POTENTIAL STORAGE AND/OR DISPOSAL STRATEGIES

The long-term management of substances produced by nuclear power plants has become a major challenge for society. One of the options is to dispose of ultimate waste, or even whole spent fuel, in geological structures with reversibility potential. Another option, which may precede this, is storage, which is already the interim solution adopted by the industry. CEA has started to demonstrate that standardized storage is feasible over centuries for all types of objects (spent fuel, packages of vitrified waste, forthcoming packages resulting from advanced separation) in heavy-duty, passive near-surface or subsurface facilities. The finer details of some technical arrangements as well as the cost of these stores remain to be worked out.

Cogema

Concrete bunker shaft on Cogema's La Hague glass-package storage site.

After the fuel-production cycle: storage *versus* disposal?

Which substances are to be **stored** and/or **disposed** of will vary widely in line with the chosen strategy. In one of the options, it could well be spent **fuel**, despite the fact that its **fissile** material inventory, that could be reused for producing energy, is high. According to current thinking, this is therefore not destined for disposal – it is most likely to end up being **recycled**. The **packages** of glass and **hulls** produced by **reprocessing** operations, are themselves considered as ultimate waste and thus in principle destined for final disposal. The same applies even more so to all the other waste from nuclear facilities (**bitumen**, **cement**, **technological waste**, etc.).

Deep geological disposal, the standard solution

Nowadays the standard solution envisaged for ultimate radioactive waste is post-conditioning disposal. The disposal method will depend on the waste category. Low- and very-low-level waste can be disposed of in

near-surface facilities, and this industrial solution is in place in France and most other countries (see box H, ***What are other countries doing?***). The **high-level**, **long-lived** waste contained in packages of glass and hulls is quite another matter as it can remain extremely harmful over time spans as long as up to tens of thousands of years. Furthermore through the nature of its radioactivity it releases significant amounts of heat, which calls for special measures.

Long-lived HLW is a prime candidate for deep geological disposal. Through this mode of management firstly the packages are placed in a very stable chemical, thermal and mechanical environment over geological time scales and secondly the threshold is crossed so that monitoring can be cut down on after a certain amount of time. The initial **conditioning** (see box G, ***Conditioning, a vital phase***) and the **engineered barrier** provide the **containment** and the geological **barrier** prevents intrusions, and in the last resort isolates any **radionuclides** that might potentially escape. The technical aspects of deep geological disposal are being researched into by Andra (the French National agency for Radioactive Waste Management) in France. Today's concepts are based on a few key principles. The first is modular design. This allows different types of packages to be placed in compartments accessed *via* handling galleries and thus to be separately managed. The packages will be taken down to depths of the order of 500 m through a system of vertical shafts. The heat load will be lowered by conduction, which calls for generous spacing to be left between the packages. A series of life phases is envisaged from operating phase to "post-sealing" phase (see box I, ***How can disposal be reversible?***) to cater for the requirement for **reversibility**. Backfilling the compartments and handling galleries will be held off until the final phase.

Furthermore in deep disposal, the packages will be surrounded by additional containment barriers. Compacted clay and concrete standoffs could gradually be incorporated between the packages and the geological barrier (**host rock**) to protect the packages even more effectively, postpone the arrival of water and fix the **radioelements** once the packages' containment properties have decayed.

Andra is currently constructing a laboratory at Bure, in the Meuse *département*, to conduct geochemical, geomechanical, thermal and hydrogeological experiments. Geological disposal is currently at the research stage. Parliament will apply appropriate safeguards to monitor the choice of a site for installing this type of final disposal facility. There are still many technical choices open.

Long-term storage, a flexible formula

Another chapter in the downstream management of the nuclear power cycle is storage, the essential, albeit non-permanent, stage prior to any disposal. Industrial storage facilities are now operating in France for every category of waste: **category B waste** stores, pools for spent fuel, shafts for high-level waste and for certain types of fuel, but this is a temporary catch-all solution that can only last a few decades.

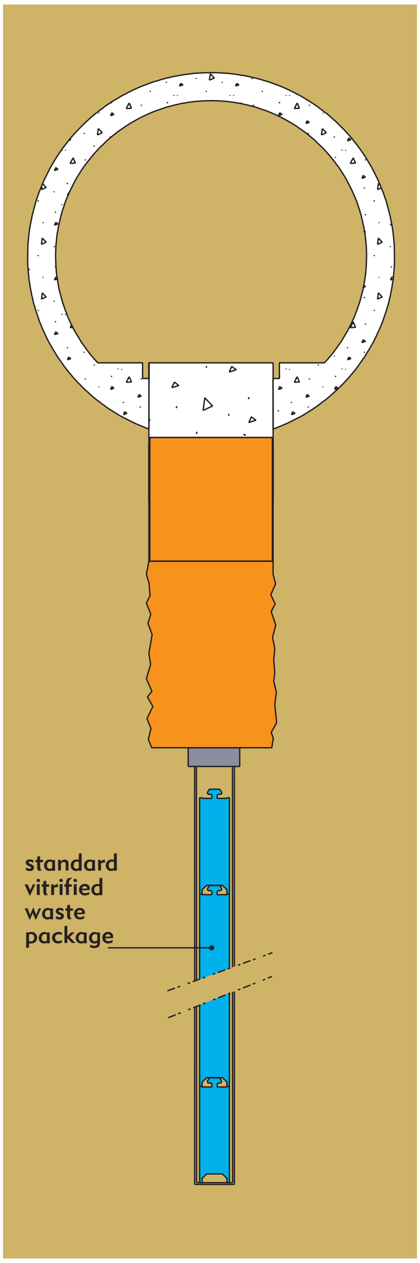
As the nuclear industry's typical time spans are long, temporal and technological uncertainties make a long-term vision a necessity. If current installations can be periodically renewed, it is in our interest to plan new facilities to cater for long periods of time right from the drawing board.

Long-term storage is a flexible formula for post-nuclear power-generation management. It enables spent radioactive fuel to be managed while waiting for it to be reprocessed at some future date. The timing between storage and reprocessing depends on industrial flow management and decision-making and could take as long as a century. This formula allows us to come safely to the final decision on the disposal and operational considerations of ultimate waste and offers breathing space by taking advantage of **radioactive decay** to optimize heat dissipation. Lastly it provides the opportunity to proceed with standardizing conditioning and methods in a centralized unit, which, given the great diversity of category B waste, is particularly challenging (see *Working towards a universal container for category B waste*).

Long-term storage aims to ensure that packages can be held in safe conditions for long, yet undefined periods at the time of loading, while guaranteeing that they can be safely retrieved at a later date (which is not always the case with existing facilities).

Recommendations rather than plans

The CEA is responsible for designing this type of long-term storage facility. However the product of its research is not an installation, nor even a "ready-to-build" blueprint. Over and above any technical and scientific considerations, this research will produce recommendations for designing and constructing for long-term waste management. A number of scientific and technological "hard spots" have been pinpointed through painstaking investigation of existing solutions while taking account of constraints. They are now being separately investigated.



Detail of a shaft for storing glass packages.

Engineering studies on store and container design are incorporating all the research program findings (see the following three articles on the long-term behavior of **matrices**) by considering the areas of: conditioning, transport, handling, storing, retrieval, compatibility with various outlets (such as reprocessing or disposal for fuel). As CEA's traditional areas of competence are highly regulated, one of the difficulties is to let innovation find its outlet for expression.

What are other countries doing?

Most of the countries that have a sizeable nuclear power industry have conducted research into a durable **disposal** solution for their **long-lived medium-** and **high-level radioactive** waste, irrespective of whether or not recoverable **fissile** material has been extracted. Only one country, the United States, has implemented disposal in deep geological formations, but several others besides France are preparing for it or envisage doing so.

Some twenty or so underground laboratories aimed to study the conditions of this sort of disposal *in situ*, in clay, crystalline or saline structures, have been set up in Belgium, Canada, the Czech Republic, France, Germany, Hungary, Japan, Sweden, Switzerland and also the United States.

In **France**: Andra (the French national agency for radioactive waste management) obtained authorization to build the underground laboratory at the Bure (Meuse) site, in clay, in August 1999. Experiments should start there in 2003. A site has yet to be chosen for a second laboratory in granite. The Institute for Radiological Protection and Nuclear Safety (IRSN) is carrying out its own research in the Tournemire (Aveyron) tunnel.

Andra manages the **low-level** disposal centers at Soulaines (Aube), currently operational, and in Manche *département*, now in monitoring phase.

In the **United States**, the Office of Civilian Radioactive-Waste Management (OCRWM), overseen by the Department of Energy (DOE), plans to dispose of spent **fuel** of civilian origin at the Yucca Mountain site (Nevada). The project got the go-ahead from the DOE in August 2001 and from President Bush in February 2002, and was approved by Congress in July 2002. The DOE is now going to apply to the Nuclear Regulatory Commission (NRC) for a building permit. This site was due to start up in 1998. It already operates as an underground laboratory and will be able to accommodate 70,000 metric tons of waste between 2010 and 2060 or thereabouts (40,000 metric tons of spent fuel are currently stored in pools that are approaching saturation level).

The WIPP (Waste Isolation Pilot Plant) has been accepting medium-level waste of military origin containing **transuranic elements** in a deep layer of salt near Carlsbad (New Mexico) since March 1999. The WIPP obtained its license to operate on 10 March 2000 and should accept waste for about thirty years.

In **Switzerland**, the national cooperative for radioactive-waste **storage** (Nagra/Cedra) has been operating the Zwilag (*Zwischen-Lagerung*) spent-fuel storage facility at Würrenlingen (Aargau) since 2001. Waste disposal is scheduled to go into crystalline or clay formations (Opalinus). Very-deep-bore surveys have been carried out in similar formations at Benken (Zürich). Research into clay is being conducted at the Mont-Terri (Jura) international underground laboratory and in granite in the GTS at Grimsel (Bern) managed by Nagra.

Hans Krebs/Zwilag

The Zwilag storage facilities for high-level radioactive vitrified waste and spent fuel, in operation since 2001 at Würrenlingen by the Swiss Nagra/Cedra co-operative. The Beznau nuclear power plant can be seen in the background.

A **subsurface** storage project at Wellenberg (Nidwald) is under investigation for low- and medium-level waste.

On 18 May 2000, the parliamentary deputies of **Finland**, including the Greens, voted by a sweeping majority to authorize construction of a deep-disposal center for spent fuel (in this case considered as ultimate waste) in granite rock over the period 2010–2020. This center run by Posiva Oy, subsidiary of the reactor operators charged with managing radioactive waste, should come on stream in 2020 and will be located at Olkiluoto (in the district of Eurajoki), the site of one of the country's two nuclear power stations (four units).

In **Sweden**, research has been going on in the underground laboratories of Stripa and Aspö where the HRL (Hard-Rock Laboratory) operates, into the final disposal solution for spent fuel in granite rock, 500 m below the surface, adopted about twenty years ago. This is in the same district of Oskarshamm where a subsurface centralized storage center for irradiated fuel, CLAB, opened in 1985. The final disposal center will be operational between 2015 and 2050–2060, the date set for it to be finally sealed, accommodating 9,300 metric tons of spent fuel in all. Surface surveys are planned for three sites (Oskarshamm, Tierp and Östhammar).

SKB (Svensk Kärnbränslehantering AB) the Swedish radioactive fuel and waste management company, disposes of **short-lived** low- and medium-level waste under the Baltic in the SFR set in granite rock one kilometer out to sea from the Forsmark nuclear power plant.

In **Belgium**, a radioactive waste-disposal research laboratory (Hades) set in clay has been operating at Mol (Antwerp province) since 1980. The Praclay program has been under way there since 1997. The Ondraf/Niras body envisages disposing of spent fuel and/or reprocessed, vitrified waste in deep layers and subsurface disposal of short-lived low-level waste in the future. A report on the feasibility of high-level waste disposal was to be submitted to the Belgian government at the end of 2001.

In **Japan**, where a law on final disposal of radioactive waste was promulgated in June 2000, a low-level waste-disposal site has been run by Japan Nuclear Fuel Limited on the Rokkasho-Mura site since 1992. Vitrified high-level waste originating from reprocessing will be stored there for 30–50 years before being finally disposed of in an as yet unspecified site. Disused mines have been used as methodological laboratories in the granite and sedimentary rock at Kamaishi and Tono. Dedicated laboratories are being prepared at Mizunami and planned for Horonobe.

In **Korea** the Korea Atomic Energy Research Institute is investigating two types of host rocks for future disposal of high-level waste.

In **Germany**, the disposal of all radioactive waste in deep geological sites (and particularly in salt mines) has been envisaged since the 1960s. Experimentation has been going on in Lower-Saxony at Asse, Gorleben and Konrad. The latter site – an iron mine – was chosen for long-lived, medium-level waste. Gorleben was abandoned on 1st October 2000 as a "final" disposal site. Given the program to gradually shut down nuclear power production, a single deep geological disposal site is still planned for the disposal of all radioactive waste (including waste reprocessed in France). Spent fuel is currently stored at Gorleben, Ahaus (North Rhine-Westphalia) and Griefswald (Saxony-Anhalt). Research into proposed stores near the power plants (17 sites) is ongoing.

H

The former salt mine at Morsleben was used for disposal of low- and medium-level waste (ERAM) between 1981 and 1998.

Spain will not take a decision on long-term spent-fuel and high-level radioactive waste management before 2010. It plans to construct a centralized disposal center for this unacceptable fuel and waste by 2040 on the El Cabril site (the equivalent of the Aube center in France, reserved for low-level waste).

The **Netherlands** plan to dispose of high-level waste from 2003 in a near-surface facility, Habog, currently being constructed by Covra, the central organization for radioactive waste, on the Borsele site. The country has rejected in principle any **irreversible** solution. The final CORA research-program report on deep disposal was submitted to the Dutch parliament on 21 February 2001.

Italy is looking for a storage site for spent fuel and high-level waste and a disposal site for low-level waste.

A low- and medium-level waste storage and disposal site was opened in 1998 at Himdalen, **Norway**.

In the **United Kingdom**, the underground research laboratory project on geological waste disposal at Sellafield was abandoned in 1997, but the idea of reversible underground disposal is still on the table. There is a low-level waste disposal site at Drigg, near Sellafield.

Canada, where an underground laboratory, URL, is operated by AECL at Whiteshell, near Pinawa (Manitoba), is looking for a geological disposal site.

Australia plans to dispose of its high-level waste on an as yet unspecified near-surface site prior to final medium-depth storage (less than 100 m), and its low- and medium-level waste in subsurface sites from 2003 onwards in the South of the country in the Billa Kalina region.

Research into disposal in geological formations has also been undertaken in other countries, in particular **Hungary** and the **Czech Republic** and is at various stages of advancement.

Projects involving the import of foreign radioactive waste have furthermore been discussed in **Russia**.

A project on control over time

A storage facility is a basic nuclear installation(1). Subsequently when factoring in nuclear and non-nuclear risks, it is tied to conventional safety analysis. The aim of CEA's studies is to give operational sense to the notion of long term, by converting this to technical measures that will enhance safety significantly, measurably and demonstrably all at the same time. The principles of management over time have been defined to complement conventional safety analysis along with methods for analyzing the lifespan of a system, largely inspired by approaches developed for the dependability of complex systems. These principles are essentially rooted in minimizing operating and maintenance loads for future generations, by incorporating aging processes from the design stage, proper dimensioning of monitoring, and organizational set-up so that the whole operation can be periodically reappraised.

By distinguishing between the active and passive phases, the principles of ruggedness can be applied to each. This entails firstly minimizing the risks of failure of all components, human presence and specifications on the environment, and secondly maximizing **passivation**, hardiness and simplicity.

(1) A BNI (INB in french) is a major nuclear installation in the terms of the 1963 decree, namely a nuclear reactor, a particle accelerator, a plant for preparing, manufacturing or transforming radioactive substances, or an installation destined for disposal, storage or use of radioactive substances including waste, when the quantity or total activity of radioactive substances that can be held there exceeds the minimum laid down by legal order.

The social uncertainties linked to the long term

There are major uncertainties surrounding environmental and societal conditions on periods spanning several generations. The way to make allowance for this uncertainty is to imagine hypothetical scenarios that would lead to the temporary loss of technical control and quantify its impact. This approach means that the risks can be assessed and the relevant technical and organizational solutions devised. The difficulty of gaining acceptance for such a facility before the decision has been taken to build is exacerbated by its long-term nature, which results in social and technical controversy (see *Technological aspects, a starting point for debate*).

Research achievements

The research conducted at CEA has yielded major findings, both in terms of what will be stored and major technical choices and by pinpointing so-called "hard spots".

Items for storage

The CEA project has selected spent fuel as its priority research area from all the items currently produced by industrial nuclear facilities. As it stands, France has no dry-storage sector for spent fuel apart from the reference Cascad facility, at CEA/Cadarache, which only accepts experimental fuel. A dry-storage facility is up and running at La Hague

Emmanuel Joly/CEA

Shaft heads containing various types of fuel in the Cascad dry-storage bunker facility at CEA/Cadarache, the current reference design concept.

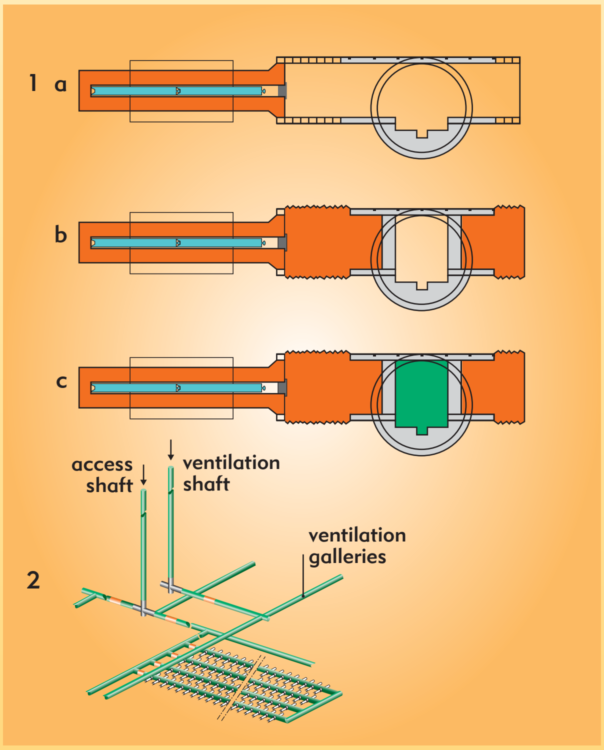
I

How can disposal be reversible?

While radioactive waste **storage** is by definition reversible as it is an interim, albeit possibly very-long-term solution (say one or more centuries), **disposal** can be final. The requirement for **reversibility** is to retain the option to retrieve the **packages** from the facility following their emplacement there, for a set amount of time, prior to final sealing. Compared with irreversible storage this calls for many constraints, especially a major facility-management phase.

In France, Andra currently defines reversibility along the lines of successive stages that present diminishing "reversibility levels". It works on the following principle: each stage consists of carrying out a technical sealing operation that will make package retrieval more difficult than it was at the previous stage. Thus from the starting point, where it is easy to access the packages, disposal is gradually brought to a state in which it is finally sealed. There is thus more flexibility in making the decision to seal and passing from one stage to the next is carried out in line with well-defined criteria.

The process envisaged today comprises five stages. In the initial stage, the tunnel capping is in place and disposal is analogous to storage (figure 1a); in the second, the compartment is sealed (figure 1b); in the third the handling gallery is in turn sealed (figure 1c). Then during the fourth and fifth stages, the rolling galleries and shaft are backfilled (figure 2). (Source: Andra; presentation to the French National Assessment Committee (CNE) on April 25, 2001).

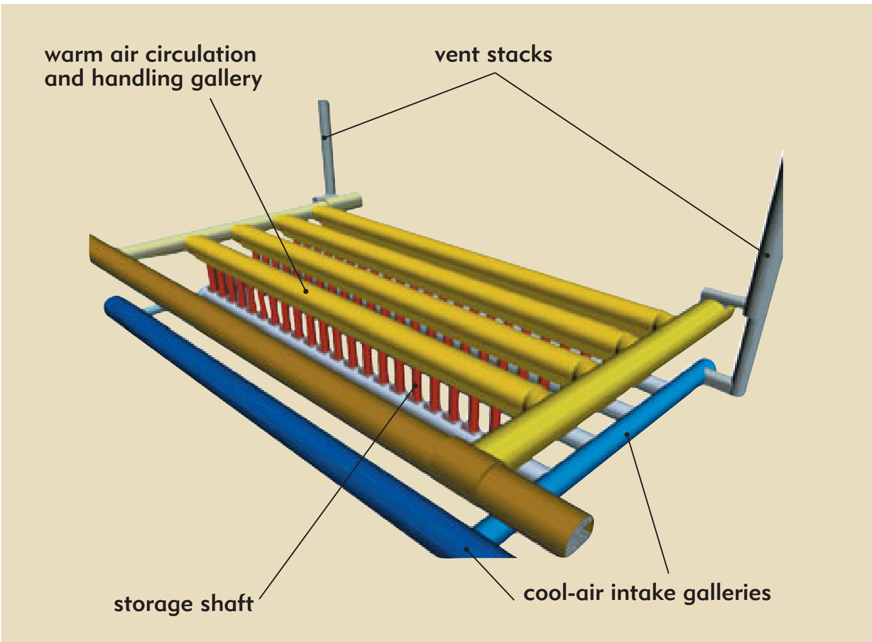


(Manche) for glass packages, designed to be cooled naturally by ventilation shafts. Research conducted in conjunction with the operator, Cogema, has concluded that the long-term feasibility prospects for this facility are good and that its limitations in this respect have been clearly identified. Accordingly, CEA has chosen to propose this type of solution for managing glass packages, entailing investigation into improvements as part of its spent-fuel research program. The storage of other potential packages from the advanced separation sector (see *Tailor-made matrices for long-lived radionuclides*) could then be considered and largely extrapolated from research already carried out.

The major technical options

Dry storage is the basic option of the chosen designs. Industrially operational pool storage does not match the principles adopted for long-lived waste, especially when it comes to monitoring and maintenance. That explains why natural-ventilation cooling systems have been chosen, excluding any active system (at least in the interim phase).

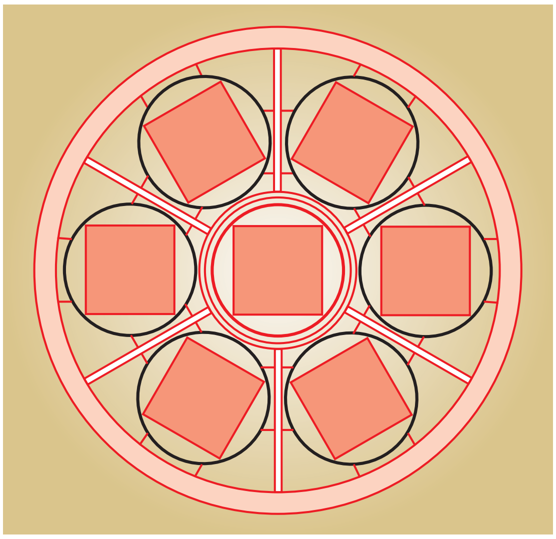
Provision of containment is entirely reliant on the package, as it turns out that the long-term integrity of spent-fuel cladding cannot be guaranteed (see articles below). Consequently the choice has been made to condition fuel **assemblies** in a cartridge, subsequently enca-



Network of galleries and shafts of a subsurface storage facility. This sort of store, located roughly 50 meters underground, would be installed in a rock mass with land form comprising hard rock above the water table, with seepage water draining by gravity. Access to the store would be horizontal from the edge of the land form. The rock mass would provide the store with physical protection from external aggression.

CEA/DEN

sed in an envelope, or **container**. The stored containers must be intact and present the minimum possible corrosion so that retrieval objectives can be met. The store must thus ensure that the packages are kept in dry-corrosion conditions and also provide the biological protection that the container itself cannot do. Finally store design is modular to maximize flexibility for industrial scenarios. These choices are technically and economically compatible with the storage options.



CEA

Figure 1. Section of a metal canister with seven cartridges each containing a uranium-oxide spent-fuel assembly – CEA's current design concept.

The pinpointed hard spots

The "hard spots" remaining to be investigated have been identified in four areas: package sealing, thermal output in the facility, monitoring and criticality management.

Package sealing

How well the containment of the irradiated fuel package performs is at the crux of the long-term storage device (figure 1). The procedures for inserting spent fuel into cartridges and moving the fuel from the pit to a dry atmosphere must meet very precise specifications to minimize the amount of residual water. Short-term tests must be used to extrapolate the behavior of the crucial elements of the cartridge and canister sealing systems over centuries. Thus full-penetration welding, the standard method, and the innovative fusible weld system will be subjected to representative storage-condition experiments (figure 2). A program is under way, due to end around 2004, to conduct a demonstrator in full-scale test so that the adopted technological solutions can be validated. As for the choice of materials, for the external **canister** used for storage, cast iron or carbon steel are suitable while the cartridge will be in stainless steel to make decontamination easy and avoid simultaneous contamination of the two barriers. This "package" program is being undertaken as a joint venture between CEA, EDF and Andra.

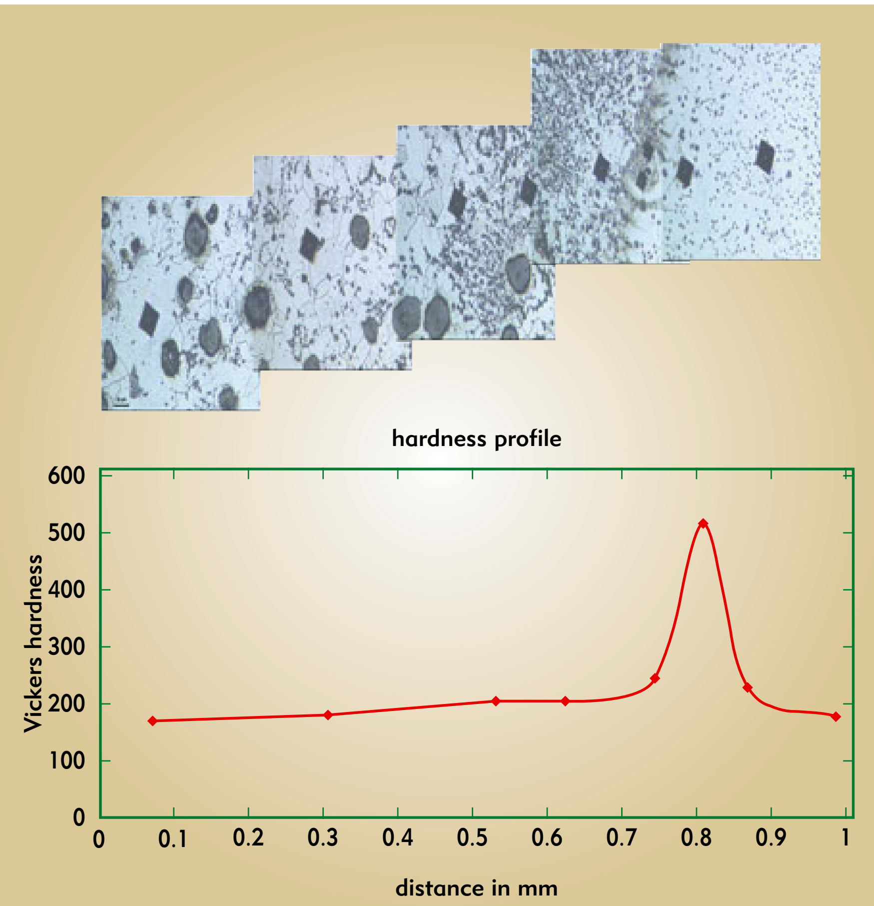


Figure 2. Container weld-microstructure evolution obtained by measuring microhardness on metallographic section being studied to assess the durability of these structures.

Thermal exchange in the facility

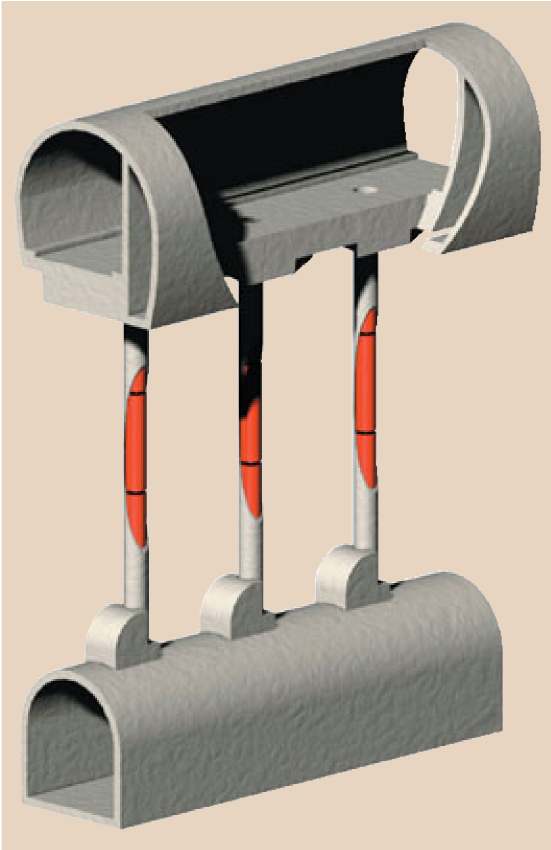
The overall thermal operation of the facilities calls for in-depth investigation to find the technological devices to enable them to operate in dry conditions, which curbs corrosion rates appreciably (1 µm per century). Currently the maximum admissible temperature for infrastructure materials is 80 °C, compatible with sub-350 °C cladding temperatures, which protect them from fast **creep**. The heat given off by the packages themselves, which is difficult to control at the start of storage when facility constraints need to be limited, becomes a hard spot for preventing corrosion when the packages have cooled down.

Monitoring

Implementing a dual barrier will be so much safer that it will be possible to guarantee the integrity of each barrier for a long time and independently. In-depth research is going on to assess how to forecast and verify their state.

Criticality

It must be demonstrated that a situation will never arise that presents a **criticality** risk over such long time spans and for potentially up to several thousand metric tons of spent fuel. Special provisions have been made for the geometry governing the collection of assemblies in the store, and against



CEA

Cutaway view of shafts containing cartridges of spent fuel in a subsurface store.

the risk of a criticality situation arising from a flood, yet avoiding costly resort to borated material[2].

Two integrated concepts examined in detail

Having envisaged several possible avenues, CEA research workers are examining in detail two main concepts for package storage, one for a **subsurface**, the other for a near-surface facility.

A *subsurface* store, on a hillside for example, makes for appreciable gain in ruggedness to fend off external aggressions (plane crashes, exceptional climatic events, intrusions…). The industrial feasibility of this innovative concept remains to be investigated in certain special areas (water management, handling, air systems) without the benefit of industrial feedback based on experience. Building this sort of store is more involved than a near-surface facility and carries greater handling risks in the event of an incident. The standard solution, whose thermal functioning has been approved, is based on the emplacement of the packages in vertical shafts.

The concept of a modular bunker for a *near-surface* store, on a plain, is similar to existing industrial stores. Research into it will yield specific long-term, fine-tuned measures (figure 3). The containers are arranged vertically in halls with concrete walls. Handling is carried out from behind a wall that provides biological protection. Research is going on into the feasibility of transverse air- current cooling to increase thermal exchanges. Furthermore an in-depth investigation will be made of whether Nuhoms[3] bunkers, in industrial use in the United States and Armenia, and most suited for decentralized storage, are conducive to long-term applications.

The economic constraint

The economic aspects of nuclear energy production must be taken into account. In the context of liberalized electricity markets this is a prime challenge for the industry. Assessment of the whole chain from output from the reactor to disposal is very complicated and awaits consolidation. At least one initial storage phase is accepted as inevitable. The cost of storage is currently estimated at over 300,000 euros per metric ton of fuel (initial investment, operation for 60 years and cost of additional facilities included). The current standard for dry storage is the American horizontal silo, whose cost (without any "long-term" device) is estimated at a little over 38,000 euros per metric ton of fuel. The solutions proposed will have to be compared against this yardstick.

The year 2002 should see the completion of technical research on a preliminary design. On the back of its research effort CEA is in a position to propose solutions to the post-energy-production-cycle issue that not only meet the legal requirements of the law, but also, by sharing its R&D capacity with its industrial partners, mean that CEA is playing a major role in the development of tomorrow's industrial concepts for nuclear power.

Alain Lioure
Nuclear Energy Division
CEA/Valrhô-Marcoule

(2) See *Clefs CEA* No. 45, Nuclear Physics and safety, p. 55.
(3) From NUtech (name of the US company that developed the concept) and HOrizontal Modular Storage.

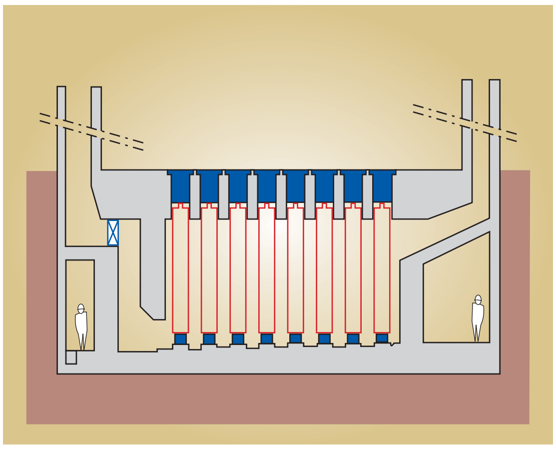


Figure 3.
Example of a CEA concept for a concrete-bunker storage facility similar to existing industrial systems.