High Cycle Thermal Fatigue : experience and state of the art in French LMFRs

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ABSTRACT

High cycle thermal fatigue may be induced as soon as a transition or mixing zone between 2 fluids at different temperatures exists. The downstream region from a tee junction and vicinity of a stratification interface are characteristic of this phenomenon.

Simulation is not easy owing to the following specific problems : turbulence phenomena, thermal exchanges with the wall, random feature of the thermal solicitations, fatigue strength reduction factors at high cycle number…The experience proves that the damage induced can be severe, leading to leakage or rupture of components.

This paper constitutes a state of the art in the domain of high cycle thermal fatigue as regards the French LMFRs' experience. The general methodology applied to design a component when submitted to high cycle thermal fatigue is described together with the layout conditions of flow mixing devices. Contributions by different programs of research and development are shown. From the thermalhydraulic and structural analysis point of view, recommendations are given on numerical simulations and damage assessment. All along this paper, the problems really encountered in Phénix or Superphénix plants illustrate the outcome and recommendations provided. Finally, the technical key points of the problem are pointed out.

INTRODUCTION

This paper deals with thermal fluctuation problems. Such problems are not easy to solve due to the particular feature of these fluctuations. Owing to studies performed subsequently to damages occurred on materials of operating LMFRs, a good experience has been gained on the knowledge of phenomena and has permitted to draw the lines of a methodology for simulation of such problems.

In LMFRs, several areas may give rise to thermal fluctuations phenomena : they are found at the core outlet, due to the different types of fuel assembly and at tee junctions of pipes flowing fluids at different temperatures. Also interfaces of stratification occurring in particular in the lower part of the hot pool induce thermal fluctuations on neighbouring structures. Free level areas if they oscillate, like the gas/fluid interface in tubes of steam generators, may be the source of fluctuations.

First, it is proposed to describe how these problems are managed at design stage of LMFRs.

Second, the different phenomena involved in these problems are analysed. Concerning the simulation, the practices following from the experience gained are highlighted. Uncertainties are mentioned and actions to improve the knowledge of the simulation are listed.

Two problems encountered in Phénix reactor are briefly presented in figures 1 to 4. The tee junction problem (fig. 1 and 2, [1],[2],[3]) lead to a unique through-wall crack involving a main pipe of the secondary circuit in which a small pipe flowed hot sodium inside. The temperature difference was 90°C. The second problem (fig. 3 and 4, [4]) concerns the expansion tanks of Phénix in which hot sodium flowed along walls. The temperature difference when entering the tank was 170°C. A thermal striping damage feature was observed in the mixing area, and also a through-wall crack in a meridian weld.

Another case involving Superphénix reactor is taken up (fig. 5, [5]). It deals with the "corps mort" (buffer structure) area which is the lower part of the hot pool. No damage was observed, but measurements and studies performed are stated.

DESIGN APPROACH

Originally the design of LMFR's circuits takes into account the thermal striping risk by the installation of exchangers or heaters upstream from the mixing areas in order to reduce the temperature differences. However, the installation of such materials is not always conceivable for economic or technical reasons, and also because a perfect homogenisation may be sometimes impossible in all operating conditions.

During the design stage, every area able to be solicited by thermal fluctuations is examined. The temperature difference between fluids is compared to a limit value established for the whole life time of the material. If this criterion is not satisfied the operating conditions or the layout require adaptation.

Since 1993, RCC-MR code provides fatigue curves up to 10^9 cycles for stainless steel type 316 L(N) : the defined strength limit corresponds to 0.104 % of strain range at 550°C at 10^9 cycles. Its translation in term of peak-to-peak temperature range at skin is 46°C considering the signal of temperature is sinusoidal with a 1 Hz period. These curves were settled on the basis of strain controlled tests performed in the frame of the European Fast Reactor work program.

In welded joints, a strength reduction factor is applied :

- Kf = 1.25 for flush welds. The criterion falls to 37°C.
- Kt for welds without grinding, the value depending on the type of the weld (geometry, size of the bead...). Using Kt = 1.7 (as recommended for circumferential weld in RCC-MR) the criterion becomes 27°C.

If the temperature differences in the mixing zones identified are in excess of this criterion, thermalhydraulic calculations are necessary. These calculations allow the precise localisation of the mixing zone. For the estimation of strains, in a first step, only sinusoidal signals and conduction through the wall can be used. The previous criterion can then be refined. If this is not sufficient, finer calculations modelling the random feature of fluctuations can subsequently be carried out. Following these studies if the set criterion cannot be reached the installation of a flow mixing device becomes indispensable.

In LMFR's practice, the installation of a flow mixing device for mixing tee is recommended as soon as the fluid temperature difference between tee branches is higher than 60°C. Nevertheless, thermalhydraulic studies and/or in-site measurements can be performed to demonstrate the acceptability of such a difference, and then to lighten or to eliminate the mixing device.

PHENOMENA ANALYSIS

A realistic simulation of the fluctuating temperature problem needs to take into account the random feature of the loading, leading to model turbulent phenomena inside the fluid and also low frequency instabilities able to affect the flow. Then to evaluate the consequences on materials, exchanges between fluid and metal must be correctly represented, and the thermal field representative of the material.

Step by step, the different phenomena involved in the problem are examined.

Damageable frequency range

The scope of this step is to define the range of frequencies which are damageable for the structure. This evaluation can be done by means of simple unidimensional calculations considering sinusoidal thermal signals as fluctuations. Knowing the thickness of the wall and its conductivity, the response of the structure can easily be found. It appears that the low frequencies (f_1) do not result in a significant temperature difference across the wall. The high frequencies (f_2) do not penetrate inside the wall. Both will not damage the structure. The range [f_1 ; f_2] is defined once the criterion of non damage chosen. The latter is left to the judgement of engineer.

This step is important for the thermalhydraulic calculation. The boundary frequencies $f_1$and f_2 are such as :

- the thermalhydraulic calculation shall be run on a period as long as 10 periods of frequency f_1. The thicker the wall the longer the physical time of calculation must be.
- the time step shall be small enough to be able to catch the highest damageable frequency f_2.

Thermalhydraulic analysis

The thermal signal in fluid can be obtained by different ways :

1. Direct simulation of the signal T = f(t) using either an unstationary thermalhydraulic calculation, or measurements in situ, or mock-up measurements.
2. Signal T = f(t) reconstituted from sinusoidal signals, every sinusoidal signal obtained from an amplitude ΔT and a frequency f.

   The amplitude ΔT can be obtained either from envelope assumptions (source temperature difference for instance) or from stationary turbulent calculation or from experimental tests. The frequencies f can be evaluated either from envelope assumptions (consideration of all the damageable frequencies for instance), or from experimental tests on similar configurations or from examinations of the stationary flow.

The interest of an unstationary calculation is to provide directly the solution. There is also an interest for the determination of the average field. Indeed the use of permanent standard calculations which are submitted to the hypotheses and limits of a K-ε model is not always satisfying. The more performing approach to simulate the turbulent phenomena is a Large Eddy Simulation (LES) or a direct Navier Stokes simulation if no sub-grid model is available [6],[7]. It has to be noted that these approaches are not completely validated in certain configurations. Concerning the modelling some precautions has to be taken : the domain of calculation must be large enough in order to let perturbations develop (5 to 10 diameters for a pipe), must be refined in the interest region and the upstream conditions must be correctly represented. The effects of secondary flows due to upstream circuit such as swirl flow must be particularly represented as they can divert the main flow and hence modify the fluctuations [2],[3].

The simplified approach consisting in performing a stationary calculation to localise the mixing zone and then to consider sinusoidal type fluctuations appears not satisfying as the real random feature is not represented and can give incorrect results if frequencies of the signal are not well chosen. Nevertheless it can be a conservative alternative approach in a design stage as it is really simple to use provided that all damageable frequencies are taken into account.

Real cases have been analysed using sinusoidal signals and presents results coherent with the damage observed ([1],[2],[3],[4] and fig. 1 to 4).

Another phenomenon often exists in circuits which needs a special attention : the presence of valves , pumps, ... can induce low frequencies in the flow. Such frequencies have been observed on the secondary circuit of the Phénix plant where low frequencies of about 1/ 70 Hz were measured on the tee junction between the main pipe and the small pipe (fig. 1).

Also low frequencies were measured on the "corps mort" area of the Superphénix reactor (fig. 5). The stratification interface which separates the two fluids at different temperatures moves axially on frequencies lying between 1/40 and 1/100 Hz.

Even if these frequencies do not generate by themselves a significant damage, they can induce a supplementary excitation in the turbulent spectrum and amplify the fluctuations. It is important to take them into account in the simulation of the problem, for instance via boundary conditions.

Fluid-wall thermal exchange

The convective exchanges in transient regime between fluid and wall are not well known. The knowledge of these thermal exchange coefficients is important as they play a role in the stress amplitude. Coefficients defined using a stationary calculation have a risk of being not conservative. In practice, severe coefficients, even infinite, are considered in analyses.

Among the few available references, an order of magnitude of the thermal exchange coefficient between fluid and wall is given by the French FAENA tests (mixing of two sodium flows along a plate [8]) and the Japanese TIFFSS-3 tests (impact of a single sodium jet on a plate, [9]). The curve deduced from the measurement of the fluid temperatures near the wall shows there is a high attenuation when the frequencies increase. The minimum attenuation is about 15 % on FAENA and 10 % on TIFFSS-3.

A calculation including fluid-wall coupling and a fine discretization of the boundary layer would avoid the estimation of such coefficient. For simulation, it is recommended to increase the conduction transfer within the conductive sub-layer with an empirical function.

Stress estimation

The thermal field in the structure can be defined either directly by the thermalhydraulic analysis if the structure and the fluid-wall transfer is finely modelled, or by a separate conductive calculation once the fluid temperature and the fluid-wall exchange coefficient are known everywhere at every moment. However the problem here is the great quantity of available information provided by the thermalhydraulic approach which is practically impossible to manage in mechanical codes. So a manual selection of the thermal input data is generally done and the estimation of the stress field can be done in two steps :

- calculation of the fluctuating temperature and stress in function of time in a section of the wall (1D approach). The thermal peak in inner skin must be represented finely, in particular if a geometrical singularity like a weld bead exists. This singularity affects the peak stress participating in the initiation of a crack. When the stress concentration is unknown, values provided in codes like RCC-MR or RCC-M may be used. This effect is extremely important knowing that an amplification of a factor 2 on the stress range multiplies the fatigue damage by 1000 owing to the flatness of the fatigue curve at high cycle numbers.
- static calculation of the mean thermal field and mean stress using a global model (generally 3D).

This approach is correct if an important part of the thermal fluctuations affects the skin of the structure and a small part the mean fiber which is the case when turbulent phenomena in fluid are present [1],[2],[3],[4].

At the opposite when low frequencies affect the structure, such an approach may not be severe enough. This behaviour has been observed in the "corps mort" area of Superphenix reactor (fig. 5, [5]). The slow displacement of the interface of stratification produces in the neighbourhood shells, in addition to the variable through wall gradient, a variable axial gradient whose magnitude was not negligible (about 150°C/m). This requires to carry out a time-history calculation on a bidimensional model.

Fatigue damage analysis

When the random feature of the temperature signal is represented, a method of cycle counting is required. The most current method is the Rainflow method. It is applied on the measured or calculated sampling whose duration is generally far less than the life time. The point is then to extend the sampling over the whole life time. The practice leading to multiply the number of cycle of the sampling proportionally to the life time considered may induce an under-estimation of the maximum peak to peak temperature. A solution is to use other techniques allowing to extend properly the signal. The technique of Gumbel [10] can be pointed out although some results are not completely convincing [1].

The RCC-MR code gives for various temperatures a fatigue curve up to 10^9 cycles for the stainless steel type 316 L(N). This curve includes the design coefficients of 2 on the strain range and of 20 on the cycle number. For a flush welded joint a reduction coefficient of 1.25 must be applied. For weld in as-welded conditions, this coefficient is too small. For this kind of weld an acceptable practice seems to apply a stress concentration factor on the elastically calculated stress range . This approach appears satisfying according to the FAENA tests and according to the experience gained [1],[2],[3],[4]. In the case of a best estimate analysis, care must be taken with some parameters as ageing, surface finish, environment, reducing the fatigue strength. Concerning the surface finish, a reduction of 1.49 can be reached for a roughness greater than 350 μm [11]. The influence of the ageing on the fatigue strength is not obvious, FAENA tests [8] found no influence which is not consistent with other references.

It has to be noted that there are very few data as regards the high cycle thermal fatigue strength. Indeed, it is really difficult to settle such values because of the very low strain amplitude, the high number of cycles necessary and the unstable cyclic behaviour at high temperatures [12]. This concerns also the welded joints for which the experimental data are presently limited to 2 10^5 cycles [13].

On the other hand, it is known that mean stresses in a structure may affect the high cycle fatigue strength. These mean stresses are considered in the fatigue analysis for cycles greater than 10^6. A Goodman formulation is generally used. This Goodman correction is done for the mean membrane stresses generated by global loading, due to self-weight, pressure, thermal expansion and also due to a thermal spot or stratification. Peak stresses and residual stresses are excluded. Indeed, it is considered that a stress concentration factor applied on the stress range is sufficient to take into account the effects of welding residual stresses.

In our practice the likelihood of cracking is predicted using the RCC-MR code. If necessary the plasticity influence is considered by means of the triaxiality coefficient K_ν. The coefficient K_ε can also be considered when an important spring effect is expected in structures.

Combination of cycles is required if other stress cycles happen, for instance operating transients. This means that each component of the fluctuation stress range is added to each component of the other stress range. The fatigue damage is then estimated taking into account this enhanced stress range with the associated cycle number. Such way to proceed is more severe than a classical linear summation.

Fracture analysis

The classical Paris law is used. The stress intensity factor range is corrected to include the plastic zone and the R ratio ($R = K_{min}/K_{max}$), with K the stress intensity factor. However, thermal striping produces multiple cracks. This phenomenon is not considered and the propagation is made as if the crack studied (in general the largest) behaves independently from the others. This behaviour has been observed in SPLASH tests [14].

The accuracy of the crack growth analysis is linked to various parameters such as the threshold value and the ratio R considered in the value of the threshold and in the estimation of the stress intensity factor. This ratio includes the mean stresses of the loading and also the residual stresses arising from the manufacturing process. In practice, a parametric study is often interesting as there are uncertainties on the values and distribution of residual stresses. [1] and [2] present the discrepancies brought by the consideration of different mean stresses. The time to propagate through the wall changes by a factor between 5 and 10 whether the mean stress is in compression or in tension.

Moreover the crack growth is sensitive to the formulation chosen for the stress intensity factor, the strain controlled formulation being preferred to the stress controlled one.

PERSPECTIVES AND CONCLUSIONS

A methodology and recommendations for the simulation of high cycle thermal fatigue were defined. Our experience was fed back into these recommendations. Several tools exist to analyse these problems and confidence is in progress on the result validity. However the understanding of the influence of certain parameters must be clarified :

- the LES models are promising. They will became more and more performing even if today they are heavy computer time consumers. Benchmarks would be interesting to validate more the LES calculations and to quantify the influence of hypotheses necessary to the realisation of models.

- there is a lack of data concerning unstationnary exchange coefficients . Two ways could enable to get more data : experimental tests or very fine discretisation of the boundary layer with a fluid calculation-wall conduction coupling.

- better tools for the extension of signals are necessary, knowing the fatigue damage depends mainly on the highest peak-to-peak stress ranges.

- the influence of relevant parameters such as surface finish, welds, mean stress, is not known enough and needs experiments to confirm our methodology are required.

- the tridimensionnal temporal feature of the stress field cannot be generally taken into account due to the too large amount of input themalhydraulic data. The influence of taking into account the 3D geometrical feature is not quantified and needs clarification.

Finally, it appears that numerical tools are progressing together with the capacity and power of computers. This would allow to improve our simulation both in thermalhydraulic and thermomechanical domains. Nevertheless, some experimental activities are still indispensable to get validation points in different topics. Noticing that by the past, benchmarking between experimental and numerical but also between different numerical approaches appeared to be a very interesting way to make progress and to achieve objectives.

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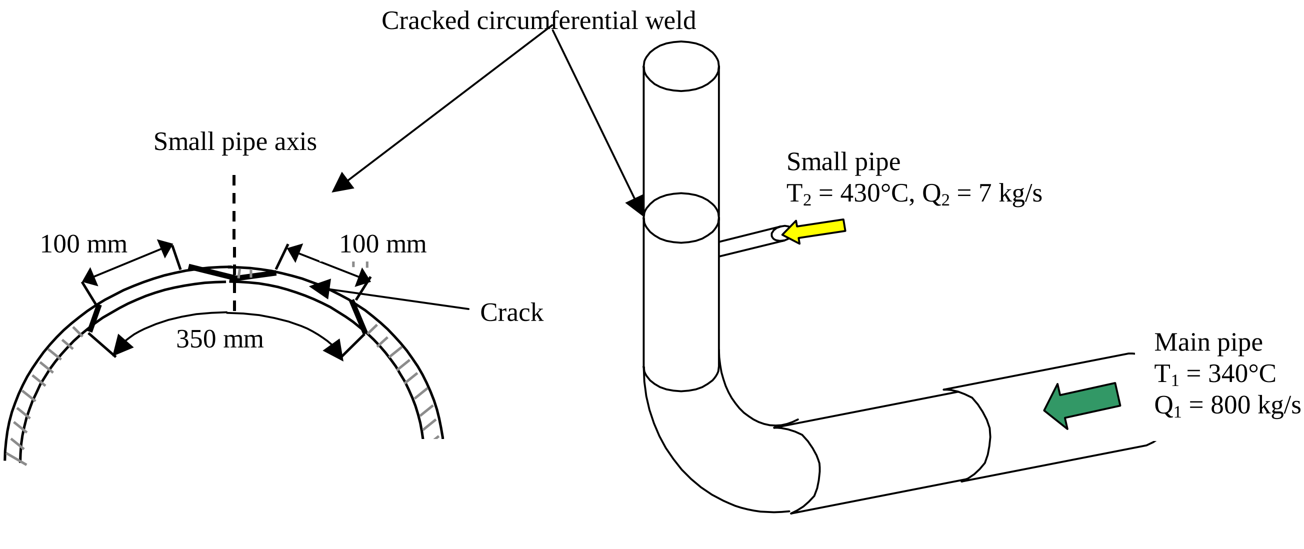

Figure 1 : PHENIX tee junction problem

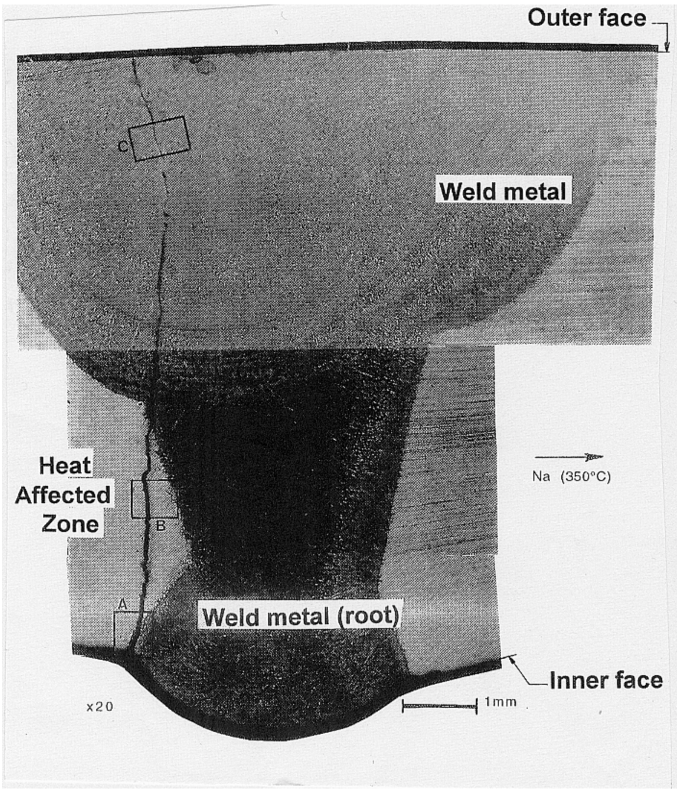

Figure 2 : PHENIX tee junction crack

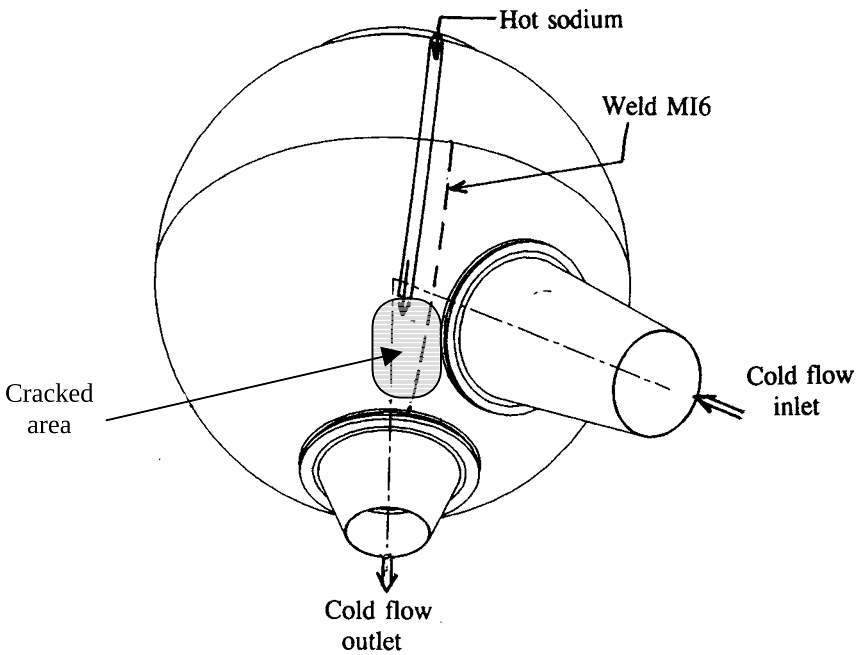

Figure 3 : PHENIX expansion tank problem

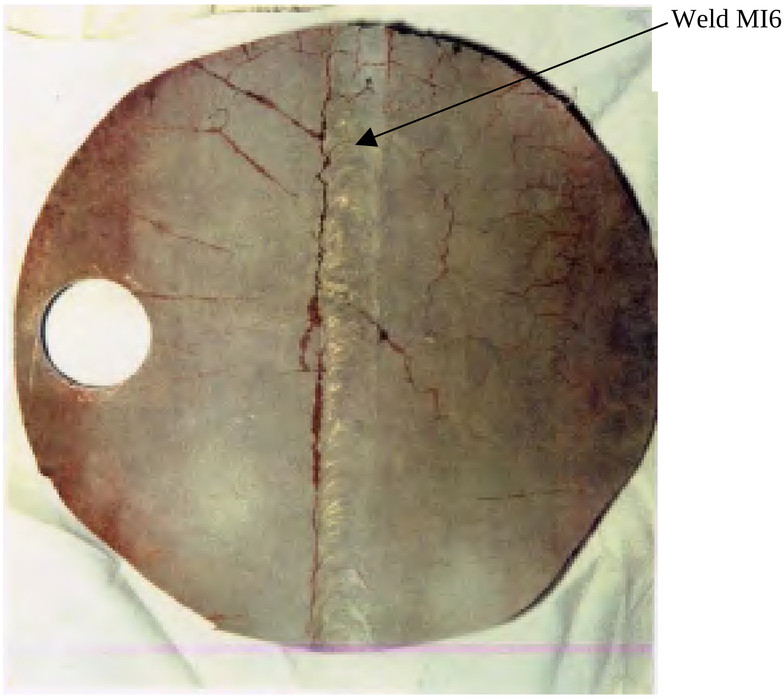

Figure 4 : PHENIX expansion tank – cracks feature

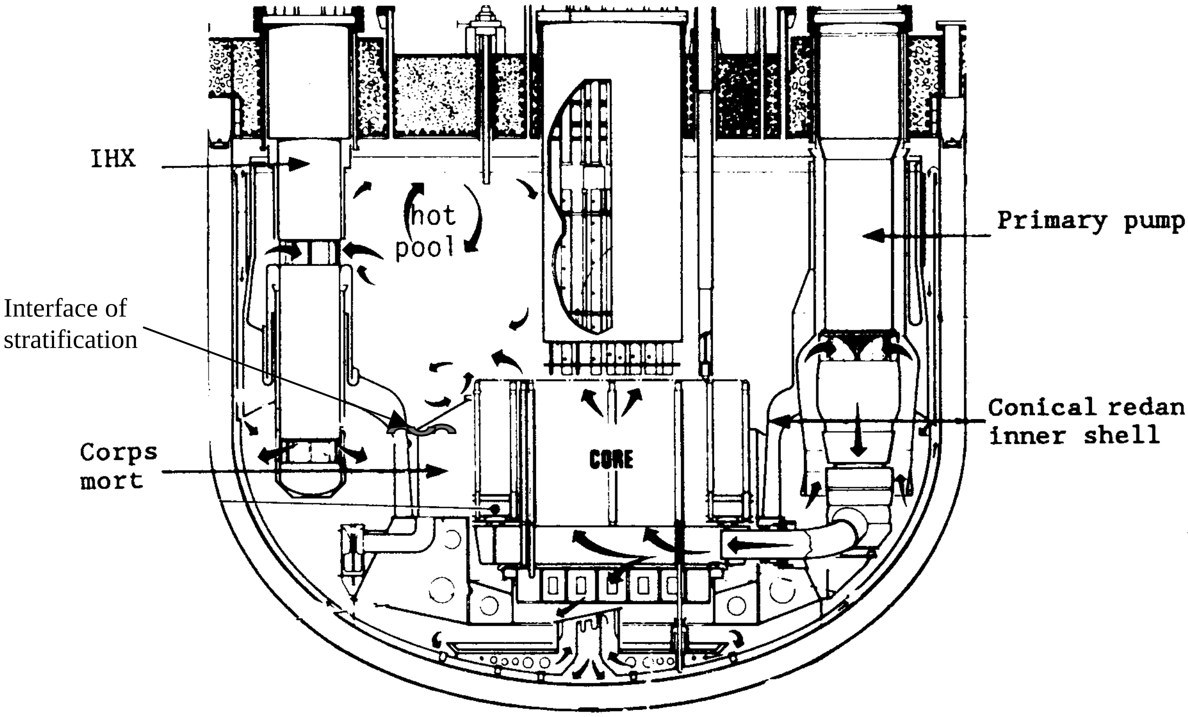

Figure 5 : SUPERPHENIX reactor – Corps mort problem