

DEVELOPMENT OF A BACKFILL MATERIAL WITHIN THE BELGIAN CONCEPT FOR GEOLOGICAL DISPOSAL OF HIGH-LEVEL RADIOACTIVE WASTE: AN EXAMPLE OF SUCCESSFUL INTERNATIONAL CO-OPERATION

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ABSTRACT

The development of concepts for radioactive waste disposal is narrowly linked to the national context. However, due to the very specialised as well as the multidisciplinary nature of R&D related to repository development, international co-operation has proved to be essential. In this paper, we describe the international experiences and perspectives of the Economic Interest Grouping EURIDICE (EIG EURIDICE, formerly known as EIG PRACLAY), a joint venture between the Belgian Nuclear Research Centre SCK•CEN and the Belgian Radioactive Waste Management Agency NIRAS/ONDRAF. The mission of EIG EURIDICE consists in demonstrating the current concept for geological disposal of High-Level radioactive Waste in Belgium. EIG EURIDICE also manages the underground facilities (constructed by SCK•CEN in the eighties) and is currently extending these to allow for large-scale demonstration. This demonstration experiment requires many scientific and technical skills, and therefore EIG EURIDICE is also working with external partners. A successful example of such co-operation is the development of materials for backfilling the disposal galleries. For several years, EIG EURIDICE has closely collaborated on this subject with the Waste Storage and Disposal service (SESD) of the French Atomic Energy Organisation (CEA). Starting from a well defined list of specifications on the desired thermal, hydraulic and mechanical characteristics, several candidate backfill materials have been developed, tested and manufactured, both on a laboratory and on an industrial scale. Two main types have been developed and tested at large scale: precompacted blocks and high-density pellets (mixed with powder). The precompacted blocks have been developed to fill up the space between a central disposal tube (containing the waste forms) and the lining of the disposal galleries (horizontal configuration), and are currently tested in a surface mock-up. The pellets-powder mixtures are intended for the backfilling and sealing of a shaft and are presently being tested in vertical boreholes and shafts. Current investigations do not only deal with the behaviour (thermal, hydraulic, mechanical, chemical) of the materials at real scale, but also with their application (mechanised installation techniques), and the development of appropriate techniques for the measurement of for example the swelling pressure, and the evolution of hydration. The large expertise built up by CEA through the years proves to be very useful in the current design works of a HLW disposal site. The current large-scale tests on the other hand give very interesting feedback on the performance of the engineered materials. Other joint international research programmes have allowed external organisations to use these facilities, which has proven advantageous to both the owner as the visiting organisation. The international co-operation allows EIG EURIDICE to better assess its different scientific and technical approaches related to the radwaste disposal research; the co-operating organisations profit from the readily available infrastructure with scientific and technical resources for a successful experimental set-up. They range from mechanical workshops, drilling equipment, numerical modelling tools for geomechanical and geochemical processes, in situ instrumentation, up to the management and interpretation of the measurement data. To obtain an optimal scientific valorisation of the opportunities created by the extension of the current underground facilities, EIG EURIDICE promotes a policy of active participation by external organisations. This approach will lead to perspectives for EIG EURIDICE (get in touch with organisations which may develop specific parts of the current concept), and to opportunities for prospective partner organisations (use of the infrastructure and know how in various domains).

INTRODUCTION

The development of concepts for the geological disposal of radioactive waste is narrowly linked to the national context. The sensitive nature of all nuclear related issues from a socio-political point of view, has resulted in quite a number of different national approaches. In Belgium for instance, more than half of the annual electric power consumption is supplied by nuclear power plants, while some neighbouring countries are less dependent on nuclear power production for electricity supply. In addition, the geological diversity has led to a lot of different concepts that have been proposed or are being developed on an international scale. The Belgian approach has always been focused on disposal in argillaceous host rock, as these are the only suitable geological formations available. Other countries consider salt deposits, hard rock (granite) formations or other host rocks as environment for the waste.

Within the current Belgian disposal concept, High-Level radioactive Waste (HLW) will be disposed off in horizontal galleries that will be excavated in the Boom Clay Formation (Figure 1). The HLW results from the reprocessing of the fuel elements; fission products are vitrified and packaged in cylindrical, stainless steel waste containers. These containers are, with a protective overpack, placed inside a stainless steel disposal tube. The remaining space between the concrete gallery lining and the disposal tube is then backfilled. The current nuclear programme in Belgium will require a surface of 1 km² to dispose off the HLW containers. The extent of this surface is explained partially by the thermal load, as a part of the HLW containers is heat-generating. Actual thermal criteria involve a maximum thermal power of 100 kW/ha, and a maximum temperature of 100 °C at the outer surface of the disposal tube.

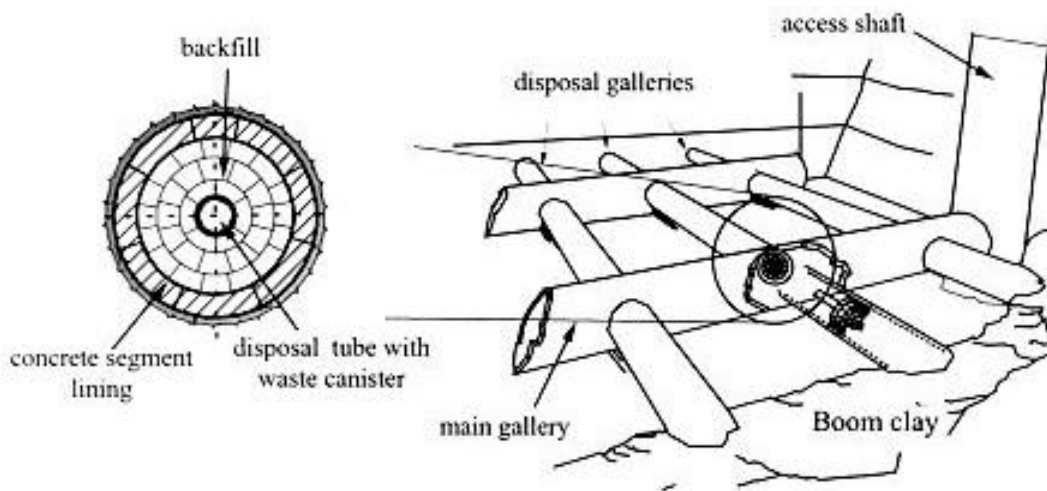


Fig. 1: The Belgian concept for the geological disposal of HLW in a clay formation. The figure shows the main and disposal galleries, which are located in a clay formation, as well as a cross-section of a disposal gallery

The implementation of a disposal concept is a lengthy activity that will span, in the Belgian context, several decades. The demonstration of the concept is an essential factor in the implementation process. For this objective, involving large investments, a dedicated joint venture between the Belgian Nuclear Research Centre SCK•CEN and the Belgian Waste Management Agency NIRAS/ONDRAF was established in 1995 under the name EIG (Economic Interest Grouping) PRACLAY. At the end of 2000, the name of the joint venture has been modified in "EURIDICE".

R&D on radwaste disposal is characterised by its very specialised nature on one hand, and by its multidisciplinary nature on the other hand. The problems encountered in radwaste disposal have sparked research on unexplored and very diverse domains such as tunnelling in deep clays with minimal damage to the surrounding formation, or on the societal perception of the long-term consequences related to radwaste disposal.

Within these constraints, international co-operation to join efforts has been present from the early beginning for scientific and economical reasons. In Europe, organisations such as EURATOM have played a major role in establishing networks and promoting joint research and development. Complementary to these actions, bilateral agreements have been set up to work on specific items. The lack of standard test procedures has also been a driving force for international co-operation in many research areas. As in other fields where pioneering research is performed, interlaboratory comparisons help to guarantee a minimum level of quality assurance. The large investments required for research in underground research facilities also call for a joint use of these facilities to optimise the return on investment. This paper outlines the context and give some successful examples of such co-operation from the Belgian point of view.

THE BELGIAN DEMONSTRATION PROGRAMME FOR HLW DISPOSAL

SCK•CEN initiated R&D work on HLW disposal in the late seventies. Given the geological context in Belgium, it became soon evident that a sedimentary clay formation would be the best (and only) option for further investigations. After preparatory desk studies and field tests in clay outcrops and quarries, SCK•CEN started in 1980 the construction of the underground laboratory "HADES" in the Boom Clay Formation, a tertiary (Oligocene) Clay Formation with a thickness of 100 metres at the Mol site and starting at a depth of some 180 metres. The construction works have provided a wealth of experiences and have proven to be essential to obtain a good picture of the geotechnical behaviour of the clay (1).

The geological environment, with aquifers covering the Boom Clay Formation, necessitated the use of the freezing technique for shaft excavation. This freezing technique was also applied for the first gallery excavations in clay. The actual construction experience in a non-frozen part of the clay indicated however that freezing was not required. In addition, it was found that the geotechnical characteristics of the clay even became less favourable through freezing. Because of the practical underground access and space restrictions, excavation had to be performed exclusively by hand. This however limited excavation speed and therefore increased the damage to the surrounding clay.

In addition to the geotechnical aspects, in situ experiments within the Boom Clay Formation have proven to be extremely useful for the upscaling of experimental work performed at surface laboratories, especially for experiments studying geochemical (2) and corrosion behaviour (3) in the Boom Clay formation. The experimental set-ups require a lot of boreholes, and specific drilling techniques had to be adopted. An all-air solution had to be used instead of conventional techniques based on drilling fluids, which cannot be used in these clays at the depths considered. These developments have also been applied to in situ investigation techniques, such as pressuremeter tests. Furthermore, specific instrumentation techniques were developed, of which the patented, versatile piezometer system is one of the best examples.

The next step, from in situ investigations to concept demonstration at real scale, required the development of several scientific and technical aspects, which were not yet investigated in detail. One example is the modelling of the thermo-hydro-mechanical behaviour of partially saturated clay media. Another example, which we will describe further in this paper, is the development and realisation of the backfill material.

JOINT DEVELOPMENT OF BACKFILL MATERIAL

Most concepts for disposal of HLW waste (or spent fuel) include some form of backfilling around the waste containers. The specifications for this material are dependent on the repository concept and usually deal both with operational issues, short-term and long-term characteristics and performance. Operational aspects include the manufacturing, handling and installation; a good example is the mechanical strength when dealing with clay-based blocks, as these have to remain intact from the manufacturing up to the on-site installation. Short-term issues usually deal with the initial thermal, hydraulic and mechanical behaviour of the material, such as the ability to fill all voids by swelling (through hydration of smectite clays), and the speed and homogeneity of hydration. The behaviour at longer term may include the maintaining of low permeability or the retardation of radionuclides, which is usually required with a granitic host rock.

Within the Belgian repository concept, backfill materials are applied to obtain an environment with low permeability and high thermal conductivity in the near-field of the canisters and the central tube of the disposal gallery. The principal specifications for a backfill material were related to mainly thermal, hydraulic and mechanical properties. The thermal loading (due to the heat dissipation of the waste canisters) can be dealt with by providing a material with a high thermal conductivity. Of course, the overall temperature in the clay formation will not be influenced as the source term (heat generation) is not modified, but local gradients, and hence the maximal temperature (which is in the waste canisters) can be limited. The hydraulic condition consists primarily of a low permeability to limit water flow near the central tube and as such to prevent the formation of hydraulic short circuits in the disposal system. At present, no reliable data are available on the time needed to obtain full saturation of the initially partly saturated material. The concept allows for a separate hydration and heating of the material, as the waste canisters will only be installed a certain time after emplacement of the backfill. Mechanically, the backfill should provide a smooth pressure on the central tube, to prevent local stress gradients, while its swelling pressure must not be larger than the in situ effective stress (2.5 MPa).

The horizontal nature of the concept has led to a backfill in the form of precompacted backfill blocks that can be installed on the spot. The blocks should therefore be convenient to handle (at the initial phase manually, so limited in weight), robust and with precise dimensions to obtain a backfill structure with a homogeneous density (voids between blocks, and between central tube and blocks to be minimised).

An essential aspect throughout the test programme deals with the instrumentation to monitor the evolution of the properties of the backfill material. The environmental conditions ask for specifically developed or adapted sensors to measure the relevant hydraulic and mechanical parameters, such as moisture content, swelling pressure, and deformation of structural components, in a reliable way for several years.

For several years, the Waste Storage and Disposal Service SESD (Service d'études d'Entreposage et de Stockage des Déchets) of the French Atomic Energy Organisation CEA (Commissariat à l'Energie Atomique) is carrying out research activities around nuclear waste disposal, in support of partners like the French Nuclear Waste Agency ANDRA (Agence Nationale de Déchets Radio-actifs) and the French Electric Power Company EDF (Electricité de France). One of the missions assigned to CEA/SESD has consisted of the study of engineered barriers for the filling and sealing of voids between nuclear waste canisters and host rock, according to the first French concept. A large research programme, based on the performance of swelling French bentonite "FoCa" has been developed in nineties. Through its multidisciplinary team of engineers and technicians, CEA/SESD could assume all the studies needed by ANDRA's concept. These investigations include both basic and applied studies.

This expertise has been valorised in several EC programmes, in collaboration with the Belgian nuclear research actors SCK•CEN and NIRAS/ONDRAF. Upon the start of the Belgian demonstration programme "PRACLAY" in 1995, CEA/SESD has been assigned to study and deliver the buffer material, according to the PRACLAY specifications. To obtain the optimal backfill, an extensive laboratory test programme (Figure 2) has been performed at CEA facilities. The investigations dealt with topics such as thermal conductivity, swelling pressure, and hydraulic permeability measurements. In this way, a mixture of clay, sand and graphite has been developed, with the graphite enhancing the thermal conductivity, and the sand the mechanical properties. The lab tests resulted in a first modelling of the behaviour of this mixture in terms of thermo-hydro-mechanical characteristics. Several processes, such as blending and compression, were further optimised in the industrial manufacturing process with success. Preliminary tests checked the design of the engineered barrier.

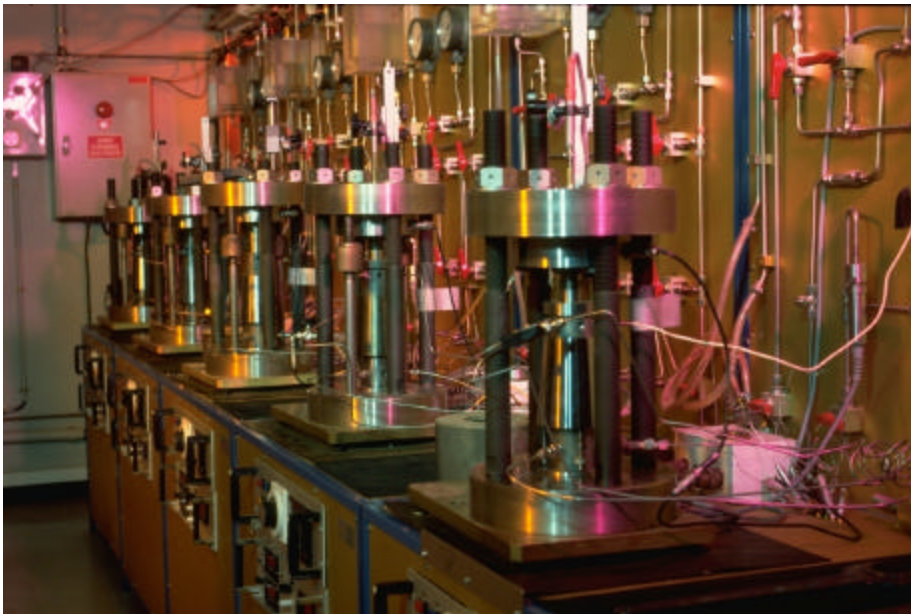


Fig. 2: Laboratory test programme at CEA facilities, showing cells to investigate the swelling pressure during hydration of FoCa clay

Another aspect of the collaboration has consisted in a development of specific instrumentation for positioning in the backfill and monitoring physical parameters such as temperature field, swelling pressure, or pore pressure. SCK•CEN and CEA/SESD have narrowly contributed to the definition of sensors and the realisation of the mock-up instrumentation.

Before the application of the backfill material developed at the in situ demonstration test, a large-scale mock-up test has been constructed at the surface (4), as shown in Figure 3. This test set-up, completed at the end of 1997, has allowed us to apply the backfill blocks according to the design. The construction of the block-based backfill barrier concluded a first phase of developments, up to the application at real scale. The blocks were produced on industrial scale, and had an outstanding mechanical and dimensional stability, allowing transport, storage, handling and installation without significant problems. The dimensional stability (tolerance in the order of 1 mm) allowed for an assembly in absence of unwanted internal voids.

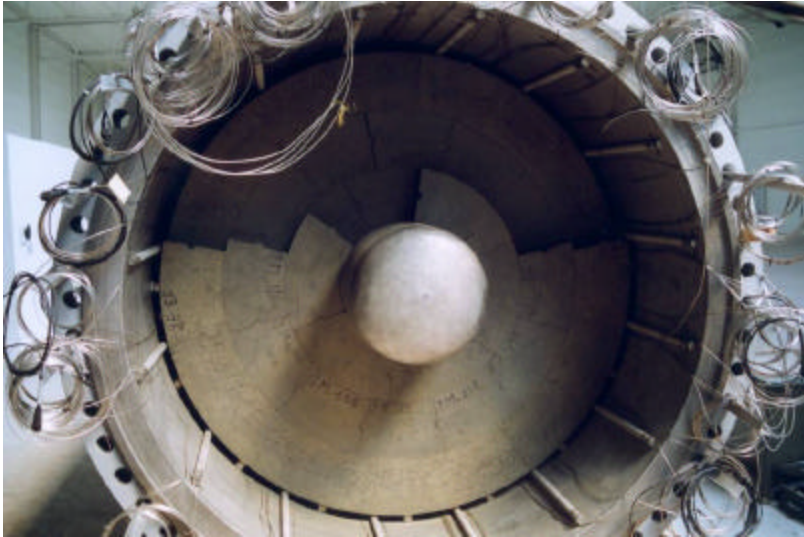


Fig. 3: Large-scale mock-up during construction

The other issues dealt primarily with the thermal, hydraulic and mechanical behaviour of the constructed barrier. Upon completion and sealing of the mock-up, water was applied in a continuous way. The hydration process consists of a time-related (how long does it take before complete saturation of the backfill will occur?) and space-related (are there deviations from the theoretical axisymmetric saturation front?) component. The swelling interacts closely with the hydration process and therefore also the hydraulic conductivity and swelling pressure will depend closely on this process. A very important aspect of this set-up is also the test of several sensors, as we look for the optimal sensors to monitor the backfill conditions. Sensors have been installed for monitoring moisture content (through relative humidity in the pores by capacitive sensing), total pressure (miniature pressure cells with modified pressure transfer body), porewater pressure (vibrating wire), deformation (strain gauges), temperature (thermocouples), and a number of other parameters. Specific modifications included the sensing part, high-temperature signal cables, and cable feed-through.

The actual mock-up results show a rather rapid saturation; based on the water uptake, we conclude that a complete saturation occurs within two years. The swelling pressure remains rather limited. Some heterogeneity has been observed and is, most probably, due to the varying void volume near the end zone where a concrete segment ring has been installed. The hydraulic conductivity has evolved to a rather low value, based on direct (pressure pulse measurements) and indirect observations, such as thermally induced pressure variations. Mid-1998, when the hydration had been applied for six months, we also applied the thermal load

(450 W/m), for a planned period of three years. According to the present planning, the heating will be switched off by mid-2001. Apart from the influence on the hydraulic behaviour (expansion of water during thermal transients), we also noticed a very high thermal conductivity (4 W/m.K); this needs further investigation as such a high value is difficult to explain for a porous material.

A phenomenon, that has proven to be very relevant, is the geochemical behaviour of the backfill barrier. The interest was raised by the first observations of (unexpected) corrosion of the internal strain gauges. Water samples indicated an elevated salt concentration – chloride concentrations of more than 1000 ppm have been observed. The combined effect of hydration and heating, creating both a hydraulic and thermal gradient, on the physico-chemical processes in the backfill are now included in the modelling of these materials. Also the interaction with the other barrier materials (steel overpack and central tube, and concrete gallery lining) is now closely involved in this modelling exercise.

It is planned to dismantle the mock-up by mid-2001, and this will enable us to verify the many hypotheses that are currently considered to explain the backfill behaviour. Apart from the observations and analyses on the backfill material itself, it will allow us to check the reliability of the other technical components.

We expect that observations during the dismantling will give us a better picture of the hydration process and the resulting hydro-mechanical characteristics of the backfill material when it has been subjected to hydration and heating. Sampling of the backfill material will allow for comparative analyses with the original material. The results will then indicate if the backfill material is suitable for the in situ test.

The condition of the steel and concrete parts will give further information on their behaviour and suitability in the backfill environment. Recalibration of the functioning measuring instruments, and diagnosis of the failed ones, will be essential to guarantee a reliable monitoring.

OTHER INTERNATIONAL CO-OPERATIONS IN HLW R&D

Almost simultaneously with the dismantling of our mock-up, a similar set-up will be partially dismantled at the Grimsel Test Site (Switzerland). It is a part of the Spanish demonstration programme "FEBEX" (5). The Spanish concept for geological disposal of spent fuel is also based on an in-gallery design, where the waste (spent fuel) is surrounded by clay blocks (based on Spanish Serrata clay). This gives us a unique opportunity to compare test procedures (e.g. sampling and analysis methods), backfill performance and concept implementation; therefore EIG EURIDICE participates actively in the second phase of the FEBEX programme.

Complementary to the research programme on the engineered barriers, there is currently an increased interest in deep excavation and tunnelling techniques in clay host rocks, due to the renewed interest in clay formations as potential host rocks for the disposal of HLW. The construction of the underground disposal infrastructure should be economical, safe in operation, and have a minimal influence on the host rock properties. Indeed, with the host rock being identified as main barrier in the safety assessment, its properties should not be altered in a significant way. Modelling tools to assist in predicting the possible influence of the excavation should therefore be validated through experimental data. The excavation of the

connecting gallery, planned for begin 2001, is therefore the subject of extensive theoretical and experimental studies (6). The added value of performing this in an international context allows for comparing different approaches, with distinctive models and parameter sets.

This research approach, together with a smaller programme around the excavation of the second shaft has further resulted in a collaboration with the French agency ANDRA, which is currently sinking a shaft near Bure (France) to get access to a selected clay formation (7). A joint monitoring and modelling programme is being developed to assess the influence of the works on the local clay formation.

In addition to common research programmes, networking is also actively pursued. This is very valuable to exchange ideas on basic decisions to be taken (e.g. role of monitoring in future disposal sites) or to share experiences on more practical issues such as test procedures and instrumentation to be applied at in situ experiments.

The (growing) interest in the suitability of clay formations for HLW disposal in several countries has also led to efforts for a generic and standardised description of clay properties. For some five years, an important test programme is currently being carried in the Mont Terri site in Switzerland (8), where the experience with experimental set-ups in HADES has proven very useful in the application of novel measurement techniques (e.g. piezometer in stiff clays).

CONCLUSION AND FUTURE PERSPECTIVES

EIG EURIDICE expects that the opportunities offered by the extension of the underground laboratory will not only be of interest to the national organisations, but that an intense international research network will be advantageous for all parties involved. By sharing the large, unique infrastructures in the different countries, we not only give and obtain access to different geological structures; also the exchange of know-how with respect to theoretical and experimental methodologies (modelling, measurement techniques, test results...) is of great importance. This makes international co-operation further essential when we want to run this kind of research in a cost-effective way.

Joint research and other networking activities also generate a large scientific added value. It allows for a specialisation of the research tasks. Benchmarking numerical models, comparing different geological media by characterising them through uniform test procedures and instruments, and investigating smectitic clay types (FoCa, Serrata, MX-80) in different labs, will allow to improve the confidence into the results obtained. This confidence in science is essential when proposing concepts and sites, and applying for operational licences. We may further expect that, once licenses for HLW disposal will be issued, internationally accepted standards will be needed.

Without doubt, the scientific confidence influences the societal perception of the HLW disposal issue; also media coverage of international co-operation generally has a positive influence, and allows for a more open atmosphere for discussion and debating of these issues by adding the global dimension.

An important field, where joint research will prove essential, is the co-operation with the Central European states and the NIS (New Independent States of the former Soviet Union). Several international organisations (European Commission, NATO) are promoting this

through dedicated programmes. Specific bilateral agreements have further resulted in training programmes for researchers, specific consulting tasks etc.

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