Parametric Study of Localized Effects on Piping due to Thermal Stratification

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ABSTRACT

Recently, several instances of unexpected thermal movements have been observed that are attributable to thermal stratification. Thermal stratification introduces both additional global bending effects as well as thermal transient loading that result in stresses and fatigue that were not typically considered in the original design. Since the upper portion of the piping is in contact with relatively hotter fluid than the lower portion, the temperature difference induces global bowing of the line. In addition, thermal stratification results in two types of thermal transient loads: (1) thermal shock due to rapid insurges or outsurges of the hot/cold fluid, and (2) thermal striping due to the fluctuation of the interface layer between the hot and cold fluids.

This study documents specific methodology and results from two dimensional finite element heat transfer analysis using ANSYS that quantify the localized effects on piping due to thermal stratification as well as an example of how to incorporate both the global and local effects into ASME B&PV Code compliance evaluations.

BACKGROUND

The USNRC has in its bulletins 79-13, 88-08 and 88-11 [1,2,3] documented several cases where thermal stratification is known to have occurred. The conditions under which thermal stratification has been identified involve cases where low flow conditions exist between systems at different temperatures. Due to the low flow conditions, it is possible for the fluid flowing along the top of the pipe to be at significantly higher temperatures than the bottom of the pipe.

Several specific cases where stratification has been demonstrated to occur follow:

- Block valve leakage existed between the higher pressure Emergency Core Cooling System (ECCS) and the Reactor Coolant System (RCS). Due to the low flow conditions from the leakage, the temperature of the water entering through the ECCS was significantly lower than the RCS temperature and resulted in measured thermal stratification and thermal fatigue induced through-wall cracks in the ECCS piping at two plants.
- Similar to the above case, outsurges from the RCS through the Residual Heat Removal (RHR) system, due to cyclic leakage through the isolation valve packing gland, resulted in thermal fatigue and through-wall cracks in the RHR piping.
- Stratification has also been observed to occur in the Pressurizer Surge line in many PWRs. Since there is by design no isolation between the Pressurizer and the RCS, low flow conditions due to pressurizer spray operations or RCS charging can cause either insurges or outsurges through the surge line.

In each of the above cases, the thermal stratification induces global bowing of the line as well as local stresses due to thermal shock and thermal striping.

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LOADING DEFINITION

It is the intent of this study to demonstrate methodology for determining localized stress levels due to shock and striping. A nominal 10 inch schedule 140 pipe cross-section typical of a pressurizer surge line was chosen for the study. A typical configuration for a pressurizer surge line is shown in Figure 1.

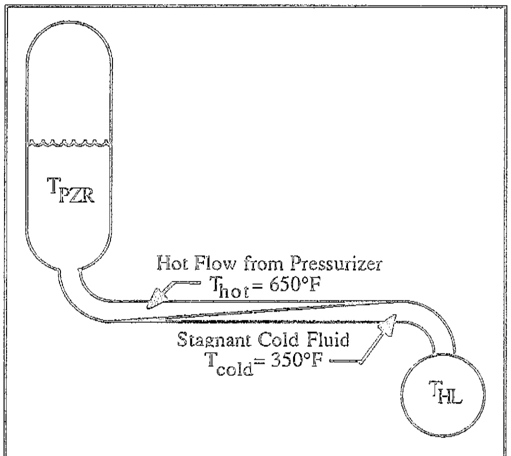

Figure 1: Pressurizer Surge Line

As indicated above, thermal stratification results in both global bending effects as well as localized effects due to thermal shock and striping. Each of these conditions is described in more detail below.

The global bending effect can be most easily compared to the heating of a bimetallic strip. When stratification occurs, the fluid in the upper portion of the pipe is at a higher temperature than the lower portion; and as a result, the upper portion undergoes compressive stress while the lower portion is in tension. The induced thermal movement, predominantly in the vertical direction, results in a global bending stress.

Thermal shock effects are due to the rapid change of temperature of the inside surface of the pipe. For example, in the case of of an outsurge of hot water along the top portion of a cooler pipe, the inside surface temperature of the pipe material can be significantly higher than the outside surface temperature. This results in localized stress in the pipe. In addition, a sharp transition in temperature of the fluid can exist at the hot/cold fluid interface; this also creates localized stresses since the portion of the piping above the interface level will tend to expand more than the bottom cooler area.

Thermal striping also causes similar localized effects. Striping is the term for the phenomena where the interface layer height between the hot and cold fluids rapidly fluctuates up and down. The stress effects are similar to those described above for the insurge or outsurge of fluid, but are further localized to the inside surface with no through-wall effects. This study demonstrates methodology to quantify the local stress effects, and by example shows how those results should be incorporated into an ASME B&PV Code [4] compliance evaluation. Methodology for the evaluation of the global bending effects have been addressed by others elsewhere [5].

LOCAL STRESS EVALUATION

In order to determine the local stress levels in the pipe, ANSYS [6] two dimensional finite element heat transfer analyses were performed. The basic model used for the heat transfer analysis is shown in Figure 2. The model discretization is such that more refinement is provided for the inside elements and also in the vicinity of where the stratification level is to be postulated for each run.

The intent of each of the analyses is to determine the temperature profile across the pipe wall in order to determine the ΔT_1 and ΔT_2 terms for later evaluation of the section in accordance with ASME Section III, NB-3600. Once the temperature distribution is known, the average, linear and non-linear components of the temperature can be determined.

Both stagnant and transient conditions were investigated. For the stagnant condition, several different stratification profiles were investigated; first with the top half of the pipe hot, second with only the top quarter of the pipe hot, and last with a linear gradient of temperature from the bottom to the top of the pipe section (see Figure 3).

In addition to the profile parameters that were investigated for the stagnant condition, the flow rate and duration of the transient were also investigated. Out-surge rates of the hot fluid were considered at 0, 10 and 20 gallons per minute, with the durations of 60 and 300 seconds. These flow rates and surge durations are typical for the surge line during pressurizer spray operation.

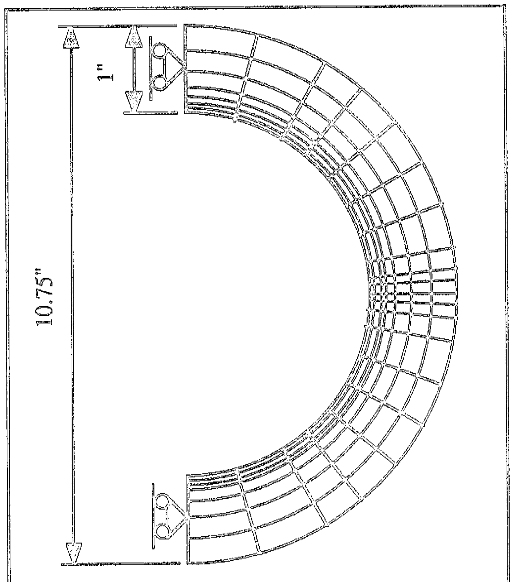

Figure 2: ANSYS Model

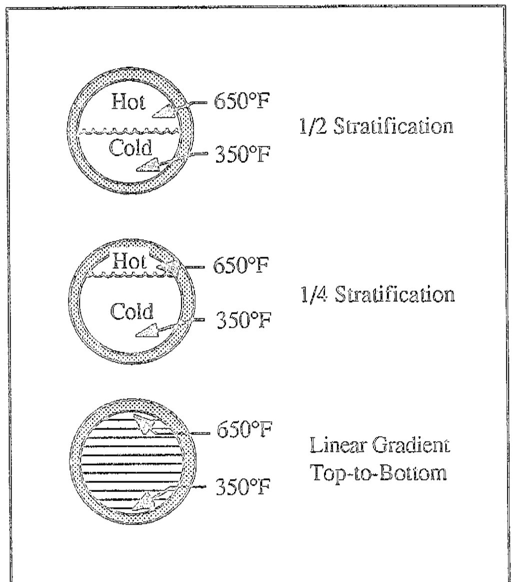

Figure 3: Stratification Profiles

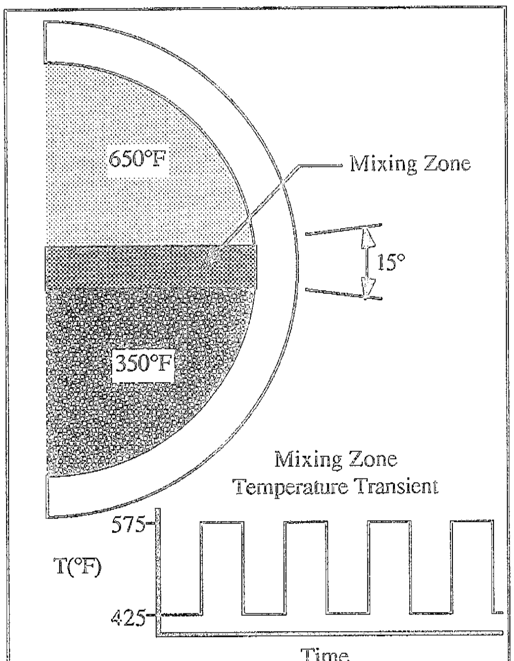

Figure 4: Striping Load Definition

Table 1: Load Case Summary

	(°F)		(GPM)		(SEC)
Strat Profile	T_{hot}	T_{cold}	Q_{hot}	Q_{cold}	Dur.
1/2 Strat.	650	350	0	0	-
1/2 Strat.	650	350	10	0	60
1/2 Strat.	650	350	10	0	300
1/2 Strat.	650	350	50	0	60
1/2 Strat.	650	350	50	0	300
1/2 Strat.	650	350	0	0	-
1/2 Strat.	650	350	0	0	-

A summary of those case considered are shown in Table 1.

The striping case was modeled assuming a mixing zone equal to approximately 15 degrees of the pipe wall at the midpoint of the pipe section. The temperature in the mixing zone was assumed to oscillate through half the temperature range of the section. The period of the oscillation was varied from 1 second to 4 seconds; actual tests have indicated periods in the range of 0.1-10 seconds [5]. The loading model is shown graphically in Figure 4.

The ANSYS analyses determined the temperature distributions through the pipe wall for each of the load cases considered. Once the through-wall temperature distributions were determined, it was possible to calculate the ASME code average (T_a or T_b), linear (ΔT_1), and nonlinear (ΔT_2) temperature components. The code defined transient stresses were then calculated directly using code equations.

As could be expected, the stagnant case results were not as significant as the outsurge transient cases analyzed. For the transient cases, it was found that the magnitude of both the ΔT_1 and ΔT_2 stresses had peaked before 60 seconds. As can be seen from in Figures 5 and 6, the ΔT_2 stress peaks out well before the ΔT_1 stress. The magnitude of the T_a-T_b stress is negligible in this case since no structural discontinuity is considered.

In addition to the magnitude of the localized stresses, it is also of interest to see the stress level relative to the circumferential location. As can be seen in Figure 7, the ΔT_1 and ΔT_2 stresses for an outsurge thermal shock are roughly constant for the upper portion of the cross section. But for the striping case, one can see from Figure 8 that the stresses are very isolated to the immediate vicinity of the mixing zone where the striping occurs. The cases for an outsurge rate of 10 gpm and for the 1 hz. striping case are similar to the above but with a lesser magnitude of stress.

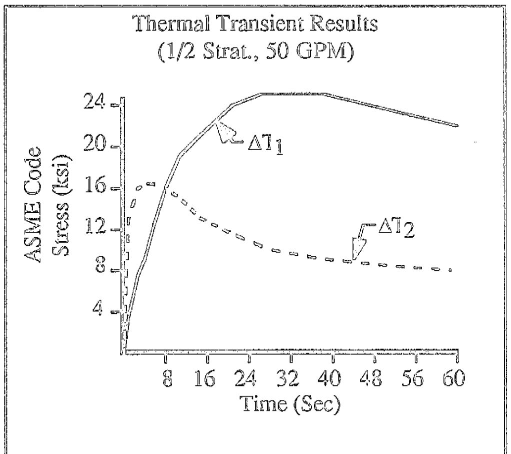

Figure 5: Outsurge Local Stresses

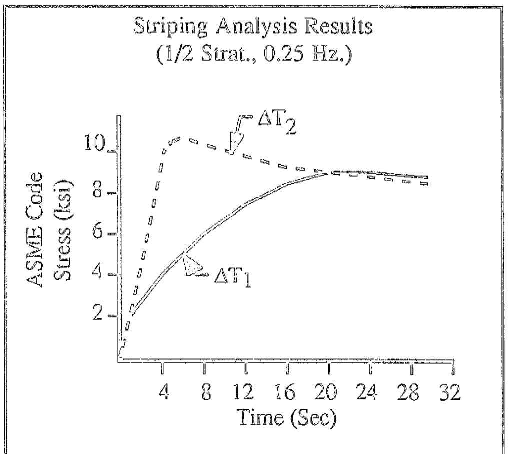

Figure 6: Striping Local Stresses

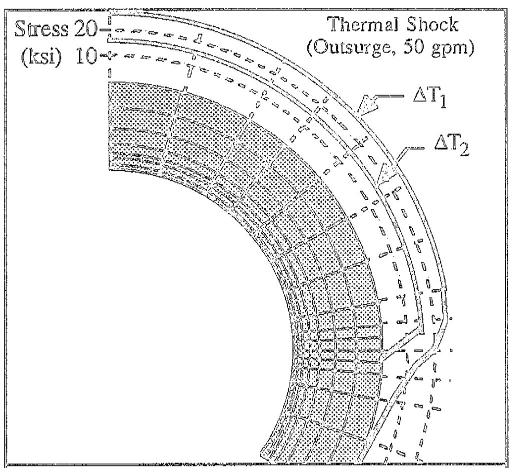

Figure 7: Outsurge Stress Distribution

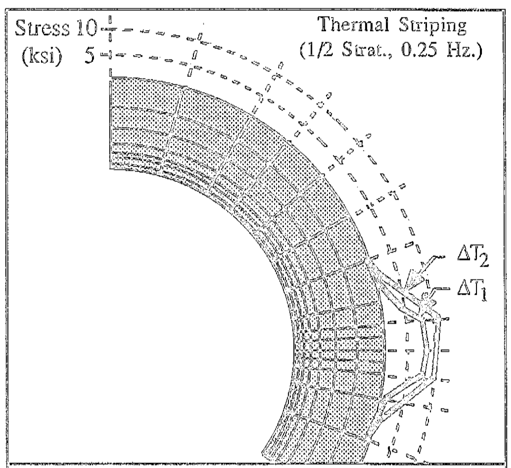

Figure 8: Striping Stress Distribution

CODE COMPLIANCE EXAMPLE

As an example, the surge line configuration described above will be used to demonstrate a compliance check in accordance with ASME B&PV Code Section III, Subsection NB-3600.

Since it is impractical to demonstrate the complete code compliance within the context of this paper, only the stress and fatigue for a typical heatup - cooldown cycle will be evaluated for stress and fatigue. The methodology for the evaluation of the remaining design basis events is the same. For the purpose of this example, only those equations effected by thermal stratification will be addressed.

Only maximum ΔT_1 and ΔT_2 transient stresses stresses from the thermal shock case will be considered for this evaluation; it is unlikely that the transient stresses due to shock and those due to striping will achieve maximum levels simultaneously. Typical bending stresses due to primary loading as well as thermal stratification as indicated in Table 2 will be considered for this evaluation. The component considered for this evaluation is a 10 inch schedule 140 elbow. The magnitude of the (T_a-T_b) stresses is negligible in this case. The code properties for this component are shown in Table 3.

Table 2: Component Stresses

Load Case	Nominal Stress (psi)	Comments
Internal Press.	10,750	$P_o = 2000$ psi
Dead Weight	3,500	
Oper.Basis EQ	3,000	
Therm. Expan.	19,500	w/ thermal strat
$T_a - T_b$	Negl.	
ΔT_1	24,700	$\Delta T_1 = 132°F$
ΔT_2	16,400	$\Delta T_2 = 43°F$

Table 3: Component Properties

Component:	10 in. Sch 140 L.R. Elbow		
Material:	SA-376 TP304		
S_m :	18,100 psi (average S_m for cycle)		
S_y :	19,400 psi (average S_y for cycle)		
Stress Indices:	$C_1 = 1.24$	$C_2 = 2.65$	$C_3 = 1.0$
	$C_4 = 1.3$	$K_1 = 1.0$	$K_2 = 1.0$
	$K_3 = 1.0$		

The first condition to be satisfied for thermal stratification loading is Code equation 10:

(EQ 10) $$S_n = C_1\frac{P_oD_o}{2t} + C_2\frac{D_o}{2I}M_i + C_3E_{ab}\left|\alpha_aT_a-\alpha_bT_b\right| \leq 3S_m$$

$$S_n = (1.24)(10.8) + (2.65)(3.0 + 19.5) = 73.0 \text{ ksi} > 3S_m = 54.3 \text{ ksi}$$

Since equation 10 fails, it may be possible to qualify the stresses using equations 12 and the stress ratchet check for a simplified elastic-plastic discontinuity analysis. There is no impact on equation 13.

(EQ 12) $$S_e = C_2\frac{D_o}{2I}M^*_i \leq 3S_m$$

$$S_e = (2.65)(19.5) = 51.7 \text{ ksi} \leq 3S_m = 54.3 \text{ ksi}$$

The thermal stress ratchet check:

$$\Delta T_1 \leq \frac{y'S_y}{0.7E\alpha}C_4$$

$$\Delta T_1 = 132°F \leq \frac{(1.8)(19,400)}{0.7(265)}(1.3) = 245°F$$

In order to determine the effect of this particular cycle on the cumulative damage, the alternating stress intensity must be calculated.

(EQ 11) $$S_p = K_1 C_1 \frac{P_o D_o}{2t} + K_2 C_2 \frac{D_o}{2I} M_i + \frac{1}{2(1-\nu)} K_3 E\alpha \left|\Delta T_1\right| + K_3 C_3 E_{ab} \left|\alpha_a T_a - \alpha_b T_b\right| + \frac{1}{(1-\nu)} E\alpha \left|\Delta T_2\right|$$

$$S_p = (1.0)(1.24)(10.8) + (1.0)(2.65)(3.0 + 19.5) + (24.7) + (16.4) = 114.1 \text{ ksi}$$

(EQ 14) $$S_{alt} = K_e S_p / 2$$

$$S_{alt} = (2.15)(114.1)/2 = 122.7 \text{ ksi}$$

Based on the calculated S_{alt} and using the ASME Code design fatigue curves, one can determine the allowable number of cycles for this event. For an S_{alt} = 123 ksi, the allowable number of cycles N_i = 900. Using 500 heatup - cooldown cycles for a 40 year life, the usage is calculated:

$$\text{Usage}_i = \frac{n_i}{N_i} = \frac{500}{900} = 0.56$$

The alternating stress and fatigue damage for each design basis cycle must also be calculated and combined with the above to demonstrate that the design basis cumulative usage is less than 1.0.

CONCLUSIONS

The localized effects due to thermal stratification have been calculated for a range of stratification profiles, flow conditions, as well as striping fluctuation frequencies. The localized effects due to the thermal shock were the most significant. Transient stresses calculated for striping was demonstrated to be very local to the mixing zone.

Much additional research is needed to quantify typical stratification profiles, limiting flow rates where stratification can occur, the range of pipe sizes, and the conditions under which thermal striping can reasonably be expected to occur.

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