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Assessment of Fatigue and Fracture on a Tee-Junction of LMFBR Piping Under Thermal Striping Phenomenon

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Abstract

This paper deals with the industrial problem of thermal striping damage on the French prototype fast breeder reactor, Phenix and it was studied in coordination with the research program of IAEA. The thermomechanical and fracture mechanics evaluation procedure of thermal striping damage on the tee-junction of the secondary piping using Green' s function method and standard FEM is presented. The thermohydraulic(T/H) loading condition used in the present analysis is the random type thermal loads computed by T/H analysis on the turbulent mixing of the two flows with different temperatures. The thermomechanical fatigue damage was evaluated according to ASME code section III subsection NH. The results of the fatigue analysis showed that fatigue failure would occur at the welded joint within 90,000 hours of operation. The assessment for the fracture behavior of the welded joint showed that the crack would be initiated at an early stage in the operation. It took 42,698.9 hours for the crack to propagate up to 5 mm along the thickness direction. After then, however, the instability analysis, using tearing modulus, showed that the crack would be arrested, which was in agreement with the actual observation of the crack. An efficient analysis procedure using Green' s function approach for the crack propagation problem under random type load was proposed in this study. The analysis results showed good agreement with those of the practical observations.

Key Words : thermal striping, LMFBR, piping, Green' s function, crack

1. Introduction

Many components and subcomponents in liquid metal fast breeder reactor (LMFBR) primary and secondary systems are exposed to sodium from more than one source, and it is common to find the impinging fluids at significantly different temperatures. When this occurs, portions of the surfaces of such components and subcomponents are subjected to fluctuations between the hot and cold sodium which are the coolants of LMFBR. This exposure of a surface to alternating hot and cold fluid temperatures during steady state reactor operation has been termed "thermal striping".

The thermal striping phenomenon, which occurs due to an imperfect mixing of sodium streams with different temperatures is one of the most significant problems in LMFBR.

Thermal stresses arising from thermal striping can initiate surface cracks by high cycle fatigue. These types of thermal fluctuations induced the cracks in reality such as the crack in the expansion tank of Phenix secondary loops, the crack at the tee-junction of Superphenix and the crack at the cold trap system of BN-600[1]. Through-the-wall failures of mixing tees have been reported several times in the test loop and FBR plant, which demonstrates this mechanism for component failure.

In this paper, an efficient numerical method based on Green's function concept and Duhamel's integral theorem was utilized to calculate thermal strains and the SIFs(stress intensity factors) to evaluate fatigue damage and crack propagation under thermal striping loads for the tee-junction of the secondary piping system. Compared with the standard finite element method, the present method was confirmed to be effective from the viewpoint of computational aspect without sacrificing the solution accuracy.

2. Description of Benchmark Problem

The present benchmark problem is based on an industrial problem which has occurred in the secondary circuit of the French liquid metal reactor, Phenix. It deals with the thermal striping phenomenon. Phenix is a 250 MWe prototype fast breeder reactor with three secondary loops operating since 1974. Problems on pipes induced by thermal striping phenomenon have effectively been observed during the course of inspection, after 90,000 hours of operation. This technical problem deals with the mixing of two flows with different temperatures in the secondary circuit of the Phenix during normal operations. The sodium in a branch line flows into the main pipe of the secondary circuit as illustrated in Fig. 1. A small bored pipe, connected with a tee junction to the main pipe discharges sodium at 430℃ into the main pipe. Two convergent flows with temperature differences of 90℃ are mixed in the tee junction area.

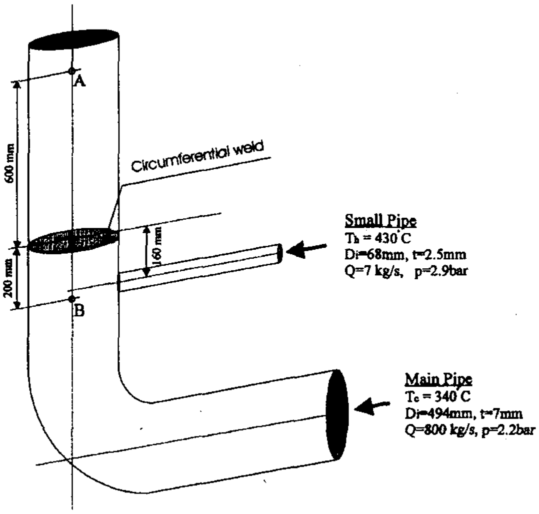


Fig. 1. Geometrical Configuration of Phenix Secondary Piping.

There is a circumferential weld at 160 mm downstream from the horizontal axis of the tee-junction. The circumferential weld on the main pipe is as-welded condition at both inner and outer surfaces. The internal pressure is 2.2 bar for the main pipe and 2.9 bar for the small bored pipe. The thermal striping damage is to be evaluated after 90,000 hours of operation.

No creep was taken into account due to the low temperature level. Only steady state operating conditions need to be considered because the operating transients induce no significant stresses in the area of interest and corresponding fatigue damage is negligible. The materials of the base metal for both pipes are AISI304 stainless steel, grade Z5 CN18.10, while the weld material of the main pipe is 16Cr-8Ni-2Mo and the circumferential welding was carried out by a plasma welding.

This benchmark problem brings opportunities to compare results of numerical analysis and observations on a practical problem, not idealized but industrial, involving a lot of parameters and different aspects of phenomenon on thermo-hydraulic, thermomechanical and fracture behaviors. All numerical evaluations should be as close as possible to reality without including any margin.

3. Thermomechanical Analysis

3.1. Green's Function Approach

In the present study, the Green function approach for the crack propagation problem of a pipe under random type thermal load was proposed, which can dramatically reduce the amount of calculation in the elastic regime. In addition, the proposed approach was also applied to the fatigue analysis of a pipe.

The Green function is defined as the response of a system to a standard step or impulse input. The Green's function contains all essential information of the system when it is properly defined. Based on the Green function concept and the Duhamel theorem when it is properly defined, the change of thermal stresses at time t due to a small change of the boundary temperature at time τ can be expressed as follows

$$\begin{aligned}\Delta\sigma_{\sigma_{ij}} &= G_{\sigma_{ij}}(t-\tau)(t-\tau)\,\Delta\Theta(\tau)\\ &= G_{\sigma_{ij}}(t-\tau)\frac{\Delta\Theta(\tau)}{\Delta\tau}\Delta\tau\end{aligned} \tag{1}$$

where the stress Green's function, $G_{\sigma ij}(t-\tau)$ can be determined from the step change of the boundary temperature. The Green function needs to be computed only once for a set of boundary condition under unit step loading.

Equation (1) can be written as

$$\sigma_{ij} = \lim_{n\to\infty}\sum_{i=1}^{n}\Delta\sigma_{ij}(t,\tau_i) \tag{2}$$

From equation (1) and (2)

$$\sigma_{ij} = \lim_{n\to\infty}\sum_{i=1}^{n} G_{\sigma_{ij}}(t-\tau)\frac{\Delta\Theta(\tau)}{\Delta\tau}\Delta\tau \tag{3}$$

Equation (3) can be expressed as

$$\sigma_{ij}(t) = \int_0^t G_{\sigma_{ij}}(t-\tau)\frac{d\Theta}{d\tau}d\tau \tag{4}$$

Equation (4) can be separated as follows

$$\sigma_{ij}(t) = \int_0^{t-t_d} G_{\sigma_{ij}}(t-\tau)\frac{d\Theta}{d\tau}d\tau + \int_{-t_d}^{t} G_{\sigma_{ij}}(t-\tau)\frac{d\Theta}{d\tau}d\tau \tag{5}$$

where t_d is decay time for the Green function. The decay time is determined from the response of the system for unit step input.

Since the Green's function $G_{dj}(\tau)$ is constant for $\tau \geq t_d$, equation (5) can be reduced as

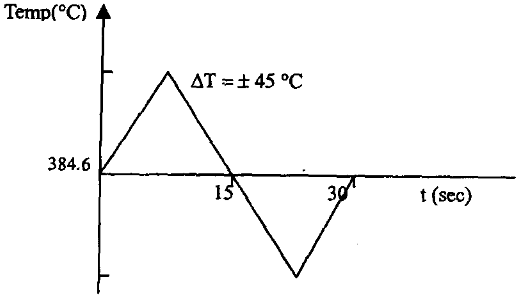
$$\sigma_{ij}(t) = \int_{t-t_d}^{t} G_{\sigma_{ij}}(t-\tau)\frac{d\Theta}{d\tau}d\tau + G_{\sigma_{ij}}(t_d)\{\Theta(t-t_d)-\Theta(0)\} \tag{6}$$

Equation (6) shows that the integration over the time range t_d only is necessary no matter how long the elapsed time may be for the calculation of the parameters such as stresses, strains or the SIFs. Then equation (6) can be expressed as follows with the time range, t_d divided into n steps for numerical integration.

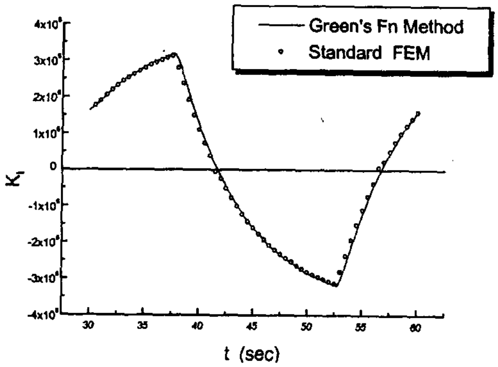
$$\sigma_{ij}(t) = \sum_{i=1}^{n} G_{\sigma_{ij}}(t-\tau_i)\{\Theta(\tau_i)-\Theta(\tau_{i-1})\} + G_{\sigma_{ij}}(t_d)\{\Theta(t-t_d)-\Theta(0)\} \tag{7}$$

where $\tau_i = \tau_{i-1} + \Delta\tau$.

Similarly, the Green function for the SIF, G_{K_I} under a unit step change of boundary temperature can be used to determine the SIF[2].



(a) input thermal load



(b) Variation of stress intensity factors for triangular thermal load of 0.033Hz

Fig. 2. Validation the Green's Function Method in Fracture Evaluation.

$$K_I(t)=\sum_{i=1}^{n} G_{K_I}(t-\tau_i)\{\Theta(\tau_i)-\Theta(\tau_{i-1})\}+G_{K_I}(t_d)\{\Theta(t-t_d)-\Theta(0)\} \quad (8)$$

The Green function method (GFM) for the SIF enables these fracture parameters to be calculated very efficiently using a simple integration scheme under thermal loads. The validity of GFM for the SIF of the present geometrical model is shown in Fig. 2 under triangular thermal loads for a temperature difference of ΔT= ±45℃ from the average temperature of 384.6℃ with 0.033 Hz (1 period = 30 sec). The SIFs by GFM showed good agreement with those by standard FEM as shown in Fig. 2.

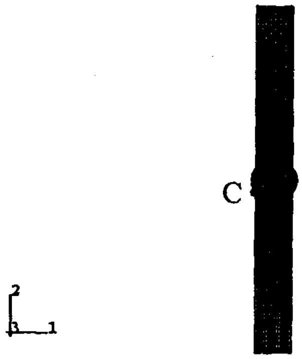


Fig. 3. Axisymmetric FE Model of the Main Pipe Near Welded Joint.

3.2. Description of the Model

For thermomechanical analysis, an axisymmetric model with 1540 isoparametric quadratic elements for the heat affected zone of the welded joint were used as shown in Fig. 3. The model has 14 elements along the thickness (7mm) direction. The axial displacements were constrained at the bottom line of the model.

In the present analysis, the ABAQUS version 5.7[3] was used for heat transfer, thermal stress and fracture mechanics analyses. In addition, some programming was carried out for stress and fracture analyses using Green's function method, and for damage evaluation per design code. In this study, the procedure specified in the ASME section III subsection NH was used for fatigue damage evaluation.

3.3. Loading Conditions

3.3.1. ThermoHydraulic(TH) Loading

The thermohydraulic behavior of the turbulent

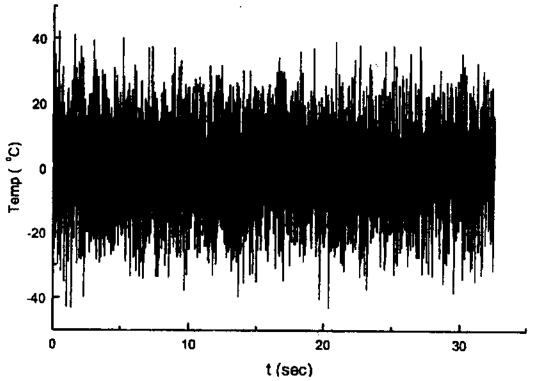


Fig. 4. History of Thermohydraulic Data Computed by UK AEA.

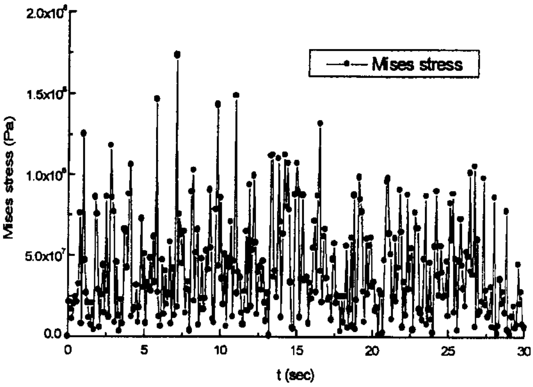


Fig. 5. Variation of Mises Stress.

flow under thermal striping phenomenon should be evaluated by using numerical analysis to predict the thermomechanical and fracture assessment of the tee-junction. An important part of this benchmark problem is to evaluate the T/H behavior of the striping phenomenon described previously. In the present analysis, the random type fluid temperature history predicted by UK AEA[4] as shown in Fig. 4 was used. The temperature history was computed for 32.5 seconds at the location of 80 mm downstream from the centerline of the small pipe, which is the random type as shown in Fig. 4. It was assumed that the temperature at the inner surface of the pipe was the same as that of the sodium fluid and the temperature history of the inner surface was the same.

Table 1. Forces and Moments in the Pipe

Location	Weight	Weight + Expansion
A	$M_x = -4.3 \times 10^6$N.mm	$M_x = -1.1 \times 10^6$N.mm
	$F_y = -91$N $M_y = 2.1 \times 10^6$N.mm	$F_y = 2{,}500$N $M_y = -2.1 \times 10^6$N.mm
	$F_z = 165$N $M_z = 5.3 \times 10^5$N.mm	$F_z = 910$N $M_z = 8.7 \times 10^5$N.mm
B	$M_x = -4.3 \times 10^6$N.mm	$M_x = 1.1 \times 10^6$N.mm
	$F_y = -91$N $M_y = -2.1 \times 10^6$N.mm	$F_y = -2{,}500$N $M_y = 2.9 \times 10^6$N.mm
	$F_z = 165$N $M_z = -4.6 \times 10^5$N.mm	$F_z = -910$N $M_z = -2.8 \times 10^6$N.mm

3.3.2. Mechanical Loading

The reaction forces and moments at the location of A and B in Fig. 1 due to the weight and thermal expansion of pipes during nominal steady state are given in Table 1.

The residual stresses in a welded joint may have an influence on the behavior of the crack initiation and propagation because it may change the levels of mean stresses. However, the residual stresses in a welded joint are mostly relaxed due to high operating temperatures or by post weld heat treatment. Therefore, the effects of residual stresses were not considered here.

3.4. Stress Analysis

The thermal stresses were calculated using Green's function approach. The history of stress intensity is shown in Fig. 5 and every three output points was plotted. The maximum value of it at welded location of 'C' in Fig. 3 was 173.3 MPa.

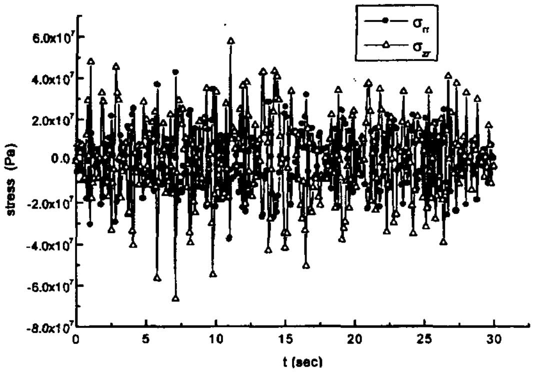


Fig. 6. Variation of Radial and Shear Stress Components at Welded Point.

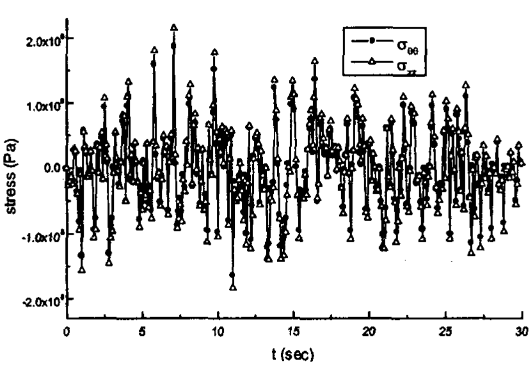


Fig. 7. Variation of Hoop and Axial Stress Components.

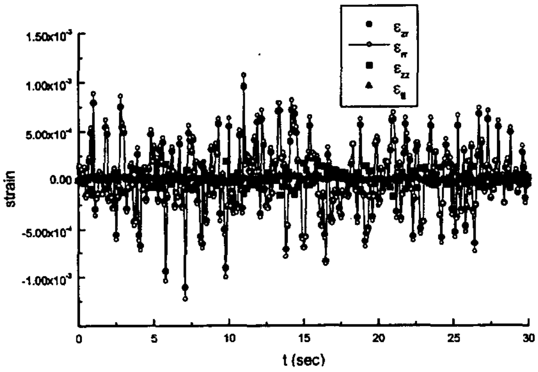


Fig. 8. Variation of Welded Strain Components.

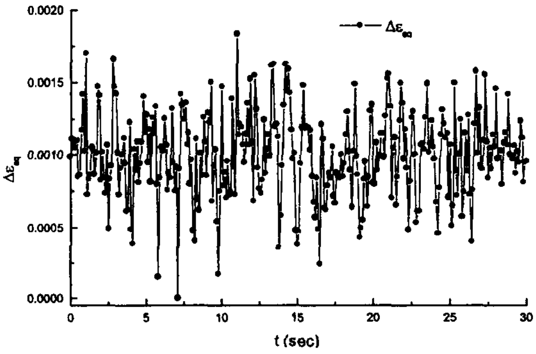


Fig. 9. Variation of Equivalent Strain Range.

The stress components at the welded joint under the random type thermal loads calculated by GFM are shown in Figs. 6 & 7. The maximum values of stress components were σ_{rr} = 42.67 MPa, $\sigma_{\theta\theta}$ = 186.67 MPa, σ_{zz} = 211.05 MPa, and σ_{zr}= 57.05 MPa.

It is interesting to note that the magnitude of the shear strain (ϵ_{zr}) level at the welded joint is as high as that of radial strain (ϵ_{rr}) as shown in Fig. 8 due to the geometric discontinuity while the other strain components (ϵ_{zz}, $\epsilon_{\theta\theta}$) are relatively small. The variations of the equivalent strain range ($\Delta\epsilon_{eq}$) for random type loads is shown in Fig. 9, which shows that the maximum value of $\Delta\epsilon_{eq}$ at the welded joint is 0.00183. The sampling time of the T/H data is 0.1 second.

The calculated stress results due to the reaction forces and moments at the welded joint of the inner surface were very small. The hoop stress due to the internal pressure was computed to be 7.863 MPa, the axial stress due to bending at the outermost location of the pipe was 1.838 MPa and the shear stress due to torsion of the pipe was 0.39 MPa. These stationary stresses would act as mean stresses in fatigue and crack propagation analysis. However, the contribution of these stresses under the stationary load to striping damage was evaluated to be very small. The magnitude of the equivalent plastic strain was about two orders lower than the elastic total stain.

3.5. Results of Fatigue Damage Evaluation

The fatigue damage evaluation was performed according to ASME code subsection NH[5]. The evaluation results of fatigue damage at the welded joint showed that the number of allowable cycles in design fatigue curve was 65,000 for the total strain range of 3.77% and the number of applied repetition of the cycle was 1.08×10^7. Therefore, the calculated usage factor for this case was 166.15 during 90,000 hours of operation. It was shown that initial fatigue failure occurred at t = 541.67 (hours) at the same location.

4. Fracture Mechanics Assessment

4.1. Description of the Criteria

The propagation law with the effective SIF parameter for AISI304 stainless steel was employed as follows ;

$$\frac{da}{dN} = C\,(\Delta K_{eff})^n \qquad (9)$$

where

ΔK_{eff} is effective SIF range described in reference [6], and the unit of the SIF is $\mathrm{MPa(m)}^{0.5}$.

4.2. Evaluation of Crack Propagation

The crack propagation analysis using GFM requires determination of the SIF range, ΔK for the incremental crack lengths. Then, the fatigue lifetime can be easily determined by integrating the crack propagation formula. To determine the fatigue crack lifetime, it is necessary to express ΔK as a function of the crack length a in the crack propagation law of equation (9). The variations of (K for each stage of the incremental crack length were calculated using the Green function for the corresponding crack length. The initial crack length was 0.5 mm. The variation of the SIF is shown in Fig. 10. The polynomial expression of ΔK for the random type load is

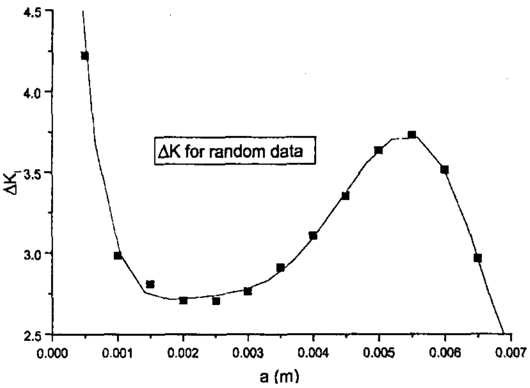


Fig. 10. Stress Intensity Factor Range as a Function of Crack Length.

$$\begin{aligned}\Delta K = {}& 7.45 - 9724.97a + 7.97\times10^{6}a^{2} - 3.32\times10^{9}a^{3} + 7.36\times10^{11}a^{4} \\ & - 8.11\times10^{11}a^{5} + 3.46\times10^{15}a^{6}. \qquad (MPa\sqrt{m})\end{aligned} \qquad (10)$$

The estimated lifetime up to a=5 mm under the random type thermal load was 42,689.9 hours.

As for the crack propagation for a>5.0 mm which is over 70% of the thickness, the validity of Paris law is uncertain because plastic deformation occurs throughout the remaining ligament.

The instability analysis would show if the crack will propagate through the thickness or not. In the present analysis, the tearing modulus based on J-integral was employed to evaluate the crack instability. The calculated tearing modulus under this thermohydraulic load at welded joint was 0.58 while the tearing modulus for this material at 427 ℃ based on the multiple-specimen J_R-curve

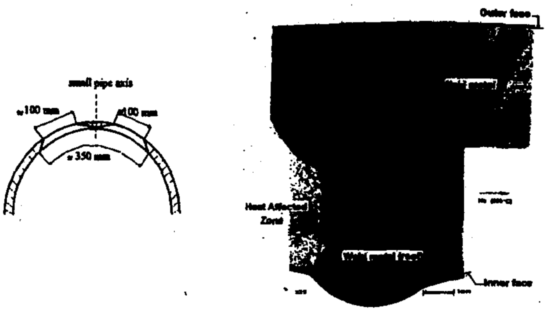


Fig. 11. Actual Observation of the Damaged Pipe of Phenix.

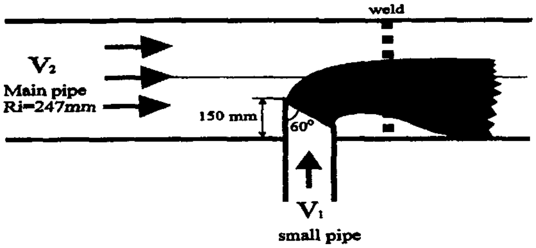


Fig. 12. Reduction of Striping Damage at Welded Zone by Extending Small Pipe into Main Pipe.

procedure was 612[7]. Therefore, the crack will be arrested between 5 and 7mm along the thickness direction.

5. Reduction of Striping Damage

The prevention of failure due to striping damage is important in a piping system of this type where mixing of the two fluids with different temperatures occurs. Fig. 11 shows the observation results for Phenix after the operation of 90,000 hours, which shows that the crack was initiated and propagated in two directions along the welded joint. It was observed that two cracks were propagated along the radial direction as shown in the left hand side of Fig. 11. Three kinds of approaches can be proposed to avoid the striping damage in the welded joint of the main pipe with a tee-junction;

- Extension of a small pipe into the main pipe

As shown in Fig. 12, the striping damage at the welded joint can be reduced by shifting the mixing zone from the welded zone by extending the branch line into the main pipe.

- Change of fluid velocities

The two fluid velocities of v_1 and v_2 in Fig. 12 can be changed to move the mixing zone from the welded joint. However, this requires overall thermohydraulic analysis as well as thermomechanical analysis in detail.

- Change of welded location

The welded location can be shifted to the downstream of the main pipe so that mixing may occur apart from the welded zone.

It can be shown that the third method of shifting welded joint is relatively simple but Phenix chose the first method to reduce the striping damage. The reduction of the thermal load at the welded joint due to fluid mixing was confirmed by measuring the surface temperatures near the welded zone after modification of the branch line carried out for Phenix. It was found that the geometrical bead shape has a very strong influence on the integrity of the welded joint because it induces a sensitive strength reduction factor due to the geometrical discontinuity.

6. Conclusions

The evaluation of the thermomechanical fatigue and fracture behavior on the tee-junction of a Phenix secondary circuit having a welded joint at the downstream of its main pipe was carried out using Green' s function method as well as standard FEM.

The evaluation by Green' s function method showed that the fatigue failure under the random type load occurred as early as 541.67 hours of operation at the circumferential welded joint of the inner surface.

The crack propagation analyses showed that crack would be propagated over 5mm during 90,000 hours of operation. The crack would be initiated and propagated up to 5 mm through the thickness direction for 42,698.9 hours. The instability analysis with tearing modulus showed that the crack would be arrested at the location between 5 and 7 mm along the thickness direction.

An efficient numerical approach using Green' s function concept was mainly employed for this random type thermal load case. The approach enabled the calculation of fatigue usage and the crack propagation lifetime by simple numerical integration.

From the viewpoint of industry, it is important to note that striping damage can be reduced by shifting the welded joint or moving the mixing zone from the critical locations with discontinuities in geometry or material.

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