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# Analysis of Socket Welded Assembly Gap

*Technical Assessment*

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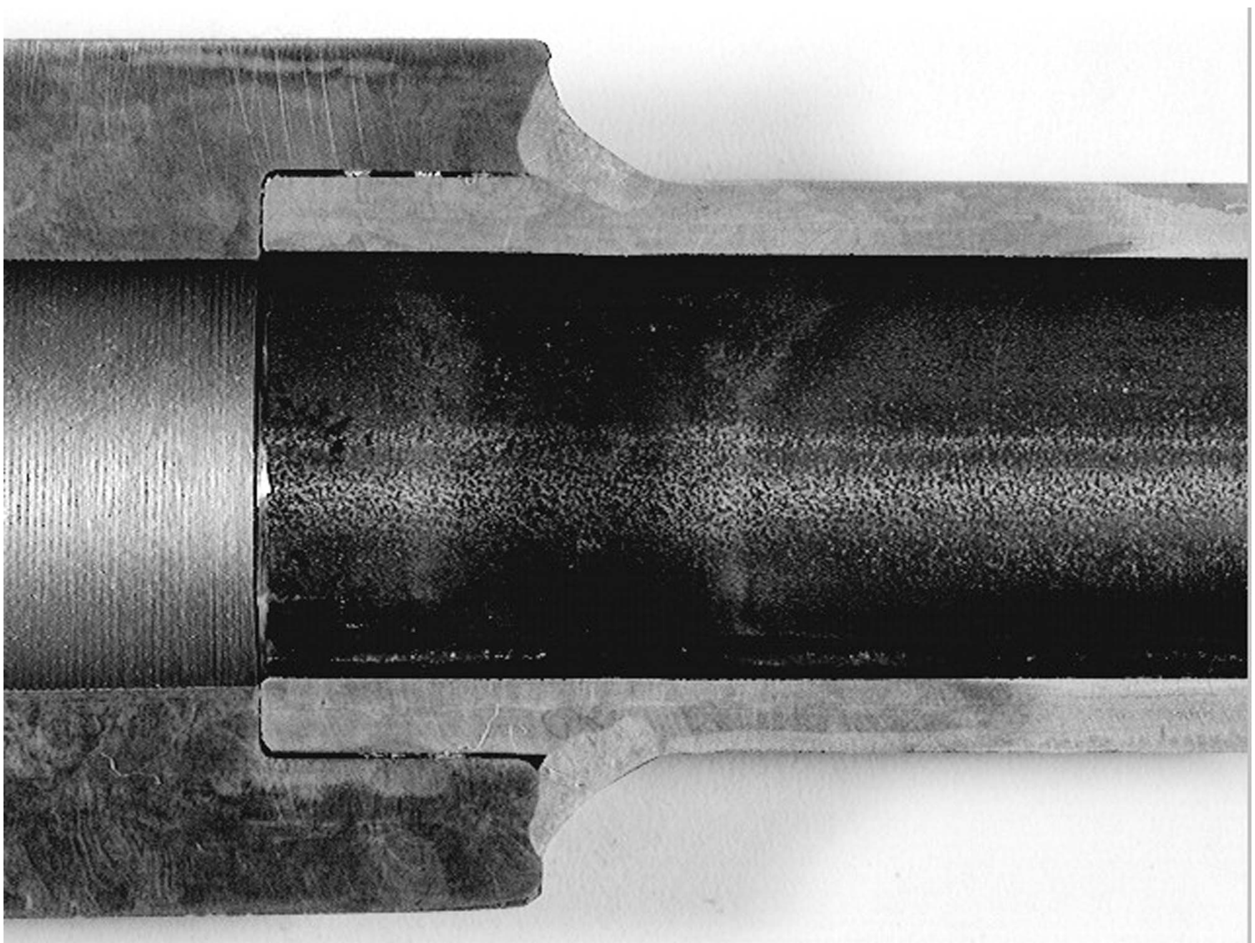

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# ABSTRACT

Socket welded joints have been identified as the most frequent source of through wall leakage in nuclear power plant piping systems. The most common cause of cracking is high cycle fatigue due to vibration. One of the requirements of the fabrication section of the ASME Section III [1] and ASME B31.1 [2] Codes is that when assembling the socket joint, a gap of 1/16 in. must be provided between the inserted pipe and the bottom of the socket. Demonstrating that a 1/16 in. gap is present after welding is difficult and can often be a source for QC rejection of the weld. High cycle fatigue testing sponsored by EPRI RRAC [3] included testing socket welded joints assembled without these gaps. The result of the testing was that whether the gaps were present or not had no conclusive effect on the fatigue life of the joint. This result has led utilities to question the necessity for the gap, and whether a basis can be put together to justify eliminating the Code requirement.

This report describes analyses performed to assess the significance of the differential thermal expansion between the pipe and the fitting during heatup transients. Excessive interference at the bottom of the socket can induce a high shear stress on the socket weld, and depending on the magnitude and duration of the interference and the frequency of the transients, can reduce the fatigue life of the joint. An objective of this analysis was to determine threshold values of temperature change and transient ramp rate below which the gap requirement could be relaxed.

From the reported evaluations, as long as some small, non-zero gap is provided for piping subject to increasing temperature thermal transients, there will be no impact of differential thermal expansion between the pipe and the fitting upon the fatigue life of the socket weld. This gap can be as small as .004 in. for piping subject to severe thermal transients, .001 in. for piping subject to moderate transients such as reactor trips, and can be essentially zero for piping subject to only normal heatup transients. For all practical purposes, such gaps will be present unless the fabricator has intentionally held the pipe tightly in the bottom of the socket while welding. Clearly, the gap does not have to be anywhere near as large as the Code specified 1/16 in.

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# 1
# INTRODUCTION

Socket welded joints have been identified as the most frequent source of through wall leakage in nuclear power plant piping systems. The most common cause of cracking is high cycle fatigue due to vibration. One of the requirements of the fabrication section of the ASME Section III [1] and ASME B31.1 [2] Codes is that when assembling the socket joint, a gap of 1/16 in. must be provided between the inserted pipe and the bottom of the socket. Demonstrating that a 1/16 in. gap is present after welding is difficult and can often be a source for QC rejection of the weld. High cycle fatigue testing sponsored by EPRI Repair and Replacement Application Center (RRAC) [3] included testing socket welded joints assembled without these gaps. The result of the testing was that whether the gaps were present or not had no conclusive effect on the fatigue life of the joint. This result has led utilities to question the necessity for the gap, and whether a basis can be put together to justify eliminating the Code requirement.

After conferring with the chairmen of the ASME B31.1 Power Piping committee [4] and the Section III Materials, Fabrication, and Examination committee as to the reasons for the Code requirement for the axial gap, there appears to be two concerns: the potential for shrinkage of the weld and fitting base metal surrounding the weld as the weld cools, drawing the pipe into the fitting; and differential thermal expansion between the pipe and the fitting during a rapid heatup transient, causing the pipe to expand axially into the fitting, putting a large stress on the weld.

The previous testing has demonstrated that the weld shrinkage issue has not had any demonstrable effect on the fatigue life of the joint. The weld is done in multiple passes (generally three) and the heat input to the joint per pass is controlled at a low temperature (the maximum interpass temperature between weld passes is 350°F [5]) to prevent sensitization and assure ferrite content. The shrinkage produced is both radial and axial. These shrinkages pull toward the socket weld, thereby potentially increasing the gap at the base of the fitting. As the pipe is thinner than the fitting, the run pipe becomes hotter over a greater area than the fitting and therefore should shrink further upon cooling, for each pass.

The second issue, stresses in the weld due to differential thermal expansion between the pipe and the fitting when the pipe experiences rapid heatup thermal transients, has not been evaluated in any testing program. When there is a rapid increase in the fluid temperature, the inserted pipe between the weld and the bottom of the socket will expand faster than the fitting (flange, half-coupling, elbow). If there is no gap, this will put an additional stress on the weld, which must also accommodate uniform thermal expansion moments, and mechanical loads such as pressure, deadweight, and vibration. The high cycle fatigue tests run on socket welded joints without gaps did not address this potential cause of failure, as the tests were run without applying temperature gradients to the inside of the pipe.

This evaluation describes analyses performed to assess the significance of the differential thermal expansion between the pipe and the fitting during heatup transients. Excessive interference at the bottom of the socket can induce a high shear stress on the socket weld, and depending on the magnitude and duration of the interference and the frequency of the transients, can reduce the fatigue life of the joint. An objective of this analysis is to determine threshold values of temperature change and transient ramp rate below which the gap requirement could be relaxed.

# 2 METHODOLOGY

Of the socket welded joints, a socket welded flange was chosen for the analysis, as it is bounding due to the deeper depth of engagement of the pipe in the socket, and consequently the differential expansion is likely to be larger. A 2-inch NPS Schedule 80 pipe was selected as a typical socket welded pipe. The socket welded flange with the corresponding pressure rating, 1500 lb., was selected, with dimensions obtained from the ANSI standard B16.5 [6]. Figure 1 gives the details of the geometry. The nominal ID of the pipe is 1.939 inches and the OD is 2.375 inches. The nominal pipe thickness is 0.218 inch. Per the ANSI Standard, there is also a small radial gap between the pipe and the fitting. This gap was conservatively considered in the analysis, as it reduces the heat transfer between the pipe and the fitting. The leg length of the weld is considered to be the Code requirement of 1.09 times the pipe nominal wall thickness [1]. The piping material was considered to be stainless steel, due to its larger thermal expansion coefficient than carbon steel.

The analyses were done using the ANSYS finite element program [7]. The model used 2D axisymmetric thermal elements (PLANE55), which were appropriately converted to structural elements for computing thermal stresses in a separate ANSYS run. 3D modeling was not necessary since no non-symmetric forces were considered.

Thermal transients were applied at the ID surface of the pipe and the temperature distribution in the assembly was computed at various times up to and past the time of peak temperature. Appropriate forced convective heat transfer coefficients were computed and applied on the ID surfaces of the pipe and the socket. The values were based on temperature and flow. On all other exposed surfaces, including the axial gap and radial gap between the pipe and the socket, natural convection coefficients were used since the velocity of flow in the small gaps is not expected to be high.

The stress distribution was computed using a separate ANSYS run from the stored temperature distribution data versus time. Stresses were calculated to obtain a qualitative measure of the relative effect of various gap sizes and various transients on the socket weld peak stress. An absolute quantitative stress in the socket weld was not calculated, as it is dependent upon the piping system geometry and its effect on thermal expansion moment distribution, which would have been completely arbitrary.

## SOCKET TYPE WELDING FLANGE
## (1500 lb. Design)

| Nominal Pipe Size | Outside Diameter of Flange O | Thickness of Flange Minimum Q | Outside Diameter of Raised Face R | Diameter of Hub at Base X | Length Through Hub Y | Diameter of Bore B | Diameter of Socket A | Depth of Socket Z | Approx. Weight in Pounds |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 8½ | 1½ | 3⅝ | 4⅛ | 2¼ | 1.939 | 2.44 | 11/16 | 24 |

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All dimensions in inches. ANSI Std. B 16.5

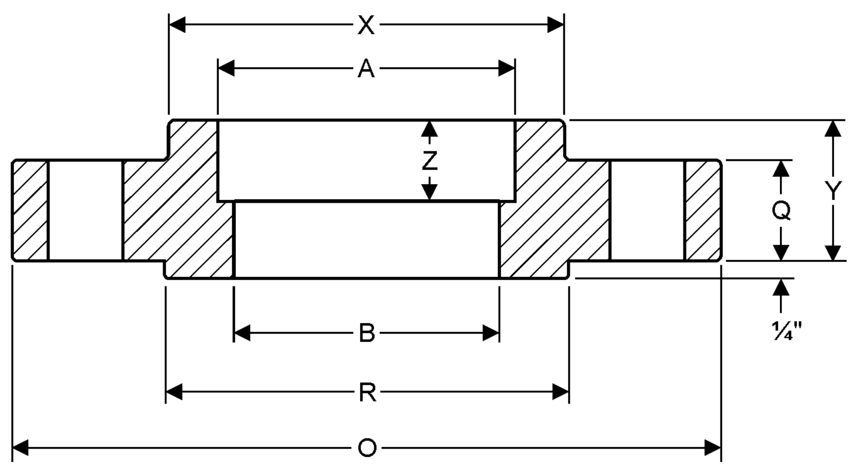


Figure 1: Socket Type Welding Flange

# 3
# ASSUMPTIONS

The assumptions in the analysis are as follows:

1. No residual stress is present in the weld and the surrounding area as the welding process is assumed to have been performed slowly enough and in multiple passes such that the residual stress is insignificant.
2. No moments or forces are considered acting on the joint. Such loads would have been arbitrary and are not affected by the presence of the assembly gap.
3. The material of the pipe, socket and the weld are considered to be the same (304 stainless steel) whose heat transfer and other properties are given in Table 1.
4. No pressure effects are considered. This may, if considered, mathematically alter the geometry of the pipe to fitting gap and thus affect the contact time between the two components upon the introduction of the thermal transient.
5. A flow of 45 gpm (such as in an auxiliary pressurizer spray line) is assumed through the pipe and socket. The heat transfer coefficients were computed at various temperatures using this flow.

The pipe section is assumed to be insulated.

**Table 1: Material Properties (304 SS) vs. Temperature**

| **Property** | 70°F | 200°F | 300°F | 400°F | 500°F | 600°F |
|---|---|---|---|---|---|---|
| **Young's Modulus (x$10^6$ psi)** | 28.3 | 27.6 | 27.0 | 26.5 | 25.8 | 25.3 |
| **Coefficient of Thermal Exp. (μin/in/°F)** | 8.46 | 9.08 | 9.46 | 9.81 | 10.1 | 10.38 |
| **Thermal Conductivity (BTU/sec-in°F)** | 8.60 | 9.3 | 9.8 | 10.4 | 10.9 | 11.3 |
| **Specific Heat (BTU/lb-°F)** | 0.116 | 0.122 | 0.125 | 0.129 | 0.131 | 0.133 |

Density of stainless steel = 0.283 lb/in$^3$ and Poisson's Ratio = 0.3

# 4
# ANALYSIS

Three transients were considered in the analysis. These are summarized in Table 2:

1. A severe transient case, in which a temperature increase of 400°F occurs in 10 seconds. This is typical of the worst nuclear plant design transients, such as Sudden Recirculation Pump Start. A variation on this transient, in which the ramp rate is 30 seconds, was also considered.
2. A moderate transient, a 100°F increase in 30 seconds. This is similar to a Reactor Trip transient (although that is a temperature drop). Such a transient can be expected to occur moderately often in plant operation.
3. A gradual transient, a steady ramp of 100°F per hour, as would be typical of a plant heatup.

Three as-installed initial gap cases were considered for the analysis, namely, axial gaps as small as 5 mils (.005 in.), 3-mils, and 1-mil. The ANSYS model was built parametrically to enable gap changes to be easily implemented.

For each of the gap and transient cases, it was ascertained whether interference (bottoming out of the pipe in the socket) occurs and for how long. The duration of interference can give an indication of how many cycles of a high cycle fatigue load, such as from vibration, would have the additional stress from the lack of the assembly gap superimposed on the alternating stress.

The estimation of the stresses for cases where interference occurs is accomplished using the surface elements available in ANSYS.

**Table 2: Transient Temperature Profiles**

| Time, sec. | Case 1a, Temperature, °F | Case 1b, Temperature, °F | Case 2, Temperature, °F | Case 3, Temperature, °F |
|---|---|---|---|---|
| 0 | 130 | 130 | 430 | 130 |
| 2 | 210 | 157 | 437 | 130.1 |
| 4 | 290 | 183 | 443 | 130.1 |
| 7 | 410 | 223 | 453 | 130.2 |
| 10 | 530 | 263 | 463 | 130.3 |
| 15 | 530 | 330 | 480 | 130.4 |
| 20 | 530 | 397 | 497 | 130.6 |
| 25 | 530 | 463 | 513 | 130.7 |
| 30 | 530 | 530 | 530 | 130.8 |
| 3600 | 530 | 530 | 530 | 230 |

# 5 RESULTS OF ANALYSIS

In general, if even a very small gap is provided, there is no effect on the weld stresses due to differential thermal expansion between the pipe and fitting, for all but the most severe transients. If the gap is truly zero, very significant stresses can occur, although for a short period of time.

Table 3 gives a summary of the results obtained for the thermal transient cases and three initial gap sizes. The root of the weld experiences the highest stress intensity for all cases. The size of the remaining gap was computed from the difference in the axial translations of the pipe end and the socket end at the ID. Figure 2 represents the plane ANSYS model of the pipe-socket joint. Figure 3 gives a typical temperature distribution at a chosen instant (here the time is 10 sec). Figure 4 shows a typical evolution of the gap between the end of the pipe and the socket. As can be seen here the contact time is about 40 seconds. The evolution of the corresponding stress intensity at the root of the weld is given in Figure 5. A contour plot of the stress intensity is given after about 15.3 seconds in Figure 6 for the severe transient with 1 mil-gap case.

For the most severe transient, ramping up from 130°F to 530°F in 10 seconds, if the initial, as-installed gap is 5 mils (.005 in.) or larger, no contact occurs between the pipe end and the socket seat, despite the severity of the transient. In this case a peak stress of 152 ksi is induced at the root of the fillet weld. This stress is due to the high through-wall thermal gradients caused by the severe ramp rate, and would be present even with the 1/16 inch gap. If the as-installed gap is 3 mils, a maximum interference of about 0.8 mil occurs for 44 seconds. A peak stress of about 161 ksi is induced at the root of the fillet weld, which means that the insufficient assembly gap causes an additional stress of 9 ksi. If the initial gap is 1 mil, this induces a maximum peak stress of 230 ksi at the weld, or an additional stress of 78 ksi. This contact remains for about 500 seconds. If no initial gap is provided, the stresses on the weld become very large due to the lack of flexibility inside the socket. The peak stress is divided by 2 when evaluating fatigue usage.

The slightly less severe case of a 400°F ramp in 30 seconds results in a slight contact at the socket/pipe seat for a 3-mil gap. The contact time is 42 seconds. The interference-induced stress here is 6 ksi. It appears that the results for this ramp rate are only slightly better than for the first transient case above.

For the moderate transient, 100°F in 30 seconds, there is no interference between the pipe end and fitting for a 3-mil or greater initial gap. If the as-installed gap is 1-mil, the gap comes very close to closing. The through-wall thermal gradient peak stress is 38 ksi if there is no contact; since the assumed transient does not cause an interference, there is no additional stress in the weld due to thermal expansion of the pipe in the socket. If the assumed transient is more severe than 100°F in 30 seconds, some amount of additional stress on the weld can occur, depending on severity of the actual transient. However, most of the design transients in nuclear plants are equal or less severe than the assumed ramp rate.

For the heatup transient, which is a ramp rate of 100°F per hour, no contact occurs for any gap size. It can be concluded that even for a zero gap, no additional stress will develop in the weld due to transient thermal expansion. The transient peak stress is only 9 ksi.

**Table 3: Results Summary**

| Transient Case | Socket Seat to Pipe end Gap Size (mils) | Interference or not | Contact Time | Max. Pure Through wall Stress Intensity (psi) | Additional Stress at Weld Root due to Interference (psi) | Peak Stress Intensity at Weld root (psi) |
|---|---|---|---|---|---|---|
| 400°F in 10 sec | 5 mil | No | N/A | 152K | 0 | 152K |
| | 3 mil | Yes | 44 sec | 152K | 9K | 161K |
| | 1 mil | Yes | 500 sec | 152K | 78K | 230K |
| 400°F in 30 sec | 5 mil | No | N/A | 149K | 0 | 149K |
| | 3 mil | Yes | 42sec | 149K | 6K | 155K |
| 100°F in 30 sec | 5 mil | No | N/A | 38K | 0 | 38K |
| | 3 mil | No | N/A | 38K | 0 | 38K |
| | 1 mil | 5% of initial gap remains | N/A | 38K | 0 | 38K |
| 100°F per Hour | 3 mil | No | N/A | 9K | 0 | 9K |
| | 1 mil | No | N/A | 9K | 0 | 9K |

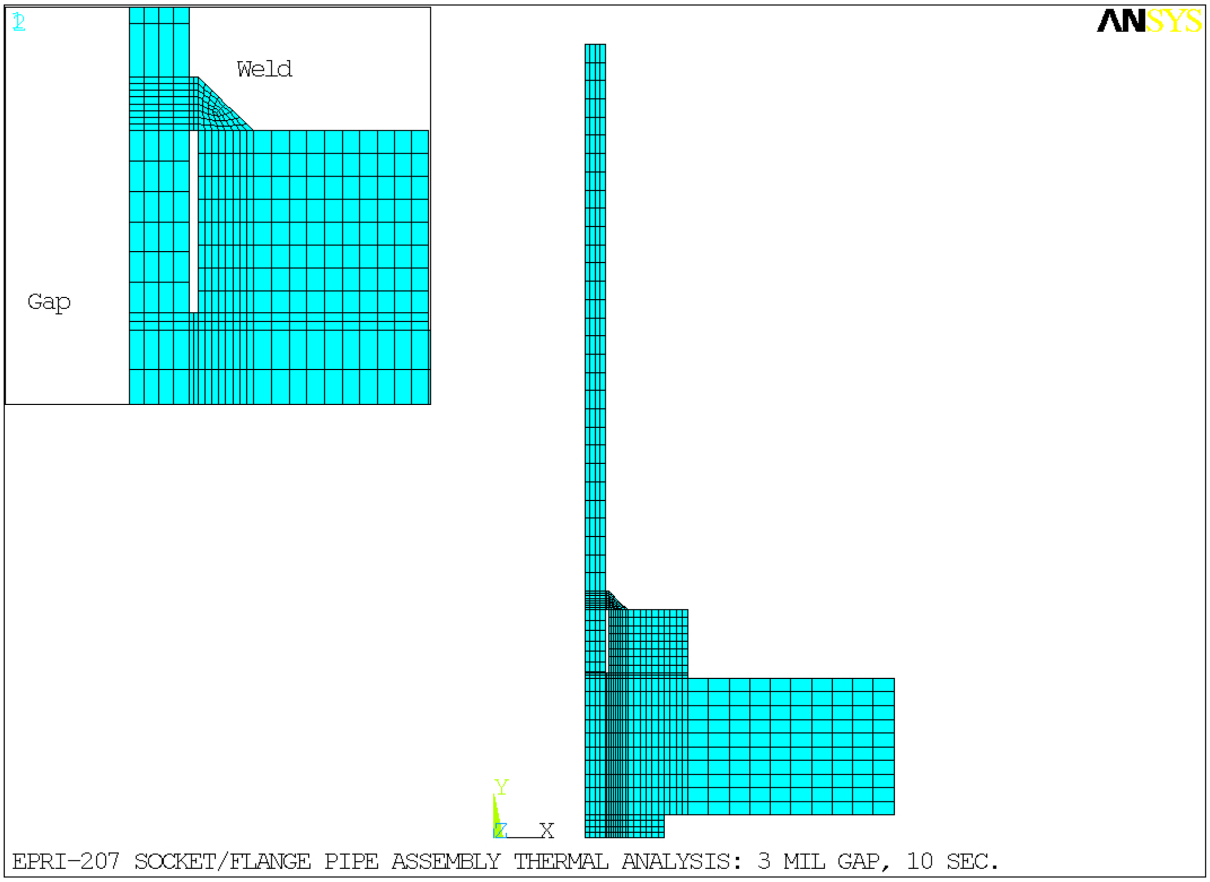


**Figure 2: ANSYS Model**

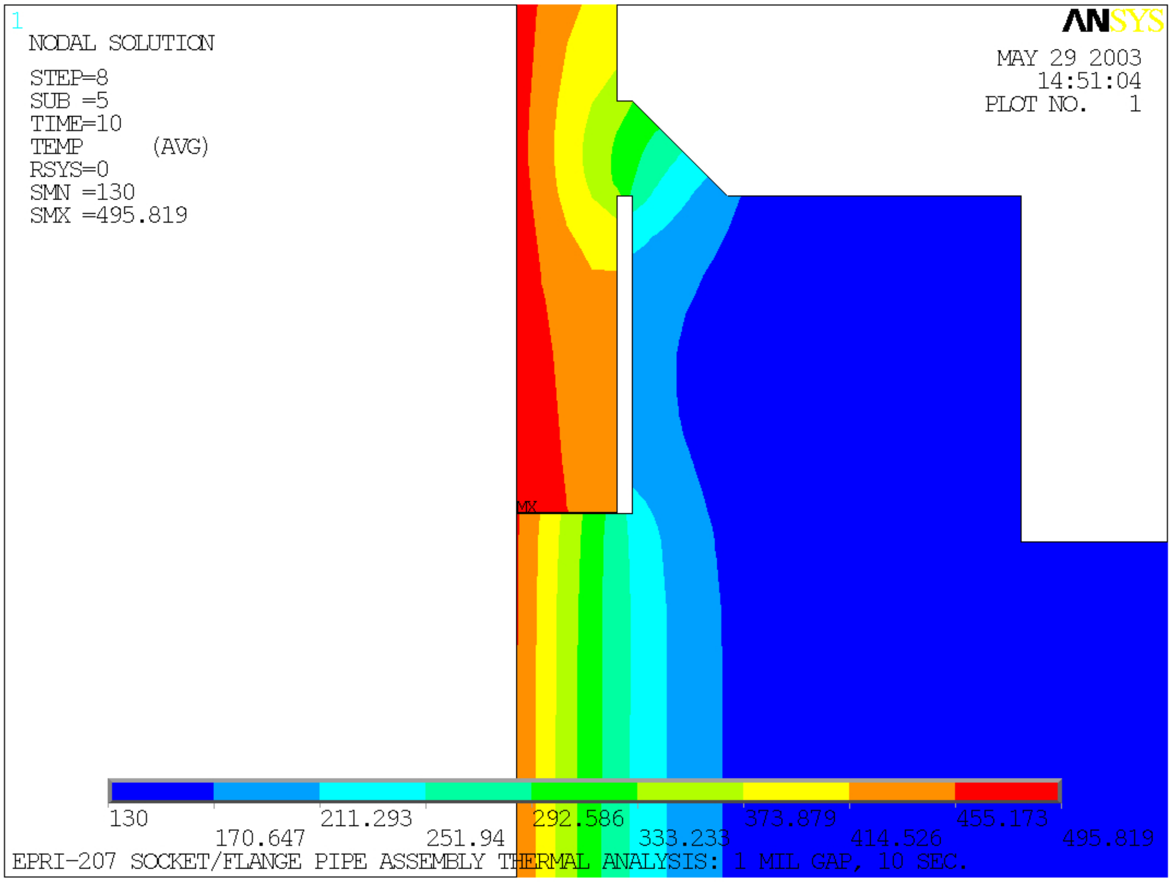


**Figure 3: Temperature Distribution in Pipe and Socket Walls after 10 Sec on the Introduction of the Transient of a Delta of 400°F in 10 Sec. Gap here is 0.001”.** *(Note: The maximum thermal gradient is observed at the root of the weld.)*

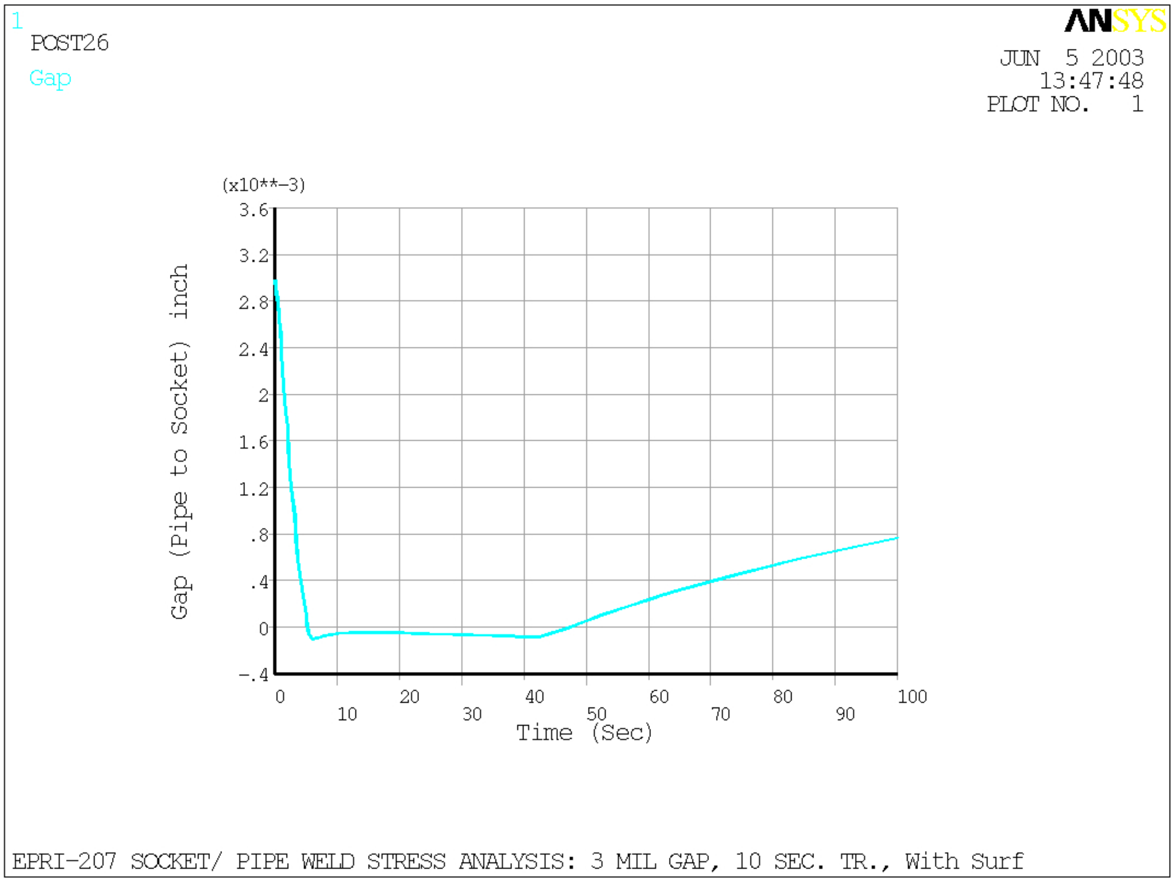


**Figure 4: Gap Evolution (3 mil gap and 10 Sec Transient)**

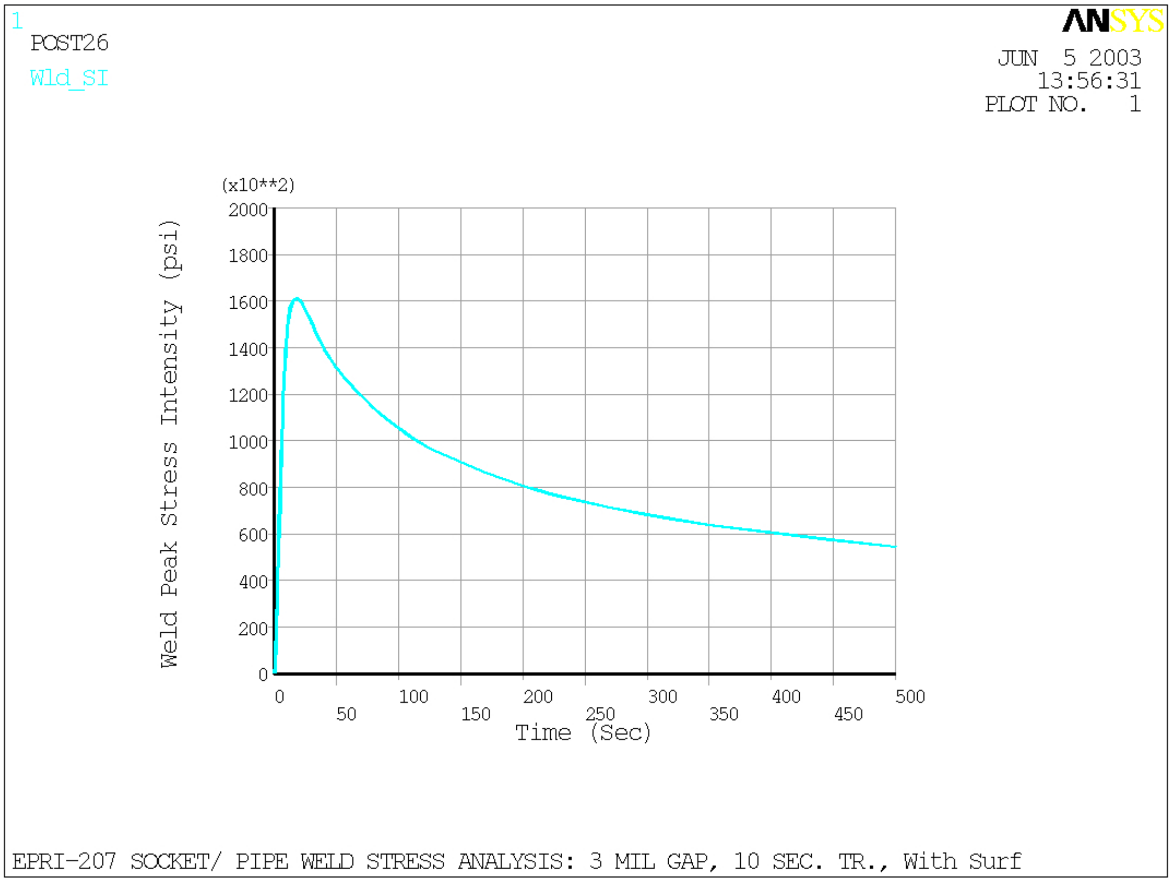


**Figure 5: Stress Intensity Evolution at Weld Root (3 mil gap and 10 Sec Transient)**

*Note: Stresses approach zero in around 4000 seconds.*

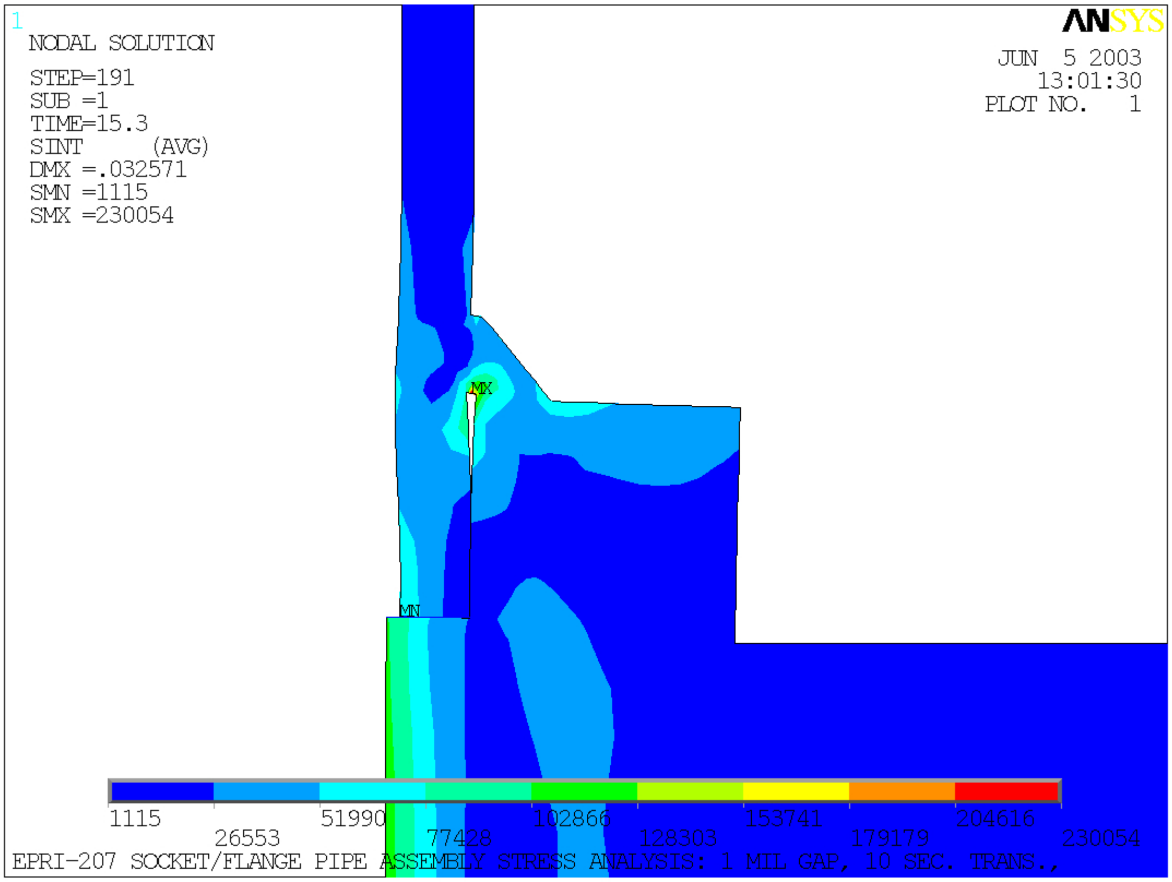


**Figure 6: Stress Intensity Contour (1 mil gap and 10 Sec Transient at 15.3 seconds)**

# 6
# CONCLUSIONS AND DISCUSSION

It is seen from the above evaluations that as long as some small, non-zero gap is provided at the bottom of the socket for piping subject to increasing temperature thermal transients, there will be no impact of differential thermal expansion between the pipe and the fitting upon the fatigue life of the socket weld. This gap can be as small as .004 in. for piping subject to severe thermal transients, .001 in. for piping subject to moderate transients such as reactor trips, and can be essentially zero for piping subject to only normal heatup transients. For all practical purposes, such gaps will be present unless the fabricator has intentionally held the pipe tightly in the bottom of the socket while welding. Clearly, the gap does not have to be anywhere near as large as the Code specified 1/16 in. However, if the gap is truly zero, high stresses can occur in the weld in the severe and moderate transient cases.

Dissimilar metal joints were not evaluated in this study. Such joints are not common at socket welds, and would most likely only occur at a half-coupling in which the branch line is a different material than the run pipe. If the branch line is stainless steel and the run pipe is carbon steel, for example, the Code requirement for a 1/16 in. gap should be followed.

The most common failure mode for socket welds is high cycle fatigue due to vibration. If the initial gap is insufficient to prevent interference between the pipe and the fitting during a thermal transient, the duration of the interference will be a very small fraction of the total operating time, therefore only a small percentage of the vibration load cycles will be subject to the additional stress on the weld due to differential thermal expansion. This should not result in a significant impact upon the fatigue life of the joint.

# 7
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