Underground Architecture and Layout for the Belgian High-Level and Long-Lived Intermediate-Level Radioactive Waste Disposal Facility- 12116

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ABSTRACT

The underground architecture and layout of the proposed Belgian high-level (HLW) and long-lived, intermediate-level radioactive wastes (ILW-LL) disposal system (repository) is mainly based on lessons learned during the development and 30-year-long operation of an underground research laboratory (URL) ("HADES") located adjacent to the city of Mol at a depth of 225 m in a 100-m-thick, Tertiary clay formation; the Boom clay. The following main operational and safety challenges are addressed in the proposed architecture and layout:

1. Following excavation, the underground openings needed to be promptly supported to minimize the extent of the excavation damaged zone (EDZ).
2. The size and unsupported stand-up time at tunnel crossings/intersections also needed to be minimized to minimize the extent of the related EDZ.
3. Steel components had to be minimized to limit the related long-term (post-closure) corrosion and hydrogen production.
4. The shafts and all equipment had to go down through a 180-m-thick aquifer and handle up to 65-Ton payloads.
5. The shaft seals had to be placed in the underlying clay layer.

The currently proposed layout minimizes the excavated volume based on strict long-term-safety criteria and optimizes operational safety. Operational safety is further enhanced by a remote-controlled waste-package-handling system transporting the waste packages from their respective surface location down to their respective disposal location with no intermediate operation. The related on-site preparation and thenceforth use of cement-based, waste-package-transportation containers are integral operational-safety components. In addition to strengthening the waste packages and providing radiation protection, these containers also provide long-term corrosion protection of the internal "primary" steel packages.

INTRODUCTION

The subsequent text provides a concise summary of the underground architecture and layout of the Belgian high-level and long-lived intermediate-level radioactive waste (HLW and ILW-LL) disposal system (repository). It also provides some of the related background information.

The underground architectural concept for the Belgian HLW and ILW-LL repository presented in this paper is mostly based on the large amount of experiences gained during the 30 years of operation of the Mol underground research laboratory (URL), including technical and phenomenological aspects. Two separate papers [1, 2] address in more detail the residual uncertainties or "open questions", and the envisioned operational aspects of the current Belgian HLW-disposal concept.

BACKGROUND

A 30-million-year old, 100-m-thick, homogenous and impervious, stable, indurated, clay formation; *the Boom clay*, beginning about 180 m below the ground surface was chosen in the late 1970s for the construction of an underground research laboratory (URL) to investigate the suitability of the Boom clay for safe disposal of HLW and ILW-LL. In parallel, alternative disposal solutions, such as deep boreholes, permanent surface storage and disposal in other geological formations than the Boom clay, were also studied. All these concepts were recently consolidated by ONDRAF/NIRAS in a "waste plan" that was subjected to public-consultation feedback and remarks. However, the current Belgian HLW- and ILW-LL-disposal concept is governed by an absence of legislation concerning the HLW and a moratorium on spent fuel reprocessing, which imposed the need to consider two variants in the waste plan. The waste plan is considered an informative tool for the legislators who had already provided the regulatory basis for the LLW-disposal concept.

Following the public-review process, HLW and ILW-LL disposal in the Boom clay formation remains the most favored solution. It is also supported by international recommendations and will lower the burden on future generations. The boundary conditions described and discussed in the subsequent text focus on the geological solution.

BOUNDARY CONDITIONS

Long-Term Safety

The disposal concept must provide all conditions required for long-term passive safety. These conditions include:

- *Confinement* of the waste packages/forms
- *Isolation* of the waste from waste from foreseeable external accidental and natural events that could cause radionuclide releases to the biosphere, e.g., earthquakes and human intrusion
- *Retardation* of radionuclides moving in the host rock
- *Limitation of the Excavated Damaged Zone* (EDZ) around the man made underground openings/structures and its evolution/progression with time

Operational Safety

The protection of the workers and of the environment must be provided during all operational phases, including the consequences of internal and external events. Although listed here, this aspect is addressed in another paper presented at this conference [2].

Waste Packages

As illustrated on Fig 1 and fuel, all primary waste packages will be sheathed/emplaced in a concrete container providing:

- Shielding protection based on a dose of no more than 25 µSv/hour 1 m in all directions from the container. The operations are then conducted in controlled areas based on a mean annual occupational exposure time of 400 hours per worker
- Transportation strength whilst being moved from the post-conditioning surface facilities to their respective final emplacement location
- Chemical stability slowing down the corrosion rate of the steel components in the primary-waste package; mainly achieved by a sustained low near-field pH

As illustrated on Fig 2, the heat-emitting HLW containers will also be placed in a carbon-steel overpack confining the radionuclides during the thermal phase, which, in turn, increases their robustness and simplifies the near field models by eliminating complex phenomena in a multi-phase clay medium.

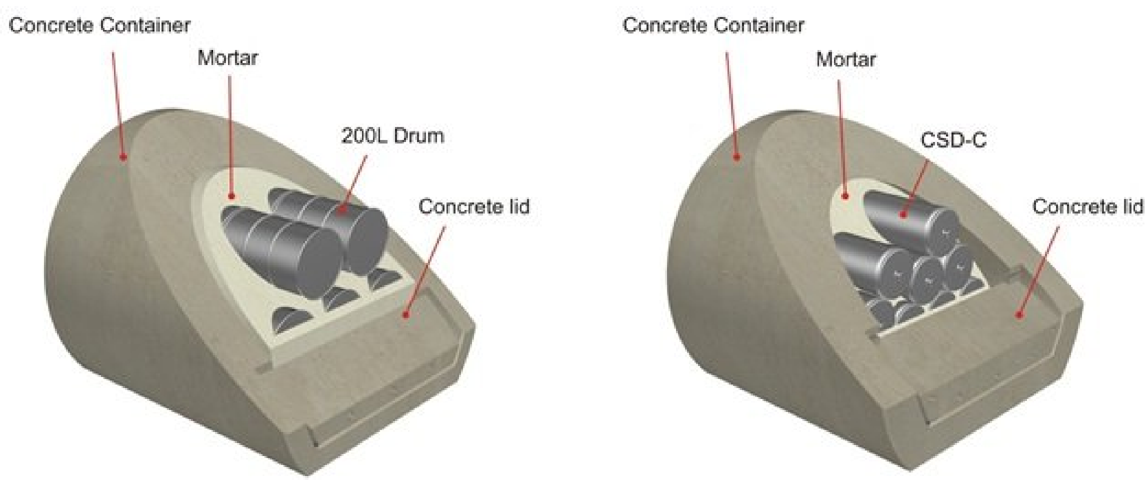

Fig. 1: 2.8 m diameter concrete monoliths for two types of primary waste packages.

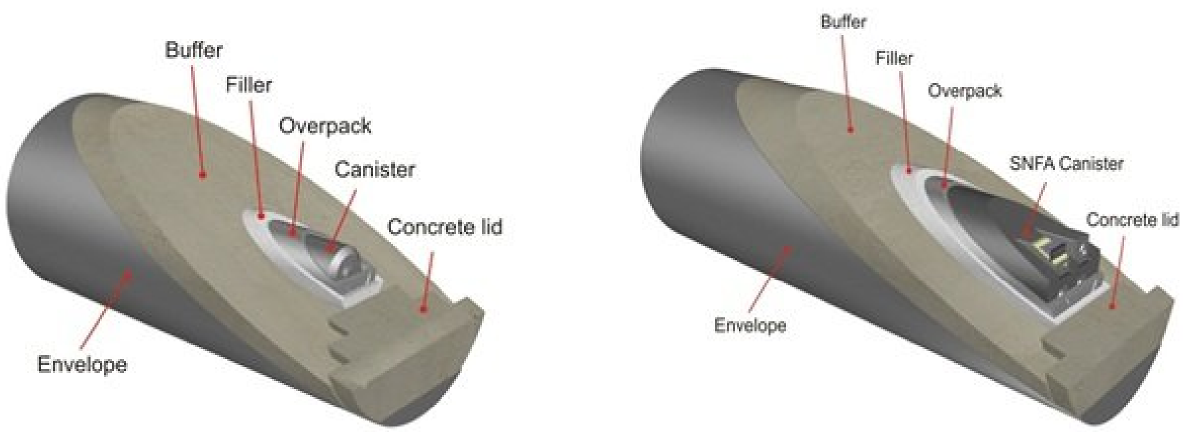

Fig. 2: 2 m diameter concrete "supercontainer" for vitrified wastes and spent fuel.

The ILW-LL "monoliths" shown on Fig 1 are about 2.5 m long and weigh up to 40 Tons. The HLW "supercontainers" shown on Fig 2 have a maximum length of 6 m and weigh up to 65 Tons.

Geological Context

As illustrated on Fig 3, At Mol, the top of the indurated Boom Clay lies at a depth of about 180 m below the ground surface and is overlain by neogene sandy aquifer layers. The local ground-water table is typically located about 2 m below the natural ground level. At Mol, the Boom clay is approximately 100 m thick and its hydrogeological, geochemical and mechanical stability over time is well known. For optimum long-term (post-closure) safety/performance, the HLW and ILW-LL will be emplaced as close as possible to the middle plane of the Boom clay.

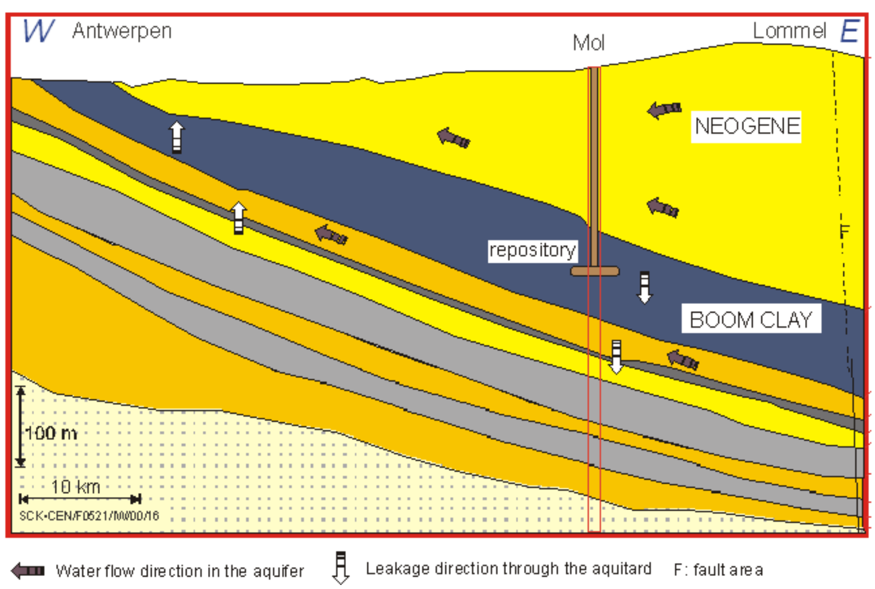

Fig 3 : Regional W-E geological cross section at Mol

The Boom clay may be characterized as a “soft” rock. It typically has an uniaxial compressive strength of about 2 MPa, a modulus of deformation (E) of about 400 MPa and a chemically-bound water content of about 24 %. The permeability of the undisturbed clay is typically no more than 10^{-12} m/s.

When tested on samples, the clay shows a soil-like behavior, but the URL construction has confirmed a rock-like behavior mostly due to a predominant scale effect attributed to fracture planes and critical block formation being formed by the stress redistribution around the excavation faces.

The clay is over-consolidated due to the overburden pressure attributed to past ice sheets/glaciers that have left their weight memory on the horizontal principal stress while the vertical stress has been gradually reduced by the slow disappearance of the ice. The result is very favorable for circular tunnels as the ratio of the horizontal and vertical principal stresses is close to 1.

The prevailing low permeability induces a predominant very slow diffusive transport mechanism; moreover, sorption capabilities will further slow down and delay radionuclide movement before they reach the sandy aquifers.

Another recently validated clay characteristic is its self-healing capacity. The fracture zone, mostly located within the EDZ, will be reduced by a gradual closing of the discontinuities created by the excavation. After closure, the transport characteristics of the healed/closed fracture planes are not discernible from the original ones.

Reversibility and Retrievability

The reversibility and retrievability requirements have yet to be defined consensually by the regulator and ONDRAF/NIRAS. In the meantime, one baseline assumption is that the design consequences of future requirements will be dealt with by an appropriate backfilling material and waste-loading sequence. Pending a decision, the current assumption is that reversibility must be possible with the same handling equipment and only be required up to the time the annular voids around the container are filled with a cement grout.

Excavation Damaged Zone

The EDZ must be minimized to optimize the radionuclide containment and isolation capability of the Boom clay. The time-dependent properties of the Boom clay favor an industrial excavation sequence performed with a tunnel boring machine (TBM). Furthermore, the stand-up time of the unsupported tunnel zone must be minimized. A tunnel lining must thus be installed as close as possible both in terms of time and distance to the excavation face to ensure the safety of the workers. The cost for the lining system is a significant part of the disposal investment cost.

In the Mol URL, advance rates of 1 m per week (manual techniques) and 3 m per day (mechanical mining) have been tested, confirming the advantages and choice of TBM mining. However, the following two particular zones of the repository will require the usage of manual excavation techniques, which, in turn, will induce larger EDZs than those induced in the mechanically-mined gallery sections:

- The shaft bottom where the main access galleries connect to the shaft
- The crossings/intersections between the main access galleries and the disposal galleries.

Thermal Aspects

As elaborated upon in the subsequent text, the thermal aspects governed the main dimensions of the repository.

First, the maximum temperature increase at the interface between the clay and the overlying aquifer must be limited to 10° C. This, in turn, is the dimensioning factor for the spacing of the waste packages and the disposal galleries.

Second, the clay may not reach an absolute temperature of more than 90° C in order to maintain its long-term safety properties. Moreover, the temperature of the engineered barriers, mainly concrete, should not exceed 70° C to ensure intact properties. These factors impose a maximum linear thermal output of no more than 300 W per meter that, in turn, governs the number of spent fuel rods per container and their 60 years cooling time at the surface.

Another thermal aspect is more related to the lining design itself and is dealt with in a subsequent sub-section.

Criticality

Criticality aspects are dealt with at the level of the carbon steel overpack design and are relatively independent of the layout geometry.

Disposal Rate

The first waste group projected to be disposed of around year 2040 is the “historic” ILW-LL, including cemented and bituminized wastes. Some LLW that does not meet the acceptance criteria for surface disposal will also be included.

The next disposal group/phase is projected to start around year 2055 and to include ILW-LL linked with the dismantling of the Belgian Nuclear Power Park and will mainly comprise cemented wastes and compressed end nozzles and zircaloy tubes of reprocessed spent fuel.

HLW will be in the last disposal group. It is projected to start around year 2080 and, contingent upon the decision to be made about reprocessing, to include either only vitrified waste or a mix also including direct disposal of spent fuel.

The above and underground facility designs are based on a disposal rate of two HLW “supercontainers” and one ILW-LL monolith per day with a working schedule of 5 days per week and one shift per day.

ARCHITECTURAL CHOICES

The *ratio between the overall excavated gallery volume and the emplaced waste volume* should be minimized to avoid unnecessary clay removal and related unnecessary EDZ extensions. it also significantly minimizes cost. However, this ration must also be compatible with the applicable operational safety requirements and planned coactivities such as concurrent mining and structural support activities.

The thermal calculations (aquifer temperature limitation) governed the following separation distances between the galleries: 120 m for the direct disposal of spent fuel; and 50 m for the vitrified wastes and the ILW-LL.

Based on common tunnel-design practices and the experience gained at the MOL URL, *the gallery openings must be circular* and excavated with a TBM. Together with an almost isotropic loading, a circular shape will only induce compressive stresses on the lining, avoiding the need for steel reinforcement, at least in current gallery sections. *Concrete is the primary lining choice* due to its more-than-adequate compressive strength and its favorable chemical characteristics that will slow down the corrosion rate of the steel components in the waste packages.

The opening design is particularly challenging at all the crossings/intersections of waste-disposal galleries and access tunnels because the resulting stress redistribution leads to anisotropic loading of the prevailing support structures. A simple rule of thumb evolving from the extensive excavations conducted for the London underground transportation system in similar clay and confirmed by calculations imposes *a ratio of 2 between two intersecting gallery diameters*. Any other ratio would require heavy steel reinforcement. The radial pressure at equilibrium amounts to more than 3 MPa with higher peak pressure values at the crossings. This aspect was the decisive reason for choosing small ILW-LL monolith dimensions rather than much larger containers that would have reduced the disposal-gallery length. Another advantage of *minimizing steel* is that it also minimizes hydrogen production because hydrogen will be produced by some of the ILW-LL and the overall hydrogen production rate must be lower than the diffusive capacity of the surrounding clay medium. Furthermore, perpendicular (90^o) opening crossings/intersections were chosen because they result in the smallest possible “combined/mutual” opening area and minimized the related EDZ.

The initial crossing-support materials and designs were first based on costly steel or cast-iron segments in order to limit the radius/thickness of the EDZ. These segments would have been placed by the TBM with a subsequent removal of the disposal gallery “eye”. But the short distance between ILL-LL and the vitrified waste galleries would have imposed an awkward constant lining change between concrete and steel. *The new crossing design is underway and will be based on conventional excavation techniques* and sequences, locally inducing a larger EDZ than that induced by the aforementioned TBM-based excavation method. This aspect is manageable by placing the waste farther away from the crossings in slightly longer disposal galleries and by accounting for the self-healing characteristics of the surrounding clay.

The *maximum disposal gallery length is 1000 m* and it is mainly based on the handling system speed and the need to emplace/dispose two HLW "supercontainers" per day. The architectural concept presented below is based on this capacity, which may change due to conventional safety aspects and pending regulatory guidance.

At the start of the study, the following two remote-controlled waste-handling systems were investigated for transporting the waste packages from their respective surface location to their respective underground disposal/emplacement location: air cushion; and rail. The air cushion system was first favored due to its absence of steel but it was recently replaced and dismissed due to several inherent difficulties, including compressed air flexible ducts design and flow rate, floor deformation due to heat output, reversibility doubts and accident analysis. An original remote-guided rail-based system has been proposed and is presently being developed.[2] Two essential design features are: a continuous low-based trolley transportation system from the post-conditioning building to the disposal location; and a turntable at the gallery crossings.

Another basic architectural feature is the complete separation of the underground construction zone and the "controlled zone" in which nuclear operations are or have been conducted. Based on the currently projected disposal schedule, concurrent construction and disposal activities mainly occur during two distant periods, the first one beginning around 2040 with emplacement/disposal of ILL-LL, followed by the emplacement/disposal of HLW around 2080. Although the most cost-effective layout is to minimize the number of shafts to the two planned for the ILW-LL disposal/emplacement, the proposed layout includes a later development of a third shaft for the HLW zone, which would further ensure the safe conduct of coactivities.

Ramps between the surface facilities and the repository were dismissed in favor of shafts due to the presence of the 180-m-thick sandy aquifer overlying the Boom clay that would have been very costly and time-consuming to cross with moderately-inclined ramps. The URL also provided essential feedback for two different shaft designs described in the subsequent text.

GALLERY DESIGN

The lining proposed in the underground openings/tunnels is of an expanded type. The proposed expanded-lining or wedge-block technique has been developed for impermeable cohesive soils with a stand-up time of several hours (such as the over-consolidated London Clay). The shields used for temporary support are equipped with a sharp cutting edge. The front edge of the shield smoothly carves out the excavation profile to a perfect circle while the area/clay inside the shield is excavated with a road header. At the rear of the shield is a narrow cylindrical un-supported zone, which facilitates the manual building of a ring of concrete segments in direct contact with the clay with no need for additional annular grouting because the perimeters of the lining and the TBM shield have the same diameter. A support ring consists of a number of unbolted unreinforced concrete segments and wedge-shaped key segments. The wedges (Fig. **5**) are used to expand the ring of concrete segments until they are in direct contact with the surrounding clay and, if needed, to induce additional "overburden" stress on the lining. All concrete segments are in direct contact, which, in turn, ensures high "ring" stiffness.

Although valid for ambient temperature condition (access galleries and ILW-LL disposal galleries), the thermal output from the HLW will almost double the stress on the constrained lining, according to $\Delta\sigma = E * \alpha * \Delta T$. An original solution has been proposed and is currently tested in the URL. It consists of inserting compressible stainless steel foam plates that deform only above the concrete yield strength. This will cancel the additional thermal induced stress (Fig. **5**).

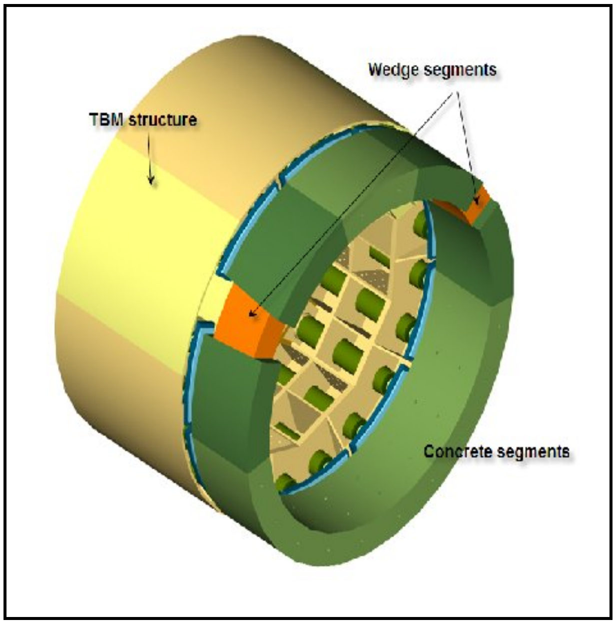

Fig 4 : Schematic illustration of the lining segments behind the TBM shield.

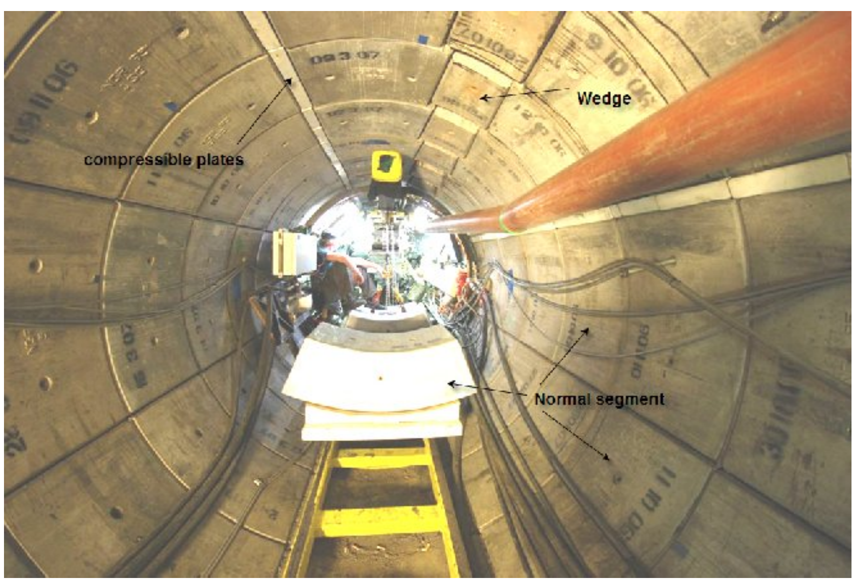

Fig. 5. Wedge block gallery with compressible plates

SHAFT DESIGN

The two existing shafts with inside diameters of 2.65 m and 3 m, respectively, at the Mol URL were excavated by freezing the 180-m-thick sand layer overlying the Boom clay. Due to the unknown related behavior of the clay at that time, the freezing for the first shaft extended into the clay down to the gallery level. For the second shaft, the freezing was limited to the sand layer, the clay portion of the shaft subsequently being dug out by conventional excavation methods and then promptly stabilized/reinforced with a sliding steel rib primary lining and a cast in-situ final lining.

The first shaft was lined from top to bottom by two cast in-situ concrete shells separated by plastic sheeting for imperviousness. The sand layer in the second shaft was stabilized by an external, thin, safety shotcrete shell and a precast concrete internal liner, that were separated by a 10-cm-thick asphalt ring. The weight of this internal precast column rests on a large foundation hand dug in the top underlying clay formation. Both shafts have a larger inside diameter in the clay portion than in the sand portion to facilitate easier gallery connections. Alternative excavation techniques are under investigation to assess the applicability of the existing lining design to long-term safety issues, including PVC durability, foundation ring necessity, asphalt behavior and removal issues. However, the most critical current issue is the shaft sealing concept. This seal is only foreseen in the clay section where the available height, i.e., the length of the seal, mainly above the waste-disposal elevation/plane is limited.

The diameter of the waste shaft proposed for the pending disposal facility will be at least 7.8 m to accommodate the uninterrupted transportation of all types of waste containers, of which the 6 m long “supercontainer” will be transported in a horizontal position on its transport trolley. TBM dimensions are not an issue because the main gallery in the Mol URL was excavated by a 4.8-m diameter TBM that was lowered in pieces through the 3-m internal-diameter shaft and assembled in a chamber located at the bottom of the shaft.

CROSSINGS

Fig 6 shows the reinforcement structure used in the Mol URL shaft/assembly chamber crossing that facilitated the direct assembly and starting of a TBM (also visible on the figure) without inducing almost any clay disturbances. As previously mentioned, the crossing design is being optimized to avoid costly steel lining while allowing some additional convergence and EDZ extension. A possible solution is the application of sliding steel ribs and sliding HEB profile together with the use of fiber glass bolting in the clay mass.

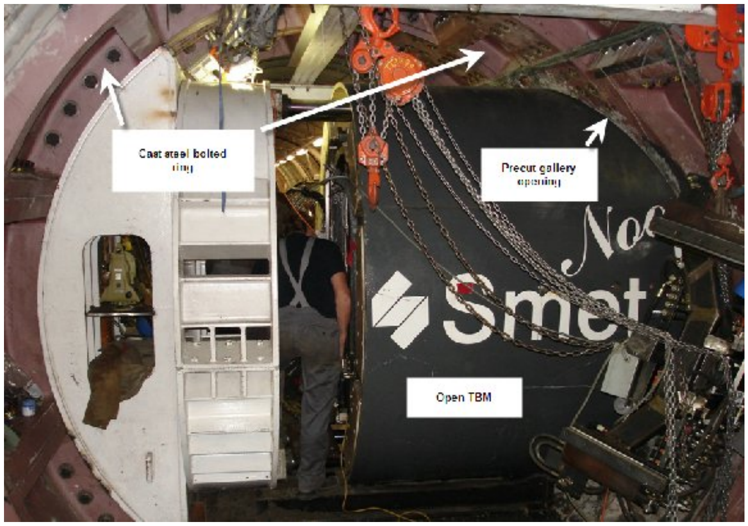

Fig 6 : View of a TBM start in a precut reinforcement steel ring.

LAYOUT

The currently proposed layout of surface and subsurface shown on Fig. **7** is in its final stage. It conforms to the boundary conditions and the architectural choices summarized in the preceding text. The layout of the underground facilities comprises a simple fishbone structure with three shafts to the surface, a central access gallery and a succession of long perpendicular disposal galleries. The entrances to the disposal galleries are located at the same place on each side of the access gallery in order to minimize the number of crossings.

The portion of the repository located between the two shafts to the right on Fig. **7**, i.e., the waste shaft and the ventilation/personnel shaft, are intended for the first operational phase (ILW-LL). The HLW zone is located to the left of the central waste shaft and it will also have its own access shaft, which can be constructed while the ILW-LL is disposed of consistent with current disposal-rate requirements.

Both perimeter shafts also serve as air-intake shafts. In both cases, the exhaust air exits through the central waste shaft, which also serves as a secondary escape route.

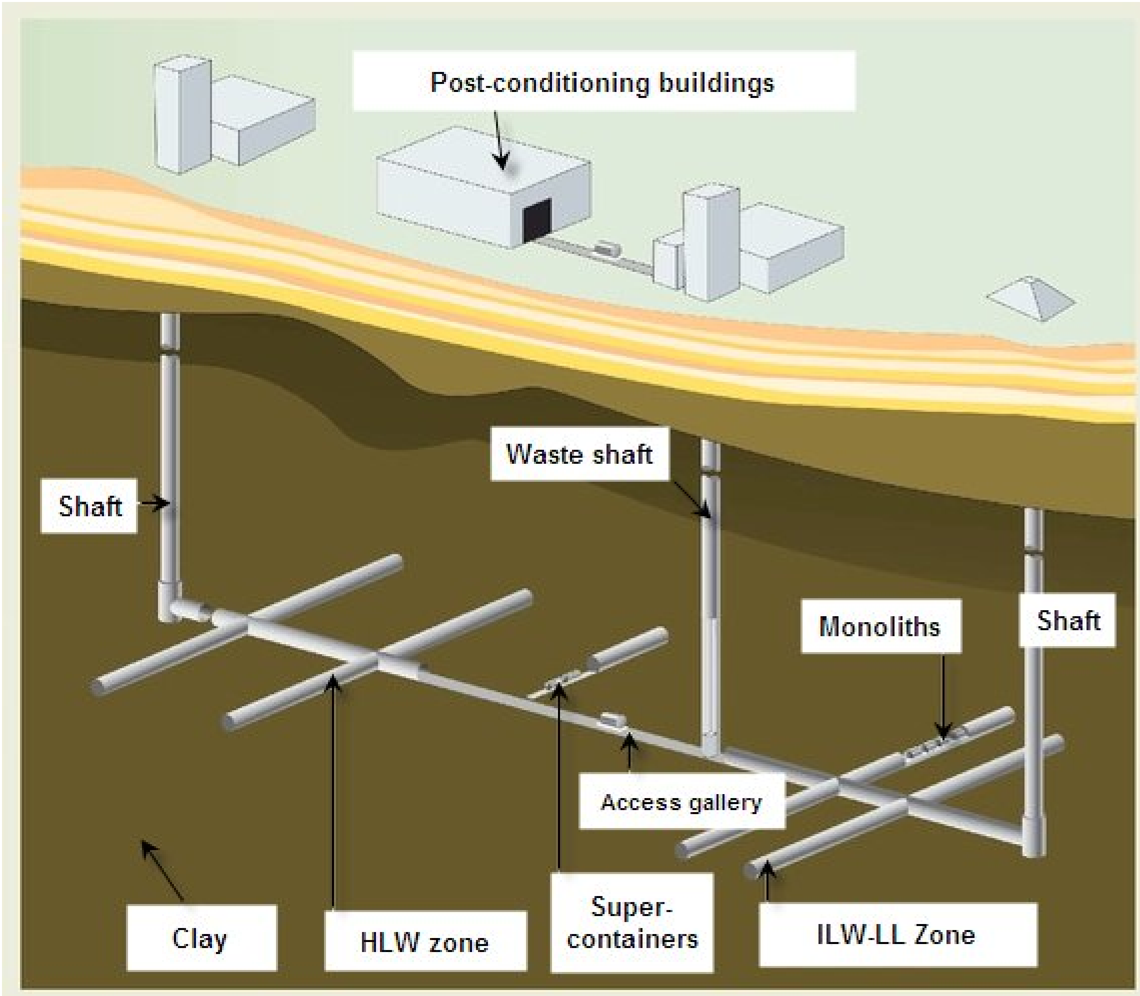

Fig. 7. Layout principle

The coactivity between the operational and the construction activities/zones is minimized because the disposal process will only occur after all construction activities are completed. The only exception is when the HLW-access-gallery construction reaches the central waste shaft bottom, which is also vital to the conduct of concurrent ILW-LLL-disposal operations. This coactivity issue is solved by foreseeing from the start a ~ 50 m long buffer gallery on the opposite side of the ILW-LL zone. Properly designed with radiological shielding plugs, it can be used as a transition zone.

In the case of full reprocessing, the total length of the main gallery is only about 500 m. If spent fuel is disposed of directly, based on current thermal constraints, the separation-distance between spent-fuel packages would be greater than those currently projected, increasing the total length of the main gallery to about 1.2 km.

The diameter of the main gallery openings is 6 m; whereas the diameter of the disposal-gallery openings is 3 m. The HLW containers insertion (with the space needed for the remote trolley below) leaves minimal residual annular space inside the concrete blocks that will be grouted after waste emplacement.

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