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Division II

DETERMINATION OF SIGNIFICANT TEMPERATURE FLUCTUATION LIMIT CONSIDERING RATE OF TEMPERATURE CHANGE

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ABSTRACT

In the scope of life extension projects of Nuclear Power Plants, cumulative usage factors (CUF) for main components need to be re-evaluated in order to guarantee safety margins for the extended period of operation. In order to do so, it is of relevance to compare design transient catalogue used to calculate the original CUF values against what really happens during the operation of the plant.

For this purpose, a temperature monitoring system needs to be installed in the plant. Normally, the information gathered with these systems leads to the discovery of transients that may have not been considered during the design stage. Naturally, these transients need to be contemplated as well. Nevertheless, some of these transients might be of no relevance when it comes to fatigue. In this paper, we establish the fatigue relevance of a temperature fluctuation by analysing it´s ΔT and ΔT/dt in order to consider it or not for fatigue calculations.

INTRODUCTION

As part of life extension projects, integral review of transient catalogues for the main systems need to be done. Normally, if fatigue monitoring information is available, the data collected by this system must be considered.

First, transient severity needs to be addressed by comparing postulated transients with registered transients. Secondly, thermal stratification transients need to be included in transient catalogues when they were not considered in the first place. Third, any other registered transient that was not included originally needs to be considered if it is deemed as fatigue relevant.

ASME III rules provides some guidance on when to consider a temperature fluctuation to be fatigue relevant. Nevertheless, these limits are independent of the rate of temperature change. In this paper, we propose a criterion to establish the fatigue relevance of a temperature fluctuation for various geometries and materials.

ASME III INTERPRETATION

For nuclear Class 1, Article NB-3222.4(d)(4) applies while for nuclear Class 2, Article NC-3219.2.2 applies. Both state that in Normal Service, if the temperature difference between any two adjacent points does not change by more than the quantity determined by Eq. 1, then the temperature difference is not significant.

$$\Delta T = \frac{S_a}{2E\propto} \qquad (1)$$

S_a is obtained from the applicable design fatigue curve for 10^6 cycles if the total specified number of service cycles is 10^6 cycles or less; otherwise, S_a is obtained for the maximum number of cycles defined on the curve, E is the elastic modulus and α is the coefficient of thermal expansion of the material.

When defining any two adjacent points, ASME specifies:

- In the axial direction (TDAD): adjacent points are defined as points that are less than the distance $2\sqrt{Rt}$, where R is the radius measured normal to the surface from the axis of rotation to the midwall and t is the thickness of the part at the point under consideration. These differences are caused by discontinuities in material or geometries which are out of the scope of this work.
- In the circumferential direction (TDCD): adjacent points are defined as any two points on the same surface. These differences are caused by thermal stratification which is out of the scope of this work.
- In the radial direction (TDRD): adjacent points are defined as any two points on a line normal to any surface. These differences are caused by bulk fluid temperature changes, which is the purpose of this work.

In order to calculate the TDRD values, apart from a computer code, the analyst needs the following information:

- Initial and final temperature
- $\Delta T/dt$ rate of temperature change
- Heat transfer coefficient
- Geometry and material properties
- Thermal Insulation geometry and material properties

Performing calculations for each geometry and materials can be time consuming. As a consequence, ΔT is usually assumed directly as the total algebraic range of the temperature fluctuation. This approach may lead to excessive conservatism when $\Delta T/dt$ is low, leading to consider a fatigue irrelevant fluctuation as relevant.

PROPOSED APPROACH

In order to account for rate of temperature change, we use the Cumulative Damage article in ASME NB-3653.5. Essentially, the article states that if Alternative Stress (S_{alt}) generated by a particular transient pair is smaller than the endurance limit, then Usage Factor (UF) may be taken as zero. In other words, the transient pair is not fatigue relevant.

In this context, we establish an "infinite life" criterion as a stress limit to be certain that each analyzed temperature fluctuation will not be fatigue relevant if the stress generated by it is lower than the limit. Finally, we calculate ΔT vs. $\Delta T/dt$ limit curves. The procedure to obtain these curves is described below.

Fatigue calculations according to ASME NB-3653

Briefly explained, the methodology to assess the fatigue damage originated by a particular transient pair is based in the calculation of the UF. To obtain the UF, the procedure is the following:

1. NB-3653.1- Calculate Primary + Secondary stress intensity range (S_n)
2. NB-3653.2- Calculate Primary + Secondary + Peak stress intensity range (S_p)
3. NB-3653.3 - Calculate Alternative Stresses ($S_{alt}= S_p/2$)
4. NB-3653.4 - Calculate Allowable number of cycles (N_i)
5. Calculate UF according to NB-3653.5 (n_i/N_i)

Assuming stresses remain below 3Sm limit, Eq. 2 governs the behavior of fatigue since it is the one that describes peak stresses. It is defined as follows.

$$S_P = K_1 C_1 \frac{PD}{2t} + K_2 C_2 \frac{MD}{2I} + K_3 C_3^{\text{`}} E_{ab} |\alpha_a T_a - \alpha_b T_b| + \frac{K_3 E\alpha|\Delta T1|}{2(1-\upsilon)} + \frac{E\alpha|\Delta T2|}{(1-\upsilon)} \qquad (2)$$

Where:

K_1, K_2, K_3: Peak stress indices
C_1, C_2, C_3: Secondary stress indices
P: Pressure [MPa]
D: External diameter [mm], t: Thickness [mm], I: Moment of inertia [mm^4]
M: Moment [Nmm]
E_{ab}: average elastic Modulus [MPa]
α: coefficient of thermal expansion [1/ºC]
ν: Poisson ratio
ΔT1: linear temperature variation through the thickness [ºC]
ΔT2: non-linear temperature variation through the thickness [/ºC]
Sm: allowable stress [MPa]

Analyzing term by term, we can see that the first term expresses the range of peak stress intensity due to pressure range. Following, the second term expresses the range of peak stress intensity due to moment range. Next, the third term expresses the range of peak stress intensity due to gross structural discontinuity. Finally, the fourth and the fifth term express the range of peak stress intensity due to the range of $|\Delta T1|$ and $|\Delta T2|$ respectively generated by the analyzed transient pair.

On the one hand, terms 1, 2 and 3 are independent of the ΔT/dt and they are directly related with the extreme states of the analyzed transient pair. On the other hand, terms 4 and 5 are directly related to ΔT/dt, since faster fluctuations will induce higher values of $|\Delta T1|$ and $|\Delta T2|$.

Thermal transient simulations

With the purpose of determining the peak (S_p) and alternative (S_{alt}) stresses generated by different types of temperature fluctuations regarding ΔT and ΔT/dt, a thermal analysis using finite elements was performed.

For each location, a wide range of ΔT and ΔT/dt was considered. Other parameters that influence the results are geometrical parameters such as thickness and material properties.

For the purpose of this work, the following locations are shown:

Table 1: Geometries and materials of locations considered.

Measuring Section	Material	Thickness [mm]
1	Carbon Steel	22.5
2	Stainless Steel	14.0
3	Stainless Steel	7.0
4	Carbon Steel	8.8

An example of the results obtained from the finite element models are shown in Figures 1 and 2 for Measuring Section 2 case when applying ΔT=80ºC and a ΔT/dt of 0.8ºC/sec and 8.0ºC/sec respectively.

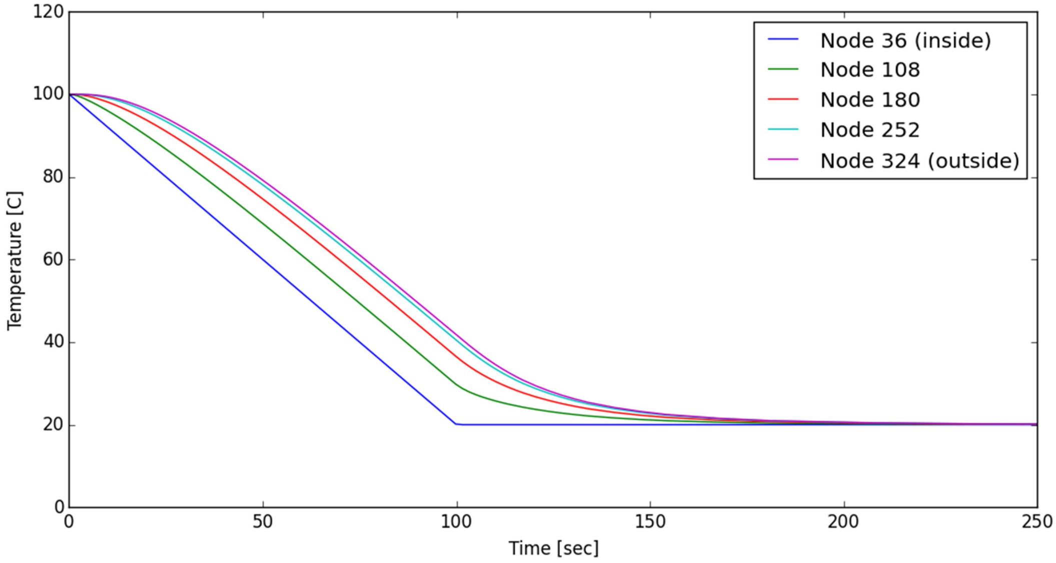

Figure 1. Temperature evolution in Measuring Section 2 for ΔT=80ºC and ΔT/dt=0.8ºC/sec

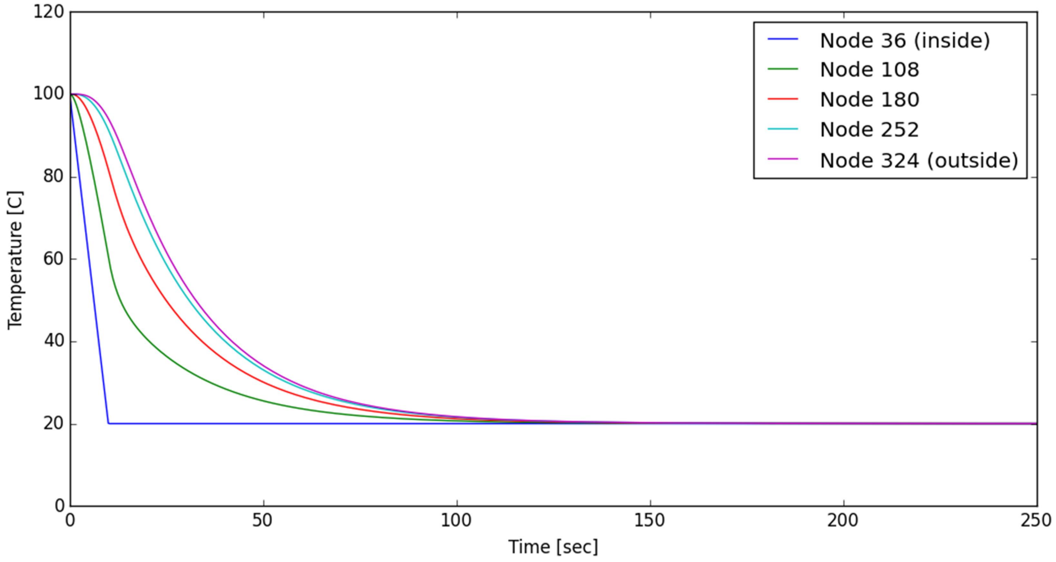

Figure 2. Temperature evolution in Measuring Section 2 for ΔT=80ºC and ΔT/dt=8.0ºC/sec

Thermal gradient linearization and stress calculation

Following the process, the temperature distribution along the thickness as a function of time calculated in the previous step is to be decomposed into $|\Delta T1|$ and $|\Delta T2|$ according to article NB-3653.2 (b). $|\Delta T1|$ and $|\Delta T2|$ as a function of time obtained from the previous example are shown in Figures 3 and 4 as an example.

Using these values and material properties, the peak stresses were calculated according to terms 4 and 5 of Eq. 2, which are summed up in Eq. 3 below.

$$S_p = \frac{K_3 E\alpha|\Delta T1|}{2(1-\upsilon)} + \frac{E\alpha|\Delta T2|}{(1-\upsilon)} \qquad (3)$$

The peak stresses as a function of time are also shown in Figures 3 and 4.

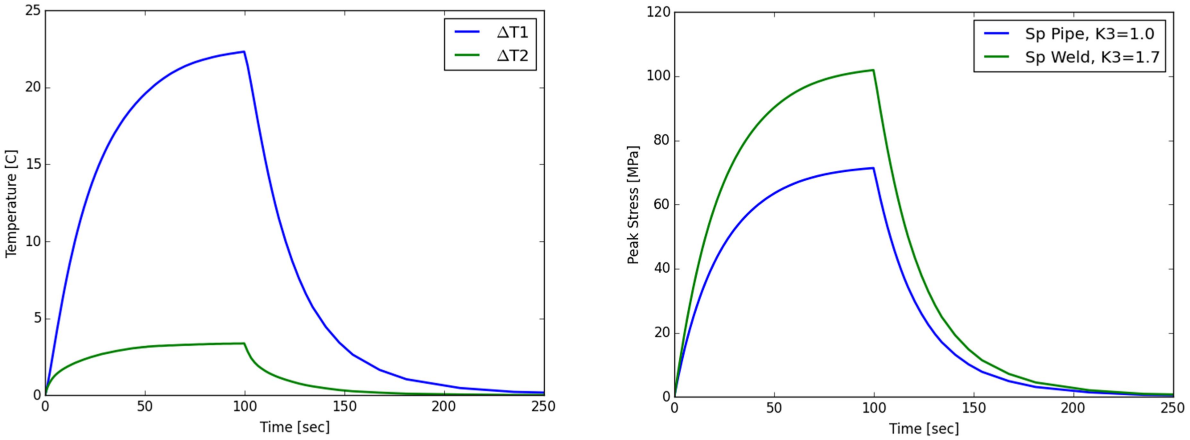

Figure 3. $|\Delta T1|$ and $|\Delta T2|$ and S_p evolution in Measuring Section 2 for ΔT=80ºC and ΔT/dt=0.8ºC/sec

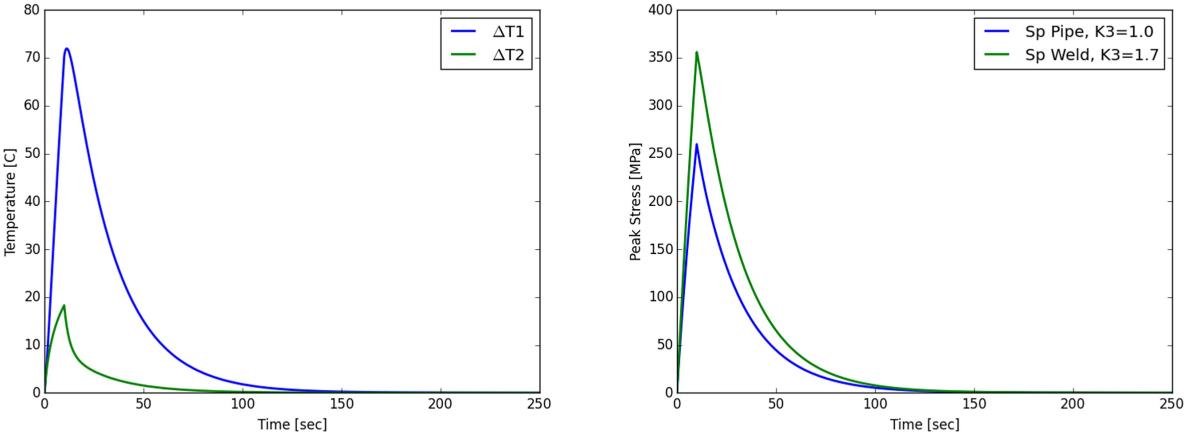

Figure 4. $|\Delta T1|$ and $|\Delta T2|$ and $S_p$evolution in Measuring Section 2 for ΔT=80ºC and ΔT/dt=8.0ºC/sec

Finally, the range of S_p was reduced to 50% according to NB-3653.3 to obtain alternative stresses (S_{alt}).

Limit criterion

As stated before, in the context of a fatigue analysis, a temperature fluctuation will not be relevant if the stress generated by it is lower than the endurance limit.

Moreover, given that in this analysis only terms 4 and 5 of Eq.2 are considered, to be conservative we established 25% of the endurance limit as the limit, which corresponds also to the limit used in NB-3222.4(d)(4).

Obtaining the limit curve

Once all the combinations of ΔT and ΔT/dt were run, alternative stress range was obtained for every combination, as shown in Figure 5. For every ΔT, a curve of alternative stress range as a function of R= ΔT/dt was fitted by adjusting parameters α, β and γ of Eq. 4.

$$S_{alt} = \propto + \beta(1 + e^{-\gamma}\ ) \qquad (4)$$

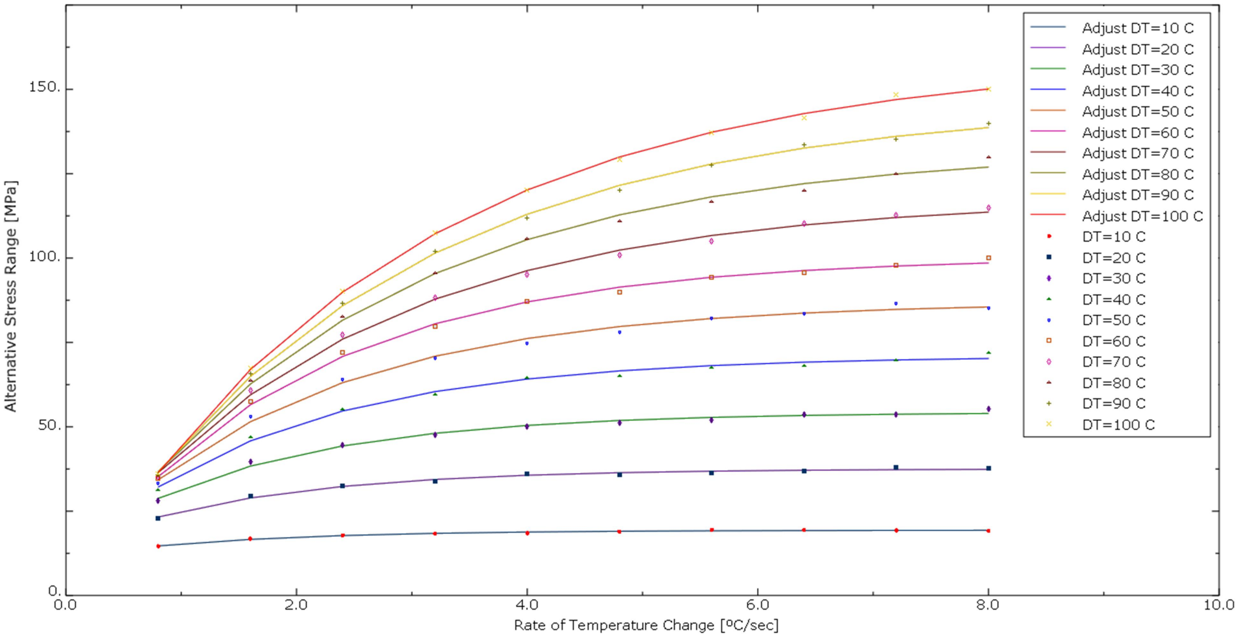

Figure 5. Alternative Stress Range as a function of ΔT and ΔT/dt in Measuring Section 2.

Finally, obtaining the value of R, for which S_{alt} is equal to the imposed limit, gave pairs of ΔT and R where the fatigue relevance is reached.

BURGREEN APPROACH

Another approach to obtain similar limits is to use the one dimensional stress model developed by Burgreen (1971). This model provides the stress due to a temperature ramp applied on the surface when provided with material, geometric and ramp parameters using Figure 6.

The limitation of this approach is that it is not possible to account for the presence of a weld for example. In the proposed approach, this is possible through K_3.

RESULTS

The obtained limit curves for all the Measuring Sections mentioned in Table 1 are shown in Figure 7 for carbon steel sections and in Figure 8 for stainless steel sections. Every combination of ΔT and ΔT/dt that falls below the curves is deemed to be a non-fatigue relevant temperature fluctuation.

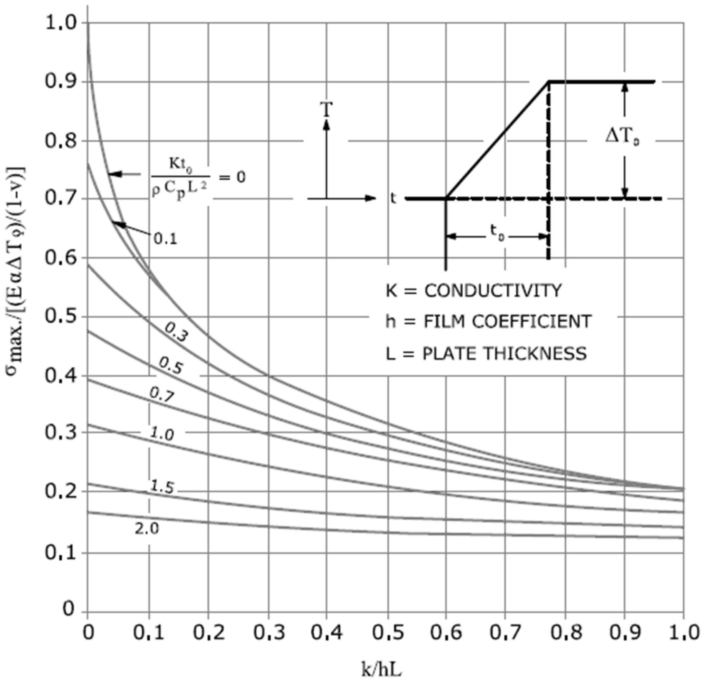

Figure 6. Stress due to ramp using Burgreen Method

The difference in behavior for carbon steel and stainless steel is mainly explained in the thermal conductivity. This parameter is roughly 2.5 times higher for carbon steels. Consequently, when the same geometry is subjected to the same transient, the developed thermal gradients and stresses will be higher in stainless steel pipes. As a result, for similar geometries, stainless steel is more sensitive to temperature fluctuations.

If we analyze the case of stainless or carbon steel separately, we see that if the same material is subjected to the same transient, the developed thermal gradients and stresses will be higher in thicker pipes. As a result, thicker pipes are more sensitive to temperature fluctuations.

Finally, in Figures 7 and 8, we also plotted the limit from Article NB-3222.4(d)(4) interpretation. The results show that considering this limit for temperature fluctuation without taking into account rate of temperature change may yield very conservative results for slow transients when assuming a location away from welds.

APPLICATION TO REAL CASECASE

As stated before, the personnel reviewing fatigue monitoring history needs to distinguish fatigue relevant fluctuations from non-relevant fluctuations in places of interest. For this purpose, the proposed criteria can be applied. In order to apply these criteria, it is of great importance to obtain the temperature fluctuations at the inner part of the pipes by means of inverse heat transfer methodology. This is important since ΔT/dt measured outside could vary significantly with respect to ΔT/dt inside, especially for thick pipes.

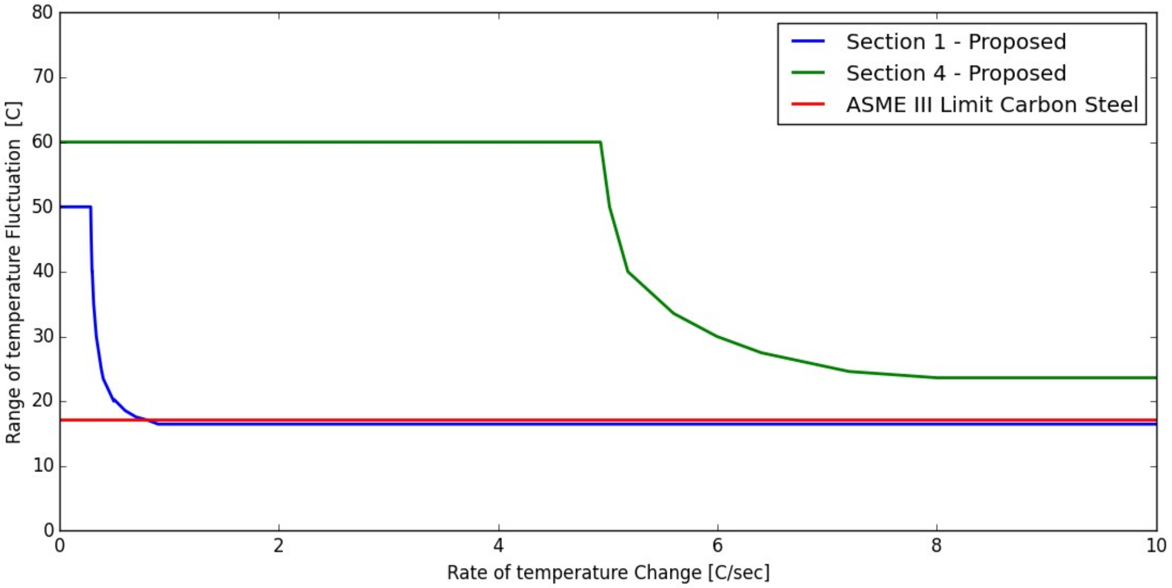

Figure 7. Limit curves for Carbon Steel Sections 1 and 4

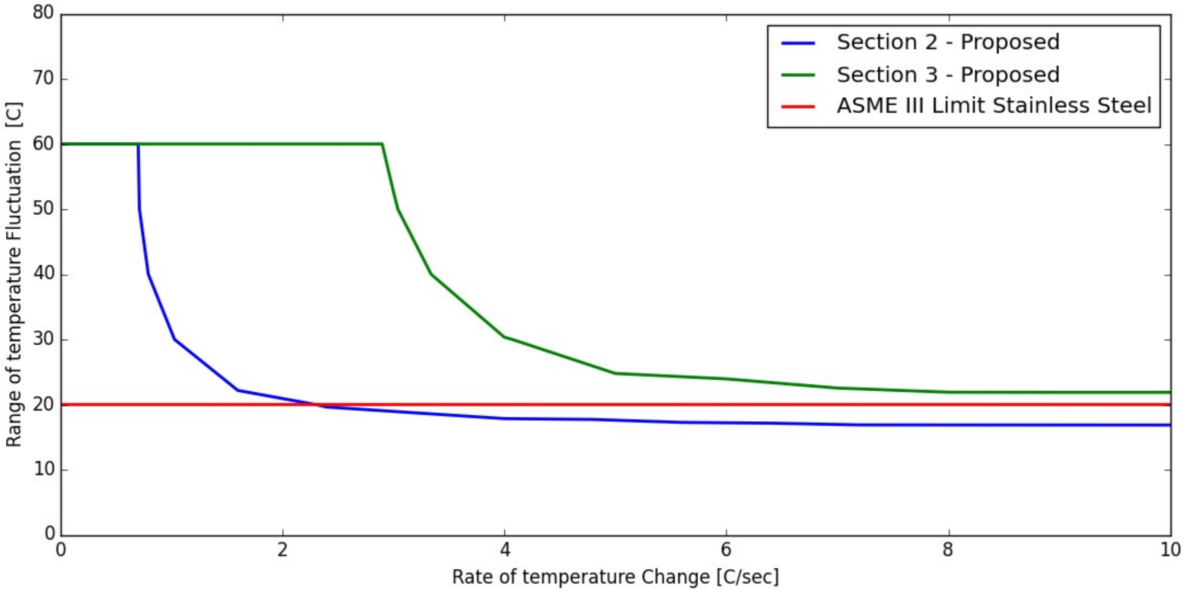

Figure 8. Limit curves for Stainless Steel Sections 2 and 3

Once inner temperature time history is available, the methodology can be applied directly by identifying ΔT and ΔT/dt for each fluctuation. As an example, we show every ΔT and ΔT/dt in Measuring Section 1 for two events of Shut Down and Start Up plotted against the corresponding limits in Figure 9.

Numerous temperature fluctuations are recorded during both events. Most of them are directly considered not to be fatigue relevant by applying ASME III limit. Nevertheless, for event #1 using ASME III limit yields 53 fatigue relevant fluctuations while using the proposed limit reduces this value to 35. Accordingly, for event #2 using ASME III limit yields 55 fatigue relevant fluctuations while using the proposed limit reduces this value to 39. This means a reduction of 32% in the considered temperature fluctuations for Measuring Section 1.

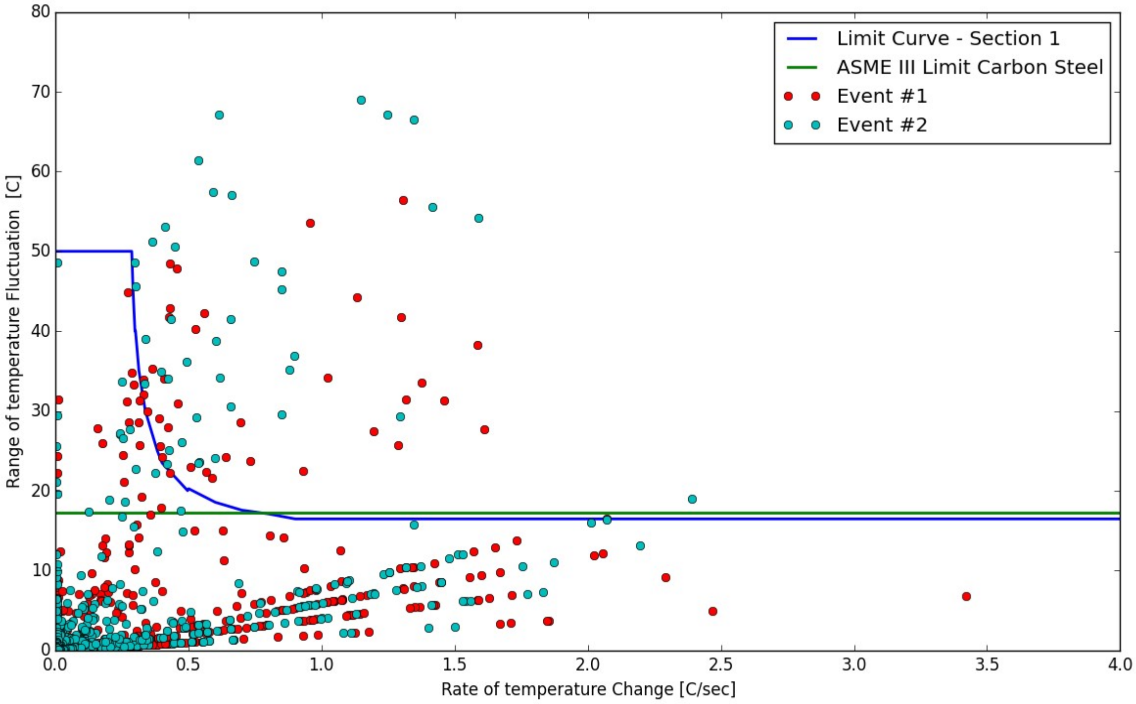

Figure 9. Recorded ΔT and ΔT/dt at Measuring Section 1

CONCLUSION

ΔT vs ΔT/dt limit curves were obtained for four Measuring Sections of different geometries and materials. The proposed approach gives an alternative to Article NB-3222.4(d)(4) interpretation. This approach provides a proper solution on when to consider or not to consider a temperature fluctuation for CUF reevaluation in nuclear power plants life extension.

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