THERMAL FLUCTUATION PROBLEMS ENCOUNTERED IN LMFRs

FRAMATOME Direction NOVATOME : O. GELINEAU
M.SPERANDIO
CEA DRN Cadarache : Ph. MARTIN
EDF CLI : J.B. RICARD
CEA Centrale PHENIX : L. MARTIN
CEA DTA SRMA Saclay : A. BOUGAULT

38

Thermal Fluctuation Problems encountered in LMFRs

FRAMATOME Direction NOVATOME : O. GELINEAU - M.SPERANDIO
CEA DRN Cadarache : Ph. MARTIN
EDF CLI : J.B. RICARD
CEA Centrale PHENIX : L. MARTIN
CEA DTA SRMA Saclay : A. BOUGAULT

1.Introduction

One of the most significant problems in LMFRs deals with thermal fluctuations. The main reason is that LMFRs operate with sodium at very different temperatures (for SUPERPHENIX : 550°C in hot collector, 400°C in cold collector, in nominal conditions), which leads to the existence, in the reactor, of several areas of transition between hot and cold sodium. These transition areas which are the critical points, may be found in the Reactor Block as well as in the secondary or auxiliary loops.

Various phenomena can be the cause of thermal fluctuations in the reactor, for instance:

- thermal fluctuations generated by the mixing of two flows at different temperatures. This is the case of tee junctions in secondary or auxiliary loops and small pipes coming into tanks.

- temperature variation induced by a cyclic movement of a sodium stratification interface. This phenomenon is encountered in the lower part of the hot pool inside the reactor block.

The characteristics of these thermal fluctuations are not easy to quantify because of their complex (random) behaviour, and often necessitate the use of thermalhydraulic mock-up tests.

A good knowledge of these phenomena is essential because of the potential high level of damage they can induce on structures. Two failure modes can occur : thermal striping when only thermal peak gradients occur, and high cycle fatigue when through-wall gradients are involved. This last case may lead to leaks of sodium and even to a failure of structures.

It is proposed in this paper, firstly, to present two typical thermal fluctuation problems encountered on operating reactors which were originally not anticipated at the design stage, the former at PHENIX, and the latter at SUPERPHENIX. A description of the

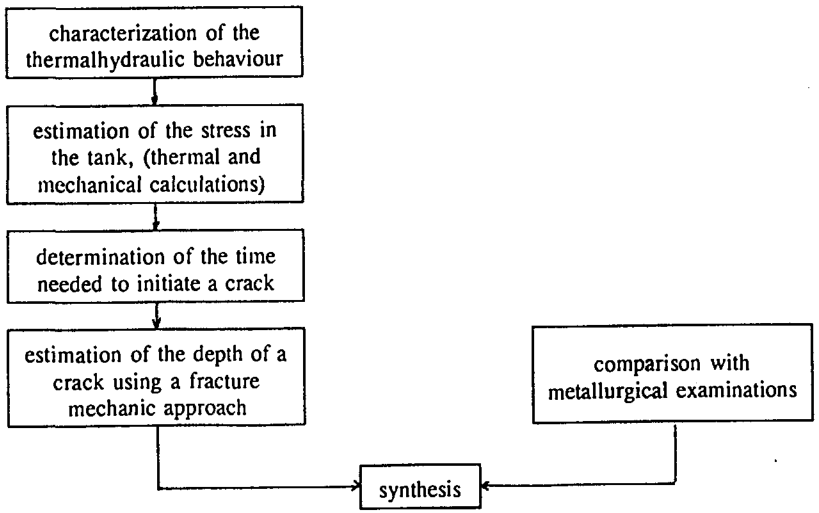
generated damages is made in each case. The analyses performed to describe the damaging process are explained step by step.
Secondly, a well known thermal fluctuation problem (one type of problem originally foreseen at design stages) is presented.
Finally, a discussion is developed, pointing out how the feedback from the damages observed on operating reactors is used now to prevent the components from any high cycle fatigue.

2. A typical case encountered in PHENIX reactor

PHENIX, a 250MWe demonstration plant, has been operating since 1974, which corresponds to more than 3700 equivalent full power days. This is a three secondary loops reactor with modular steam generators and integrated primary circuit.

Defects were detected after a campaign of inspections on the expansion tanks of the secondary loops (May 1993). All defects were found in a sodium discharge area. The sodium comes from the hot leg of the loop (550°C) and flows into the expansion tanks operating at cold temperature (350°C). The deepest cracks were localised on the welds of the tanks. One of them went through the wall. Other more superficial cracks were detected on the base material (figures 1 to 3).
The expansion tanks are made of 304 stainless steel.

Specific works aiming at explaining the damaging process were undertaken as summarized on the flow chart below :



These works are detailed as follows :

-The first step was to characterize the flow inside the tank in order to locate the possible areas of damages : thermalhydraulic computations showed that the discharge of hot sodium is situated in a recirculation zone of the tank, diverting the hot sodium near the wall of the tank. This phenomenon induces a hot thermal spot on the wall constrained by the cold adjacent zones. The risk of thermal fluctuations is maximum at the boundary of the spot where the thermal gradients are the steepest. It should be noted that a meridian weld crosses the area. The extent of the spot predicted by these calculations (about 0.3m x 0.8m) is consistent with the damaged area really found.

-The second step of the work was to estimate the loadings. Indeed, if the thermalhydraulic calculations permit to identify the potential areas of thermal fluctuations (areas with high thermal gradients), they cannot accurately provide the amplitude, nor the frequency of these fluctuations, because of their random feature. To reach such quantities some assumptions have to be made :

1/ Taking into account the proximity of the mixing zone from the wall, the amplitude of the fluctuations was assumed to be equal to the maximum difference of temperature between both fluids : 170°C.

2/ The fluctuations frequencies depend on the dynamic phenomena involved. Results of different experimental tests were used to appraise these frequencies : the frequency range of the fluctuations due to the turbulent feature of the flow was approximately : 0.2Hz - 3Hz. Nevertheless, other lower frequencies were measured recently on the secondary loops of PHENIX, during tests performed to locate a thermal spot induced by mixing two fluids : they displayed frequencies around 0.017Hz and even less, which were considered for being characteristic of slow movements of the thermal spot corresponding to variations of the whole flow.
Finally, for the expansion tank analysis three frequencies were examined : 0.017Hz, 0.2Hz and 1Hz (beyond 1Hz, the signal does not affect the wall).

3/ The exchange coefficient between sodium and metal was taken from a classical correlation for a turbulent forced convection along a flat plate (ref 1) :

$$H = (\lambda / L) \, 0.59 \, Pe^{0.61}$$

where $Pe = LV / x$
L characteristic length of the flow
V flow velocity
x sodium thermal diffusivity
λ sodium thermal conductivity.

The value of H obtained was 18000 $W/m^2{}^\circ C$.

The stress profile calculations (elastic domain) showed that the low frequency (0.017Hz) involves the whole thickness of the wall (this is not the case for 0.2Hz or 1Hz), and generated the highest stresses.

The fatigue damage was assessed separately for each frequency. Because of the high stress values obtained, the plasticity effects were taken into account using the elastic RCC-MR method. The presence of as-welded butt welds was considered by applying a factor 1.7 on the stresses calculated. The average fatigue curves of the RCC-MR (without including the design margins) were used (ref 2).

This assessment allowed to conclude that the cracks detected on the welds were probably initiated in a short time (a few hours) by the thermal fluctuations whatever their frequency in the range of the values already discussed. In the base metal, the initiation was also found to occur but after the initiation in the welds, and only in case of low frequencies, as shown on the table below.
The influence of the operating transients in the initiation process was found to be low.

RCC - MR Elastic Analysis (using the RCC-MR notations)

Welds	1 Hz	0.2 Hz	0.017 Hz
$\overline{\Delta\sigma}_{TOT} = \overline{\Delta\sigma} \times K$ (K = 1.7)	559 MPa	671 MPa	825 MPa
$\overline{\Delta\varepsilon}_{el} = \frac{2(1+\nu)}{3E} \overline{\Delta\sigma}_{TOT}$	0.3 %	0.35 %	0.46 %
$\overline{\Delta\varepsilon}_{TOT} = \overline{\Delta\varepsilon}_{el} (K_\nu + K_\varepsilon - 1)$	0.5 %	0.64 %	0.82 %
N_{adm}/h_{adm}	$4\ 10^4$ / 11 h	$1.5\ 10^4$ / 21 h	$7\ 10^3$ / 117 h

Base material	1 Hz	0.2 Hz	0.017 Hz
$\overline{\Delta\sigma}_{TOT} = \overline{\Delta\sigma} \times K$ (K = 1)	329 MPa	395 MPa	485 MPa
$\overline{\Delta\varepsilon}_{el} = \frac{2(1+\nu)}{3E} \overline{\Delta\sigma}_{TOT}$	0.18 %	0.21 %	0.27 %
$\overline{\Delta\varepsilon}_{TOT} = \overline{\Delta\varepsilon}_{el} (K_\nu + K_\varepsilon - 1)$	0.24 %	0.31 %	0.41 %
N_{adm}/h_{adm}	$>10^9$ / 280 000 h	$3\ 10^7$ / ~50 000 h	$5\ 10^5$ / ~10 000 h

A fatigue crack growth approach was then realised. A Paris law was used with envelope coefficients :

$$da / dN = C (\Delta K_{eff})^n \text{ with :}$$

da / dN propagation velocity

C and n envelope coefficients characteristic of the material in sodium environment
ΔK_{eff} stress intensity factor variation, modified to include the plasticity effects and the influence of a mean stress (residual stress).

The stress intensity factor takes into account the non-linear distribution through the wall. Each frequency considered was examined separately. The same approach was done in the welds and in the base metal.

It was shown that the crack propagated in a first time rapidly through the wall, then was slowed down and stopped at a certain depth. This threshold depth is depending on the fluctuation frequency : the maximum reached threshold depth corresponds to the mid-thickness (about 10mm), and is the consequence of fluctuations with low frequencies (0.017Hz). Fluctuations with higher frequencies lead to less deep cracks (3 or 4mm) as shown in the table below.
The presence of a mean stress of 110 MPa was found not to change significantly the threshold depth.

	1 Hz	0.2 Hz	0.017 Hz
Threshold depth	2.7 mm	3.3 mm	10 mm

From this numerical approach it was concluded that the thermal fluctuations by themselves were able to generate cracks not exceeding the mid-thickness of the tank wall, but not through-wall cracks. The through-wall crack observed on one of the tanks could be created only if other phenomena were involved (existence of a defect inside the material for example).

The metallurgical examinations, launched simultaneously at CEA, have confirmed the results obtained by calculations, especially regarding the propagation mechanism and the crack depths reached :

-In the welds, cracks were initiated at the inner face at the edge of the weld seam where the stress concentration is maximum (figure 5). They were propagated in a transgranular path following an elliptical front of 10mm maximum depth. However, a small zone, consisting in fatigue striations together with intergranular decohesions was found close to the mid-thickness of the through-wall crack (figure 6). The presence of this singularity could have contributed to propagate again the crack under the thermal fluctuations, which could explain the origin of the only one through-wall crack observed.

-Outside the welds, the cracks detected were also found to propagate transgranularly by fatigue. Their depth did not exceed 10mm (figure 4).

The numerical approach showed a good agreement with the phenomena observed. However, these analyses include uncertainties which concern, not only the thermalhydraulic data, but also the material behaviour. In particular, the characteristics of welded joints and their junctions with the base material (heat affected zone) are not accurately known, nor the behaviour of the metal after almost 100000 hours of service.

Design Feedback :

The technological solution chosen to avoid subsequent thermal fluctuations was to increase the exchange surface of the pipe inside the tank, so that the discharged sodium flows away from the wall, and to reduce its flow rate ; the difference of temperatures between both fluids was then reduced to about 20°C.
It has to be mentionned that, originally, the discharged sodium should not have been as hot as observed (a change in the operating conditions led to a flow rate inside the small pipe much higher than the design value). In that case the problem would not have been so critical.

3. A typical case encountered in SUPERPHENIX reactor

SUPERPHENIX is a 1200MWe pool type reactor with four secondary loops. It achieved its full power in December 1986.

A sodium leak was observed on a circumferential weld downstream from a tee junction on an auxiliary pipe of the secondary circuit (figure 7 and ref.3). The pipe connected to the tee junction was originally designed only for the dry-out of the circuit. After investigations, it was found that the dry-out valve was only partially closed, and allowed a sodium flow from the dry-out line to the auxiliary circuit. Two convergent flows at different temperatures ($\Delta T = 220°C$) were therefore mixed at the tee junction.

The interpretation of this phenomenon required several analyses including the estimation of the flow rate, temperature and duration of the accidental operation, the knowledge of the hydraulic behaviour, the sodium/metal thermal transfer conditions, and finally the thermal and mechanical behaviour of the structure.

A close examination of the installation lay-out and operating conditions permitted to estimate the flow rate and the duration of this unexpected flow : 4 days with a maximum flow rate of 3 m^3/h.

The location of the zone of the pipe submitted to the thermal fluctuations, and the frequencies of the fluctuations were derived from experiments.
The conclusion was that thermal striping could occur at about 30cm downstream from the

tee junction ,the predominant frequency of the fluctuations being about 1Hz. It was also established that the sodium/metal damping ratio, induced by the diffusivity inside the boundary layer, was about 50%.

Fracture mechanics studies were undertaken using envelope propagation laws and taking into account the effects of residual stresses. They showed that, under the fluctuations, a crack might be initiated downstream from the tee junction, after a 4-days loading period, and that only about 500 cycles at 1Hz frequency would be necessary to extend the crack through the wall.

The metallurgical examination of the crack, which showed a number of striations of 10^4 to 10^6, was consistent with the numerical results (figure 8).

Design Feedback :

The thermal fluctuations induced were the consequence of an abnormal operation of the dry-out valve. To avoid subsequent thermal fatigue, the solution was, after repair of the tee junction, to control the position of this valve.

4. A classical case treated at the design stage of plants

Another type of thermal fluctuations exists in reactors like SUPERPHENIX (SPX) or European Fast Reactor (EFR), involving the hot pool bottom part (referred to as the "corps mort area"-figure 9) and which is difficult to deal with. This "corps mort area" is a transition area between:

- the layers of cold sodium, due either to the cold fluxes coming from the cold parts of the reactor in the EFR case, or to the sodium leakage flow at the lower part of the subassemblies in the SPX case,

- and the hot core outlet jet recirculating in this area.

Due to pressure variations in the hot pool, the interface of stratification separating hot and cold pools oscillates generating an axially moving thermal gradient along the inner shells. High cycle fatigue may be induced.

The difference of temperature between both layers of sodium is wide (about 125°C), making this point difficult to solve. For SPX, only the tests performed during the commissioning period, have been able to confirm that the fatigue damage was acceptable and that the reactor could operate with these loadings (ref.4). For new projects, tests on mock-ups seem indispensable to show the integrity of the inner shells. The reasons are the following :

- Firstly, it is necessary to locate precisely the stratification interface in order to situate the affected part of the shell, and also to ensure the relative stability of the stratification during the power changes (the flows inside the hot pool are tridimensional, and cannot be represented properly by a simple bidimensional numerical approach)

- Mock-ups are also usefull (if not mandatory) to study devices to mitigate the mechanical consequences on the inner shells. In particular it was shown the necessity to fix a baffle (called "corps mort baffle") up to the inner shells in order to limit the recirculation of hot sodium in the bottom part and, as a consequence to stabilize the interface and limit the thermal fluctuations.
  The efficiency of such a device was confirmed by tests performed for the EFR project where the maximum amplitude of fluctuations was reduced from 125°C to 75°C by adding a baffle.

- From the experience gained from SPX for which several series of tests were carried out during the commissioning period, it was found that the thermal fluctuations could not be represented by a simple sinusoidal signal of a defined frequency, provided, for instance, by a gravity wave calculation. The problem was found to be very complex, random, with a variable axial gradient and frequencies corresponding to very different values (periods in the range 40-100s for SPX and 60-100s for EFR).

The existence of experimental data led on SPX to apply a particular fatigue design procedure. Such a procedure is today applied on the new design reactors. The innovative feature of this procedure is to take into account the temperature fluctuations measured by thermocouples during tests (commissioning tests for SPX, realistic mock-up tests for projects).A long enough recording is however needed to make sure that reliable results may be obtained.

The first step of this procedure is to assess from the recorded signals, the temperatures through the thickness of the concerned structures. A development in Fourier series of the temperatures is used.

The second step concerns the stress calculations. Bidimensional axisymmetric finite element calculations have to be used to represent the bidimensional phenomenon : the through thickness thermal gradient and the axial thermal gradient.

Then, the Rainflow method (ref. 5) is used to transform the irregular sequence of stress cycles calculated into a set of values (stress cycle amplitude/occurrence number - figure 10) directly applicable to the fatigue damage law (Miner's rule as preconised in the RCC-MR). The RCC-MR high cycle fatigue curves today available are used (ref. 2).

Finally, the high cycle fatigue damage is combined with the low cycle fatigue damage due to the operating transients.
The flow-chart of figure 11 sums up this methodology.

This methodology applied to new design reactors needs thermal data which can be predicted by mock-ups but with some uncertainties. The experience gained on SPX has permitted a greater confidence in the data coming from mock-ups. So it can be thought that a correct prediction of the high cycle fatigue life of new reactor projects may be given based on this methodology.

42

5. Conclusions

The two first problems examined were unforeseen. The damage generated was relatively important, requiring a replacement of the components. The causes of these problems are linked, first to the operating conditions which were abnormal and originally unforeseen, and second to the design not always well-adapted to such problems.

Today the experience gained by solving such problems is used in the design of new projects of plants or in the studies performed in the frame of life extension of less recent plants.
The first step of a design is to try to avoid mixing the flows at very different temperatures ($\Delta T < 30\text{-}40°C$) at least during the permanent states.

If this is not possible, some devices like flow mixers can be fixed inside pipes at critical junctions. The design of these flow mixers is nevertheless difficult because it is closely linked to the characteristics of the fluids to be mixed (difference of both flow rates and temperatures).

Inside tanks it is often possible to design the inlet of an external fluid in a zone situated far from the wall and especially far from the welds. Such a solution was chosen to solve the problem that occurred on the expansion tanks of PHENIX.

In the hot pool of reactor blocks, baffles can be added to protect the structures directly submitted to thermal fluctuations. However, this solution does not eliminate all risks but only mitigates the consequences on the structures.

The third problem examined concerns a well-known problem, largely analysed at the design stage of plants. The manner to treat this problem from the thermalhydraulic point of view, was validated by means of experiments performed in SPX reactor. For the fatigue damage a particular numerical appoach is used which allows to predict a not too conservative life duration of the components.

Nevertheless, regarding these fluctuation problems, uncertainties remain because some phenomena able to influence the fatigue behaviour are not well-known today. It can be mentionned : ageing of the material, behaviour of welded joints and effect of the surface roughness, influence of a mean stress, combination of high cycle fluctuations with other loadings...
The numerical approaches performed today in the frame of a structural analysis take into account such uncertainties by means of coefficients applied on the material characteristics. The designer has therefore to assume that these coefficients are large enough to ensure that the design will be safe.
A lot of experimental tests should be carried out to understand all the phenomena and quantify the parameters influencing high cycle fatigue. This could allow to improve the design guidelines, and as a consequence to have a better prediction of the LMFRs components fatigue life.

REFERENCES

1. Kutateladze Borichanskii 1966
   A concise Encyclopedia of heat transfer - Pergamon Press

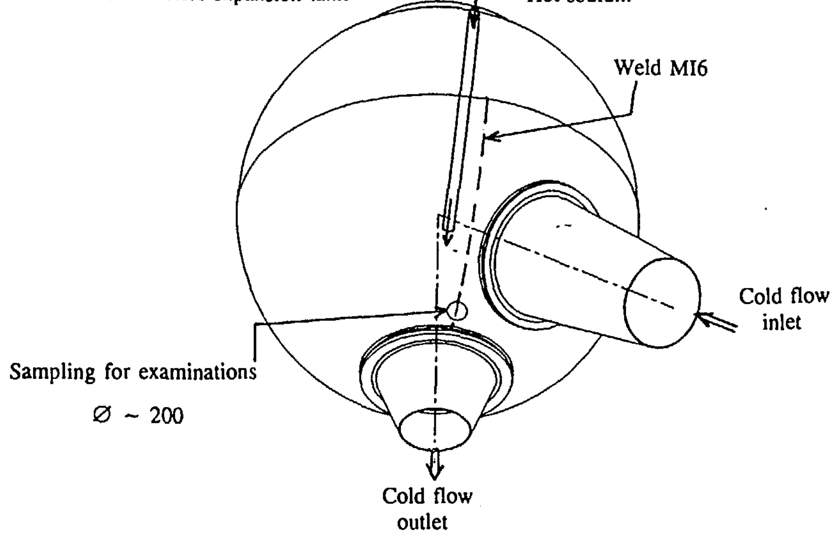
2. RCC-MR - Edition mai 1993

3. J.B. RICARD - EDF CLI, Villeurbanne
   M. SPERANDIO - Novatome, Lyon
   Fracture Mechanics applied to SUPERPHENIX Reactor Components
   SISSI n°1 Seminar at Saclay - 1992

4. O.FAURE, J.P. DEBAENE, J.B. RICARD - Evaluation of the fatigue damage of a LMFBR's structure taking into account the experience gained from operating plants - SMIRT 11 (1991)

5. YS SHIN -
   Prediction of random high cycle fatigue life of LWR components
   Journal of pressure vessel technology - 378-386/Vol 102, November 1980

FIGURE 1 : PHENIX expansion tank



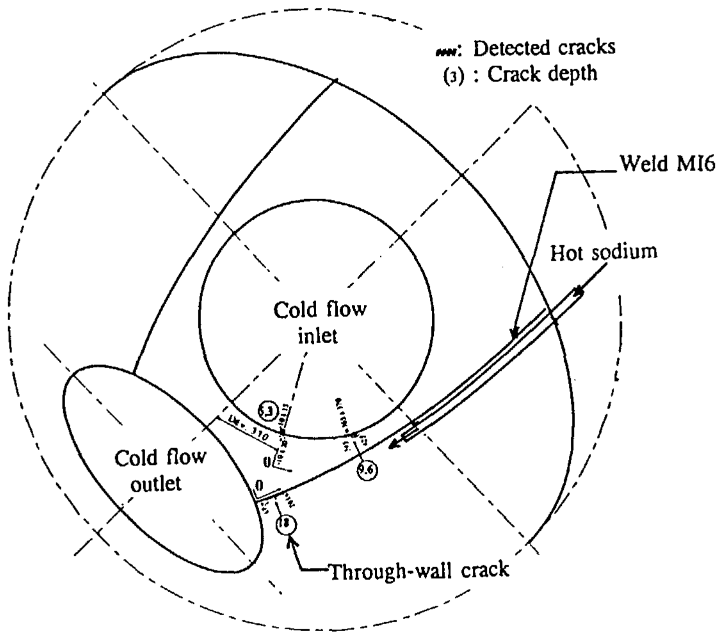
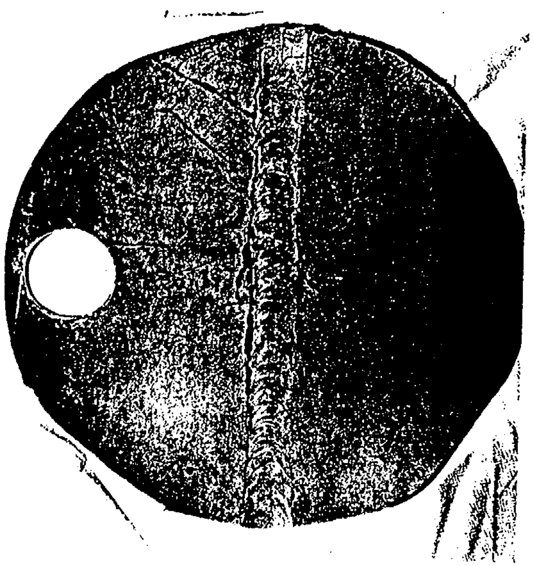


FIGURE 2 : detected cracks on the PHENIX expansion tank

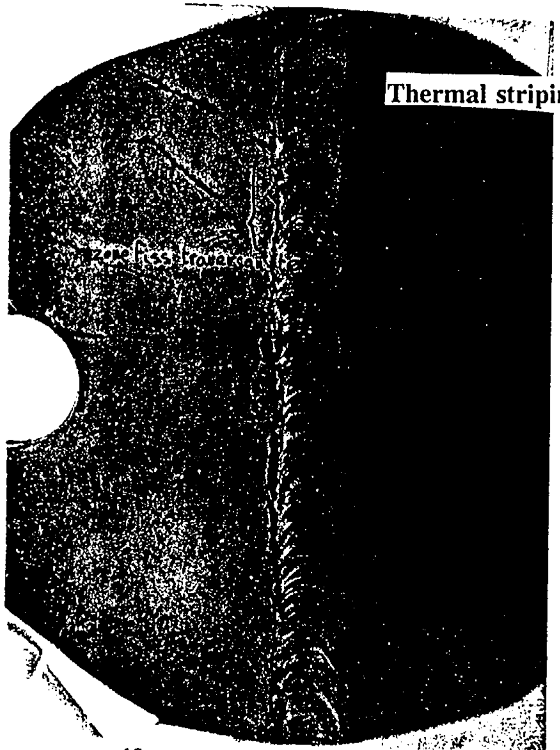
43

FIGURE 3 : PHENIX expansion tank - sampling for metallurgical examinations



Ø ~ 200

Weld MI6



Thermal striping

Through-wall crack area

44

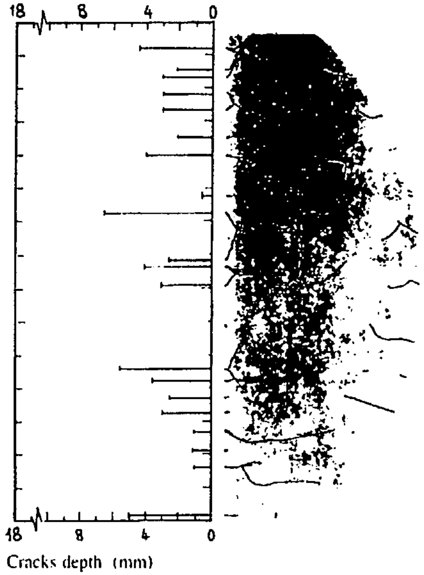


FIGURE 4
PHENIX expansion tank.
Cracks depth in the base material.

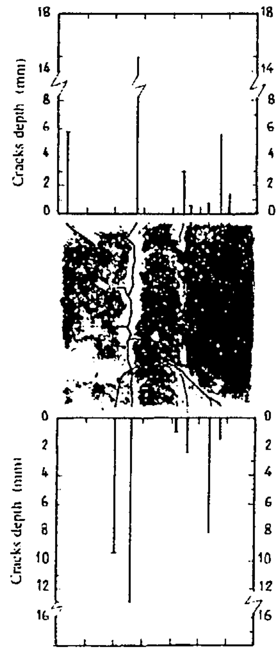


FIGURE 5
PHENIX expansion tank.
Cracks depth in the welded joint MI 6.

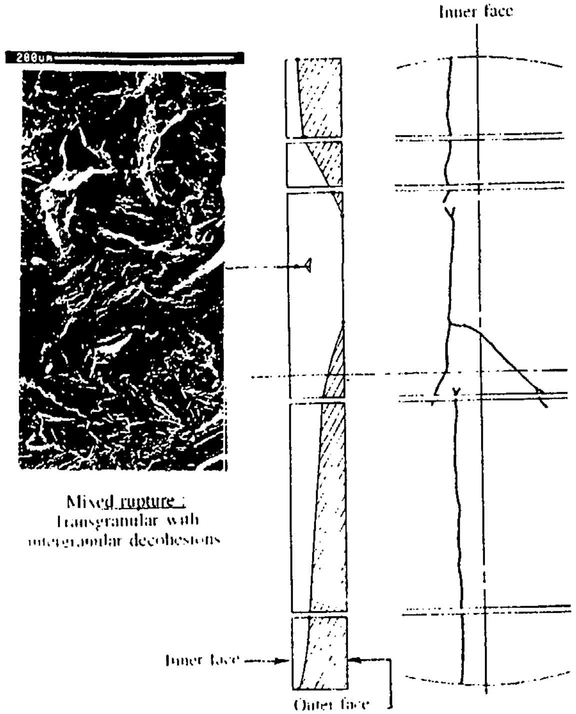


FIGURE 6 : PHENIX expansion tank. Profile of the through-wall crack.

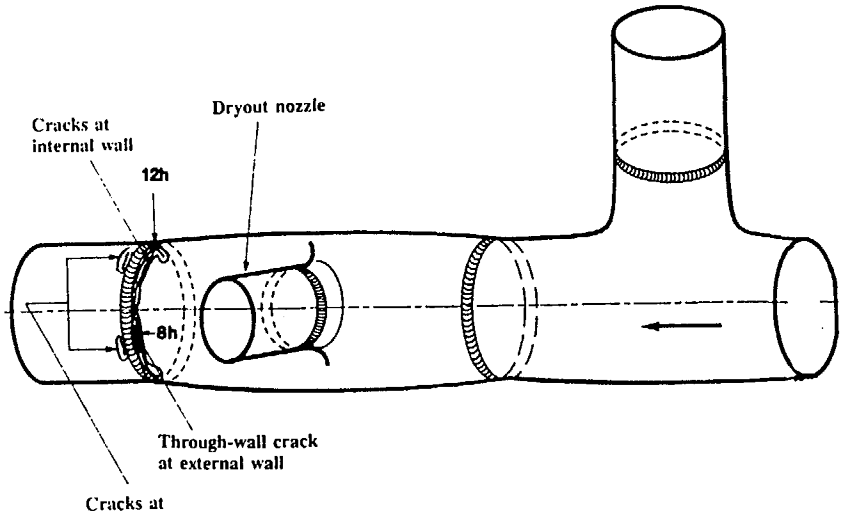
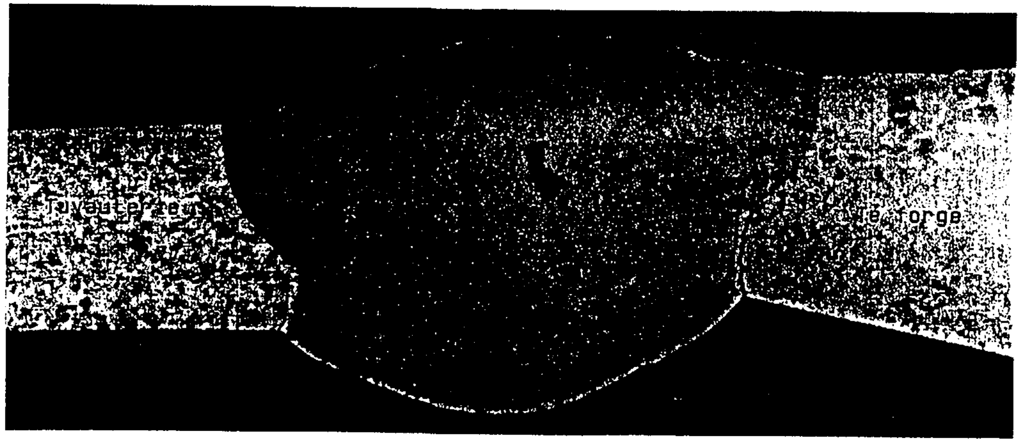


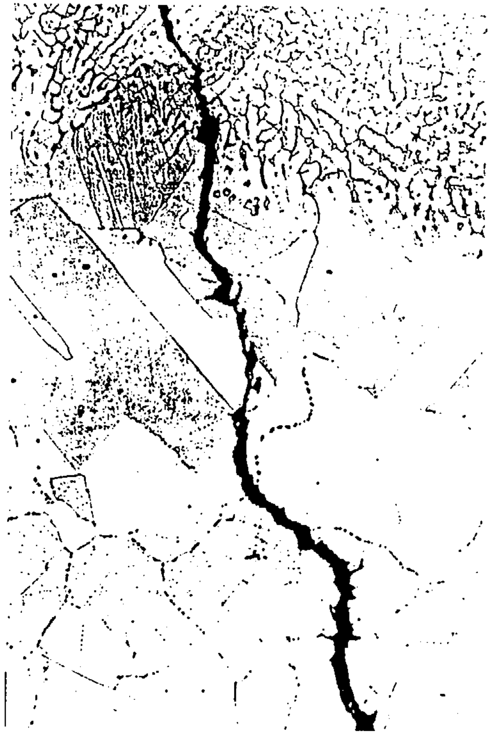
FIGURE 7 : cracks detected on the SPX tee-junction

FIGURE 8 : SPX tee junction - metallurgical examination of cracks



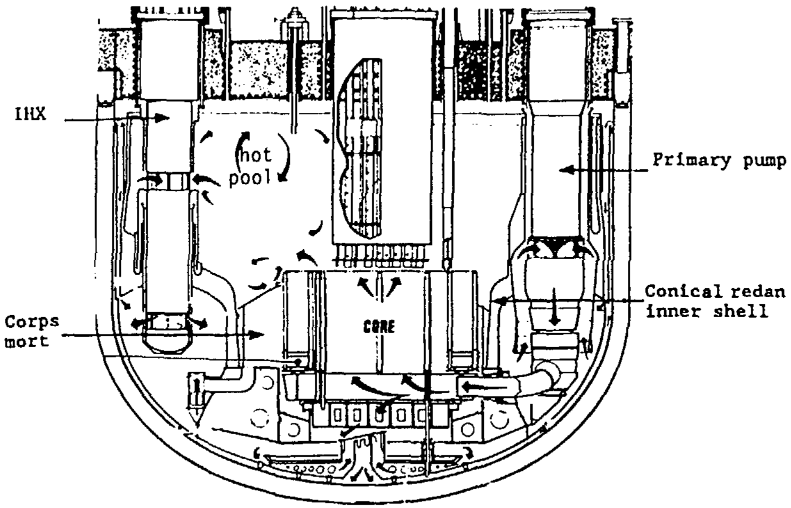
Cracks at the edges of the weld seam 20X12.4

Propagation through the heat-affected zone 21x50



Transgranular propagation 22x300

FIGURE 9 : SPX Reactor Block



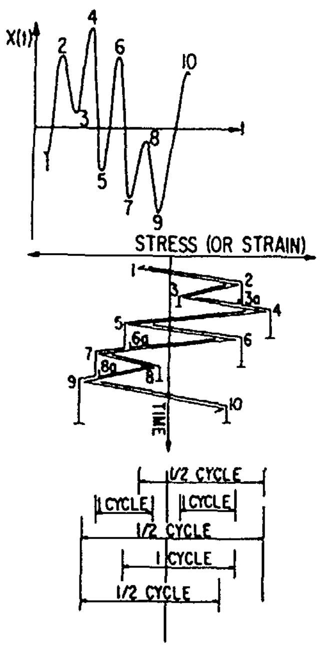


FIGURE 10 : rainflow cycle counting method

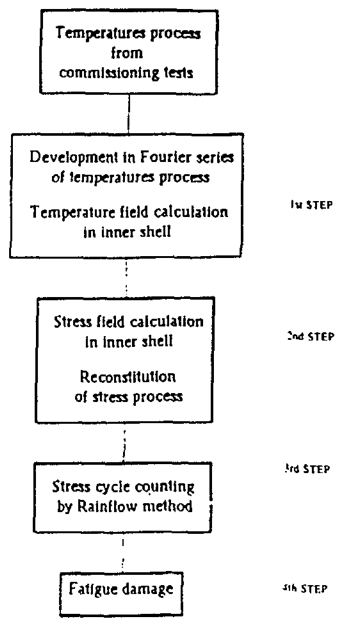


FIGURE 11 : flow diagram of the methodology used

46