The shafts give access to two main galleries 3.5 metres in diameter, which lie at right angles to the connecting gallery. The disposal galleries that will receive the radioactive waste branch out from this H-shaped vertebral column. Those for the vitrified waste and spent fuel are on one side of the connecting gallery, and those for the other waste in the geological group are on the other side. The plane of the disposal facility follows the dip of the clay layer, which is 1 to 2 %. This can be done by aligning the main galleries (or the disposal galleries) on this dip and arranging the disposal galleries (or the main galleries) horizontally on the median plane of the clay layer, or by a combination of these two options. The choice of gallery and shaft diameters is based on practical, technical, economic, and safety considerations: they must be large enough to convey construction and backfill materials as well as waste packages at the desired rate, but must not be oversized, as this would unnecessarily enlarge the clay zone disturbed by excavation and increase the costs of construction and backfilling.

The current reference design displays a number of fundamental differences compared with the design proposed in the SAFIR report:

- the *separation* of the vitrified waste and the spent fuel from the other waste in the geological group to prevent physico-chemical interactions which could compromise long-term safety (increased robustness), to facilitate thermal calculations and, more generally, to allow more convincing safety assessments;
- the use of *watertight packagings* of sufficient corrosion resistance for the primary packages of vitrified waste (the overpacks, Fig. 3.21) and the spent fuel so as to ensure the function of physical containment of the radionuclides, at least during the thermal phase of the disposal system. This avoids the need to consider the complex interactions between components and radionuclide migration under a temperature gradient (increased robustness). The thermal phase—the period during which the presence of the waste increases the temperature in the near field by more than ten degrees above that of the undisturbed clay (approximately 16°C)—is around 300 years for the vitrified waste and around 2000 years for the spent fuel of the UO_2 type.
- the use of watertight and corrosion resistant *disposal tubes* to facilitate the emplacement of the vitrified waste and spent fuel into the disposal galleries.

The reference design for the *vitrified waste* (Fig. 3.22) assumes that there will be a total of 3915 packages to be disposed of: 420 packages produced under existing reprocessing contracts, plus 3495 packages that would be produced under any new contracts. (If Belgium ultimately rejects the reprocessing option, then the existing vitrified waste will be incorporated into the disposal solution developed for the spent fuel.) To accommodate the vitrified waste, the two main galleries service eight disposal galleries that are at right angles to them, each 800 metres long and 2 metres in diameter. The disposal galleries are divided into three segments: two segments of 200 metres outside the main galleries and one of 400 metres between them. The first disposal gallery is 100 metres from the connecting gallery, with subsequent disposal galleries spaced at 40-metre intervals. This is to limit the mean temperature increase in the Neogene Aquifer, which ONDRAF/NIRAS has set at 6°C in the absence of any regulatory norm. The facility intended to receive the vitrified waste would thus occupy an area of 0.224 km^2.

Figure 3.21 The overpack used for demonstrations in the HADES–PRACLAY hall.

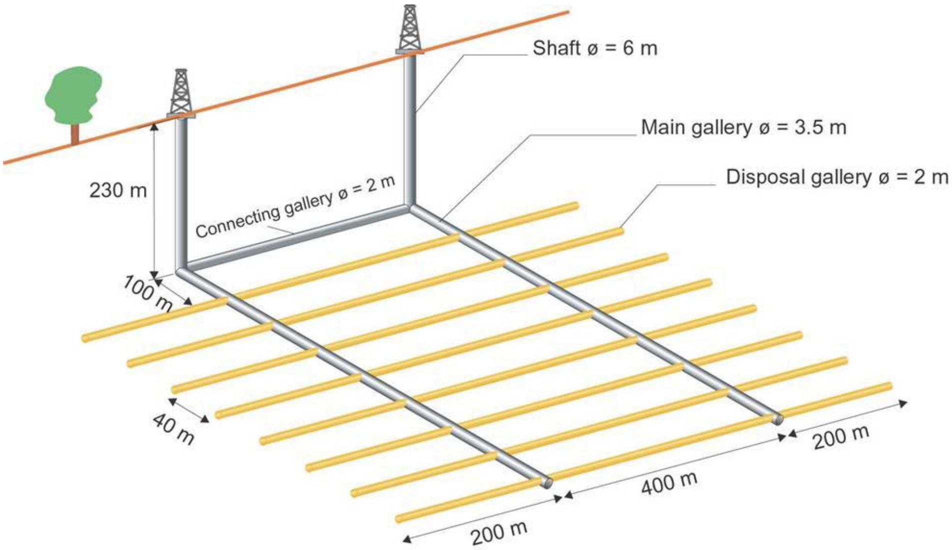

Figure 3.22 The reference design of the deep repository for the vitrified waste.

Under the principle of multiple barriers, the design of the disposal galleries provides for a succession of concentric envelopes—the engineered barriers—around the waste packages (Fig. 3.23). The primary package of vitrified waste, surrounded by its overpack, is pushed into a stainless steel tube, the 'disposal tube', aligned on the centreline of the gallery. On each end of the overpack are four wheels mounted at 90°, with permanent brakes to prevent the package moving accidentally; a gripper head is also mounted axially at one end of the overpack. Each disposal tube consists of sections hermetically welded to one another so that water cannot come into contact with the waste, as this could generate steam and induce unwanted geochemical phenomena. The space between the tube and the gallery lining has previously been filled with a backfill material that is naturally or, if necessary, artificially hydrated before the waste is placed, to make it swell and fill the interstitial voids. This material consists of prefabricated segments made from a mixture of bentonitic clay (‘FoCa’ clay, a natural product containing 80 % swelling clay), sand, and graphite. The latter is to improve the thermal conductivity of the mixture, and so dissipate the heat emitted by the waste more efficiently. Each tube is closed at the main gallery end by a temporary shield protecting the operators from the ionising radiation emitted by the packages already in place, and that can be replaced by a permanent system when the tube is full. Once full, each disposal gallery is sealed with a plug made from FoCa swelling clay and with a second plug designed to resist the swelling pressure. The gallery walls and the walls of the access shafts are lined with prefabricated concrete segments.

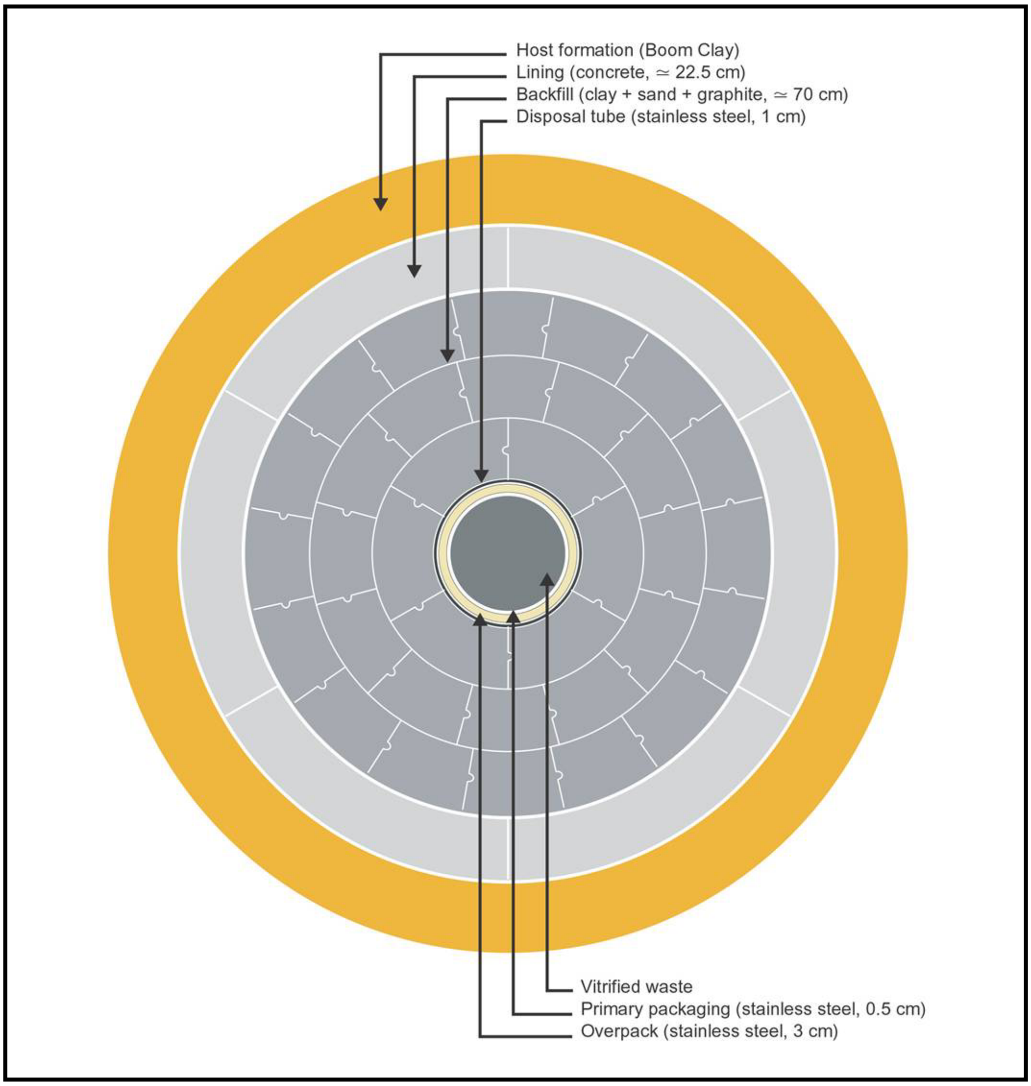

Figure 3.23 Transverse section through a disposal gallery for vitrified waste, showing the multiple-barrier principle.

The reference design for the disposal of *spent fuel* (Fig. 3.24) is an adaptation of the design developed for the vitrified waste to make it suitable for longer packages (5 metres instead of 1.6 metre), that cool down more slowly. The main differences are as follows:

- the angle between the main galleries and the disposal galleries has been reduced (from 90° to 45°) to allow longer packages to be transferred into the disposal galleries;
- the gallery spacing has been increased (from 40 to 110 metres) to prevent the mean temperature in the Neogene Aquifer rising by more than 6°C;
- to prevent the mean temperature in the Neogene Aquifer rising by more than 6°C, the number of packages has been adjusted to the acceptable thermal output per metre of gallery (four disposal tubes per gallery for the UO_2 fuel arranged in a square about the centreline of the gallery; a single disposal tube for the MOX fuel, aligned on the centreline of the gallery).

The gallery network would comprise 800 metres of galleries for the 420 overpacks of vitrified waste and 10.8 km of galleries for the 9859 spent fuel assemblies that are anticipated. It would thus cover an area of approximately 1.3 km^2.

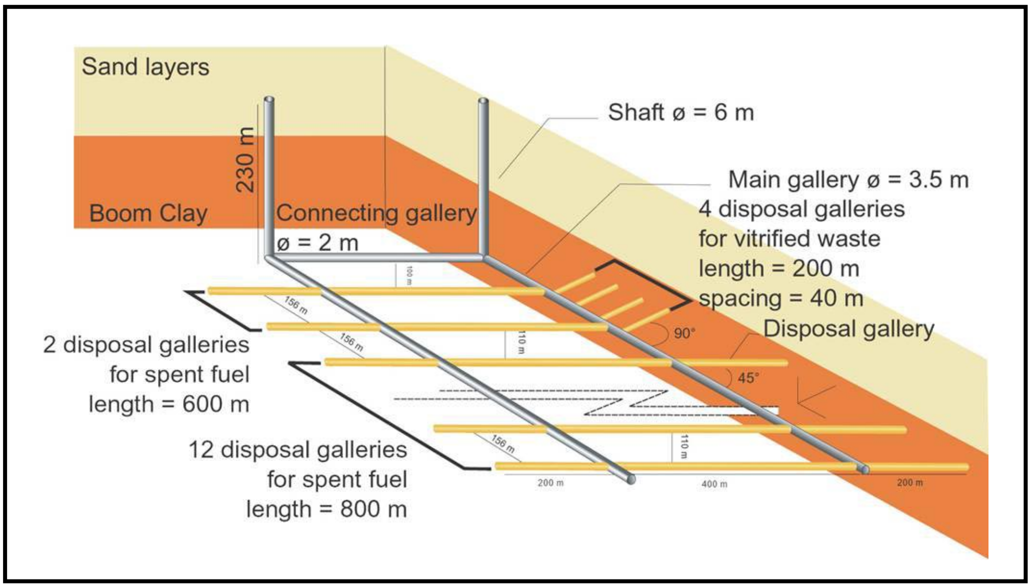

Figure 3.24 The reference design of the deep repository for the spent fuel.

Each of the various components of the disposal facility performs one or more functions (Table 3.7 and Fig. 2.5). Some perform the safety functions of 'physical containment' and 'delaying and spreading the releases', and are taken into account in long-term radiological safety assessments, i.e., assessments of radiological safety after the closure of the repository (see Chapter 4). These are the waste matrices (glass and UO_2), that retard the leaching (function *R1*), the overpack for its watertightness (function *C1*), and the material used to seal off the galleries and shafts, that retains the radionuclides (function *R2*). Other components such as the primary package and the disposal tube play a safety role that is short term and potentially longer term, but their actual contribution to safety is disregarded in safety assessments, representing instead a 'safety reserve'. Finally, some components are needed to ensure the mechanical stability of the repository and, hence, of the host formation (the gallery and shaft lining, and the backfill material), to facilitate waste emplacement (the disposal tube), or to ensure operational safety (the closure and shielding system for the disposal tube). None of these components should adversely affect the performance of the others, especially the performance of components that have long-term safety functions. Each must, for example, be chemically and mechanically compatible with the others, i.e., it must not aid corrosion or induce significant mechanical disturbances. Finally, no component should, by its presence, assist radionuclide migration towards the biosphere.

Finally, the *other category C waste*, which emits less heat, and the *category B waste* would be stacked by classes in galleries 3 to 6 metres in diameter, with the voids between the packages being backfilled with concrete or a similar material. The number of packages allowed for each section of gallery will depend, among other things, on the need to limit the mean temperature increase in the Neogene Aquifer to 6°C and on the total percentage of voids in the waste. This should not exceed 20 % so as to minimise the risk of the packages and backfill material being crushed by the pressure of the host formation, and, hence, of the host formation becoming unevenly decompacted, leading to disturbances.

3.3.2 The various operational stages of a deep repository

The operational phase of a deep repository can be divided into four main stages: construction, operation (i.e., the placing of the waste, followed possibly by a waiting period prior to closure), closure, and institutional control. During the operational phase, the disposal system must be closely *monitored*.

Monitoring the disposal system involves continuously or discretely observing and measuring—on the surface and underground—parameters that can be used to assess the behaviour of certain components of the system and to assess the impact of the repository and its operation on the environment. Monitoring must not affect the functioning of the repository barriers, and should not increase the risk of human intrusion. It starts before the construction of the repository and continues until the end of the institutional control phase. It has four primary objectives:

- before the construction of the repository, *to determine the parameters and natural processes characterising the disposal site and its environment*. This characterisation must ultimately indicate the changes to the initial situation induced by the presence and operation of the repository, and it must provide the information necessary to develop the repository design and to assess safety.
- from the start of the construction phase until the end of the institutional control phase, to assess the impact of the disposal facility on the operating personnel, the public, and the environment, so as to ensure compliance with applicable standards and make adjustments as necessary, and, also, *to compare the behaviour of the various components of the disposal system with the behaviours assumed* in the assessments carried out.

Table 3.7 Main characteristics of the repository design proposed for the vitrified waste, functions performed by the main components safety for the normal-evolution scenario (**C1** = watertightness; **R1** = resistance to leaching; **R2** = diffusion and retention. Access

Components	Characteristics	Safety functions during phases				Other
		operational	thermal	isolat.	geolog.	functions
Matrix	Borosilicate glass	Immobilisation	–	**R1**	R1	Retrievability
Primary packaging (welded cylindrical container)	Stainless steel AISI 309 height: 1.34 m external ∅: 43 cm thickness: 5 mm mean filled weight: 492 kg	Mechanical strength	C1	R2	–	Handling Retrievability
Overpack (welded cylindrical container fitted with 2 × 4 wheels at 90°)	Stainless steel AISI 316L hMo height: 1.58 m internal ∅: 46 cm thickness: 30 mm mean filled weight: 1000 kg	Radiological protection	**C1**	R2	–	Handling Reduction of thermal power per unit length Retrievability
Disposal tube	Stainless steel AISI 316L hMo internal ∅: 55 cm thickness: 10 mm length of sections: 3 to 4 m length of segments: 200 or 400 m	–	C1	R2	–	Emplacement Retrievability
Backfill material of the disposal galleries	Prefabricated blocks made from a mixture of bentonitic FoCa swelling clay (60 %), sand (35 %), and graphite (5 %)	Mechanical stability	C2	R2	R2	Heat dissipation
Lining of the disposal galleries	Prefabricated concrete segments min. thickness: 22.5 cm	Mechanical stability	–	–	–	Retrievability
Galleries	Int. ∅ total length spacing [m]					
disposal	2 8 × 800 40	–	–	–	–	Disposal
main	3.5 380 400	–	–	–	–	Handling
connecting	2 400 –	–	–	–	–	Connection
Access shafts	Internal ∅: 6 m	–	–	–	–	Handling
Access shaft lining	Concrete and asphalt	Mechanical stability Watertightness	–	–	–	Retrievability
Backfill material of the rest of the facility	Mixture of FoCa swelling clay and sand	Mechanical stability	C2	**R2**	**R2**	–
Gallery and shaft sealing material	Mixture of FoCa swelling clay and sand Concrete	Radiological protection Mechanical strength	C2	**R2**	**R2**	–

of the disposal system and of its environment and, **in bold print**, functions considered in assessments of the long-term radiological limitation L is not shown.)

Principal studies still needed to confirm the reference design
confirm that the durability of the glass matrix largely exceeds 10 000 years
–
confirm the choice of material and determine its minimum thickness decide on the method of manufacture, the place and method of filling, as well as the method of closure by welding decide on whether a filling material such as glass frit will have to be introduced between the primary packaging and the overpack to improve heat dissipation and enhance mechanical strength while minimising degradation of the glass matrix decide on whether the use of overpacks makes it possible to declare the repository a 'zone not controlled for radiological contamination'
confirm the choice of the material and the dimensional characteristics of the sections, and establish tolerances examine how to place the sections and then weld them with perfect alignment, and how to close the end of the tube verify whether, up to the end of the period of retrievability (if any), the tube will stay watertight and free from distortion, and whether it will retain an internal surface smooth and clean enough for an overpack to be pushed or pulled over a distance of 200 metres decide on the space to be left between two overpacks to allow them to expand freely under the effect of heat study the behaviour of the tube under the effect of the thermal load and an uneven swelling pressure decide whether a filling material (glass frit) must be introduced between the overpack and the tube
confirm the choice of backfill material and optimise its composition so as to obtain adequate thermal conductivity and an even swelling pressure that will neither disturb the clay nor crush the tube determine the form (blocks, pellets, etc.) in which the backfill material will be handled in the galleries and how it will be placed study the risk of the filled tube sinking into the backfill material under its own weight study the kinetics of natural hydration and any use of artificial hydration to obtain the desired swelling pressure
confirm the choice of material, optimise its composition, and decide on the dimensions of the segments determine the maximum distance between the segments and the working face, and the over-excavation
establish an emergency escape plan determine the characteristics to be given to the connecting chambers between disposal galleries and main galleries confirm the minimum distance between the connecting gallery and the first disposal gallery confirm the diameter
–
–
confirm the choice of backfill material, optimise its composition, and decide how to place it
study the design and composition of the plugs for galleries and shafts

Safeguards
Requirements established by international treaties on the non-proliferation of fissile materials designed to prevent their diversion for any purpose. These requirements include specifically the accountability and traceability of fissile materials placed in a repository (see also Section 2.2.4).

- after several years or decades of operation, *to provide a decision platform* based on experience by making it possible to optimise those aspects of the design that still offer a certain amount of flexibility and presenting all of the parties concerned with concrete and convincing arguments whenever important decisions have to be taken, especially the decision to close the repository.
- for a repository containing large amounts of fissile materials, *to ensure*, in accordance with IAEA requirements on safeguards, *that these materials cannot be diverted.*

3.3.2.1 Construction

The construction of the HADES underground research facility beneath the SCK•CEN site at Mol dates from the 1970s and was part of the first research and development programme of SCK•CEN (1975–1979) relating to the disposal of category B and C waste. This programme mainly aimed to assess the extent to which it is possible to construct, at a depth of some 220 metres in the Boom Clay layer at Mol, a network of galleries of the type proposed for the disposal of waste packages so as to protect humans and the environment from radiation doses above those that are reasonably acceptable. These galleries were also required for conducting in situ experiments to accompany those carried out at the surface on samples taken during exploratory drilling.

In line with its mission of long-term management of radioactive waste, ONDRAF/NIRAS took over the SCK•CEN project in 1985 and confirmed the Boom Clay beneath the Mol site as the reference formation for its disposal programme, thus in particular for assessing new construction techniques. Started at that time, the extension of the underground facility is still in progress. It has shown that it is possible to safely excavate shafts in aquifer sands that have been frozen and to excavate the facilities needed for disposal into the Boom Clay without the need for freezing. Together with the results of long-term safety assessments, it has also highlighted the importance of limiting the disturbance of the clay by excavation, as clay is the main barrier to radionuclide migration. Work is now at the stage of technical and economic optimisation: it must culminate in the selection of an excavation process and a lining that are easy to use, safe, and economical. This process must also limit disturbances to the formation. At least part of this optimisation will take place during excavation of the galleries required for the PRACLAY demonstration project (see Section 3.3.3).

Changes in excavation and lining techniques

The construction of the HADES underground research facility (which is still ongoing) has seen five phases since 1980 (Figs. 3.25 and 3.26). These phases have mainly involved a simplification of the excavation techniques and changes in the type of lining; this has followed increases in the knowledge of the geomechanical behaviour of the clay. The whole facility is equipped with measuring instruments placed in the clay before the lining is emplaced, as well as instruments mounted on the lining itself to measure its deformation. The different types of lining also have apertures of various sizes to allow access to the clay for experimental purposes. Finally, the research facility is not in the middle of the Boom

Clay layer, but in its upper section, at a depth of 223 metres, this being a result of the geometrical characteristics envisaged for the repository design when construction began.

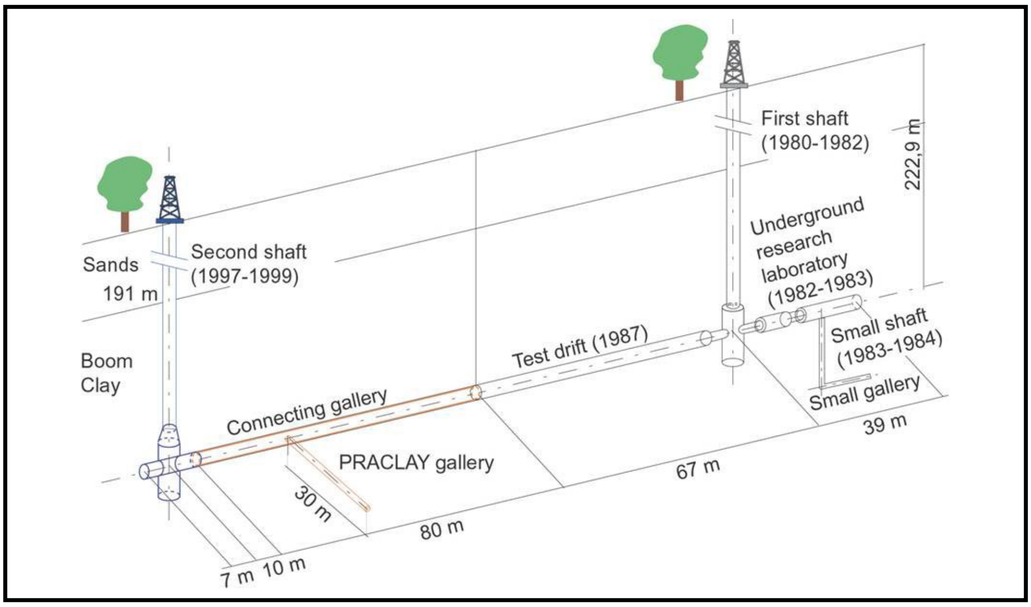

Figure 3.25 The HADES underground research facility. The excavation of the connecting gallery and of the PRACLAY gallery (in brown) is foreseen in, respectively, 2002 and 2006.

Figure 3.26 General views of the HADES underground research facility.

SCK•CEN took maximum precautions when constructing the *first access shaft* to the clay formation. This shaft was dug between 1980 and 1982 using pneumatic drills and shovels in soil previously frozen to a temperature between – 10 and – 15°C by 2 × 16 freezing tubes evenly arranged in two concentric circles. This standard procedure for excavating through aquifer sands was used, first, to hydraulically separate the shaft from the aquifer before installing the watertight lining (a sheet of polyethylene sandwiched between two 40-cm-thick layers of shotcrete) and, second, to ensure the geomechanical stability of the excavation in the sands and in the Boom Clay until the lining had been placed. The diameter to be excavated was fixed at 4.3 metres so as to produce an effective diameter of 2.65 metres minimum. The first shaft, with a depth of 214.7 metres, opens out into a connecting chamber 13 metres high and with an inside diameter of 4 metres.

The *HADES experimental gallery* was built in 1982–1983, again following freezing of the clay formation. It has an effective diameter of 3.5 metres over most of its length, and is 39 metres long from the outside face of the connecting chamber up to and including the 2-metre-thick reinforced concrete plug closing its end. SCK•CEN opted for the ‘tunnel’ approach rather than the ‘mine’ approach when designing the lining. In the mine approach, the lining is only designed to stabilise the formation in the short and medium term, while allowing rectification of the gallery diameter if required (not easy to carry out in operation). In the tunnel approach, it is designed to withstand the long-term stresses. This approach is also safer for the personnel and minimises disturbances to the formation. The lining design parameters were the lithostatic pressure (4.5 MPa), a coefficient of pressure of soils at rest K_o (ratio of horizontal to vertical pressure) of 0.6, and the conventional safety factors. The high stresses and moments calculated from these cautious design assumptions led to the choice of a very rigid lining: segments made from galvanised nodular cast iron (Fig. 3.27).

Since the freezing technique and the use of nodular cast iron segments seemed economically unrealistic for an actual disposal facility, SCK•CEN decided to assess the possibilities of excavating galleries in the clay without freezing and of using a cheaper lining. In 1983, it thus embarked on the construction of the *small shaft*, 2.5 metres from the end of the HADES gallery. This shaft was excavated by hand through the clay, which became less and less frozen as work advanced. The small shaft is 23 metres deep, has an effective diameter of 1.4 metre, and was lined with concrete segments 30 centimetres thick separated by timber spacers to reduce rigidity. The *small gallery* on which it opens has the same diameter but is only 7 metres long; it was excavated in 1984 and lined in the same way (Fig. 3.27). The clay face at its far end was left exposed so as to better monitor the movements of the formation over time.

As the construction of the small shaft and small gallery showed that it was possible to excavate the Boom Clay without freezing it, ONDRAF/NIRAS and SCK•CEN decided to explore the possibility of constructing a gallery, with a similar diameter to that of the galleries envisaged in the actual repository, without freezing the clay but still lining it with concrete segments. This gallery would also be used to conduct experiments in Boom Clay that had not been disturbed by freezing. This time, the design parameters for the linings were the lithostatic pressure (4.5 MPa), a K_o of 0.7 instead of 0.6, and lower factors of safety than previously used. The *Test Drift*, which is 3.5 metres in diameter and 67 metres long, was excavated in 1987 with pneumatic drills. It is lined with two types of support material:

concrete segments 60 centimetres thick and, over a short section operated by the French Agency for Radioactive Waste Management (*Agence Nationale pour la Gestion des Déchets Radioactifs* or ANDRA), metal sliding ribs (Fig. 3.27), which are less rigid and so tolerate a certain degree of convergence of the formation.

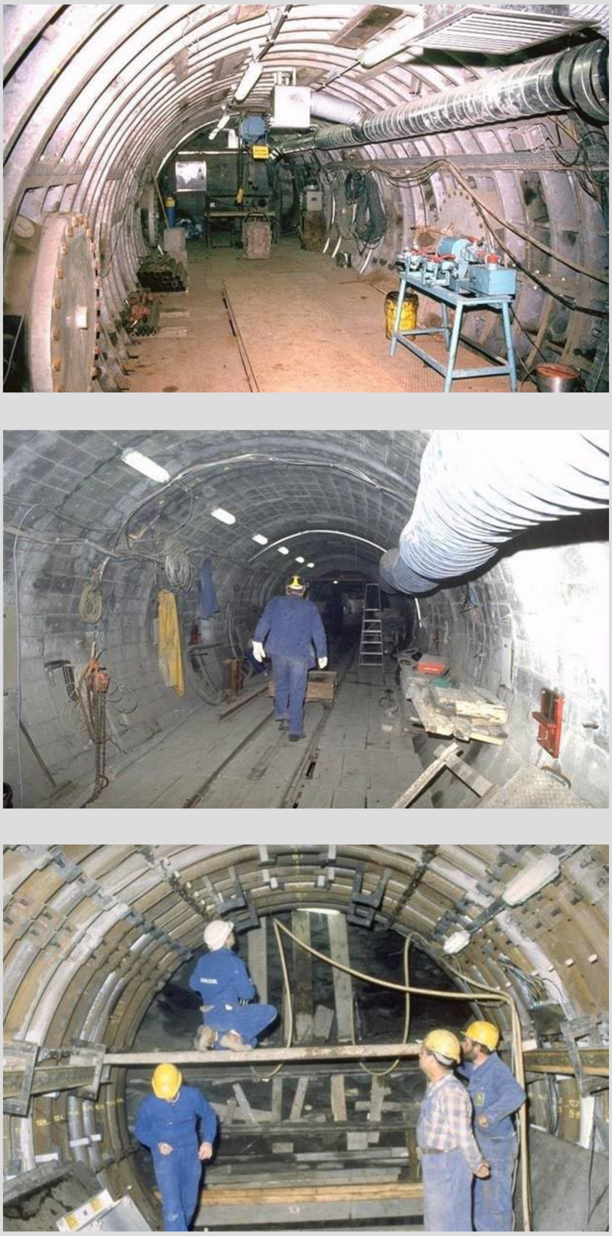

Figure 3.27 The three types of lining so far used in the underground facility. At the top: nodular cast iron segments (HADES experimental gallery); in the middle: concrete segments (small gallery and Test Drift); at the bottom: sliding steel ribs (Test Drift, ANDRA section).

Finally, the *second shaft* was excavated between 1997 and 1999. This was to comply with mining regulations that required the existing underground facilities to have an additional access before work began on the excavation of the gallery intended to be used for new experiments, specifically the PRACLAY experiment. It was excavated 90 metres from the end of the Test Drift (to which it will be connected by the so-called 'connecting' gallery) using a jack-hammer mounted on a hydraulic arm and hand-operated pneumatic drills; only the aquifer sands and the first few metres of clay were frozen. Like the first shaft, it has a constant effective diameter (3 metres) and a multi-layer lining in the aquifer sands, and opens out into a larger connecting chamber. Its lining was redesigned, however, so as to be more watertight than that of the first shaft, to improve the distribution of stresses in its inner part, and to isolate these stresses from the stresses in its outer part. The outer shotcrete lining, the thickness of which gradually increases from 0.2 to 0.4 metre, has therefore been separated by asphalt from the inner lining, which is made of hollow prefabricated concrete cylinders 0.3 metre thick and is hooped with a watertight steel sheet. The asphalt presents a viscous behaviour in the long term, and exerts a pressure on the inner lining that is equivalent to its hydrostatic pressure, setting up isotropic stresses within it. It also isolates the behaviour of the inner lining from that of the outer lining, which is exposed to the lithostatic and hydrostatic pressures from the formations through which the shaft passes.

The base of the second shaft, the connecting chamber, and the starting chamber of the connecting gallery (Fig. 3.28) were excavated based on what was then the most up-to-date knowledge of the behaviour of the non-frozen Boom Clay, namely that it has an elasto-visco-plastic behaviour and that its convergence can be rapid (see Section 3.6.2). It was, therefore, essential to install a support capable of limiting this convergence as soon as possible after excavation, both for safety reasons and to prevent the formation from becoming excessively decompacted. A temporary lining made from sliding steel ribs was therefore rapidly placed (Fig. 3.28). The permanent lining made out of concrete poured in situ over steel reinforcements was not placed until excavation was complete. Even so, slip planes and fractures that were several metres long and several millimetres wide in places appeared in the upper section of the starting chamber of the connecting gallery. These were due mainly to the fact that this zone was already decompacted by the excavation of the shaft and to delays in the execution of the work (Fig. 3.29). The characterisation programme that has been initiated in the meantime should answer questions about the origin of these phenomena (fractures that are neoformed, i.e., strictly excavation-induced, or natural fractures reactivated by the excavation), their extent, their impact on the hydraulic conductivity of the formation, their long-term behaviour (self-healing), and their impact on operational and long-term safety.

In 2002, the base of the second shaft will be linked to the existing facility by a connecting gallery. The hydromechanical behaviour of the argillaceous formation and the rate of advance of the working face will be monitored during the excavation of this gallery by sensors installed from the face of the Test Drift (CLIPEX project); these sensors were installed well in advance, to allow the instrumentation and the rock to stabilise. The connecting gallery, which will be lined with an expandable system of concrete blocks based on the wedge block technique to limit the convergence of the rock as much as possible (see below), must in particular allow the excavation of the PRACLAY gallery in 2006 (see Section 3.3.3).

Figure 3.28 Excavation of the second shaft. Excavation of the starting chamber of the connecting gallery (top) and hydraulic arm and metal sliding ribs (bottom).

Minimising disturbances around the excavations

While it is now known that large-diameter galleries can be constructed in the non-frozen Boom Clay, it is still essential that the techniques used disturb the properties of the formation as little as possible within the bounds of technical and economic feasibility (see Section 3.6.2). Optimising the choice of excavation and support techniques suitable for the construction of the repository aims to limit the geomechanical and hydraulic disturbances around the excavations by minimising convergence during excavation. These disturbances depend on the excavated diameter; however, for a constant excavated diameter, their impact will also be smaller

- the faster the excavation rate;
- the shorter the time between clay excavation and lining placement;
- the smaller the over-excavation;
- the closer the contact between the lining and the excavated profile;
- the more rigid the lining.

(A third type of phenomenon affecting the excavation-disturbed zone in clays is the change in the geochemical properties of the medium following the oxidation of the clay, especially of the pyrite, which can release sulphates and acidify the medium.)

Figure 3.29 Excavation of the second shaft. Slip planes (top) and fractures (bottom) observed during excavation of the starting chamber of the connecting gallery.

Current knowledge suggests that the tunnelling techniques, which are commonly used by civil engineers to dig long tunnels (including tunnels in soils that behave like the Boom Clay) but at shallower depth, plus the use of expanded concrete segmental lining using the wedge block technique, will meet the demand for minimising disturbances. (The microtunneller method associated with the pipe jacking technique, commonly used at shallow depths, has been considered as a potential alternative to conventional excavation techniques for digging galleries 200 metres long but only 60 cm in diameter. However, this is currently regarded as hardly feasible at the depth proposed for the repository, at least when using a conventional microtunneller, owing to the rapid convergence of the clay and the resulting high friction forces that increase the risk of jamming.)

Mechanised tunnel boring machines offer a number of advantages.

- They produce a circular excavation section, which is the most stable configuration mechanically.
- They can attain an advance rate of at least 10 metres a day. This rate far exceeds that above which the rate of axial convergence ahead of the working face is low, i.e., above which the formation is less disturbed. (This critical excavation rate has been estimated at 2 metres a day for galleries of 2 metres effective diameter.)
- They can be fitted with a cylindrical shield to support the clay, pending the installation of the permanent lining behind the machine, which must be done as rapidly as possible.

- They are safe, demountable, have a modular capability, and their cost effectiveness increases with the length of the gallery.

The difficulty with tunnelling techniques is finding the right compromise for the over-excavation. This must be small relative to the nominal diameter of the lining so as to minimise disturbances to the formation, yet large enough to prevent the tunnel boring machine jamming due to the convergence of the clay and the high lithostatic pressure at this depth. The value of the total convergence—the total movement of the rock on the periphery of a gallery compared with the rock prior to excavation, including the convergence ahead of the working face—is currently estimated to be between 4 and 9 cm over an excavation radius of 2.5 metres.

An expanded concrete segmental lining based on the wedge block technique also offers a number of advantages.

- It is intrinsically stable because—like keystones in an arch—the wedge-shaped key or keys (which give their name to the technique), which are force-fitted between the concrete blocks forming each ring of the lining, place the ring in post-stress directly in contact with the clay. (The lining rings are assembled immediately behind the tunnel boring machine, with the concrete blocks being held by an erector until the wedges are fitted.)
- Concrete as a material behaves very well in compression, the main load mode occuring in a circular lining subjected to virtually isotropic external stresses ($K_o \approx 0.9$—see Section 3.6.2).
- Concrete is an inexpensive material.

Such a lining is not watertight, but this is not a disadvantage in the operational phase, since the low hydraulic conductivity of the Boom Clay will make the flow of water towards the galleries insignificant, and this water will be completely evaporated and dissipated by ventilation.

The wedge block technique cannot, however, be used where a gallery intersects other underground structures. The main galleries that will serve the disposal galleries will, therefore, be fitted with an additional lining or with a different lining designed to take the additional stresses that occur during the construction of gallery intersections, minimise the resulting disturbances in the clay, and thereby maximise the usable length of the disposal galleries. Furthermore, the construction of connecting chambers between the shafts and the galleries, which is difficult to mechanise, will inevitably induce more significant decompaction in the near formation; the repository design allows for this by specifying a minimum distance between the shafts and the first disposal gallery.

The excavation in 2002 of the gallery intended to connect the second shaft to the Test Drift, which will be 84 metres long and have an effective diameter of 4 metres, should make it possible to demonstrate that the tunnelling technique can be used at the depth of the repository and that, when combined with the wedge block technique, it can meet the safety requirements in the short term while also minimising disturbances. The excavation will also provide an opportunity to assess the over-excavation that is needed. The advance rate of the excavation will have to be at least 2 metres a day and will probably be limited by the capacity of the second shaft in terms of removing the spoils and transporting the blocks. The hypotheses used for calculating the sections are, on the one hand, P_v = 3 MPa and P_h = 2.7 MPa, and, on the other hand, a temperature increase of 8°C, corresponding with the expected thermal load on the connecting gallery induced by the PRACLAY demonstration experiment.

3.3.2.2 Operation

Although there has so far been relatively little research into the operation of the deep repository, experience gathered from the daily operation of the HADES underground research facility and from the many experiments that are conducted in it, some of which have used or are using radioactive sources, represents a valuable fund of knowledge in operational matters.

Specifically, the operation of the deep repository will involve both *conventional underground operations* (such as ventilation, the operation of the lifting systems in the access shafts, transport and handling, lighting, and the maintenance and inspection of equipment), and the radioactive waste *disposal operations* proper. Research into the disposal operations advances as the repository design is developed and new knowledge is acquired, but it has so far been limited to the vitrified waste and spent fuel and has not progressed beyond the stage of a feasibility study for these waste classes. The disposal operations for these two waste classes should be quite similar; the main differences arise from the difference in the length of the packages, which can be as much as 5 metres for the spent fuel. These operations will be entirely mechanised and performed by remotely-controlled robots, and will be accompanied by precautions designed to guarantee the radiological protection of the operators.

In the current reference design, the *vitrified waste* is received in a surface facility at the disposal site where the overpacks are removed from their transport packaging and placed in a transfer wagon which will take them to their final destination. The transfer wagon has a shielded barrel with four chambers, each of which can contain one overpack; the barrel is at right angles to the track on which the transfer wagon runs. The wagon is then taken to one of the access shafts and lowered down to the level of the underground galleries where it runs to the entrance of the designated disposal gallery. There its moving chassis is raised until it is level with the disposal tube and then advances to allow the shielding valve on the barrel to dock with the shielding valve of the disposal gallery to ensure continuity of the radiological shielding. The two valves are locked together by rams and are then opened, and the barrel rotates to bring the first chamber into line with the tube. A device known as the ‘pushing robot’, which is installed in a housing on the wagon, now pushes the first overpack into its final position in the disposal tube. Once it has placed the overpack in position, the robot returns empty to its housing. This sequence is repeated three more times (for the three remaining overpacks), after which the two shielding valves are closed, the rams retracted, and the chassis lowered. The transfer wagon returns to the shaft and is raised back up to the surface to be loaded with four more overpacks.

The transfer wagon and the pushing robot are already in an advanced stage of development: almost full-scale prototypes of each machine are being demonstrated in the HADES–PRACLAY exhibition hall at Mol (Fig. 3.30). Depending on the location of the repository within the clay layer, either the transfer wagon or the pushing robot will have to be capable of negotiating a dip of 2 %. The pushing robot will also be required to push packages weighing about 1 000 kg over a distance of 200 metres and should have a positional tolerance of around one centimetre in order to be capable of leaving a small space between two successive overpacks to allow for thermal expansion. The clamp that is fitted to the robot will allow it to grip the head of the overpack for retrieval, if necessary. The conclusive tests that have been carried out with weighted overpacks over at least ten metres have yet to be corroborated by tests over 200 metres, and the effects of temperature and radiation on the electronic and mechanical systems must also be studied in greater detail.

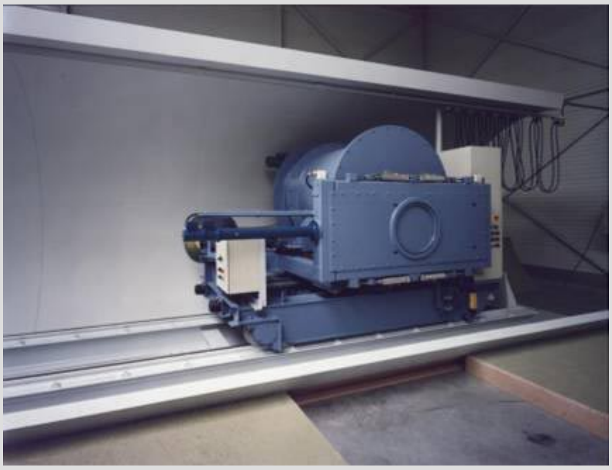

Figure 3.30 The handling device for the overpacks of vitrified waste being demonstrated in the HADES–PRACLAY hall.

The disposal of *spent fuel* packages would be a variant of the disposal of vitrified waste overpacks. Because these packages are too long to be lowered into the disposal facility horizontally, they would be placed in a shielded transfer container, which would be lowered vertically down the access shaft, rotated into the horizontal position at the bottom of the shaft, and placed on a wagon that would take it to the designated disposal gallery. Like the transfer wagon for the vitrified waste, this wagon could line up the shielded container with the disposal tube and would be equipped with a pushing robot. Because of their size, however, the use of transfer containers with four chambers like the barrel on the transfer wagon would involve enlarging the main galleries in the disposal gallery area to a diameter of 6 metres, a complicated and expensive exercise. Using ‘single-seater’ transfer containers would be an alternative solution.

3.3.2.3 Closure

According to the reference schedule, the closure of the repository, which will involve the decommissioning of the surface facilities and the permanent isolation of access routes to the waste, will take place several years after completion of the disposal activities at the latest. A decision to close the repository will not be taken until, first, the monitoring of the facilities during the operation has confirmed that the system functions properly and, second, the authorities responsible and all of the other parties involved are confident that the system is robust and offers an acceptable level of passive safety. In theory, however, the main galleries and shafts could be kept open longer to provide a significant level of flexibility in the decision-making process. Such a decision would have to be fully justified, based in particular on a detailed analysis of its potential adverse impact on safety. This open phase could certainly not last for more than a hundred years or so without having a considerable impact on operational and long-term safety. Major maintenance and refurbishment works would be required in such a situation, and different types of disturbance could affect the containment capacity of the disposal system and its robustness. Changes in economic conditions could also interfere with the decision-making process, with the open disposal facility being neglected and even left unsupervised in the long term.

As well as marking the transition from a system of active monitoring of the waste to one of passive containment, the closure of the repository is vital to ensure its long-term safety. Closure must indeed

- ensure the geomechanical stability of the host formation, so as to prevent the gradual collapse of the disposal galleries with the attendant risk of crushing the waste packages and enlarging the disturbed area of the formation (backfilling);
- prevent any preferential migration of radionuclides via the galleries and shafts (sealing);
- reduce the probability and consequences of any human intrusion on the site, whether on the surface or underground (sealing and backfilling).

The proper execution of the closure will thus make a major contribution to the future performance of the repository, and so the conditions of its implementation, especially as regards the choice of materials and installation techniques, will require careful study (see Section 3.4.2.2).

In practice, the closure of the repository will mainly involve first *backfilling*, with a swelling clay-based material mixed with sand, and then *sealing* the main galleries, the connecting gallery, and the access shafts to prevent the formation of preferential migration pathways for the radionuclides. (The disposal galleries will have been gradually backfilled before or during the phase of waste emplacement, then sealed off once filled.) Although the lining of the galleries and shafts has a higher hydraulic conductivity than the Boom Clay and can therefore be a preferential migration pathway for the radionuclides, it will be kept, except where the main galleries are sealed, where it will be removed together with the clay that has been disturbed by excavation. The resulting cavity will then be packed with a swelling clay of the same type as the backfill material used for the disposal galleries. This will thus exert pressure on the argillaceous formation and will be sandwiched between two concrete anchoring plugs. Each main gallery will be sealed with at least two such watertight plugs placed in series. These plugs must have a hydraulic conductivity that is at least as low as that of the host formation, they must resist the lithostatic pressure and disturb the initial geomechanical and geochemical characteristics of the host formation as little as possible.

There will be two final stages to the closure phase of the repository: marking the site and archiving, for an indefinite period of time, all of the data characterising the disposal system and the disposed waste. Clearly *marking the site* using several types of surface and underground markers mainly aims to minimise the likelihood of human intrusion. The *archiving of data* will facilitate waste retrieval (if required) over a certain period of time. It will also help prevent any human intrusion in the medium and long term by administrative means, and may be useful in the medium term as a basis for appropriate decisions following any human intrusion. This data could be stored on a variety of different media and a number of copies deposited with one or more bodies, including a foreign or international organisation. Ideally, they would be backed up periodically before each data medium expires. Finally, the location of the repository would also have to be shown on all national and regional topographical documents covering the repository site.

3.3.2.4 Institutional control

Although the period of institutional control following the closure of the deep repository certainly cannot guarantee its safety, a monitoring programme, which would last from several decades to several centuries depending on the choices made by future generations, could help sustain the confidence of the public and of the other parties involved in the effective safety of the disposal system. As well as inspection and monitoring activities, which should not, of course, compromise the long-term passive safety of the repository, this control would include measures designed to prevent the uncontrolled use of the site and to ensure that knowledge of and about it is preserved. This active monitoring would then gradually give way to a period of basic official checks, after which the site would be finally released for unrestricted use. Knowledge about the disposal facility would then gradually dissipate, but the location of the site would have to be remembered.

3.3.3 The PRACLAY demonstration project

The main objective of the PRACLAY demonstration project (Preliminary Demonstration Test for Clay Disposal), begun in 1995, is to demonstrate by direct experiment between now and around 2015 that it is technically and economically possible to dispose of vitrified waste into the Boom Clay, while meeting the requirements that emerge from safety studies. This key project, which is open for international collaboration, involves constructing in situ a full-scale section of disposal gallery identical in all aspects with the galleries proposed in the reference design. This will be done using the industrial excavation techniques and materials currently proposed in that design, so far as possible. The gallery will then be filled, the waste being simulated by electric heater elements but no radioactive sources (Fig. 3.25). The project also aims to promote a better understanding of the disposal system and of the interactions between its various components. This is to confirm the results that will have been obtained by the end of the phase of methodological research and development (‘enhancing confidence’ in the models, their underlying assumptions, and their predictions) and to then optimise the reference design and its components. Finally, the project will include the design and construction of an intersection between a main gallery and a disposal gallery. This project is managed by the EIG EURIDICE (European

Underground Research Infrastructure for Disposal of Nuclear Waste in a Clay Environment), which at the end of 2000 took over from the EIG PRACLAY set up in 1995 by SCK•CEN and ONDRAF/NIRAS. EURIDICE has expanded its activities to include the complete operation and valorisation of the HADES underground research facility.

A full-scale instrumented mock-up of the underground gallery has been built on the surface in preparation for the in situ experiment (Fig. 3.31). The OPHELIE mock-up (On Surface Preliminary Heating Simulation Experimenting Later Instruments and Equipment) has a threefold purpose:

- to show that it is possible to place the backfill material and study its behaviour under conditions of temperature, pressure, and hydration that are representative of actual conditions;
- to confirm that placing the instrumentation system on the disposal tube, in the backfill material, and on the lining will not significantly disturb the clay;
- to confirm the performance and dependability of the measuring instruments and equipment under severe experimental conditions that are representative of the conditions in situ, before they are used underground.

The results and final conclusions of the tests carried out will be available when the mock-up is dismantled in 2002. It is already clear, however, that a number of instrumentation systems are not able to withstand the severe repository conditions for the required periods of time. This was also found during the experiments conducted in situ in the HADES underground research facility. Furthermore, the presence of chlorides in the mock-up will need to be analysed both in terms of their source and in terms of their potential impact on the durability of metal materials and on the behaviour of radionuclides. Finally, the construction of the OPHELIE mock-up and preparations for the PRACLAY experiment have already been used to highlight or formulate a set of unanswered issues about the practical implementation of the reference design (Table 3.7).

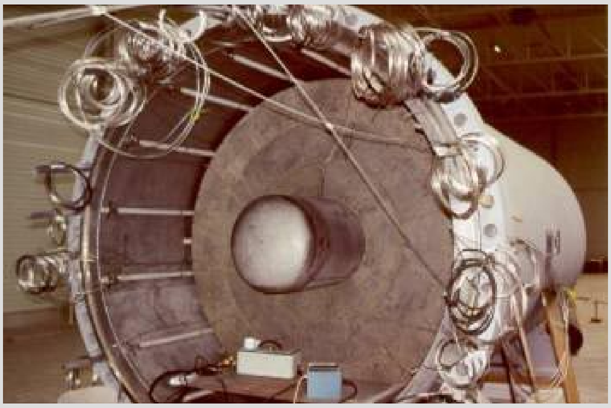

Figure 3.31 The OPHELIE mock-up.

The PRACLAY experiment proper, which will run from 2008 to around 2013, aims to study the thermo-hydro-mechanical behaviour of the Boom Clay in the near field, of the lining, of the backfill material, and of the disposal tube, when exposed to a temperature increase. It will also investigate the geochemistry of the interstitial water and the interactions between the various components of the system during the hydration and heating phases. Data about their behaviour will have to be collected under conditions that are as near as possible to those prevailing in an actual repository. Most of the measurements in the argillaceous formation will have to begin as soon as excavation work starts and continue throughout the experiment. The instrumentation around the future PRACLAY gallery will be installed at the start of the project in around 2005, and will be duplicated to ensure the gathering of data until the end of the experiment.

Although it is a demonstration experiment, PRACLAY has certain intrinsic limitations:

- in the absence of any hard evidence of really inappropriate choices, its duration (ten years) is too short for it alone to produce any convincing findings about the choice and behaviour of materials and measurement systems in the long term;
- it cannot be used to prove long-term safety, which can only be indirectly demonstrated;
- it is being conducted without a radiation field.

Under the present schedule, the 30-metre-long PRACLAY gallery will be excavated in 2006 starting from the connecting gallery, with the various components of the near-field design (disposal tube, hydration system for the backfill material, backfill material, sealing, etc.) and instrumentation of PRACLAY itself being installed in 2007. The experimental facility will then be heated up over a period of five years, allowed to cool down for one year and then dismantled, and the data collected throughout the experiment will be analysed.

3.3.4 Outlook

Although the reference repository design is at a relatively advanced stage of conceptual development for the vitrified waste and spent fuel, the many very specific issues raised by the preparation of the OPHELIE mock-up and the PRACLAY experiment, and during the drafting of the SAFIR 2 report, are good reasons for it to be reassessed in depth. This will be done as it is being extended to cover the other waste classes in the geological group. This development, which remains iterative, must be systematic and system-oriented, and based on the safety functions as an essential analysis tool. The future programme will seek mainly

- to define consistent technical criteria for the general design of the repository, its components, and its environment, especially in terms of acceptable temperatures and retrievability;

- to review all of the design bases of the disposal facility in the light of the requirements of long-term radiological safety and of operational safety;

- to develop an overall repository design that incorporates the solutions developed for each class, or homogeneous group of classes, of waste and, hence, to refine the design of the repository intended for the spent fuel, and to develop a disposal design for a waste class of category B that is regarded as especially demanding;

- to optimise the repository design as a whole, i.e., optimise the geometry of its different components and the choice of all of the materials used (Table 3.7), while taking all of the interactions between them into consideration;

- to continue the work on the practical aspects of the excavation of underground facilities;
- to describe in detail the operational aspects, both as regards conventional underground operations such as ventilation and fire protection, and as regards disposal operations;
- to define in detail the aspects of closure;
- to ensure the representative nature of the PRACLAY demonstration experiment by confirming the key characteristics of the disposal design intended for the vitrified waste;
- to continue the PRACLAY demonstration experiment;
- to specify the role of repository monitoring and its links with retrievability and safety, and to define—especially on the basis of possible future legislation, for example regarding safeguards—what aspects should be monitored, i.e., aspects that are representative both of the state of the disposal system and of its evolution, and that are likely to involve a corrective action that is measurable in practice;
- to assess the economic aspects of the construction and operation of the disposal facility.

3.4 Behaviour of waste and materials under disposal conditions

There are two aspects to the study of the behaviour of the waste forms and of the proposed materials for the construction of the underground disposal facility. First, the way in which each evolves under disposal conditions can be studied, i.e., analysing their individual performance, especially their durability. Second, their compatibility can be studied, i.e., analysing their effect on the performance of the other components of the disposal system. For example, the adverse effect of the waste matrices on the properties of the near field must not be excessive (see Section 3.6.5), and the backfill material should not adversely affect the corrosion of the overpacks.

3.4.1 Behaviour of the conditioned waste

As well as obtaining basic data that is vital for long-term radiological safety assessments (see Chapter 4), studying the behaviour of the waste forms in the Boom Clay aims to validate some of the simplifying hypotheses used in those assessments. These studies, carried out by SCK•CEN, have so far mainly concentrated on the vitrified and bituminised waste (see Table 3.2 for the inventory of waste belonging to the geological group).

Compatibility
Property of a conditioned waste package in a disposal facility, or of a material used for the construction of the facility, of having no adverse effect on the anticipated behaviour of the other components of the disposal system, especially on that of the Boom Clay.

3.4.1.1 Vitrified waste

In addition to the various tests conducted in the surface laboratory, one particular element in the studies of the glass behaviour conducted as part of the Belgian disposal programme are the in situ tests performed in the underground facility on samples of inactive and weakly-doped glasses (^{134}Cs, ^{90}Sr, ^{239}Pu). These glasses have been shown to possess a behaviour representative of that of real active glasses. At the end of the 1980s, for example, SCK•CEN embarked upon a series of long-term experiments in the HADES