

(Contract Number: FI6W-CT-2003-508851)

Module 3 (Heavy load emplacement technology)

Final report

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Date of issue of this report: 29 September 2008

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
СО	Confidential, only for partners of the [ESDRED] project	No





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PUBLISHABLE EXECUTIVE SUMMARY OF ESDRED MODULE 3

The disposal of certain types of radioactive waste canisters in a deep repository involves handling and emplacement of very heavy loads. The weight of these particular canisters can be in the order of 20 to 50 metric tons. They generally have to be handled underground in openings that are not much larger than the canisters themselves as it is time consuming and expensive to excavate and backfill large openings in a repository (the creation of voids around the waste packages is also detrimental to the long term safety function and must subsequently be reduced to its minimum extent). This therefore calls for the development of special technology that can meet the requirements for safe remote operation (a radioprotection requisite) at an industrial scale in restrained operating spaces. In the present case those spaces are narrow annular gaps, since both the canisters and the disposal drifts have a cylindrical shape.

Air/water cushion systems are used world wide in the industry for moving heavy loads on flat surfaces. However, until now the technology needed for emplacing heavy cylindrical radioactive waste packages in circular excavated drifts with diameters only a few cm greater than the diameter of the waste packages had not been previously designed, developed or demonstrated.

Within Module 3, the following 3 specific emplacement systems were designed, developed and demonstrated:

- ➢ For SKB & Posiva, a water cushion deposition machine with all ancillary equipment for the safe remote disposal of a Super Container (also referred to as the "Container") with a length of 5.6 m and an outer diameter of 1.7 m. The weight of this Super Container is about 45 tons. The horizontal drift (300 m long, excavated in granite) for disposal of the Super Container has a diameter of 1.85 m. This disposal concept for spent nuclear fuel is called "KBS-3H" in SKB's & Posiva's programmes.
- ➢ For ANDRA, an air cushion deposition machine with all ancillary equipment for the safe emplacement of sets of 4 pre-assembled bentonite rings (acting as a buffer or an engineered barrier) into the perforated liner of a horizontal disposal drift (40 m long, excavated in clay). The weight of each set of 4 bentonite rings is about 17 tons, with a length of about 2 m. The rings have an outer diameter of about 2.25 m.
- For ANDRA, an air cushion deposition machine with all ancillary equipment for the safe emplacement of a spent fuel canister (called "CU1" in the ANDRA's concept) into the inner tube of the disposal drift. The weight of the CU1 canister with spent nuclear fuel is about 43 metric tons. The length of the canister is about 5 390 mm with an outer diameter of 1 255 mm. The emplacement of bentonite rings and spent fuel canisters is part of the ANDRA's concept for direct disposal of spent nuclear fuel that is not reprocessed.

The figures below show in 3 steps the basic principles of the air/water technology, in its application for underground disposal of waste canisters (the slide plate shown in yellow is necessary to compensate for the surface irregularities of the invert (granite or steel liner) on which the machine is travelling, since air/water cushions can only work on smooth surfaces):





During Step 1, the waste canister is typically standing on its feet with a height that allows the air/water cushion to be moved under the canister. A sliding plate is inserted in the clearance between the bottom part of the canister and the drift invert in between the feet of the canister. The length of the slide plate exceeds the length of the canister by about 1.5 m for the water application & by about 1 m for the air application. ANDRA's design replaces the feet on the canister with rails fixed to the drift liner invert to obtain the clearance between the canister and the invert.



During Step 2, the media (air or water) is injected into the cushions (fixed on the extrados of a lifting cradle) with a pressure that is high enough to elevate the waste canister. The operating pressure needed to activate the system is in the order of 2 to 3 bars (depending on the cushion location on the lifting cradle) for the water application and 5 to 7 bars for the air application.

Step 3



During Step 3, the waste container is pushed forward one stroke of about 1.5 m for the water application (1 m for the air application) with the deposition machine. As the container is "floating" on air or water, the force required to move it is only that needed to overcome the resulting force due to the inclination (2 to 3 degrees) of the disposal drift.



For SKB / Posiva, the full scale demonstration, was carried out successfully in situ (at Äspö HRL in Sweden) and showed very good results. The testing and demonstration campaign took place from February 2006 to February 2007. Beyond that period, an additional endurance testing phase was implemented from February 2007 until June 2008, simulating a cumulated emplacement length of approximately 25 000 m. The installation of the emplacement equipment is presented below, showing the deposition machine positioned in the chamber in front of the disposal drift (located behind the rear white shielding gate in the background of the picture).



For ANDRA, the full scale demonstrations of the 2 deposition equipments (i.e. one for the set of pre-fabricated buffer rings and another for the CU1 spent fuel canister) were both carried out in the MECACHIMIE workshop (surface) facilities in Beaumont-Hague, France (the demonstrations could not take place in situ (i.e. underground), since ANDRA's underground facility was not sufficiently advanced at the time.

The CU1 demonstrator was successfully tested from May 2006 to September 2006. The related layout is shown below, with the CU1 dummy canister (brown), the electrical cart (white) on the right, the shielding gates (middle) and the disposal drift mock-up on the left.





The bentonite rings demonstrator was successfully tested from September 2006 to December 2006. The related layout is presented below, with the perforated liner and a set of 4 dummy rings at the rear of the photograph and the electrical cart at the front.



In conclusion, one may say that the series of industrial scale tests in workshops and underground carried out between February 2006 and September 2007 by SKB / Posiva and by ANDRA on their respective demonstrators helped to validate the use of fluid (air or water) cushion technology as a valuable and reliable means for emplacing heavy loads in excavations with diameter not much bigger than the canisters being disposed. This work also made it possible to identify some of the operational limitations of the various pieces of equipment as well as the necessary refinements (retrofitting). Weak components that should be modified prior to an effective full scale industrial application in a future deep geological repository (in clay or granite) were also identified. Following the initial testing programme, SKB / Posiva decided to proceed with additional work related to the KBS - 3H concept which is deemed an interesting alternative to the reference case, the KBS – 3V. This equipment is still installed in the Aspö HRL in Sweden and shown to visitors.

As for ANDRA, no further development is considered at the time. Priority is now being given to the development of emplacement solutions for the storage of vitrified waste canisters, without an engineered barrier. The CU1 demonstrator in its current configuration however will be displayed in ANDRA's show room, near the Bure Underground Laboratory site, as of mid-2009. It will contribute to the public information on ANDRA's works and to the related and most necessary confidence building process.



1 - INTRODUCTION

1.1 Summary of the 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 organizations. ESDRED was coordinated by the French National Radioactive Waste Management Agency (ANDRA) and was part of the European Union'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 EU'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:	Technological R&D Organizations:
ANDRA, France	AITEMIN, Spain
ENRESA, Spain	CSIC, Spain
NAGRA, Switzerland	DBE TECHNOLOGY, Germany
NDA (Originally NIREX), United Kingdom	ESV EURIDICE EIG, Belgium
ONDRAF/NIRAS, Belgium	GRS, Germany
POSIVA, Finland	NRG, the Netherlands
SKB, Sweden	

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 organized 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 ton 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 bentonite pellets. 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 seismology 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 tons, 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 ton 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 tons.

• 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 and a long plug were subsequently constructed in 2 different URL's and then loaded to failure i.e. slippage. At time of writing the long plug had not started to slip.

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 2 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, developed and presented university lectures, and finished up by organizing an international conference on the operational aspects of deep geological disposal. A web site (<u>www.esdred.info</u>) 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 at least the end of 2009.

1.2 Background of Module 3 (Heavy Load Transportation Technology):

1.2.1 The KBS-3H system in Sweden and Finland

In Sweden and Finland two (2) concepts for direct disposal (in granite type formations) of spent nuclear fuel canisters are 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 inside a prefabricated super container with includes the buffer material in the package to be emplaced.

The KBS-3V disposal method is the reference case, both in Sweden and Finland, but the KBS-3H concept has a high potential, since it is more cost effective and because it has also environmental advantages as less rock needs to be excavated and backfilled. However, the KBS-3H concept is still under development and the long term safety factor still has to be thoroughly assessed. It also contains 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 to excavate long horizontal disposal drifts with a diameter of 1.85 m in hard rock with very stringent geometrical mining requirements.

1.2.2 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 June 2006 law) by ANDRA is focused on the development of disposal concepts for vitrified waste (by-product of spent fuel reprocessing) canisters only. In this new reference scenario

the vitrified waste canisters are no longer surrounded by an engineered barrier. However, direct disposal of spent fuel canisters in horizontal cells (excavated in clay) is 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 canister is a feasible option, which has been technically explored. It is also important to demonstrate the capacity to manufacture large compressed blocks of buffer material and to demonstrate the ability to emplace them in a confined space around the emplaced canisters.

Therefore what has been demonstrated by ANDRA within the ESDRED project will remain as a worthy reference, should the waste disposal scenario ever evolve again.

1.3 Objectives of ESDRED Module 3

The objectives for Module 3 were, starting from a conceptual design stage which was preexisting at time of start-up of the ESDRED Project, to develop (i.e. to design, build, erect, test and finally evaluate) 3 specific demonstrators capable of transporting and emplacing the following types of cylindrical shaped heavy loads:

• A 45 ton Super Container to be positioned inside a long narrow drift in the Swedish / Finish concept (adapted to a granite type host rock),

• A set of 4 pre-assembled buffer rings weighing 17 tons (with a diameter of 2.25m) inside a horizontal perforated liner (in order to build an engineered barrier around the waste canisters), as well as

• A CU1 canister with a weight of 43 tons and with a diameter of only 1.25 m inside a metallic sleeve, for the French concept (adapted to a clay type host rock).

• To test the reliability and availability, in a longer perspective, of the 3 developed machines and of their ancillary pieces of equipment,

• To identify the necessary improvements (adaptation of the working principles or parameters, retrofitting of certain pieces or components) 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.

1.4 Project technical evolutions

Module 3 followed, as all the other Technical Modules of ESDRED, a very classical and careful (stepwise) approach in Research & Development, well in line with the original planning of the work.

Module 3 started with the writing of a precise outline of the input data available and of the technical requirements (including the expected performances) deemed achievable for a successful and convincing demonstration of the 3 emplacement machines being considered. This first work was carried out in *Work Package 1*.

SKB and Posiva had already done (prior to the start-up of ESDRED) some prototype testing of the air and water cushion (at a reduced scale) which indicated that it would be possible to use this technology for the disposal of a Super Container with a weight of 45 tons and an outer diameter of 1.75m, inside an 1.85m ID horizontal drift.

However, the CU1 spent fuel canister considered in the French concept had a diameter of only 1.25 m with almost the same weight (43t). The radius of curvature of the cushions (mounted on the lifting cradle) being significantly smaller than in the SKB/Posiva case, it was therefore considered necessary by ANDRA to first carry out a prototype testing (at a reduced scale) with the air cushion technology, for the CU1 spent fuel canister application, in order to check that the technology was still relevant and adapted to the purpose. This successful work (a pre-requisite to a full scale development) was carried out in *Work Package 2*.

The detailed design and fabrication of the 3 emplacement machines, respectively for the Super Container, the set of 4 pre-assembled bentonite rings and the CU1 spent fuel canister could then take place within *Work Package 3*. Those tasks were implemented with the help of sub-contractors (Industrial Integrators) selected through a bid and tender process. CNIM was contracted by SKB for the KBS-3H application, while MECACHIMIE was contracted by ANDRA for the CU1 and the set of Bentonite Rings application.

Work Package 4 of Module 3 was then dedicated to the full scale demonstration phase of the 3 emplacement machines. For the KBS-3H Super Container emplacement equipment, this took place in situ at Äspö HRL, Sweden. The full scale demonstrations of the emplacement equipment for the set of pre-fabricated buffer rings and the spent fuel canister were done in the MECACHIMIE workshop (surface) facilities in Beaumont-Hague, France.

Work Package 5 consisted of the reporting of the results obtained at the end of the different testing campaigns: the factory acceptance testing (**FAT**) and the site acceptance testing (**SAT**).

Finally, *Work Package 6* is this Report on the achievements and results of Module 3, i.e. the **Final Report**. It also contains a critical evaluation of the work carried out and elaborates briefly on the perspectives envisaged for the future of the demonstrators.

1.5 Results and Conclusions

The main results and conclusions related to the testing of the water cushion system for SKB and Posiva are the following:

• The tests performed so far have shown that the emplacement equipment designed and fabricated within the framework of the ESDRED Project can operate effectively for the transport and deposition of Super Containers with a weight of 45t into horizontal drifts excavated in hard rock. However, further tests are required to verify the availability and the reliability of this equipment over longer periods of time and to identify the modifications that would be needed for an industrial application in a harsh nuclear and mining environment.

• It has also been observed that the water cushion technique used by SKB/Posiva is sensitive to load variations. This means that the Super Container to be transported must be well balanced at time of spent fuel loading. This requirement implies that all spent fuel housings in the canister must be completely filled with spent fuel elements or fuel dummies.

• Finally, the system is also sensitive to the proper set-up alignment between the deposition drift, the Super Container transport tube and the launch tube of the deposition machine. This requirement implies that a proper pre-positioning device must be integrated in the industrial application.

The main results and conclusions related to the testing of the 2 air cushion systems for ANDRA are the following:

• The tests performed have shown that the emplacement equipment designed and fabricated within the scope of the ESDRED Project can be operated effectively and safely for the transport and emplacement of a CU1 Spent Fuel Container with a weight of 43t or of a set of 4 pre-assembled bentonite rings with a weight of 17t, inside mock ups of horizontal disposal cells. Of course, further tests also need to be conducted in real underground conditions and over a longer period of time to assess the availability and the reliability of this equipment. This new phase of work, which is out of the ESDRED programme, is not considered at this time, since priority is being given to the disposable of vitrified waste canisters.

• It has also been observed that the air cushion technique used by ANDRA is sensitive to load variations. This means that the air cushions must be individually monitored and controlled. The air that pressurizes the cushions must first go into a dessicator to prevent condensation phenomena and the problems linked to that.

• Finally, an efficient spooling system is considered necessary for a proper functioning of the air hose winch over a distance of 40m, which is most likely the maximum acceptable disposal cell length, considering the air pressure loss observed during the testing.

2 - PROGRAMMEME IMPLEMENTATION

2.1 The KBS-3H Deposition Concept (SKB / Posiva)

2.1.1 Introduction

The Conceptual Design phase for the KBS-3H deposition concept was carried out during the year 2003, i.e. before the start-up of the ESDRED Project.

The main objectives of the conceptual design of the deposition equipment were:

- The elaboration of a functional description and of the related guidance drawings of such a system, complete enough for ordering the design and fabrication of the equipment via a Request for Proposal (RFP).
- The verification that the fluid cushion 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 however reduced to ¹/₄ of the length of the real Super Container.

The workshop tests were satisfactorily performed in April and in July 2003 with the assistance of the SOLVING Company, from Finland. 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 RFP documents issued for the selection of a contractor (**Industrial Integrator**) in charge of the development of the machine.

After the final tendering evaluation, CNIM (France) was awarded in December 20, 2004 the detailed design and fabrication of the KBS-3H Deposition Equipment.

For test purposes, a 95m long drift was excavated in granite, with a special tunnel boring machine, early 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.

All those elements formed the Input Data of the KBS-3H deposition equipment concept.

2.1.2 Functional 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 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. A typical layout of a KBS-3H deposition drift is illustrated in Figure 1.

- The length of the deposition drifts is assumed to be up to 300 m,
- The diameter of the deposition drift is 1.85 m,
- The inclination of the deposition drift is $2^{\circ} \pm 1^{\circ}$.

Figure 1: Typical layout of the KBS-3H deposition drift.

Figure 2 shows the so-called Super Container, which contains the copper canister with encapsulated spent nuclear fuel, the compacted buffer material and the perforated steel shell. The Super Container is provided with feet to allow the container to be transported with the deposition machine inside the drift.

Figure 2: Composition of a Super Container.

The Super Container has the following dimensions and weight:

- Steel shell outer diameter 1765 mm \pm 5,
- Steel shell overall length 5550 mm \pm 5,

- Height of feet 45 mm¹,
- Weight approx 45 tons.

The Distance Blocks (or spacers) are circular blocks made of compacted bentonite without any supporting shell. 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 \pm 5,
- Length 900 mm,
- Height of feet 45 mm,
- Weight approx 4.6 tons.

For test purposes, the Super Container and Distance Block mock-ups were made with concrete instead of bentonite. The mock-ups had the real payloads and correct physical dimensions.

Some Functional Requirements were related to the following machine operating performances:

Average Transport Speed with Super Container	Min 20 mm/s
Average Transport Speed with Distance Block	Min 30 mm/s
Transport Speed (only machine)	Min 100 mm/s
Positioning Accuracy of Distance Blocks	$\pm 10 \text{ mm}$

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.
- The machine should be design to prevent water from coming into contact with the buffer material contained in the Super Container.

Note: The complete list of Input Data and Functional Requirements is specified in Module 3 Deliverable 1, called "Input Data and Functional Requirements" [1].

2.1.3 Design Work & Demonstration layout

For economical and practical reasons some simplifications were made to the deposition machine by comparison with what would have been necessary for a real industrial machine. This means that some of the requirements, which would apply to a future deep repository, were not included in the list of functional requirements. The most important

¹ Due to some changes introduced in the cradle design, the feet height for the tests was changed to 50 mm.

exemption was that the demonstration equipment would not be designed for the radiation emanating from a canister with spent fuel but the radiation effects would be partly considered in the design requirements.

The equipment developed and fabricated during 2005 by CNIM, France for the deposition of Super Containers/Distance Blocks consisted of the following main components:

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

Figure 3 shows a 3-D illustration of the set-up of the equipment manufactured for the tests carried out at Äspö HRL (at level - 220m) during 2007, to verify in full-scale that the KBS-3H transport concept with water cushion technology was technically feasible for the emplacement of Super Containers and Distance Blocks.

Figure 3: 3-D Lay-out of Deposition Equipment.

The main components of the deposition machine design are shown in Figure 4 and Figure 5. The machine is wheel driven with electrical gear motors on all wheels.

Figure 4: 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 frame. The slide plate is provided with two cameras equipped with lighting with one facing forwards and another backwards. The slide plate is also provided with sensors (forward and backward) for detection of obstacles in front of the machine and for positioning of the Super Container.

Figure 5: Deposition Machine, view from front right side.

The lift cradle is attached to the radiation shield, which is connected to the machine frame (body) via three (3) synchronized actuators (horizontal hydraulic pushing jacks) allowing for the stepwise movement. The stroke of the 3 actuators is 1.5m.

The lift cradle, which is provided with 24 water cushions positioned in two (2) longitudinal rows (left/right), is shown in Figure 6 below.

Figure 6: View of underside of the lift cradle during installation of water cushions.

Note: The detailed design of this emplacement system is described in a specific Module 3 report [3].

2.1.4 Implementation of Full Scale Tests (in factory & in situ)

The 2 testing phases initially considered for this emplacement machine were as follows:

• A first phase called FAT (Factory Acceptance Tests), to be carried out in the Integrator's facilities, namely CNIM at La Seyne-sur-Mer (France),

• A second phase, called SAT (Site Acceptance Tests), to be carried out in situ, namely in the Aspö HRL, at -220m level.

Figure 7: Set-up of equipment at the test site at Äspö HRL, level -220m. The Super Container is inside the transport tube with the 2 shielding gamma gates open. The control room is on the left side on this photo.

Figure 7 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 - 220m level. For proper positioning of the equipment in the chamber in front of the drift, some adjustable position blocks were embedded in the chamber concrete floor while the drift entrance was provided with a flange allowing for proper docking of the transport tube to the drift mouth.

In fact, the FAT partially took place in the CNIM factory and was completed in Aspö. A specific report on the commissioning of the manufactured equipment was then issued [4]. The FAT was immediately followed by the SAT. The main results of the FAT & SAT are summarized below.

Originally one requirement was that the deposition machine should be able to handle the Super Containers with SF copper canisters with one ore more empty fuel positions inside (this was due to the constraint regarding the maximum allowed residual heat effect of the spent fuel located in one copper canister). However, free spaces in a copper canister, placed inside a Super Container, can create an unbalanced situation. It was evidenced during the pre tests performed at Äspö, before start-up of the SAT, that it was impossible to properly handle an unbalanced Super Container. Therefore all the tests were performed with a properly balanced Super Container (i.e. all positions in the copper canister filled).

It was also observed that the mobile ballast (used as a balancing means) on the machine could not prevent or control the rotation of the Super Container. The ballast system 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 started to rotate left or right. The rotation of the container happened very quickly and could therefore not be corrected/controlled with the balancing system on the machine. The only way to keep the Super Container from turning during transport was to guide the lift cradle along the slide plate edge (by installing longitudinal rails acting as a guide system)

to prevent rotation. The guides (which were subsequently installed) are shown in Figure 8: and turned out to be quite effective in preventing derailing.

Figure 8: Guides between the cradle and the slide plate.

The tests with the emplacement machine showed that there was a high risk that the impact of rotation about the long axis of the container could be cumulative. Each time the container was moved, it would rotate approximately +/-0.2-0.3 degrees at each stroke due to the 5 mm gap between the guides mounted respectively on the cradle and on the slide plate.

However the tests performed showed that this detrimental phenomenon could be offset thanks to the ballast system if the correction was done as soon as a deviation in inclination was detected. Therefore, the ballast system was made to operate in automatic mode in order to compensate for any rotation that occurred between the guides.

It was also observed that if the Super Container together with the cradle and the slide plate was (cumulatively) rotated more than 3.5 - 4 degrees, then this movement could create problems for the good functioning of the water cushions (due to the uneven load distribution resulting from such a configuration). The problem resulting from too much rotation was that some of the cushions, which were getting more loaded than normal, were not capable anymore of lifting the container. It was therefore considered impossible to properly handle an unbalanced Super Container with the present water cushion system.

Another problem observed 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 new brand that was less sensitive to pressure variations and/or load changes.

The analysis and investigations of the problems revealed during the initial tests were done in close cooperation with CNIM. The additional tests that were carried out on the water cushions and the subsequent change of cushions were treated as a change order.

Other problems were identified, mainly in relation to the water control valves and to sensors allowing the machine to operate in automatic mode. After trouble shooting, these problems were also solved.

The performance requirement for the average deposition speed of 20 mm/s 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, interrupted only by the transport tests with distance blocks in June2007 and for the summer vacation period in July 2007. The cumulative transportation distance reached since the SAT started in February 2007 to mid 2008 is approximately 25 km.

Figure 9: *The deposition machine has entered the deposition drift (left) - The Super Container is deposited approximately 20 meters into the deposition drift (right).*

Note 1: The initial transportation tests performed with Distance Blocks showed that the fixation of the feet to the Distance Blocks must be improved before further tests can be conducted.

Note 2: The results from the Test campaign carried out on the KBS-3H emplacement machine are detailed in a specific Module 3 report [4].

2.1.5 Summary and Analysis of main achievements

The tests performed in situ demonstrated that the emplacement equipment can operate effectively for the transport & 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. This requirement implies that all fuel positions in the SF canisters must be filled with fuel elements or fuel dummies,

- The system/technique is also 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 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.

2.1.6 Possible Improvements to the design developed

The tests have revealed a number of weak points that need to be improved in the future. The main ones are listed below.

• Water Cushion Lift Cradle:

The mounting of the cradle to the radiation shield should be improved to allow for a faster installation and easier alignment. For the real repository it is not advised to have the cradle and the slide plate retractable underneath the machine to simplify the transportation of the machine. Tests have shown that the system is very sensitive to a correct installation and alignment of the cradle with the rest of the equipment and it is therefore advised to transport the emplacement machine in its full length. This will minimize the risk for installation errors and it will also minimise the preparation time needed for the setup of the equipment.

• Lift Sensors

The lift sensors on the cradle should be improved with regards to the accuracy of the measured values. The present design seems to be affected by the water flow underneath the cradle. A solution could be to protect the sensors from the water stream. It is also advised to investigate if other systems/sensors are available on the market for such conditions.

• Splashguard

Due to the introduction of the guides between the slide plate and the cradle, the splashguard was removed. The need for a splashguard has still to be confirmed, however it is advised to investigate different solutions to ensure that water is prevented from coming into contact with the bentonite buffer.

• Slide Plate

The slide plate should be provided with a channel along the edge of the plate to allow water draining from the rock to run underneath the slide plate instead of running over the front of the slide plate and entering the water system on the machine. This change would

prevent the salty drainage water from entering the system; it would probably also minimize the amount of silt particles (lying on the drift floor) which enter the system and jam the control valves. This change would also affect the profile of the cradle, which should be adapted to the new shape of the slide plate.

• Ballast System

It is advised to increase the ballast weight and also increase the speed of the motion of the ballasting device for a faster reaction when compensation of an unbalance is needed. The control loop for the motion of the ballast should also be further optimized.

Note: *The results obtained after the test campaign and the critical analysis of the machine are detailed in a specific report [4].*

2.2 The SF (CU1) Canister Emplacement System (ANDRA)

2.2.1 Introduction

In France, in 2003, ANDRA 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 4 pre-assembled buffer rings when constructing the disposal cell. In the ANDRA case (unlike the KBS-3H concept described above), the sets of 4 pre-assembled buffer rings and the SF canisters are handled separately and not as one package for various reasons, including in particular a) the need for assuring the retrievability of the SF canisters and b) the limitations related to the maximum allowable during transfer in a shaft cage.

The two (2) 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 emplacement of SF canisters and of sets of 4 pre-assembled bentonite rings are shown in **Figure 10**.

Figure 10: Main components of ANDRA's emplacement concept for a CU1 (spent fuel) canister disposal cell

Air was selected as the appropriate lifting medium for two main reasons: i) it is a medium compatible with the host formation (clay), 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 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 and the inside diameter of the cell wall. This geometrical optimization results in lower construction costs as there is less material excavated and also in lower

operating costs as there is less material to backfill the disposal cell and no need to fill the small annular gaps.

2.2.2 Input data and Functional Requirements

The weight of the SF canister is 43 tons and it has an OD of 1.25 m and a length of 5.39 m. Figure 11 shows its main characteristics.

The disposal cell is excavated in clay (argillite). It has a length of approximately 40 m from mouth to cell dead end. The annular clearances presented below in Figure 12 are those chosen as the best compromise between the necessary mechanical gaps (for construction of the cell and later emplacement of SF canisters while maintaining a retrieval option) and the confinement (long term safety) requirements.

In accordance with the above data, the Emplacement Machine operating performances were specified as follows:

Average Transport Speed with SF Canister	Min 20 mm/s
Travel increment with sliding plate	1000 mm per stroke
Transport Speed (machine only)	Min 100 mm/s
Positioning Accuracy	$\pm 10 \text{ mm}$

Figure 11: Main characteristics of a CU1 (Spent Fuel) canister

Figure 12: Main components of ANDRA's emplacement concept for a spent fuel canister disposal cell c/w annular clearances

Note: The complete list of Input Data and Functional Requirements is specified in Module 3 Deliverable 1, called "Input Data and Functional Requirements" [1].

2.2.3 Implementation of a Preliminary Prototype Test Programme

The CU1 spent fuel canister considered in the French concept has a diameter of only 1.25 m with almost the same weight (43t) as the SKB/Posiva Super-Container, which has a weight of 45t and an OD of 1.76m.

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

This work (a positive result was a pre-requisite before proceeding with a full scale development) was successfully carried out in November/December 2004 with the selected contractor, BERTIN, a company specialized in air cushion application solutions.

The purpose and results of the test programme were as follows:

• to verify that the overall air cushion lifting system functioned correctly according to the geometry defined,

- to assess the required power needs for the proper operation of the overall system (for the mock-up used in the feasibility test, and by extrapolation for a full scale demonstrator),
- 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" (air-cushion failures, loss of flow or pressure, dissymmetry of package load such as radial offset of the centre of gravity in particular, etc.),
- 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. A failure-combination test was also conducted and justified as being the most critical combination of failures,
- 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.

The Prototype Test Bench built for this purpose is shown in **Figure 13.** This bench is full scale regarding the radius of curvature of the canister, and at a reduced scale (1 to 3) regarding the length of the canister.

Figure 13: The Preliminary Air Cushion Prototype Test Bench at BERTIN premises (Montigny-le-Bretonneux, near Paris)

Note 1: This bench will be permanently displayed as of mid-2009 in ANDRA's Cte (show-room), near Bure, to facilitate the understanding (by the general public) of the basics of air cushion technology.

Note 2: *The detailed results and recommendations are described in the report related to this Preliminary Prototype Test* [2].

2.2.4 Design Work for the Full Scale mock-up

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

For economical and practical reasons some simplifications were incorporated in the emplacement machine by comparison with what would have been a real industrial machine. This means that some of the requirements, which would apply to a future deep repository, were not included in the list of functional requirements. The most important exemption was that the demonstration equipment would not be designed for radiation from a canister with spent fuel but the radiation effects would be partly considered in the design requirements (overall geometrical dimensions in particular). Furthermore, ANDRA, having at the time no space available in its URL facilities in Bure (where priority was given to scientific acquisition), it was decided to run the experiment in a surface workshop only.

The equipment designed during 2005 by Mécachimie (contractor selected after completion of a Request for Proposal process) for the emplacement of the CU1 (SF) canisters consisted of the following main components:

- Deposition Machine complete with slide plate, air cushion cradle, electrical cart, control & monitoring system, motorized winches for steel cable/air umbilical/electrical wire,
- 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.

All these components are illustrated and detailed more thoroughly in Chapter 2.2.5.

Note: The detailed design of this emplacement system is described in a specific Module 3 report [3].

2.2.5 Implementation of Full Scale mock-up Tests

The test campaign related to the testing of the machine for emplacement of the CU1 (SF) canister 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 14.

Figure 14: ANDRA - Set-up of the CU1 canister emplacement system at Mécachimie's premises in Beaumont-Hague, France

The complete test bench was composed of the following main parts:

- a supporting frame equipped with adjustable feet for simulating the geometrical defaults likely to be encountered in a real disposal cell underground or/and the steps/misalignment between the docked shielding cask and the disposal cell mouth;
- a polycarbonate tube (for viewing during demonstrations) with stainless steel sliding track sections fixed to the full length of its invert. These sections have two (2) guide rails welded to the upper surface of the sliding track. When the SF canister is set down onto the rails, there is enough clearance between the bottom of the canister and the top of the sliding track so that once the air cushions are deflated the slide plate attached to the electrical cart can be advanced or retracted, i.e. the cradle and sliding plate can be moved separately from the SF canister. The rails also act as a guide for the slide plate and air cushion cradle, which follow the path of the SF canister to its final destination. The ID of the polycarbonate tube is similar to the diameter of the inner steel sleeve in a real disposal cell;
- two (2) gamma gates: one attached to the cell mouth and one attached to the shielding cask. The shielding cask gate is motorized and it moves the passive cell mouth gate;
- an electrical cart (the deposition machine) equipped with a radioprotection shield and an electrical pushing jack for advancing the SC in 1 m increments (see Figure 15);
- a slide plate attached to the body of the electrical cart;
- an air cushion cradle attached to the pushing jack;
- a control & monitoring console (see Figure 15)
- a 43 ton dummy canister (5.4 m long) whose centre of gravity could be adjusted longitudinally and radially.

Figure 15: Details of electrical pushing jack connected to the spent fuel canister (left) and Control & Monitoring Console (right)

The primary objectives and challenges in this test programme 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, inside the polycarbonate/steel tube , 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 (2) 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 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.

The tests executed during the FAT & SAT were recorded. 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 polycarbonate 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 (moving the air cushion cradle over the slide plate), 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 1 m. 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 dessicator 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 (combination of longitudinal imbalance together with a change of inclination of a tube section), the canister could not be moved.

Note: The results obtained after the test campaign and the subsequent critical analysis of the machine developed are detailed in a specific report [4].

2.2.6 Summary and Analysis of main achievements

Despite the issues noted above, the test programme turned out to be a complete success. The specified emplacement performances were exceeded as the average emplacement speed over one complete cycle was found to be 1.8 m per minute (m/min) versus the 1.2 m/min specified. In addition, the SF canister emplacement process turned out to be very smooth, without shocks. The stability of the canister on the cradle was maintained even in the case of radial load unbalance or of geometrical defaults in the polycarbonate/steel sleeve.

2.2.7 Possible Improvements of the design developed

Issues not fully solved within the framework of the test programme but that should be addressed in a future version of this equipment, are listed below:

- since the air cushions are sensitive to load variation, a more accurate air flow control is needed, such that fine tuning of each air cushion is possible;
- in order to avoid derailing of the air cushion cradle, the air cushion lifting height must not only be monitored, but also controlled (see previous point);

- since the air cushions are sensitive to moisture content in the air, the compressor should be equipped with a air-dryer;
- the air feed inlet should be modified so that the air cushions can be activated and deactivated more quickly thus resulting in a reduced overall cycle time;
- in automatic mode, the winding and unwinding of the air hose umbilical attached to the back of the electric cart was not perfect and "needed a hand" from time to time. This was due, at least in part, to the friction coefficient of the hose on the invert slide track, which created a parasitic (drag) force. A different hose material might reduce the friction coefficient (and also the wear on the hose) and consequently reduce the drag force exerted on the electrical trolley. Finally, a spooler mounted on the hose winch would improve the winding/unwinding of the hose on the winch drum;
- alternately a more powerful electrical motor mounted on the electrical cart could compensate for the friction force (drag) exerted by the hose;
- the very heavy weight (43 ton) of the SF canister induced some inertia efforts, which were a real strain on the electrical pushing jack frame, which occasionally emitted some "cracking noise". A stiffer jack frame would reduce the stresses and the bending effects on the jack;
- Finally a slide plate made of composite material (carbon fibre or similar) instead of stainless steel would help to reduce the friction between the bottom of the slide plate and the top of the slide track fixed to the invert of the polycarbonate tube.

Note: *The results obtained after the test campaign and the critical analysis of the machine developed are detailed in a specific report [4].*

2.3 The Set of Bentonite Rings Emplacement System (ANDRA)

2.3.1 Introduction

In France, in 2003 ANDRA 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 pre-fabricated buffer rings when constructing the disposal cell. In the ANDRA case (unlike the KBS-3H concept described previously), the sets of buffer rings and the SF canisters are handled separately and not as one package for various reasons, including in particular a) the need for assuring the retrievability of the canister and b) the maximum allowable load during transfer in a shaft cage.

The two (2) ANDRA systems were totally developed within the framework of the ESDRED Project, as of early 2004. The main components in the ANDRA disposal system for emplacement of Bentonite Rings are shown in **Figure 10** above. The reasons for selecting air as a lifting medium are also detailed in chapter 2.2.1.

It was decided to proceed first with the design, construction and development of the SF canister emplacement system, since it was the most technically challenging. If successful, work would then proceed with the development of the buffer rings emplacement system,

with an adaptation of as many SF components as possible. These would then be common to the 2 machines (including most of the control & monitoring system, the electrical cart, the bench support substructure and all the motorized winches) for the sake of standardization, economy and schedule.

Those technical choices were forced by time and budget constraints. For the same reasons there was also a single RFP and a single contract for the development of the 2 machines, i.e. for the SF canister emplacement system and the pre-fabricated bentonite rings emplacement system respectively.

In France the reference scenario nowadays (i.e. since the passing of the June 2006 law) being studied by ANDRA is focused on the development of disposal concepts for vitrified waste (by-product of spent fuel reprocessing) canisters and these are not anymore surrounded by an engineered barrier. However, direct disposal of spent fuel canisters in horizontal cells (excavated in clay) remains an option that may be reconsidered in the future, e.g. for fuel not suitable for reprocessing.

At the time of the ESDRED Project start-up (February 2004), the disposal of spent fuel canisters was still considered as a likely application and the technically related emplacement system was subsequently developed. The emplacement of an engineered barrier around the waste canisters was also considered as scientifically relevant, **both** around spent fuel canisters **and** around vitrified canisters.

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, which has been technically explored. It is also important to demonstrate the capacity to fabricate large compressed blocks of buffer material and demonstrate the know-how and technology to emplace them in a confined space. Therefore what has been demonstrated within the ESDRED project will remain as a worthy reference case, should the waste disposal scenario ever evolve again.

2.3.2 Input data and Functional Requirements

It was decided within the framework of the ESDRED Project to fabricate and later emplace bentonite rings deemed adapted to the C type canister disposal concept. The fabrication of the bentonite rings as well as the design and supply of their lifting and assembling devices were part of Module 1 of ESDRED. The data concerning the set of rings considered were as follows.

- The buffer (bentonite/sand) rings are assembled in sets of four (4). Each set of rings has a weight of 17 tons, with an OD of 2.25 m and a length of 2 m.
- The set of rings (the payload) and the disposal cell cross section of a C type canister disposal cell concept are illustrated in **Figure 16**.

Figure 16: Cross section of a C type canister disposal cell with engineered barrier (left) and view of a set of 4 pre-assembled bentonite rings (right)

The operating performances of the emplacement machine were specified as follows:

Average Transport Speed with Buffer Sets	Min 30 mm/s
Transport Speed (machine only)	Min 100 mm/s
Positioning Accuracy	"At contact"

Note: The complete list of Functional Requirements is specified in the Module 3 Deliverable 1, called "Input Data and Functional Requirements" [1].

2.3.3 Design Work

For economical and practical reasons some simplifications were incorporated in the emplacement machine by comparison with what would have been a real industrial machine. The most important simplification was that the demonstration equipment would not be specifically designed for bentonite rings emplacement, but would be adapted from the SF canister equipment already available. Furthermore, ANDRA having at the time no space available in its URL facilities in Bure (where priority was given to scientific acquisition), it was decided to run the experiment in a surface workshop only.

The equipment designed during 2005 by Mécachimie (contractor selected after completion of a Request for Proposal process) for the development of the emplacement machine consisted of the following main components:

- Deposition Machine complete air cushion cradle, electrical cart, control & monitoring system, motorized winches for steel cable/air umbilical/electrical wire,
- Mock-up of disposal cell section (first 10m),
- A supporting frame.

All these components are illustrated and detailed more thoroughly in Chapter 2.3.4.

Note: The detailed design of this emplacement system is described in a specific Module 3 report [3].

2.3.4 Implementation of Full Scale mock-up Tests

The tests campaign related to the emplacement of the sets of Bentonite Rings took place from September 2006 to January 2007. In fact, they followed the tests first implemented for the SF canister emplacement system. This campaign started with the erection of the equipment necessary for that purpose. In this case it involved mainly a modification of the test bench initially used for the SF canister.

The main configuration changes made to the SF canister emplacement system were:

- an adaptation of the structural frame supporting the bench to deal with the change of diameter from one type of payload to the other,
- a new "test tube" composed of a perforated steel liner in its upper part (including a lateral polycarbonate window) and of a stainless steel sliding track in its invert lower part,
- the suppression of the sliding plate (emplacement of bentonite rings is implemented via a continuous travel versus SF canister emplacement which is carried out with 1m strokes) and of the radioprotection shield which were both attached to the electrical cart, whose wheel span was also adapted to the new guiding rails gauge,
- a new air cushion cradle adapted to the payload length and diameter,
- a new PLC programming of the control & monitoring system.

The test bench set up, after modifications for emplacing a set of 4 bentonite rings, is shown in **Figure 17**.

Figure 17: ANDRA - Set-up of the bentonite rings emplacement equipment at the test site (Mécachimie's premises in Beaumont-Hague)

There were 3 types of challenges in this test programme:

- fulfil all the technical performances specified, including the successive emplacement (and later retrieval) of 2 sets of 4 dummy concrete rings (same weight and same dimensions as the real bentonite rings) in automatic mode, inside the perforated liner (the 2 sets being emplaced to make contact with each other, so as to create a continuity for an engineered barrier),
- down-load the set of 4 dummy rings onto the launching table with the lifting system (see **Figure 18** right) developed for the set of 4 rings by the GME (Module1 Contractor, in charge of the design and fabrication of such devices),
- check the behaviour of the rings, which were disassembled after their loading onto the air cushion cradle, and their stability under the various accelerations induced by the emplacement operations,
- check the relevance of the pre-defined operating parameters since, by contrast with the SF emplacement machine, no Preliminary Testing had been performed.

Note: The liner shown above is perforated as also shown in the disposal concept. This is to enable the progressive saturation of the bentonite with the seeping water coming from the host rock.

Figure 18: The air cushion cradle on launch table (left) and a set of 4 rings on its transportation base (right), ready to be lifted

The simplification of the electrical cart (the suppression of the radiation shield) enabled the installation of a 3D camera (mounted on a horizontal mast), to facilitate the remote control at time of docking a set of rings onto a set previously emplaced in the cell. The camera mast is shown in Figure 19.

Figure 19: Set of Rings before and after emplacement inside the perforated liner

2.3.5 Summary and Analysis of main achievements

What follows is an overview of the main results and observations made during the tests and also an evaluation of the performance with reference to the main functional requirements mentioned in earlier paragraphs:

- Since the trouble shooting of the emplacement system took place during the previous testing of the CU1 configuration, no particular difficulties were encountered during the test programme, which turned out to be a complete success.
- The specified emplacement performances were easily met (average emplacement speed over one cycle was 6 m/ min versus 1.8 m/ min specified).
- The emplacement of the set of rings was very smooth, without shocks. Thus, the lateral stability of the rings (disassembled after their downloading on the air cushion cradle) was not affected.

- The air cushions (and the air flow control) being sensitive to water content in air, a compressor equipped with a dessicator was used and as a consequence, no troubles such as those encountered with the CU1 system appeared.
- As no sliding plate was used to provide a perfectly smooth and homogeneous invert, the air cushions turned out to be also quite sensitive to voids (gaps, rough surfaces), so that it was necessary to install a temporary layout of a fibre glass carpet which was positioned on the liner invert, between the guiding rails. The installation of such a carpet was very easy and executed manually, since the carpet weight was limited and the access to the inside of the perforated liner was compatible with man height (liner is about 2.3 m ID).

2.3.6 Possible Improvements of the design developed

The remaining (i.e. not solved within the framework of the test programme) difficulties for operating the system are listed below together with the remedial solutions:

- The air cushions are sensitive to load distribution, thus there is a need for a better air flow control (most likely an individual control and monitoring for each air cushion),
- Air cushion lifting height must also be monitored and controlled to avoid derailing of cradle with load (lifting height was in practice only monitored),
- Winding and unwinding of the air hose in automatic mode was not perfect and "needed a hand" from time to time, while the friction coefficient of the hose on the invert side track was penalizing. A different hose material would reduce the friction and the wear of the hose and would also reduce the drag force exerted on the electrical cart. Finally, a spooler mounted on the hose winch would facilitate the winding/unwinding of the air hose.

Note: The results obtained after the test campaign and the subsequent critical analysis of the machine developed are detailed in a specific report [4].

3 - SUMMARY AND CONCLUSIONS

The series of industrial scale tests carried out from May-June 2006 to September 2007 by SKB/Posiva and by ANDRA on their respective emplacement equipment helped to validate the use of fluid cushion technology for placing heavy loads in very confined spaces. This work also identified some of the limitations of the equipment as well as the necessary refinements/modifications that should be implemented prior to a full scale industrial application in a future deep geological repository in clay or granite. These tests and their results were compiled in a technical report [5].

3.1 Conclusions Related to the Testing of the Water Cushion System (SKB/Posiva)

The tests performed have shown that the emplacement equipment designed and fabricated within the scope of the ESDRED Project can operate effectively for the transport and deposition of Super Containers with a weight of 45 tons in horizontal drifts excavated in hard rock. Further tests are however required to verify the availability and the reliability of this equipment over longer time periods.

It has also been observed that the water cushion technique used by SKB/Posiva is sensitive to load variations. This means that the Super Container to be transported must be well balanced. This requirement implies that all fuel positions in the canister must be completely filled with fuel elements or fuel dummies. Finally, the system is also sensitive to the set-up alignment between the transport tube for the Super Container, the deposition drift and the start tube for the deposition machine. A re-engineering of the alignment devices would have to be carried out for an industrial machine.

3.2 Conclusions Related to the Tests of the Air Cushion System for SF canisters (ANDRA)

The tests performed have shown that the emplacement equipment designed and fabricated within the scope of the ESDRED Project can be operated effectively for the transport and emplacement of spent fuel containers with a weight of 43 tons in mock-ups of horizontal disposal cells. Further tests will also need to be conducted in real underground conditions and over a longer period of time to assess the availability and the reliability of this equipment. It has also been observed that the air cushion technique used by ANDRA is sensitive to load variations. This means that the air cushions must be individually monitored and controlled. An air dessicator is required to prevent condensation of water contained in the compressed air. Finally, an efficient spooling system is considered necessary for a proper functioning of the air hose winch.

3.3 Conclusion Related to the Tests of the Air Cushion System for sets of Rings (ANDRA)

The conclusions drawn for the SF canister emplacement system are also valid for the machine developed for the emplacement of the set of bentonite rings.

4 - LIST OF REFERENCES

[1]: "Input Data and Functional Requirements" (Project Deliverable Module 3 WP1 D1).

[2]: "Report on Prototype Test for Spent Fuel Canister CU1" (Project Deliverable Module 3 WP2 D2).

[3]: "Detailed Design and Manufacturing of Equipment" (Project Deliverable Module 3 WP3 D3).

[4]: "Report on Emplacement / Transportation Tests" (Project Deliverable Module 3 WP4 D5).

ANNEX 1: LIST OF ORGANISATIONS & PEOPLE WHO PARTICIPATED IN ESDRED MODULE 3

The following organisations were engaged in the Research & Development work carried out within the frame of **ESDRED Project Module 3**:

- > ANDRA, France,
- > **Posiva**, Finland acting jointly with
- SKB, Sweden assisted by Vattenfall Power Consultant AB, Sweden. Furthermore, SKB acted as Module 3 Leader.

The main subcontractors involved in the design, manufacturing and testing of the concerned demonstrators were:

- > MECACHIMIE (France) & BERTIN (France) for the ANDRA related activities,
- > CNIM (France) & SOLVING (Finland) for the SKB / Posiva related activities.

The following persons participated in ESDRED Module 3:

Company	Name	First Name
ANDRA	BOSGIRAUD	Jean-Michel
ANDRA	GUENIN	Jean-Jacques
ANDRA	SEIDLER	Wolf
POSIVA	AIKAS	Timo
POSIVA	SALO	Jukka-Pekka
SKB	LINDGREN	Eric
SKB	PETTERSSON (Nota 1)	Stig
SKB	THURNER	Erik
Vattenfall Power Consultant AB	HALVARSSON	Во

Nota 1: Stig PETTERSSON also acted as Module 3 Leader Representative

ANNEX 2: LIST OF MODULE 3 DELIVERABLES COMPLETE WITH DISSEMINATION LEVEL

Reference	Title	Date	Dissemination Level
	WP1: Input Data and Functional Requ	irements	
Mod3-WP1-D1.1	"Input Data and Functional Requirements"	29/05/2007 (Rev.1)	PU
Mod3-WP1-D1.2	Tender document	05/10/2004	RE
	WP2: Prototype Test for Spent Fuel C	Canister	
Mod3-WP2-D2	"Report on Prototype test for Spent Fuel Canister CU1"	15/04/2005	СО
	WP3: Detailed Design & Manufacturing of Equipment		
Mod3-WP3-D3	"Detailed design and Manufacturing of Equipment"	31/01/2006	RE
Mod3-WP3-D4	"Commissioning Report"	12/01/2007	СО
	WP4: Full Scale Demonstration		
Mod3-WP4-D5	"Report on Emplacement/Transportation tests"	21/08/2007	PU
WP5: Evaluation & Final Report			
Mod3-WP5-D6	"Final Report & Evaluation"	Date of this Report	PU

Dissemination Level:

PU: Public

RE: Restricted

CO: Confidential

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

ANNEX 3: LIST OF ESDRED FINAL REPORTS

Dissemination Level:

PU: Public

RE: Restricted

CO: Confidential

ANNEX 4: LIST OF ACRONYMS

ABBREVIATION	MEANING
μSv	Micro-sievert
ALARA	As Low As Reasonably Achievable
ВН	Borehole
BSK 3	German thin walled fuel rod canister (Brennstabkokille 3)
BWR	Boiling Water Reactor
С	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
EIA	Environmental Impact Assessment
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
HRL	Hard Rock Laboratory
ICRP	International Commission of Radiation Protection
ID	Inside Diameter
ILW	Intermediate Level Waste (synonym for MLW)
IPC	Integrated Project Coordinator
KBS-3H	SKB/POSIVA Horizontal Disposal Concept (ESDRED Reference)
KBS-3V	SKB/POSIVA Vertical Disposal Concept (National Reference)
КТА	German Nuclear Safety Standards Commission

ABBREVIATION	MEANING
LILW	Low and Intermediate Level Waste
LL	Long Lived
LT	Long Term
LWR	German equivalent of PWR or Pressurized Water Reactor
MLW	Medium Level Waste
Mod1	Module 1
MPa	Mega Pascal
mSv	Milli-Sievert
N/A	Not Applicable
NPP	Nuclear Power Plant
O/N	ONDRAF/NIRAS
OD	Outside Diameter
OPC	Ordinary Portland Cement
рН	Unit of measure for acidity and alkalinity of a material
Pkg	Package
PWR	Pressurized Water Reactor
QA	Quality Assurance
QC	Quality Control
RB	Rock Bolt
Rc	Resistance to compression
RFP	Request for Proposal
SF	Spent Fuel
SL	Short Lived
Sv	Sievert
U/G	Underground
UCS	Unconfined Compressive Strength

ABBREVIATION	MEANING
URL	Underground Research Laboratory
UVP	German for "Environmental Impact Assessment"
Vw	Vitrified (High Level) Waste
VHLW	Vitrified High Level Waste
WPi	Work Package i

ANNEX 5: GLOSSARY

WORD	Per IAEA	DEFINITION
ALARA	yes	An optimization 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 radio nuclides 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 colored 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 clay stones and argillites. Clays differ greatly mineralogically and chemically but ordinarily their base is hydrous aluminum 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 over pack.

WORD	Per IAEA	DEFINITION
Criticality	Per US Nuclear Regulator y Commissi on	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.
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 over pack or the Primary Package without over pack.
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 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 Requirements		Generally refers to expected functions and associated levels of performance that must be met by one or several design elements. 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

WORD	Per IAEA	DEFINITION
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
Long Term		Generally intended to mean extending in time beyond the final closure of a repository
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 microfractures of the adjacent rock matrix and vice versa
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
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 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.

WORD	Per IAEA	DEFINITION
Salt		One of the 3 main host rocks being considered worldwide for the disposal of highly active waste materials.
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 process.
Shaft		A vertical access way, excavated in rock, 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.
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

WORD	Per IAEA	DEFINITION
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 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

