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Failure Investigation of Eddystone Main Steam Piping

Cause of through wall cracks in 316 stainless steel is established

BY J. F. DELONG, J. E. BYNUM, F. V. ELLIS, M. H. RAFIEE, W. F. SIDDALL, T. DAIKOKU AND H. HANEDA

ABSTRACT. In March 1983, personnel at Philadelphia Electric's Eddystone No. 1 power plant discovered a through wall leak in the main steam outlet piping. This pipe was designed to carry steam at a pressure of 5300 psi (36,538 kPa) and a temperature of 1210°F (654°C). The pipe was made of 316 stainless steel and had been operated approximately 130,000 hours at the time that failure was discovered. Subsequent inspection revealed that many OD cracks existed in this piping system.

This paper details the investigation into the cause of the failure. The following elements are highlighted: the in-place metallography which successfully used the plastic replica technique; the elastic-plastic stress analysis and life prediction techniques carried out to assess probable failure modes and loadings; and the experimental stress analysis which was conducted to confirm analytical hypotheses.

Introduction

The discovery in March 1983 of extensive cracking in the main steam lines at Philadelphia Electric's Eddystone Unit No. 1 power plant led to a forced outage of the plant and the present failure investigation. This investigation was conducted by Philadelphia Electric Co. (PECO), Combustion Engineering, Inc., and Mitsubishi Heavy Industries, Ltd.

Eddystone Unit No. 1 commenced commercial operation on February 5, 1960. The plant was designed for turbine conditions of 5000 psi (34,470 kPa) at 1200°F (649°C) temperature with two reheats to 1050°F (566°C). The turbine was rated at 325 MW. The unit is a coal fired, supercritical monotube design with a once through twin furnace manufactured by Combustion Engineering, Inc.

From the first startup to the discovery of the main steam line crack, the 316 stainless steel piping system accumulated 130,520 hours of high temperature operation. During this period, the unit experienced 326 startup cycles, many of which were due to forced shutdowns. The main steam line, including the welds, performed satisfactorily until the first indication of a problem in 1980. At that time, a small area of outside diameter cracking was discovered by visual examination near a hanger lug location. Immediately, one-third of the piping system, including all pipe sections from the same heat as the cracked section, was examined with dye penetrant. No other cracks were found. The cracked section was removed and high temperature stress rupture tests were performed on it. The rupture data was analyzed by parametric methods

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Table 1—Chemical Composition of 4B Steam Line from Eddystone Unit 1

Element	Wt. %
C	0.035
Mn	1.72
P	0.014
S	0.020
Si	0.36
Ni	12.62
Cr	17.10
Mo	2.30
V	0.03
Cb/Ta	<0.01
Ti	<0.01
Co	0.12
Cu	0.10
Al	<0.01
B	<0.001
N_2	0.033

Fig. 1 — Typical OD longitudinal cracking in 4B main steam line

Fig. 2 — Section of 4B steam line having nearly through wall cracking

and indicated adequate remaining creep rupture life. Hence, the unit was permitted to operate at normal conditions. It was with complete surprise that a through wall leak in the main steam piping system was discovered subsequent to these tests. The failure was in a vertical section of one of the steam lines and was not weld related. The safety problem mandated that the unit be repaired immediately; the need to insure that the problem would not recur required that the cause of the cracking be found. Therefore, an extensive failure investigation was undertaken. This paper will discuss the details of this failure investigation in chronological order.

Preliminary Failure Assessment

The steam line is a forged and bored type 316 stainless steel having a 9.05 in. (229.87 mm) outside diameter (OD) and 2.525 in. (64.14 mm) minimum wall thickness. The selection of type 316 piping material and 16 Cr-8 Ni-2 Mo welding electrode was based on a metallurgical study by Caughey and Benz (Ref. 1). All the cracking was confined to the piping material with no welds involved. Cracks found by the dye penetrant inspection method were confined to four of the 14 heats used in the piping system and only in that piping upstream of the boiler stop valves. The main steam line consists of 8 parallel lines numbered 1A, 1B, 2A, 2B, 3A, 3B, and 4A, 4B, originating at the eight superheater outlet headers.

All laboratory specimens reported here were taken from an 11 ft (3.35 m) section of the 4B steam line containing the leak position. The chemical composition of the piping is given in Table 1. Specimens were also sent by PECO to Failure Analysis Associates (Ref. 2), University of Pennsylvania (Ref. 3), Sumitomo Metal (Ref. 4), General Electric Co. (Ref. 5), Central Electricity Research Laboratory (Ref. 6), Oak Ridge National Laboratory (Ref. 7), and Ishikawajima-Harima Heavy Industries. Standard light optical

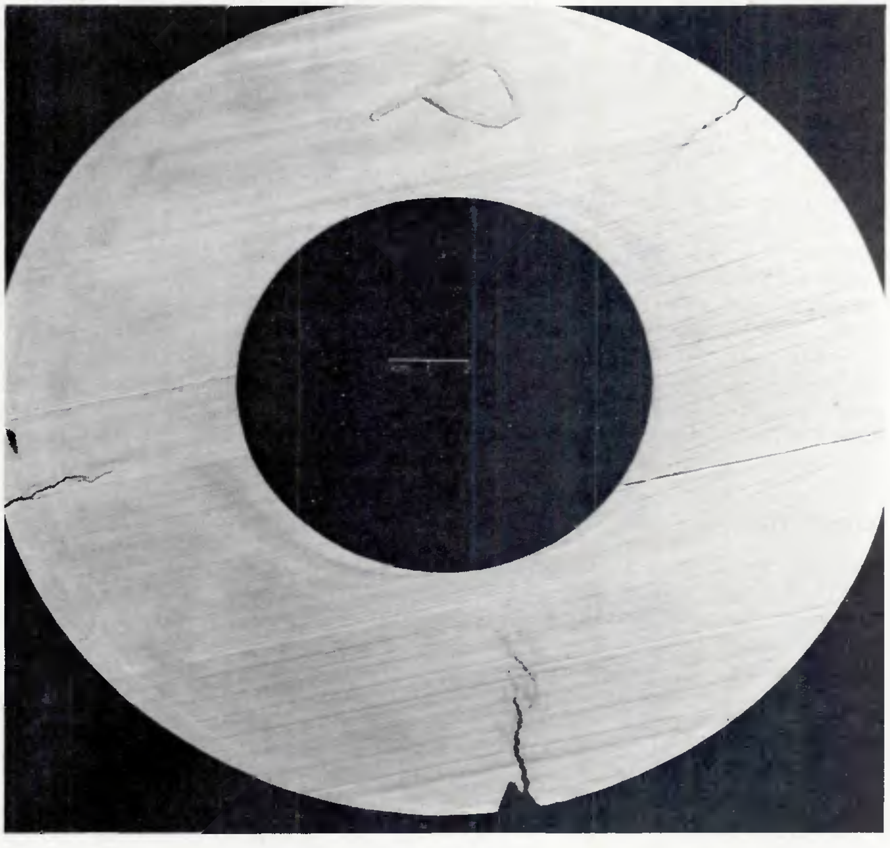


Fig. 3 — As received ring section with three major cracks

Fig. 4 — Intergranular oxide filled cracks perpendicular to hoop stress direction (Unetched)

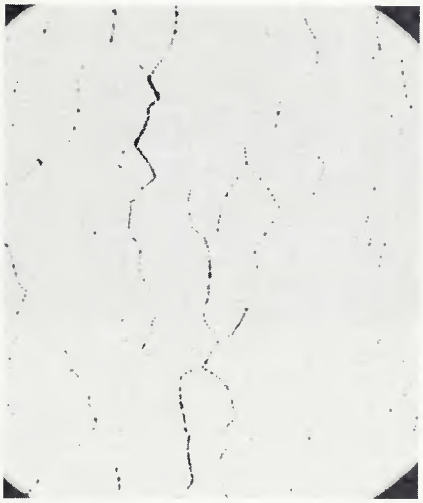


Fig. 5—Damage adjacent to main crack consisting of cavities and single grain facet (sgf) cracks (Unetched)

Fig. 6—Oriented cavitation in OD and midwall position while ID region is undamaged

and scanning electron microscopy (SEM) techniques were used to examine sections of the failed pipe. In addition to the metallographic examination, tensile, creep, Charpy, and compact tension tests were performed.

Metallographic Examination

The longitudinal cracking on the outside of the failed pipe is shown in Fig. 1. A crack nearly through the wall and the surface appearance of the cracking are shown in Fig. 2. Figure 3 shows a transverse ring which has three major cracks.

The damage in all specimens examined was similar. At low magnification, intergranular oxide-filled cracks perpendicular to the hoop stress direction (Fig. 4) were found near the OD. Figure 5 shows single grain facet (sgf) cracks and grain boundary cavities in the region adjacent to the main crack. Use of a multiple etch polishing procedure (Ref. 8) facilitated detection of the cavities which occurred at grain boundaries oriented either normal or nearly normal to the hoop stress direction. This oriented cavitation is observed on the OD and midwall positions, but the inside diameter (ID) region is free of damage. The density variation of these cavities' through the wall thickness is remarkably consistent from one circumferential location to another. Figure 6 shows this through wall variation at a circumferential position 90° from the major crack.

In every piece examined, the cracking starts at the OD or immediately beneath the surface, as shown in Fig. 3. It is presumed that the oriented cavities link up and form the sgf cracks, which precede the major cracks and subsequent failure. Figure 7 shows the oriented cavities detected on the outside using a tangential section rather than the more common transverse sections. The combination of OD crack initiation and detection of oriented cavitation on tangential sections led to the use of plastic replica techniques for field inspection of the main steam line at the plant.

Examination at higher magnification revealed that the microstructure of the failed pipe consists of matrix precipitates (probably $M_{23}C_6$) and large sigma phase particles in the grain boundaries. Although decohesion at the sigma-austenite interface is cited as a potential failure mode for this sigma phase morphology, the cavitation found during this investigation occurs primarily in the ligament region between the sigma phase particles, as shown in Fig. 8.

It is possible to produce grain boundary fracture in the highly damaged micro-

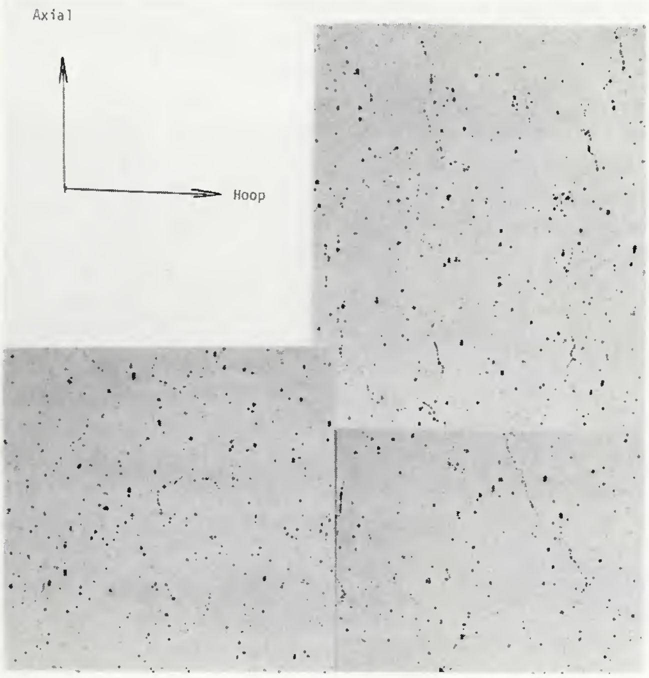


Fig. 7—Oriented cavities on outside surface of pipe (50X)

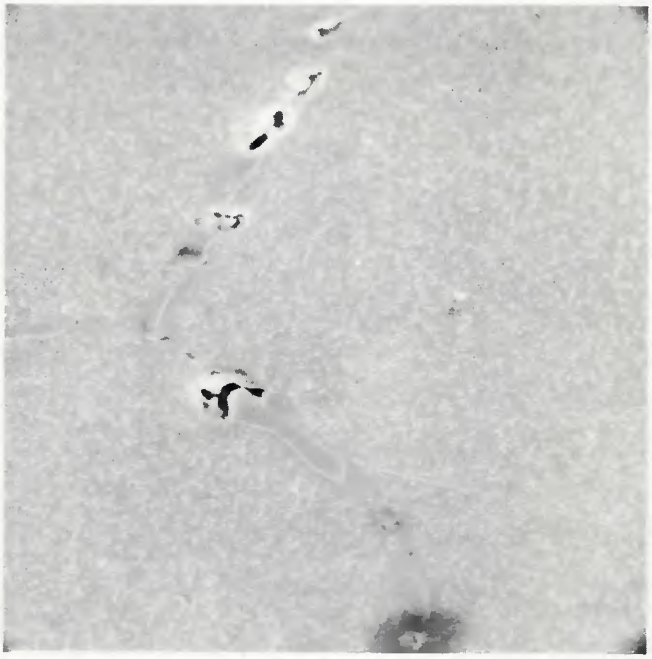


Fig. 8—SEM photomicrograph showing grain boundary cavities in ligament between sigma phase particles

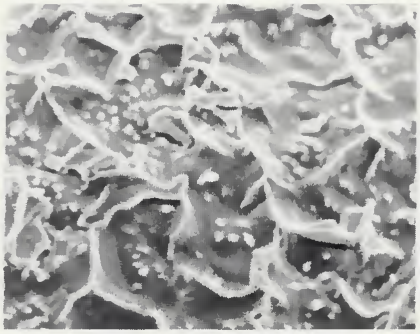


Fig. 9 — Grain boundary cavities and small particles on cavity walls

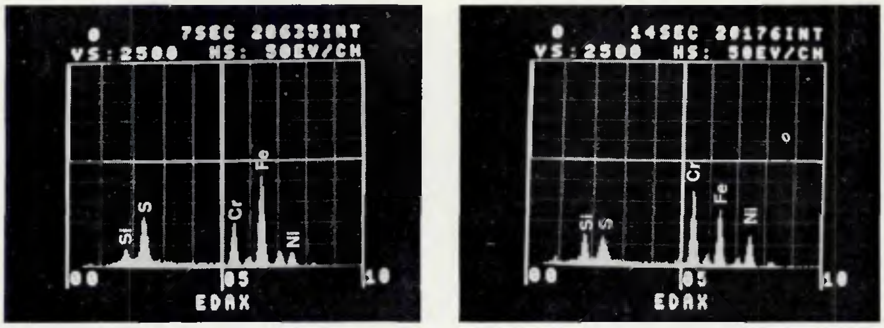


Fig. 10 — EDAX showing high sulfur content of small grain boundary particles

structure even at room temperature and relatively slow loading rates. Figure 9 shows multiple cavities on a grain boundary facet produced by room temperature impact loading of a thin slice taken from the OD of the failed pipe. The structure consists of cavity walls (the ridges) and small particles on the base of the cavities. The largest particle in the center of the photograph was analyzed by Energy Dispersive X-ray Analysis (EDAX) and shown to contain sulfur (Fig. 10 — the molybdenum peak occurs at nearly the same energy as sulfur, but is a double, while the observed peak is symmetrical). At high magnification, the cavities have the faceted appearance shown in Fig. 11. Similar observations have been made by other investigators (Refs. 2-5). At present, the interpretation of the source and role of sulfur in the failure is controversial. Definitive answers to these questions are not provided by this study. However, based on the work of Yoshihara, Kurahashi and Nii (Ref. 11), it is clear that (for iron) native sulfur will segregate at free surfaces (or grain boundaries) given sufficient aging time.

A transverse section of the impact loaded specimen is shown in Fig. 12 and cavities with small particles between large sigma phase particles can be seen on the grain boundary facets. The compact tension specimens were loaded slowly at room temperature and also showed the same small particle decorated grain boundary facets in the creep damaged region. A careful re-examination of Fig. 9 also reveals the presence of the small particles in the cavities adjacent to the sigma phase particles.

The 2B steam line material removed in 1980 for creep rupture testing (Ref. 12) was re-examined using the same techniques applied to the 4B line material. A piece of material removed from the OD of the 2B line and fractured at room temperature is shown in Fig. 13. The same small particles and cavity morphology found in the 4B line material are present.

Creep specimens removed from the ID of the 2B steam line had 3 to 4 times the rupture strength of specimens taken at other radial locations and subjected to identical test conditions. Figure 14 shows the intergranular cracks and cavitation found in a creep specimen from the ID of the steam line. Figure 15 shows fracture faces exposed to low temperature deformation of the creep specimen. Numerous sigma phase particles are seen on the grain boundary facets, but the small particles found closer to the OD of the pipe are missing.

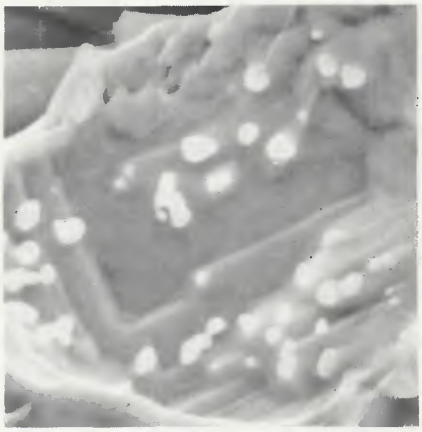
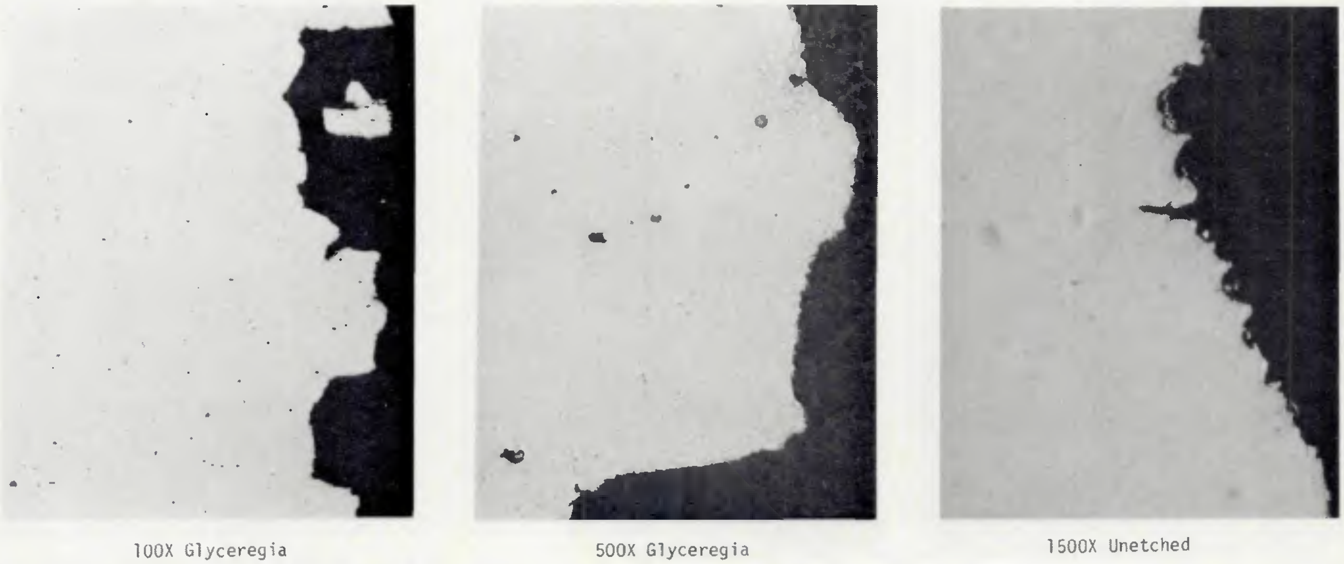


Fig. 11 — Facets on cavity interior



100X Glyceregia

500X Glyceregia

1500X Unetched

Fig. 12 — Transverse view of fracture face showing cavities with small particles on grain boundary facets

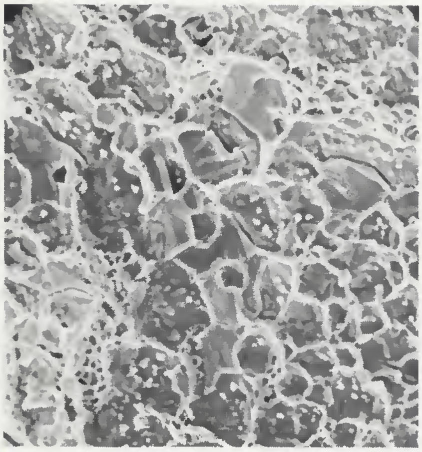


Fig. 13 — Room temperature fracture face of 2B steam line material removed in 1980 at position near OD of pipe

Table 2—Tensile Properties of 4B Steam Line from Eddystone Unit 1

Property	Specimen Code DE-1	DE-2	DE-3	DE-4
Yield Strength (ksi)	44.1	42.9	42.8	44.1
Tensile Strength (ksi)	60.0	47.3	83.6	66.3
Elongation (%)			10.0	

Table 3—Charpy Impact Properties of 4B Steam Line from Eddystone Unit 1

Specimen Location	Test Temperature (°F)	Absorbed Energy (ft-lb)	Shear (%)	Lateral Expansion (mils)
OD	77	3	0	1
1/4t	77	4	0	1
3/4t	77	6	0	3
ID	77	23	5	18
OD	77	4	0	1
1/4t	77	6	0	4
3/4t	77	8	0	5
ID	77	24	5	21
OD	535	4	0	2
1/4t	535	9	0	10
3/4t	535	10	0	15
ID	535	38	99	39
OD	1150	5	0	6
1/4t	1150	7	0	7
3/4t	1150	10	0	11
ID	1150	36	100	41

Creep and Tensile Testing

A creep test on the 4B material ruptured in 270 hours at 1382°F (750°C) and 6.8 ksi (468.8 MPa). At the same conditions, the 2B material (Ref. 12) ruptured in 648 hours for a difference in log rupture time of 0.38. Both creep curves exhibited similar primary and secondary creep behavior up to strains of about 0.5%. Subsequently, the 4B material entered the tertiary creep stage accounting for the shorter rupture life.

Four circumferential tensile specimens were cut from the OD of the 4B steam line. The specimens had a 0.252 in. (6.4 mm) diameter, a 1 in. (25.4 mm) gage length and were tested at room temperature. The test results are listed in Table 2. The relatively low ductility values reflect the damaged condition of the material.

Fracture Testing

In order to assess the susceptibility of cracks to propagate rapidly in the steam lines, several fracture toughness tests were conducted. Charpy impact specimens and 1 in. (25.4 mm) thick compact tension specimens were cut from the steam line which contained several cracks. The specimens were positioned so their fracture planes and the crack planes had similar orientations.

The Charpy impact testing was performed in accordance with ASTM Standard Method E-23. The data, which are shown in Table 3, indicate a significant increase in toughness as the inside diameter is approached. This coincides with the radial damage distribution revealed by the metallography. Increasing the test temperature from 77° to 1150°F (25°C to 621°C) does increase the toughness somewhat, but not enough to indicate that any ductility or fracture mode transition takes place.

The compact tension specimens were prepared and tested in accordance with

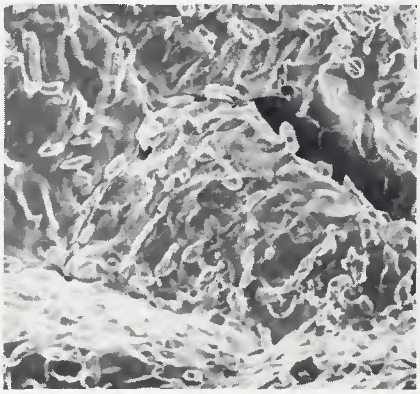


Fig. 15 — Grain boundary facet, sigma phase particles and sgf cracks on fracture surface for specimen shown in Fig. 14. Specimen was fractured at LN_2 temperature

Fig. 14 — Collage of creep specimen from 2B steam line. Specimen fractured at 750°C (1382°F) and 47 MPa (6.8 ksi)

Table 4—Fracture Toughness Properties of 4B Steam Line from Eddystone Unit 1

Specimen Code	Test Temperature (°F)	Fracture[a] Toughness-K_Q (ksi $\sqrt{\text{in.}}$)
PBB	76	41.2
PBD	77	38.3
PBF	76	35.8
PBE	270	35.6

[a] K_Q was determined using the load at the intersection of a 95% secant offset line and the load-deflection plot. This is considered a conservative estimate of the onset of stable crack extension.

ASTM Standard Method E-399. The numerical test data are shown in Table 4. These specimens, which were loaded slowly, did not exhibit any evidence of fast fracture. Only slow stable crack growth took place. Consequently, none of the tests met the linear elastic behavior requirements of the Standard Method. The toughness values in Table 4 are considered conservative estimates of the stress intensity for crack propagation because they were calculated using the load at the intersection of a 95% secant offset line and the load-deflection plot. To prove that this technique does, in this case, produce conservative values, specimen PBF was loaded to a point just beyond where a 95% secant offset line would intersect the load-deflection plot. The specimen was then heat tinted and broken open. Microscopic examination of the fracture surface failed to locate any evidence of crack propagation in the heat tinted region. This indicated that the stable crack growth started at a stress intensity higher than the point used for toughness calculations.

One compact tension specimen (PBC) was located astride a crack found in the steam line. This test was designed to load and open up a "natural" crack and determine if there was anything at the crack front that might initiate a fast fracture. This specimen behaved the same as the standard compact tension specimens which had fatigue sharpened notches as crack fronts.

Examination of the fracture surfaces revealed only grain boundary separation near the steam line outside diameter. As the inside diameter was approached, on either the succession of Charpy specimens or on the compact tension, some grain distortion accompanied the intergranular separation.

Leachants from Insulation Polythionic Acid

Because the cracks were found to be intergranular in boat samples removed from three failed areas of the piping system, insulation material was obtained from locations in original insulation directly from the surface of the pipe. The insulation was taken from locations where pipe cracking was evident to determine contaminant levels for elements which may cause intergranular fracture in austenitic stainless steel.

The insulation was analyzed to determine its pH value and weight percent leachable elemental composition for sodium, potassium and lithium. Also, the chloride and sulfur concentrations were obtained by colorimetric and x-ray fluorescence spectrometry, respectively. Results obtained from a typical analysis are shown in Table 5.

Because of the basicity of the solution and the low or non-existent leachable amount of chloride or sulfur in the insulation, intergranular stress-assisted corrosion cracking was discarded as a cause of failure.

Table 5—Leachants from Insulation Polythionic Acid pH of 50% Water Slurry—9.4 Basic

Element	Wt-%
Sodium, as Na^{+1}	0.032
Potassium, as K^{+1}	0.019
Lithium, as Li^{+1}	0.000
Chloride, as Cl^-	0.014
Sulfur, as SO_4^{-2}	0.000

Conclusions from Preliminary Assessment

The following statements summarize the findings of the preliminary assessment portion of the investigation:

1. The longitudinal cracks in the 4B steam line originate at the outside surface.
2. The crack planes and direction are predominantly normal to the direction of the hoop stress.
3. In addition to the major cracks, creep damage in the form of grain boundary cavities is found fairly uniformly around the pipe circumference and to within approximately ½ in. (12.7 mm) of the ID.
4. The cavities occur primarily in the ligament region between large sigma phase particles.
5. On fresh fractures of material away from the ID, the cavities are decorated with small particles which have a high sulfur content. It has been confirmed that the sulfur did not come from external sources.
6. The cavities are faceted.
7. The creep damaged material did not exhibit any propensity for rapid crack propagation.

Field Metallography

Technique Development

Field metallography of the steam pipes was initiated with metallographic examination of the spool piece shown in Fig. 2. A number of specimens were removed from this section and metallographically prepared for microscopic examination, as described earlier. Der, et al. (Ref. 8) had developed a repeated polish/etch procedure for the detection of cavities in low alloy steels. For the TP316 piping, the specimen remote from the fracture was experimented with using a repeated polishing/etching technique. After a number of trials, a suitable combination was developed, whereby the evidence of creep damage, oriented cavitation, could be detected.

Field Application

In order to adapt the repeated polishing/etching technique to field metallography, a series of experiments was conducted on the OD surface of the test piece. These experiments consisted of using portable grinding and polishing equipment, swab-etching, and repeated polishing/etching, followed by plastic replication of the etched surface. Confidence in use of this method of preparation was achieved when surface areas void of any indications by visual and/or dye penetrant examination showed clear evidence of oriented cavitation known to be present.

Using these procedures, a total of 72 locations at Eddystone Unit No. 1 was examined and documented. These inspections showed creep damage for all piping upstream of the boiler stop valve and no indication (oriented or sigmatized isolated cavitation) for those pipes downstream of the boiler stop valves, even in those pipes with the blocky sigma microstructure.

Validation of Data

In order to further insure the integrity of the data obtained from field metallography, four boat samples were removed from the outlet headers for laboratory examination. The boat samples were about ½ × ½ × 3 in. (12.7 × 12.7 × 76.2 mm) long and were removed with the long dimension along the longitudinal axis of the header. Each boat sample contained a surface previously examined by the replicating technique. Two specimens were removed from each boat sample and metallographically prepared, using standard laboratory technique, for microscopic examination. One specimen from each boat sample was mounted in such a manner to permit viewing of the surface at the same location as that from which the replica was taken, while the other specimen showed a transverse view of the piping material at the same location. The similarity of the three microstructures (replicating technique, direct viewing and transverse view) is demon-

Fig. 16 — Comparison of microstructure revealed by OD plastic replication and metallographic mount of boat sample for the superheater outlet header. Left — replicating technique; center — direct viewing; right — transverse view

strated in Fig. 16 for one location. The other locations from which the boat samples were taken exhibited the same similarity.

Metallography Conclusions

From the tests conducted and the data collected, it was determined that the microstructure observed at the surface of the components was a representative structure and not merely a surface phenomenon. The material upstream of the boiler stop valve showed creep damage when sigma phase was present, and the material downstream of the boiler stop valve showed no creep damage, even in pipe sections which had a blocky sigma microstructure.

Failure Scenario

At this point in the failure investigation, we had established the following facts and observations:

1. Cracking started from the pipe OD and propagated axially along the pipe and radially through the wall thickness.
2. Cracks were intergranular.
3. Creep voids had opened in grain boundaries.
4. No cracks or creep voids were detected downstream of the boiler stop valves.
5. Ductility tests showed the outer two-thirds of the pipe wall to have low ductility.
6. The pipe showed no evidence of creep swelling.
7. Chemical analysis of the 316 stainless steel material indicated compliance with the original requirements of the specification.

Facts one, two and three taken together would indicate the classic case of creep rupture of a pressurized cylinder under internal pressure. In order to accept this failure scenario, one would have to conclude that: one, the material was substandard, or two, the allowable stress in the ASME Code was very optimistic.

Fact seven established that the material was not substandard, but it should be noted that cracking did correlate with the weaker heats of material. Because of facts four, five, and six, we became convinced that we were not dealing with the classic case of stress rupture.

If this material was merely weak in creep, it would have swelled before it ruptured. The stress rupture conclusion also did not explain the fact that no cracking or creep voids had been found downstream of the boiler stop valves. It was these inconsistencies which forced us to abandon failure scenarios which assumed bad material or incorrect allowable stresses.

The fact that the failed pipe had not swelled and that a definite ductility gradient was present across the wall thickness directly led to the following speculations:

1. Residual stresses combined with primary stresses to cause premature failure.
2. Since a residual stress field must be self-equilibrating, the outer two-thirds of wall thickness must have been tensile and the inner third compressive.
3. The most likely source of this residual stress field is a severe thermal downshock.
4. Since the material downstream of the stop valves appears undamaged, this down-shock must occur when the boiler stop valve is closed.

This failure theory was arrived at because it appeared to be the only hypothesis which was consistent with the facts and observations determined during the preliminary assessment phase of this investigation. In order to test the likelihood of this theory being correct, analytical studies were carried out using assumed thermal loadings. The objective of these studies were twofold: one, to numerically demonstrate that the failure scenario was in agreement with established mathematical laws and theories; and two, to assess the severity of thermal shock required to predict failure due to creep rupture in the known time frame.

Stress Analysis

A transient heat transfer and thermal stress analysis was performed for a forced cooldown of 500°F (278°C) in 5 minutes using the computer program, CREPLACYL. CREPLACYL is a CE program which calculates the plastic and creep strains induced in thick wall cylinders due to transient thermal and pressure load-

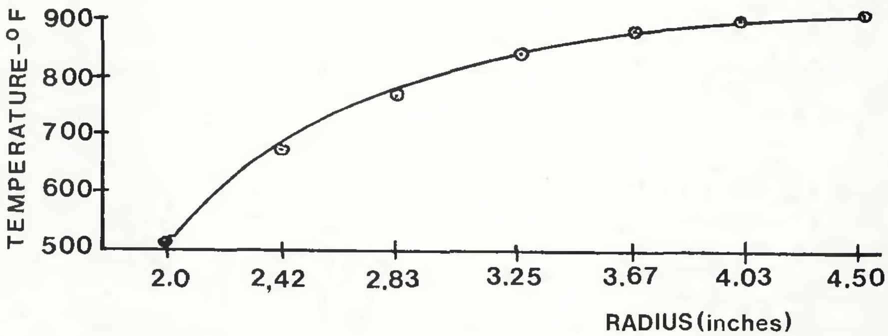


Fig. 17 — Thermal gradient main steam pipe — 500°F in 5 minutes down-shock transient

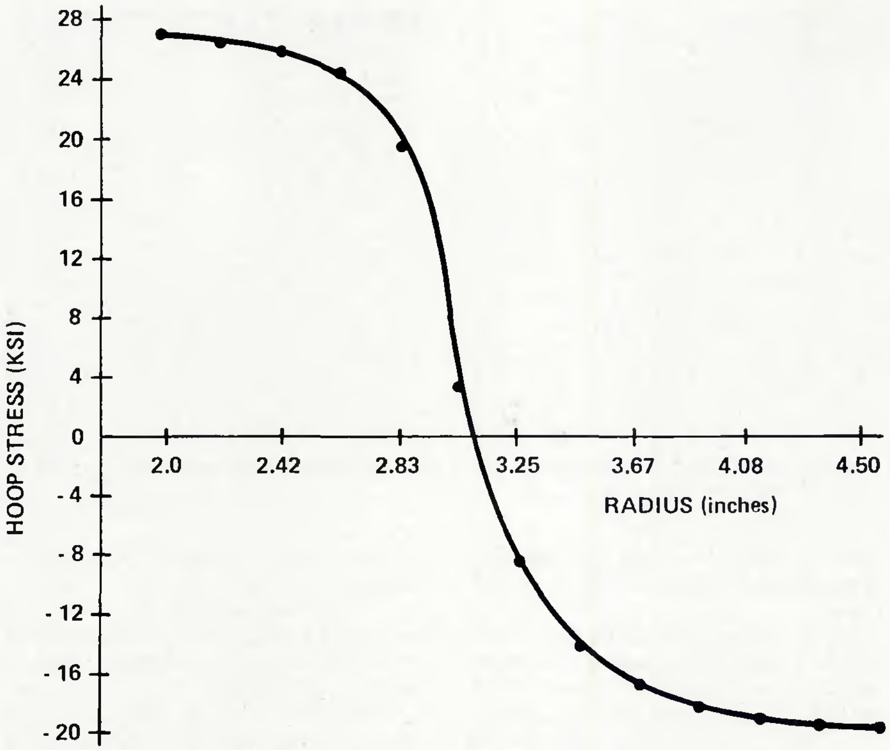


Fig. 18 — Elastic-plastic hoop stress resulting from thermal gradient Fig. 17

ings. The program features temperature dependent material properties, kinematic hardening based on Prager's hardening rule, and solutions for heat transfer, compatibility and equilibrium by finite difference methods. Material properties for 316 stainless steel were taken from the *Liquid Metal Fast Breeder Materials Handbook*.

The operational cycle which was simulated in this analytical study was a 200°F/hr (111° C/hr) normal start-up followed by a 2000 hour hold period at 1140°F (616°C). At the end of the hold period, the pipe was cooled slowly to 1000°F (538°C). At this time, the thermal shock was imposed on the pipe.

Results

Figure 17 is a plot of the maximum temperature gradient induced in the pipe due to the assumed thermal shock loading. This gradient was approximately 390°F (217°C). Figure 18 shows the elastic-plastic peak hoop stress distribution which results from this gradient. A stress of +28 ksi (193 MPa) was calculated at the inner bore and −19.8 ksi (−136.5 MPa) at the outer diameter. This loading condition resulted in a plastic strain field being induced in the cylinder. We calculate 0.15% plastic-strain at the inner bore and 0.08% at the outer diameter.

Upon removal of the thermal gradient, the vessel was cooled to room temperature and the pressure removed. Figure 19 plots the room temperature residual stress field which is necessary to balance the plastic moment that has been induced in the cylinder. It should be noted from Fig. 19 that at room temperature the inside bore is in compression and the outside diameter is in tension. The present analysis indicates bore stresses of −30 ksi (−207 MPa) and OD stresses of +20 ksi (138 MPa).

The next loading step was to reapply the internal pressure and heat the pipe slowly to 1140°F (616°C). The resulting stress field is shown in Fig. 20. The solid lines show the stress distribution at the beginning of a 2000 hour hold period and the dotted lines indicate the relaxation which has taken place due to creep. It should be noted that the average tensile stress during the hold period is in excess of the value which would cause stress rupture in 100,000 hours.

Conclusion

The results of the elastic/plastic/creep analysis described above lead directly to the following conclusions:

1. Repeated severe thermal downshocks could explain this failure.
2. The magnitude of this down-shock was less than 500°F (278°C) but greater than 150°F (83°C). The exact number is indeterminate because of the temperature dependency of the material properties.
3. If this failure scenario is correct, the failed pipe should have significant residual stresses at its inside and outside diameters. Furthermore, the OD residual stresses should be tensile and the ID residual stresses should be compressive.

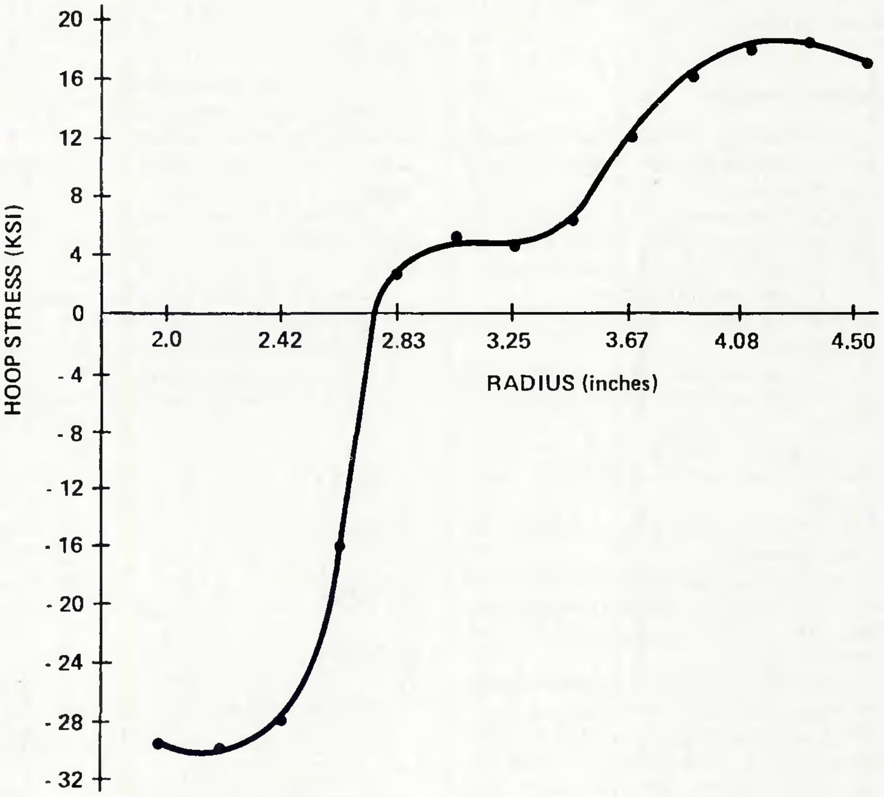


Fig. 19 — Main steam pipe residual stress field 100°F, 14.7 psi

Residual Stress Measurements

The laboratory and field residual stress measurements on the Eddystone TP-316 piping were made using a modified air-abrasive hole drilling technique (Ref. 13). In this technique, a special 45 degree rectangular strain gage rosette is bonded to the surface of the material to be tested. A small hole, approximately 0.070 in. (1.8 mm) in diameter and depth, is then drilled in the center of the rosette pattern such that each of the three elements is equidistant from the edge of the hole. The strain changes measured by each element after stress redistribution in the vicinity of the hole are used to compute the magnitude and direction of the maximum and minimum principal residual stresses.

The hole is drilled by propelling 50μ aluminum oxide particles through a 0.0625 in. (1.6 mm) ID tungsten carbide nozzle using compressed gas or air as a carrier. The particles impinge on the material being measured and abrade a sharply defined hole of proper diameter and depth in approximately 8-9 minutes. Air-abrasive drilling is a low energy, essentially "stress free" method of introducing a hole and offers a distinct advantage over mechanical drilling methods. In mechanical drilling, the stresses induced from the machining operation can actually be greater than the residual stresses to be measured, depending on a number of factors, such as type and sharpness of cutter, operator technique, and material characteristics. These variables are eliminated with air-abrasive drilling. The overall measurement error using the modified air-abrasive hole-drilling technique has been shown to be less than ± 10 percent (Ref. 13).

For the Eddystone TP-316 piping, residual stress measurements were first made in the laboratory on a cylindrical section from the 4B main steam line. The results of these measurements, shown in Table 6, indicated ID compressive and OD tensile hoop stresses were present. From these results, the decision was made to conduct on-site measurements at various OD locations in the plant. The results of these field measurements are also shown in Table 6.

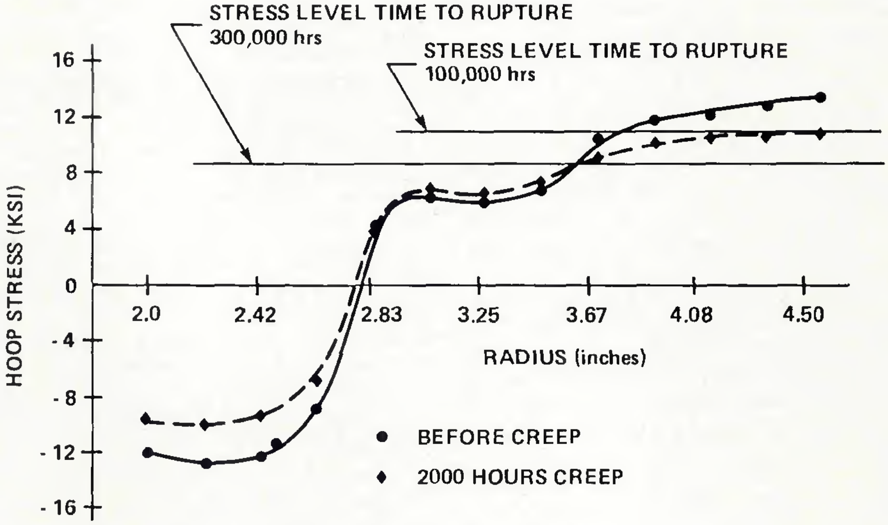


Fig. 20—Main steam pipe steady state conditions 1140°F, 4500 psi

The tabular results are arranged by floor level beginning at the penthouse on the eleventh floor and continuing downward to the fourth floor, first floor, and the basement. In all but one instance, the maximum (most positive) principal residual stress was nominally oriented in the axial direction with the minimum principal residual stress being nominally oriented in the circumferential direction. The one exception was in line 3B on the fourth floor where the two principal stresses were very nearly equal. The maximum principal stress direction is shown in the table by the angle, Θ, which is the direction relative to element 1 of the strain gage rosette. In all cases, element 1 was aligned with the axis of the pipe or header.

Relatively large tensile axial residual stresses were measured at every location except in outlet steam header 4B in the eleventh floor penthouse. The largest measured axial stresses were in lines 2A and 2B at the stop valves on the first floor. These were areas of complex geometry where spool pieces containing thermocouple wells had been welded in the lines.

In contrast to the axial residual stresses, the circumferential residual stresses formed a much different pattern. Measurements on two outlet steam headers on the eleventh floor showed small hoop stresses, one being compressive and the other tensile. Measurements above the stop valves on the fourth floor and at the stop valves on the first floor showed large tensile hoop stresses. Finally, a measurement well below the stop valves on the 1A steam line at the basement level (before the line enters a junction header) showed a small compressive stress.

Summary

The cause of this premature piping failure was creep rupture. This failure mode occurred because of residual stresses induced in the piping by a repeated thermal down-shock. It should

Table 6—Laboratory and Field Residual Stress Measurement Results on Philadelphia Electric, Eddystone Unit 1 Headers and Steam Lines

	Location	Component Identification	Max Principal Stress—ksi	Min. Principal Stress—ksi	Θ Direction—degrees[a]
Laboratory Measurements	Pipe ID	4B Steam Line	−8.1	−14.0	166.5
	Pipe OD	4B Steam Line	3.1	−3.6	95.2
On-Site Measurements in Unit 1	Floor 11	1A Outlet Header	13.7	3.8	160.4
	Floor 11	4B Outlet Header	0.9	−6.6	14.3
	Floor 4	1B Steam Line	17.0	13.0	10.1
	Floor 4	3B Steam Line	11.5	8.8	92.7
	Floor 1	2A Steam Line	21.2	13.6	170.9
	Floor 1	2B Steam Line	30.3	20.2	4.0
	Basement	1A Steam Line	12.5	−5.2	0.0

[a] Direction of maximum principal residual stress measured clockwise from rosette gage element 1. Element 1 is axially oriented in all cases.

also be noted that the material with sigmatization failed first.

The commercial impact of these findings was to replace all piping from the outlet headers to the boiler stop valves. The material downstream of the boiler stop valves was judged to be acceptable for service because there were no signs of cracking, creep damage, or dangerous tensile residual stress. It can also be concluded that the results of this study indicate that 316 stainless steel does not have any inherent liabilities to high temperature operation. However, the specification for the replacement piping required a positive nickel balance to minimize the formation of sigma phase.

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WRC Bulletin 306
July 1985

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By J. R. Payne

Over 180 completed questionnaires were received from a distribution list of 295 flanged joint users. The results of the survey provided guidance in establishing research needs and priorities for flanged joint improvement programs.

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