LOW LEVEL WASTE CONCEPTUAL DESIGN ADAPTATION TO POOR GEOLOGICAL CONDITIONS

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ABSTRACT

Since the early eighties, several studies have been carried out in Belgium with respect to a repository for the final disposal of low-level radioactive waste (LLW).

In 1998, the Belgian Government decided to restrict future investigations to the four existing nuclear sites in Belgium or sites that might show interest.

So far, only two existing nuclear sites have been thoroughly investigated from a geological and hydrogeological point of view. These sites are located in the North-East (Mol-Dessel) and in the mid part (Fleurus-Farciennes) of the country.

Both sites have the disadvantage of presenting poor geological and hydrogeological conditions, which are rather unfavourable to accommodate a surface disposal facility for LLW.

The underground of the Mol-Dessel site consists of neogene sand layers of about 180 m thick which cover a 100 meters thick clay layer. These neogene sands contain, at 20 m depth, a thin clayey layer. The groundwater level is quite close to the surface (0-2m) and finally, the topography is almost totally flat.

The upper layer of the Fleurus-Farciennes site consists of 10 m silt with poor geomechanical characteristics, overlying sands (only a few meters thick) and Westphalian shales between 15 and 20 m depth. The Westphalian shales are tectonized and strongly weathered.

In the past, coal seams were mined out. This activity induced locally important surface subsidence.

For both nuclear sites that were investigated, a conceptual design was made that could allow any unfavourable geological or hydrogeological conditions of the site to be overcome.

In Fleurus-Farciennes, for instance, the proposed conceptual design of the repository is quite original. It is composed of a shallow, buried concrete cylinder, surrounded by an accessible concrete ring, which allows permanent inspection and control during the whole lifetime of the repository. Stability and drainage systems should be independent of potential differential settlements and subsidences. Potential radionuclides releases are controlled and have a single discharge point to the biosphere.

INTRODUCTION

Nuclear and non-nuclear industrial activities in Belgium give rise to the production of low level radioactive waste (LLW). According to the most recent estimations, Belgium will have to dispose of a total amount of about 60,000 m^3 LLW, mostly coming from the operation of nuclear power plants, from decommissioning of nuclear facilities and from medical industry.

At the end of 2001 about 11,500 m^3 LLW was temporarily stored in surface facilities on the Belgoprocess site in Mol/Dessel. So far, no repositories providing a final solution for the LLW have been constructed in Belgium.
Many investigation programs have however been carried out by the Belgian Agency for radioactive Waste and fissile materials (ONDRAF/NIRAS) and by its partners and subcontractors since the London convention moratorium on sea dumping of LLW in 1983.

The current study programme for LLW disposal is based on a decision taken by the Government in 1998. This decision stated that the disposal solution for LLW should be reversible (ability to retrieve the waste), progressive, flexible and definitive (long term storage being no longer an option). Furthermore, only the existing nuclear sites and other sites showing an interest should be considered. Finally, public acceptance should be taken into account and involvement of local representatives should be implemented in the working programme.

So far two sites have been thoroughly investigated from a geological and hydrogeological point of view. These sites are located in the North-East (Mol/Dessel) and the mid part (Fleurus-Farciennes) of the country. The two other nuclear sites are located at the nuclear power plants of Doel and Tihange. Until now, the local authorities at the latter sites have not shown any interest in carrying out preliminary investigations on their territory.

As both sites (Mol-Dessel and Fleurus-Farciennes) show rather poor geological and hydrogeological conditions, the safety of a surface disposal facility for LLW could be jeopardized in the absence of special conceptual adaptations.

In this paper we will describe these unfavourable geological and hydrogeological conditions for both sites and we will point out how the conceptual design was adapted in order to maintain a high level of safety of the repository. The designs that are described in this paper are generic, meaning that they can also apply, in general, to sites that represent similar (hydro-)geological conditions. More thorough studies, in collaboration with local representatives, are in progress in Belgium in order to transform these generic concepts into concepts adapted to a particular chosen location.

HYDROGEOLOGY AND GEOLOGY OF THE MOL/DESSEL SITE

Nuclear activities have been carried out for several decades on the Mol/Dessel site. Belgoprocess, daughter company of NIRAS/ONDRAF, is responsible for processing and temporary storage of the waste produced, SCK•CEN is the Belgian research center for nuclear energy and EIG Euridice manages the underground research facility located at a depth of 230 m in the Boom clay formation which is being investigated for the disposal of high level and heat emitting waste. The center of the municipality of Dessel as well as a number of non-nuclear industrial activities are situated in the immediate vicinity (< 3 km) of the site.

The Mol/Dessel nuclear site, occupying a total surface of circa 10 km^2, is situated in the Flanders Kempen area, which is essentially characterized by a flat topography. The vegetation outside built-up areas consists mostly of woods and grass fields.

The underground of the Mol/Dessel site (1) consists of neogene sand layers of about 180 m thick, covering a 100 m thick Oligocene clay layer (Boom Clay) with very low permeability.

The characteristics of the different neogene sand layers and their lateral extension were investigated during a geological campaign (2) carried out in 1999 and composed of several borings, cone penetration tests, flow measurements, observation wells, a pump test, a tracer test and one drilling with pressuremeter tests.

These shallow boreholes and electrical cone penetration tests have revealed some differences between the northern and southern part of the site which are separated by the Bocholt-Herentals canal:

- The northern part contains white quartz sands (sands of Mol), becoming narrower in western direction;
- The southern zone (see Figure 1) contains fine homogeneous and glauconitic sands (sands of Kasterlee 10 to 13 m thick) which cover, at the base, a clayey layer of 6 to 8 m thick, overlaying the Sands of Diest. These layers are dipping gently to the north-east.

So far, the presence of the above mentioned clayey layer could not be confirmed for the northern part due to the limited penetration depth of the cone in the very high resistant sand layer.
A more thorough knowledge of the thickness, characteristics and lateral extension of this clayey layer is however important for several reasons:

- The zone of the Mol/Dessel site can be considered to be a two layer aquifer system, separated by this clayey layer on top of the sands of Diest;
- The influence of this clayey layer on the far field is important. The hydrogeological modeling should take this fact into account;
- Impact of this layer on the geotechnical stability and (delayed) settlement behavior;
- Possible use of diaphragm walls, down to this clayey layer, around the site in order to create a physical separation between the repository and the surrounding (hydro-)geology.

In this area of the Flanders Kempen, the local presence of a thin peat layer in the Mol formation is not excluded but this layer was not observed during the geological campaign of 1999.

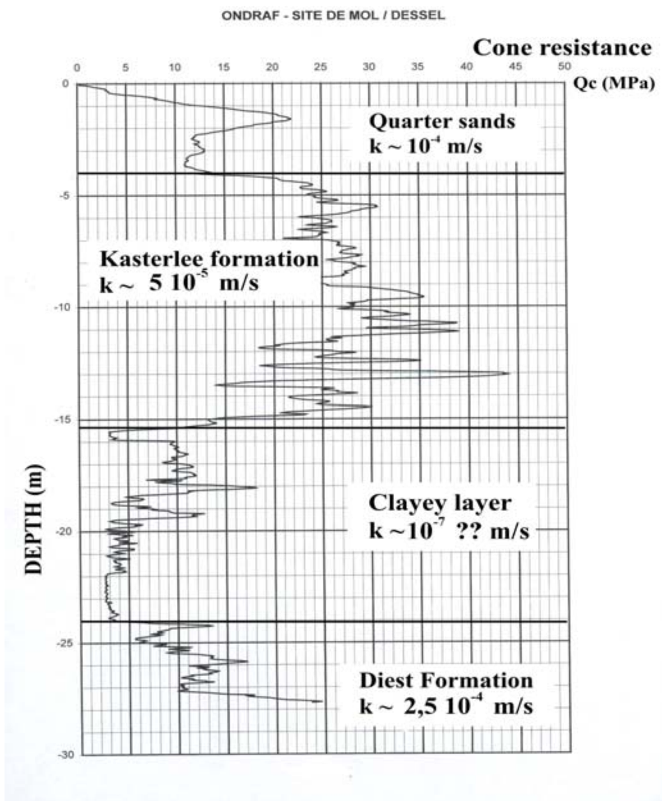

Fig. 1: Typical profile of the shallow formations on the Mol/Dessel site – south of the Bocholt-Herentals canal

The geotechnical data gained within the scope of the above-mentioned survey were used to evaluate (3) the absolute and differential settlements due to the relatively high distributed repository loads on the underlying soil layers (up to 0,5 MPa). Given the fact that theoretical, maximum absolute settlements of 40 cm can be expected, constructional adaptations are required to guarantee the normal functioning of the repository and its components (e.g. slope of the drainage system).

The ability to predict and model the hydrogeology is important in order to evaluate the impact of the LLW repository on man and the environment and to justify its location from a safety point of view. Moreover, monitoring during the period of active control requires sufficient knowledge of the groundwater flows. For LLW repositories a period of institutional control of about 300 years is considered.

The Mol/Dessel site hydrogeology shows a number of unfavourable characteristics:

- A first disadvantage is the presence of a very high water table. In the conceptual design, the water table is considered to be at the level of the ground surface (an additional safety margin of 50 cm above the ground surface not included);
- Secondly, the groundwater flow is very slow due to very small hydraulic gradients. This means that the groundwater flow model can be sensitive to possible changes in the future e.g. a change in precipitation rate or widening of the nearby canal. Consequently, different scenarios have to be considered in hydrogeological and transport modelling;
- Finally the neogene aquifer constitutes an important drinking water reservoir. The presence of a drinking well in the direct vicinity of the repository should be taken into account in safety and performance assessments (PA) and these PA should comply with specific national and international standards.

REPOSITORY DESIGN ADAPTATIONS FOR THE MOL/DESSEL SITE

The repository design used for the Mol/Dessel site is basically comparable with operational repositories for LLW in other European countries (like *El Cabril* in Spain or *Centre de l'Aube* in France) but special adaptations were made to counter the unfavorable conditions mentioned before as well as to take into account the retrievability of the waste during a certain period of time as required by the Belgian government.
As in most countries, the repository design is based on a multibarrier-approach which aims to avoid as long as possible advective or diffusive transport of the radionuclides present in the waste, towards the biosphere by the use of several mutually independent barriers.
These barriers fulfill various safety functions namely physical containment of the waste, delay and spread releases of radionuclides into the biosphere and limited accessibility of the waste.

The generic repository design for the Mol/Dessel site is based on the following barriers (see Figure 2):

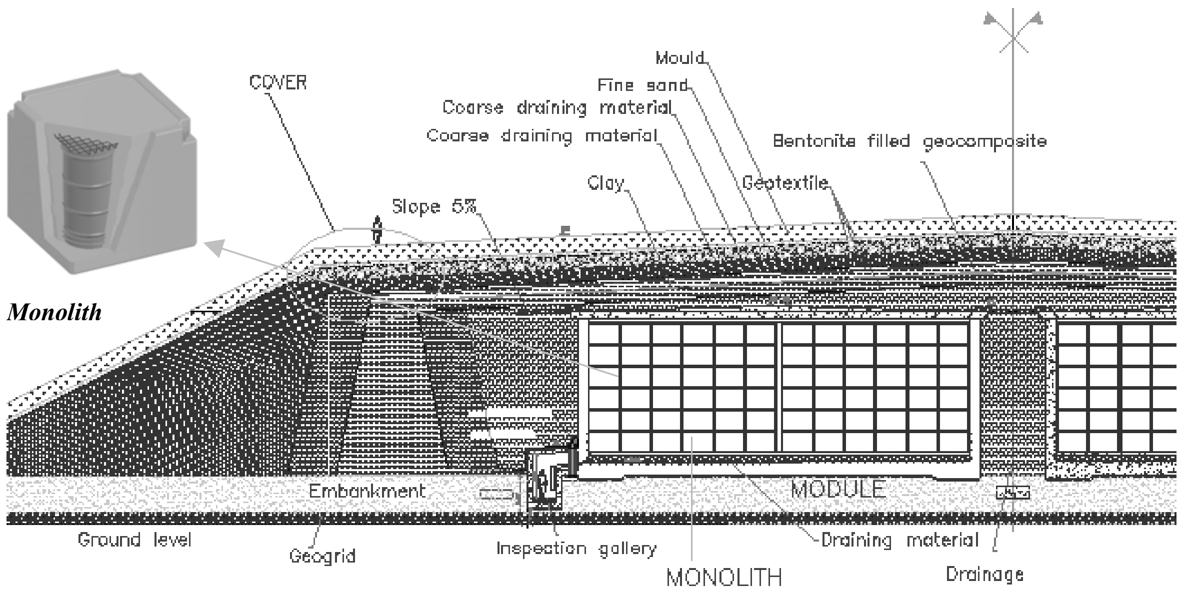

Fig. 2: Cross-section of cover and module containing the monoliths (936 monoliths per module)

- The first barrier is the physical-chemical form of the waste and its direct vicinity. The 400 l waste drums (e.g. operational waste) or the waste in bulk (e.g. decommissioning waste) are immobilized by a filling material (cement, mortar) after insertion in a concrete container . This container, once filled with the waste and the immobilization mortar, is called monolith. All LLW waste will be disposed of in these monoliths (external dimensions: 1.94 m x 1.94 m x 1.34 m; total weight: 130 kN). The monolith will be licensed as a transport container (IP-2[4]) and is equipped with four lifting eyes for handling and transport purposes[5];
- The second barrier is formed by the confining structures around the monoliths. The monoliths are placed in reinforced concrete structures, called modules (ground surface 25 m x 27 m; height 9.9 m). These modules are, at the top, closed by a 40 cm thick concrete roof slab and an impermeable liner (see Figure 2). The exact moment of applying this liner has not been decided yet. The total height of the module, cover included, varies from 24 m in the middle to 20 m at the edges. The modules (in total 40) are designed to withstand an earthquake during the operational phase and the period of institutional control (also see

"design features" of the Fleurus-Farciennes repository). During the design of the floor slab and of the drainage system, particular attention was paid to countering the effects of delayed differential settlements. Finally, special measures will be taken, during the design and execution phase to minimize the occurrence of cracks or premature degradation of the concrete components.
The cover is composed of a biological layer protecting a composite layer. This composite layer should reduce as much as possible the infiltration rate of rain water into the modules. It is composed of successive natural materials like gravel, loam and clay. A geomembrane is also applied but is not considered in the performance evaluations due to its limited lifetime. The use of test platforms to verify the performance of the cover and the durability of its components is considered;
- The geology or hydrogeology on the Mol/Dessel site cannot be considered a natural barrier. However, the application of diaphragm walls around the repository, down to the previously mentioned clayey layer, would create an additional physical isolation between the repository and the surroundings and is currently studied. The compatibility of this solution with the long-term radiological safety and performance requirements is still to be demonstrated.

Due to the high water table on this site, an embankment of 3 m (mixture of limestone and loam) under the concrete modules is necessary to make sure that the ground water stays beneath the lowest level of the inspection gallery. The characteristics of this embankment (composition, safety functions, deformations,…) will be studied more in detail in the next iteration of the design process.

Given the hydrogeological and geological context of the Mol/Dessel site, continuous monitoring of the appropriate functioning of all the components of the repository and of the disposal system as a whole during the operational phase and the period of institutional period is of the utmost importance. Moreover an emergency plan should be worked out to mitigate and minimize the effects in case of unacceptable releases of radionuclides into the biosphere.

The following monitoring measures will be taken or are currently studied[6]:

- Detection of accidental water intrusion (inspection gallery, standpipe piezometers, tracers, geogrids, fiber optics,…). The inspection galleries, located next to the modules, are conceived in such a way that any accidental water infiltration through the liner or the walls into the modules can be observed and analyzed. This (potentially contaminated) infiltration water is collected by a special drainage system connected to each module (see Figure 2);
- Detection of possible releases or effects of such releases in the vicinity of the repository (piezometers, analyses of water samples,…);
- Monitoring (e.g. piezometers) of the change of hydrogeological parameters and continuous adjusting of the used models;
- Constructional stability and settlement monitoring of the different components (modules, lining, drainage,…)
- Measurements of physical and chemical parameters (e.g. relative humidity, temperature, pH, gas) in and around the modules;
- Radiological measurements

HYDROGEOLOGY AND GEOLOGY OF THE FLEURUS/FARCIENNES SITE

The site of Fleurus is about 16ha. It is located on a plateau, at an elevation of 180 meters , 90 meters above the Sambre river.

The upper layer of the Fleurus-Farciennes site consists of 10 m silt with poor geomechanical characteristics, overlying sands (only a few meters thick) and Westphalian shales between 15 and 20 m depth (see Figure 3). The Westphalian shales are tectonized and strongly weathered.

In the past, coal seams were mined out. The last mine closed down in 1975. This activity induced locally important surface subsidence and one may consider that the biggest part of the subsidence is now completed. The amplitude of the coalmine subsidence could reach several meters. Nevertheless, three different areas could be identified (see Figure 4).

The first is at located at the south-west of the site. The coal seams there were vertical and were filled after mining. The fill was not properly compacted, so that large subsidences and even sink holes generation may occur.

The second, located in the centre was only mined out at a large depth, at more than 500m. The coal seams are only slightly dipping and the total thickness of the mined coal seams does not exceed 5 m. For this zone, it is expected that the subsidence that is still to come will never exceed values that can be measured in centimeters.

The third is located on the east of the site. The numerous coal seams were mined out between 50 m depth and 800 m depth. The observed subsidence is considerable and in the coming three centuries additional subsidence of one to several decimeters may be expected.
Therefore, it has been recommended to focus the investigations on the central area which is the most appropriate and which also provides a nice solution to the problem of the lack of available area. One also has to consider the possible sink hole formation above an abandoned internal shaft or above a gallery after a wash-out. Different sink holes have been observed in the area, with diameters up to 6 meters.

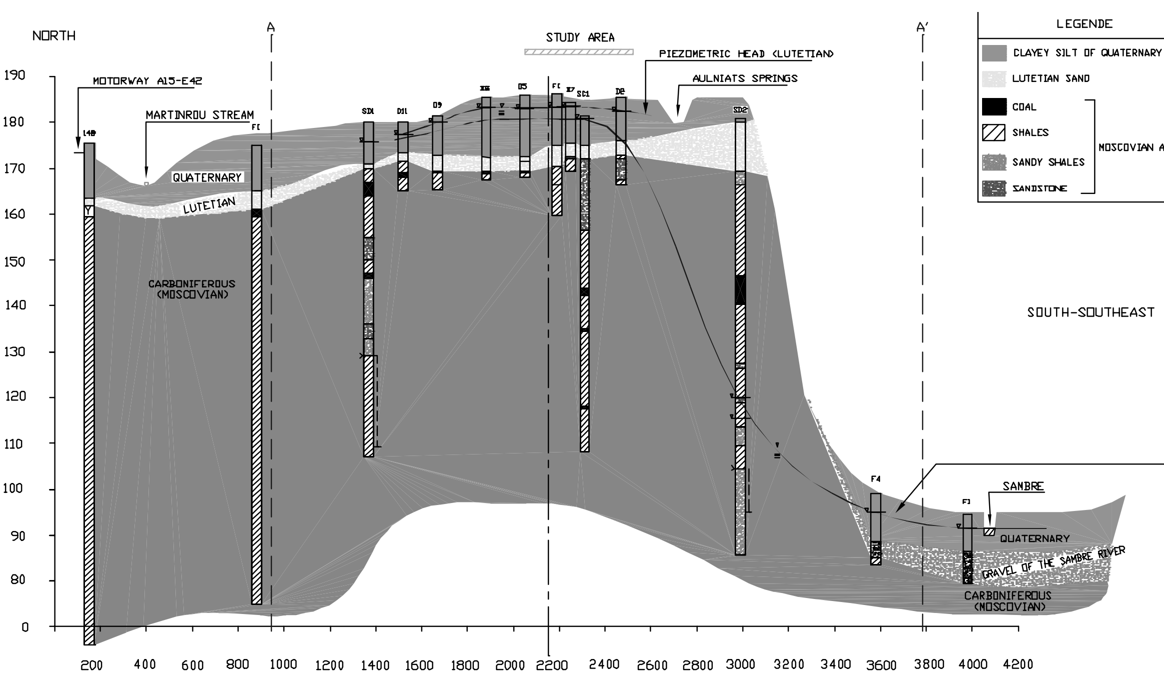

Fig. 3: Geological cross-section of the Fleurus-Farciennes site

Two aquifers are observed, one located in the Lutetian sands overlying the weathered clay, the other in the fractured Westphalian shales. The water level in the first is one meter higher than in the second, but both aquifers are linked.

The lower aquifer (Westphalian) is the most important. Extended hydrogeological investigations have been performed and the aquifer has been modelled.

The aquifer is recharged by infiltration through the Lutetian sands. Its outlets are:

- to the south a north-south drainage gallery, built during the previous stages of mining to drain the upper part of the mines by gravity. In addition, an east-west gallery collects the groundwater and is connected to the major north-south gallery;
- to the north and to a major limestone aquifer through a south-west/north-east normal fault.

Different climate change scenarios (increased or reduced infiltration over a long period) and scenarios with increases in water withdrawal in the northern limestone aquifer show that in order to avoid the possibility of radionuclides transport to the northern aquifer a drainage gallery below or close to the disposal has to be buried, so that the Westhphalian aquifer is always controlled and drained by gravity towards the Sambre.

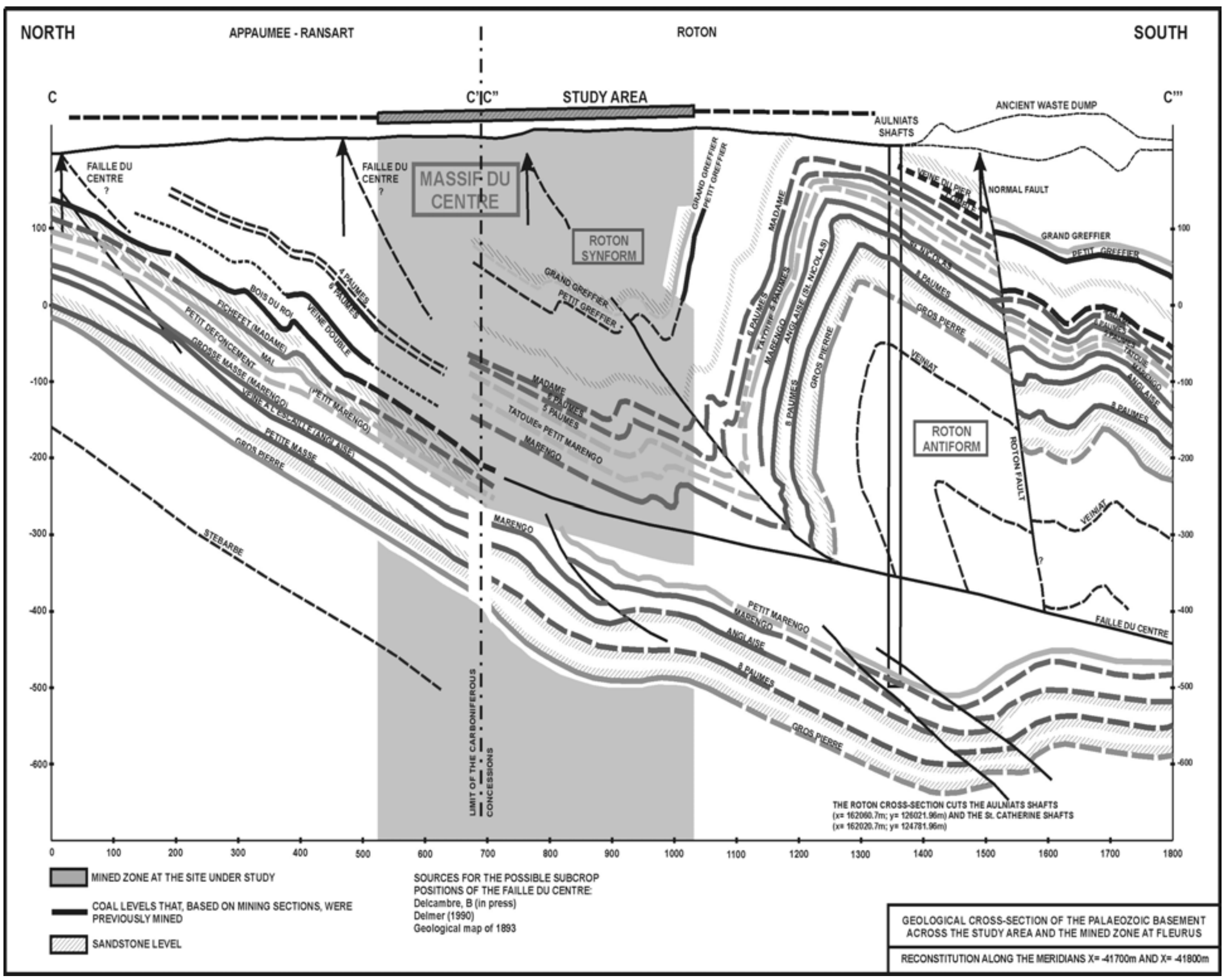

Fig. 4: Tectonic cross-section of the Fleurus-Farciennes site

REPOSITORY DESIGN ADAPTATIONS FOR THE FLEURUS/FARCIENNES SITE

Basic Concept

The first conceptual challenge arises from a combination between:

- The geotechnical weakness of the upper geological layers;
- The presence of a water table close to the natural ground level;
- Possible subsidence and sink hole formation.

Based on a classical scheme identical to the one planned in Mol/Dessel, the low bearing capacity of the upper layers and its high settlement potential would require that the structure be lightened and that the disposal be spread over a wide area. Such a scheme is not compatible with the limited area identified above the deep mining works. It would also lengthen the rainwater network and poses additional risks due to differential settlements - such as reverse flow.

The only reasonable alternatives are:

- to go below ground level in order to find a suitable bearing strata on the shale bedrock at a depth of 20 to 30 m ;
- to create an underground network of galleries.

Only the first option is currently being studied.

In order to deal with basic safety requirements, the disposal must be *isolated from the phreatic surface*. During construction, the water level should also be maintained to avoid settlement on neighboring industrial installations such as a cyclotron.

Our original solution to this problem is the construction of a double structural shell (see Figure 5):

- the outer shell consists of a deep circular retaining wall on the side with a bottom concrete foundation slab;
- the inner shell, the disposal structure itself, is a simple circular concrete reservoir.

Several columns between both base slabs provide the connection.
The annular and bottom empty spaces act as an *impervious barrier* and a drain for leaking water coming from:

- percolation through the retaining wall joints;
- rain water through imperfection in the earth cover;
- in the long term, infiltration water from the bedrock.

This water may be naturally diverted by gravity through an underground drainage gallery sloping down to the existing Sambre river, some 1,200 m away. *The natural topography of this site is providing this unique opportunity.*

Apart from problems arising from mining subsidence, the main weaknesses are thus:

- the water table is artificially and permanently lowered by gravity alone, isolating the waste from it;
- bearing capacity if found at a reasonable depth, construction-wise;
- the site exiguity is solved by providing a deep large vault with great storage capacity.

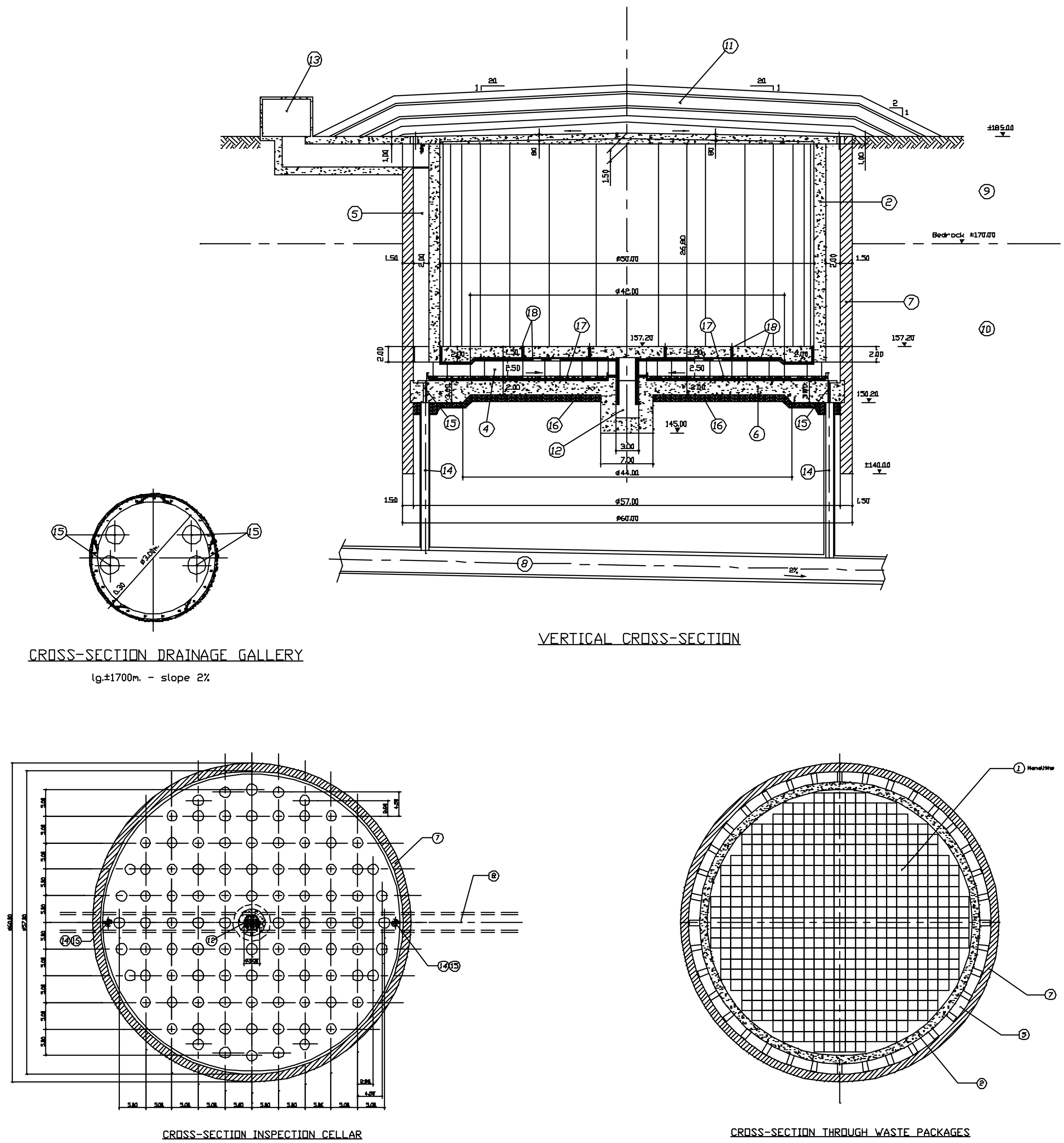

Fig. 5: Plan and cross-section of the cylindrical solution with double shells for the Fleurus-Farciennes site

Additional Features

The concept's additional features are:

- acceptable *site integrati*on : the main part of the repository lies beneath ground level, with only the earth cover or part of it protruding;
- The annular and bottom voids provide *permanent access around the waste* for inspection, control, maintenance and repair. The unobtrusive entrance is located on the side with a short underground access trench and technical spaces for pumps, monitoring power units and occasional ventilation systems;

- The waste package is the same monolith as discussed for the Mol/Dessel site. In order to maximize the filling ratio of such cylindrical shape, the basic unit has been chosen with a *50 m diameter*. Four identical structures will be required to store the 37,500 monoliths for the Belgian nuclear programme;
- The drainage gallery, featured on the drawing above, runs under the four units with two vertical bores as a connection for the evacuation of uncontaminated leaking water;
- A central sump with an impervious steel liner is planned to collect potentially contaminated water. This water may appear in the long term by degradation of the earth cover and the top concrete cover. It is collected at the bottom trough a complex of embedded drains and an underhung network of adjustable pipes. The water is inspected and if found contaminated, pumped to the surface for treatment. In normal condition, this sump is dry.

Operational Features

- The waste is handled with an overhead portal running on parallel tracks, outside the retaining walls. Layers of monolith (20) are evenly placed to avoid differential loading on the foundation;
- Each monolith is carefully placed in direct contact with each of the others in order to avoid degradation during earthquake shocks of the handling hooks (which are provided for possible retrieval);
- When full and in order to confer necessary stiffness, the residual voids between the waste and the concrete shell are filled with gravel;
- The relatively thin top slab is poured on the top monolith layers and later covered with the impervious earth cap. Its load is directly transferred to the rock. This makes it possible to easily retrieve the waste package by the removal of the top slab.

Mining Subsidence

The residual potential mining subsidence may pose a threat for such a large radioactive waste disposal structure. A sound and convincing approach must be made in order to assess the long-term safety of the disposal with confidence.

The methodology chosen at this design level is the following:

- compilation and encoding of all existing mining records;
- uncertainty assessment for all geometrical and geomechanical data;
- local rock failure behavior assessment based on FEM models, determination of settlements laws;
- probabilistic assessment of residual subsidence based on analytical formulas;
- deterministic evaluation on one or two scenarios based on large FEM models (2D or 3D).

This work will provide information on the total residual settlement and maximum ground level slope for which the disposal must still be operational and safe. In case of an unacceptable subsidence level, a contingency plan will be elaborated such as filling the abandoned mine workings from the surface by gravity grouting or hydrofracturing.

The collapse of an old mine shaft will be taken into account at the structural level (see next item).

Design Features and Load Cases

The structure is evaluated on the following load cases:

- *self-weight* of the structure, earth cover and waste package;
- global *tilting* due to deep residual mining settlements;
- *seismic loading*. The earthquake levels were assessed for two different periods in the disposal lifetime:
  - *Operational phase*. Construction and loading may take several decades during which all equipment but mainly the overhead crane must sustain a seismic event without severe damages to the existing stored packages. A peak ground acceleration of 0.12 g (4) was chosen (90 % probability of non-return period of 50 years). Intermediate construction phases will be checked.
  - *Monitoring phase* (after closure i.e. after placement of the earth cover and intersperse filling with gravel) : the whole structure must keep its integrity. According to the latest seismic assessment in Belgium and for a non-return period of 250 years, the peak ground acceleration is set at 0.24 g. this loading is the most severe for the structure. Within the disposal, a check has been made on the behavior of the individual waste package against slipping, lifting (the vertical seismic component) and structural integrity;
- *Old shaft collapse under the structure*. The disposal is verified for a random void with a 6 m diameter under the foundation slab, the central sump or under the retaining wall. This may occur due to a lack of information on old deep mining works;
- *Water pressure*: the bottom slab is laid on drainage layers, evacuating water to the gallery. After several decades, these layers may become clogged. The slab must then resist the full hydrostatic pressure and be anchored in the retaining wall right from the start. Flotation is checked in case of full retrieval of all waste packages.

Drainage Principle

As explained, the drainage is foreseen with *two separate flow patterns*:

- non-contaminated water (leakage) on the outside of the structure with direct evacuation down to the gallery;
- potentially contaminated water to a central sump.

The drainage system is designed to work in extreme conditions when a general tilt is induced by mining subsidence. This is possible by providing drainage capability on the outside circumference of both flow patterns.

CONCLUSIONS

The design of a repository for LLW is an iterative process that should take into account all parameters susceptible to have an effect on the long term safety. The demonstration of this long term safety constitutes a key factor in the confidence building process towards the scientific community as well as the public. Unfortunately, its seems impossible to develop a unique, safe and robust solution that can apply, in general, to all hydrogeological and geological conditions. In this paper we have demonstrated, however, that special constructional and civil engineering adaptations can be made in order to maintain the safe functioning of the disposal system as a whole and the integrity of its components during the operational phase and the period of institutional control.

Physical isolation between the surface aquifer and a surface disposal facility can be compromised in the case of a very high water table. This problem has been solved for the Mol/Dessel site by applying an additional embankment of 3 m between the disposal modules and the ground surface. Application of diaphragm walls around the repository, if compatible with long term safety requirements, can provide additional isolation of the waste from the neogene aquifer. For the Fleurus-Farciennes site, a double structural shell guarantees the physical isolation of the disposal structure from the phreatic surface. Gravitational diversion of non-contaminated leaking water is possible thanks to the important hydraulic gradient between the site and the Sambre river.

In the case of the Mol/Dessel site, the effects of differential settlements are taken into account in the design of the structure itself (e.g. floor slab) whereas, for the Fleurus-Farciennes site, settlements of the weak surface layers are prevented by burying the disposal structure down to the resistant shale bedrock at a depth of about 20 to 30 m. For the latter site, former mining activities and the possible occurrence of residual mining subsidences constitute an additional problem. These future subsidences are evaluated and mitigating measures, if needed, are being studied.

Both designs offer the possibility to retrieve the waste packages during a certain period of time, as required by the Belgian government.

Finally, for both sites, a monitoring program adapted to the local geological and hydrogeological conditions is elaborated. For the Mol/Dessel site, for instance, possibly contaminated water infiltrations can be detected by means of an inspection gallery connected to the modules, whereas the double shell structure, proposed for the Fleurus/Farciennes site, allows visual inspections around and under the inner concrete reservoir containing the LLW packages.

FOOTNOTES

[1] ONDRAF/NIRAS, the Belgian National Waste Management Agency
[2] TRACTEBEL DEVELOPMENT ENGINEERING, BELGATOM and KUL (Leuven University), Belgium
[3] TRACTEBEL DEVELOPMENT ENGINEERING AND BELGATOM, Belgium
[4] According to IAEA standards
[5] The monolith was specially designed in order to maintain the possibility of retrieving waste packages during the operational phase and the period of institutional control
[6] Studies with respect to the specific implementation of these measures are in progress, in collaboration with local representatives.

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