# SUPERPHENIX Fuel Storage Tank Investigations Concerning the Sodium Leak - Dimensionnal and Material Aspects

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## 1. INTRODUCTION

Following the detection, in march 1987, of a sodium leak from the fuel storage drum (figure 1) of the SUPERPHENIX LMFBR reactor, investigations have been undertaken by NOVATOME in order to :

. check again that the design of the storage main vessel was right,
. make an assessment of the vessel behavior under the actual loadings supported during its two first years of life,
. check the mechanical properties of materials (in purchase and present conditions),
. find whether the leak could be explained by design failure or unexpected material properties.

## 2. DESCRIPTION OF THE STRUCTURES

The fuel storage drum is an intermediate storage area of fuel assemblies :
. for the storage of new assemblies before loading into the reactor,
. for the storage of irradiated assemblies before their transfer to the outside water storage facility. This transfer is performed after residual power decay.

The fuel storage drum includes :
. a main vessel :
- diameter : 9.5 m
- height :12 m
- thickness :20 m
- material : ferritic steel :15D3

This vessel contains 700 tons of sodium normally at a temperature of 200°C.
. A safety vessel which encloses the main vessel at distance of about 150 mm. The space between the two vessels is filled with nitrogen.
. Fuel assemblies supporting structures : 409 locations distributed on two levels. The standard use conditions correspond to the unloading of a half core, i.e. about 200 assemblies located on a same level. Under specific conditions, a full core can be loaded.
. 2 heat exchangers with immersed coils near the main vessel, guided by supports mounted on plates welded on this vessel.

The fuel storage drum is connected to :
. the primary system through the elevator of the rotating transfer lock : this connection is closed by two valves during the plant operation and between the handling downtimes.
. the new assemblies loading system through two vertical pits above which a handling flask is positioned.

. the handling cell : a fixed structure used for the assemblies removal through two vertical pits.

## 3. INVESTIGATIONS CONCERNING DESIGN ASPECTS

Owing to the fact that the date of the detection of the leak (March 1987) and the date of the localization of the cracked zone (September 1987) are separated by a long period (6 months), these investigations were focused on two aims :

. before the localization of the leak :
NOVATOME has checked again, by means of accurate studies, the design of the structures in order to :
- assess the eventual risks due to the sodium leak,
- bring out the possible locations of the cracked zone.

. following the localization of the leak :
NOVATOME has performed some stress calculations in order to determine if the actual, or assumed, mechanical and thermomechanical loadings supported by the cracked zone could explain this leak.

### 3.1 Investigations before the localization of the leak

a) In spite of the presence of the leak on the main vessel, the plant safety has never been questioned because the vessels had been designed so that the sodium levels between the main vessel and the safety vessel could counterbalance each other without involving the assemblies drying out (cooling was always provided).
However, the potential risk which had to be examined was the behavior of the safety vessel in case of a filling by sodium. Indeed, the safety vessel is a tank composed of :
- a cylindrical shell,
- a torospherical bottom shell,
- a "bec de cafetiere" (figure 2) : an inclined nozzle implemented on the cylindrical shell, which permits the handling of the fuel assemblies.

The junction "bec de cafetiere"/cylindrical shell was supposed to be the most sensitive point of the safety vessel, owing to the geometrical discontinuity in this region.
In order to check the behavior of this junction, a Finite Element computation has been performed by means of the SYSTUS Code, using six and eight-noded shell elements.
The resulting F.E. model (figure 3) has been subjected to three kinds of loadings :
- hydrostatic pressures induced by various sodium filling levels,
- uniform pressure induced by the presence of gas in the space between the two vessels,
- self weights of the structures.

The calculations showed that the most highly loaded regions were the upper and the lower junctions between the "bec de cafetiere" and the vessel (figure 3). In order to have stresses within the allowable values, a plot showing the allowable values of gas pressure versus the sodium filling level has been built. This plot enabled to determine operating conditions for repairing the structures. These conditions were in a good compliance with the scheduled actions.

b) The safety aspect being examined, the second action which had to be undertaken was the research of possible highly loaded zones on the main vessel, in order to try to localize the leak.
One region has been particularly investigated :
- the junction between the main vessel and the strongback (figure 4).

The load cases considered concern the actual thermal loadings supported by the structure during its two first years of life. These loadings correspond to various operating conditions and induce axial temperature gradients :

- injection of "cold" sodium in the lower part of the vessel in the case of startup of the cooling system.
- temperature control in the main vessel.

The temperature gradients corresponding to these operating conditions may change, with regard to their range and their location. So a set of parametric computations has been carried out in order to determine the most pessimistic conditions.

These calculations, performed with 2D axisymmetric Finite Elements, showed that even with a temperature step at the junction vessel/ strongback, the fatigue damage induced by 200 cycles loading <> unloading was not significant.

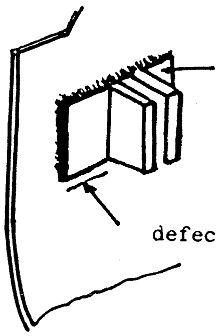
Therefore, these studies could not bring out any particular region which could have been highly stressed under actual loadings, and from which the leak could have been initiated.

### 3.2 Investigations following the localization of the leak

In September 1987, the leak was located at level 10400 in azimuth 270°, which corresponds to the lower weld of a fastener guide plate of the cooling systems (figure 5). In this region, austenitic 316 L and ferritic 15D3 steels are welded together.

An investigation on this particular structure enabled to bring out three kinds of possible loadings :

a) The thermal loadings induced by the normal operating conditions may provoke mechanical efforts on the plate, if we assume that structures designed in order to expand freely may be blocked owing to a jamming phenomenon or an insufficient gap.
Stresses are therefore due to temperature differences and to the difference of the expansion coefficients between 15D3 vessel steel and austenitic 316 L cooling system steel (tubes and supports).




b) Stresses may be induced by axial temperature gradients, in the same way as it occurs on the junction between vessel and strongback.
c) Stresses may be provoked by the differential expansion, at 200°C, due to the difference of expansion coefficients between ferritic and austenitic steels.

In order to assess the consequences of these loadings on the considered structures, three-dimensional Finite Element computations have been carried out. The load cases which have been taken into account are the loadings explained above.

All the calculations performed have shown that load cases induced by normal operating conditions provoked only low stresses which could not explain the initiation or the propagation of a crack during the operating period of SUPERPHENIX.

In order to derive high stresses, it was necessary to make quite irrealistic assumptions.

It has also been attempted another investigation in order to determine if a through-crack on the main vessel could be opened or not by the normal operating loadings (hydrostatic pressure and thermal loading).

A 3D Finite Element model has thus been built (figure 4) including :
- the main vessel
- the strongback

The through-crack was supposed to be 435 mm long (which corresponds to the average value of the real crack). The computations performed showed that the sodium hydrostatic pressure could open the crack :

the computed axial opening is : 0.038 mm

The calculated value, necessary to permit the measured sodium flow-rate (20 l/h), was 0.04 mm.

This good agreement allowed to validate the following assumption : the through-crack being initiated by other than design reasons, the normal operating conditions may induce a sodium leak of 20 l/h flow-rate.

## 4. INVESTIGATIONS ABOUT MATERIAL ASPECTS

### 4.1 Chemical and mechanical characteristics of the steel of the drum

We have used a steel (15D3) for boilers and pressure vessel according French standard NF A 36206. It is a low alloy steel with addition of 0,3 % of molybdenum (tab 1). Equivalent standards are in Germany : 15 Mo3 (DIN 17155. oct 83), in UK : C.Mo.240 (BS 1501), in Japan : class 5 SB 46 M. (JIS 3103).

The check of acceptance tests of the plates purchased before 1980 and used for the fuel storage drum is summarised in tab. 1 for chemical analysis and in tab. 2 for mechanical characteristics. Plates used for the drum were quite in agreement with specifications. Recent tests included in tab. 1 and 2 show that analysis and mechanical characteristics in the close vicinity of the leaking crack are also quite similar to initial values after more than 2 years of operation in Na at 180-200°C. (KCV level at 0°C -> 4daJ/cm$^2$ - was also well kept up).

TABLE 1 - 15D3 CHEMICAL ANALYSIS

| | C | Mn | Si | Mo | Cr | P | S | Cu | V |
|---|---|---|---|---|---|---|---|---|---|
| SPECIFICATIONS ON PLATES | 0,20 max | 0,45 0,85 | 0,10 0,35 | 0,25 0,40 | 0,30 max | 0,035 max | 0,035 max | 0,25 max | 0,04 max |
| DRUM PLATES CHECK ANALYSIS MAX | 0,17 | 0,70 | 0,26 | 0,29 | 0,13 | 0,010 | 0.021 | 0,22 | <0,01 |
| DRUM PLATES CHECK ANALYSIS MIN | 0,15 | 0,63 | 0,23 | 0,27 | 0,09 | | 0,006 (mean 0,012 | 0,13 | |
| ANALYSIS (EDF) ON SAMPLES NEAR CRACK | 0,150 | | | | | 0,007 | 0,018 | | <0,01 |
| | 0,160 | 0,67 | 0,24 | 0,29 | 0,13 | 0,013 | 0,015 | 0,23 | |

TABLE 2 - 15D3 MECHANICAL CHARACTERISTICS

| | AT ROOM T° | | | | AT 200°C | | | |
|---|---|---|---|---|---|---|---|---|
| | R0,002 MPa | Rm MPa | A % | Z % | R0,002 MPa | Rm MPa | A % | Z % |
| SPECIFICATION | ≥262 | 430 530 | ≥25 | | ≥245 | | | |
| ACCEPTANCE TESTS FOR DRUM PLATES (Head transverse) | 350 | 500 | 32 | | 280 | 535 | 19 | |
| EDF TESTS - CRACK ZONE | 333 | 499 | 35 | 67 | | 589 | 22 | |
| - SAFETY VESSEL (mean) | 337 | 497 | 34 | 68 | 264 | 572 | 22 | 54 |

### 4.2 Welding

Welding of the drum was made with basic covered electrodes with preheating. Equivalent carbon of the plate of the drum was average : 0,367 , max : 0,372. Hydrogen content of covered electrodes used was less than 4 ml/100 g of weld deposit.

Independently of these good chemical characteristics all welding tests made before fabrication and during recent investigations have shown that the "weldability" of this steel is excellent even in severe conditions (low energy, no preheating, humidity...).

### 4.3 Crack explanation

The leaking crack (≃ 450 mm length) and other samples were examined. All the fracture facies are typical of a mechanism of hydrogen induced cracking in region of high residual stresses.
The 15D3 steel was found, in test performed since the leak, as rather sensitive to hydrogen. On the other hand, if numerous sources of hydrogen are possible : welding, water test of drum, reaction between Na and rust, hydrogen impurity in Na (about 1 ppm as HNa), they have all to be considered as low or very low sources and the last one can only produce a long term effect.

### 4.4 Tests

Numerous tests were performed or are in progress. The more important of them are an attempt to obtain cracks on welded test coupons of 15D3 fabricated and treated to reproduce as far as possible all the fabrication and operating conditions in sodium of the drum.

## 5. CONCLUSIONS

The investigations undertaken following the detection of a sodium leak on the fuel storage drum of SUPERPHENIX have permitted to :
- confirm the plant safety during the leak,
- make sure that no load cases (design loadings or service life loadings) could induce high stress levels which could have initiated a crack.

The design of the SUPERPHENIX fuel storage drum has thus been well confirmed by the new calculations.

The cause of cracks has now to be more thoroughly investigated in the field of hydrogen induced cracking under residual stresses. This cracking mechanism has to be understood in association with metallurgical properties of 15D3 steel and with very specific and weak hydrogen sources.

## RERERENCES

SYSTUS. Release VAX 229. User's Guide January 1987.

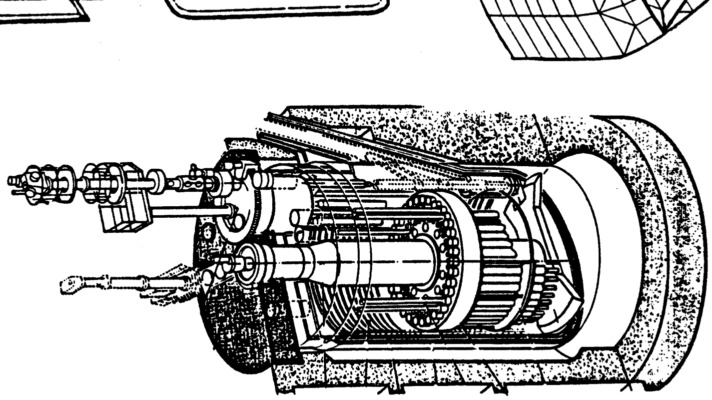


FIGURE 1

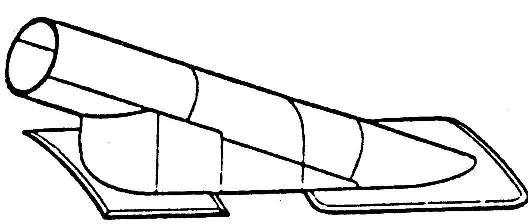


FIGURE 2

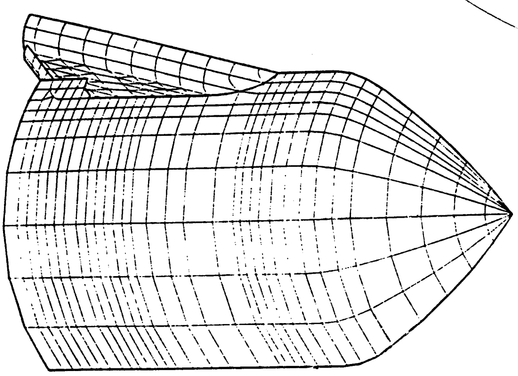


FIGURE 3

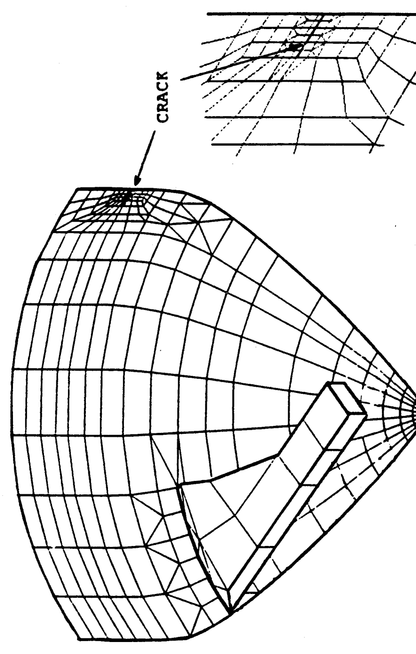



FIGURE 4

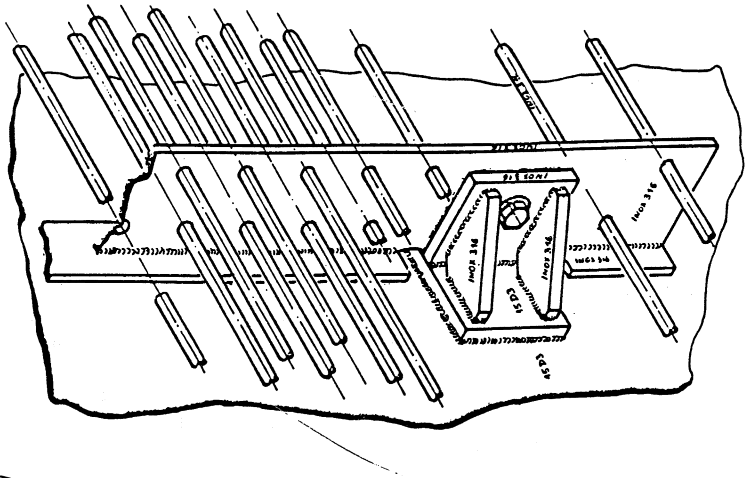


FIGURE 5