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THE RESIDUAL STRESS DISTRIBUTION IN WELDED PIPE INNER SURFACE OF STAINLESS STEEL FROM THE NUCLEAR POWER PLANT IN RINGHALS

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ABSTRACT

The axial residual stress distribution on the inner surface of welded pipes of stainless steel SS 2333 (AISI 304) have been measured using the X-ray diffraction technique. Four halves of two pipes with the outer diameter of 114mm and wall thickness of 10mm were investigated. The result on the pipe inner surface shows compressive stresses in the weld metal and tensile stresses within a region between 8-23 mm with a maximum of 180MPa at a distance of 17 mm from the weld centerline.

The maximum axial and circumferential residual stresses on the pipe outer surface are of the magnitude of 100 MPa. By cutting the pipes into two halves these stresses are relaxed by about 35 MPa.

1. INTRODUCTION

The observations of intergranular stress corrosion cracking (IGSCC) on pipe inner surface in piping systems of nuclear power plants have initiated a number of studies on the weld residual stress distribution. Normally tensile stresses are stated in the weld, and in HAZ as shown e.g. by Rybicki et al (1) although the opposite trend has been noticed by Rybicki et al (1) and by Brust and Stonesifer (2).

The present investigation was carried out to obtain the residual stress on the inner surface of stainless steel piping from the nuclear power plant in Ringhals.

2. EXPERIMENTAL WORK

The specimens consisted of two pipe to pipe welded pipes of stainless steel, SS 2333 (AISI 304) denoted A11 and DG 66 respectively with a total length of 300 mm, an outer diameter of 114 mm and a wall thickness of 10 mm. The weld was formed in four layers. There are, however, no data available for the true welding technique used and it is a difficult task to reconstruct all parameters in the process. Rough values for the heat inputs used are 0.12-0.24 kJ/mm in the first three layers and 0.22-0.84 kJ/mm in the last upper layer, respectively.

The residual stress measurements were obtained by means of the $\sin^2 \psi$ technique using X-ray diffraction, see e.g. (3). Normally five ψ-angles were used to evaluate the stress at each measuring position. The oxide layer at all measuring points was removed by electropolishing to a depth of 0.05 mm.

The axial and the circumferential residual stresses on the outer surface were measured along the axial direction 7 and 13 mm from the weld centerline of the pipe denoted A11. The measuring positions are defined in figure 1. The stresses were measured before and after axial cutting of the pipes A 11 and DG 66 into two halves to obtain the relaxation of the stresses caused by the cut.

On the pipe inner surface only the axial residual stresses were measured at various distances from weld centerline on each of the four halves.

3. RESULTS

The residual stresses on the outer surface are shown in table 1. All the stresses are tensile at the positions measured. The axial stresses before cutting are of the magnitude of 90 and 170 MPa 7 and 13 mm from the weld centerline. The circumferential stresses are about 160 and 70 MPa at the similar positions. After cutting the stresses were relaxed with about 35 MPa.

The axial residual stresses on the pipe inner surface are given in table 2 and plotted as a function of the distance from the weld centerline in figure 2. The figure shows compressive stresses of about 200 to 300 MPa in the weld and tensile stresses in the region between 8 and 23 mm from the weld centerline. The maximum tensile stress is of the magnitude of 125 to 185 MPa.

In figure 3 the mean values of the axial stresses on the pipe inner surface are plotted against the distance from the weld centerline. The axial and circumferential stresses obtained on the outer surface are marked in the figure.

4. DISCUSSICN

The present investigation of residual stresses on the pipe inner surface of the welded pipes with a diameter of 114 mm (4.56 in) and a wall thickness of 10 mm (0.456 in) shows compressive axial stress of about 250 MPa within the weld metal and in the vicinity of the weld and tensile axial stresses within a region between 8 and 23 mm with maximum tensiles of about 180 MPa at a distance of 17 mm from the weld centerline.

Rybicki et al (1) computed residual stresses on the pipe inner surface of a 4-in pipe. They found tensile axial stresses within the region 0 to 17 mm from the weld centerline with a maximum of about 240 MPa and compressive stresses at longer distances with a maximum stress of about 310 MPa. The heat input in their computation was 30 kJ/cm. They also found that an increase of the pipe diameter and wall thickness decreased the tensile stresses until these were changed into compressive ones at a pipe diameter of 250 mm (10-in) and a wall thickness of 2.80 mm (1.25-in). The last computation was compared with X-ray stress data showing resonable agreement.

The proposed explanation for the presence of tensile stresses in the weld metal is that thinner girth welded pipes exhibit more local inward deformation near the weld than thicker pipes.

In a paper by Gilman et al (4) it is shown that there is a large scattering of experimental residual axial stresses obtained near the fusion line on pipe inner surface as shown in figure 4. The relevant range of values for the 4-in pipe is marked in figure 3. The lower values overlap the data in the present work. It may be observed, however, that X-ray gives stress data from a much thinner outer layer (0.0015 mm) than that computed by the finite element model. It is found by Brust and Stonesifer (2) that the weld heat input greatly affects the residual stresses in and in the vicinity of the weld. A lower heat input can change the tensile stresses into compressive ones as shown in figure 5. To a smaller extent a decrease of the yield stress lowers the residual stresses as demonstrated in figure 6. The two last informations are based on computational models. The model also predicts large compressive stresses at a far distance from the weld centerline as illustrated in figures 5 and 6. No experimental data have been found, however, to compare with the predicted ones in 4-in pipes.

The distribution of the temperature during the last weld pass is mainly responsible for the residual stress distribution on the pipe inner surface. The temperature along pipe surface are shown in figures 7 during each pass of a three layers weld (2). It can be seen that the heat input affect the pipe inner surface to a distance of 15 mm from weld centerline.

The computational model predicts compressive axial stresses between 12 and 60 mm from weld centerline with maximum stresses of 250 MPa around 25 mm from centerline as shown in figure 8. The curve denoted heat sink is related to a weld technique within pipe flowing water during the weld process leading to high compressive weld stresses in pipe inner surface. It is a little surprising that such high compressive stresses are predicted in a region at a distance so far from the heat affected area.

The residual stress distribution on the pipe inner surface depends mainly on the shrinkage of the cooling weld metal and the stiffness of the pipes. This means that the application of the last outer weld layer controls the generations of the stress on the inner surface due to the heat distribution on this surface and the yield point at normal and elevated temperatures of the weld and base materials. The complex thermomechanical behaviour of the welding process may thus give rise to local variations in the stress distribution caused for example by a variation of the heat input into the last upper weld layer.

The effect of temperature and pressure during start-up operation of a reactor on the residual stress distribution is not yet clarified. Iwasaki (5) shows the change of these parameters and the oxygen concentration during the start-up operation. The applied pressure gives about half the yield strength at the operation temperature 280 °C (500°F). This means that the sum of this applied stress and a residual tensile stress of the same magnitude extend the yield strength and in cooperation with a sensitized structure and the BRW environment give rise to IGSCC.

7. CONCLUSION

The present work shows compressive stresses in the weld and tensile stresses next to the weld on the pipe inner surface and with a maximum tensile stress of 190 MPa. These stresses must be related to the present microstructure and environment before any conclusion concerning the damage of the magnitude and position of these stresses can be drawn.

The residual axial stress on the pipe outer surface is about 100 MPa but seems to increase in the direction of the weld. The circumferential stresses show a maximum of 100 MPa but in this case the values decreases in the direction of the weld.

The relaxation of the stresses on the pipe outer surface by cutting the pipes into two halves is of the magnitude of 35 MPa.

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Table 1 The axial and circumferential residual stresses (MPa) on the outer surface of welded pipe (denoted A 11) of stainless steel SS 2333 (AISI 304). Data before and after axial cutting of the pipes. The measuring points A1, A2, B1, B2 etc defined in figure 1

	Axial residual stresses				Circumferential residual stresses			
	before cutting		after cutting		before cutting		after cutting	
Measuring points	1	2	1	2	1	2	1	2
A	106	195	67	126	132	74	95	51
B	70	147	29	92	168	94	132	72
C	99	189	71	162	163	66	121	55
D	81	167	48	137	184	50	154	36

Table 2 The axial residual stresses (in MPa) on the welded pipes inner surface as a function of the distance from weld centerline. Data obtained at 2 halves of each pipe denoted A 11 and DG 66 respectively according to the definition in figure 1.

	A11/$_0$	A11/$_{90}$	DG/$_0$	DG/$_{90}$	
Distance from weld centerline	σ_A MPa	σ_A MPa	σ_A MPa	σ_A MPa	Mean values
(mm)					
0	- 193	- 290	- 215	- 251	- 237
3*	- 215	- 251	- 245	- 274	- 246
5	- 178	- 165	- 142	- 181	- 167
7	- 124	- 113	- 69	- 96	- 100
9	- 117	- 145	+ 10	+ 85	- 42
15	+ 124	+ 186	+ 153	+ 184	+ 162
20	+ 128	+ 22	+ 54	+ 89	+ 73
25	- 69	- 10	- 44	- 44	- 42
35	+ 22	+ 4	0	+ 5	+ 7
45	+ 3	+ 0	- 3	+ 3	0

*) Fusion line

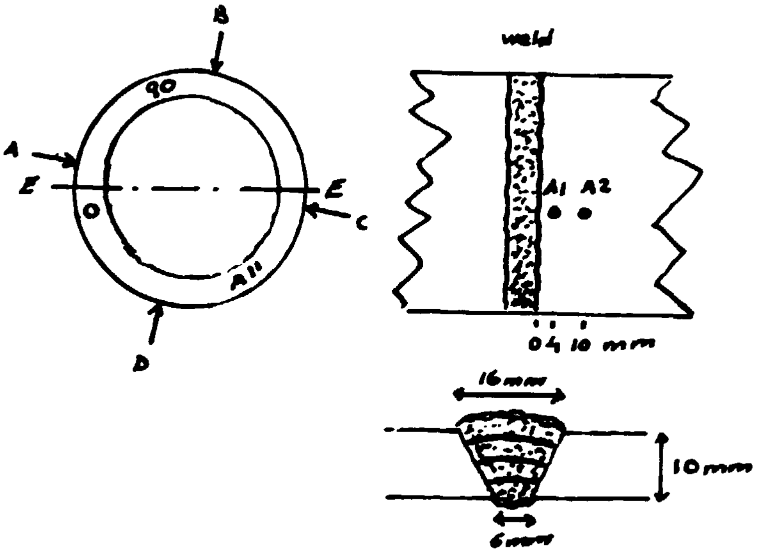

Fig 1 Illustration of measuring positions on pipe outer surface for measuring axial and circumferential residual stresses before and after the pipe was cut in the axial direction. Along EE.

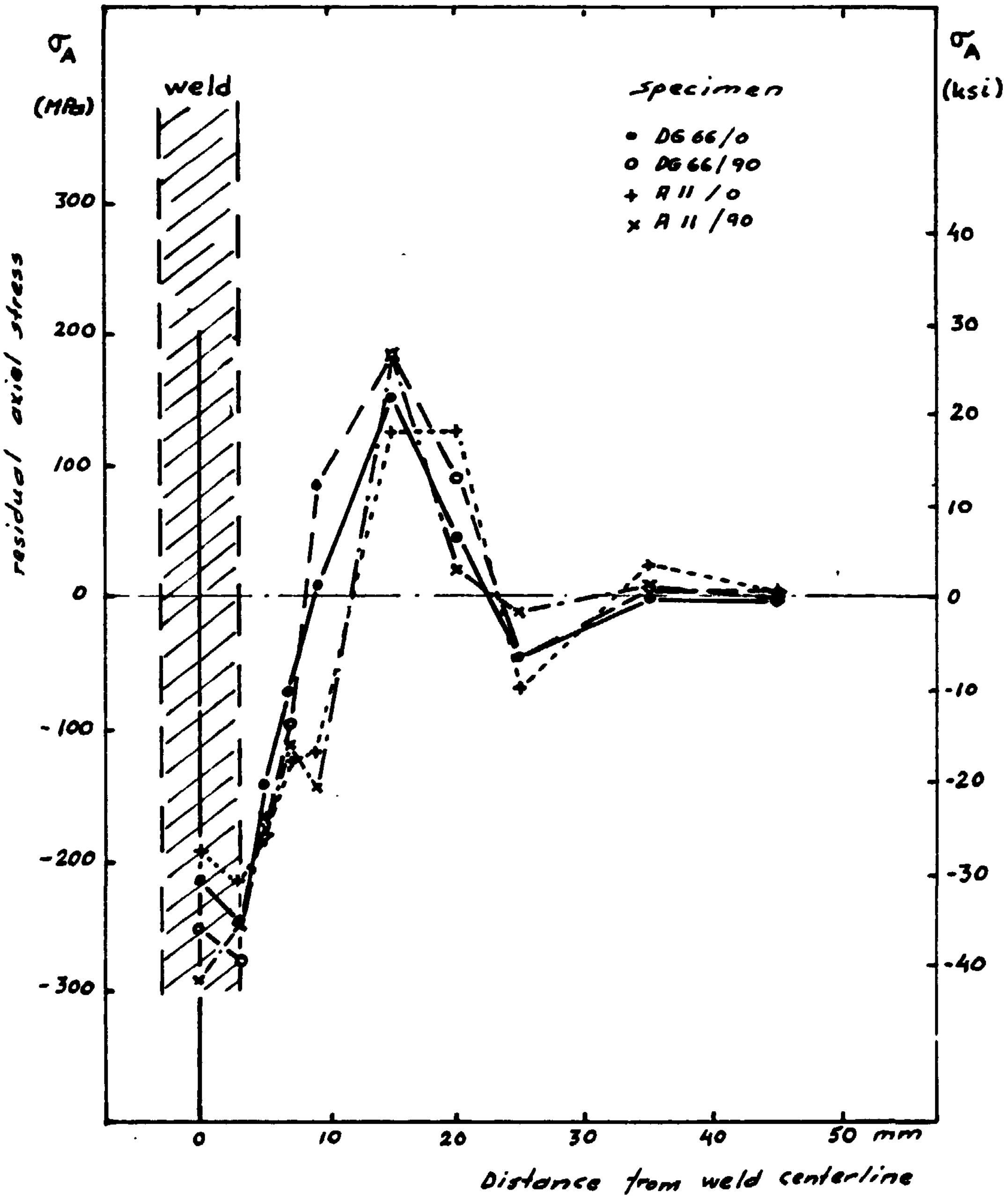

Fig 2 Residual axial stresses as a function of the distance from weld centerline on the inner surface of welded stainless steel pipes with an outer diameter of 114 mm and a wall thickness of 10mm.

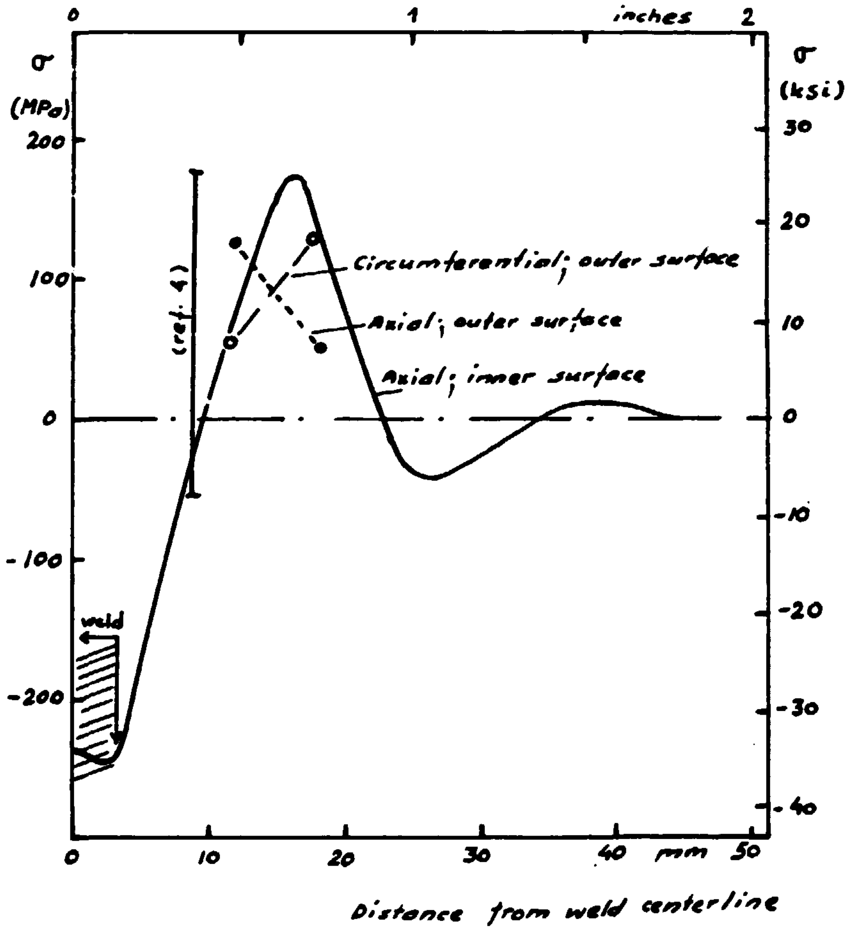

Fig 3 The mean value of the residual axial stress on the pipe inner surface, calculated from data in table 2, as a function of the distance from weld centerline. Axial and circumferential stresses obtained on the outer surface are marked in the figure. The line denoted (ref 4) shows the scatter of residual stress data compiled from several sources.

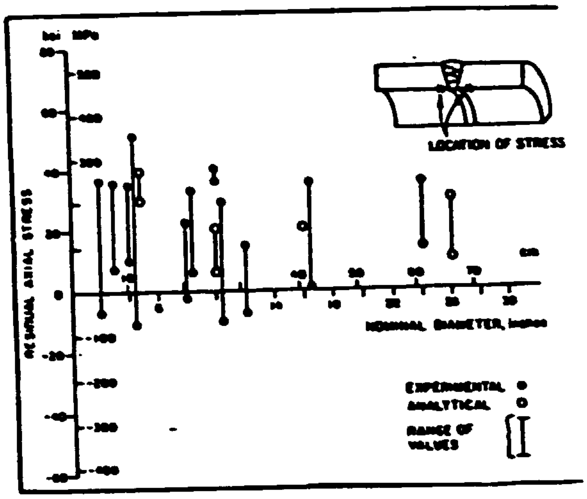

FIGURE 4 — Computed and measured weld induced residual axial stresses near weld fusion line on inner surface of Sch 80 pipes. (ref. 4)

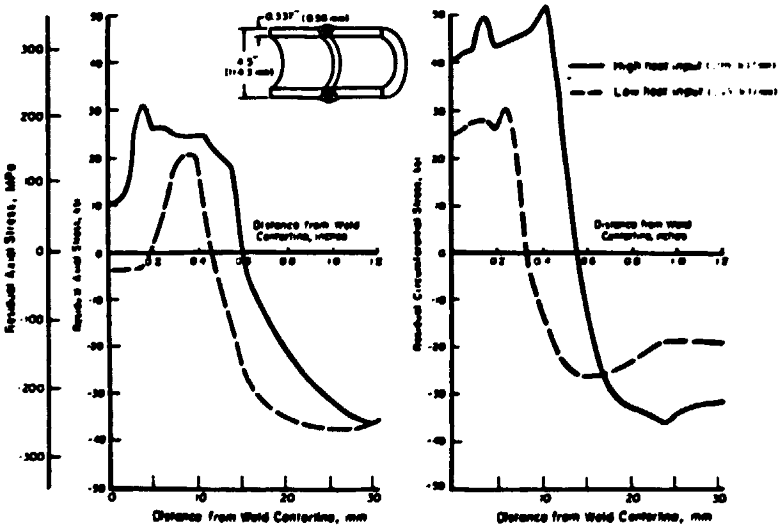

Figure 5 Comparison of predicted residual stress distribution in 4-inch (102-mm) pipe welded with two different heat inputs (ref. 2)

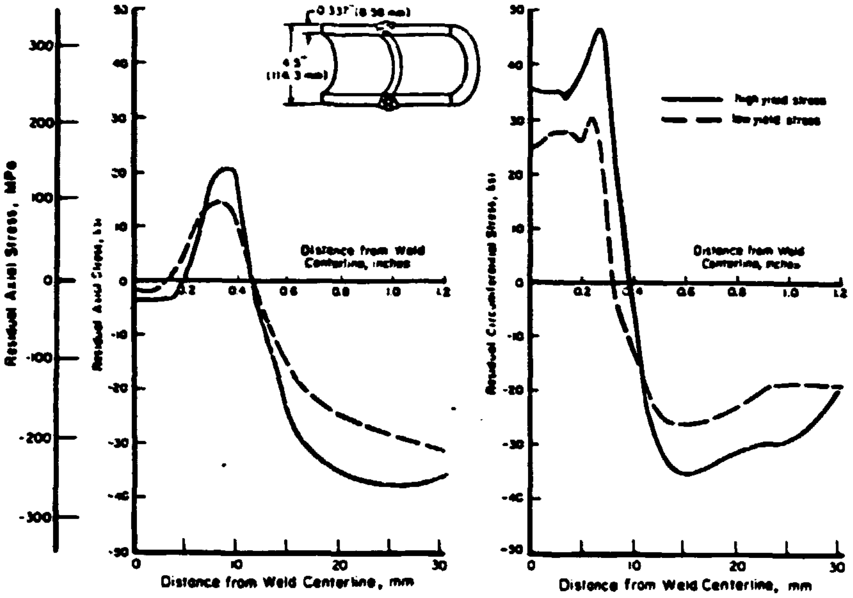

Figure *6* The effect of yield stress on the predicted residual axial and circumferential stress distributions along the inner surface of 4-inch (102-mm) pipe (*ref. 2*)

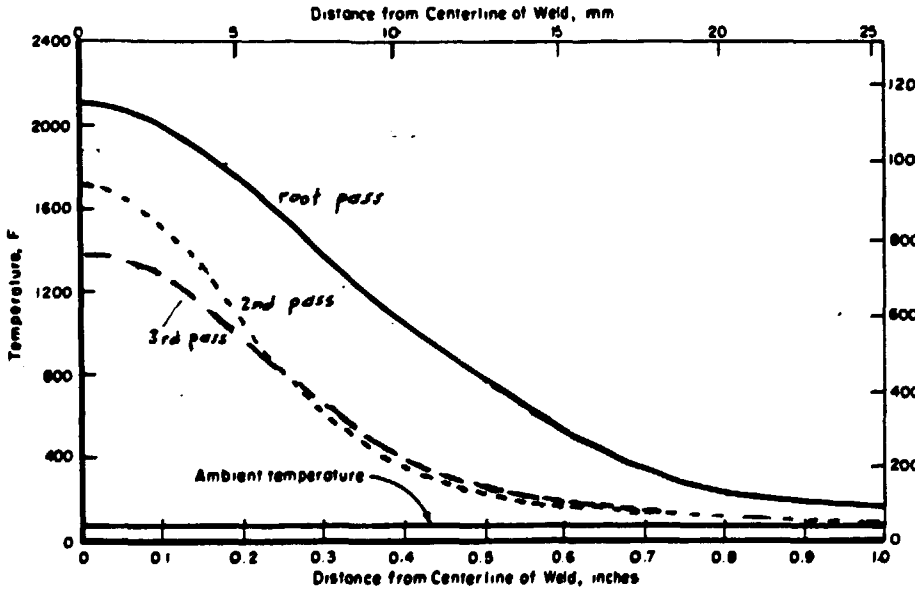

Fig 7 Temperature distribution along pipe inner surface during a weld with three passes of 4-inch (102mm) pipe. (*ref. 2*)

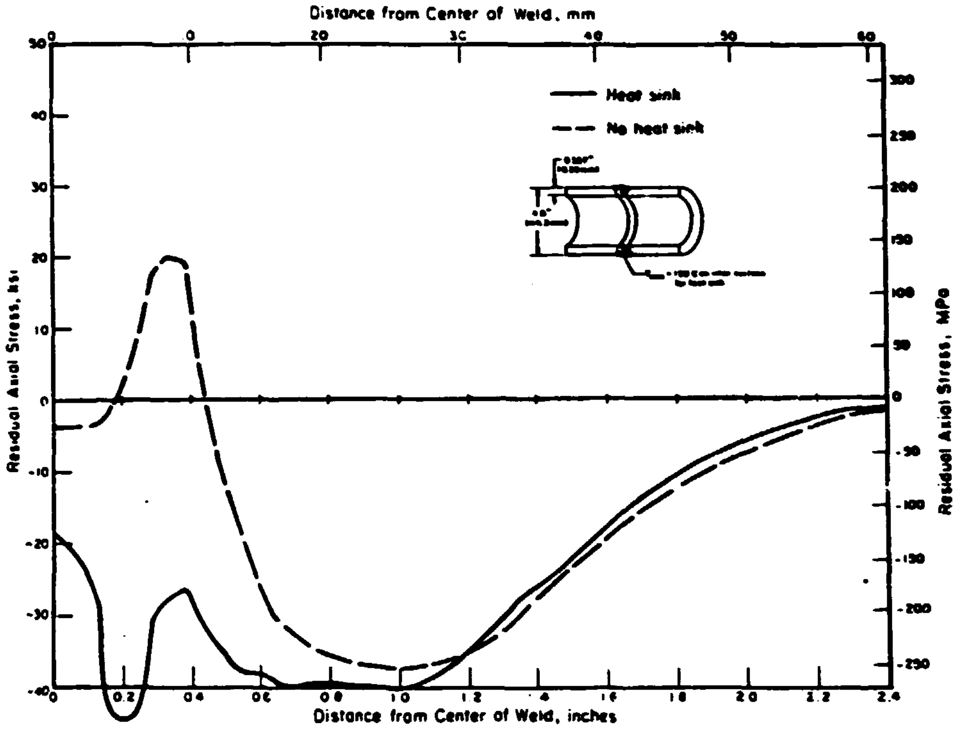

Figure 8 Predicted axial stress distribution along inner surface of 4-inch (102-mm) by-pass pipe with and without heat sink (ref. 2)

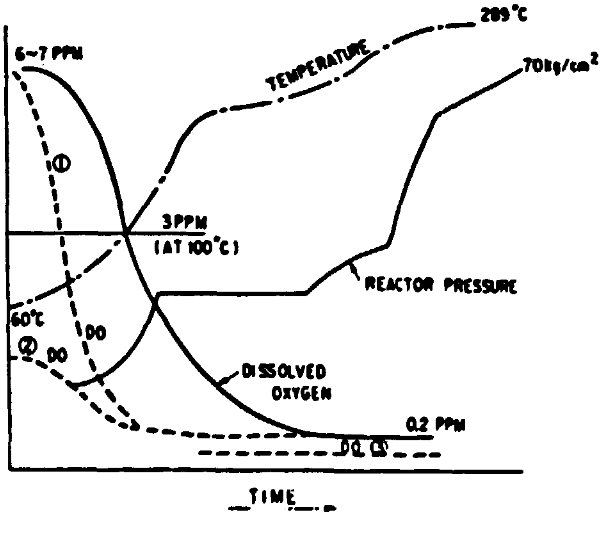

FIGURE 9 – Oxygen concentration, water temperature, and reactor pressure curves during startup operation. (ref. 5)

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