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Review of Predictive Methods Applied to Thermal Striping Problems and Recommendations

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ABSTRACT

This paper is a synthesis of the work performed under a European Community study contract on a benchmark concerning a thermal striping problem occurred on PHENIX Reactor. The objectives of the benchmark are to examine the ability of the assessment methods to explain the actual phenomena observed.

The synthesis highlights the differences between the results predicted by each participant and with the actual observations. The causes of theses differences are pointed out and recommendations are expressed in order to improve the prediction of such problems.

NOTATIONS

DNS	Direct Navier-Stokes	LES	Large Eddy Simulation
D (d)	Hot (cold) pipe diameter	x	Abscissa
k	Turbulent kinetic energy	ε	Rate of turbulent kinetic energy dissipation
θ'^2	Temperature variance	U_i	Velocity component
FSRF	Fatigue Strength Reduction Factor	HAZ	Heat Affected Zone
$\Delta\varepsilon$	Strain range	$\Delta\theta_p$	Peak to peak temperature range

1. INTRODUCTION

This paper is a synthesis of the work performed under a European Community (Working Group on Codes and Standards) study contract on a benchmark on thermal striping

The benchmark concerns a tee junction of a secondary circuit of the Fast Breeder Reactor PHENIX for which thermal striping phenomena are involved. The objectives are to examine the ability of the assessment methods to explain the actual phenomena observed in order to determine whether the design methodologies without being too severe could successfully avoid any damage on the component.

After a short description of the benchmark, the observations made on site are described, a synthesis of the thermal hydraulic works and of the thermomechanical assessments are made, and a list of recommendations regarding thermal striping problems is defined.

2. DESCRIPTION OF THE BENCHMARK

PHENIX is a 250 MWe demonstration plant, with three secondary loops, modular steam generators and integrated primary circuit. It has been operating since 1974.

A main pipe of the secondary circuit of PHENIX is subjected during nominal operation to a mixing zone between two fluids at different temperatures. This zone is located downstream from a tee junction between the main pipe having sodium at 340°C and a small pipe with sodium at 430°C. In the mixing area the main pipe has a circumferential butt weld in "as welded" condition which bulges off the inner wall by about 1.3 mm into the flow.

The construction material is stainless steel AISI304. Time of operation is 90 000 hours.

The main features of the circuit in the tee junction area are shown in figure 1.

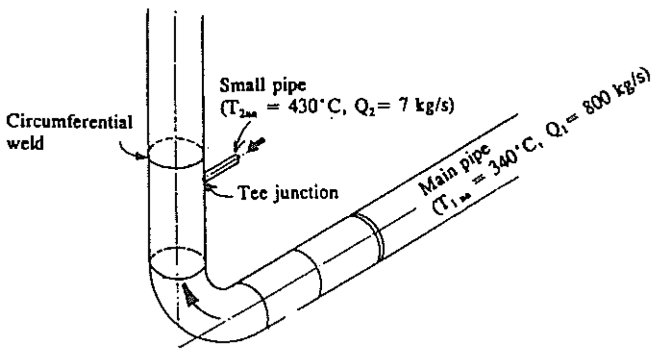

Figure 1
Description of the problem

3. ACTUAL RESULTS

3.1 Temperature Measurements

The tee region has been equipped with 15 thermocouples on the outer skin of the pipe (see figure 2 for location of the main thermocouples). Each of those thermocouple measurements have been recorded during the plant operation.

On the outer skin the amplitude of the fluctuations reaches its highest values in a region extending from 1.5 D to 3D (from the axis of the small pipe). The maximum value encountered is 19 °C at TC5 (figure 2), at the periphery of the hot spot. Such a value means that the hot jet oscillates at a low frequency, the high gradients being encountered at the "edge" of the jet.

3.2 Experimental Observations

Cracks were discovered on the circumferential weld of the main pipe during a campaign of inspection : after grinding of the outer surface weld bead two indications of 100 mm each located symmetrically from the tee have appeared. No crack is observed in parent metal.

Pipe was cut in air to observe the nature of cracks on the inner surface. An immediate appearance of a white spot around the tee (first plume) in the direction of sodium flow was observed. Subsequently after a few minutes, a black spot surrounding the first plume was also noticed. While the white spot was due to the constant wetting of hot sodium, the black spot may be due to oxidation due to contact of air in the zone where hot and cold sodium mixing takes place. The cracks appeared on the black spot in the weld adjacent to heat affected zone originated from the inner surface.

3.3 Metallurgical Examinations

Macrographic, micrographic and fractographic examinations were launched. The characteristics of the cracks indicate that these cracks are due to high cycle fatigue clearly :

- on the outer surface two indications of cracks in the weld metal were observed, with an extension of 100 mm each and separated of 100 mm (figure 2).
- on the inner surface, a crack located at the upward side of the weld was observed. The crack starts in the weld metal at the geometrical singularity of the weld bead, then propagates in a rectilinear way transgranularly up to the outer surface crossing the HAZ and the weld metal.
- there is no particular starting point of the crack but multiple initiations along the root edge. It has been observed a step like appearance with presence of numerous and thin striations.

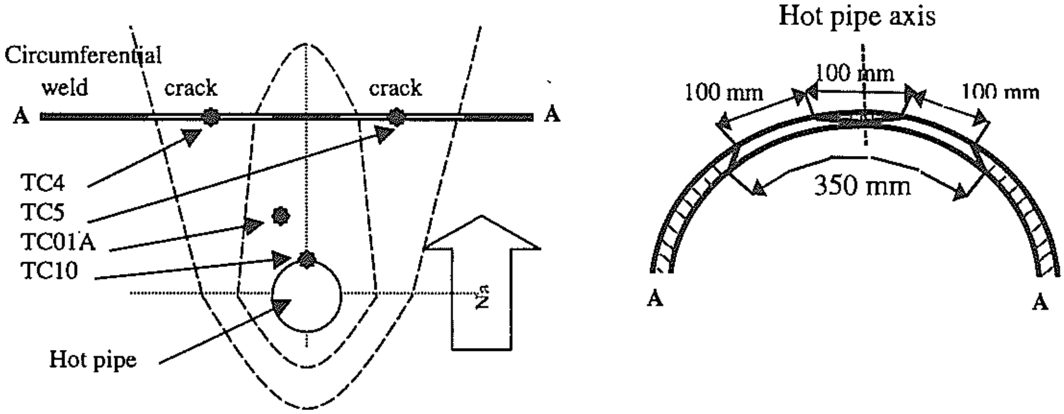

Figure 2 : Extension of the crack

3.4 First Thermomechanical Analysis

The analysis of the temperature measurements has been carried out. It was concluded that the fluctuations recorded on the outer skin do not bring a significant damage and that the high frequencies due to turbulent movements inside the fluid mixing area, not visible on the outer skin, are able to induce higher amplitude fluctuations on the inner face. So, complementary calculations and analyses were undertaken to take into account high frequency fluctuations.

4. SYNTHESIS OF THERMAL-HYDRAULICS ANALYSES

Thermalhydraulic calculations were performed by FRAMATOME, CEA, AEA and ENEA.

4.1 Data-Models

The input data are common to each of the 4 computations. All the features of the computations are summarised in table 1.

Table 1 : General features

Computation characteristics	AEA	ENEA	CEA	FRAMATOME
Code	CFX4	Castem 2000	Trio-VF	Star-CD
Fluctuations calculated from	k-ε-θ'^{2}	Pseudo DNS	LES	pseudo DNS
Spatial scheme (order)	High upwind (2)	(1)	QUICK (3)	Ui : central diff (2) T : cent diff. + upw.
Boundary conditions	Pipe profiles	Constant steady	constant steady + 5 % noise	Constant Steady + swirl
Wall treatment (thermics)	Damping function	Laminar (conduction)	Wall function in sublayer	Laminar (conduction)
Domain size :	Pipe + elbow	Part of pipe	Half pipe	Pipe + elbow
Grid (total of cells)	102 984	50 000	167 854	96 727 – 1 456 solid
Physic duration of simulation	(steady)	~ 1 s	27.4 s	85 s

4.2 Mean Temperatures

The CFX4 result gives a hot jet directed towards the centre of the main pipe while the 3 others computations show a jet turned down along the main pipe wall as shown on figure 3.

One must note that for the Star-CD case, the small amount of swirl flow is needed to obtain the hot jet turned down along the main pipe wall. Without this swirl flow, the hot jet is found to be directed toward the centre of the pipe.

The longitudinal profiles of temperature (obtained from values at thermocouple locations) are presented on figure 4.

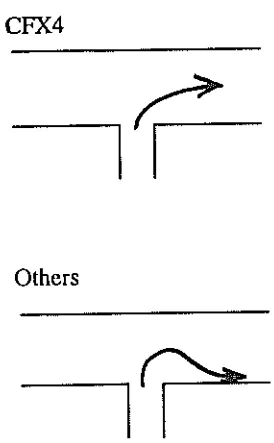

Figure 3 : feature of the hot jet

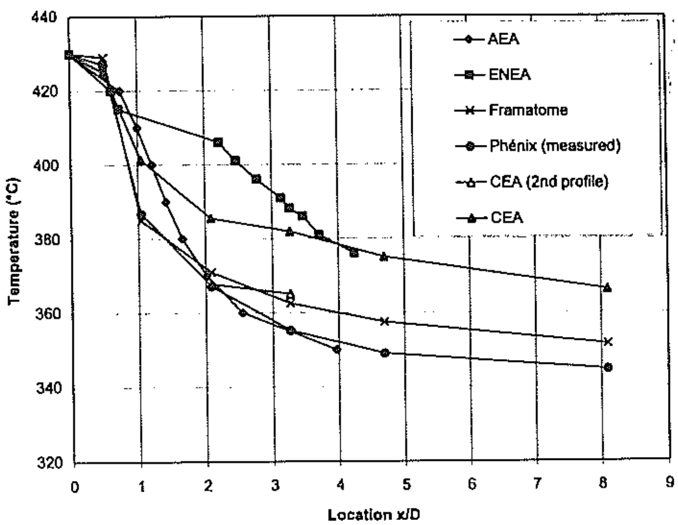

Figure 4 : mean temperature profile (fluid cell adjacent to wall)

4.3 Temperature Fluctuations

Figure 5 presents the peak to peak values of the fluctuations calculated in the sodium adjacent to the wall and the corresponding values for the outer skin of the pipe are shown on figure 6.

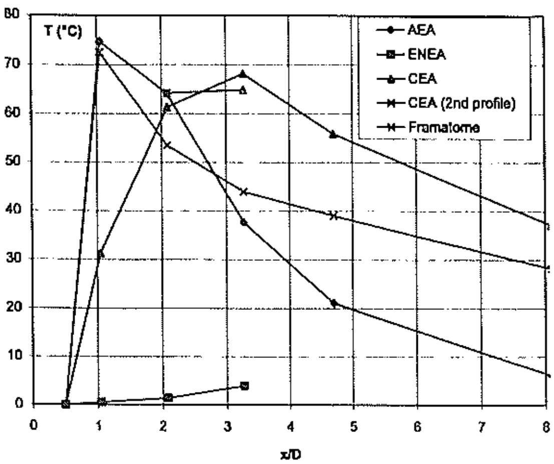

Figure 5 : peak to peak temperature in sodium adjacent cell to the inner skin

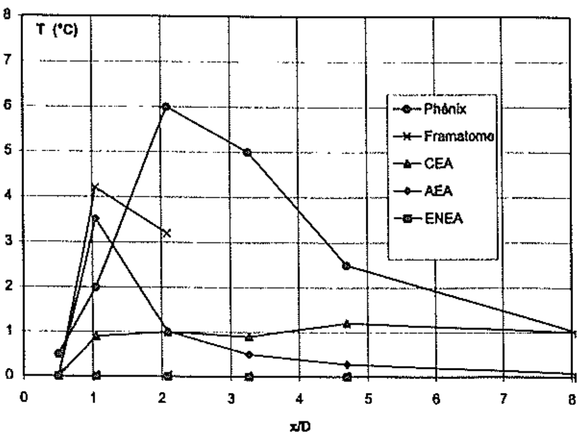

Figure 6 : peak to peak temperature at outer skin

The CASTEM 2000 calculation without any turbulent modelling produces very low fluctuations (negligible on outer skin). This has two causes : a first order scheme in space for convective terms and upstream steady boundary conditions are not set far enough.

The CFX4 values at inner skin are close to the STAR-CD ones for $x/D < 4$. For $x/D > 4$, CFX4 values become low because the hot jet does not stay along the pipe wall. For those two analyses, the bend before the tee is modelled and (steady) inlet conditions are imposed far upstream from the tee. At outer skin, the amplitude is overestimated just behind the tee ($x/D \simeq 1$) but then underestimated ($x/D \geq 2$). The very low amplitude found for $x/D \geq 3$ are due to the hot jet directed towards the centre of the pipe.

The TRIO-VF predicted fluctuations (LES technique) at inner skin have a maximum value at $x/D \approx 3$. The inlet boundary conditions are set only few diameters D before the tee. This distance is not long enough to allow the development of instabilities, even with a white noise.

For $x/D \approx 8$, STAR-CD and TRIO-VF values merge together.

At outer skin CEA and FRAMATOME calculations imply too low amplitudes. This may be the consequence of a too short physical time of simulation. The better fit of the STAR-CD analysis can be attributed to the extended domain of calculation, to the exact description of the geometry, to the mesh refinement behind the junction and to taking account of the swirl.

5. SYNTHESIS OF THERMOMECHANICAL ANALYSIS

AEA, NNC and FRAMATOME companies have carried out the mechanical assessments.

All the participants have worked with the same temperature signal (that provided by AEA at TC01A location in the fluid) in order to allow cross comparisons between each other.

5.1 Stress Evaluation

The fluctuating stresses were calculated either using analytical formulas for long cylinders or using the finite element method with 2D axisymmetric elements (without including a geometrical discontinuity). The stress range values obtained are between 340 and 386 MPa.

5.2 Fatigue Assessment

5.2.1 Fatigue Assessment Methods

The participants have used their own procedures which are presented in table 2.

Table 2 : Fatigue assessment methods

AEA	NNC	FRAMATOME
2 procedures : $\Delta\varepsilon$ = function($\Delta\theta_p$ max) or $\Delta\varepsilon$ = function($\Delta\theta_p$,time) (Rainflow analysis) Use of FSRF on the base fatigue curve provided	UK curve using a crack based model $\Delta\varepsilon$ = function($\Delta\theta_p$ max)	RCC-MR procedure $\Delta\varepsilon$ = function($\Delta\theta_p$,time) (Rainflow analysis) Use of a stress concentration factor

Two ways have been chosen to allow for the weld effect : the first one is to include a coefficient into the fatigue curve. This is the way chosen by each participant. The value retained is 1.25 according to the value proposed by the RCC-MR code. The second one is to include a coefficient representative of the geometry of the weld bead at the stress calculation stage. This way was only chosen by FRAMATOME, a value of 1.7 was taken (RCC-MR value). The originality of the AEA procedure is to consider that the material does not follow the mean fatigue data but is affected by different parameters (referred to as FSRF) which are surface finish, ageing, environmental effects. Considering these parameters leads to decrease the specified base metal curve by an average factor 1.6 (by a factor ranging from 1.3 to 1.9 considering the cast-to-cast variation).

Finally, the cumulated coefficient applied relatively to the mean base metal fatigue curve used is given in table 3 together with the corresponding allowable strain range at 10^8 cycles.

Table 3 : FSRF used and allowable strain range

Coefficient applied for :	AEA	NNC	FRAMATOME
• Parent metal	(between 1.3 and 1.9) average : 1.6 corresponding to $\Delta\varepsilon_{all} = 0.163\%$	1 corresponding to $\Delta\varepsilon_{all} = 0.266\%$	1 corresponding to $\Delta\varepsilon_{all} = 0.261\%$
• Weld	(between 1.6 and 2.4) average : 2 corresponding to $\Delta\varepsilon_{all} = 0.13\%$	1.25 corresponding to $\Delta\varepsilon_{all} = 0.213\%$	2.5 corresponding to $\Delta\varepsilon_{all} = 0.105\%$

For parent metal, AEA gives a lower limit due to the FSRF applied. For the weld, FRAMATOME provides the lowest limit which is the consequence of the factor 1.7 applied on the stress range.

5.2.2 Fatigue Assessment Results

Table 4 summarises the likelihood of cracking predicted and gives a margin regarding the limit imposed by the method (margin = $100.[1-\Delta\varepsilon/\Delta\varepsilon_{all}]$).

Table 4 : Likelihood of cracking and margin

	AEA (*)	NNC	FRAMATOME
Parent metal	Yes margin = -10%	No margin = +22%	No margin = +20%
Weld	Yes margin= -4%	Yes margin ≅ 0	Yes margin = -91%

(*)result with FSRF of 1.6 on the fatigue curve for parent metal and 2 for the weld

The comparison with the experience shows that the AEA fatigue assessment appears too penalising at least in the parent metal, showing that the FSRF chosen are too large for the present material. Margin value for the weld is not very different from that for the parent metal suggesting that the weld effect included is not sufficient.

NNC results appear just sufficient to demonstrate the failure in the weld. This also suggests that the influence of the weld is probably greater than the coefficient 1.25 considered.

FRAMATOME assessment finds correct results as regards the observations. However, the results in the weld are in excess of about 100% of the limit. This could be due for a part to have taken a plasticity effect into account (RCC-MR route).

5.3 Fracture Assessment

The Paris law was used to assess the propagation. The stress intensity factor was calculated from classical formulations for plate with both stress and strain controlled assumption. A threshold effect was considered on the crack growth. The influence of mean stresses was included.

The predictions show that the crack can propagate deeply in the thickness. However, the results are scattered, pointing out the importance of assumptions. : the strain controlled assumption gives less pessimistic results than the stress controlled one and the mean stress effect can be more or less favourable, the time to failure can change by a factor between 5 and 10. The comparison of results is given on table 5 relatively to time to failure at a 5 mm depth:

Table 5 : Time to failure for a 5mm crack depth

NNC		FRAMATOME (Stress controlled)	
Strain controlled	Stress controlled	Mean stress in tension	Mean stress in compression
25000 h	530 h	160 h	2200 h

6. RECOMMENDATIONS

The previous analysis leads to propose the following recommendations.

Domain for thermal-hydraulic analysis : the domain must extend sufficiently upstream the region investigated, in order to let perturbations develop (5 to 10 diameters for a pipe). The geometry must be precisely modelled around the region of interest.

Thermal-hydraulic simulation : the AEA approach using a steady calculation, much faster and requiring less computing resources than the other analyses (LES or DNS), is interesting. Nevertheless, it uses hypotheses on the frequency spectrum of the fluctuations, obtained in experimental conditions different from that of a tee junction. A complete prediction of fluctuating flow would require a Large Eddy Simulation, or a Direct Navier Stokes simulation if no subgrid scale model is available in the CFD code. The space discretisation scheme must be at least of 2nd order, while the time discretisation scheme can be of first order only.

Boundary conditions of thermal-hydraulic model : a white noise or other unsteady boundary conditions are not necessarily required to obtain a fluctuating solution if they are prescribed sufficiently far upstream, but they can improve the development of instabilities. The effect of secondary flows due to the upstream circuit, such as a swirl flow, is not negligible on the main flow, and hence on the fluctuations.

Wall attenuation : the quantification of the attenuation to the wall is of great importance. For thermal hydraulic simulation, it is recommended to increase the conduction transfer within the conductive sub-layer, with an empirical function. The small amount of turbulent heat transfer near the wall is then accounted for. One must note that the weld bead which bulges inwards into the fluid could disturb the flow inside the boundary layer and as a consequence reduce the attenuation.

Sampling of time history signal : the computation must provide the range of frequencies of interest. For a given thickness of wall, there is a band of frequencies which are potentially damageable. Hence, the numerical simulation must be carried out over a sufficiently long physical time (condition for low frequencies) and the time step must be sufficiently small (condition for high frequencies). The thicker the wall, the longer the physical time of calculation must be. Moreover, very low frequencies may have influence on the flow and on fluctuations. It is better to try to model them via boundary conditions.

Stress intensity variation formulation : for the crack propagation analysis it appears that the time to propagate a crack is sensitive to the formulation chosen for the stress intensity variation, the strain controlled formulation being preferred to the stress controlled one for this problem.

Mean stress effect on mechanical assessment : the mean stresses have a sensitive effect on the crack propagation assessment. A parametric study is recommended to quantify this influence on the crack propagation which can be reduced or enhanced as a function of stress value. Residual stresses arising from the manufacturing process shall be included in the analysis. Mean stress effects must be introduced in the fatigue damage assessment if any.

Weld influence : the experimental observations highlight the important influence of the weld. The weld bead must be taken into account as geometrical discontinuity in the fatigue assessment (or must be avoided in a thermal striping zone). The factor 1.25 applied on the fatigue rupture curve to represent a material effect is too low to cover all the consequences induced by the « as-welded » joint whose aggravating effects must be taken into account.

REFERENCES

(1) Benchmark on thermal striping - EC study 95-D11-001119 - Synthesis Final Report