reserve an important part of future development efforts to the study of these logistical needs and the development of equipment to satisfy these. Further, it is recommended to have more in situ sealing experiments, spanning relatively long periods of time to allow a sufficiently lengthy observation of events and phenomena. Working at full scale and in close collaboration with industrial companies mastering the state-of-the-art in underground construction technologies, will enable WM organisations to get a better understanding of the technological challenges and the performance/capacity of the systems involved. Regarding prefabricated buffer components, issues such as production line manufacturing (to reduce costs and improve quality control), handling and storage are worthy of further investigations – also with the participation of qualified industrial counterparts.

Regarding waste canister transport and emplacement it is recommended to repeat the demonstration tests (so far performed only on surface in a simulated mockup environment) under real in situ boundary conditions in order to assess possible impacts (if any) on the functionality and reliability of the technical components. This should be done with the BSK 3 emplacement system preferably in a salt environment and with the Pushing Robot system in a clay environment.

In the course of the heavy load emplacement work a number of issues were identified that could be the subject of future development activities. These would mostly fall into the category of natural evolutionary improvements and optimisations of prototype demonstrators and none indicate potential fatal flaws. Technical issues to be addressed include moisture reduction in the compressed air feed, adjusting for canister instability (centre of gravity induced), improving the alignment of the system components as well as endurance and reliability assessments. Additional work might also be undertaken to assess the limits with regard to canister/disposal drift diameter and the emplacement distance limitations.

There is a natural reluctance on behalf of decision makers to make irreversible decisions on complex matters such as deep geological disposal. The adoption of a "*stepwise approach*", as noted in the ESDRED desk top study on retrievability, could avoid difficulties due to disquiet over irreversible decisions. In such a staged-decision-making process the need for large, more difficult to reverse decisions, is avoided by introducing smaller, possibly reversible intermediate decisions (steps) that each have to be accepted before progressing to the next phase. One important element of the "*stepwise* approach" is the concept of the possible retrieval of the waste – a notion that is attracting ever more attention amongst the European WM agencies.

Whereas the formulation of low-pH cement/concrete/shotcrete has been successfully demonstrated any real time application will require the development of new site specific formulations. Several low-pH workshops have identified the need for a common protocol for measuring pH in concrete pore waters. An integrated project is already underway in this regard. Other matters that could be the subject of joint research programmes might include rebound of aggregate, shrinkage of shotcrete (under which conditions and to what extent shrinkage is relevant, how to measure it and how to reduce it) and how to mitigate the problems this creates when using shotcrete to construct plugs/seals and the development a better understanding with regard to the use of various additives such as set accelerators and superplasticizers.

There is lots of opportunity for future integrated work related to the use of low-pH shotcrete for rock support. Among other things larger and more comprehensive test work, which is monitored over a much longer time frame, needs to be envisaged in order to observe the long term effects of low-pH shotcrete. At the same time issues related to the use of reinforcing materials (e.g. corrosion of rockbolts and/or rebar) and of additives such as set accelerators and superplasticizers need to be studied in order to better understand the effect of low-pH chemical composition.

Concepts for non-intrusive monitoring using seismic tomography have been developed within Module 1 and more work needs to be done. Furthermore it is important that a Common European View be developed which defines general monitoring requirements and which can be easily adapted to the different national programmes. This work should encourage the development of improved monitoring technologies which will have capabilities matched to these requirements. It is therefore recommended that further work on understanding the potential for seismic tomography be undertaken (including enhancement of full waveform inversion approaches and better understanding of signal propagation in different media) and that the context of monitoring is enhanced through the development of clear monitoring objectives and strategies which need to be linked to the capabilities of monitoring techniques. Some work in this regard is currently underway as part of the MoDeRn Project, which is part of the EC 7th Framework programme. The ongoing PhD work which was supported by this sub-module will, among other things, focus on full waveform inversion of the data set collected during the ESDRED Project.

4 List of references

[1] Jockwer, N., Miehe, R., Müller-Lyda, I. (2000): Untersuchungen zum diffusiven Transport in Tonbarrieren und Tongesteinen. Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Köln, GRS-167;

[2] Miehe, R., Kröhn, P., Moog, H., (2003): Hydraulische Kennwerte tonhaltiger Mineralgemische zum Verschluss von Untertagedeponien (KENTON). Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Köln, GRS-193;

[3] M. Van Geet et al. (2004), SCK•CEN, UPC, CIEMAT, CEA, Andra, "Large Scale In Situ Demonstration Test for Repository Sealing in an Argillaceous Host Rock - The RESEAL project";

[4] Toshihiko AWANO et al. (2002), Manufacturing and Handling Techniques of the Monolithic Buffer Material for HLW Disposal, JSME International Journal Series B Vol. 45 (2002) No. 3 Special Issue on International Conference on Power and Energy System pp.615-620;

[5] Mayor, J-C et al. (2005): Engineered Barrier Emplacement Experiment in Opalinus Clay for the Disposal of Radioactive Waste in Underground Repositories (EB), Final Report, EC EUR 21920;

[6] European Commission (2004). Thematic Network on the Role of Monitoring in a Phased Approach to Geological Disposal of Radioactive Waste, Contract No. FIKW-CT-2001-20130;

Annexes:

1. List of people who participated in the Module
2. List of Module Deliverables complete with Dissemination level
3. List of ESDRED final reports (*4 technical & as well as Module 5 & 6)*
4. List of acronyms
5. Glossary

ANNEX 1

LIST OF PEOPLE WHO PARTICIPATED IN THE MODULE 6

Company	Name	First Name
AITEMIN	BARCENA	Ignacio
AITEMIN	GARCIA-SIÑERIZ	José Luis
ANDRA	BOSGIRAUD	Jean-Michel
ANDRA	FAUCHER	Bernard
ANDRA	GAUSSEN	Jean-Louis
ANDRA	LESAVRE	André
ANDRA	SEIDLER (*Nota 1*)	Wolf
CSIC	ALONSO	María Cruz
CSIC	LUCO	Luis Fernandez
DBE TECHNOLOGY	BOLLINGERFEHR	Wilhelm
DBE TECHNOLOGY	FILBERT	Wolfgang
ENRESA	ALONSO	Jesús
ENRESA	FARIAS	Joaquín
ENRESA	HUERTAS	Fernando
EURIDICE	BERNIER	Frédéric
EURIDICE	VERSTRICHT	Jan
GRS	ROTHFUCHS	Tilmann
NAGRA	BLÜMLING	Peter
NAGRA	FRIEG	Bernd
NAGRA	KICKMAIER	Wolfgang
NAGRA	SCHWYN	Bernhard
NAGRA	WEBER	Hanspeter
NDA	BREEN	Brendan
NDA	JOHNSON	Mark
NRG	HAVERKATE	Benno
NRG	O'SULLIVAN	Patrick
ONDRAF/NIRAS	BEL	Johan
ONDRAF/NIRAS	DE BOCK	Chris
POSIVA	AIKAS	Timo
POSIVA	SALO	Jukka-Pekka
POSIVA	VUORIO	Petteri
SKB (Vattenfels Power Consultant)	HALVARSSON	Bo
SKB	LINDGREN	Eric
SKB	PUGGIOLI	Anna
SKB	PETTERSSON	Stig
SKB	REISTAM	Louise
SKB	THURNER	Erik
SKB	WEDIN	Lisa

Nota 1: Module Leader

ANNEX 2

LIST OF MODULE 6 DELIVERABLES COMPLETE WITH DISSEMINATION LEVEL

Reference	Title	Date	Dissemination Level
WP1: Relevancy and Consistency of Input Data and Functional Requirements			
Mod6-WP1-D1	Report on Common Input Data and Functional Requirements	**01/06/2007 (Rev.3)**	**PU**
Mod6-WP1-D2	Experts Assessment on Input Data and Functional Requirements	**08/04/2005**	**CO**
WP2: Relevancy and Consistency of Design Studies			
Mod6-WP2-D3	Report on Common Features of Design Studies	**01/06/2007 (Rev.1)**	**PU**
Mod6-WP2-D4	Experts Assessment on Design Studies	**13/10/2006**	**RE**
WP3: Consistency of Fabrication and Demonstrations			
Mod6-WP3-D5.1	First Experts Assessment on Demonstrations	**11/07/2006**	**RE**
Mod6-WP3-D5.2	Second Experts Assessment on Demonstrations	**13/10/2006**	**RE**
Mod6-WP3-D5.3	Third Experts Assessment on Demonstrations	**30/04/2007**	**RE**
WP4: Integration in Reporting			
Mod6-WP4-D6	Final Summary Report and Global Evaluation	**Date of this report**	**PU**

Dissemination Level:
PU: Public
RE: Restricted
CO: Confidential

ANNEX 3

LIST OF ESDRED FINAL REPORTS

Reference	Title
Mod1-WP6-D6	Module 1 (Buffer Construction Technology) Final Technical Report
Mod2-WP7-D8	Module 2 (Waste Canister Transfer & Emplacement Technology) Final Technical Report
Mod3-WP5-D6	Module 3 (Heavy Load Emplacement Technology) Final Technical Report
Mod4-WP4-D9	Module 4 (Temporary Sealing Technology) Final Technical Report
Mod5-WP5-D11	Final Report on Communication Actions
Mod5-WP9-D12	Leaflet on Final ESDRED Results
Mod6-WP4-D6	Final Summary Report and Global Evaluation (Final ESDRED Project Report)

ANNEX 4

LIST OF ACRONYMS

ABBREVIATION	MEANING
µSv	Micro-sievert
ALARA	As Low As Reasonably Achievable
BH	Borehole
BSK 3	German thin walled fuel rod canister (Brennstabkokille 3)
C	Waste Canister Containing High Level Vitrified Waste
CU	Spent Fuel Canister (ANDRA)
CU1	SF Waste Canister Containing 4 Spent Fuel Rods (ANDRA)
CU2	SF Waste Canister Containing 1 Spent Fuel Rod (ANDRA)
D1	Deliverable 1
EB	Engineered Barrier
EBS	Engineered Barrier System
ESDRED	Engineering Studies and Demonstrations of Repository Designs
GNB	Gesellschaft für Nuklearbehälter mbH now part of GNS - Company for Nuclear Service Ltd.
HLW	High Level Waste
ID	Inside Diameter
IPC	Integrated Project Coordinator
KBS-3H	SKB/POSIVA Horizontal Disposal Concept (ESDRED Reference)
KBS-3V	SKB/POSIVA Vertical Disposal Concept (National Reference)
LT	Long Term
LWR	German equivalent of PWR or Pressurized Water Reactor
MLW	Medium Level Waste
Mod1	Module 1
mSv	Milli-sievert
N/A	Not Applicable
NPP	Nuclear Power Plant
O/N	ONDRAF/NIRAS
OD	Outside Diameter
OPC	Ordinary Portland Cement
pH	Unit of measure for acidity and alkalinity of a material
Pkg	Package
PLC	Programmable Logic Controller
QA	Quality Assurance
QC	Quality Control
RB	Rock Bolt
SF	Spent Fuel
SiF	Silica Fumes
Sv	Sievert
U/G	Underground
UCS	Unconfined Compressive Strength
URL	Underground Research Laboratory
Vw	Vitrified High Level Waste
WMO	Waste Management Organisation
WP1	Work Package 1

ANNEX 5

COMMON GLOSSARY

WORD	Per IAEA	DEFINITION
ALARA	yes	An optimisation process for determining what level of protection and safety makes exposures, and the probability and magnitude of potential exposures, “as low as reasonably achievable, economic and social factors being taken into account”.
Backfill	yes	The material used to refill excavated portions of a repository (drifts, disposal rooms or boreholes) during and after waste has been emplaced
Barrier	yes	A physical obstruction that prevents or delays the movement of radionuclides or other material between components of a system, for example a waste repository. In general a barrier can be an engineered barrier (see EBS below) or a natural or geological barrier.
Behind		away from the dead end of a disposal cell/drift
Bentonite	yes	A soft light coloured clay formed by chemical alteration of volcanic ash. It is composed essentially of montmorillonite and related minerals of the smectite group. Bentonite is used as backfill and buffer material in repositories.
Buffer	yes	Any substance placed around a waste package in a repository to serve as an additional barrier to: stabilize the surrounding environment; restrict the access of groundwater to the waste package; and reduce by sorption the rate of eventual radionuclide migration from the waste
Canister		See *waste container*
Cask	yes	A vessel for the transport and/or storage of spent fuel and other radioactive materials. The cask serves several functions. It provides chemical, mechanical, thermal and radiological protection, and dissipates decay heat during handling, transport and storage.
Clay		Within ESDRED this refers to indurated clay in the form of claystones and argillites. Clays differ greatly mineralogically and chemically but ordinarily their base is hydrous aluminium silicate. NB: “Swelling clays” refers to specific types of clays used in EBS (see “Bentonite”) and in seals.
Conditioning	yes	Those operations that produce a waste package suitable for handling, transport, storage and/or disposal. Conditioning may include the conversion of the waste to a waste form, enclosure of the waste in canisters, and, if necessary, providing an overpack.
Criticality	Per US Nuclear Regulatory Commission	A term used in reactor physics to describe the state when the number of neutrons released by fission is exactly balanced by the neutrons being absorbed (by the fuel and poisons) and escaping the reactor core. A reactor is said to be "critical" when it achieves a self-sustaining nuclear chain reaction, as when the reactor is operating. In waste disposal designs the objective is to keep any fissile material in a sub-critical state so that any heat generated is due to natural decay only.
Decline		An excavation, in rock, for providing access from surface to the underground. Also called a ramp or access ramp. Essentially an inclined tunnel.

WORD	Per IAEA	DEFINITION
Demonstrator		A custom designed prototype piece of equipment built to prove a design concept and to show that it works; hence used to demonstrate.
Disposal	yes	The emplacement of waste in an appropriate facility without the intention of retrieval i.e. permanently.
Disposal Cell		Typically a short tunnel/drift/borehole excavated in an underground repository for the purpose of disposing packages of radioactive waste.
Disposal Drift		Typically a long tunnel/drift excavated in an underground repository for the purpose of disposing packages of radioactive waste
Disposal Package		The final Waste Package which is placed into a repository without further conditioning i.e. the Super Container, the Primary Package with Overpack or the Primary Package without Overpack.
Drift		A horizontal or nearly horizontal mined passageway
EBS	yes	Engineered barrier system; the designed or engineered components of a repository including waste packages and other engineered barriers. See also definition of barrier above.
EDZ		Excavation damage zone; used to describe the area surrounding a rock excavation which has been altered by excavation from its initial state usually by the formation of fractures or micro fissures.
ESDRED Concept		This is a variation of the reference National Concept which is used within the ESDRED Project. Example: Sweden's national concept is "Vertical" however SKB's concept within ESDRED is horizontal
Front, in front of		towards the dead end of a disposal cell/drift
Functional Req'mts		Within ESDRED, similar to flexible design criteria or flexible input data; generally refers to criteria or elements that are open to discussion and/or negotiation
Functional Requirements		Generally refers to expected functions and associated levels of performance that must be met by one or several design elements. Within ESDRED the term was used loosely to define design criteria that was somewhat flexible at the outset and needed to be fixed.
Gate		A type of radiation protection door installed on a cask as well as on the head of a disposal cell.
Hoist		A machine, driven by an electric motor, used to raise or lower a conveyance in a shaft.
HRL		Like a URL (see below) but located in hard crystalline rock.
Implementer		The private corporation or public body responsible for constructing and operating a repository.
Input Data		Within ESDRED, similar to fixed design criteria; generally refers to criteria or elements that are unavoidable and not open to discussion and/or negotiation
Input Data		Within ESDRED the term was used loosely to define design criteria and other data which was well fixed from the beginning.
Long Term		Generally intended to mean extending in time beyond the final closure of a repository
Long Term		Generally intended to mean extending in time beyond the final closure of a repository and covering the time period where safety needs to be demonstrated.
Matrix		A non-radioactive material used to immobilize waste. Examples of matrices are bitumen, cement, various polymers and glass
Matrix diffusion		Diffusion of solutes from a water-bearing fracture to pores and micro fractures of the adjacent rock matrix and vice versa

WORD	Per IAEA	DEFINITION
Overpack	yes	A secondary (or additional) outer container for one or more waste packages, used for handling, transport, storage or disposal.
Plug		Sometimes used interchangeably with SEAL but not within ESDRED where it refers to a concrete mass that serves as a backstop or abutment to resist the pressures eventually exerted on a seal by the swelling buffers.
Primary Package		A package of radioactive material as delivered by the producer; before conditioning, for disposal
Primary Package		A package of radioactive material as delivered by the producer to the repository; prior to further conditioning before disposal.
Ramp		See decline.
Repository		A nuclear facility where waste is emplaced for disposal
Repository system		The combination of the repository and the host rock
Retrievability		The ability to remove radioactive waste from the underground location at which the waste has been previously emplaced for disposal.
Retrievability (EUR 19145)		The ability provided by the repository system, to retrieve waste packages for whatever reason retrieval might be wanted for.
Reversibility		Implies a step wise disposal process and in particular refers to the ability of a repository system, for whatever reason, to reverse the steps that have been executed so far in its development.
Safety Case	yes	An integrated collection of arguments and evidence to demonstrate the safety of a facility. This will normally also include a safety assessment.
Salt		One of the 3 main host rocks being considered world wide for the disposal of highly active waste materials. The rock form of common salt.
Seal	yes	Engineered barriers placed in passages within and leading to a repository to isolate the waste and to prevent seepage leakage of water into or radionuclide migration from the repository area. Sealing is performed as part of repository closure.
Shaft		A vertical access way, excavated in overburden (if any) and bedrock, used to connect the surface with one or more horizons underground. Typically outfitted with one or more hoist and one or more conveyances unless used exclusively for ventilation in which case it may be left bald.
Shielding	yes	A material interposed between a source of radiation and persons, or equipment or other objects, in order to absorb radiation and thereby reduce radiation exposure.
Shotcrete		Mortar or concrete pneumatically projected onto a surface at high velocity.
Spent Fuel	yes	Nuclear fuel removed from a reactor following irradiation, which is no longer usable in its present form because of depletion of fissile material & build up of poison or radiation damage.
Storage	yes	The holding of spent fuel of radioactive waste in a facility that provides for its containment, with the intention of retrieval. Storage is by definition an interim measure.
Super Container		Generally seen as a disposal package that, unlike other disposal packages also incorporates bentonitic or cementitious buffer material.
Transmutation	yes	The conversion of one element into another. Transmutation is under study as a means of converting longer lived radionuclides into shorter lived or stable radionuclides.
Transuranic Waste		Alpha bearing waste that consists of material contaminated with elements that have atomic numbers greater than that of uranium (92), the heaviest natural element.

WORD	Per IAEA	DEFINITION
URL	yes	Underground Research Laboratory constructed for the purpose of conducting in situ testing. The objective is to conduct tests in a geological environment that is essentially equivalent to the environment of a potential repository.
Waste		Material in gaseous, liquid or solid form for which no further use is foreseen
Waste Container	yes	The vessel into which the waste form is placed for handling, transport, storage and/or eventual disposal; also the outer barrier protecting the waste from external intrusions. The waste container is a component of the waste package. For example, the “canister” into which molten HLW glass would be poured.
Waste Container	yes	The vessel into which the waste form is placed for handling, transport, storage and/or eventual disposal; also the outer barrier protecting the waste from external intrusions. The waste container is a component of the waste package. For example, molten HLW glass would be poured into a specially designed container (canister) where it would cool and solidify. NOTE: One or more waste packages can be put inside an overpack to become a Disposal Package.
Waste form		Waste in its physical and chemical form after treatment and/or conditioning (resulting in a solid product) prior to packaging. The waste form is a component of the waste package
Waste Package	yes	The product of conditioning that includes the waste form and any container(s) and internal barriers (e.g. absorbing materials and Liners), prepared in accordance with the requirements for handling, transport, storage and/or disposal.
Wireless Monitoring		System for monitoring phenomenology in front of a seal or plug without installing cables or wires through any of the barriers intended to isolate one or more disposal packages
Wireless Monitoring		Monitoring in which the transmission of the signal does not rely on an electrical wire or optical fibre connection. For example this allows for monitoring the phenomenology in front of a seal or plug without installing cables or wires through any of the barriers intended to isolate one or more disposal packages.