THE *OPHELIE* MOCK-UP EXPERIMENT FIRST STEP IN THE DEMONSTRATION OF THE FEASIBILITY OF HLW DISPOSAL

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ABSTRACT

In the late 1980s, Belgium developed a reference design for disposal of the vitrified high level waste forms. Disposal was to be carried out in galleries in a sedimentary clay formation, acting as the main barrier. Engineered barriers (overpack, gallery backfill) complemented the host rock by retarding the release of radionuclides. To demonstrate the feasibility of this design, the Belgian Waste Management Agency (NIRAS/ONDRAF) started a demonstration project to construct and operate a dummy disposal gallery similar to the real ones. Several technical aspects of this in-situ testing not being worked out yet in detail, NIRAS/ONDRAF decided to carry out first a large-scale surface mock-up test called OPHELIE. This test would allow the review of the chosen options for the backfill material, the disposal tube and the monitoring devices. The mock-up was constructed and put into operation in 1997 for some five years. The five years of hydration and heating of the backfill material have generated a large measurement database, as the set-up was heavily instrumented to monitor the main thermal, hydraulic and mechanical phenomena. In addition, a lot of unexpected observations have given more insight in physico-chemical phenomena (e.g. corrosion) that might take place in such an installation. The whole set-up was finally dismantled at the end of 2002.

The paper will mainly focus on the last stage of this experiment i.e. the dismantling phase. It will detail how the sample analysis programme has been elaborated in order to support both the preparation of the in-situ PRACLAY experiment and the current review of the disposal design. The dismantling of such large-scale experiment required a thorough preparation by a multidisciplinary team of scientists, engineers and technicians. Also the actual dismantling operations will be presented. Finally, this paper will discuss the lessons already learned, the first observations during the dismantling and the preliminary results during the operational phases of this experiment.

INTRODUCTION

Research on the disposal of high level radioactive waste (HLW) in Belgium is being performed since 1974 (1). It has been concentrated primarily on disposal in argillaceous formations, and more particularly on the Tertiary Boom Clay layer, a 100-m thick clay formation at a depth between 180 and 280 m present under the Mol/Dessel nuclear site. A milestone in this research has been the construction of the underground research facility HADES, which started in 1980. The first research results pointed to the overall importance of the clay formation as the main barrier to the release of radionuclides. A reference architecture for disposal of HLW in such formations, based on a 'multi-barrier' design, has then been developed in the late 1980s. The waste forms, 150-l cylindrical containers filled with the vitrified waste resulting from the reprocessing of spent fuel, are disposed off in a network of horizontal galleries. In these galleries, the vitrified waste forms are surrounded by several engineered barriers (overpack, backfill material) in order to delay the release of radionuclides into the host rock. This is especially important during the thermal phase estimated at some 500 years, during which the temperatures at the disposal site are significantly higher.

To demonstrate the feasibility of this design, the Belgian Waste Management Agency (NIRAS/ONDRAF) started the PRACLAY (Preliminary demonstration test for clay disposal of high-level radioactive waste) project in the late 1980s. For this purpose, it is planned to install and operate a dummy disposal gallery in the Boom clay similar, as far as possible, to the real ones. Several technical aspects of this in-situ testing not being worked out yet in detail, ONDRAF/NIRAS decided in the early 1990s to first design and construct a large-scale surface mock-up called OPHELIE (On-Surface Preliminary Heating simulation Experimenting Later Instruments and Equipment). The main objective was to review the chosen options for the design and in-situ testing of the disposal system such as the backfill material (specifications, manufacturing, installation, hydration), the disposal tube and the monitoring devices. The mock-up also allowed a large-scale investigation of the thermo-hydro-mechanical (THM) behaviour of the clay-based backfill material.

To realise the PRACLAY project, SCK•CEN and NIRAS/ONDRAF joined their efforts and created an Economic Interest Grouping (EIG, a special form of consortium under EU regulations) "EURIDICE" to handle the large investments, such as the extension of the underground research infrastructure by a second access shaft and connecting gallery (2). Also the management of the OPHELIE experimental mock-up is one of the main tasks of the EIG EURIDICE. The construction of the mock-up was evidently based on the reference design as it was in the mid nineties. The first results of the OPHELIE mock-up and the preparation of the Praclay in situ test as well as the preparation of the SAFIR II report (Safety Assessment and Feasibility Interim Report II) by NIRAS/ONDRAF lead to the decision by NIRAS/ONDRAF of the review of the reference design.

MOCK-UP EXPERIMENTAL DESIGN

We will give a short overview of the actual set-up; a more in-depth description has been published previously (3). The mock-up is basically a steel cylinder of 2 m diameter and 5 m long, simulating a section of gallery in which the waste will be disposed. The cylinder is equipped with a 0.5 m diameter central tube, in which heating elements – simulating the heat dissipation of the waste forms – are placed. The annular gap between the central tube and the outer lining is backfilled with pre-compacted blocs of clay-based material. A small concrete segmented ring has been installed to investigate the behaviour of concrete in this environment as the concrete segment lining of an actual waste gallery has been substituted by the steel liner to limit the size of the set-up. An external temperature control system has been added to the confining structure to apply the thermal boundary conditions. The mock-up is further instrumented with some 150 sensors to monitor the thermo-hydro-mechanical behaviour of the backfill material.

Figure 1 shows the mock-up structure, partially filled with the backfill blocks, during construction. The concrete segmented ring was installed in the final part of the mock-up and replaced the middle ring of backfill blocks; the inner ring was filled with sand, while the outer ring consisted of backfill blocks with an increased amount of bentonite clay.

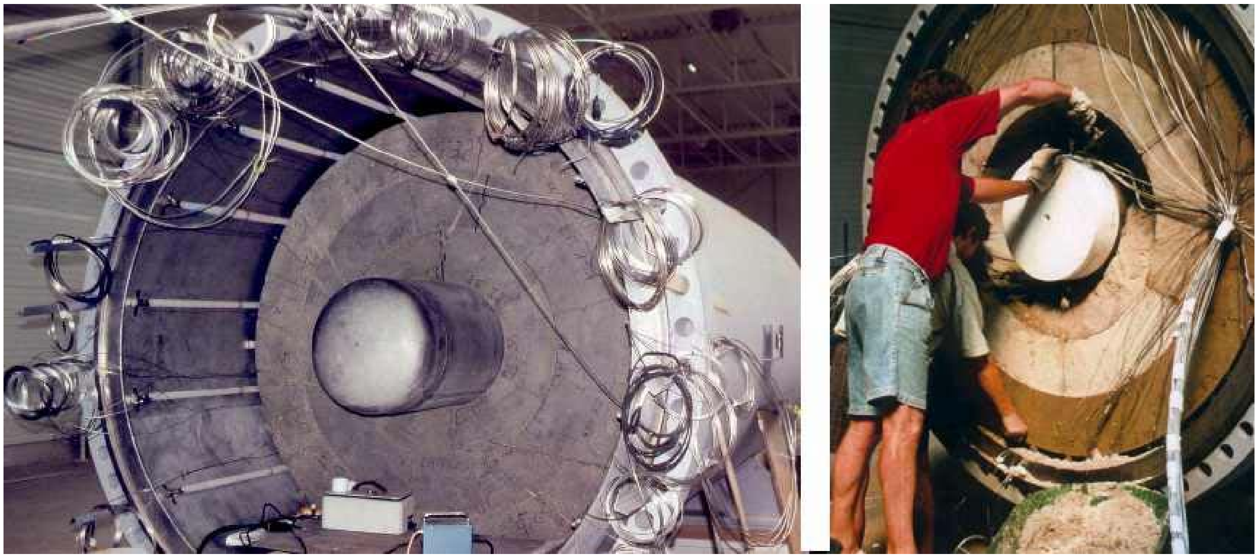

Fig. 1. View of the mock-up during construction; installation of concrete segmented ring and filling central void with sand (right)

Backfill material

The backfill blocks have been developed in cooperation with the French Atomic Energy Commission (CEA) taking into account design specifications dealing with swelling pressure, thermal conductivity and handling (4). The design resulted in a mixture of FoCa clay (a sedimentary swelling clay coming from the Paris Basin, France), sand and graphite. This mixture was compressed in moulds to obtain stable blocks that could be positioned manually. The complete set-up contained 36 sections of backfill blocks, each consisting of 3 rings (except for the 4 last sections due to the concrete segmented ring).

Heating and hydration

Hydration of the backfill blocks to a saturated state is essential to arrive at their sealing function. Swelling and the subsequent closure of the joints and voids is indeed essential to limit water circulation around the rock. In the host rock, hydration would occur in a natural way by the saturated clay environment (although very slowly). In the experimental mock-up, we simulated and accelerated this by 16 hydration tubes at the outside of the backfill block assembly. The water composition was based on the original water present in the Boom Clay.

The heating of the central tube was performed at constant power of 450 W/m. This rating is higher than the actual heat release by the waste forms. However, a higher power during a shorter time was also suggested for the in situ experiment to obtain thermal conditions that were representative for the actual disposal site over longer time spans.

Instrumentation

The internals of the mock-up were instrumented with some 150 sensors, mainly thermocouples to monitor the temperature field. The swelling pressure was monitored by strain gauges on the central tube and total pressure sensors in the backfill. Humidity sensors and water pressure sensors followed the hydration of the backfill material. The concrete segmented ring was also equipped with sensors to monitor pressure on, and loads between the segments.

MAIN TEST RESULTS

Hydration

After closure of the set-up, the water supply was connected on Dec 2, 1997. The void volume of some 1.55 m^3 was filled in a short time (some 20 minutes). Gradually we increased the pressure at which the water was supplied up to 1 MPa. The flow rate dropped also rather quickly during the next months. The last two years, the water in- and outflow seemed mainly to be related to temperature variations. During the cooling period, a important amount of water had to be injected again to compensate for the thermal contraction of the water.

Temperature

Six months after the hydration started, the internal heating elements were switched on. The thermal loading has been performed in four phases. After about two months of heating, a first maximum of temperature was reached, with a temperature at the central tube of about 105°C. In November 2000 the external heating was switched on to increase the overall temperature level in the backfill material. The temperature level was increased in three steps during the experiment. In June 2000, maximum temperatures were reached in the backfill (to be representative of the in-situ conditions) i.e. about 117°C on the outside of the backfill up to about 137°C near the central tube. This temperature profile was maintained until the end of the heating phase.
The temperature gradient observed indicated a high thermal conductivity (around 4 W/mK and higher), which is higher than can be expected for a porous material.

Physico-chemical observations

The measurement database generated by the mock-up experiment, as well as other events and observations have pointed the attention to some unexpected phenomena, such as the high apparent thermal conductivity of the backfill material and the low and decreasing swelling pressure exerted by the backfill material. Other important observations deal with the chemical state of the backfill material. Water samples, obtained through a leaky sensor cable, indicated an unexpectedly high content of solutes (such as Cl^-) close to the central tube, showing evidence for transport mechanisms that require further characterisation. The presence of sulphides could indicate sulphate reducing mechanisms in the backfill. The operational stages of the experiment have already highlighted the importance of the chemical behaviour of the backfill material in the experimental conditions (based on the design). Chemical phenomena occurring in the backfill material could have a detrimental effect on the mechanical behaviour of the backfill material itself but also on the integrity of the metallic barriers.

DISMANTLING

The heating of the mock-up was switched off at 27 August 2002; after a cooling period of one month, we started the dismantling. The dismantling of the experimental set-up and the sample analysis of the mock-up components should allow the better characterisation and understanding of the phenomena occurring during both the hydration and the thermal phase of the experiment, their causes and their consequences on the integrity, and performance of the barriers surrounding the waste canisters in the conditions of the current disposal design.

Objectives

A thorough characterisation and understanding of the phenomena occurred during the hydration and heating of the set-up was the main objective for the dismantling. The measurements and other observations during the experiment had pointed the attention to some unexpected phenomena, such as the high apparent thermal conductivity of the backfill, the low and decreasing swelling pressure, high salt (Cl) concentration in the backfill, and the corrosion of some sensors.

The dismantling should provide us with a unique "hands-on" experience by visualising the backfill and other materials after several years of hydration and heating. Together with the subsequent analyses of the samples obtained, it should help us to better understand the mock-up measurements on the evolution of the THM conditions. A possible heterogeneity in the backfill could be detected. A recalibration of the functional sensors, and the diagnosis of the broken sensors would further help us to improve the specifications for future long-term monitoring in disposal sites. Furthermore, chemical and microbiological processes occurring in the backfill material could also be characterised by dismantling and sampling the mock-up. The metallic confinement of the mock-up should give us also the opportunity to evaluate the corrosion susceptibility of various metallic components and their interference with the engineered barrier in HLW disposal conditions.

The modelling of the backfill behaviour will benefit from the characterisation of the material exposed to the experimental conditions. Parameters could be adjusted, and the numerical models could be further validated.

The dismantling should further deliver additional data for the optimisation of the experimental set-up of the in-situ PRACLAY test from both a scientific point of view (e.g. which processes should be monitored), as well as from a technical point of view (e.g. which sensors will give the most reliable measurement results.). It would also provide valuable input data for the current review of the design of HLW disposal architecture.

Methodology

The dismantling programme has been based on key phenomena that were defined by a multidisciplinary team of scientists and engineers. These phenomena were:

- hydration process of the backfill material;
- thermal transfer in the backfill (to explain the high apparent thermal conductivity);
- geochemical and microbiological processes linked with corrosion;

- hydro-mechanical properties of the backfill material;
- performance of the sensing equipment.

For each phenomenon, we defined tests and analyses to be performed on samples. This was then complemented by a sampling plan, where we defined the exact location of the samples to be taken.

For each type of sample, a sample procedure specified the sampling process, such as sampling tools and packaging. A sample track record assured a correct follow-up of each sample by recording all relevant data of the sample (operator, sampling time, exact location, conditions, packaging,...).

A simple example is the hydration process, which could be investigated by measuring the saturation degree of the backfill and its homogeneity. The test consisted then in the determination of the spatial distribution of the density and water content in the backfill. The corresponding sampling plan is shown in Figure 2 and resulted in a number of 116 samples to be taken. The test procedure further described the determination of dry density (pycnometer or weighing in paraffin oil) and water content (gravimetric, loss of weight at 105 °C).

A similar methodology was applied for other aspects of the backfill material: mineralogical and physicochemical investigations, porewater chemistry analyses, hydro-mechanical properties, thermal properties, and microbiological analyses in the backfill. The hydro-mechanical properties dealt with several parameters, which were defined by the modellers to describe more accurately the behaviour of the backfill material in unsaturated conditions at elevated temperatures. The tests included permeability, swelling, retention, and oedometric and triaxial tests

Apart from the backfill samples, also samples from the concrete segmented ring and from the steel structure were specified to study the interaction of the structural materials with the backfill. Finally, also many sensors were to be retrieved recalibration or diagnostic (for non-functioning sensors) purposes.

All sampling operations were summarised in a sampling book, to which the dismantling team had to adhere strictly during their operations. However, the sampling book was flexible enough to cope with unexpected or unknown conditions, requiring e.g. extra samples to be taken or to take them at a different location.

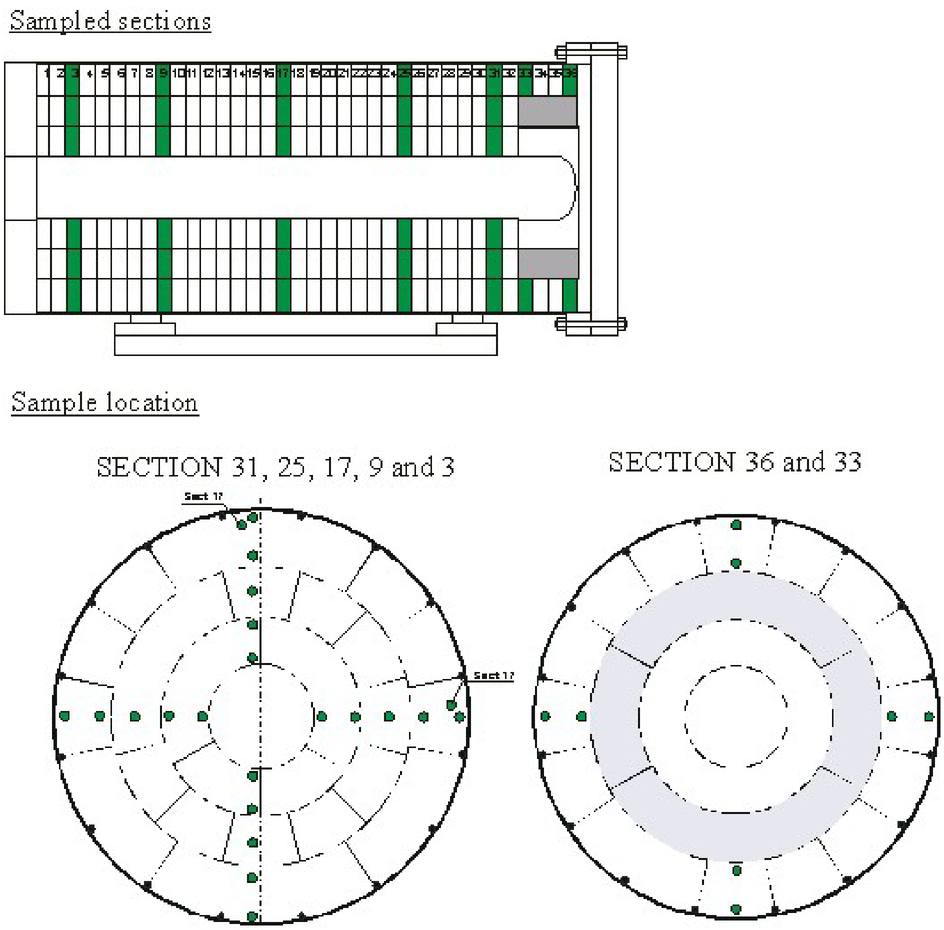

Fig. 2. Location of the samples taken to determine the density and water content distribution

Dismantling operations

Before the actual dismantling, the set-up was cooled down by switching off the heating elements and removing the thermal isolation. This required also a large amount of water to be injected (some 70 litres) to keep the water supply at a pressure of 1 MPa. Care was taken to supply de-aired water, in order not to change the prevailing anaerobic conditions inside the mock-up.

The mock-up had cooled down to ambient temperatures after some two weeks (versus a conservative estimation of four weeks). A fast cooling sequence was preferred over a gradual temperature decrease in order to "freeze" the situation present just before cooling down.

The dismantling was further preceded by a cored sampling (in radial direction) of the backfill through the 55 mm thick steel outer lining. This was our first contact with the backfill material. After removing the steel liner core, we observed some immediate swelling of the backfill material, and we could verify that this backfill had completely filled all the voids present at the installation time. The original objective of coring the whole backfill profile, up to the central tube, could, despite four trials, not be obtained as the backfill had kept its original stiffness towards the centre.

The actual dismantling started on October 2, 2002, by removing the large cover. From then on, dismantling and sampling progressed continuously during 10 days and nights in two shifts.

Results

We will concentrate here on the observation made during the dismantling, as at the time of writing (February 2002) few results are available on the analysis of the samples.

Figure 3 shows that the backfill blocks had expanded to close the voids. This expansion had taken place mainly in the outer ring, which has also verified by measuring the geometry of the blocks. The beige colour at these places confirmed that swelling of the clay platelets. A good contact between the backfill and the steel surfaces (the central tube and outer lining) was also experienced. The joints between the blocks were still well visible, but there was a strong mechanical bond, with only a slight preferential behaviour along these joints. The hydraulic behaviour of these joints still has to be assessed. Overall, one can state that the backfill blocks behaved as expected, but the saturation seems to be a very slow process. The hydration state, showing swelling that mainly occurred at the outside, is also visualised by the measurements of the water content, dry density and saturation degree as shown in the figure 4.

Fig. 3. Swelling of the backfill blocks (left, line) mainly occurred near the hydration tubes; the joints between the blocks, and even the identification marks were still well visible. The sections separated quite easily during the dismantling works (right).

The corrosion inside the mock-up was limited to a few very specific cases. All steel parts in contact with the backfill were made from stainless steel (AISI 304L or equivalent). One hydration tube showed a green-blue colour (spreading up to a few cm in the backfill), which is most probably related to the corrosion of a humidity sensor. SEM-EDS analysis indicated a presence of Cr-salts. On some other hydration tubes, a grey coating was observed, which might be due to pyrite recrystallisation. All sensors of this type were severely damaged by galvanic corrosion (copper – stainless steel), and the power supply of these sensors probably made this corrosion even worse. Also some corrosion was visible on the central tube where it was in contact with the sand. In general, the sand had allowed some circulation of the water, which proved to be detrimental. Avoiding any significant water flow is essential to obtain stable chemical conditions.

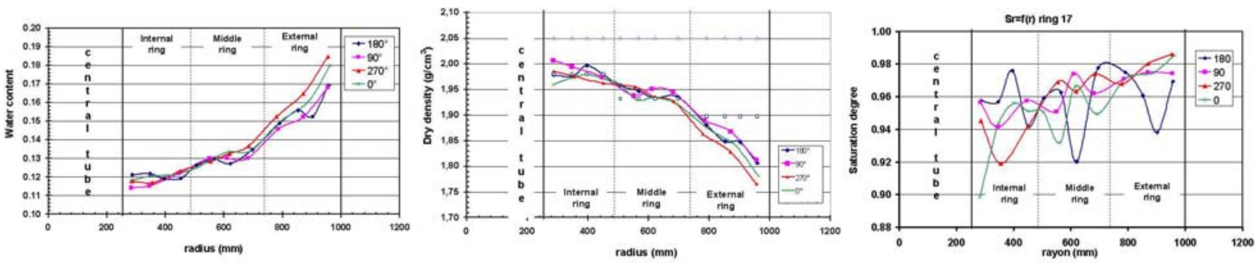

Fig. 4. The water content, dry density and saturation degree show that swelling occurred mainly at the outside

A lot of useful feedback came from the sensors. Some types, such as thermocouples and piezometers, were well designed for their task. Other sensor types suffered from corrosion. A particular example are the internal strain gauges, where we had selected a hermetically sealed type, specially designed for underwater applications, had been selected. It turned out that the solder used at the connection between the sensor had completely disappeared. Other sensors seemed not to comply with their temperature specifications.

Microbiological analyses are also still going on. The main activity seemed to be related to the hydration circuit, where the water temperature ranged from above 100 °C to ambient temperature. With the circulation in some tubes due to thermo-convection, it is not surprising that high concentrations of different species were detected. We were interested in sulfato-reducing bacteria, thio-sulfato-reducing bacteria and methane forming bacteria, and all were detected in high numbers (> 140 000 / ml). The results in the backfill are less clear. In principle, bacteria can hardly survive at high temperatures and with possibility to move (small pore size), but the possible contamination by the injection of hydration water during the cooling phase troubles the current interpretation.

CONCLUSION

The dismantling of the mock-up has provided us with essential information on the behaviour of an engineered barrier system. The mock-up test has largely met its main objective – preparing the in situ test – by providing us with many experiences, both scientifically and technically.

The structured approach of the dismantling has resulted in an efficient operation, in which a maximal amount of information has been gathered in a short time span.

The scientific results and their discussion have spurred the re-evaluation of the current disposal design, and to propose some alternative designs that are currently being assessed.

At the more technical side, the mock-up and its dismantling have provided us with very valuable experience on the long-term behaviour of sensors. Apart from its evident use for the demonstration tests, such knowledge will be indispensable when discussing the operational or post-closure monitoring at disposal sites.

ACKNOWLEDGEMENTS

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REFERENCES

(1) B. NEERDAEL, P. VAN ISEGHEM, J. MARIVOET, P. DE CANNIERE, "Progress and Trends in the Belgian Programme on HLW Disposal," WM'00, Tucson (AZ), 2000.

(2) W. BASTIAENS, M. DEMARCHE, "The extension of the URF HADES: Realization and observations," WM'03, Tucson (AZ), 2003.

(3) J. VERSTRICHT, D. DE BRUYN, B. DEREEPER, "Mock-up Simulation for the Demonstration of the Belgian High-Level Radioactive Waste Disposal Concept," ICEM'01, Brugge, 30 Sept – 4 Oct 2001, Belgium.

(4) J. VERSTRICHT, M. DEMARCHE, C. GATABIN, "Development of a backfill material within the Belgian concept for geological disposal of high-level radioactive waste: an example of successful international co-operation," WM'01, Tucson (AZ), 2001.