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# Evaluation of thermal striping damage for a tee-junction of LMR secondary piping"

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## Abstract

This paper presents the thermomechanical and fracture mechanics evaluation procedure of thermal striping damage on the secondary piping of LMFR using Green's function method and standard FEM. The thermohydraulic loading conditions used in the present analysis are simplified sinusoidal thermal loads and the random type data thermal load.

The thermomechainical fatigue damage was evaluated according to ASME code subsectionNH. The analysis results of fatigue for the sinusoidal and random load cases show that fatigue failure would occur at a geometrically discontinuous location during 90,000 hours of operation

The fracture mechanics analysis showed that the crack would be initiated at an early stage of the operation. The fatigue crack was evaluated to propagate up to 5 mm along the thickness direction during the first 944 and 1083 hours of operation for the sinusoidal and the random loading cases, respectively.

## 1. Introduction

The thermal striping phenomenon, due to imperfect mixing of sodium streams at different temperatures is one of the most significant problems in liquid metal fast reactors (LMFRs). The thermal fluctuations in LMFRs were caused by the movement of temperature distribution induced by a cyclic movement of sodium stratification interface, which usually occurred in the lower part of the hot pool inside the reactor vessel, and caused by mixing and fluctuating of the two flows at different temperatures. 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 tee-junction of Superphenix and the crack at the cold trap system of BN-600[1].

In this study, an efficient numerical method based on Green's function concept and Duhamel's Integral theorem was used to calculate thermal strains and the SIFs(stress intensity factor) to evaluate fatigue damage and crack propagation under thermal striping loads for the tee-junction of secondary piping system.

Compared with the transient finite element method, the present method is confirmed to be more effective in view of computational aspect without sacrificing the solution accuracy.

## 2. Description of Benchmark Problem

The present technical problem deals with the mixing of two flows at different temperatures in the secondary circuit of the French Phenix during normal operation[2]. The sodium in the small pipe flows into the main pipe of the secondary circuit as shown in Fig. 1. A small pipe, connected with a tee junction to the main pipe discharges sodium at 430°C into the main pipe. Two convergent flows, at different temperatures ($\Delta T = 90°C$) are mixed in the tee junction area. There is a circumferential weld at 160 mm upstream 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 thermal striping damage is to be evaluated after the reactor has operated for 90,000 hours of the reactor. No creep is taken into account due to the low temperature level.

## 3. Thermomechanical Analysis

### 3.1 Description of the model and loading conditions

For thermomechanical analysis, an axisymmetric model for the heat affected zone of the welded joint with 1540 isoparametric quadratic elements were used as shown in Fig. 2. The model has 14 elements along the thickness direction. The axial displacements were constrained at the bottom line of the model as boundary conditions for the axisymmetric model.

In this analysis, the ABAQUS version 5.7[3] was used for heat transfer, thermal stress and fracture mechanics analyses. In addition, Fortran programs were composed to carry out thermal stress and fracture analyses using Green's function method and damage evaluation according to the design code, ASME section III subsection NH[4].

Two types of thermal loading conditions were considered. Thermal fluctuations were assumed to occur in simplified sinusoidal form with constant alternating magnitude of 90°C which is the temperature difference of the hot and cold fluids. As another case of the temperature difference($\Delta T$), $\Delta T$=70°C case was also considered difference from power spectral density analysis. The striping frequencies considered here were 0.1 Hz, 0.5 Hz and 1.0 Hz, which are usually the most damageable ones on the wall of the piping.

The temperature histories predicted by AEA[5] for the location of 80 mm upstream from the centerline of the small pipe were used, which is random type data as shown in Fig. 3.

### 3.2 Thermal stress analysis

The temperature history at geometrically discontinuous welded point A of Fig. 2 is assumed to fluctuate in sinusoidal form with a magnitude of around 90C° while the predicted temperature profile by AEA calculation is a random type as shown in Fig. 3. The computed maximum values of the stress intensities, $\Delta\sigma$ was 292.7 Mpa for the case of 0.5 Hz.

The variations of the equivalent strain range ($\Delta\varepsilon_{eq}$) for random type AEA TH loads are shown in Fig. 4, which show that the maximum value of $\Delta\varepsilon_{eq}$ = 0.00183. The sampling frequency of the data is 0.1 sec.

### 3.3 Results of Fatigue Damage Evaluation

The fatigue damage evaluation was performed according to ASME code subsection NH[4]. The evaluation results of fatigue for various loading cases are shown in Table 1. As shown in the table, the case of 0.5 Hz was most severe among the three cases for elastic analysis. The damage values show that fatigue failure would occur at the early stage of 90,000 hours of operation. However, the damage results by inelastic analysis for 0.1 Hz showed the damage value of 0.32, and for the case of 0.5 Hz, the damage value showed 1.08, which predicts that failure would occur during 90,000 hours.

The damage evaluation for the case of random type thermal loading also showed a high level of fatigue usage which is 166.15. The analyses of the sinusoidal loading cases was performed using standard FEM, while that of random type loading was performed using Green's function method.

## 4. Fracture Mechanics Assessment

The crack propagation analysis using Green's function method requires determination of the SIF range for the incremental crack lengths. To perform crack propagation analysis, $\Delta K$ should be expressed as a function of crack length. Then the fatigue lifetime can be easily determined by integrating the crack propagation equation.

The crack propagation analysis requires polynomial regression of $\Delta K$ as a function of crack length $a$. The polynomial expressions for the sinusoidal load and random type load over the crack length of 0.5 mm to 5.0 mm are as follows ;

$$\Delta K = 7.709 - 0.185a + 0.016a^2 - 5.709\times10^{-4}a^3 + 1.08\times10^{-5}a^4 - 7.877\times10^{-8}a^5 \quad (MPa\sqrt{m})$$

The estimated times for crack tip to propagate 1 mm, 3 mm and 5 mm along the thickness direction are shown in Table 2. As shown in the table, the crack would be propagated up to 5 mm in 944.06 hours. The Green's function of SIF for each crack length will be predetermined and used to calculate SIFs. The estimated lifetime up to crack length of $a$=5 mm was calculated as 1083.62 hours as shown in Table 2. The two results of sinusoidal fluctuation (944.06 hr) and random type case (1083.62 hour) gave similar fatigue propagation lifetime The variations of the SIFs during random type loading and the sinusoidal loading are shown in Fig. 5 and 6, respectively..

As for the crack propagation for $a$>5.0 mm which is over 70% of the thickness, it is no longer valid to apply the Paris law. The crack would not penetrate through the thickness because the primary stress level is very low from the engineering judgement.

## 5. Conclusions

The evaluation of the thermomechanical fatigue and fracture behavior of Phenix secondary circuit tee-junction having a welded joint near upstreem of its main piping were carried out using Green's function method and standard FEM. Two types of thermohydraulic loading were considered. One is the simplified sinusoidal temperature fluctuation with the alternating temperature difference of the two fluids with the frequencies of 0.1 Hz, 0.5 Hz and 1.0 Hz. The other is random type thermal loading[4].

The evaluation of the nalyses can be summarized as follows. The fatigue evaluation showed that the frequency of 0.5 Hz is most damageable and fatigue failure occurred for elastic and inelastic analysis. The inelastic analysis results with the Chaboche model showed that the degree of damage is far lower than that of elastic analysis. In addition, random type loads also cause fatigue failure in the circumferential welded zone of the inner surface during 90,000 hours of operation.

The evaluation of crack propagation using SIF parameter was carried out for the load cases of sinusoidal load and random type load by Green's function method. The crack was evaluated to be propagated up to 5 mm at 944 hours for sinusoidal load and at 1083 hours for random type load. The crack would not penetrate through the thickness due to the low level of primary stresses.

Therefore, the crack would be initiated and propagated quickly up to 5 mm through the thickness direction but the crack would be arrested between 5 mm and 7 mm because of the low level of primary stresses.

## References

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3. ABAQUS version 5.7, H.K.S Inc., 1998.
4. ASME Section III Subsection NH , Class I Components in Elevated Temperature Service, Dec. 1995.
5. Thermal striping benchmark exercise – Thermohydraulic analysis of the Tee-Junction, UK

AEA Technology, 1996.

**Table 1. Fatigue usage factors**

| [illegible] | Elastic / plastic | [illegible] | Sinusoidal fluctuation ($\Delta T = 90°C$) | [illegible] |
|---|---|---|---|---|
| Fatigue usage | **Elastic** | [illegible] | **77.14** | 16645 |
| | | [illegible] | **162.0** | |
| | | [illegible] | **81.0** | |
| | **Inelastic** | [illegible] | **0.324** | |
| | | [illegible] | **1.08** | |

**Table 2. Anlysis results of crack propagation**

| *a* | Estimated lifetime (hour) | |
|---|---|---|
| | Sinusoidal loading | Random type loading |
| 1 mm | 104.846 | 120.28 |
| 3 mm | 524.43 | 601.70 |
| 5 mm | 944.06 | 1083.62 |

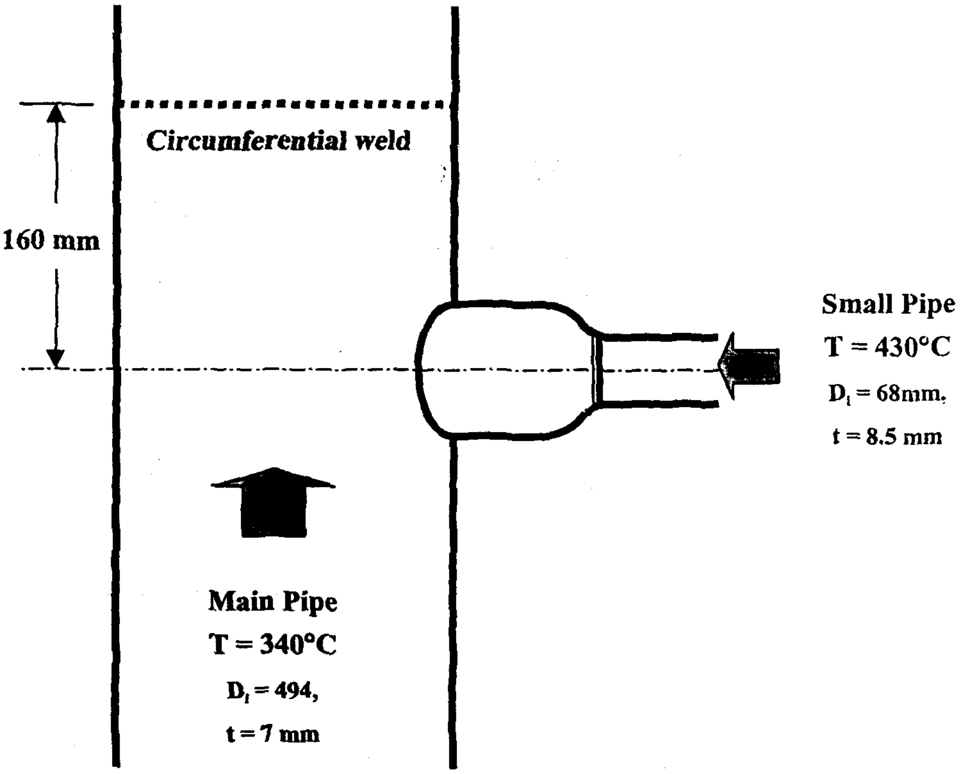

Fig. 1 Tee-junction of Phenix secondary piping

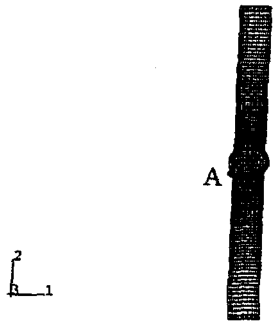

Fig 2. Axisymmetric model of Tee-Junction

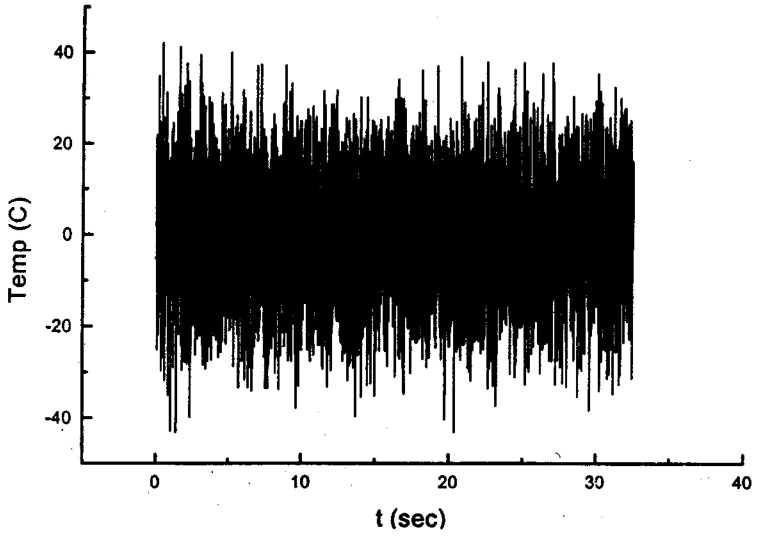

Fig. 3 Temperature history at the location of 80 mm upstream from small pipe

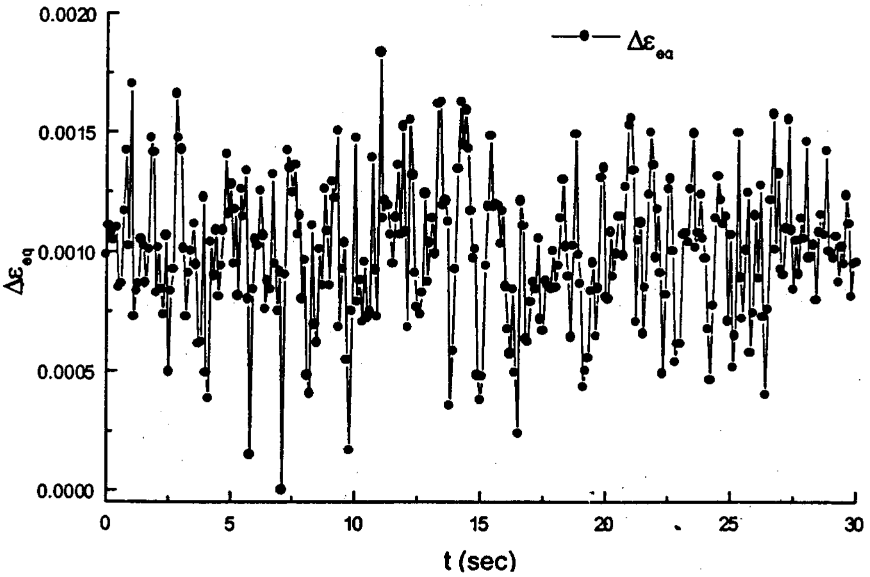

Fig. 4 History of equivalent strain ranges for random type thermal load

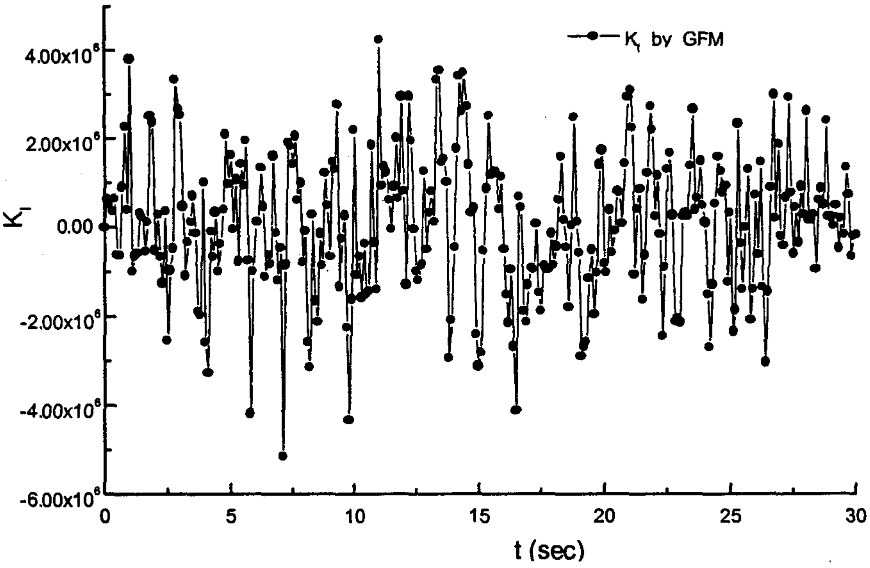

Fig. 5 Variation of stress intensity factors for random type load case

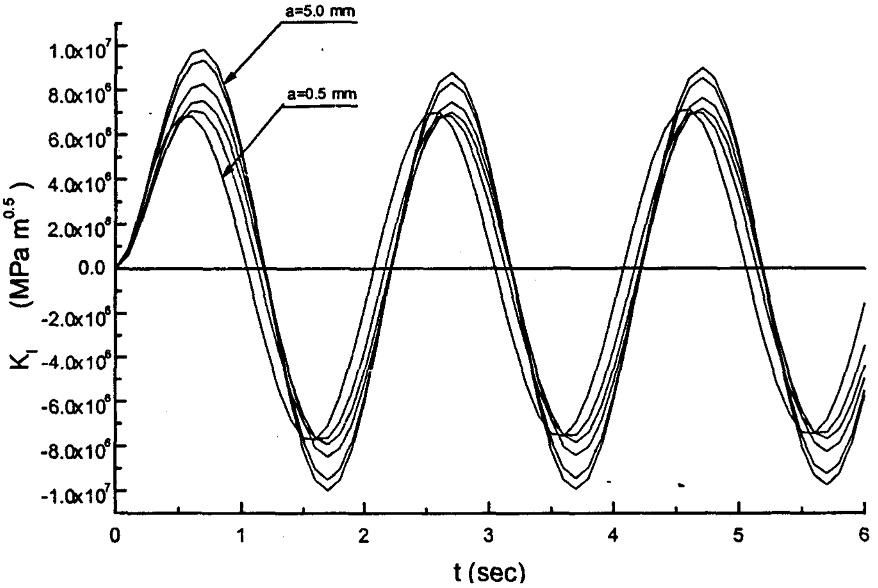

Fig. 6 Variation of stress intensity factors for sinusoidal load case of 0.5 Hz