SUPERPHENIX Dismantling – Status and lessons learned

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Abstract. Following Superphenix definitive shutdown announcement in 1997, enacted by a decree in late 1998, it was rapidly decided to start the reactor dismantling, for technical reasons (keeping in liquid form large amounts of sodium) and human resources availability.
Out of the 19 sodium fast reactors having been operated worldwide, 13 are dismantled or being dismantled. So there is already a great experience in this domain. Superphenix, taking over some of this methodology processes, got in 2006 the decree authorizing its definitive shutdown and dismantling, which allowed it to start sodium treatment and nuclear dismantling and to have completed by 2015 the entire sodium destruction.
Dismantling of a fast reactor presents specificities related to this presence of sodium and to the necessity to eliminate it, before being able to undertake the usual dismantling procedures. The procedures used to eliminate this sodium in the Superphenix primary vessel, are explained in this paper.
Explanations are given on the last events of these dismantling operations as the use of a dedicated robot to cut internal structures of the primary vessel where residual sodium was accumulated.
This Superphenix experience validates a methodology but shows that there are some remaining points needing further developments for complete elimination (oxidized NaK, oxidized sodium aerosols or cold traps).
Moreover, this experience enables to propose recommendations in terms of future reactor design, aiming at make their dismantling easier.
Key Words: Dismantling – Decommissioning – Superphenix

1. Introduction

Following Superphenix definitive shutdown announcement, made in 1997, and enacted by a decree in late 1998, it was rapidly decided to start the reactor dismantling, for technical reasons (keeping in liquid form large amounts of sodium) and to profit available human skills (sodium, operation, maintenance..).

Establishing the cases, started in 1998, would allow obtaining in 2006 the reactor dismantling authorization decree. The proposed and accepted strategy, for Superphenix dismantling, was able to rely on a significant international experience in this domain.

2. International experience for sodium-cooled fast reactor dismantling

Out of the nineteen sodium fast reactors having been operated worldwide, thirteen are dismantled or being dismantled. So there is already a great experience in this domain. This experience is internationally well shared, in particular during IAEA workshops and FBR WANO (*World Association of Nuclear Operators*) group annual meetings.

The French reactor Rapsodie

During Rapsodie reactor dismantling operations, a serious accident occurred, following the use of heavy alcohol (ethyl carbitol) in large quantities in a sodium storage container, so as to destroy a residual sodium (100 to 150 kg) pool. At one point, the reaction got oversped. The temperature rise led to the alcohol vaporization and then to a high intensity explosion, which resulted in the death of one worker and to four injured.

Since this accident, there is no longer use of alcohol in the sodium destruction procedures, this requirement having been confirmed by international working groups.

This International experience shows the outlines of the processes to use:

- The drained sodium destruction is carried out with water, by NOAH-type processes, so as to transform it into sodium hydroxide. Several possibilities were then tested for this sodium hydroxide: transformation in salt, direct discharge, storage under the form of solid sodium hydroxide, etc.
- If significant clad failures have occurred during the reactor life, a purification of the primary sodium (or of the products obtained after its destruction) is necessary, in particular, so as to recover the traces of caesium.
- Cleaning (in the sense of the sodium destruction) of facilities from their residual sodium after draining was usually performed with wet nitrogen or wet CO_2.
- A water immersion of the reactor block is recommended before starting the structure cutting operations.

3. Superphenix operation progress

Superphenix dismantling is underway at the end of 2016, and takes place in several phases.

Phase 1 Evacuation of the core and of all the lateral neutron shieldings

This evacuation is carried out by the normal handling pathways (Fig 1) provided for this purpose and enables to lead to the washing of most extracted elements. These operations may usually be performed during the preparatory phase before obtaining the dismantling authorization decree.

At Superphenix, sub-assemblies were, after washing, stored in the APEC pool.

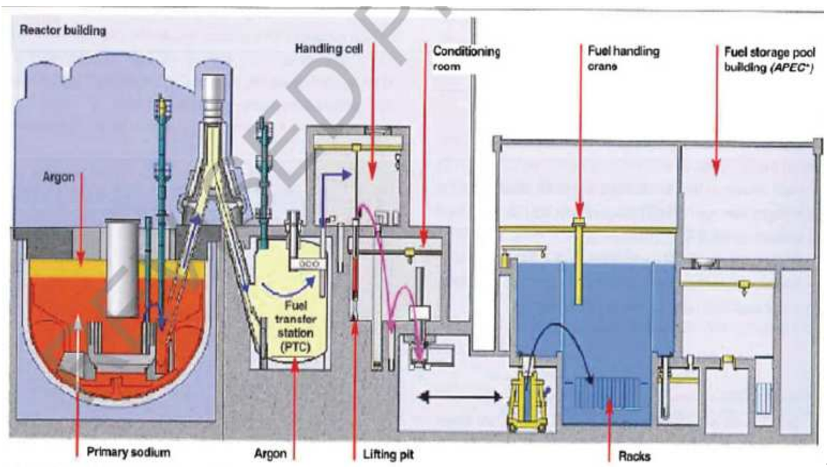

Fig. 1 – Evacuation of the core and all the lateral neutron shields

The lateral neutron shieldings were placed in containers aimed to ANDRA (Fig. 2).

Fig. 2 - PNL storage containers towards ANDRA.

However, it should be noted that 82 lateral neutron shieldings (PNL), located at the core periphery edge, had to be brought back in a position, where they could be accessed to by the normal handling means, via a special device, 14-metre long, because these PNL were not accessible (fig. 3).

Fig. 3 – In–reactor introduction of the special device for PNL evacuation.

It should also be noted that the control rods contain a mix of very fractured boron carbide and sodium, which does not allow their washing by following the usual procedures. These rods were transferred to CEA ISAI facility, their dismantling requiring the development of a process that does not exist at present.

Phase 2 Evacuation, treatment and cutting of all the reactor vessel removable components

Removable components (pumps, intermediate heat exchangers...) can be got out via the operating means (special handling casks). They are then cut, after a carbonation in a pit. The entire (or by strings) component washing process in pits provided for the operating phase (so as to carry out these component maintenance), had then not been implemented at Superphenix, which saved effluents, and the decontamination was not retained because it appeared non-necessary and would have too generated effluents. A specific workshop was built for the dismantling of the large components (Fig.4).

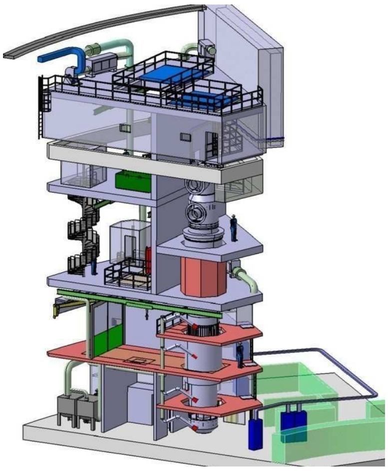

Fig. 4 - Large removable component dismantling workshop.

The component removal sometimes caused problems, because of sodium clusters in the slab penetration annular space (likewise it sometimes happened at Phenix). The components then tend to get stuck to the slab. Heating means of the related penetrations had thus to be used.

A provision was set up at inception (buckets - also called as circular trenches - that prevent aerosol deposits in the slab penetration, see Figure 5). In fact, this device partially prevents deposits, only for the space between the thermal shield (shell between component and slab shell on Figure 5) and the slab shell. It is not efficient for the space between the component and the thermal shield. The components could therefore get stuck to the slab. It should be noted that the thermal shield plays an important part in the reduction of thermosiphon phenomena in the slab penetrations.

This device, which almost seals the space between the thermal shield and the slab, will raise an awkward problem for the reactor block carbonation: so as to provide carbonation gases for an access to this space, cutting operations of these structures (especially the buckets) are necessary. Those operations are realised in 2016 with the ELOISE robot for slab penetration bucket and thermal shields cuttings (figure 6).

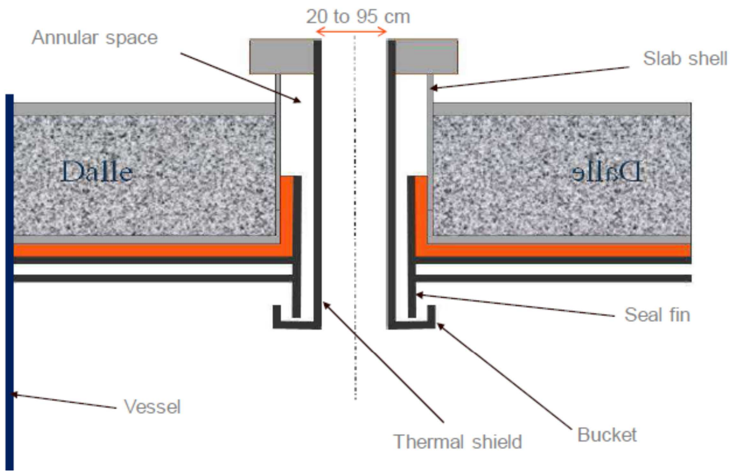

Fig. 5 – Bucket and thermal shield aimed at preventing sodium aerosol rise in the component penetration annular spaces.

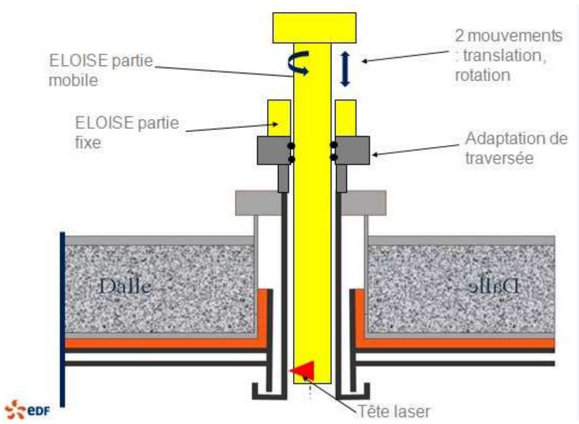

Fig. 6 – ELOISE robot for slab penetration buckets and thermal shields cuttings

Phase 3 Drained sodium destruction

The sodium has to be neutralized. Superphenix was particularly clean because the reactor had experienced no clad failures. It was selected to transform it into sodium hydroxide to be incorporated in concrete blocks. A facility, fed with water and sodium, produced, according to the NOAH process, sodium hydroxide from primary and secondary sodium (see Fig. 7). Then a concrete-making facility used this sodium hydroxide to produce concrete blocks (see Fig. 8). The corresponding blocks were arranged in an on-site interim storage. Nearly 45,800 concrete blocks are thus stored in a 140 × 31-metre building, on fourteen layers (about fourteen metres high). Each block weighs two tons.

Fig. 7 - Reaction vessel producing sodium hydroxide from sodium and a water supply (NOAH process).

Fig. 8 - Concrete blocks obtained from the sodium.

Phase 4 Cleaning and dismantling the sodium circuits (secondary and auxiliary circuits)

The residual sodium, after having drained these circuits, is essentially in the form of films on the walls. The techniques of wet CO_2 injection and of carbonation by venting enable to neutralize this residual sodium, and then to dismantle these circuits in a conventional way. Moreover, these secondary sodium very low activities make easier these operations. This process however could not be used for small diameter piping networks, due to retentions and local clogging risks in these networks, as well as for some components with significant sodium retentions, in singular points, which could not be neutralized by carbonation. It remains thus to dismantle some of the circuits involved under a sodium constraint.

Phase 5 Preparation of the main vessel carbonation and filling-in with water, and realization of these two operations

The vessel being emptied from its sodium, there is thus access to the primary circuit internal structures. The main problem is then to identify the zones of possible sodium retention (Fig. 9). Hence, each of these zones is a special case that can be treated individually. Two cases are possible:

- The retention has a volume sufficiently low to be compatible with the final vessel immersion: no special treatment upstream.
- The sodium volume has to be removed before filling-in with water: a preliminary processing is applied: setting up siphons so as to eliminate the retention during **the** vessel draining phase or drilling and then reheating so as to collect, at the vessel bottom, the recovered volumes, etc.

Therefore, prior to the vessel draining, a siphon was set up to for the inner vessel toroidal section, and holes were drilled on the core catcher plateau so as to ensure to empty such retentions.

For some areas, such as primary pump/diagrid link (LIPOSO), a laser-cutting robot machine, named as CHARLI robot (see fig.10), was developed so as to carry out cutting actions ensuring the disappearance of retention zones (see fig. 9), the thus-drilled holes enabling sodium flow, which is heated and liquefied after the cutting phase.

Significant sodium retention is located at the metal heat insulation of the slab underneath surface. But these condensates are sufficiently thin (in the order of 0.5 cm) so that their effective carbonation could be guaranteed.

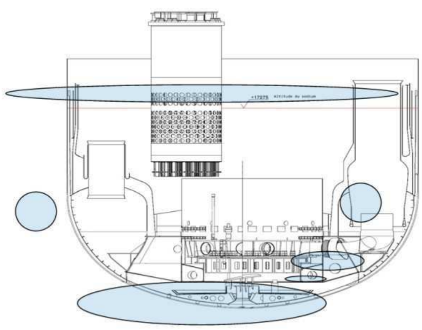

Fig. 9 - Determination of several retention zones to be processed at the core support plate, the pump bottom, the inner vessel siphon and the slab.

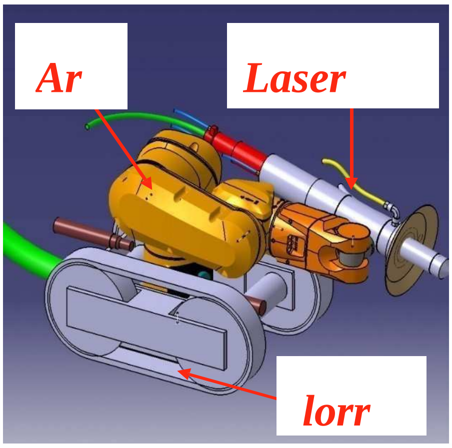

Fig. 10 - Schematic view of the "CHARLI" robot developed to locally make cuts in the zones likely to have sodium retentions.

Cutting the buckets and thermal shields (see Figure 6) located outside the immersion zones, containing sodium, enables to process the slab penetrations with the carbonation gas and subsequently to eliminate the sodium from the buckets during the vessel immersion phase (since the buckets fall into the reactor vessel during their cutting), in order to eliminate the sodium issues before subsequent dismantling operations.

After these retention zone removal operations, a dry and a wet CO_2 carbonation, then an overall washing (by filling-in the reactor with water) will be carried out as a preparation for the reactor block "conventional" dismantling operations.

The CO_2 carbonatation has started in November 2016 (Fig 11). In 2017, all the residual sodium of the vessel will be eliminated with water (by filling-in the reactor with water).

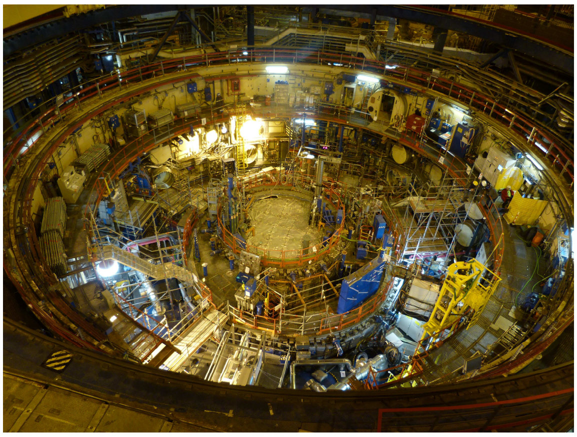

Fig. 11 – CO2 carbonatation of the wessel in November 2016.

Phase 6 Dismantling the reactor inner structures and the vessel

This phase will be conducted via remote-controlled cuttings, for radiation protection reasons. The scenario retained *in fine* is an extraction of the diagrid under biological protection and a remote-controlled dismantling in a dedicated workshop.

Phase 7 End of dismantling operations: Radioactive disposal of premises + Buildings demolition

Superphenix end of dismantling operations is then intended with elimination of the total radioactivity from the installations. A schedule is provided at the end of the paper.

4. Fast reactor dismantling general specificities

Superphenix experience, in addition to past experiences, enables to better outline the recognized specificities and methodologies for dismantling a fast reactor.

Sub-assembly washing

Reactor dismantling first act is to evacuate the fuel elements. These have therefore to be removed from the sodium via the handling means used during operations, then washed in water so as to make the residual sodium film disappear. This is the procedure used during operations, and it does not pose any particular problems. These sub-assemblies are then sent either to interim storage or to reprocessing so as to recover the materials.

However, it should be noted the problem of sub-assemblies with clad failures (in the event when there would have been one or several clad failures), for which the presence-of-sodium risk in the failed pin prohibits direct washing. It may be mentioned that Russians, in some cases, do immerse these sub-assemblies in a container filled with lead for subsequent storage.

The fertile elements, the various devices and the lateral neutron shielding, are removed too.

However, it may be noted difficulties on absorbent sub-assemblies, for which washing and cutting techniques are not available at present.

Keeping sodium under liquid form

Sodium is generally kept under liquid form so as to be easily drained and processed. This keeping at a temperature above 140°C is achieved via the pump rotations and the related energy dissipation. Before removing the pumps (or the core), heating devices must therefore be provided as a replacement. The pre-heating devices may sometimes be used for this purpose, or as a complement. At Superphenix, heating resistors were fitted on the reactor safety vessel. These were enough to keep the primary sodium temperature.

Getting out removable components

The whole set of removable components has to be removed for washing, decontamination (or carbonation only in Superphenix case) and disassembling or possible cutting. The related procedures are, for most of them, known and have generally already been applied during the reactor operations for repair or maintenance operations. It will be noted that some components may be transferred directly to the storage centres after washing and with no disassembly. Again, there are therefore no particular difficulties, apart from the management of sodium and tritium risks during the operations.

Provisions for cold traps containing active products

A number of cold traps, during the reactor life, trapped all non-desired products (sodium oxides and hydrides, tritium, caesium and fission products in the event of clad failures, corrosion products...).

The first possibility is to store these traps as such, but the presence of sodium makes it difficult today to accept that for a long-term storage.

Techniques using the cold trap own enclosure as a chamber for chemical reactions can then be proposed. This is the case at Superphenix for secondary traps, via a thermolysis (which releases the tritium), followed by a WVN (Water Vapour Nitrogen) hot treatment, which destroys sodium and sodium oxide. Sodium hydroxide is then recovered. This method was successfully used at Superphenix.

The first Superphenix primary cold trap cartridges have been processed in 2016 with the same process, in a pit (since they have no own enclosure able to contain the chemical reactions). The last cold trap cartridges will be treated in 2017.

The problem is more complex for the primary cold trap if the reactor has experienced clad failures, and if fission products, released during these failures, can be found in it. Even with no clad failures, a concentration of activated corrosion products (manganese-54 and cobalt) will be found in these primary cold traps.

After these possible operations, the choice remains between a storage as such (including after possible infilling with lead) and the trap cutting so as to reduce the final volumes.

Sodium processing

In terms of activity, the secondary sodium is generally barely active and poses no problem. Nevertheless, it contains tritium, and precautions are thus necessary. The primary sodium will contain the activity from the sodium-22 (period 2.6 years), possible activated corrosion products and, in case of some clad failures during the reactor life, some fission products, mainly caesium (it also contains tritium). For reactors having had many clad failures, caesium traps are used during filtration so as to get the desired levels of activity before sodium destruction. As to Superphenix its primary sodium was very clean.

These tonnes of sodium from primary and secondary circuits, if they are not re-used in another reactor, have to be processed. This is often achieved by devices for controlled and simultaneous injection of water and sodium, in a device to transform sodium into sodium hydroxide. These devices do vary depending on the reactors, but are all based on this same principle (NOAH process). The solutions containing soda can then either be disposed of, or diluted or neutralized in the form of salts.

At Superphenix, it was chosen to transform this sodium hydroxide (soda) into concrete. This choice was not made on the basis of technical considerations, but was imposed by the difficulties that applications for discharge authorization would have raised, with a potential impact on schedules. If this choice did effectively generate no release, it is nevertheless a choice that created, from the sodium initial 5,520 tonnes, 70,000 tonnes of unusable concrete that had to be stored in a devoted building and whose ultimate future remains unclear (fig. 13).

Processing of all the circuits having contained sodium

The reactor vessel and the secondary circuits will contain, after draining, sodium traces in films on the walls, and possibilities of residual sodium in small clusters forming retentions after the draining.

Fig. 13 - Inside the building devoted to the storage of 70,000 tonnes of concrete created with sodium hydroxide obtained by the sodium destruction.

For the secondary circuits, where activities remain low, preliminary cutting and carbonation processing with wet CO2, can neutralize the sodium remaining traces. Nevertheless, for small diameter piping, Superphenix experience showed that this was not possible (see above), it then remains only to dismantle these small piping under sodium constrains.

For the primary circuit, it has to be used video means so as to visualize and quantify the different retentions.

For this primary circuit, carefully-done drainings are conducted with sometimes, locally, suctions or siphoning. Then, the retention zones, where sodium residual volumes may have remained, have to be identified and dealt with, one by one. It should be noted that, since the accident at Rapsodie in 1994, the use of alcohols so as to dissolve the sodium remaining pools has been totally abandoned. Carbonation with wet CO2, then immersion in water remain the privileged way before the cutting/removal procedures.

Prior to the carbonation, some confined spaces have also to be freed by cutting or lifting, so that the carbonation gases can access them (as an example, in Superphenix case, lifting the dummy diagrid, or bucket preliminary cutting, so that carbonation can also concern the slab penetrations).

One problem is MESOS (sodium and oxides clusters) removal that may have accumulated under the slab or in the slab penetrations.

NaK processing

This sodium/potassium eutectic has the advantage of remaining liquid at room temperature. As such, it was used at Superphenix in a number of applications: waveguide for VISUS (under sodium visualisation device, used for fuel handling), secondary cold trap double envelope, bubblers (also called as spargers) so as to purify argon, and liquid for hydraulic safety valves.

On an other hand, in the event of this NaK oxidation, the experience shows that its handling present explosion hazards related to simultaneous releases of hydrogen by hydrates and of oxygen by potassium peroxides.

If this oxidation remains yet accidental for uses such as waveguide, or double envelope, or liquid for valves, it is real for bubblers. After "clean" NaK draining, it is necessary to separately process the oxides, which remains an awkward operation.

More radical solutions have already been used (Phenix): freezing of the whole lot and transportation in a frozen state towards a destruction facility.

As a conclusion, the processing of these devices containing NaK remains an awkward operation for the operator.

5. Reminder of the difficulties and necessary developments

Superphenix experience shows that, if there is a consensus on the general methods for the dismantling of a sodium-cooled fast reactor, a number of points, however, still require some developments.

Sodium residual volumes in the reactor block

In a large dimension reactor block and with complex internal structures, robot systems for a final inspection for verification and possible action, are to be expected and developed. This was the case for Superphenix, with endoscopic devices and the CHARLI robot and the ELOISE robot for slab penetration bucket cuttings.

Control rods

The boron carbide, used in the absorbent elements, is in contact with the sodium entering these elements (which helps the B4C cooling, the "vents" enabling this sodium penetration are also used to let go gases getting formed in the control rods). This residual sodium substantial presence makes it impossible to complete the entire washing, and therefore the absorbent element "as such" definitive storage seems difficult to consider.

The boron carbide fractured final state (besides the significant presence of sodium) also makes awkward the control rod dismantling by cutting.

Development and justification studies for the adjustment of either dismantling processes or storage as waste, without washing or dismantling, are needed.

Cold traps

It should be noted that there was, at Superphenix a good experience feedback of the "thermolysis + hot WVN" process.

Activity Level

Calculations show that the diagrid zones with stellite are going to be major elements for the dosimetry of the structure cutting actions, which, in any case, will have to be remotely carried out. The introduction in the reactor, via the stellites, of significant cobalt quantities has to be, if possible, avoided in the future.

Tritium

Most of the tritium is trapped in the cold traps, but a small part may get attached to the walls and their residual sodium film. During carbonation or cutting operations, tritium releases do occur. The enrichment factor values in the films are not reproducible and vary with an important factor, depending on misidentified parameters.

Two main issues related to tritium were encountered during Superphenix dismantling:

- First, in 1999, when unloading the first irradiated sub-assemblies, a tritium alarm was triggered in the fuel transfer station (PTC). The incident interpretation was going to show that the hydrogen contents were higher in the PTC (20 to 50 vpm) than in the core cover gas (1 vpm), because of PTC wall slow degassing phenomena. An isotopic exchange between the tritium present in the handling pot sodium and in-excess hydrogen did occur, with a corresponding signal rise. The alarm threshold was raised up to $5 \cdot 10^8$ Bq/m^3.
- Then, during the rotating transfer lock dismantling, in 2011, another problem was observed: when scavenging and carbonating the lock, 325 GBq of tritium were released, whereas the released activity had been estimated at 18 GBq in an envelope case (accidental). In-tritium enrichment higher than expected for the residual sodium film, explains most of the difference. As mentioned above, the enrichment factor may vary in a very significant range, depending on non-identified parameters.

It also should be noted that there were differences between what was expected and what was measured, for released tritium during carbonation and cutting of the reactor removable components; again it is due to the enrichment factor variability.

Furthermore, the tritium diffused in the various structure materials may be non-compliant with expected values, and punctual measurements are not always representative.

MESOS

Oxidized sodium aerosol deposits (MESOS) were identified in slab penetrations. These confined areas are little favourable both to inspections and to carbonation processes. Bucket cutting, prior to Superphenix main vessel carbonation, has enabled this processing to neutralize these MESOS.

Furthermore, it remains the problem of underneath-the-slab heat insulation spaces, which cannot be easily inspected and might also contain residual sodium. As to Superphenix, the inspection was completed and it shows that the carbonation will be efficient. However this is a point to consider in a general way, and it may be a major issue if residual sodium does remain in a zone with little access by the carbonating gases, or if the aggregate is sufficiently thick so that the carbonation cannot be complete.

Dismantling environmental impacts

This is a major aspect, the control of these impacts is obviously necessary, all the more that they are significantly more important than during the operations phase, in particular in terms of waste production.

- For the production of effluents, it is essentially the tritium atmospheric release, which is relatively high during some years, when processing the cold traps or their cartridges. For Superphenix, the four secondary circuit cold trap processing resulted in an about 70 TBq release. For that related to the primary cold trap eleven cartridges (which has partially been carried in 2016 and remains to be finished in 2017), it should result, as it is expected, in a released activity almost equivalent in magnitude. However, as a rule (but with proved exception), the first results for a few cartridges do show tritium releases much lower than expected.

- As to waste production, Figure 14 shows the expected figures for the entire dismantling phase. The estimate is based on November 2015 knowledge.

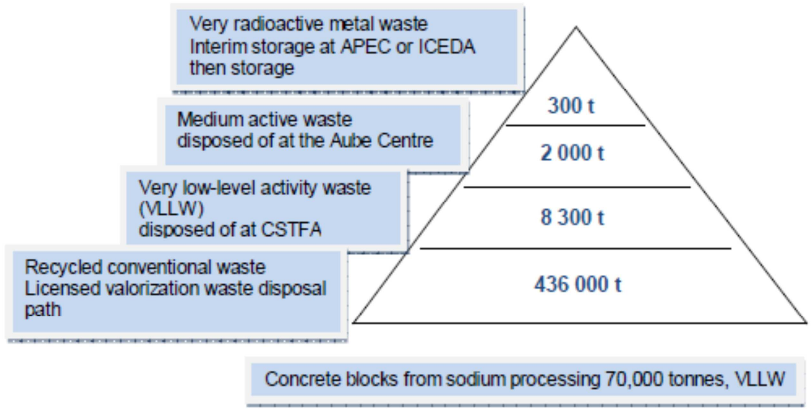

Fig. 14 - The waste produced during dismantling.

6. Recommendations for the design of future reactors

Superphenix dismantling experience leads to prescribe some points for the design of future sodium-cooled fast reactors.

Materials

The use, as hard coating, of cobalt-based stellites, leads to a significant activation of these areas, when they are under neutron flux. The development, for example for the diagrid support columns, of nickel-based coatings (Colmonoy or Tribaloy or Nucalloy) would be necessary but is not guaranteed. The choice of the "ideal" couple coating and its deposit method is the subject of an R & D substantial programme. For some uses, instead of stellites, chromium carbide could also appear interesting.

Accessibility to PNL (Lateral Neutron Shielding)

Handling systems should be designed, from inception, so as to enable to remove not only the core, but also the whole neutron shielding surrounding the core, providing that this does not increase unreasonably handling system costs.

Reactor block draining capacity

The structures present in the reactor block must be designed so as to enable sodium draining without creating retention zones. The holes necessary for draining must be in sufficient number and with large diameters so as to prevent any plugging.

Minimization of aerosol deposits

Provisions (semi-warm slab, no heat insulation capable to trap condensates, etc.) enable to minimize aerosol or MESOS deposits in the upper parts and must be taken into account at design time.

Avoid the use of NaK

As much as possible and, in particular, for uses where oxidation cannot be avoided (bubblers also said as spargers), the use of NaK must be avoided.

Waste Zoning

To define an initial zoning enabling to maintain a very high radiological cleanliness during the operations phase, also makes easier the dismantling, while minimizing nuclear waste.

Tritium

A better understanding of tritium migration and trapping mechanisms is necessary to better assess the amounts of tritium remaining in the residual sodium films after draining. So it should be useful to more reliably estimate the residual film enrichment factor.

Primary cold traps

The concentration of a high radiological source term in primary cold traps, throughout the operations phase, may lead to difficulties for these components dismantling (risk of excessive releases and too significant dosimetry). So, in terms of dismantling ease, it is better to limit, by design, the amount of trapped radioactive products, by reducing the filter element size: use of small-sized removable primary cartridges rather than large-sized traps.

Various cold traps or their cartridges processing

So as to prevent tritium releases, two solutions could bring improvement: either to trap the tritium released during processing of the traps or their cartridges, or not process these elements and consider them as waste to get disposed of, with no processing (likewise practiced in the US).

Control rods

This waste will have to get an outlet, otherwise a dismantling process will have to be found, in particular for the "sodium removal". Furthermore, the B4C fragmentation in very fine particles makes the absorbent pin cutting very awkward. An Ideal solution (not currently possible) would be to store the used rods as such, without any processing or cutting. This same problem also arises for the future SFR upper neutron shieldings, if they are, unlike those at Superphenix, with B4C and of vent-type.