Transactions, SMiRT-23
Manchester, United Kingdom - August 10-14, 2015
Division V, Paper ID 675

DRAFT Paper #675 High Cycle Thermal Fatigue Analysis of Pipe Mixing Tee with Internal Sleeve

P R Hurrell [1], R Philipson [1], K F Carter [2], L Davenport [1] and K Wright [1]

[1] Rolls-Royce plc, PO Box 31, Raynesway, Derby, UK
[2] RAEng Visiting Professor, University of Leicester, Leicester, UK

ABSTRACT

This paper describes high cycle thermal fatigue analysis performed in support of a conceptual design study for a pipe branch connection, subjected to large temperature fluctuations due to mixing of hot and cold flows. An internal sleeve protects the pipe junction pressure boundary from temperature shocks, but the sleeve end is subjected to high cycle fatigue due to turbulent eddy flows. This behaviour was investigated using Computational Fluid Dynamics (CFD) Large Eddy Simulation (LES) modelling techniques. Thermal stresses and fatigue damage were predicted using analytical methods consistent with the recommendations in the European NESC procedure EUR 22763. The 2010 ASME design fatigue curve was austenitic stainless steels in air was used, since thermal cycling is too rapid for PWR water environment effects to be significant. The most conservative approach used was to assume in-phase cycling around the tube circumference at the 1 Hz frequency generating the maximum thermal stress range, applying the largest fluid Heat Transfer Coefficients (HTCs) calculated by CFD modelling. Stress ranges were scaled for other thermal transients based on the ΔT ratio. Fatigue Usage Factor (FUFs) were predicted to be high using this method.

Thereafter a more sophisticated analytical technique was developed, mapping the CFD temperature fluctuations directly onto the 3D Finite Element (FE) tube model. Temperature cycling was computed to be incoherent around the tube circumference, at a range of frequencies between 0.1 and 20 Hz approx. Nodal stress ranges were statistically analysed over the CFD sampling period. A less conservative fatigue analysis method was developed, whereby the mean plus 2 standard deviation stress range was assumed to be applied at the worst cycling frequency of 1 Hz. Using this maximum stress range (~95% confidence) the calculated FUF was substantially reduced compared to the in-phase cycling analysis. The analysis was further refined using Rainflow cycle counting, in accordance with the ASTM E1049 standard. Bands of nodal stress ranges and associated cycling frequencies were determined. Only frequencies ≤ 1Hz generated stress ranges above the endurance limit on the ASME design fatigue curve. Using Rainflow counting the FUF was reduced by approximately 50% compared to the maximum stress approach.

INTRODUCTION

This paper describes High Cycle Thermal Fatigue (HCTF) analyses performed in support of a conceptual design study for a pipe branch connection, subjected to large temperature fluctuations due to mixing of hot and cold flows. An internal sleeve protects the pipe junction pressure boundary from severe temperature shocks, but the sleeve end is subjected to high cycle fatigue due to turbulent eddy flows. This behaviour was investigated using CFD LES modelling techniques.

A European Network for the Evaluation of Structural Components Thermal Fatigue (NESC-TF) research programme developed conservative methods for predicting FUFs due to high cycle turbulent mixing at piping tees, reported in EUR 22763 EN (2007). The NESC-TF Level 2 Sinusoidal (SIN) method idealises the thermal loading as a sine wave, cycling in-phase around the circumference of the pipe junction at the most damaging frequency. However when this conservative approach is used, in conjunction with the

2010 ASME design fatigue curve for austenitic stainless steels, high FUF values are typically evaluated. These analysis results can indicate a short operating period for fatigue crack initiation, such that frequent in-service inspection or more reliance on component defect tolerance may be required.

More realistic, but still conservative thermal fatigue analysis methods are developed using the cyclic loading spectra predicted by the CFD LES model, consistent with a NESC-TF Level 3 approach. A worked example is presented to illustrate the differences in analysis methods and calculated FUF values.

DESIGN FEATURES OF PIPE BRANCH CONNECTION WITH THERMAL SLEEVE

An internal sleeve design was developed to protect a pipe junction pressure boundary from thermal hot shock stresses generated by various branch line fluid temperature transients of up to 200°C. This design incorporates a curved sleeve end welded to the main pipe and projecting downstream in the main pipe run flow (see schematic drawing in Figure 1). Mixing of hot and cold water occurs within the bulk flow remote the large pipe wall, thereby minimising temperature transients experienced by structural components downstream. The internal sleeve has a short straight length beyond the tube bend, thereby eliminating ovality or tube bending residual stresses at the sleeve end. A curved sleeve design was considered better than a straight sleeve projecting into the main flow, as this minimises potential for flow-induced vibrations arising from vortex shedding due to cross flow turbulent eddies and drag forces. The ratio of branch to main pipe diameters is approximately 0.15 and ratio of water flow-rates is < 0.1. The sleeve wall thickness is only 3mm and is polished to a fine surface finish, with the objective of maximising the component thermal fatigue endurance. The region subjected to HCTF at the sleeve end is not a structural component. No significant mechanical loads are applied at this location by internal fluid pressure and water flows. Only thermal cyclic hoop stresses are generated at the free end of the tube, as a result of unstable turbulent eddy mixing of hot and cold flows. However, one drawback is that the internal sleeve end is not amenable to any remote in-service inspection techniques such as ultrasonic or radiographic examinations to monitor the condition through life. Therefore analysis is required to provide confidence that fatigue crack initiation is unlikely to occur during the component life.

EUROPEAN GUIDANCE ON HCTF ANALYSIS OF PIPE MIXING TEES

The NESC-TF research programme developed conservative methods for predicting FUFs due to high cycle turbulent mixing of hot and cold flows at piping tees, reported in EUR 22763 EN (2007). The Level 1 screening criterion is a simple way of assessing whether a particular tee requires further fatigue assessment. A threshold $\Delta T_{nom} = T_{branch} - T_{run}$ is defined based on the temperature differential between the water flows upstream of the pipe junction. For stainless steel components the threshold $\Delta T_{nom} \leq 80°C$ was derived, based on a large database of inspections from Electricité de France (EDF) nuclear plants. Since this criterion is exceeded, the next step is a simplified conservative analysis using the Level 2 SIN method. The thermal loading is treated as an idealised sine wave at the most damaging cyclic frequency. This method is applicable to simple 1D axisymmetric radial heat transfer through the pipe wall of the mixing tee. Only the local thickness at the pipe intersection is required for this simplified analysis. Fluid HTCs are calculated either from a turbulent flow correlation (eg Dittus-Boelter), CFD analysis or by direct measurement on a test rig. NESC-TF notes that a typical value from measurements in turbulent mixing zones is 15 kW/m^2 ºC.

The SIN method has four basic steps:

1. Apply a sinusoidal temperature variation to the fluid $T = \Delta T/2 \cdot \sin(2\pi f \cdot t)$. ΔT is the local temperature range, f is the frequency and t is time.
2. Determine elastic stress (or strain) variation as a function of frequency.
3. Apply appropriate reduction factors to the stress/strain variation (for example fatigue strength reduction factor for un-flushed weld, or plastic strain enhancement factor).

4. Determine allowable number of cycles for a specific ΔT from the computed stress (or strain) variation on the inner surface and appropriate fatigue curve. The frequency which gives the shortest life is selected. Then the FUF value is evaluated.

The SIN method should normally give conservative fatigue life estimates, since it assumes all the pipe inner surface is subjected to an in-phase thermal cycle, at the worst cycling frequency. NESC-TF notes that the local temperature variation in the fluid mixing zone is typically less than the temperature difference between fluids in the two branches upstream of the pipe intersection (ΔT_{nom}) and recommends assuming 80% of the upstream ΔT value, based on measurement data. The NESC-TF report describes Level 2 SIN analysis calculation methods in detail. Recommendations were also made for further research to develop and validate more realistic analysis methodologies. NESC-TF proposed that in a Level 3 assessment ‘the fatigue usage factor is determined by analysis of the complete local load spectra’. A Level 4 analysis is ‘based on fracture mechanics and deals with the calculation of the growth of detected or postulated crack-like flaws’.

This paper describes HCTF methods employed to analyse the thermal sleeve component, which are broadly consistent with the NESC-TF Level 2 SIN method, followed by the development of more realistic Level 3 methodologies to reduce analysis conservatism.

CFD MODELLING AND ANALYSIS RESULTS

CFD Reynolds Averaged Navier-Stokes (RANS) and LES modelling techniques were valuable tools aiding the design optimisation of the internal sleeve, in order to minimise thermal fatigue damage of the pipe junction pressure boundary. CFD RANS modelling methods with conjugate heat transfer were used to predict fluid flows and metal temperatures in the pipe-work remote from the sleeve end. The Shear Stress Transport (SST) (κ-ω) turbulence model was selected using the ANSYS CFX software, version 12.0, as validation studies exhibited good correlation with experimental data. A flat velocity profile was modelled upstream, both in the main pipe run and branch pipe.

Fluid HTC values were also computed in the vicinity of the sleeve end using the CFD RANS model. These HTC predictions were compared with the Dittus-Boelter (DB) correlation for fully developed turbulent flow in pipes and the Churchill-Bernstein correlation for cross-flow over a cylinder. For the most damaging 200°C ΔT thermal transient analysed, the area averaged HTC values in the final 10 mm of the sleeve end were predicted to be 6, 12 and 13 kW/m^2 °C on the sleeve bore, outside surface and sleeve end respectively. The sleeve bore HTC value of 6 kW/m^2 °C calculated by the CFD RANS model is higher than the DB HTC of 3.6 kW/m^2 °C; however such a discrepancy is not unexpected since flow around the tube bend is not fully developed.

This analysis demonstrated that the main pipe wall was protected from significant thermal shocks. The temperature distribution during the steady state condition of the maximum ΔT flow transient is plotted in Figure 2. Transient metal temperatures were thereafter used to evaluate thermal stresses and fatigue usage factors in the pipe-work pressure boundary against ASME III Level A Service limits.

CFD LES models were used to investigate in more detail the turbulent eddy flow patterns and rapid surface temperature fluctuations in the vicinity of the tube tip. The period of interest generating high cycle thermal loading is the steady state hot discharge flow from the branch line, mixing with cold flow in the main pipe run. This was an adiabatic heat transfer model, considered conservative in terms of temperature cycling at the sleeve end, since no upstream heat losses due to conduction and convection were represented. Only the fluid and adjacent pipe wall surfaces were represented. The Wall Adapted Local Eddy (WALE) viscosity model was employed in the ANSYS CFX software, as recommended in the CFX-12 User Guide and by Westin (2008). Using the WALE sub-grid turbulence model it was necessary to use small timesteps of ~0.5 milliseconds. A transient duration of at least 9 seconds was run to characterise the nature of temperature fluctuations and obtain sufficient cycle counts to statistically analyse the stress cycling behaviour. Subsequently, the CFD sampling period was extended to 27 seconds to gain additional cycle counts in stress range bands of interest, for use in a Rainflow fatigue analysis. An example of maximum temperature fluctuations recorded on the tube tip during the 9 seconds CFD sampling interval of the 200°C ΔT transient is plotted in Figures 3. The metal surface temperature cycling at a particular node is traced in Figure 4. The CFD LES analysis of turbulent eddy flow behaviour computed a wide spectrum of temperature cycling frequencies, approximately in the range 0.2 to 20 Hz. The average value was around 10 Hz.

Sensitivity studies were conducted investigating the effect of tilting the tube end by up to 10° (vertically or horizontally) relative to the perfectly aligned case. This was done to account for potential misalignment as a result of welding induced distortions in making the thermal sleeve to pipe weld. These analyses predicted that although the region of maximum temperature cycling did vary around the tube rim, but the essential characteristics in the most affected zones were similar to Figures 3 and 4.

STRUCTURAL FE MODEL ANALYSES

2D and 3D FE models of the sleeve end were generated to calculate metal temperatures and thermal stresses. The idealised in-phase cycling modelled in this study is an enhanced version of the NESC-TF Level 2 analysis, but still retaining a sinusoidal temperature variation. Subsequently more detailed FE analyses of the cyclic loading spectra were performed, mapping the surface temperature fluctuations computed by the CFD LES model analysis, consistent with the NESC-TF Level 3. Abaqus FE analysis software was used, applying thermal surface boundary conditions via a *FILM subroutine.

2D Axisymmetric and 3D Curved Sleeve Models used for In-Phase Cycling Analysis

This axisymmetric model of a short straight length of the sleeve end was used for initial conservative thermal stress and fatigue analyses, also identifying the most onerous cycling frequency. The model used second order reduced integration elements (Abaqus type CAX8R) and had 16 elements across the 3mm thickness of the tube, with a bias to thinner elements near the inside and outside surfaces. CFD RANS model predicted area averaged HTC values were applied. The tube tip HTC was increased from 13 to 20 kW/m^2 °C to ensure conservatism, in recognition of the considerable HTC variation in this region. The axisymmetric model was run for the maximum 200°C ΔT transient at a selection of cyclic frequencies between 0.2 and 5 Hz, in order to calculate the variation in hoop stress range. Higher frequencies were judged to be too short to impose significant through-thickness temperature and stress gradients. Analysis results are plotted in Figure 5 showing that a maximum stress range of 440 MPa was calculated at a cycling frequency of ~1 Hz. This analysis also predicted that a 'bell-mouthing' distortion of the sleeve end occurs. The mean metal temperature at the sleeve end is higher than the upstream tube material.

A curve sleeve end 3D model was then constructed with idealised thermal boundary conditions more closely resembling the CFD LES analysis results. The in-phase surface temperature cycle applied to the structural FE model is plotted in Figure 6. The maximum ΔT was applied over a 180° arc centred at the intrados of the tube tip, but only 50% of this ΔT range was applied to the extrados. At the worst frequency of 1 Hz, this analysis computed a maximum thermal hoop stress range of 390 MPa, see Figure 5.

Direct FE Analysis of CFD LES Model Results

For this assessment the metal surface temperature fluctuations and 'area averaged' fluid HTC values were mapped from the CFD LES model onto a structural FE model of the curved sleeve end. The Abaqus *FILM subroutine was used for this purpose. Temperature distributions were then calculated within the

304 stainless steel pipe as a function of time over the CFD data sampling period. It was necessary to interpolate at the nearest surface node positions as a refined (hexahedral) brick FE mesh was used in the structural model, whereas a tetrahedral mesh was used in the CFD model. Results from the CFD LES model analysis predicted that the rapid surface temperature fluctuations, due to turbulent eddy flows, are incoherent around the tube circumference. The typical wavelength of these fluctuations is ~3mm. The hoop stress cycling at a node location in the region of maximum damage during over a CFD analysis period of 27 seconds is plotted in Figure 7. The mean hoop stress is between 150 and 200MPa at the sleeve end. A maximum nodal hoop stress range of 310 MPa was calculated on the intrados at the tube tip, significantly lower than that evaluated from the in-phase cycling analysis.

FATIGUE ANALYSES

Fatigue usage calculations were performed using the maximum stress ranges calculated by each of the structural FE models. To allow direct comparison of results common set of cyclic loads was used in conjunction with the 2010 ASME the same design fatigue curve. The fatigue analysis methods and results are described in the following sections:

Cyclic Loads used in Worked Example

A representative duty of cycle thermal loads was used in this worked example, as defined in Table 1:

Table 1: High Cyclic Thermal Fatigue Loads

Transient ΔT (°C)	Flow Duration (hours)
200	10
175	30
150	60
125	120
100	200
75	500
50	3000

Stress ranges were scaled on ΔT ratio for lesser thermal transient magnitudes (< 200°C). This was considered a reasonable assumption for full bore hot flow transients from the branch line. A plasticity correction factor $F_p > 1.0$ was applied when the maximum surface stress intensity range exceeded $3S_m$, where S_m is the material design stress intensity (116 MPa at 300°C). The elastic modulus specified on the ASME design fatigue curve is 195 GPa at 20°C. An elastic modulus correction for an assessment temperature of 300°C of 1.11 (=195/176) was also conservatively applied for each thermal transient, in accordance with the ASME III, Subsection NB-3222(e) procedure for cyclic loading.

Design Fatigue Curve

The 2010 ASME Section II design fatigue curve for austenitic stainless steels in an air environment was applied in this analysis. It was assumed that at the rapid thermal cycling frequencies of interest (> 0.1 Hz), there is no significant deleterious effect of PWR primary water environment. NUREG-CR-6909 describes the derivation of the design fatigue curve, shifting the best fit curve to specimen test data by a factor of 2 on stress or 12 on cycles, whichever is more conservative. These are adjustment factors to allow for uncertainty in effects of environment, data scatter, material variations, surface finish and component size.

The endurance limit specified on the 2010 ASME design fatigue curve, corresponds to an alternating stress range S_{alt} of 94 MPa at 10^{11} cycles, rising to 126 MPa at 10^6 cycles. This limit is a factor of 2 on stress range below the best fit to the large database of air environment fatigue specimen tests on austenitic stainless steel and nickel based alloy materials (parent and weld metals), NUREG-6909. A Goodman correction is applied to account for the maximum effect of mean stress.

Interestingly, the obsolete 2007 version of the ASME design fatigue curve had greater fatigue strength, S_{alt} of 194 MPa at 10^6 cycles. It was subsequently recognised that cold work applied to the test specimens, thereby raising the material yield strength. When solution annealed material test data was included, a lower endurance limit was derived.

Fatigue Analysis Results for In-Phase Cycling

For the in-phase cycling analysis, conservative FUF calculations were performed using a maximum stress range approach and corresponding effective sinusoidal cycling frequency f_{eff} , which can be summarised in Equation 1:

$$FUF_{(\text{max stress})} = f_{eff} \,.\, FUF\,(\Delta\sigma_{max}) \qquad (1)$$

A total FUF of 6.1 was conservatively calculated using the stress ranges obtained from the idealised 2D axisymmetric model (440 MPa maximum), assuming in-phase cycling at 1Hz. When the stress ranges from the 3D curved tube model are utilised (390 MPa max), the FUF reduces to 3.3. These results illustrate that the surface damage is sensitive to the stress ranges applied at the high cycle ‘run-out’ end of the design fatigue curve. The partial usage is mainly attributed to the large ΔT cycles, whereas temperature fluctuations < 75°C generate $S_{alt} < 80$ MPa (below the damage threshold). In both cases the FUF exceeds >1.0, indicating potential for fatigue crack initiation at the tube tip.

Fatigue Analysis using CFD Data (Modified Maximum Stress Approach)

In order to reduce analysis conservatism, the CFD LES model surface temperature fluctuations were mapped directly onto the structural FE model. This is a much more computationally intensive analysis. Stress ranges were evaluated at each node in the sector region of maximum thermal cycling on the tube rim during the CFD simulation period. The sector or area approach ensures that the region of maximum damage is captured, making best use of limited CFD data. The effective maximum stress range was then evaluated by assuming a normal distribution about a mean range with an appropriate number of standard deviations. The maximum stress approach determined an upper 95% confidence bound stress range (mean plus two standard deviations) from the cyclic analysis of 9 seconds of CFD data. In this case the maximum stress range applied was 310 MPa. This analysis is still conservative, because a worst case cycling frequency of 1 Hz was applied. In this study the total FUF value was calculated to be 0.87.

Fatigue Analysis using CFD Data (Rainflow Cycle Counting Procedure)

The most realistic fatigue analysis employed was a detailed Rainflow cycle counting in accordance with ASTM E1049 (2001), following the computed loading spectra from the CFD LES model analysis. Further analysis was undertaken using a longer CFD analysis period of 27 seconds, in order to generate sufficient cycle counts of large stress ranges to undertake a Rainflow fatigue analysis. For the Rainflow cycle counting approach, the individual nodal stress histories are decomposed into a number of stress range events of a given magnitude. This is done by examining the stress history at a node and identifying the peaks, both positive and negative, but also taking account of the sequence in which these peaks occur. The advantage of the Rainflow approach is that the method takes account of the loading sequence and thus more closely matches the hysteresis stress-strain loops in the material. The Rainflow cycle counting method was applied to the nodal stress histories around the outer rim within the sector of interest. This sector is chosen as a series of adjacent nodes with the greatest stress range typically over an arc of about 5, 10 or 20 degrees. The turbulent mixing is not restricted to a single worst nodal location but occurs over a sector of the outer rim. The number of counts of stress range events of a given magnitude at a given node is then calculated by the proprietary software code FE-Safe, version 6.2.

The number of counts in each stress range band is approximately normally distributed except at high stress range values, where there are insufficient counts to deduce any particular probability distribution function. To be conservative, the mean plus two Standard Deviations (SDs) of the cycle counts in each stress range band was taken when calculating the frequency of occurrence. Frequency versus stress range distributions are plotted of Figure 8 for stress range bands of 24 MPa. The endurance limit of 188 MPa is intersected at approximately 1Hz, for the 24 MPa stress range bands. Only stress range bands above the fatigue endurance limit can cause significant damage. The validity of the normal distribution curve was checked, for the counts obtained in each stress range band. A P value of > 0.05 was calculated for the majority of bands, indicating the data falls within the 95% confidence intervals. One exception was the largest stress range band (288 to 312 MPa), with insufficient cycle counts for valid statistical analysis. Although few counts were obtained above a stress range of 260 MPa for valid statistical analysis, it is possible to define an approximate cut-off on the graph. An estimate of the maximum thermal stress can be obtained from Roark thin cylinder shell theory. At the free end of a tube, the thermal bending stress σ_t due to a through thickness temperature gradient is given by Equation 2:

$$\sigma_t = (5/4).\ E\alpha\Delta T \ / \ (2(1-\upsilon)) \qquad (2)$$

For a maximum through-thickness ΔT of 100°C, the Roark equation predicts a thermal stress of 310 MPa. This is close to the maximum stress range of 312 MPa applied in the Rainflow analysis. The effect of increasing the duration of the CFD simulation is to sample a greater amount of the distribution of stress fluctuations. In effect this allows sampling further into the tail of the distribution where the largest stress ranges are found. As these large stress ranges have a disproportionate effect on fatigue life, the calculated FUF value from the maximum stress range approach is likely to increase with the CFD simulation duration when the same effective frequency is used. However since the temperatures of the mixing flows are fixed, the stress range cannot be greater than a certain maximum. Thus the FUF would tend to a limiting value. Using Rainflow cycle counting, the Partial Fatigue Usage Factor (PFUF) is evaluated for each stress range band above the endurance limit. Low stress range events have less effect on the fatigue life of the component, particularly those below the endurance limit of the material, although the frequency of these low stress range events is relatively high. The number of cycle counts (and hence frequency f_{band}) associated with each stress range band is counted for. Then a damage summation is carried out to evaluate the total FUF as described by Equation 3:

$$FUF_{(Rainflow)} = \Sigma \ \{f_{band} \ . \ PFUF \ (\Delta\sigma_{band})\} \qquad (3)$$

For the detailed Rainflow fatigue analysis, a total FUF of 0.38 was evaluated. This is approximately 50% of the FUF value calculated using the maximum stress approach. A sensitivity study was undertaken reducing the size of the stress range bands from 24 MPa to 12 MPa. In this case the fatigue endurance limit 188 MPa was intersected at approximately 0.5 Hz. There was no significant difference in the total FUF calculated (~0.4). As the stress range bands are reduced a longer CFD analysis is typically needed to obtain statistically valid cycle counts.

DISCUSSION

For the cyclic duty considered in the worked example, the detailed analysis of CFD data indicates that fatigue crack initiation is unlikely to occur since the total FUF <1.0. These results illustrate the potential benefits to be gained by analysing the cyclic loading spectra, rather than a simplistic conservative sinusoidal in-phase cycling analysis at the most onerous frequency. However, in the context of providing a nuclear safety case it is likely that a degree of experimental validation will be required, if the component fatigue life prediction is based on a NESC-TF Level 3 analysis. Practical difficulties are likely to be encountered in any attempt to experimentally validate CFD LES model predictions. Measurements on a representative flow test rig would be problematic in the region of the thermal sleeve tip. If any thermocouples are attached there, they would tend to disrupt the characteristic flow patterns in the region of turbulent mixing. Thermal fatigue life endurance testing is considered to be a more viable alternative, either by performing specimen tests, or by using a prototypic flow rig.

Nevertheless some confidence can be gained that the characteristic rapid eddy cycling behaviour plotted in Figure 7 is similar to that computed by independent CFD LES analyses at the inner surface of piping tees where turbulent mixing of hot and cold flows occurs; for example Kamaya et al (2011).

Another option is the generation of a material specific design fatigue curve, by performing tests on polished Type 304 stainless steel specimens, with the objective of demonstrating superior fatigue strength compared to the 2010 ASME Section II design fatigue curve. If the fatigue endurance limit is raised, it is more likely that a simplistic NESC-TF Level 2 analysis would predict an acceptable fatigue initiation life.

CONCLUSIONS

1. CFD RANS and LES modelling have proven to be valuable analytical tools to aid the optimisation of an internal thermal sleeve design at a pipe junction to minimise high cycle fatigue damage.
2. Analytical methods were developed to predict FUFs at the thermal sleeve tip using the cyclic loading spectra evaluated by the CFD LES model, consistent with a NESC-TF Level 3 approach. These methods are much less conservative, compared to a simplistic NESC-TF Level 2 fatigue analysis applying in-phase sinusoidal cycling at the most onerous frequency and stress range.

REFERENCES

ASME Boiler and Pressure Vessel Code, Section III, Division 1, Appendices, Mandatory Appendix 1 Design Fatigue Curves (2009).

American Society of Testing and Materials, ASTM Standard E1049, 2001, In “Annual Book of ASTM Standards”, Volume 03.01, pp 739-748.

ANSYS CFX, Release 12.0, ANSYS Inc.

EUR 22763 EN, “Development of European Procedure for Assessment of High Cycle Thermal Fatigue in Light Water Reactors”, Final Report of the NESC-Thermal Fatigue Project, 2007.

Fe-Safe, Version 6.2, Durability Analysis Software for Finite Element Models.

Kamaya M, Utanohara Y, and Nakamura A, “Thermal Fatigue Analysis at a Mixing Tee by a Fluid-Structural Interaction”, ASME 2011 *Pressure Vessels and Piping Conference Proceedings*, PVP2011-57585, Baltimore, Maryland, USA.

NUREG/CR-6909 “Effect of LWR Coolant Environments on the Fatigue Life of Reactor Components”, Final Report, Argonne National Laboratory, 2007.

Roark’s Formulas for Stress and Strain, 7th Edition.

Westin J et al, High Cycle Thermal Fatigue in Mixing Tees. Large Eddy Simulations Compared to a New Validation Experiment, ICONE Proceedings, 11-15 May 2008, Orlando, Florida, USA.

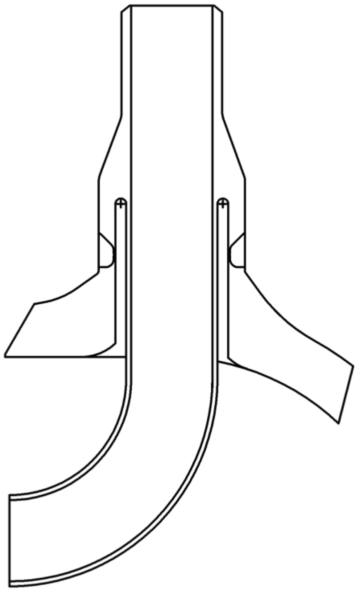

Figure 1 - Thermal sleeve connection at pipe junction

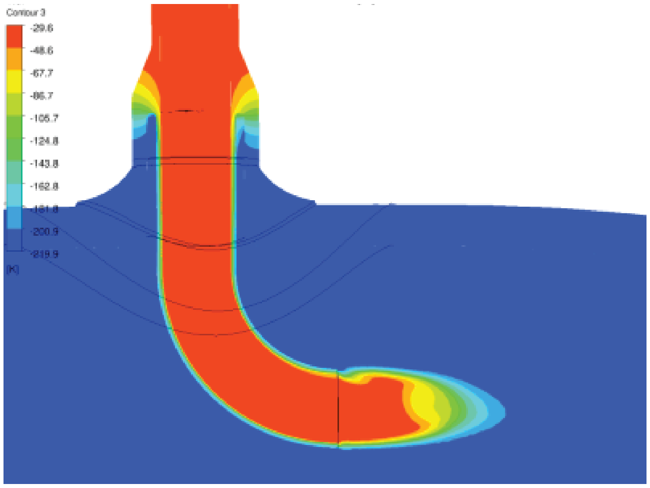

Figure 2 – Maximum ΔT transient – steady state temperatures predicted by CFD RANS model

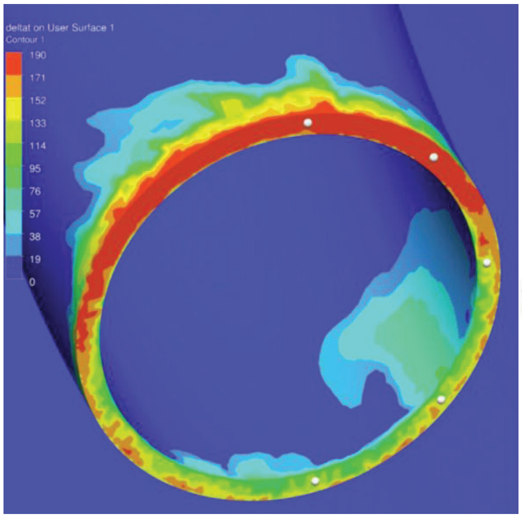

Figure 3 CFD LES model maximum ΔT at sleeve tip for aligned position

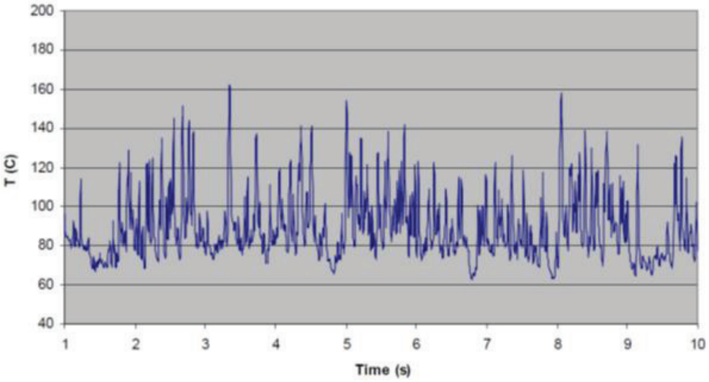

Figure 4 Metal surface node temperature cycles

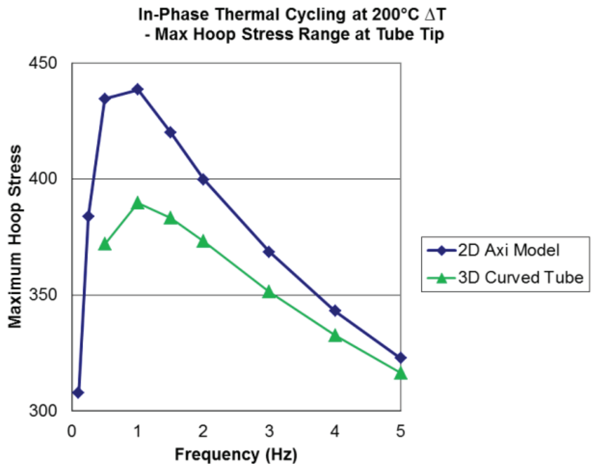

Figure 5 Maximum hoop stress range versus frequency for in-phase cycling

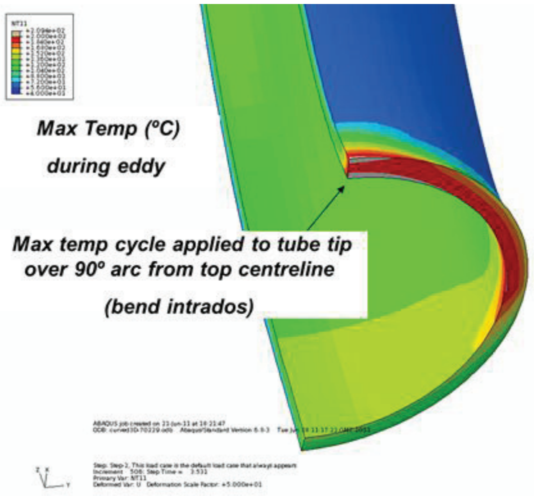

Figure 6 FE model in-phase cycling, max ΔT

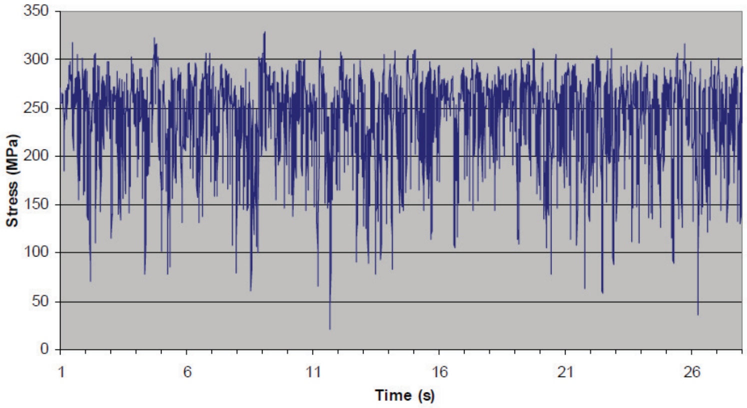

Figure 7 Hoop stress history at node on tube tip (using CFD model temperatures)

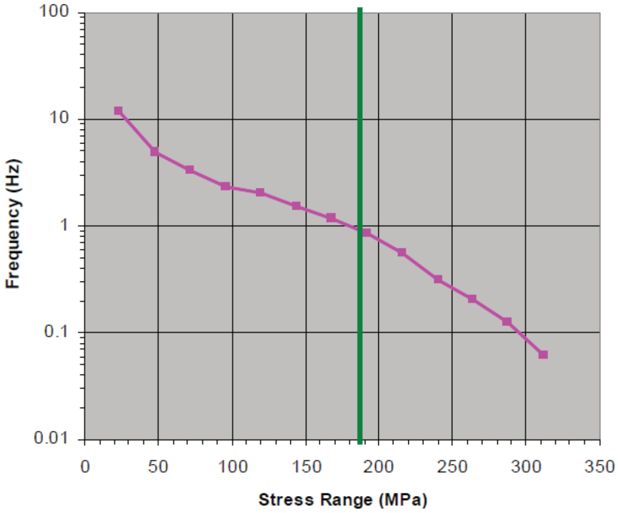

Figure 8 Rainflow analysis, cycle frequencies (mean + 2SD) for 24 MPa stress range bands, where green line is fatigue endurance limit