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Technical study of a thermally dense long term interim storage facility

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ABSTRACT

The COFRE concept is aimed at the surface and thermal densification of the interim storage facility for irradiated fuels. The facility provides the biological shielding. A conditioning cell is used to load and retrieve the fuel assemblies. The facility container is the second containment barrier.

The high power levels are managed by an auxiliary cooling system whose original feature is the passive use of a water evaporation-condensation cycle in a sealed circuit. The removable evaporator abuts the container. The air cooled condenser is placed outside the facility. Contact resistance and heat pipe mode were successfully modelled and are undergoing experimental validation on the THERESE and REBECA loops.

KEYWORDS

- Irradiated fuels – Interim storage – Heat transfer – Heat pipe -

1 - INTRODUCTION

As part of guideline 3 of the 1991 law on nuclear waste management, the EtLD project is aimed to compile the conceptual data on different solutions for very Long Term interim Storage (EtLD) of nuclear material (irradiated fuels) and very high level long-lived waste.

Among the available concepts for facilities meeting the long term criterion, an EtLD concept of the concrete bunker / adjustable cooling type, named COFRE, is currently the focus of preliminary design to address the following factors :

- Exploration of a solution in slight continuity with the storage facility, a feature implying the presence of an interface with the outside (the conditioning cell, for loading and retrieving objects of nuclear origin) and a « containing compartment » interim storage (called containers below) which is an integral part of the storage facility ;
- Densification of the interim storage, both in terms of space occupancy and of heat transfer : the aim is to take over as early as possible any object of nuclear origin, irradiating and hot as the case may be (for example, PWR MOX assemblies 5 years after leaving the reactor), in containers offering large numerical capacity (up to 30 objects each) and high heat transfer capacity (up to 100kW per container).

2 - PRESENTATION / PERIMETER OF THE CONCEPT

COFRE (Fixed container with adjustable cooling system) is a very long term interim storage concept which, in addition to its inherent characteristics, meets the general objectives of these installations :

- continuous control, for century-long service life, of the ongoing Safety functions, as well as reversibility ;
- economic competitiveness with existing interim storage systems.

The management of this concept is accordingly subject to two major constraints, to maximise the [useful capacity / immobilised material] ratio and the management capacity for natural (diversity of storable objects) and temporal (decay of heat fluxes) thermal flexibilities..

We can add that the three life phases of a very Long Term Interim Storage facility form part of the perimeter of the Concept :

- Loading phase : the nuclear components are provided by the interim storage site with the current transport systems and procedures, and placed in containers in a dedicated cell (« classic » BNI). They are accordingly isolated from the outside by a « double barrier » type containment (two metal containers, closed, sealed and imbricated). The assemblies thereby created become packages. These packages are then transferred to the actual interim storage location.
- Waiting phase : the facility meets the requirements of robustness and adaptability to the changes in the environments, both external (meteorology, pollution) and internal (ongoing deterioration).
- Retrieval phase : this must contend with the problems of accessibility (with notice) of the packages and of the storage location, as well as the availability of the conditioning cell, and all this in highly variable contexts : partial retrieval for monitoring, inspection, or in case of incident, or massive retrieval after a waiting period up to a century.

These three phases can succeed each other in several cycles over a century.

This concept meets the above objectives and characteristics by a centralised layout chiefly deriving from the management mode selected, which employs :

- a conditioning / retrieval cell, a specific BNI, which should preferably be a single unit for obvious reasons of investment and operating costs :
- « containing compartments » for internal and temporary use, metal barriers forming an integral part of the facility for their « nuclear » use (new concept fuel cycle object, with deliberately limited functionalities).

The technical principle of the double barrier selected today for the COFRE concept is the placement of the fuel assemblies in canisters, followed by the placement of these canisters in containers. It is in fact assumed that the demonstration of the integrity of the clads over a century-long period is unfeasible.

3 - MAJOR DESIGN GUIDELINES

3.1 - GENERAL CONTEXT

An integration was performed on the interim storage of Irradiated MOX G3 900 MW Fuel Assemblies after 5 years of cooling in pond BK (3 kW/assembly).

A first image was constructed (figure 1) based on the major characteristics stated previously :

- The requirement to maximise the [useful capacity / immobilised material] ratio, which requires dimensioning the container to the essential functions of capacity, maintenance of subcriticality, containment and participation in heat dissipation. Thus radiological shielding is not provided by this component, but by the facility. Similarly, the drop dimensioning is minimised (a few tens of cm), implying transfers in the horizontal direction only in a ground level installation from the loading cell to the interim storage location. The entire process takes place under a radiological shielding slab which the packages (entities comprising the nuclear objects) never cross.
- The strategy of low continuity between the storage and interim storage functions entails the use of a cell capable of accommodating, conditioning, managing and deconditioning for shipment, any elementary object that is irradiating and hot (concept of flexibility, dimensioning on the most constraining components). Hence the packages are not dimensioned for transport. The entire process takes place behind the radiological shielding walls that the packages never cross.
- Maximised performance in terms of densification and high heat transfer capacity demands the use of water as coolant (case of MOX with unit power 3kW), by means of a heat pipe , for example, during the first interim storage decades, subject to the flexibility (adjustability) of the cooling system for the [package + heat pipe + facility] system : eventual transition to natural air convection.

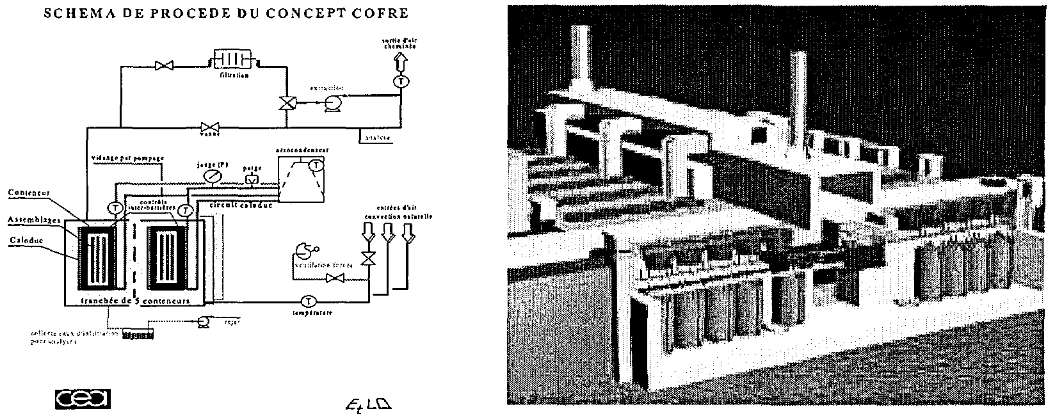
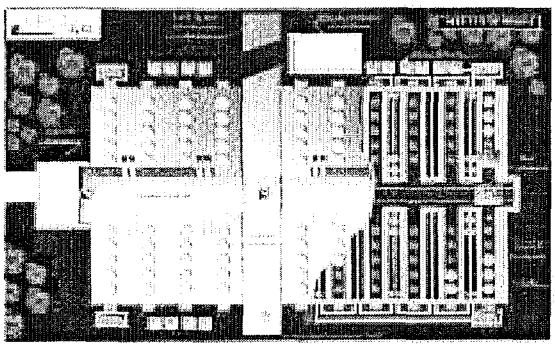


FIGURE 1 : PROCESS FLOWCHART AND GENERAL SECTIONAL VIEW OF THE CONCEPT

It may be observed that the installation of COFRE at ground level basically raises no major technical problem. The guarantee of no contact with the groundwater table (sufficient distance, hillside location / consideration of maximum potential variations) is a decisive factor for demonstrating its very long term behaviour, unless evidence of the tightness of the structures is required for a century-long period.

3.2 INTERIM STORAGE FACILITY

The interim storage of 2500 MOX irradiated fuel assemblies can be achieved in a unit « module » (figure 2), comprising some twenty buried « spans » each containing five 2.5 metre diameter containers at a one-metre spacing, distributed via a « central corridor ». On conclusion of the preliminary feasibility study, such a facility can be in the form of a moderately long rectangle (about 100 m * 70 m, not including control, maintenance and loading premises), representing a ground load of about 110 000 tons. The concrete walls and roofs are about 1.4 m thick, a thickness necessary to classify the external portion of the facility as a « green » zone (DED < 25 μ Sv/h). The unit structure of 12 spans (figure 2) represents the reasonably largest dimension, for reasons of overall and surface loading and seismic behaviour, suitable for installation on a single raft without rigid interface (connections by watertight seals and allowing differential movement between structures) with the other rafts. This structure allows the separate management of the rainwater and radioactive effluents. Tightness is guaranteed by a composite structure (high density polyethylene, felt insulation, concrete).



The roof slab represents level 0 of this version and the container positioning depth is then about -15 m. This level is only indicative, and, for a deeper facility, various items would simply have to appear at the surface, air inlets and outlets, heat pipe condensers, access to the technical galleries, maintenance and monitoring-control rooms, down-grade for empty containers and fuel transport casks.

FIGURE 2 : PLAN VIEW OF A « MODULE »

For safety reasons (presence of water) concerning the second barrier materialized by the container, the heat pipe is an object in its own right, consisting of vertical pipes where the evaporation processes occur, intimately linked with an independent shell closely abutting the outer shell of the container. Remote control (arm carried by the handling trolley) allows mechanical connections and disconnections (replacements in case of incident) as well as hydraulic connections (systematic operations) for the heat pipes in situ.

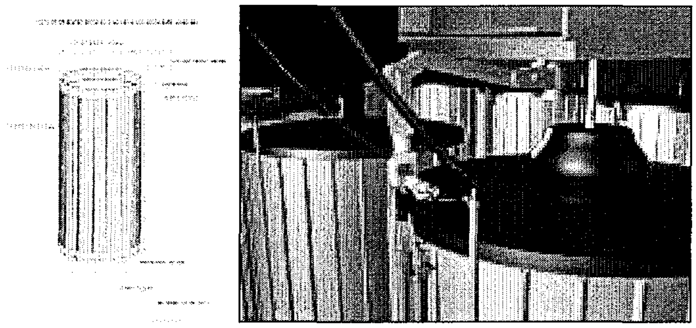
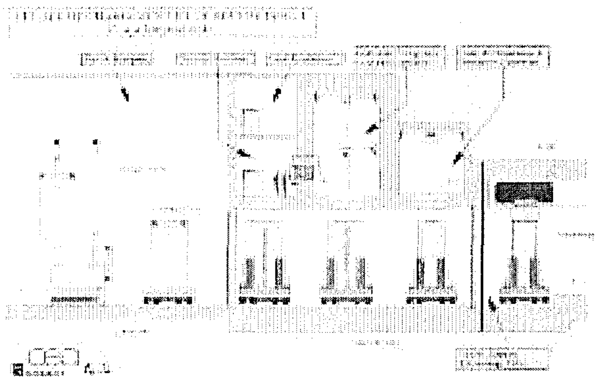


FIGURE 3 : HEAT PIPE AND REMOTE CONTROLLED CONNECTION/ DISCONNECTION OPERATIONS IN A SPAN

A loading/unloading cell (figure 4), positioned at the entry of the facility, allows the loading of a COFRE container from a standard transport cask, and, during a retrieval operation, the transfer of the fuel assemblies in a container identified by the storage controller. It is felt today that the fuel assemblies, before transport to the interim storage location, will be placed in sealed canisters in an appropriate installation. The container is cooled by forced draft during the loading operation (shell featuring air segmentation). In case of blower failure, natural convection takes over, and its wall temperature rises to about 150°C.



In case of « very long term » management, the installation could be put on « standby » (removal of sources and decontamination, continuous monitoring, ventilation, maintenance), which would allow a complete reconfiguration in about 12 months, extendable to 24 months after « mothballing » (add dismantling of mechanical equipment to placement on standby ; reduction of surveillance requirements to the minimum).

FIGUE 4 : CELL AND LOADING/UNLOADING OPERATIONS

The container loading flow (objective : interim storage of 500 irradiated fuel assemblies per year for 10 years, design value for the first interim storage exercises) is feasible by this type of cell, and the limiting factor could be the monitoring of the tightness of the fuel assemblies (feedback from the TO cell at La Hague : 6 hours per fuel assembly with the current procedure in aqueous media ; on this basis, it should be possible to inspect 2 to 3 fuel assemblies per day).

3.3 - MATERIALS

The juxtaposition of corrosion control and design criteria led to the choice of so-called « nominal » materials for the two major components, namely the container (« containing compartment ») and the heat pipe : the former of low alloy steel, and the latter of aluminium alloy. This will provide cathodic protection for the steel (even stainless steel) in the crevasses in case of condensation, so that it can be left in place after its use. As to the internal materials of the container, the canister could be of 304L stainless steel : good experience in nuclear environment, excellent thermal, mechanical and irradiation behaviour. In general, the installation and closure processes must help guarantee the absence of any risk of aqueous corrosion (limited volume of residual water).

3.4 - CONTAINER

The COFRE container, a « containing compartment » for temporary use, is a mobile metallic structure of cylindrical shape, 1.8 to 3 m in diameter and 5.5m high, which is an integral part of the facility and consequently becomes a waste when its use is terminated (massive retrieval / on incident).

Its design optimises the quantity of immobilised material to meet the following objectives :

- numerical and thermal capacity (dimensioning object / 100 kW max) ;

- second containment barrier, with presence of helium in each cavity ;
- investment, operating and decommissioning costs.

The dimensioning arrangements respond to subcriticality requirements (overpressures and thermal stresses) and heat transfer performance (removal of heat). From the heat transfer standpoint, the dimensions are determined on PWR 900 assemblies enriched to 8.28% with plutonium and irradiated to 47.5 GWd/t, for a unit thermal power of 3 kW. The limit value (internationally recognised today) of the fuel assembly temperature is about 350°C, in steady state conditions (450 to 500°C for short periods). The cavities created by the barriers are filled with helium (removal of oxygen, very good thermal conductivity). At the beginning of storage, the heat pipe imposes an outer shell temperature of 140°C on the container.

For the maximum power of 3kW / irradiated fuel assembly and a container diameter from 1.8 to 3.0 m, and for the miscellaneous basket technologies available (wall thicknesses, clearances), the capacity extends from 20 to 30 assemblies, for total weights of 45 to 90 tons. The basket in the container is a critical design component of the system (by acting directly on the internal thermal gradient of the container, it directly conditions its capacity) : for the above range of values, its weight can range from 5 to 30 tons, and its material is aluminium, selected for its excellent conductivity.

3.5 - REMOVAL OF HEAT

This section does not address the internal heat transfers in the container, but its cooling. In terms of general heat transfer, the COFRE concept meets two major objectives :

- performance pertaining to the very high heat transfer capacity - up to 100kW per compartment,
- flexibility for optimal management of the variety of objects and the decay over time of their thermal power.

This dual ability to control the cooling of very hot objects and to adapt to the diversity and variation in thermal powers imparts an original character to COFRE, strongly differentiating it from the other long term interim storage concepts.

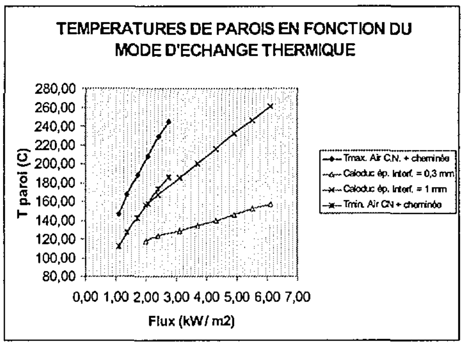
FLEXIBILITY

- To accommodate the variety of objects contained, the COFRE concept has introduced the flexibility of its single container model (containing compartment) : this is the variable geometry of its internal conditioning, in other words, a matching basket.
- The variable response to the problem of optimal cooling, depending on the different cases and the periods, is reflected by the passive and temporary use of a heat transfer fluid like water, and also water and natural air in a combined adjustable system, and finally, natural convection alone at a progressively decreasing rate.

PERFORMANCE

Up to 100 kW, performance is expressed by control of the wall temperature of the containing compartment at a level that guarantees the durability of the hottest fuel element.

To do this, the heat is evacuated by a passive heat exchanger of a secondary circuit type. This is actually the added and interchangeable evaporator of a heat pipe, of which the static condenser is placed outside the structure of the site for heat exchange with the surrounding air by simple natural convection (figures 5 and 6).



To meet the COFRE objective of 100kW / container, i.e. heat flux between 2.5 and 3 kW/m2, heat exchange by natural air convection carried out in the best conditions (steeply sloping curves, installation of a « stack » shell around the container) leads to wall temperatures higher than those obtained by the use of a two-phase water thermosiphon, on condition of optimal dry contact between the container and the thermosiphon evaporator, expressed here as an average air gap (target : 0.3mm)..

FIGURE 5 : WALL TEMPERATURES IMPOSED ON A CONTAINER BY THE APPROPRIATE USE OF HEAT PIPES VS HEAT EXCHANGE BY NATURAL CONVECTION

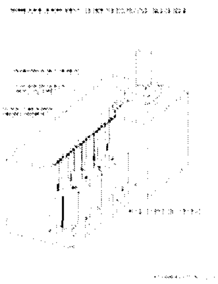


FIGURE 6 : INSTALLATION OF HEAT PIPES IN A SPAN

Reasonably dimensioned industrial air cooled condensers can remove all the energy released by a group of 5 to 10 containers. The respective distance between the two main components of the loop is not a dimensioning factor of the system ; the difference in altitude could actually be a favourable factor (less risk of « dewatering »).

This cooling mode accordingly draws on two main factors :

- dry and direct contact between two industrial structures ;
- operation of a heat pipe type system

At all events, and for the above two factors, final validation can only occur after an experimental procedure. This is carried out on representative mock-ups 2 m in diameter and 1.5 m high.

ANALYSIS OF CONTACT

The auxiliary cooling system for the container, for powers higher than 60 kW, is a passive system of the heat pipe type of which the evaporator is a jacket added on and clamped around the container.

The quality of the container-heat pipe thermal coupling necessarily results from an optimisation and control of the contact of the two structures. To solve this problem, a thermo-mechanical analysis and an industrial scale design approach were conducted in the form of a technico-economic analysis for a container with outside diameter 2 600 mm, inside height 5 000 mm, of 304 L stainless steel or low alloy steel such as 15CD2-05. The uniform heat flux is 2 to 3 kW/m2 (or 60 to 100 kW for the container) and the internal pressure is 7 bar.

In these conditions, a 50 mm thick shell and 100 mm ends of low alloy steel guarantee the integrity of the structure, and the deformations do not exceed 0.3 mm at the shell bottom radius for a realistic internal flux and penalising pressure of 7 bar.

The industrial feasibility study, carried out on a reference solution (juxtaposed finned tubes) ultimately provides a complete analysis of generic industrialisable variants.

The 2D heat transfer analysis, conducted in parallel, gives the efficiency of the container-heat pipe contact and quantifies it for all the cases identified by industrial prospecting.

The following two generic solutions emerge from the coupling of the two studies, with a temperature constraint ≤ 150°C for the shell (or T°C ≤ 350°C for the hottest fuel element) :

- one (selected as the reference solution) with surface contact, is an evaporator consisting of finned tubes (thickness 5 mm) of aluminium alloy sectioned and assembled by welding. The calculation results show that the efficiency of the heat pipe strongly depends on the clearance between the tubes and the container, and not on the average clearance between the two surfaces (container and heat pipe, figure 7). The width of the section is about 200 mm and the tube diameter is 33 mm (t = 5 mm) ;

- the second (selected as a variant) of the linear contact type, consists of aluminium alloy tubes pressed against the container by an outer shell.

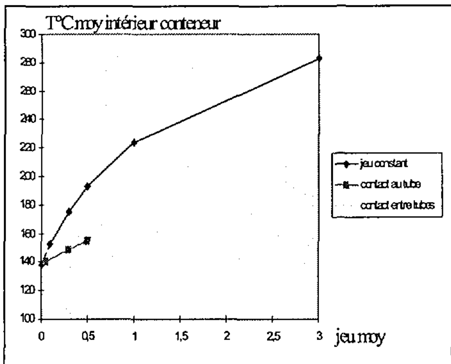
For information, a third alternative is available, in which the tubes are directly welded to the container. While the calculations illustrate the thermal efficiency of this solution, it raises technological problems, and above all, does not meet the interchangeability requirement of the COFRE specification.

This flexible evaporator is clamped to the container. The thermomechanical analysis, assuming a clamping point approximately every 500 mm, converges towards values of 4 000 N per point for optimum contact (in all cases > 2 000 N). For the first facility concept, with plugs in the slab opposite each container (figures 1 and 2), a heat pipe locking-unlocking system was the subject of a feasibility study. An optimised solution was devised in which closure occurs by the application of a simple vertical force directed from the top downward, and opening by identical action from the bottom upward. The system comprises compensation of differential expansion between the heat pipe and the container, as well as two emergency opening systems. This lock will be mounted on the THERESE 2 and REBECA heat transfer mock-ups.

A second feasibility study of the heat pipe lock was carried out for a site with a solid slab (or split, in any case without plug) in which the heat pipe evaporator is replaced sideways to the container. In this case, the evaporator consists of two hinged half-shells: the study concludes in the existence of a simple system that meets the same requirements as the previous lock. Its concept also provides a response to the site variant in which the hinged evaporator of the heat pipe is an integral part of the host structure and is controlled from a technical gallery.

The thermomechanical and design study, as well as the industrial feasibility prospecting, demanded an experimental validation. A heat transfer test program was therefore drawn up, comprising two phases :

- A « THERESE 1 » mock-up for the first basic studies to back the thermomechanical study and the selection of generic solutions. The dimensions selected are those of a 500 mm sided square for the contact surface. The results of this mock-up have been acquired and consigned to a report in publication. They conform to the thermomechanical calculations.
- a « THERESE 2 » mock-up representative of the COFRE concept : the 30 mm thick shell of low alloy steel is built to diameter 2 000 mm and height 1 500 mm. It is equipped (electrical resistors) and allows fluxes over 3kW/m2. This shell will successively receive the two generic heat pipe evaporator solutions previously described, as well as the locking system in which the « clamping force » parameter is scanned from 1 000 N to 6 000 N. The thermal loop is created by forced circulation of water. The first results from the tubes pressed by an outer-shell evaporator are expected in late 2000.



Although the intrinsic extraction capacity of such a thermal loop (two-phase thermosiphon) is far greater than 100 kW, the success of its efficiency nevertheless resides in the optimisation of the coupling between the container and evaporator surfaces (patent pending). The answer was supplied by an in-depth thermomechanical and design study which takes account of the topographic reality of industrial objects : two generic industrial solutions at controlled cost ; they use an aluminium alloy on a low alloy steel container (§ materials).

FIGURE 7 : WALL TEMPERATURES IMPOSED ON A CONTAINER AS A FUNCTION OF CONTACT MODE WITH THE HEAT PIPE EVAPORATOR

ANALYSIS OF HEAT PIPE MODE

Passive operation in heat pipe mode was the subject of a preliminary in depth study. This relies on a previous work in which the system proposed by the term « heat pipe » is actually a two-phase loop assisted by gravity with an evaporator and a condenser placed in series : the system is driven by the heat flux generated in the container. In its study, the GRETH (DRN/D TP at the Grenoble Nuclear Research Centre) is exploring various alternatives accounting for seasonal and daily variation in the temperature of the cold well, the decrease over time of the power dissipated by the irradiated fuels, and the production of non condensable gases resulting from internal corrosion of the aluminium by the water and the radiolysis of the water. The GRETH ultimately proposed a number of potential alternatives : none is totally passive in the strict sense of the term. One is a variable conductance condenser operating at a constant temperature level ; the second is a conventional condenser with a variable temperature level. In both cases, the evaporator is either a two-phase loop, or thermosiphons of the heat pipe type. However, a mechanical adjustment system is necessary in both cases (either a slaved mobile register to adjust the airflow, or a variable-rate circulator slaved to the outdoor temperature.

This study ultimately demonstrates the feasibility of the system, but makes a number of assumptions and does not find a strictly passive solution. In these conditions, experimental validation on all the different parameters is an absolute necessity.

The REBECA mock-up with the mechanical components (shell and evaporator) of Therese 2, will help to simulate operation in heat pipe mode on a complete evaporator + air cooled condenser loop.

A second study is under way at the GRETH. Using a different approach, it aims to find a totally passive operating range. The preliminary results are very positive, and in the same way, an experimental validation will be conducted on the REBECA mock-up the years 2001 and 2002.

The THERESE 1, THERESE 2 and REBECA mock-ups are and will all three be successively installed at the Grenoble Nuclear Research Centre, DTP/SETEX.

ADJUSTABILITY

Adjustability has been selected as the ideal response to the concern for optimised cooling over time. At the present time, the service life of the heat pipe, through the consideration of the maximum permissible temperatures of the internal components of the containers (350 TO 400°C for fuel assemblies, 250 to 300°C for the aluminium baskets) and of the concrete walls (Tmax 80°C, the wall temperature of the container is dependent on the airflow), is the subject of a precise evaluation connected with a broad heat transfer study integrating all the components and the setting (the site). It will ultimately be harmonised with the service life, estimated by feedback at about 50 years.

Moreover, a first choice of materials for the container and its associated heat pipe is resolutely based on the durability of the containing compartment, without the need to dismantle the added heat exchanger after its final shutdown (see § materials).

Finally, the geometry adopted for this evaporator in contact with the container minimises the thermal resistance with respect to the site, to promote the progressive take-over of the cooling of the site by natural convection with air.

In fact, this passive, safe and durable cooling mode is precisely the subject of preliminary design in thermoaeraulics beyond the consideration of the surrounding climatic and meteorological conditions. The aim of this exercise is to culminate in a site arrangement permitting the constant effectiveness of the « natural convection motor », including in the transient phases of placement in interim storage and the modification of the storage facility. The approach will be pursued in order to achieve a progressive reduction in the airflow, ultimately tending towards a site closed on itself.

Finally, two advantages can be mentioned which are directly linked to the use of heat pipes to cool the interim storage containers :

- maintenance of the apparent external temperature of the packages at the operating values of the water evaporation processes of the heat pipe, or around 100°C or less (adjustment possible) : this limits the source of heat radiation which heats the surrounding concrete structures ;
- maintenance of « security » cooling of the containers, by means of a confined fluid, in case of need to block the natural convection in a storage span (for example, to prevent the dispersion of radionuclides in case of seal failure).

4 - CONCLUSIONS

The challenge of surface and thermal densification of the COFRE concept, which must ultimately result in a significant reduction in the cost of interim storage of fuels and wastes, has led to the development of an original cooling system, capable of passively extracting the high heat flux emitted by a container over a period of some 50 years, and conducting it outside the facility through the use of water in a two-phase closed thermosiphon in a sealed circuit. The evaporator technology enables it to match the surface of the container, and the air cooled condenser placed outside the facility is dimensioned to account for the temporal change in thermal power, climatic variations, and the presence of non condensable produced by the internal corrosion of the materials and the radiolysis of the coolant.

This cooling system, which has demonstrated its potential effectiveness, could, beyond the strict application to the dry interim storage of irradiated fuels, advantageously offer maintenance-free solutions to the problems of temperature control for miscellaneous installations and numerous high heat generating industrial objects.