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RUPTURE PROPERTIES OF 2-1/4 Cr - 1 Mo, CMo, 3 Cr - 1 Mo, AND TYPE 347 STAINLESS STEEL PIPES FROM ESSEX, SEWAREN, BURLINGTON AND KEARNY GENERATING STATIONS OF THE PUBLIC SERVICE ELECTRIC AND GAS COMPANY

by

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RUPTURE PROPERTIES OF 2-1/4 Cr - 1 Mo, CMo, 3 Cr - 1 Mo, and TYPE 347 STAINLESS STEEL PIPES FROM ESSEX, SEWAREN, BURLINGTON AND KEARNY GENERATING STATIONS OF THE PUBLIC SERVICE ELECTRIC AND GAS COMPANY

SUMMARY

Rupture tests were used to evaluate the properties of eight samples of steam piping from the generating stations of the Public Service Electric and Gas Company as follows:

Sample RT1 - Essex Generating Station Number 1 Unit Main 1000°F Steam Pipe. New 2-1/4 Cr - 1 Mo Steel 12.952-inch O.D. x 9.530-inch I.D. x 1.711-inch wall.

Sample RT2 - Essex Generating Station Number 7 Unit Main 950°F Steam Pipe. CMo Steel Pipe after 75,054 Hours of Service - No Graphite.

Sample RT3 - Essex Generating Station Number 26 Boiler Steam Lead CMo Steel Pipe after 81,536 Hours of Service at 950°F - Segregated graphite.

Sample RT4 - Sewaren Generating Station Number 3 Unit Main 1050°F Steam Piping. New 3 Cr - 1 Mo Steel 13.2-inch O.D. x 2.4-inch Wall Pipe.

Sample RT5 - Sewaren Generating Station Number 2 Unit Main 1050°F Steam Piping after 22,716 Hours of Service.

Type 347 Stainless Steel 6.625-inch O.D. x 5.189-inch I.D. x 0.718-inch Wall Pipe.

Sample RT6 - Sewaren Generating Station Number 2 Unit Main 1050°F Steam Piping Weld after 22,716 Hours of Service.

Weld in Type 347 Stainless Steel 6.625-inch O.D. x 5.189-inch I.D. x 0.718-inch Wall Pipe.

Sample RT7 - Burlington Generating Station Number 5 Unit, Number 13 Boiler Header 950°F Steam Lead after 93,144 Hours of Service at 950°F.

CMo Steel 12.75-inch O.D. x 10.126-inch I.D. x 1.312-inch Wall Pipe-General Nodular Graphite Present.

Sample RT8 - Kearny Generating Station Number 7 Unit 1100°F Steam Turbine Leads

New Type 347 Stainless Steel 6.625-inch O.D. x 4.705-inch I.D. x 0.960-inch Wall.

The rupture tests were in general run at the normal operating temperature and at a temperature 50°F higher. The rupture strengths obtained are summarized in Table I. The table also includes average values established for the types of steel involved.

The unused 2-1/4 Cr - 1 Mo steel pipe (Sample RT1) exhibited rupture strengths 2000 to 3000 psi lower than the average for the steel. The strengths, however, appear more than adequate for the reported operating stress and temperature.

The CMo steel pipe samples (RT2, RT3 and RT7) all exhibited much lower rupture strengths up to 10,000 hours than average values for new steel. Rupture strengths for 100,000 hours were generally equal to or above the average for unused material. Elongation and reduction of area were generally much higher than for unused CMo steel. It was concluded that this is the natural consequence of prolonged exposure to temperature and stress and the resulting structural changes in the metal, commonly identified as spheroidization. Insofar as could be established the nominal operating stress did not use up a measurable amount of rupture life since the estimated times for rupture under the operating conditions ranged from several hundred thousand to several million hours.

The direct influence of graphitization in Samples RT3 and RT7 was very meager. Insofar as could be ascertained it had little, if any, effect on rupture strength. When fracture occurred through graphite concentrations in Sample RT3, elongation and reduction of area were low. The elongation and reduction of area in all specimens of Sample RT7 with general graphitization were high. There was metallographic evidence of cracking or graphite growth away from the nodules of graphite during the rupture tests.

The unused 3Cr-1 Mo Steel pipe (Sample RT4) had rupture strengths very nearly the same as published average values for the steel. The ductility in the rupture tests was high.

The Type 347 pipe (Sample RT5) which had been in service for 22,716 hours had rupture strengths well below the average for the steel but within the scatter band of published data. Apparently the service tended to lower the short time strength with less effect on long time strength. The reported operating stress was so far below the rupture strengths that any rupture life used up would be negligible. It is presumed, therefore, that the low strength was either due to structural changes in the metal during service or to the steel initially having strength on the low side of the range for the alloy.

The rupture tests on the welded section of Type 347 steel (Sample RT6) showed strengths slightly lower than the pipe metal of Sample RT5 at 1050°F and slightly higher at 1100°F. Fracture occurred mainly in the base pipe metal with fracture in the heat-affected zone in one case or starting in the heat-affected zone and progressing through the base metal in one other sample. All samples necked down in the pipe metal on both sides of the weld-deposited metal, indicating the higher strength of the weld-deposited material. Whether fracture occurred in the base metal or heat-affected zone seemed to be a matter of chance depending on several factors.

The unused Type 347 pipe (Sample R T8) had rupture strengths and ductility which were practically identical with the average for Type 347 steel.

TABLE I

Summary of Rupture Strengths Obtained for Eight Samples of Pipe Submitted from the Essex, Sewaren, Burlington, and Kearny Generating Stations

Sample No.	Service Life (hrs)	Grade Steel	Temp. (°F)	Stress for Rupture in Indicated Time Period (psi) 10-hr	100-hr	1000-hr	10,000-hr	100,000-hr
RT1	None	2-1/4CR - 1 Mo	1000	40,000	29,000	21,000	15,000	11,000
			1050	31,000	22,000	16,000	11,500	8,200
Average Values for Annealed 2-1/4Cr-1 Mo Steel (from ASTM STP No. 151)								
			1000	--	30,000	23,500	17,500	14,000
			1050	--	24,500	19,000	13,500	10,000
RT2	75,054	C-Mo	950	31,000	29,500	26,500	21,000	17,000
			1000	27,000	24,000	19,500	12,500	8,200
RT3[a]	81,536	C-Mo	950	25,000	21,500	18,500	16,000	13,500
			1000	22,000	18,500	14,500	11,500	9,000
RT7[b]	93,144	C-Mo	950	31,000	27,000	22,500	19,000	16,000
			1000	25,500	21,500	18,000	15,000	12,000
Average Values for New C-Mo Steel (from ASTM STP No. 151)								
			950	--	42,000	35,000	28,000	10,500[c]
			1000	--	38,000	26,000	16,500	7,000[c]
RT4	None	3Cr-1Mo	1050	27,000	21,000	16,500	12,500	9,800
			1100	23,000	17,000	12,500	9,400	7,000
Average Values for 3 Cr-1 Mo Steel (from ASTM STP No. 151)								
			1050	--	23,000	15,500	11,500	--
			1100	--	18,000	12,000	8,750	--
RT5	22,716	Type 347	1050	--	40,000	33,500	28,000	23,500
			1100	--	33,000	27,000	21,000	17,000
RT6[d]	22,716	Type 347	1050	--	39,000	32,000	27,000	22,000
			1100	--	36,000	28,000	22,000	17,000

(a) This pipe material contained segregated graphite.
(b) General nodular graphite was present in this pipe.
(c) These values are probably low. It is estimated that values of 16,000 and 8,500 psi are probably closer to the real average.
(d) Specimens taken across welded joint.

(Continued on next page)

TABLE I (continued)

Sample No.	Service Life (hrs)	Grade Steel	Temp. (°F)	Stress for Rupture in Indicated Time Period (psi) 10-hr	100-hr	1000-hr	10,000-hr	100,000-hr
RT8	None	Type 347	1100	--	39,000	34,000	28,000	23,000
			1150	--	34,500	28,500	23,000	19,000
Average Values for New Type 347 Steel (from ASTM STP No. 124)								
			1050	--	50,000	43,000	32,000	26,500
			1100	--	39,000	34,500	26,500	21,500
			1150	--	32,000	27,500	21,500	17,000

PART I

ESSEX GENERATING STATION NUMBER 1 UNIT MAIN 1000°F STEAM PIPE

New 2-1/4 Cr - 1 Mo Steel Pipe - Sample RT1

Rupture tests were conducted at 1000° and 1050°F on samples cut from a length of pipe submitted under the designation "RT1". The pipe was made of 2-1/4 Cr - 1 Mo steel and had not been in service. The pipe dimensions were 12.952-inch O.D. x 9.530-inch I.D. x 1.711-inch wall. The normal operating conditions were to be 1000°F and 1350 psi pressure.

Description of Pipe and Service Conditions

An eight-inch length of pipe, identified as Sample RT1, from the Essex Generating Station was furnished for machining into test specimens. The information supplied regarding the sample was as follows:

Steel: 2-1/4 Cr - 1 Mo steel (ASTM: A-213-Grade T22)

Location: Main steam pipe, Number 1 Unit

Size: 12.952-inch O.D. x 1.711-inch wall thickness x 9.530-inch I.D.

Chemical Composition (percent):

C	Mn	P	S	Si	Cr	Mo
.06-.08	.48-.62	.012-.015	.013-.017	.13-.50	2.14-2.32	.92-1.02

Mill Heat Treatment: 1550° ±25°F for 3 hours before machining.

Physical Properties:

Tensile Strength (psi)	63,950 to 69,300
Yield Strength (psi)	29,200 to 43,600
Elongation in 2 inches (%)	25.5 to 35.0
Reduction of Area (%)	56.0 to 71.6
Brinell Hardness	163

McQuaid-Ehn Grain Size:	ASTM 1-4
Service Conditions:	
Service hours	None
Calculated hoop stress($S=Pd/2t$)	4,890 psi
Operating Temperatures:	
Normal	1000°F
Average	--
Maximum (Rating for short swings. Not to exceed 1% of operating time.)	1050°F
Operating Pressures:	
Normal	1350 lbs.
Maximum	1500 lbs.

Procedure

Standard 0.505-inch diameter specimens with a 2-inch long gage section were taken parallel to the length of the pipe. Specimens representative of both the outer and inner portions of the pipe were tested. Those identified in the results section as "O" were obtained from the outer half of the pipe wall and those marked "I" from the inner half.

Sufficient tests were conducted to establish the stress-rupture time curves out to 1000 to 2000 hours for testing temperatures of 1000° and 1050°F.

Results

The individual rupture-test data at 1000° and 1050°F are given in Table II and the resulting stress-rupture time curves are plotted on logarithmic coordinates in Figure 1. Table III shows the stress-rupture strengths indicated by the stress-rupture time curves.

Figure 1 shows that for tests of about 1000 hours duration at 1000°F and 2000 hours at 1050°F no evidence of breaks in the stress-rupture time curves was observed and that the two curves are parallel. A longer test was not conducted at 1000°F because the absence of a break at 1050°F and the parallel relationship of the curves indicated beyond any normal question of doubt that a longer test at 1000°F would have fallen on the curve as drawn.

No difference in rupture strength was observed between specimens taken near the outer and inner surfaces of the pipe. This is shown by the points plotting on the same curves in Figure 1.

Table II indicates that the pipe material showed high elongation at both 1000° and 1050°F. Little or no difference in elongation was observed between the specimens from the inside and outside of the wall at 1000°F, although at 1050°F the average elongation of the specimens from the outside of the wall appeared to be higher than the inside specimens. There was no difference in reduction of area values.

The microstructure of the as-received 2-1/4 Cr - 1 Mo pipe material is shown in Plate 1, and Plates 2 and 3 illustrate the microstructure at the fracture and at the surface of the specimen after prolonged testing at 1000° and 1050°F, respectively.

The original structure consists of ferrite grains, very small grains of pearlite, and the remains of larger ferrite grains which had recrystallized to many small grains of ferrite. This structure is typical of a relatively coarse-grained, hot-worked initial structure which has been heat treated between the upper and lower critical temperatures. The reported heat treatment at 1550°F would be expected to produce this structure.

During testing at 1000° and 1050°F the grains were extensively elongated in the direction of the applied stress, and at 1050°F the pearlite spheroidized during the test. No evidence of intergranular separation at either the fracture or adjacent to the fracture was observed for the specimens tested at 1000° or 1050°F. Both specimens showed evidence of the light general surface oxidation which occurred during the test.

The structures of the rupture specimens were typical of 2-1/4 Cr - 1 Mo steel with the initial structure exhibited by the pipe. The extensive deformation of the grains was due to the high elongation at fracture. At 1000° and 1050°F fracture would be expected to occur with little or no evidence of intergranular separation, and carbide spheroidization would be expected in the highly deformed area near the fracture after 2000 hours at 1050°F.

Discussion of Results

The rupture strengths of the pipe are compared in Figure 2 with the average strengths for annealed 2-1/4 Cr - 1 Mo steel as given in Reference 1. The pipe material exhibited 2000 to 3000 psi lower strength than the average and was also lower than any of the individual test points on which the average was based. Numerical comparative values are included in Table III.

The estimated 100,000-hour rupture strength at 1000°F of 11,000 psi is 2.25 times the reported hoop stress of 4,890 psi. The rupture time under 4,890 psi, according to extension of the 1000°F curve in Figure 1, would be in the millions of hours. The ratio is also near the normal for the ratio of stress for rupture in 100,000 hours to 0.01-percent per 1000 hour creep strength. There does not, therefore, appear to be any reason for concern over the lower strength. Certainly, it is not surprising that large heavy wall pipe had lower strength than bar stock on which the average curve was based.

The steel had relatively low carbon content in comparison to that for most published data. This in itself would be expected to result in slightly low comparative rupture strengths. There is also uncertainty as to the effect of annealing within the two phased ferrite plus austinite range. The structure of the steel, Plate 1, shows that the temperature of annealing was not sufficiently far into the two phased region, due to the low carbon content, to break up the as-rolled structure.

TABLE II

Rupture-Test Data for 2 1/4 Cr - 1 Mo Steel Main Steam Pipe Prior to Service in Number 1 Unit of the Essex Generating Station

Sample RT1

Test Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elongation in 2-inch (%)	Reduction of Area (%)	Specimen
1000	35,000	25.4	29.3	79.7	I
	29,000	103	35.0	87.8	O
	25,000	314	42.5	84.5	I
	22,000	703	55.0	85.4	O
1050	30,000	11.5	38.5	82.5	I
	22,000	112	78.0	88.5	O
	19,000	301	63.4	87.5	O
	16,000	874	34.7	88.0	I
	14,500	1976	51.0	85.0	I

I - Specimen taken from inner half of wall
O - Specimen taken from outer half of wall

TABLE III

Stress-Rupture Strengths for 2 1/4 Cr - 1 Mo Steel Main Pipe Prior to Service in Number 1 Unit of the Essex Generating Station

Sample RT1

Temp. (°F)	Stress for Rupture in Indicated Time Periods (psi)				
	10-hr	100-hr	1000-hr	10,000-hr	100,000-hr
	Pipe Sample RT1				
1000	40,000	29,000	21,000	15,000	11,000
1050	31,000	22,000	16,000	11,500	8,200
	Average Values for Annealed Steel (from ASTM STP No. 151)				
1000	--	30,000	23,500	17,500	14,000
1050	--	24,500	19,000	13,500	10,000

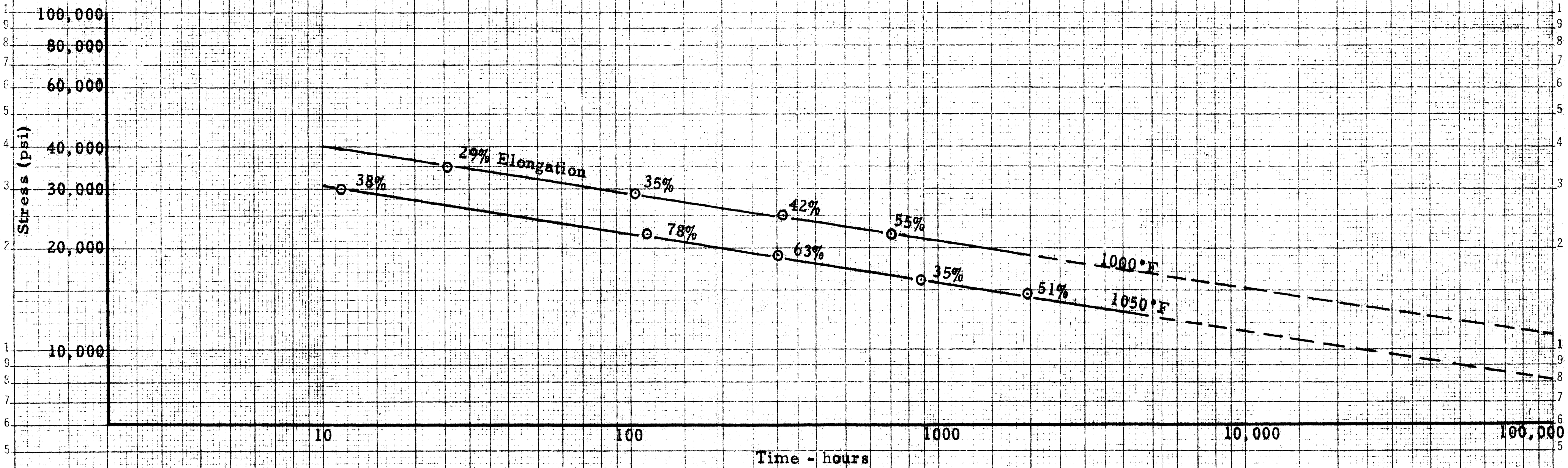


Figure 1. - Stress-Rupture Time Curves at 1000° and 1050°F for 2 1/4 Cr - 1 Mo Steel Main Steam Pipe Prior to Service in Number 1 Unit, Essex Generating Station.

(Sample RT1)

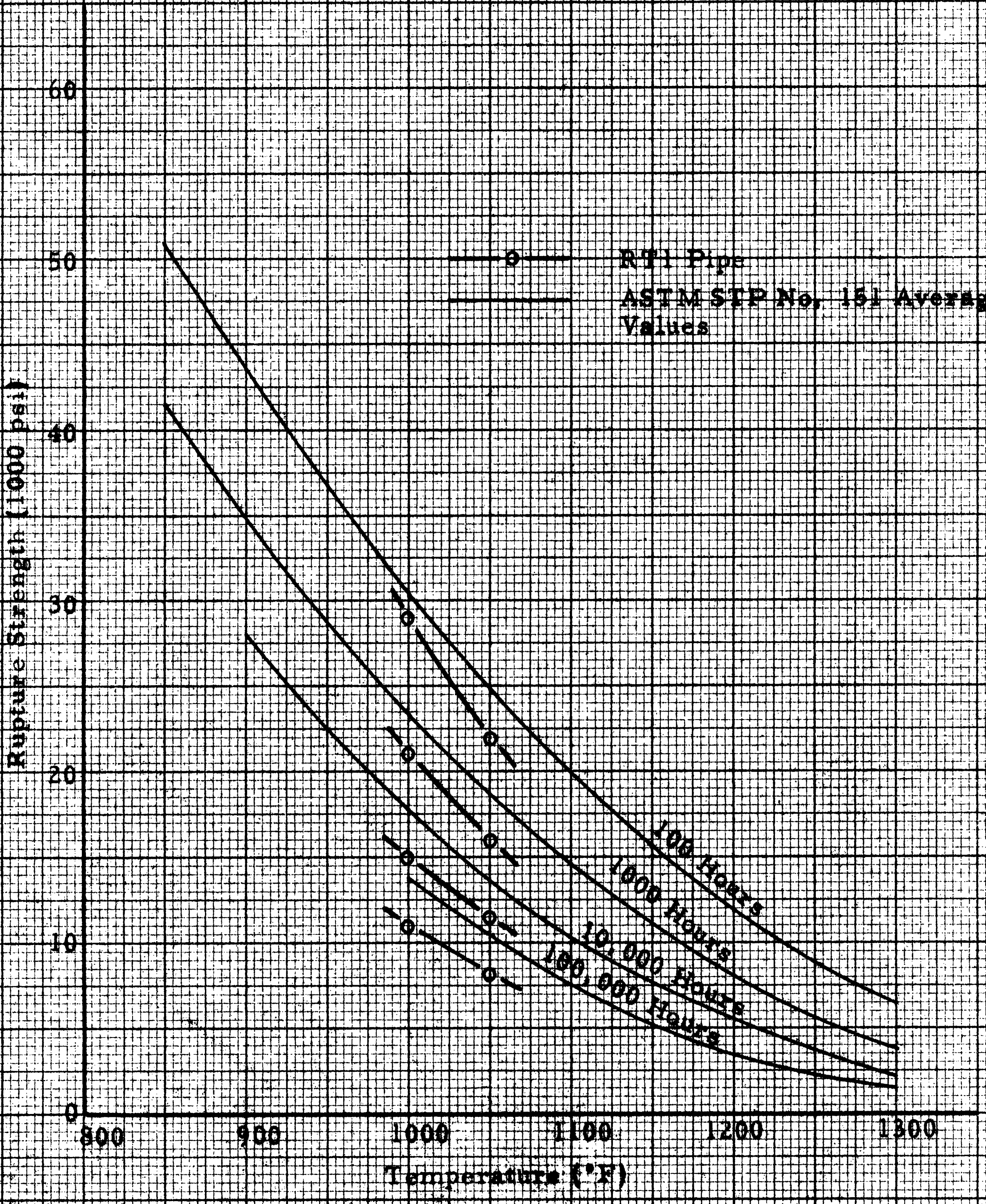
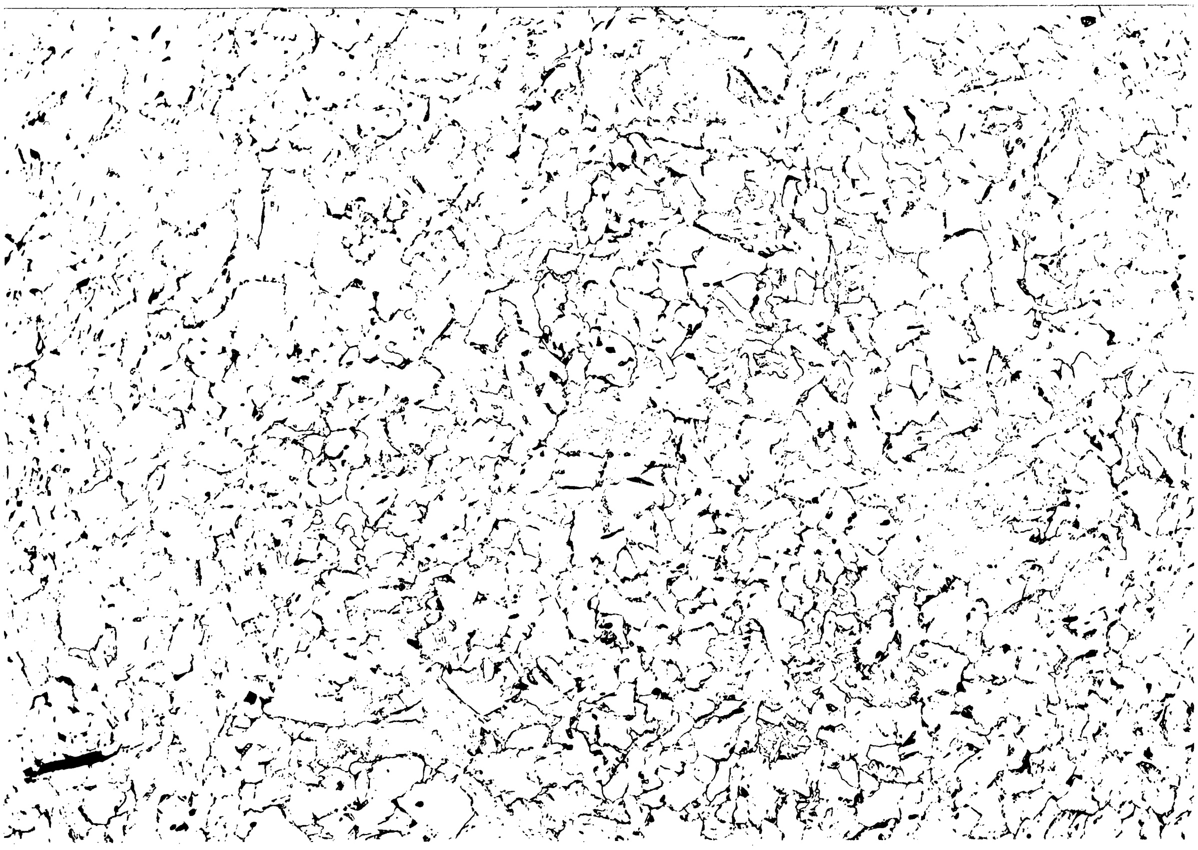
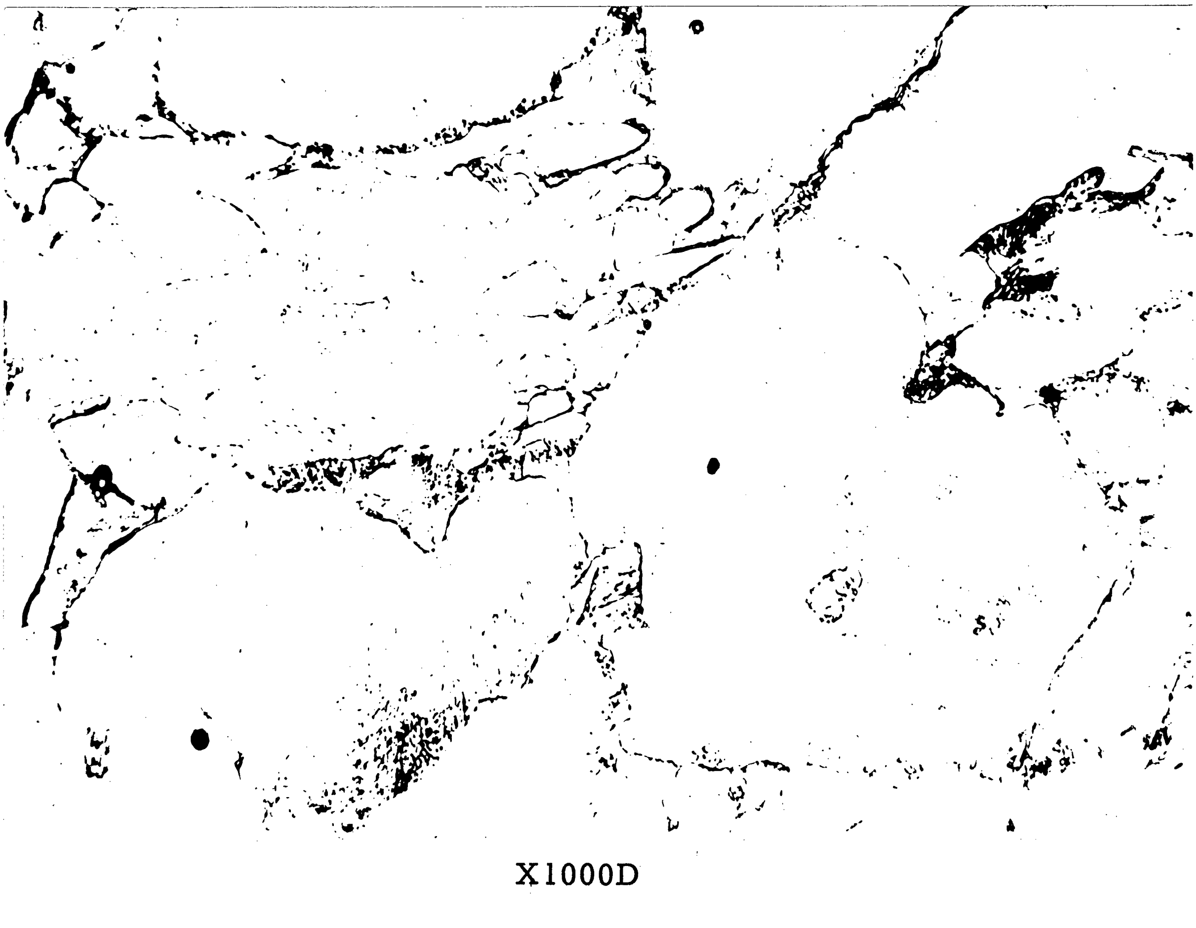


Figure 2. - Comparative Rupture Strengths for 2-1/4 Cr - 1 Mo Pipe RTI and Average Values for Annealed 2-1/4 Cr - 1 Mo Steel.



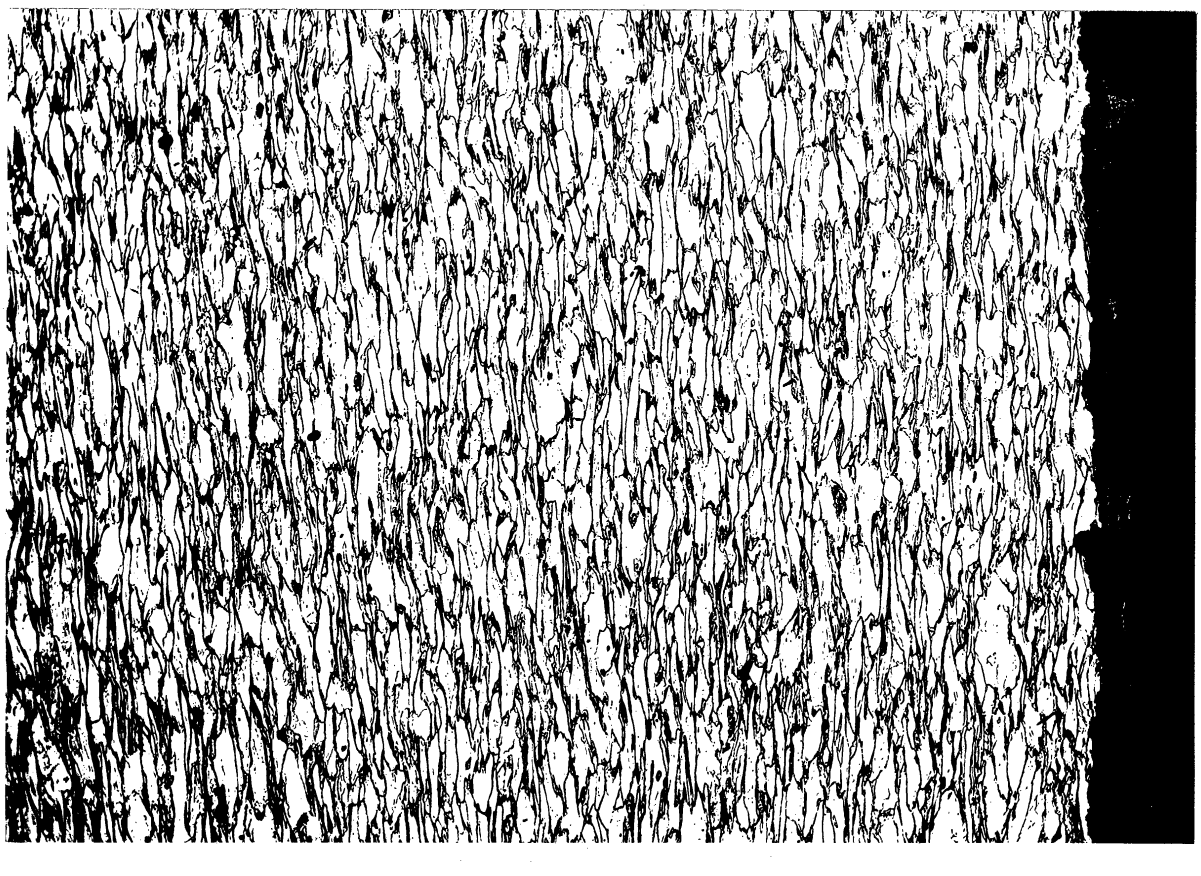
X100D



X1000D

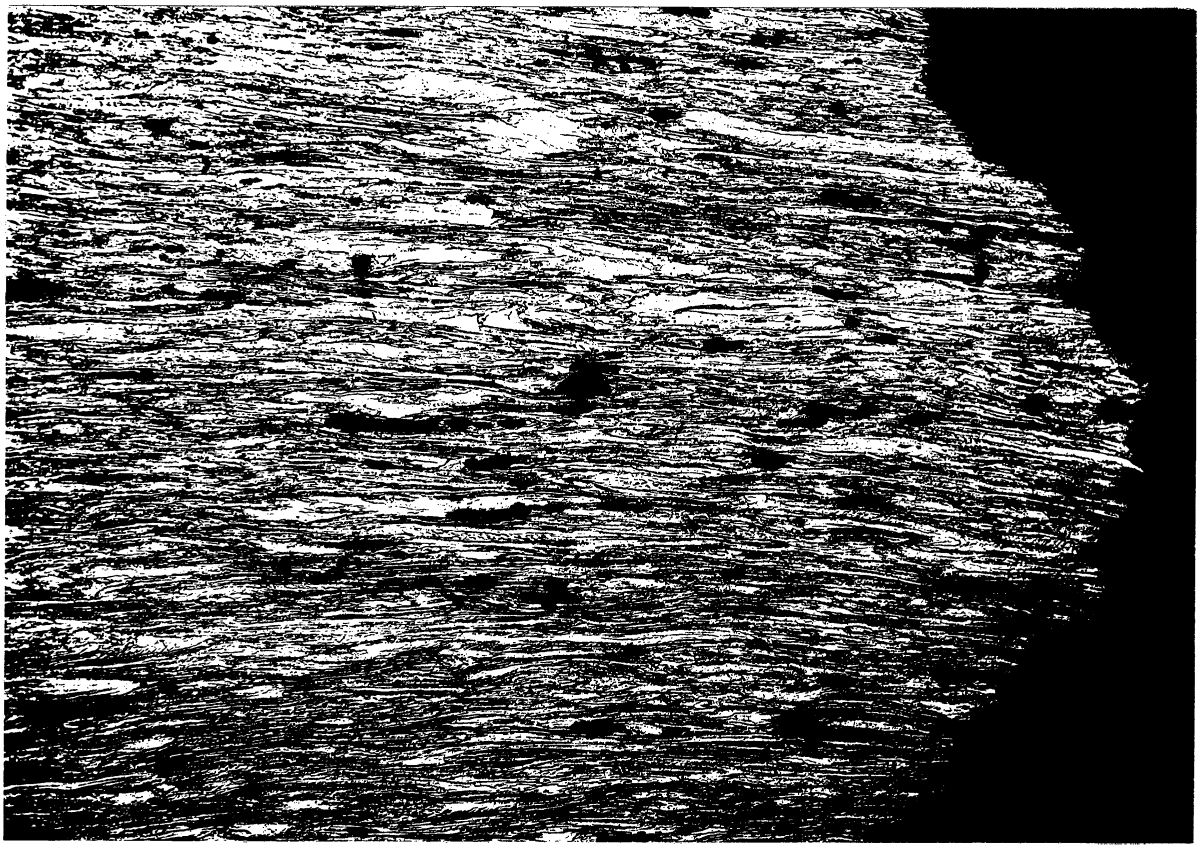
Plate 1. - Original Microstructure of 2-1/4 Cr - 1 Mo Steel Pipe (RT-1) from Essex Generating Station, No. 1 Unit. No Time in Service.

X100D - Fracture

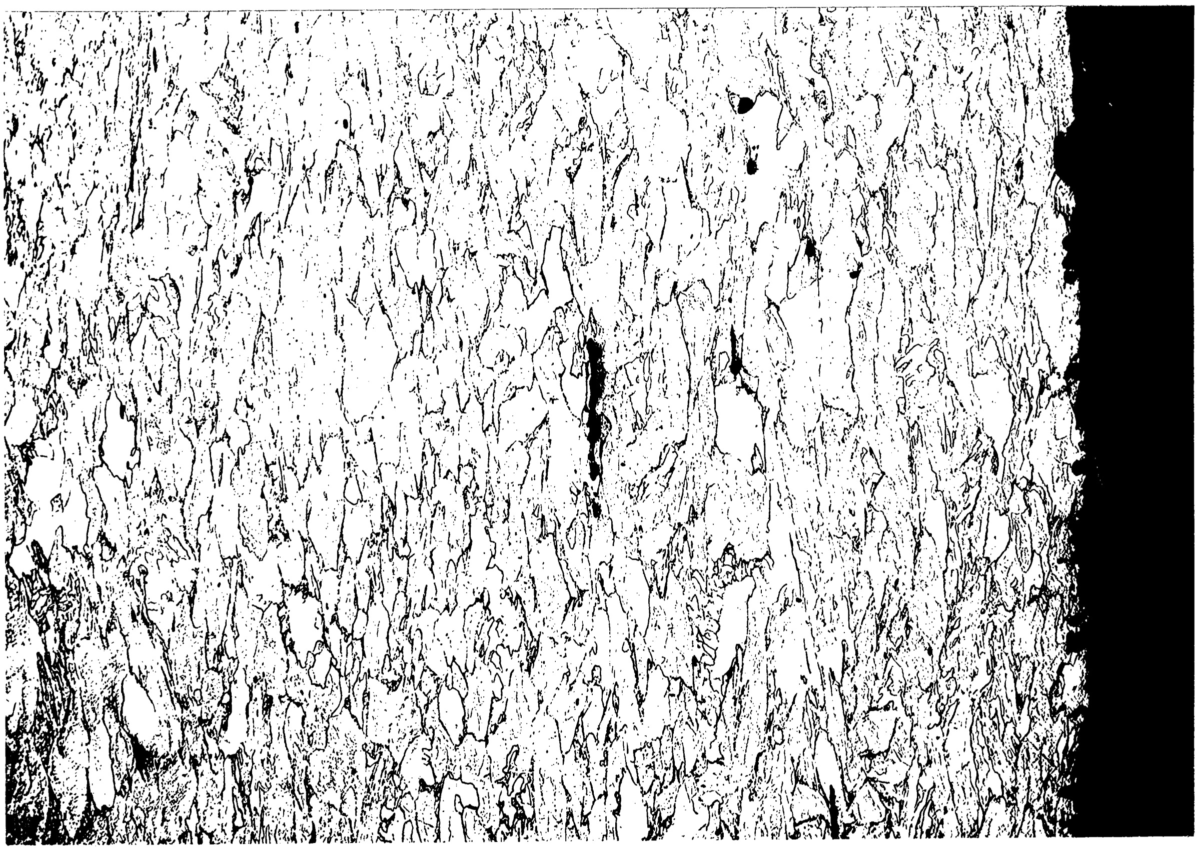


X100D - Surface

Plate 2. - Microstructure of Stress-Rupture Specimen from 2-1/4 Cr - 1 Mo Steel Pipe (RT-1) Fractured in 703 Hours Under 22,000 Psi at 1000°F.



X100D - Fracture



X100D - Surface

Plate 3. - Microstructure of Stress-Rupture Specimen from 2-1/4 Cr - 1 Mo Steel Pipe (RT-1) Fractured in 1976 Hours Under 14,500 Psi at 1050°F.

PART II

ESSEX GENERATING STATION NUMBER 7 UNIT MAIN 950°F STEAM PIPE

CMo Steel Pipe After 75,054 Hours of Service - Sample RT2

Rupture tests were conducted at 950° and 1000°F on samples cut from sections of pipe submitted under the designation "RT2". The pipe was carbon 0.5-percent molybdenum steel and had been in service for 75,054 hours. The pipe dimensions were 12.75-inch O.D. x 10.126-inch I.D. x 1.312-inch wall. The normal operating conditions were 950°F and 1350 psi pressure.

Description of Pipe and Service Conditions

Two samples consisting of an 8-inch long full ring and a 16-inch long half ring, identified at RT2, were submitted for testing. The information supplied with the samples was as follows:

Steel: CMo steel (ASTM: A-158-36 Grade P1)

Location: Number 7 unit - Public Service Specification 133

Size: 12.75-inch O.D. x 1.312-inch wall x 10.126-inch I.D.

Chemical Composition: 0.20% maximum carbon specified
1.9 pounds of aluminum added per ton

Mill Heat Treatment: 0.5 hours at 1650°F + 0.5 hours at 1200°F

Shop Heat Treatment: 3 hours at 1200°F

Physical Properties: 55,000 psi minimum tensile strength specified.

Service Condition:

Service hours	75,054
Calculated hoop stress (S=Pd/2t)	5,910 psi

Operating Temperatures	
Normal	950°F
Average	912.6°F
Maximum (Rating for short swings. Not to exceed 1% of operating time.)	1000°F
Operating Pressures	
Normal	1350 lbs.
Maximum	1500 lbs.

Procedure

Standard 0.505-inch diameter specimens with a 2-inch gage length were taken parallel to the length of the pipe. In addition, a tangential specimen with an 0.250-inch diameter and 1-inch gage section was obtained for a check test at 1000°F.

During the sectioning to obtain test bars, it was noted that the 8-inch full ring had circumferential cracks visible to the eye parallel to the length of the pipe and approximately in the center of the wall. Consequently, care was exercised to avoid the cracked area in removing test coupons.

A sufficient number of tests were made to establish the stress-rupture time curves out to 1000 to 2000 hours at 950° and 1000°F. The tangential check test was run at the stress which could give a rupture time of 1000 hours at 1000°F as determined from the stress-rupture time curves obtained from the longitudinal specimens.

Results

The results of the individual stress-rupture tests at 950° and 1000°F are given in Table IV and the resulting stress-rupture time curves are shown on logarithmic coordinates in Figure 3. Table V shows the stress-rupture strengths indicated by the stress-rupture time curves.

The extrapolation of the stress-rupture time curves of Figure 3 beyond the test points is open to considerable question. The curves were extended by strict adherence to the available test points. There is no question but that the data show a change in slope in the curves between 600 and 700 hours. Such changes in slope are usually found in rupture testing 0.5 Mo steel at these temperatures. The uncertainty of extrapolation arises from the considerable differences in slope between the 950° and 1000°F curves for time periods beyond the change in slope. Usually it would be expected that such curves should be nearly parallel. It is, therefore, uncertain whether the curves are correct as drawn or if one or the other of the curves has an incorrect slope. Two additional tests, one of at least 3000 hours duration at 950°F and one of 2000 hours at 1000°F would have been required to resolve this uncertainty. As discussed later, however, it is felt that the 1000°F curve is drawn with a steeper slope than was actually the case; and the 950°F curve is probably nearly correct.

The one tangential specimen tested had about one half the rupture time of the longitudinal specimens at 1000°F.

The elongation and reduction of area of the rupture specimens were quite high for CMo steel and did not show as rapid decrease as is normally observed for this steel with increasing fracture time. The one tangential specimen tested had about the same ductility as the longitudinal specimens.

The microstructure of the as-received CMo pipe material is shown in Plate 4, and the microstructure after prolonged testing is illustrated by Plates 5, 6, and 7. Plate 8 shows the appearance at 100 and 1000 diameters magnification of the defect detected during sectioning of the pipe.

The original structure of the pipe consisted of ferrite grains and small grains of spheroidized pearlite. The ferrite grain size was ASTM 5 to 8. This type of structure appears to be consistent with the reported heat-treatment and long service life of 75,054 hours at 900°F.

The microstructures of the most prolonged longitudinal rupture test specimens show that fracture was both intergranular and transgranular with a medium amount of intergranular cracking adjacent to the fracture. Oxidation of the surface was normal for the testing conditions and only slightly intergranular. No significant differences were noted between the longitudinal and tangential specimens. Although no appreciable spheroidization of the pearlite during testing at 950°F could be discerned, considerable occurred during testing at 1000°F.

Discussion of Results

The main objective of the investigation was to establish the amount of available service life used up by the 75,054 hours of service. Because CMo steel tends to have rather variable rupture strengths, depending on melting practice during steel making and on heat treatment, the initial rupture properties of the particular steel in the pipe are uncertain. It is, therefore, necessary to compare the properties of the used pipe to average properties of new CMo steel in attempting to arrive at an answer.

The average rupture strengths for new 0.5 Mo steel from ASTM Special Technical Publication No. 151, Reference 1, have been included in Table V for comparative purposes. It is immediately evident that the prior service greatly reduced the rupture strengths at short time periods; but if anything may have increased long time strength.

During service at 950° to 1000°F two factors occur to alter the rupture strengths. Creep occurs to use up the rupture life. This would result in the stress-rupture time curve for material after service being offset towards lower strength by the percentage of life used up during service. At the same time the steel undergoes structural changes which alter rupture properties. In the case of CMo steel this is commonly attributed to spheroidization of the carbides. It is well established that spheroidization lowers the short time rupture strength and tends to remove the sharp break in slope which leads to low long-time strengths for new steel. This is believed to be the main effect of the 75,054 hours of service prior to testing.

It is probable that the average value for rupture in 100,000 hours given in ASTM Special Technical Publication No. 151 is lower than the true average due to too few data being available for the compilation. A better comparison seems to be possible for 10,000 hours where more data were used to develop the average. Reference to Table V shows a reduction to about 71% and 76% of the average rupture strength for 10,000 hours by the prior service. This agrees remarkably with the amount of reduction predicted by Weaver, Reference 2.

Weaver carried out rupture tests on specimens which had been given various initial treatments and then spheroidized various amounts prior to testing at 900° and 1000°F. The material which came nearest to the RT2 pipe was annealed from 1560°F and reheated for 4 hours at 1200°F. This material showed the following rupture strength changes at 1000°F when spheroidized for a time equivalent to 75,000 hours at 900°F:

As Annealed and Tempered.................. 16,000 psi for rupture in 10,000 hours

Initial + equivalent of 75,000 hours at 900°F.... 13,000 psi for rupture in 10,000 hours

This represents a reduction to about 80 percent of the initial value. However, the pipe was in service at slightly higher temperatures under stress and had been deoxidized with aluminum. These are all factors which would increase the spheroidization effect over that examined by Weaver. The microstructure of the pipe also show slightly more spheroidization than Weaver's specimens.

Weaver also showed that the spheroidization lowered the stress rupture time curve at short time periods and removed the knee in the curve for the annealed condition. This was based on tests of 10,000 hours duration at both 900° and 1000°F. His tests also predicted nearly equal rupture strengths for the initial and spheroidized conditions at 100,000 hours. Furthermore, his tests showed the high ductility for spheroidized specimens similar to those found for the pipe samples.

For these reasons it is concluded that the main effect of the prior service was to reduce short time rupture strengths and flatten out the stress-rupture time curves due to the spheroidization effects of the prolonged exposure to stress in the temperature range of 900° to 1000°F. It is believed, for this reason, that the stress-rupture time curve at 1000°F was probably drawn with too steep a slope and that an average curve through the last three points would have given a truer appraisal of the rupture strength.

The stress-rupture time curves of Figure 3 indicate that the rupture times under the reported operating stress of 5,910 psi would be:

950°F. . . . . many millions of hours

1000°F. . . . . ~650,000 hours

It is thus evident that even with the uncertainties of the extrapolation, the pipe metal was nowhere near failure by rupture. It is true that the tangential specimen tested at 1000°F did show lower strength. Since the service stress was a hoop stress, it could well be that creep damage during service might have been greater in the tangential direction than in the longitudinal. If it is assumed that there is a separate stress-rupture time curve for tangential specimens at a lower stress level but parallel to the longitudinal curve, the rupture time left in the pipe under a stress of 5,910 psi is still of the order of 450,000 hours.

The 75,054 hours of service represents far less than 1 percent of the total available rupture life originally present in the steel or that present after service. The average operating temperature was only 912.6°F which would reduce the fraction of the total life under stress below that estimated for 950°F. Less than 1 percent of the time was at 1000°F so that swings to high temperature did not use up a measurable part of the rupture life of the metal.

It is, therefore, concluded that the tests measured only the effect of spheroidization on rupture properties and that this had little effect on the rupture strength under operating stress. The life used up by creep was negligible. The spheroidization did reduce the rupture strength for time periods of 10,000 hours or less to about 70 percent of new material. The flatter stress-rupture time curves resulted in very little loss in strength for service of the order of 100,000 hours or longer.

So far as this investigation is concerned the data indicate that the pipe metal was good for an almost indefinite time period under the stated service conditions. Certainly, for failure to have occurred in less than a million hours, it would have had to be due to some extraneous factor. Stresses arising from other sources to increase the stress level well beyond the calculated hoop stresses would have had to be present in the piping system. Flaws in the pipe, such as the seam noted in the sample, or concentrated graphitization, as well as extraneous stresses from the system, are possible sources of difficulty. The nominal stress and sound metal certainly left most of the life originally present.

TABLE IV

Rupture-Test Data for CMo Steel Steam Pipe After 75,054 Hours Service in Number 7 Unit of the Essex Generating Station

Sample RT2

Test Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elongation in 2-inch (%)	Reduction of Area (%)
950	32,000	(5 minutes)	--	--
	30,000	40.5	30.6	77.1
	28,000	614.	34.0	53.8
	27,000	626.	35.5	54.0
	25,000	1780.	22.5	30.7
1000	26,000	27.1	38.2	77.2
	25,000	52.	54.6	74.9
	22,500	360.	37.2	58.8
	21,000	673.	43.2	55.6
	19,000	1088.	43.0	50.0
1000	19,150[a]	613	34.0	48.4

(a) Tangential specimen-all other specimens were taken lengthwise to pipe.

TABLE V

Stress-Rupture Strengths for CMo Steel Pipe After 75,054 Hours of Service in Number 7 Unit of the Essex Generating Station

Sample RT2

Temp. (°F)	Stress for Rupture in Indicated Time Periods (psi) 10-hr	100-hr	1000-hr	10,000-hr	100,000-hr
950	31,000	29,500	26,500	21,000	17,000
1000	27,000	24,000	19,500	12,500	8,200
Average Values for New 0.5 Mo Steel (from ASTM STP No. 151)					
950	--	42,000	35,000	28,000	10,500*
1000	--	38,000	26,000	16,500	7,000*

* These values are probably low. It is estimated that values of 16,000 and 8,500 psi are probably closer to the real average.

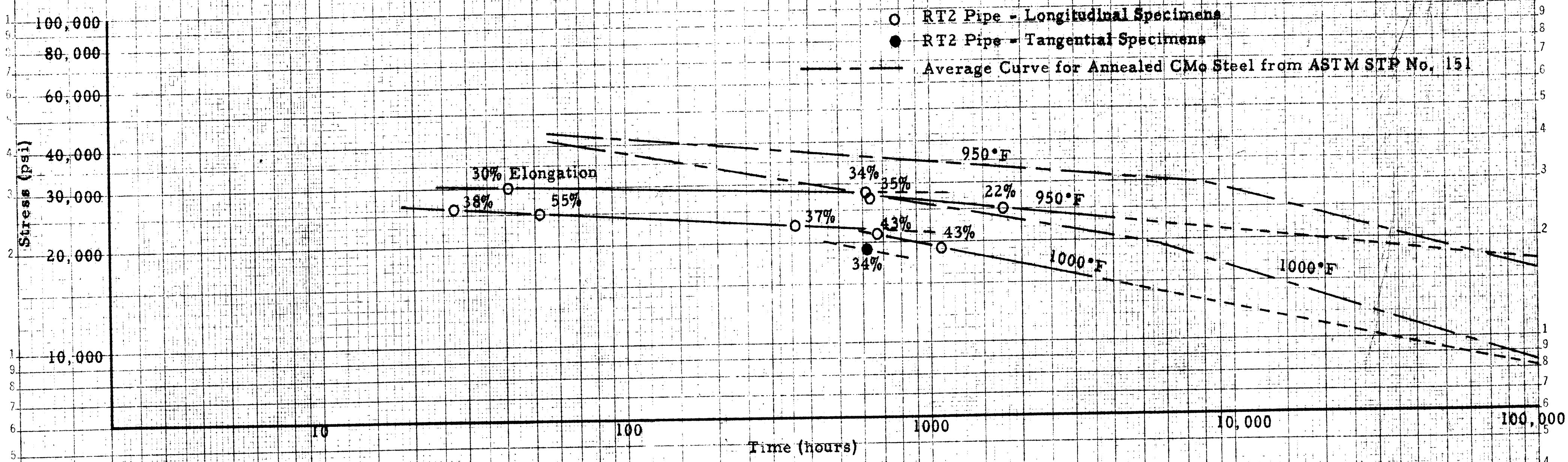
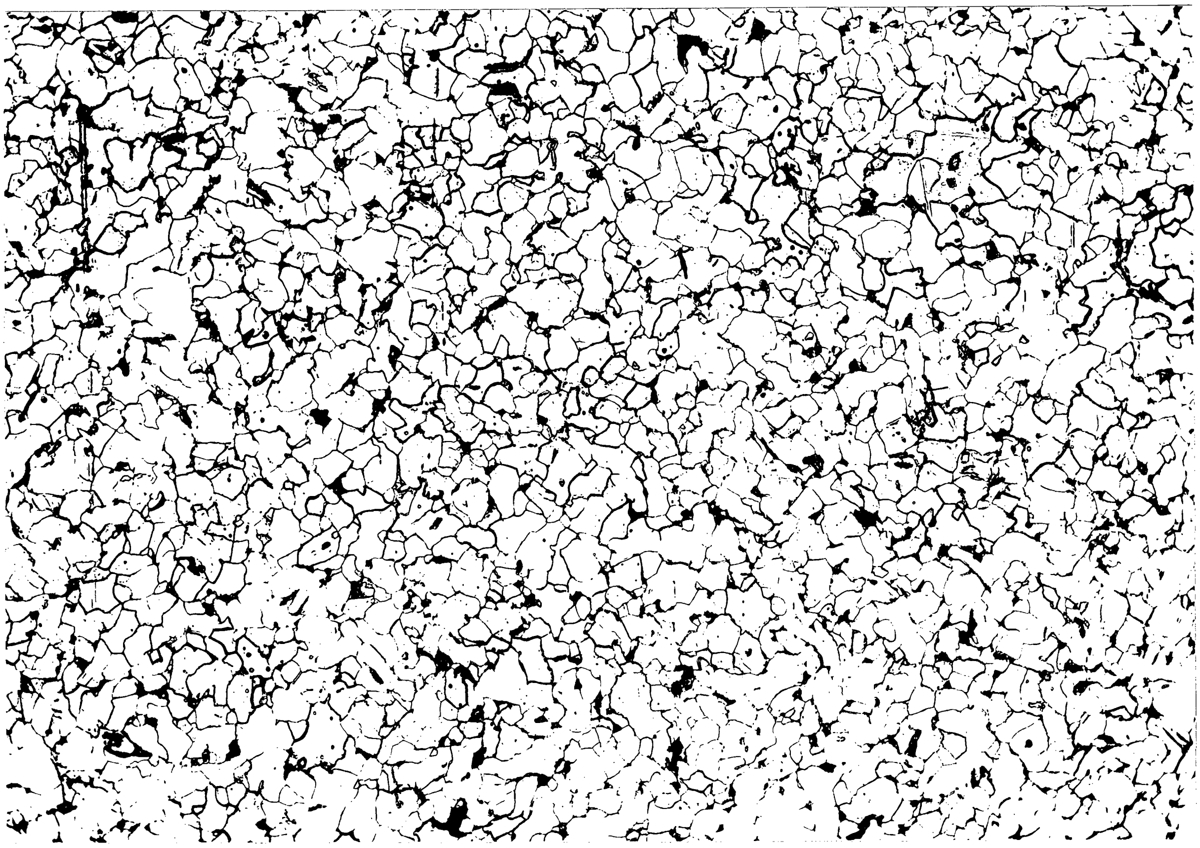
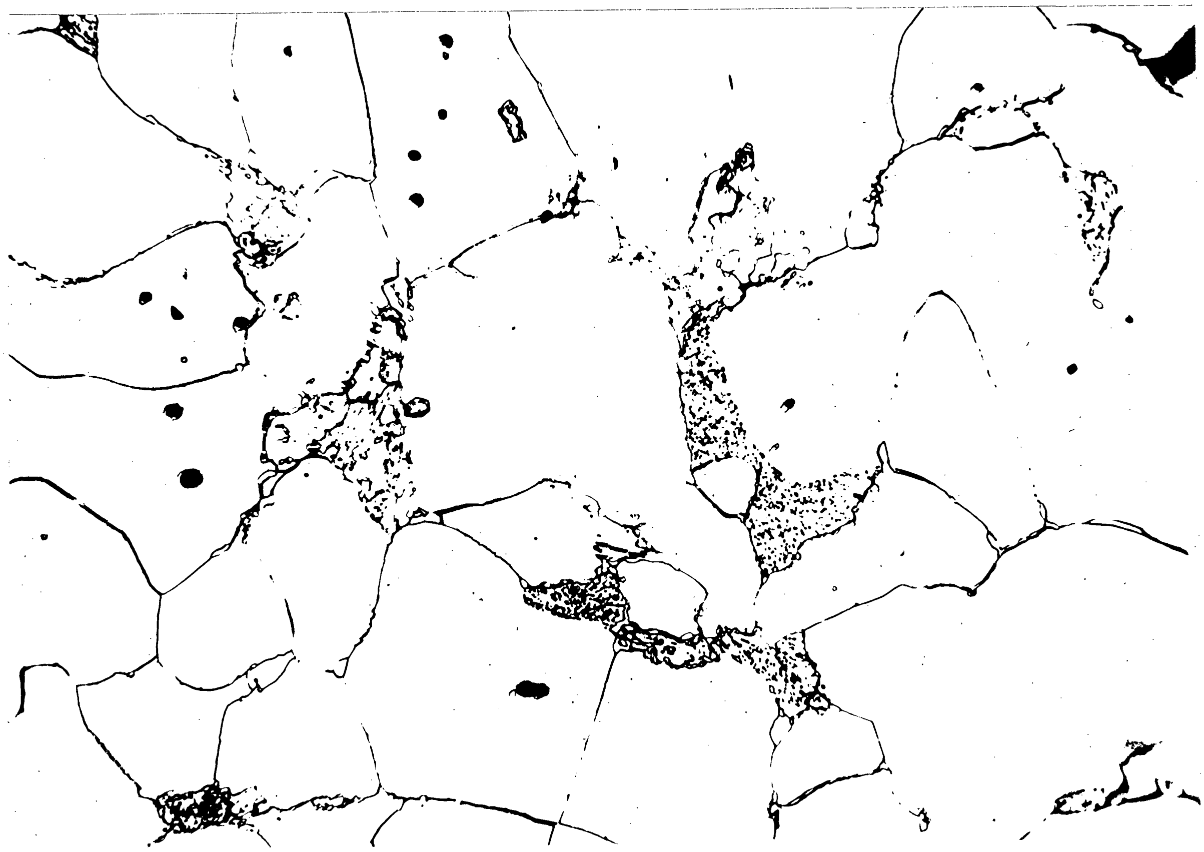


Figure 3. - Stress-Rupture Time Curves at 950° and 1000°F for CMo Steel Steam Pipe after 75,054 Hours of Service in Number 7 Unit of the Essex Generating Station.

(Sample RT2)

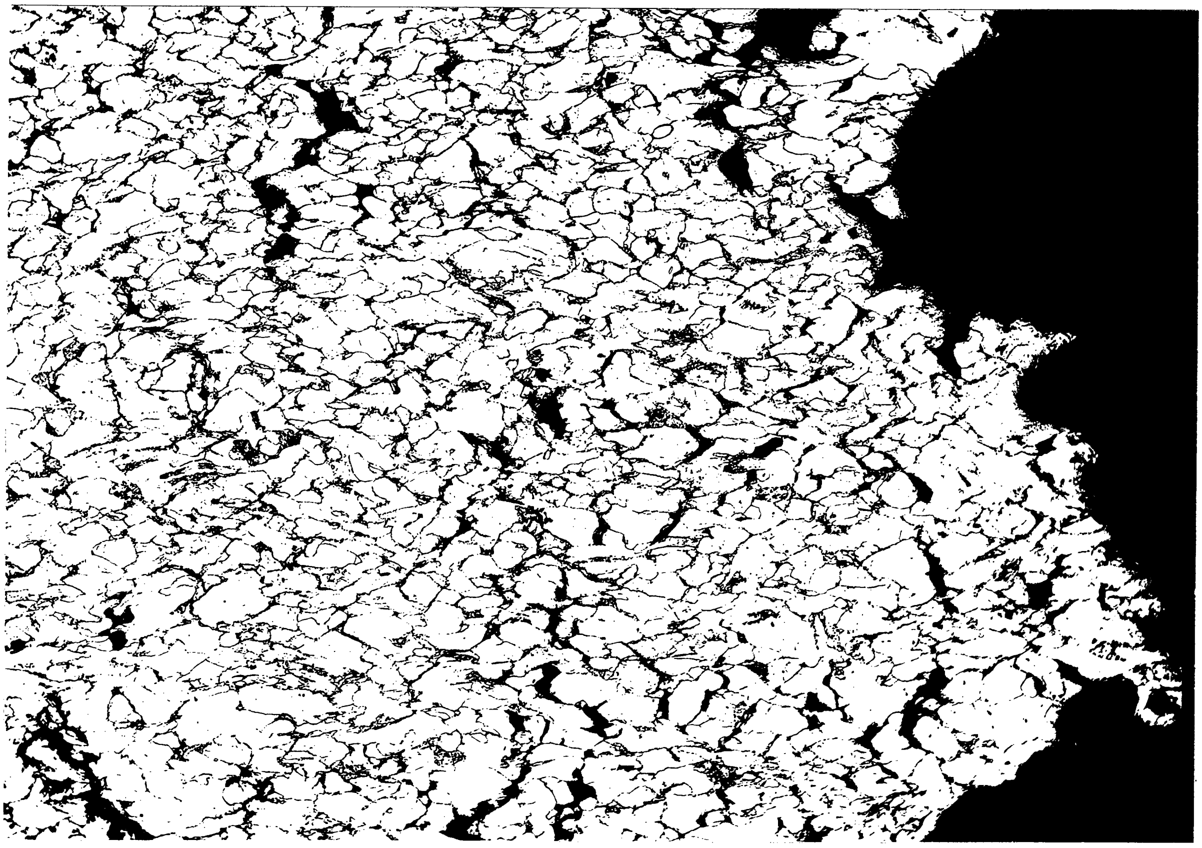


X100D

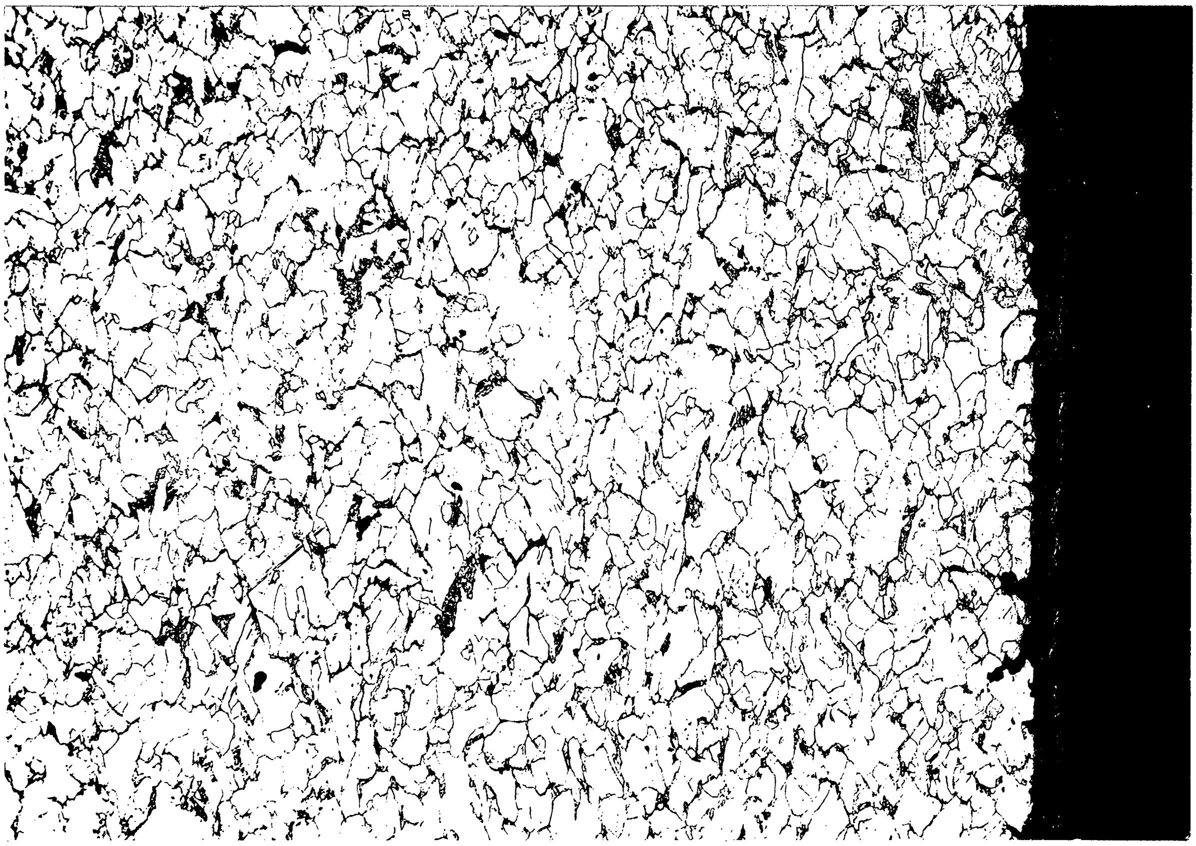


X1000D

Plate 4. - Original Microstructure of Carbon-Molybdenum Steel Pipe (RT-2) from Essex Generating Station, No. 7 Unit. In Service 75,054 Hours at Normal Operating Temperature of 950°F.

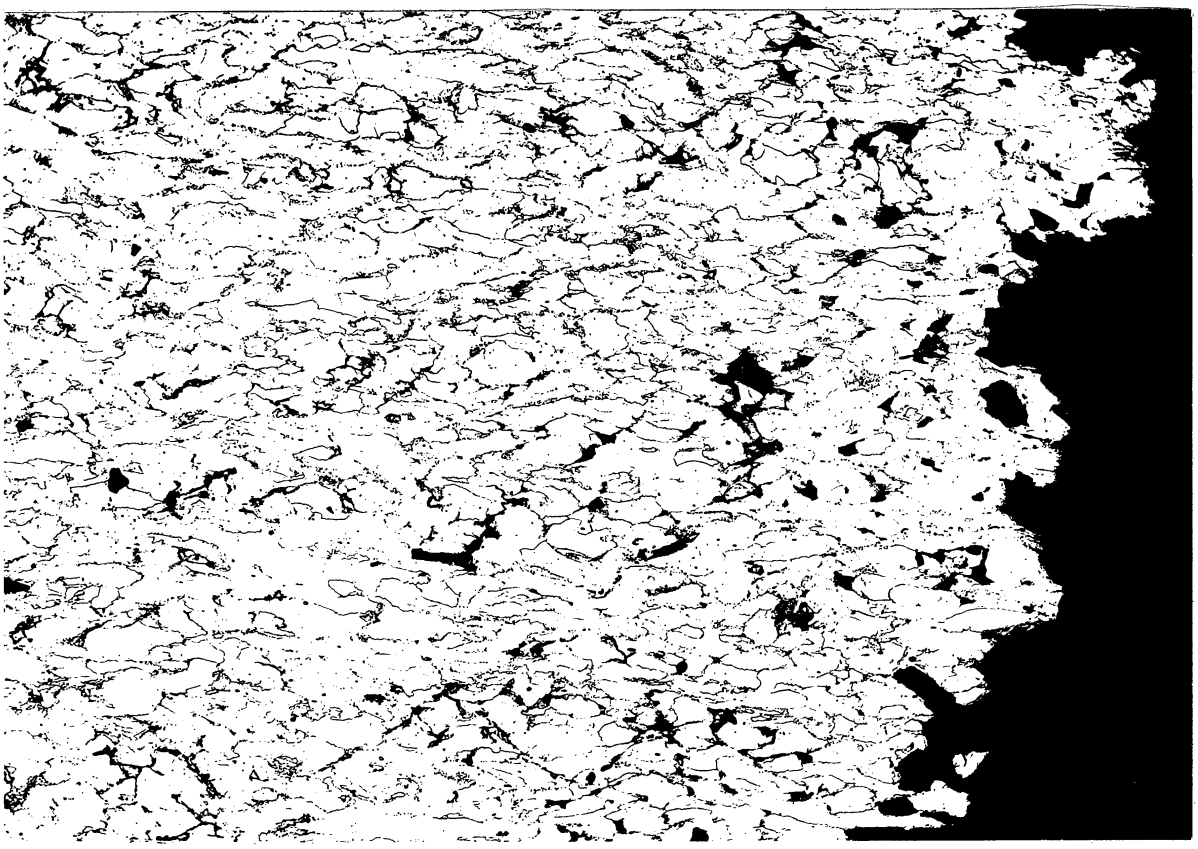


X100D - Fracture

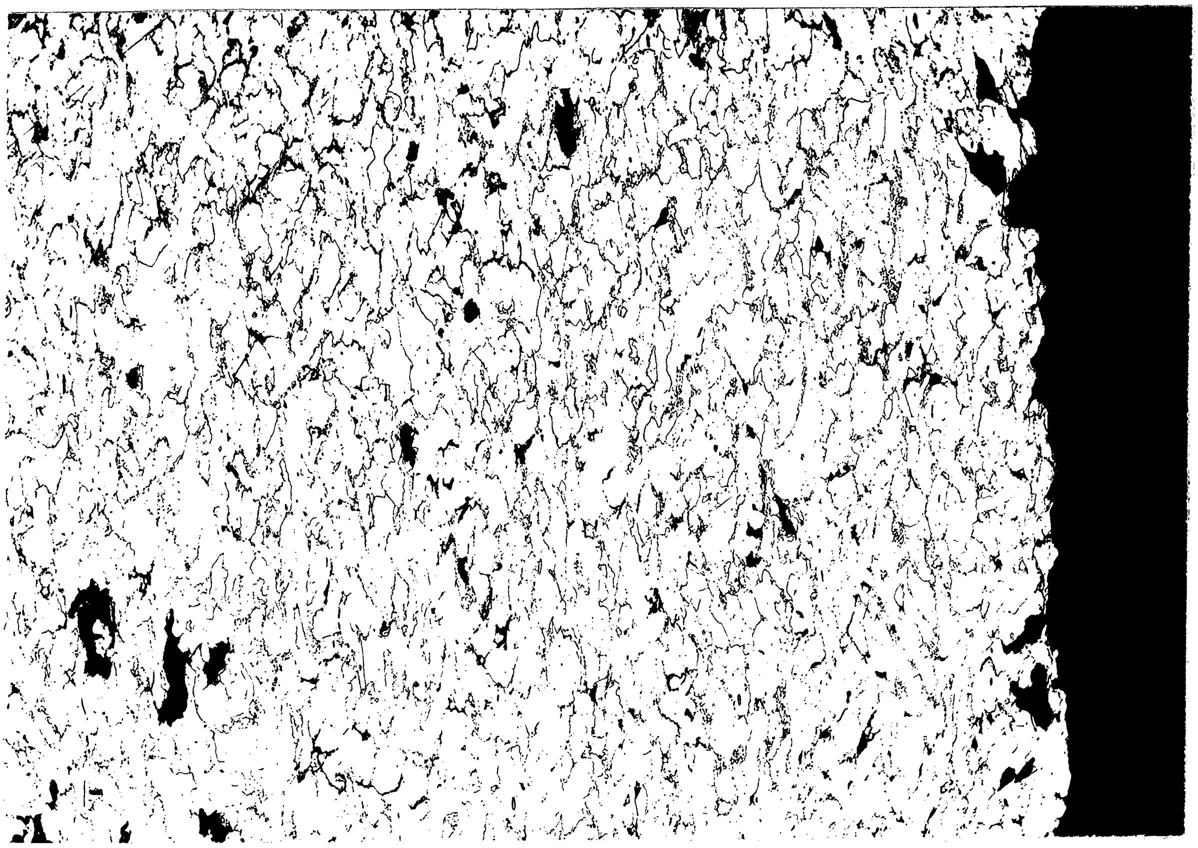


X100D - Surface

Plate 5. - Microstructure of Stress-Rupture Specimen from Carbon-Molybdenum Steel Pipe (RT-2) Fractured in 1780 Hours Under 25,000 Psi at 950°F.

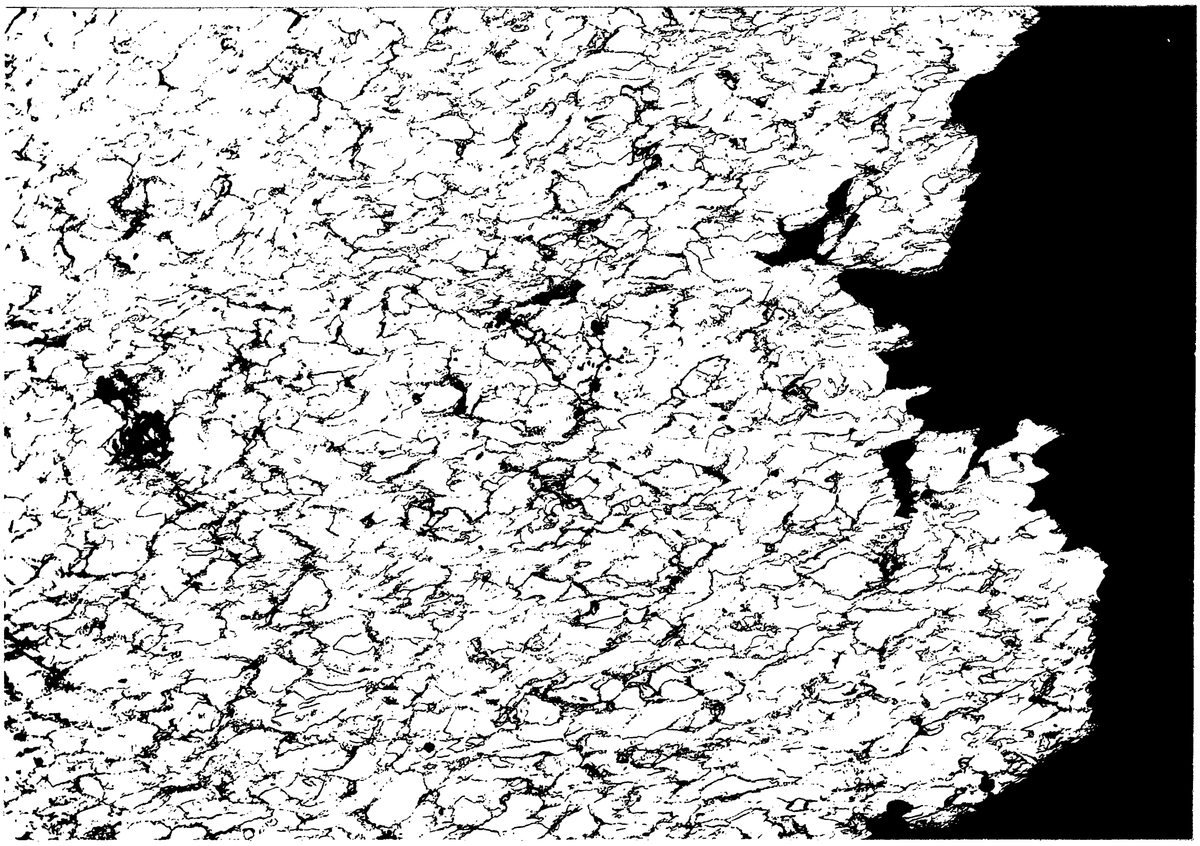


X100D - Fracture

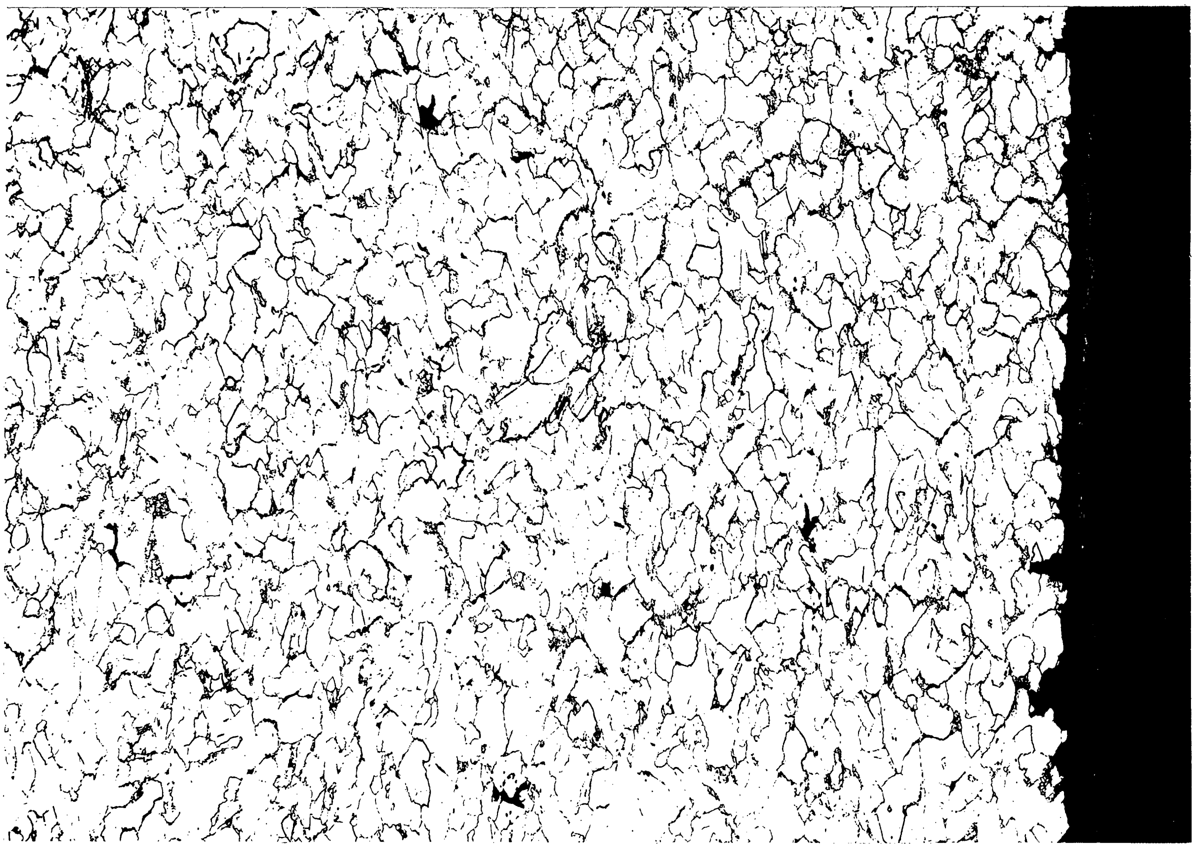


X100D - Surface

Plate 6. - Microstructure of Stress-Rupture Specimen from Carbon-Molybdenum Steel Pipe (RT-2) Fractured in 1088 Hours Under 19,000 Psi at 1000°F.

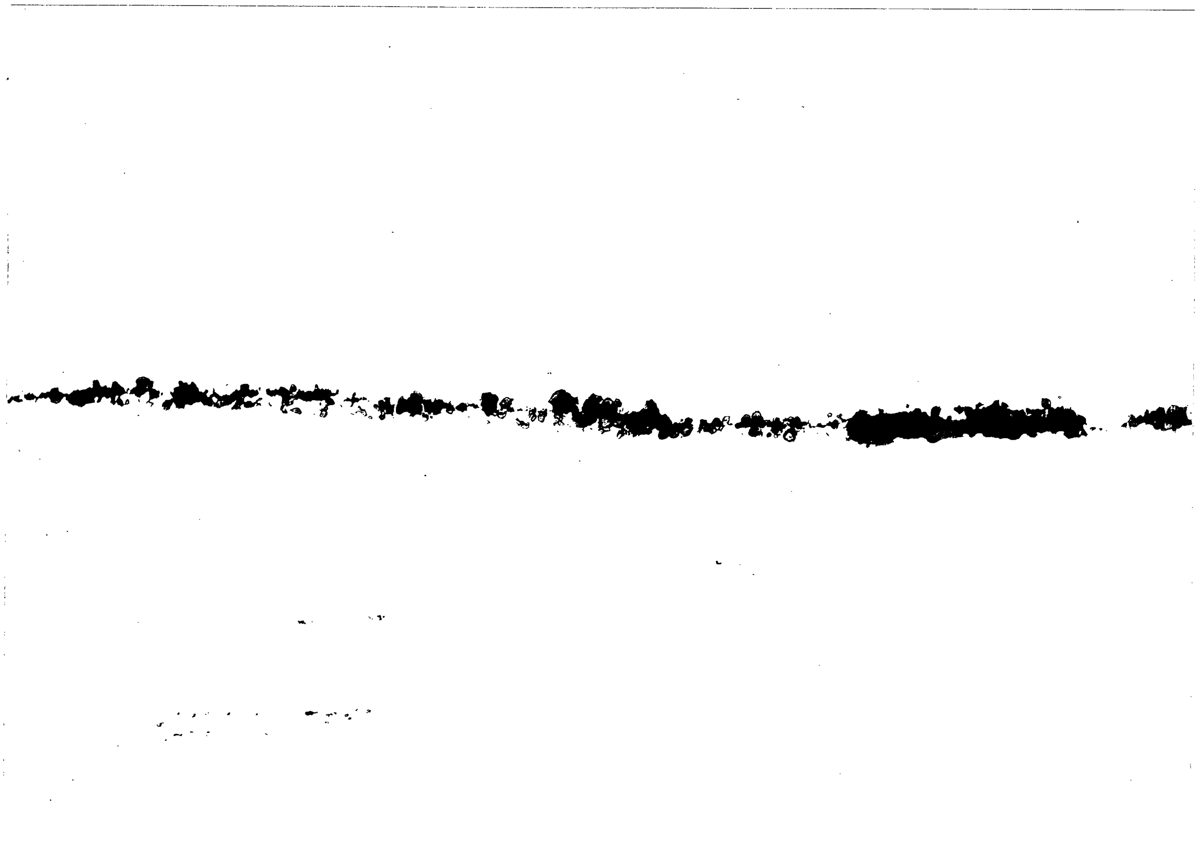


X100D - Fracture

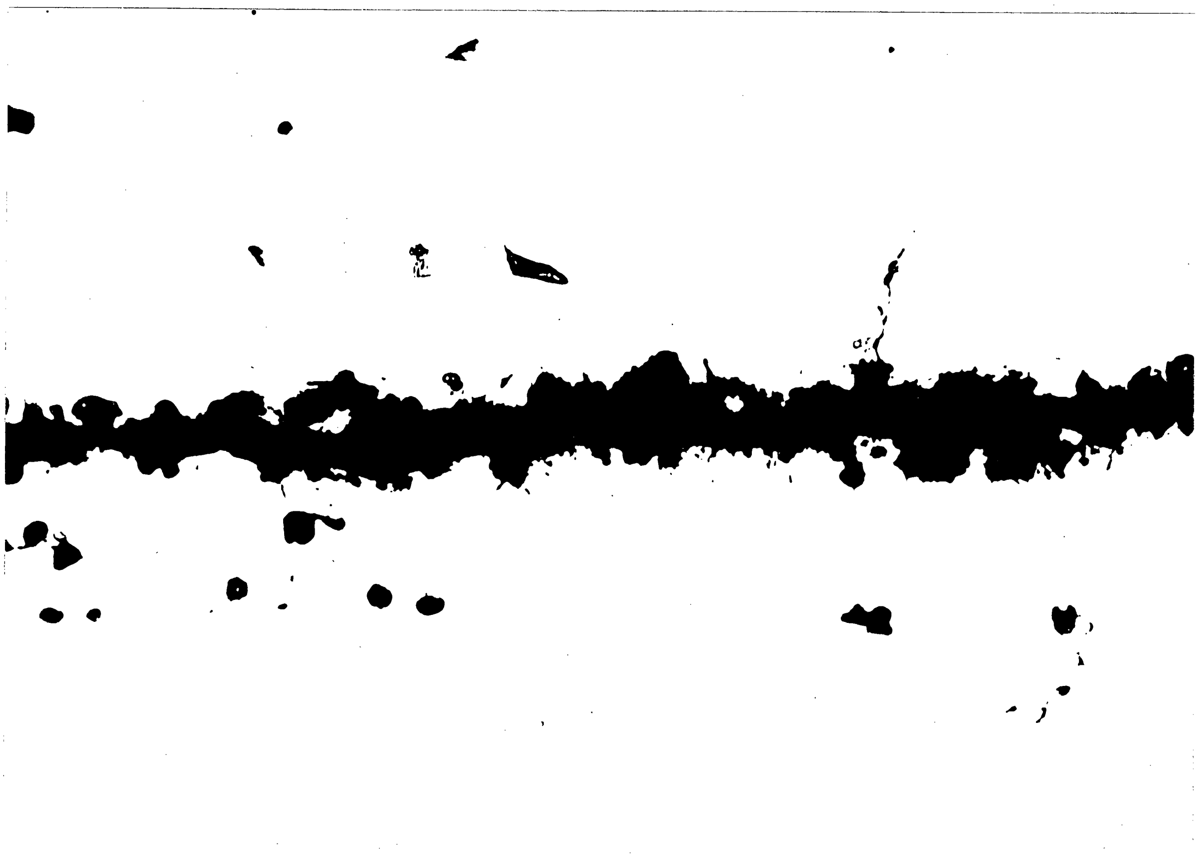


X100D - Surface

Plate 7. - Microstructure of Tangential Stress-Rupture Specimen from Carbon-Molybdenum Steel Pipe (RT-2) Fractured in 613 Hours Under 19,150 Psi at 1000°F.



X100D - Unetched



X1000D - Unetched

Plate 8. - Defect in Carbon-Molybdenum Steel Pipe (RT-2) from Essex Generating Station, No. 7 Unit. In Service 75,054 Hours at Normal Operating Temperature of 950°F.

PART III

ESSEX GENERATING STATION NUMBER 26 BOILER STEAM LEAD

CMo Steel Pipe after 81,536 Hours of Service at 950°F

Sample RT3

Rupture tests were conducted at 950° and 1000°F on samples cut from a section of pipe submitted under the designation "RT3". The pipe was carbon - 0.5-percent molybdenum steel and had been in service for 81,536 hours. The pipe dimensions were 8.723-inch O.D. x 6.911-inch I.D. x 0.906-inch wall. The normal operating conditions were 950°F and 1350 psi pressure. The pipe metal contained considerable graphite.

Description of Pipe and Service Conditions

A full ring eight inches in length, identified as Sample RT3, from the Essex Generating Station was submitted for testing. The information supplied with the sample was as follows:

Steel: CMo steel (ASTM: A158-36 Grade P1)

Location: Number 26 Boiler Steam Lead-Public Service Specification 227

Size: 8.723-inch O.D. x 0.906-inch wall x 6.911-inch I.D.

Chemical Composition: 0.20 maximum carbon specified.
1.9 pounds of aluminum added per ton

Mill Heat Treatment: 0.5 hours at 1650°F + 0.5 hours at 1200°F

Shop Heat Treatment: 3 hours at 1200°F

Physical Properties: 55,000 psi minimum tensile strength specified

Service Condition:

Service hours	81,536
Calculated hoop stress(S=Pd/2t)	5,910 psi

Operating Temperatures	
Normal	950°F
Average	909.06°F
Maximum (Rating for short swings. Not to exceed 1% of operating time)	1000°F
Operating Pressures	
Normal	1350 lbs.
Maximum	1500 lbs.

The operating temperatures were amplified by the following statement: "--- the piping from which the carbon-moly samples were taken runs at 950°F at full load, with short swings to 1000°F. At partial loads, however, the temperature drops down considerably, so that the average operating temperature is as indicated, approximately 910°F. For the first few years of operation the average temperature was higher and nearer the 950°F than it is now".

The following additional information was supplied after the presence of graphite had been observed and reported.

"The RT3 sample was taken from an 8-inch boiler lead at Number 26 Boiler, Essex Generating Station, following the removal of this piping after the presence of graphite in Luder lines had been observed at the edge of the weld probe specimens from the piping. The piping was replaced with 1Cr-1/2Mo ASTM Specification No. A315.

"For your information the presence of considerable nodular graphite had also been observed in the contact zones of the weld, but no connected chain-type graphitization had developed. Please let us know how the graphite which you found was distributed".

Procedure

The section of pipe supplied was cut longitudinally to provide test coupons suitable for machining into 0.505-inch diameter specimens. These specimens were used to establish the stress-rupture time curves at 950° and 1000°F out to approximately 3000 hours. In addition, one tangential check test was conducted at 1000°F. The tangential specimen was necessarily smaller, having a 0.250-inch diameter and a 1-inch gage length.

The observance of unexplained "lines" on the gage length of RT3 specimens lead to macro- and microexamination which disclosed the extensive graphitization discussed in the "Results" section.

Results

The results of the individual stress-rupture tests at 950° and 1000°F are tabulated in Table VI, and presented as log stress-log rupture time curves in Figure 4. The stresses for rupture in 10, 100, 1000, 10,000, and 100,000 hours derived from these curves are shown in Table VII.

The stress-rupture time curves of Figure 4 show that remarkably consistent data were obtained for the longitudinal tests despite the presence of the extensive graphitization. At 1000°F the determination of three data points past the change in slope in the stress-rupture time curve permits considerable confidence in the extrapolated 10,000 and 100,000-hour values. However, the data from tests at 950°F out to 3000 hours duration did not show a change in slope for the stress-rupture time curve. Apparently much longer time tests would have been necessary to establish whether such a change would occur at 950°F. It will be noted, however, that the difference in slope between the 950° and 1000°F curves is rather small and any error in the extrapolation of the 950°F curve is therefore relatively small.

Table VI shows that relatively good ductility in the rupture test was obtained at both 950° and 1000°F. However, the elongation and reduction of area values were lowered considerably when fracture occurred through graphitized zones as indicated by the range in values shown in the same table.

The microstructure of the as-received pipe is shown at 100 and 1000 diameters in Plate 9, and Plate 10 is a macrograph illustrating the appearance of the lines of graphitization observed during sectioning for testing. Plates 11 and 12 show the fractured surface and the surface of the longitudinal test bars near the fracture after prolonged testing at 950° and 1000°F, respectively. Similar micrographs of the tangential specimen are shown in Figure 13.

The microstructure of the as-received pipe consisted of ferrite grains with small areas of highly spheroidized pearlite. The ferritic grain size was ASTM 6 to 7, and the microstructure appeared to be consistent with the reported heat treatment and long service life at an average temperature of 910°F. As previously mentioned, numerous lines of graphite were observed. These appeared as stringers visible to the eye. Some started at the inside surface and extended into the wall approximately perpendicular to the axis of the pipe. Other stringers were wholly internal and randomly distributed in direction. Plate 9 shows that the graphite particles within the stringers were dispersed and nodular in form.

As would have been expected from the as-received microstructure, no apparent change in structure was observed after prolonged testing at 950° and 1000°F. As shown in Plates 11 and 12, the fractures of the longitudinal test specimens were transgranular in nature with extensive elongation of the grains in the direction of the applied stress. Although considerable intergranular separation occurred near the fracture during testing at 950°F no evidence of such separation was seen after testing at 1000°F. No evidence of intergranular cracking along the surfaces near the fracture was observed after testing at either 950° or 1000°F.

The tangential specimen failed through one of the graphite concentrations with little distortion of the structure as shown in Plate 13. The fracture, however, was still transgranular with no intergranular separations adjacent to the fracture.

Discussion of Results

The results of this investigation provide information on the effects of a particular type of graphitization and other effects of 81,536 hours of steam-pipe service on the temperature range of 900° to 1000°F on the high temperature strength of 0.5 Mo steel.

The rupture strengths were very low in comparison to those for new pipe for time periods up to 10,000 hours, as is shown by the average values for unused 0.5 Mo steel included in Table VII. The relatively small slope of the stress-rupture time curves, however, indicated strengths for rupture in 100,000 hours which were above the average for new material as given in ASTM STP No. 151, Reference 1, and not much below a probably better true average.

The influence of prior service on creep-rupture properties of 0.5 Mo steel was discussed in some detail in Part II for Sample RT2. As discussed in that case, the percentage of rupture life used up under a stress of 5,910 psi would be negligible in comparison to the total rupture life of new material or of the pipe metal in its present condition.

The main difference between the pipe material represented by Sample RT3 and the sample discussed in the previous section, Sample RT2, is the presence of the graphite and more extensive spheroidization of remaining carbides. The graphite might be expected to have two effects. Graphitization removed any strengthening effects from carbides in the microstructures. The ungraphitized carbides left in the structure were spheroidized far more than they were in the case of Sample RT2. Both factors would tend to give lower rupture strength at short time periods than were observed for Sample RT2. Because the graphite was segregated in narrow bands, it could introduce planes of weakness. Several specimens fractured through segregated graphite with very little effect on rupture time but considerably reduced elongation and reduction of area.

The rupture strengths for the graphite free Sample RT2 are compared in the following tabulation and in Figure 5 with those obtained for the graphitized material of Sample RT3:

		Temp.	Rupture Strength (psi)				
Sample	Structure	(°F)	10-hr	100-hr	1000-hr	10,000-hr	100,000-hr
RT2	No graphite	950	31,000	29,500	26,500	21,000	17,000
RT3	Graphite	950	25,000	21,500	18,500	16,000	13,500
RT2	No graphite	1000	27,000	24,000	19,500	12,500	8,200
RT3	Graphite	1000	22,000	18,500	14,500	11,500	9,000

Because there was very little difference reported in the operating temperatures and the stress was reported to be the same, the differences between the two pipe materials could be due to the effect of graphitization. On the other hand, experience indicates that these differences could well be due alone to the greater progress of spheroidization and the removal of carbides by graphitization in Sample RT3. This suggests that the graphite in itself had little effect on rupture strength. However, since there was considerable graphite in all samples it is safest to assume that lower strength was due to both the structural changes and the presence of graphite.

The relationship of the graphite streaks to the fractures was studied in some detail. It appeared that fracture occurred in the graphite only when a layer of graphite happened to be oriented normal to the specimen axis. Even when the graphite was oriented at only slightly smaller angle to the axis, fracture did not occur through it preferentially. No significant difference in rupture time appeared to be related to the location of the fracture.

The influence of the graphite on creep-rupture characteristics, therefore, seems to be fairly clearly established. The increased ductility and lowered creep resistance at high stresses due to spheroidization and breakdown of carbides to graphite prevented any appreciable stress concentration effect from the graphite. Consequently, the graphite had little effect on the overall rupture strength. The volume of metal occupied by the graphite was too small to appreciably alter the overall strength. On the other hand, when the graphite was oriented normal to the specimen axis, it was easier for fracture to progress along the line of graphite flakes than through the graphite free metal. This resulted in lower ductility. The difference, however, was very small so that the graphite had to be oriented in the normal fracture direction for it to effect the results even this much.

There are several features of the graphite which made this a more or less special case. The graphite was present in disconnected small spheroidal flakes. If it had been present as more continuous "chain graphite" flakes it would have had a far greater weakening effect. The lowered ductility when it was oriented normal to the stress suggests that the graphitization would not have had to proceed much further before it would have dangerously lowered strength. The lowered ductility also suggests that the coincidence of a layer of graphite and a stress concentration could have led to premature failure.

It is also important to note that the graphitization was more severe near the surface than at the center. A good deal of the surface was machined off in preparing the gage length of specimens. Furthermore, streaks of graphite rarely crossed the entire diameter of the test specimens. Thus, it seems highly probable the graphite was less detrimental in the test specimens than in the entire pipe wall.

There are, therefore, a number of reasons why the pipe represented by Sample RT3 was not in a suitable condition for continued service even though the rupture tests did not show any significant lowering of strength under the low nominal operating stress. The test results did show the profound loss in strength for short times at high stresses due to the structural changes occurring during service. It is an excellent example of the influence of structural changes on rupture strength. If the changes occur during testing the usual high values are obtained for short-time periods. If the changes are made to occur before testing the short time strengths are reduced but the long time strength will be unaffected or even higher than for the initial structure.

One source of uncertainty involves the reason for graphitization in Sample RT3 and not in RT2. The information supplied gives no clue as to the difference. Reported operating conditions were so similar that this does not seem to be an explanation. Heat treatment, composition and deoxidization were also reported to be similar. The type of graphite formed is almost certainly related to stress over and above normal operating stresses. If such stresses existed for an appreciable time it would seem as if there ought to have been a more noticeable reduction of rupture strength.

TABLE VI

Rupture-Test Data for CMo Steel Pipe after 81,536 Hours of Service in

Number 26 Boiler Steam Lead, Essex Generating Station

Sample RT3

Test Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elongation in 2-inch (%)	Reduction of Area (%)
950	25,000	0.5	15.1*	54.5*
	25,000	19.	27.0*	32.4*
	20,000	281.	45.1	83.1
	17,000	2977.	48.0	68.0
1000	25,000	1.6	19.0*	34.5*
	22,500	5.9	19.6*	26.7*
	20,000	55.9	36.4	84.1
	18,000	110.8	14.0*	13.2*
	15,000	639.	20.6	34.1
	13,500	2245.	45.0	80.0
1000	15,000[a]	341.	12.5*	12.3*

(a) Tangential 0.250-inch diameter specimen
(*) Fractured through concentrated graphite

TABLE VII

Stress-Rupture Strengths for CMo Steel Pipe after 81,536 Hours of Service in

Number 26 Boiler Steam Lead, Essex Generating Station

Sample RT3

Temp. (°F)	Stress for Rupture in Indicated Time Periods (psi) 10-hr	100-hr	1000-hr	10,000-hr	100,000-hr
950	25,000	21,500	18,500	16,000	13,500
1000	22,000	18,500	14,500	11,500	9,000
Average Values for New 0.50 Mo Steel (from ASTM STP No. 151)					
950	--	42,000	35,000	28,000	10,500*
1000	--	38,000	26,000	16,500	7,000*

*The values are probably low. It is estimated that values of 16,000 and 8,500 psi are probably closer to the real overage.

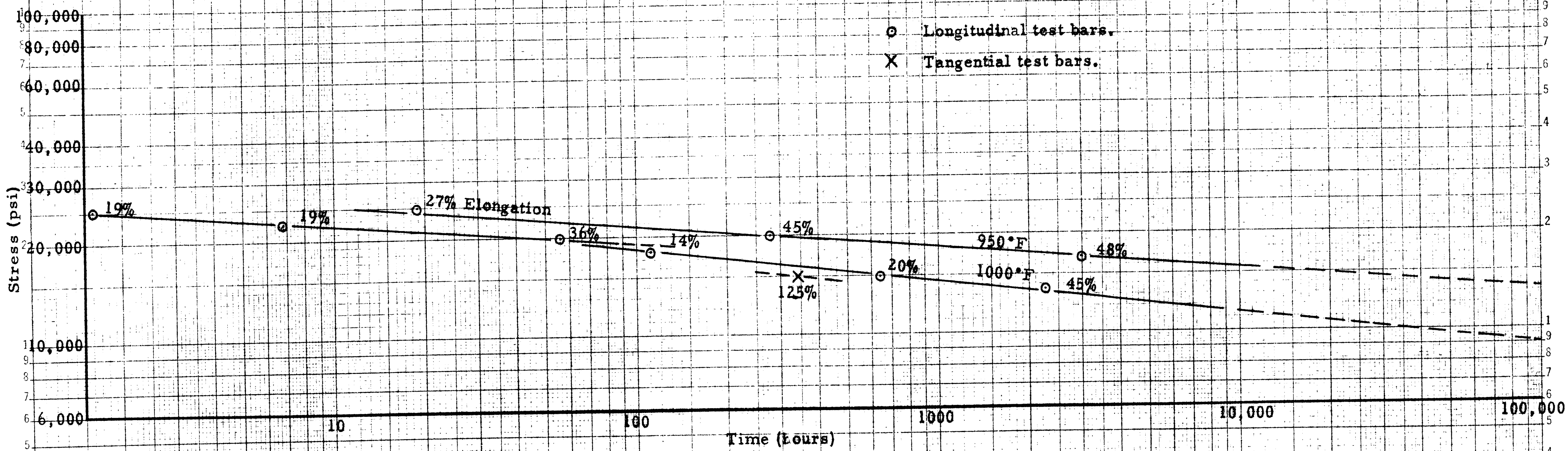


Figure 4. - Stress-Rupture Time Curves at 950° and 1000°F for CMo Steel Pipe after 81,536 Hours of Service in Number 26 Boiler Steam Lead, Essex Generating Station

(Sample RT3)

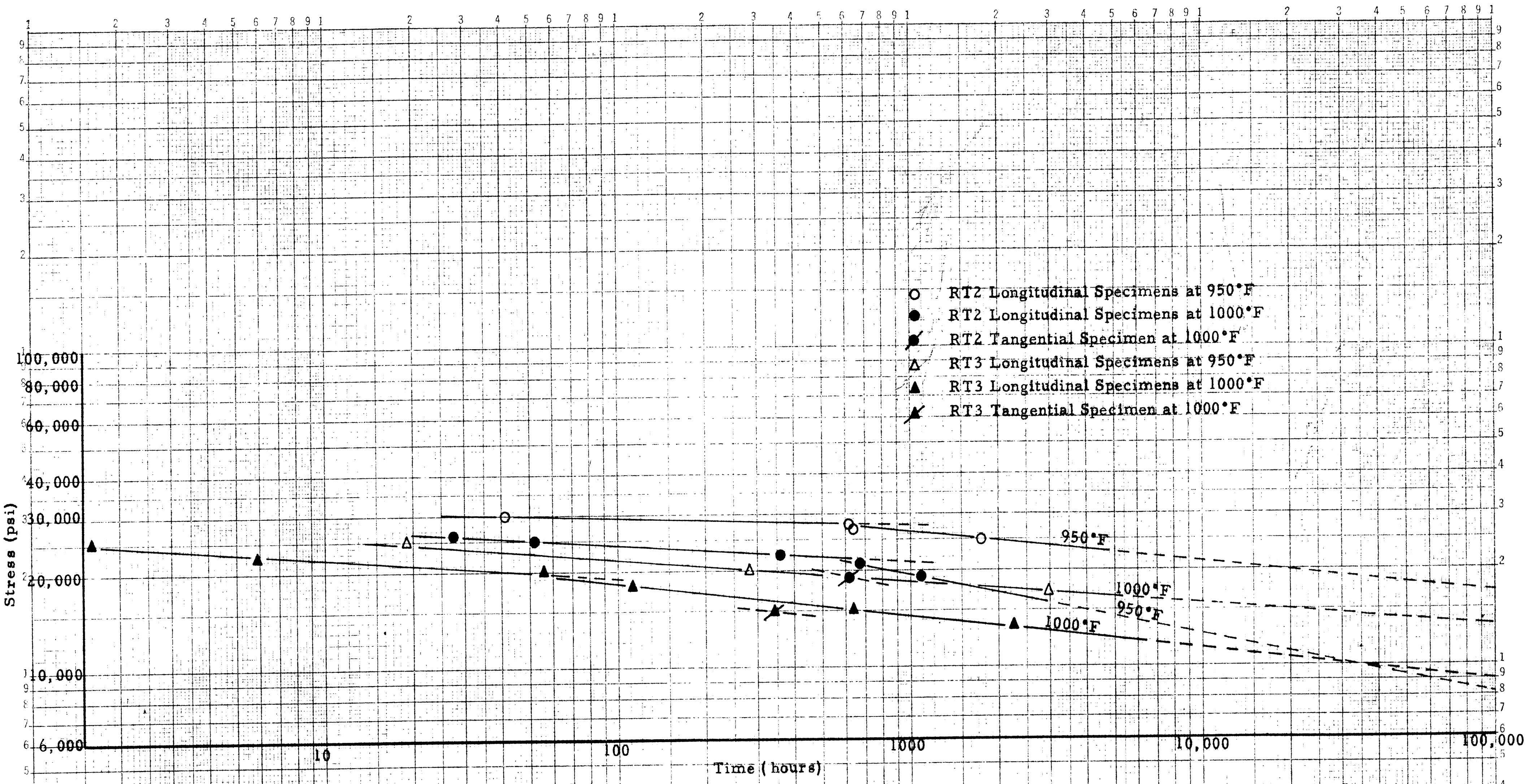
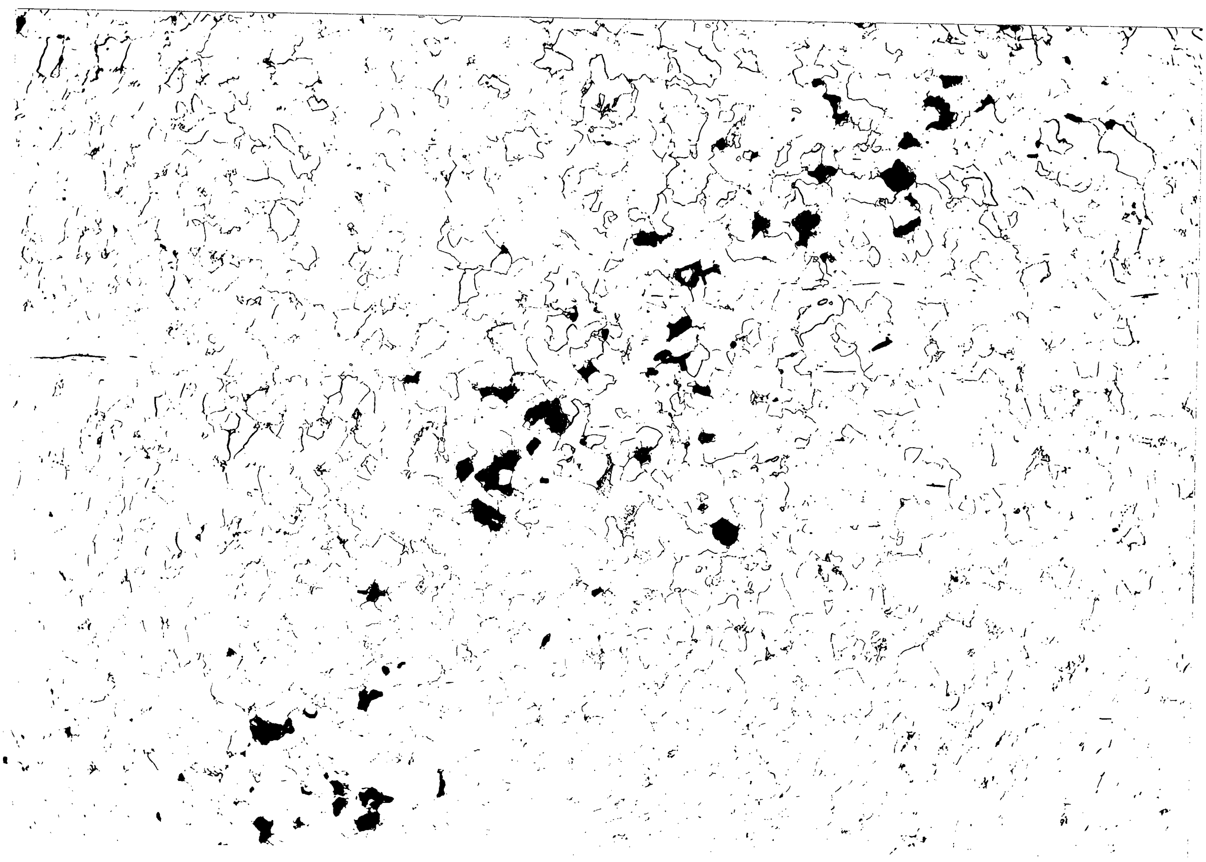
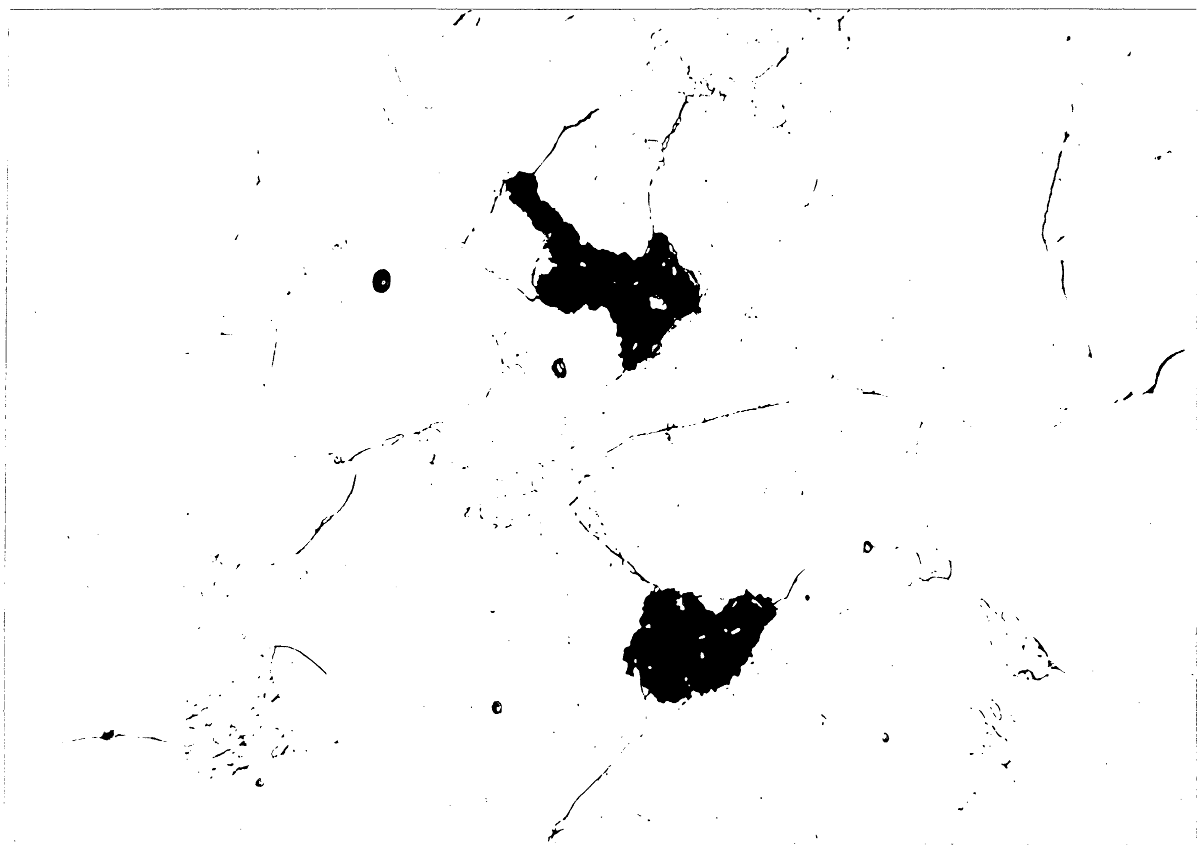


Figure 5. - Comparison of Stress-Rupture Time Curves at 950° and 1000°F for CMo Steel Pipe after 75,054 Hours of Service in the Number 7 Unit (Sample RT2) and after 81,536 Hours of Service in the Number 26 Boiler Steam Lead (Sample RT3) in the Essex Generating Station.



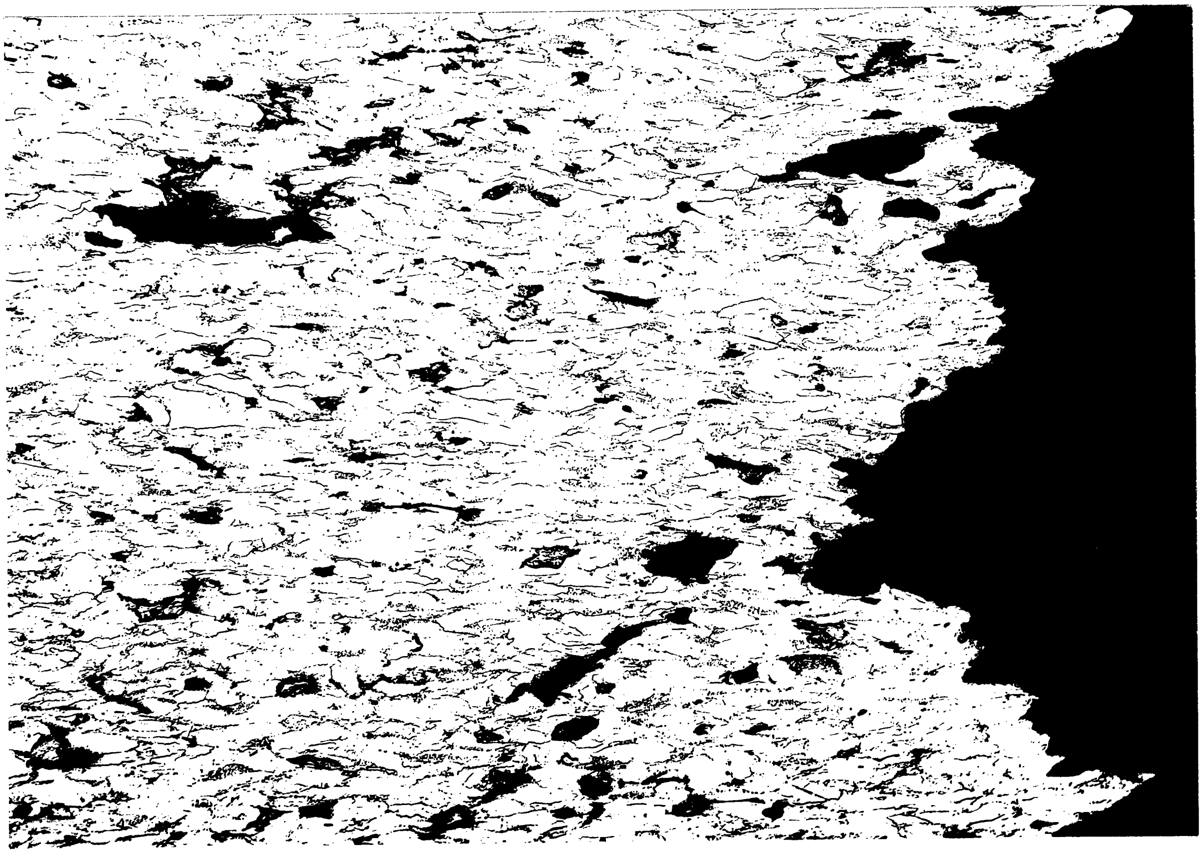
X100D



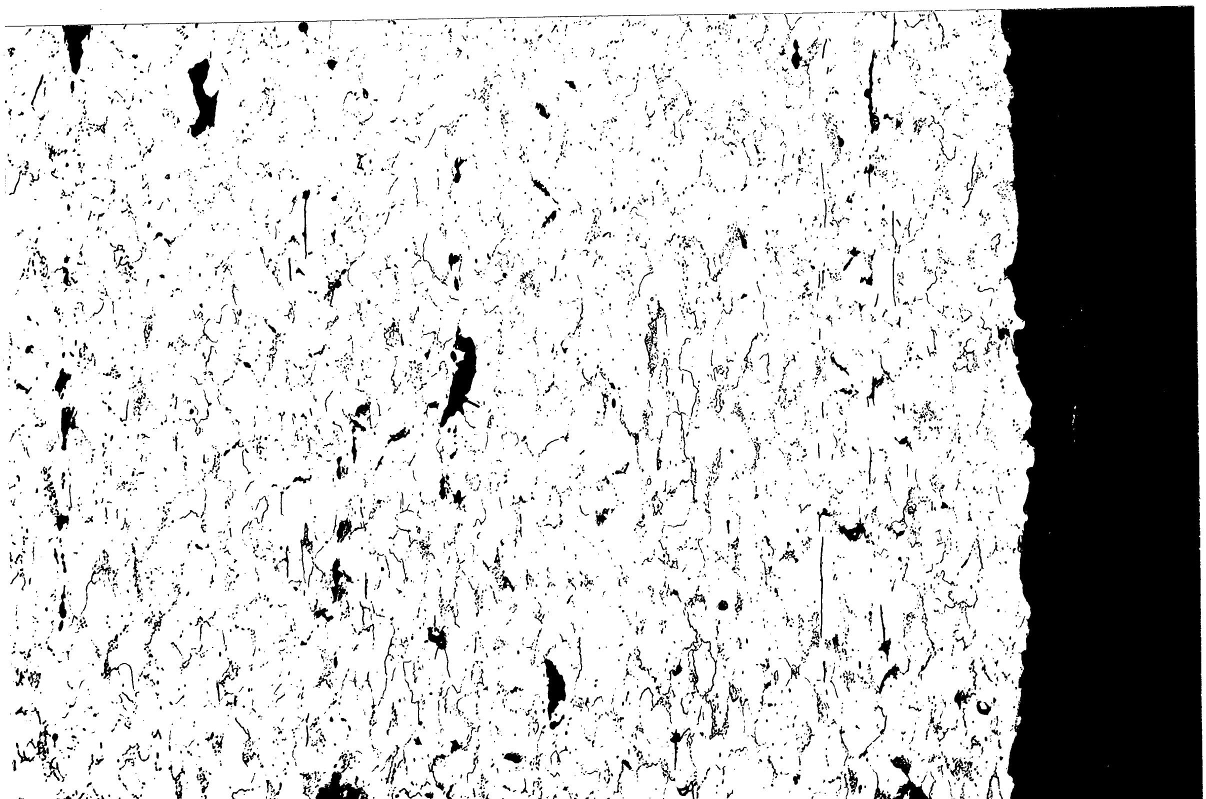
X1000D

Plate 9. - Original Microstructure of Carbon-Molybdenum Steel Pipe (RT-3) from Essex Generating Station, No. 26 Boiler Steam Lead. In Service 81,536 Hours at Normal Operating Temperature of 950°F.

Plate 10. - Macrograph of Graphite in Carbon-Molybdenum Steel Pipe (RT-3) from Essex Generating Station, No. 26 Boiler Steam Lead. In Service 81,536 Hours at Normal Operating Temperature of 950°F.

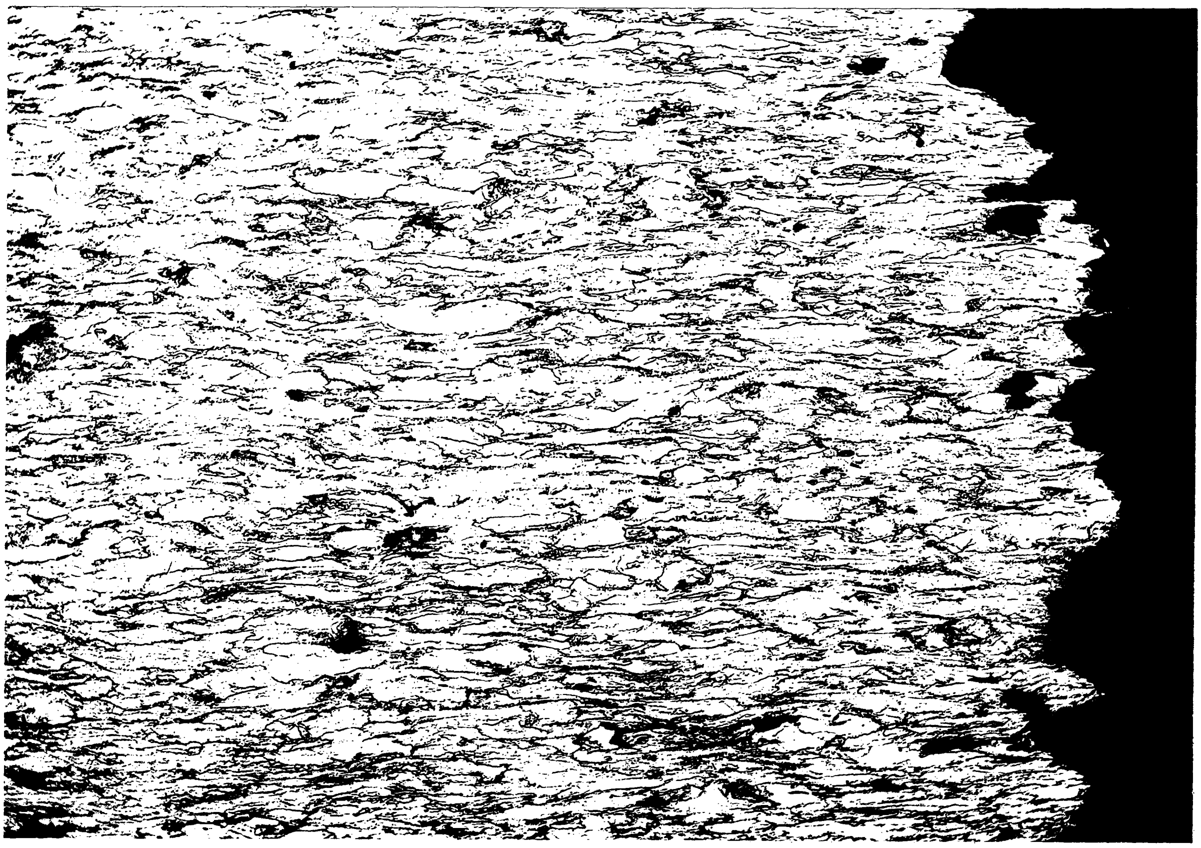


X100D - Fracture

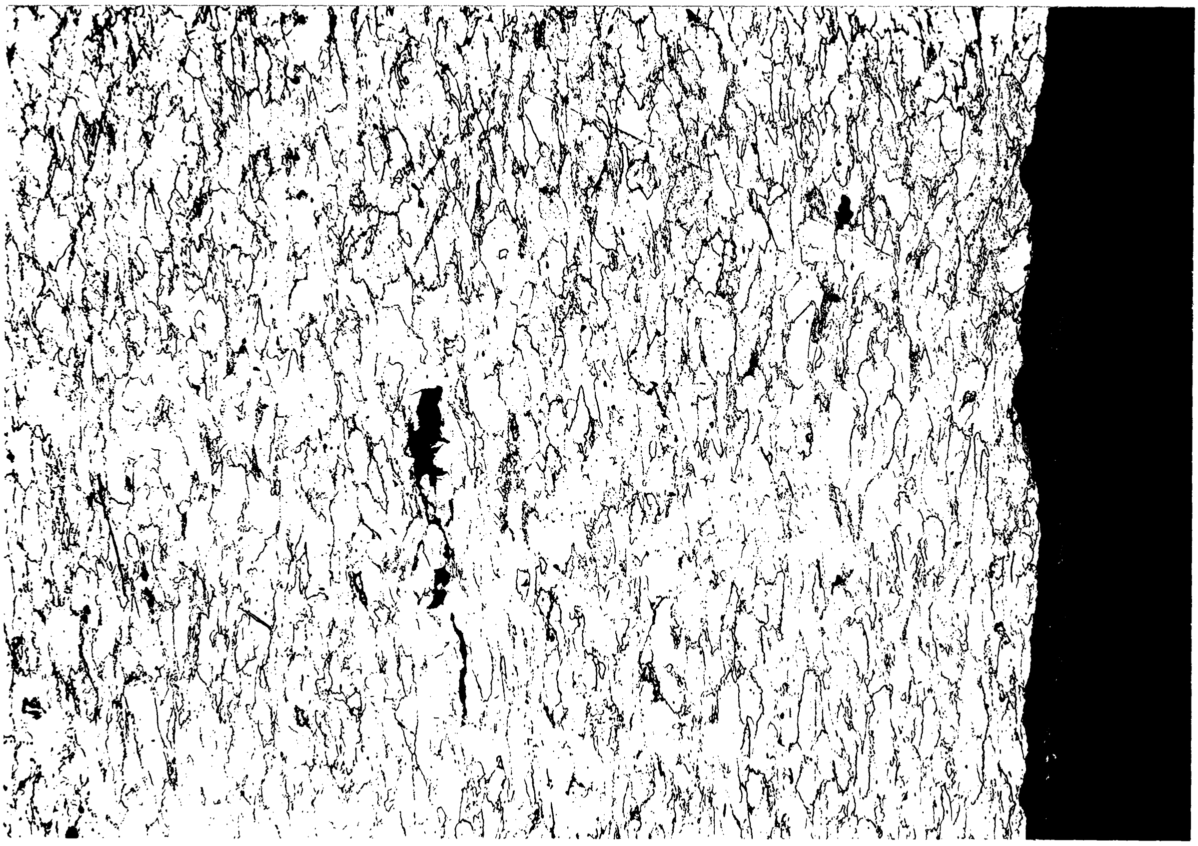


X100D - Surface

Plate 11. - Microstructure of Stress-Rupture Specimen from Carbon-Molybdenum Steel Pipe (RT-3) Fractured in 2977 Hours Under 17,000 Psi at 950°F.

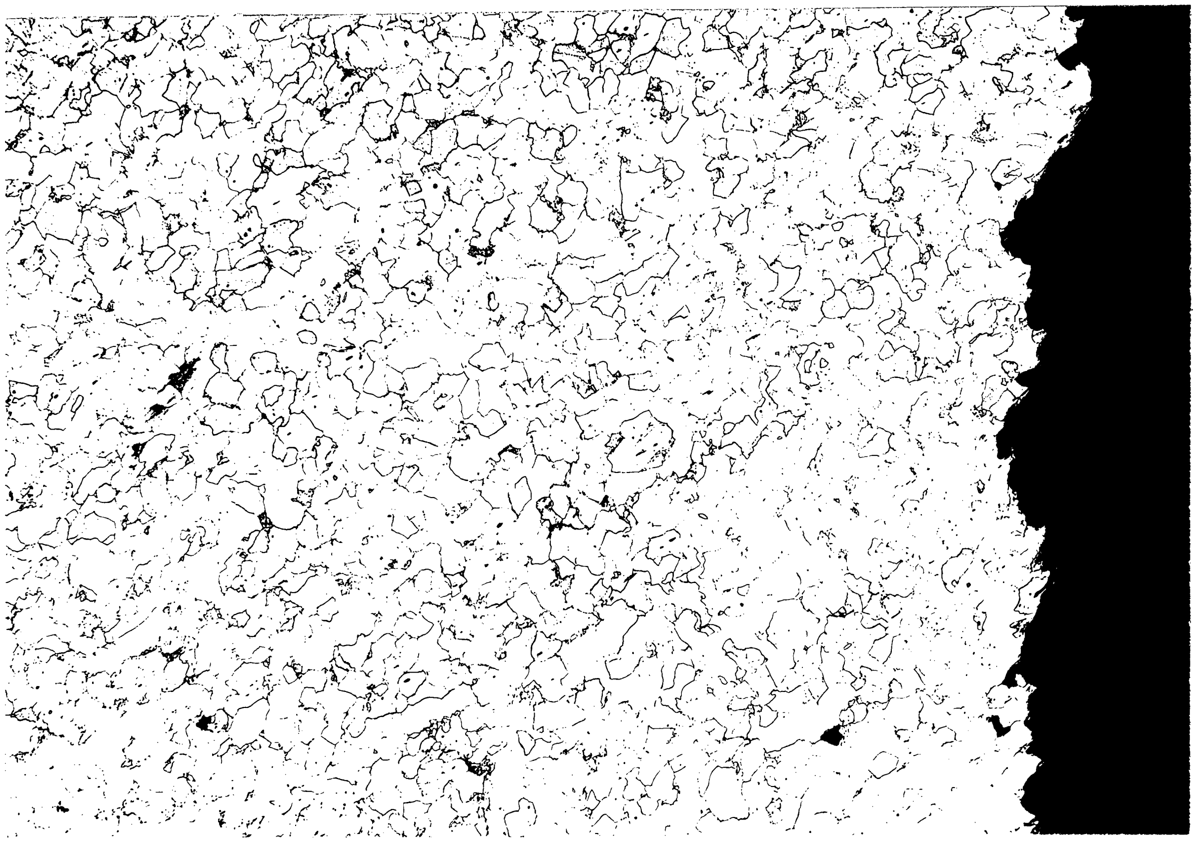


X100D - Fracture

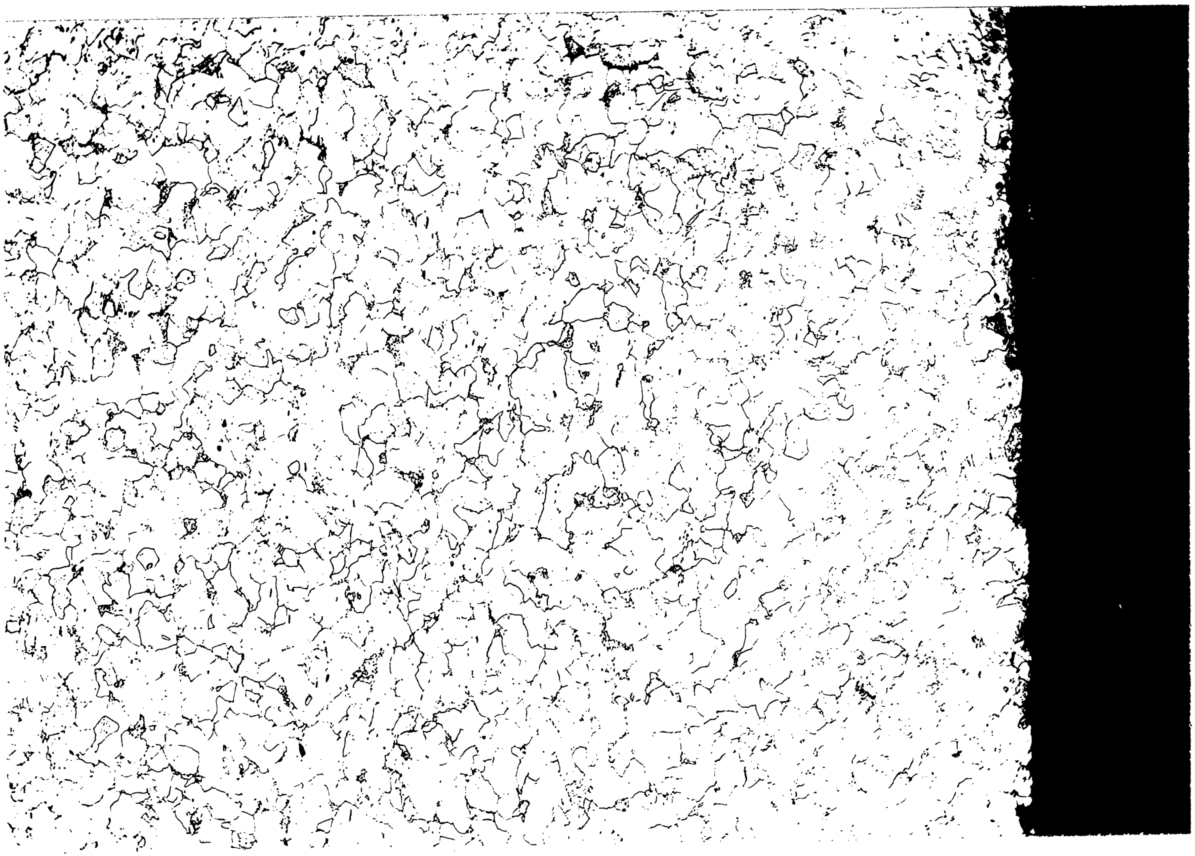


X100D - Surface

Plate 12. - Microstructure of Stress-Rupture Specimen from Carbon - Molybdenum Steel Pipe (RT-3) Fractured in 2245 Hours Under 13,500 Psi at 1000°F.



X100D - Fracture



X100D - Surface

Plate 13. - Microstructure of Tangential Stress-Rupture Specimen from Carbon-Molybdenum Steel Pipe (RT-3) Fractured in 341 Hours Under 15,000 Psi at 1000°F.

PART IV

SEWAREN GENERATING STATION NUMBER 3 UNIT MAIN 1050°F STEAM PIPING

New 3 Cr - 1 Mo Steel Pipe

Sample RT4

Rupture tests were conducted at 1050° and 1100°F for time periods out to 1000 hours on samples cut from a length of pipe designated as "RT4". The pipe was made from 3 Cr - 1 Mo steel and had not been in service. The pipe dimensions were 13.2-inch O.D. x 2.4-inch wall. The anticipated normal operating conditions were 1050°F and 1500 psi pressure.

Description of Pipe and Service Conditions

An eight inch length of pipe was submitted for the preparation of test bars. The information supplied regarding the history of the pipe was as follows:

Steel: 3 Cr - 1 Mo Steel (ASTM: A 213-GradeT21)

Location: No. 3 Unit. Main Steam Piping

Size: 13.2-inch O.D. x 2.4-inch wall thickness x 8.4-inch I.D.

Chemical Composition:

C	Mn	P	S	Si	Cr	Mo
0.07-0.10	0.37-0.52	0.023-0.026	0.028-0.029	0.30-0.35	2.60-3.23	0.88-0.94

Heat Treatment: Not supplied

Physical Properties:

Tensile strength (psi)	66,750-71,000
Yield strength (psi)	33,900-37,500
Elongation (% in 2 in)	30.5 - 31.5
McQuaid Ehn Grain Size	4 - 5

Service Conditions:

Service hours	none
Calculated hoop stress(S=Pd/2t)	3035 psi
Operating Temperature	
Normal	1050°F
Maximum (Rating for short swings. Not to exceed 1% of operating time.)	1100°F
Operating Pressures	
Normal	1500 lbs.
Maximum	1770 lbs.

Procedure

Standard 0.505-inch diameter specimens with a 2-inch long gage section parallel to the length of the pipe were machined for testing. Specimens representative of both the outer and inner portions of the pipe were tested. Those specimens identified as "O" in the results section of this report were obtained from the outer half of the pipe and those marked "I" from the inner half.

Sufficient tests were conducted to establish the stress rupture curves at 1050° and 1100°F out to 1000 hours.

Results

Table VIII presents the results of the individual stress-rupture tests, and the resulting stress-rupture time curves are plotted on logarithmic coordinates in Figure 6. The stress-rupture strengths obtained from the stress-rupture time curves are given in Table IX for time periods out to 100,000 hours.

Figure 6 shows that for times to about 1000 hours duration the stress-rupture time curves are nearly parallel, and that there is no evidence that changes in the slopes of the curves might be expected at longer time periods.

No difference in rupture-strength was observed between the specimens obtained from the inner and outer surfaces of the wall. Figure 6 shows that specimens obtained from both locations plot on the same curve.

Table VIII shows that the material exhibited good elongation at fracture and that no difference in ductility was observed between specimens taken from the inside and outside of the wall.

The microstructures of the original pipe metal and the fractured rupture specimens are shown in Plates 14, 15, and 16. The original structure consisted of a relatively fine intermediate transformation product separated into grains which represent the grain size of the austenite at the time of transformation. A small amount of pro-eutectoid ferrite was present at the location of the austenite grain boundaries. The carbides were spheroidized.

Plates 15 and 16 show that the fractures were transgranular through highly elongated grains. There was no evidence of intergranular cracking or oxidation. The structures were in accordance with the normal characteristics of 3Cr - 1Mo steel with the initial structure observed.

Discussion of Results

The rupture strengths obtained are very close to the average values for annealed material of Reference 1, as is shown by Figure 7. This average was based on rather sparse data so that the agreement was somewhat surprising. An average curve was not given for 100,000 hours due to the few data.

3 Cr - 1 Mo steel appears to be characterized by stress-rupture time curves which show little or no change in slope with increasing time and have very high

ductility to fracture. Data in Reference 1 show no great difference in slope for curves at 1050° and 1200°F. Apparently, therefore, no change in slope would be expected for the 1050° and 1100°F curves and the extrapolation to 100,000 hours appears to be reasonably safe.

TABLE VIII

Rupture-Test Data for 3 Cr - 1 Mo Steel Main Steam Pipe Prior to Service in Number 3 Unit of the Sewaren Generating Station

Sample RT4

Test Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elongation in 2 in (%)	Reduction of Area (%)	Specimen
1050	25,000	13.5	40.7	87.3	O
	20,000	182	46.5	87.4	O
	17,000	780	48.0	89.5	I
1100	20,000	28	54.0	88.5	I
	16,500	135	55.0	90.0	I
	14,000	475	73.5	92.0	O
	12,500	1108	43.5	90.6	O

TABLE IX

Stress-Rupture Strengths for 3 Cr - 1 Mo Main Steam Pipe Prior To Service in Number 3 Unit of the Sewaren Generating Station

Sample RT4

Temp. (°F)	Stress for Rupture in Indicated Time Periods (psi)				
	10-hr	100-hr	1000-hr	10,000-hr	100,000-hr
1050	27,000	21,000	16,500	12,500	9,800
1100	23,000	17,000	12,500	9,400	7,000
Average Values from ASTM Special Technical Publication No. 151					
1050	--	23,000	15,500	11,500	--
1100	--	18,000	12,000	8,750	--

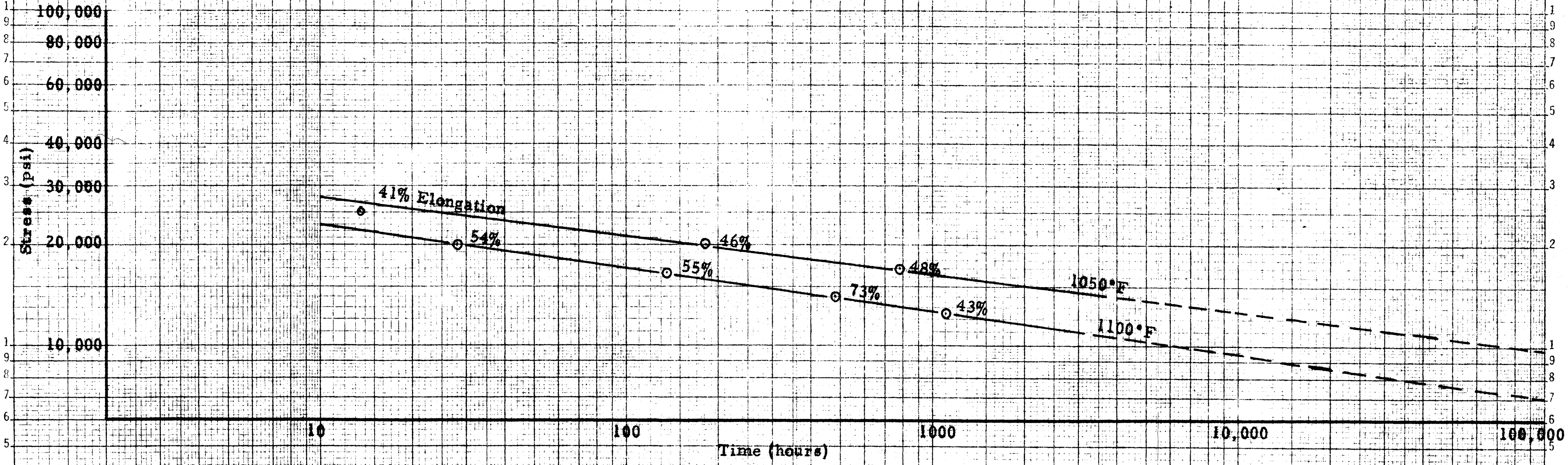


Figure 6. - Stress-Rupture Time Curves at 1050° and 1100°F for the 3 Cr - 1 Mo Steel Main Steam Pipe Prior to Service in Number 3 Unit of the Sewaren Generating Station.

(Sample RT4)

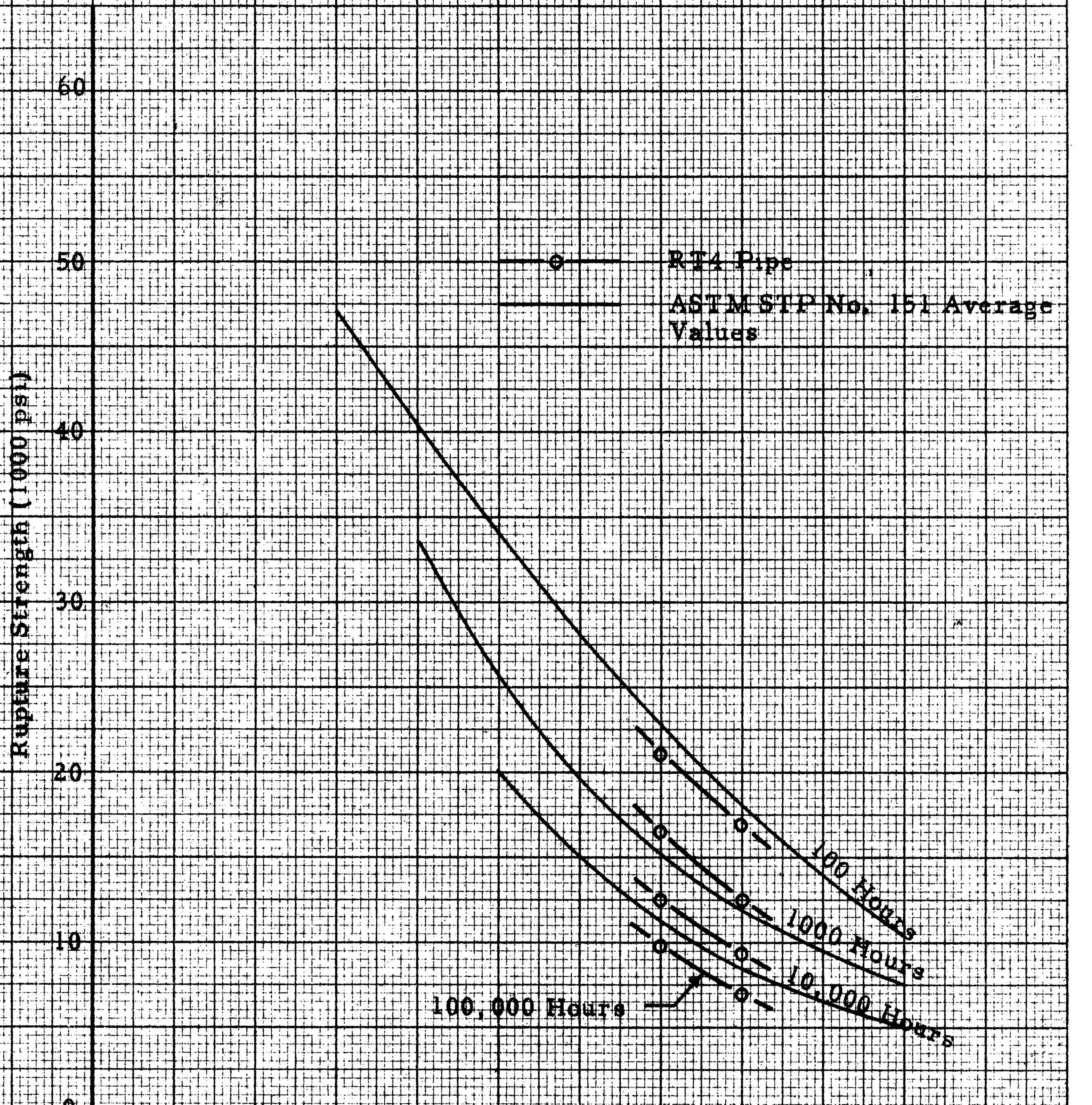
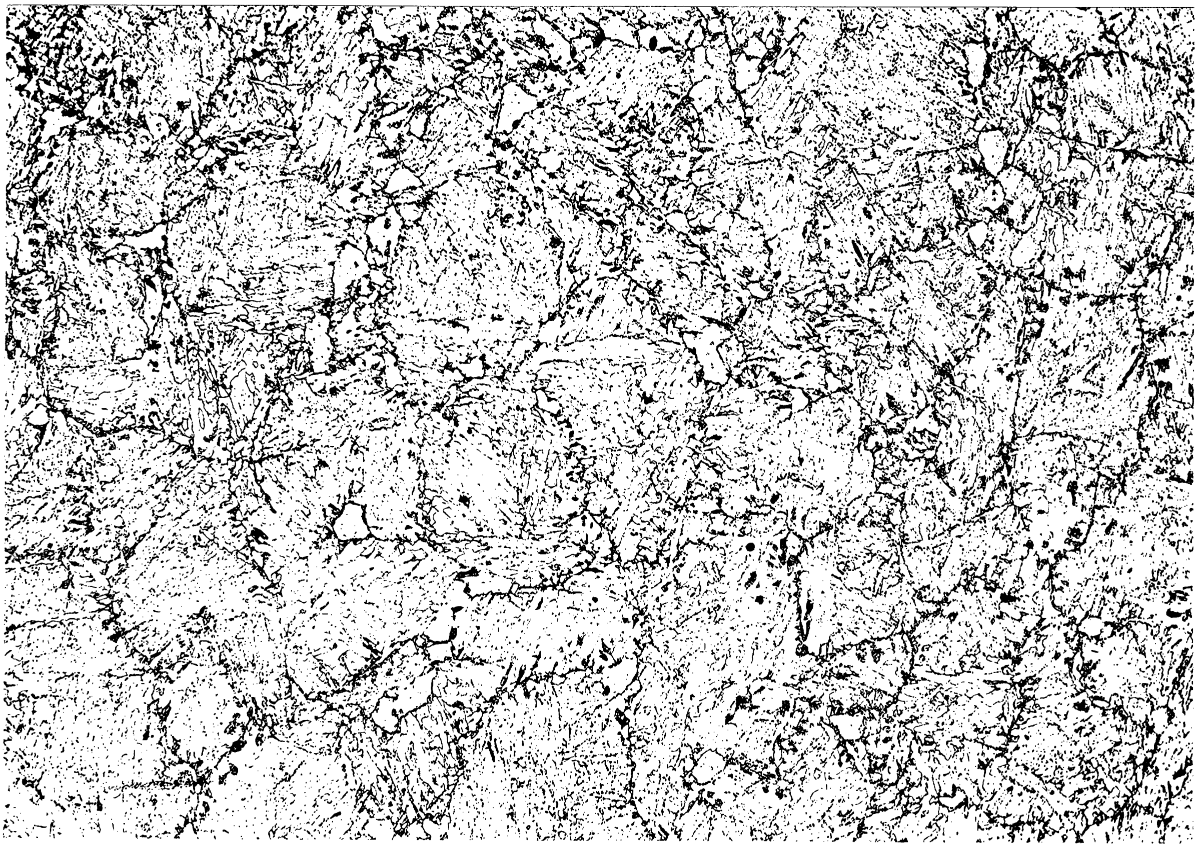
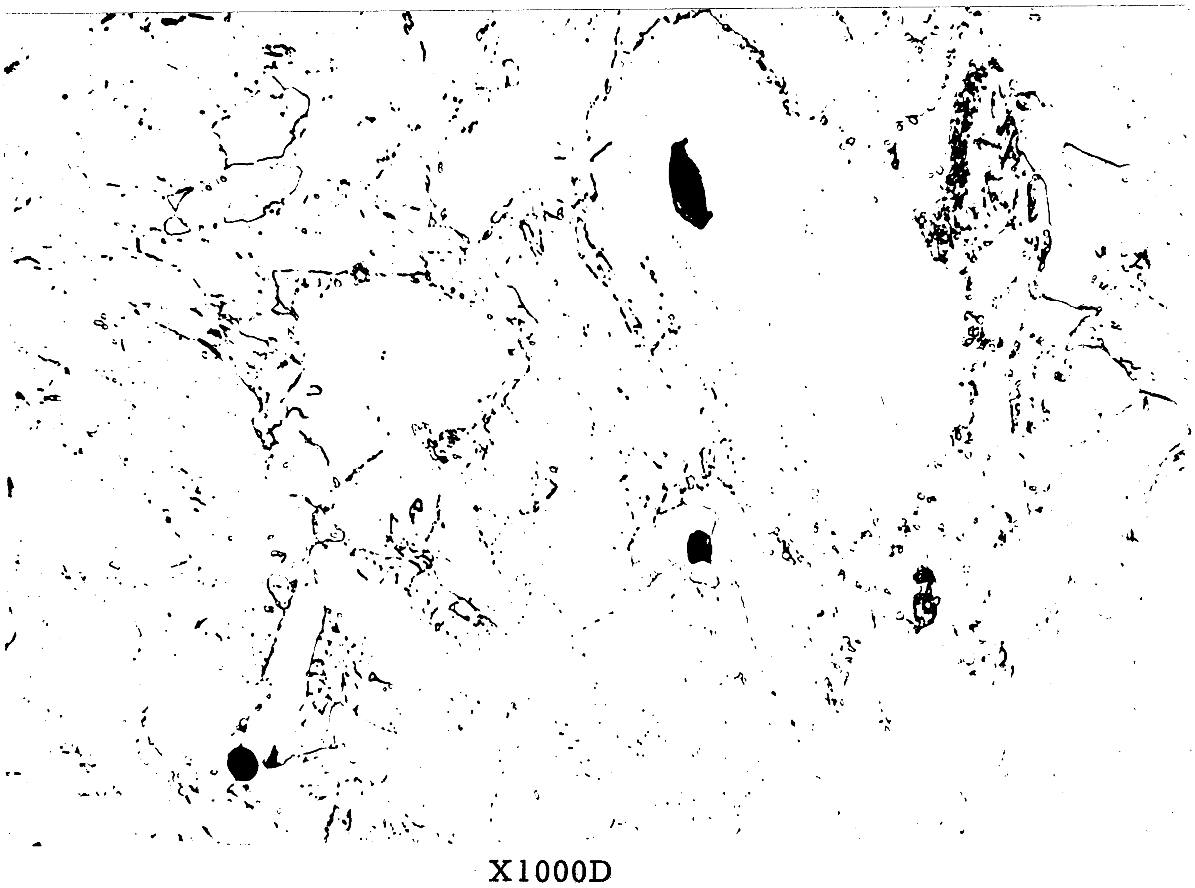


Figure 7. - Comparative Rupture Strengths for 3 Cr - 1 Mo Pipe RT4 and Average Values of Annealed 3 Cr - 1 Mo Steel

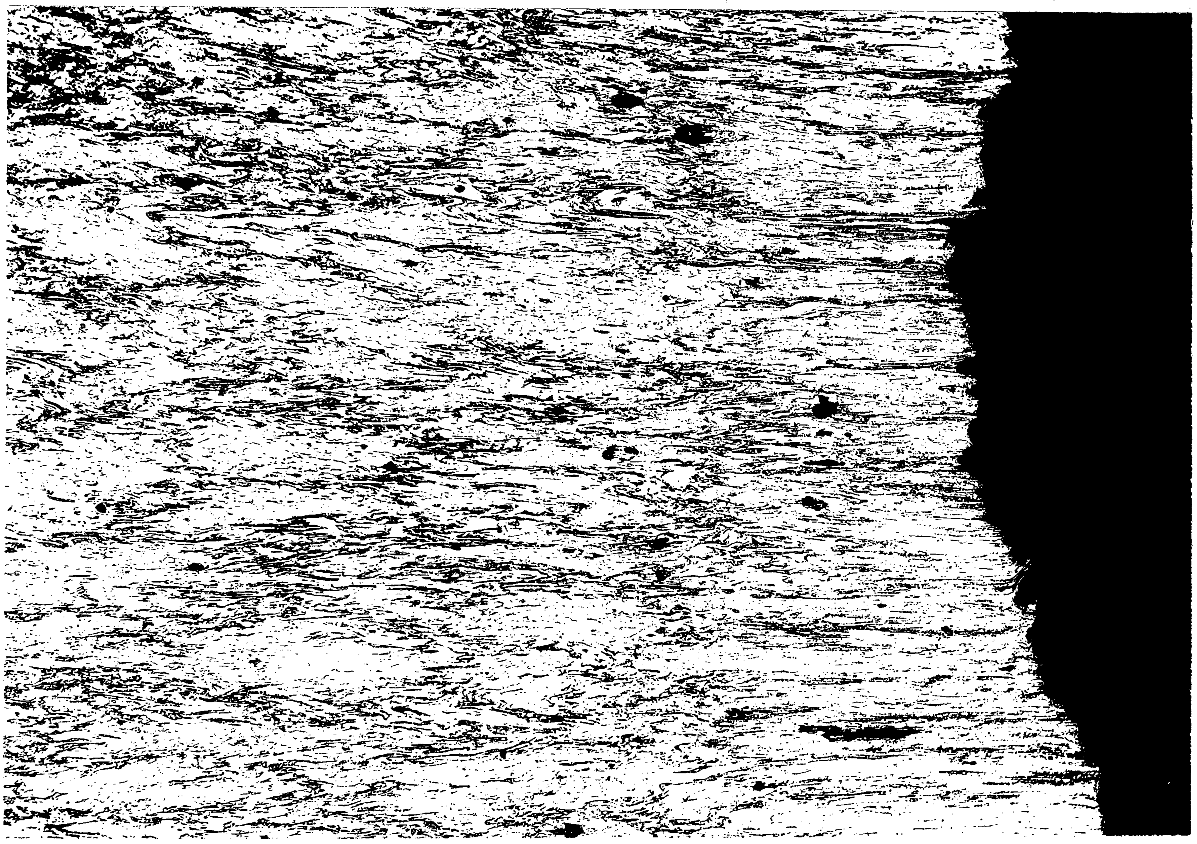


X100D

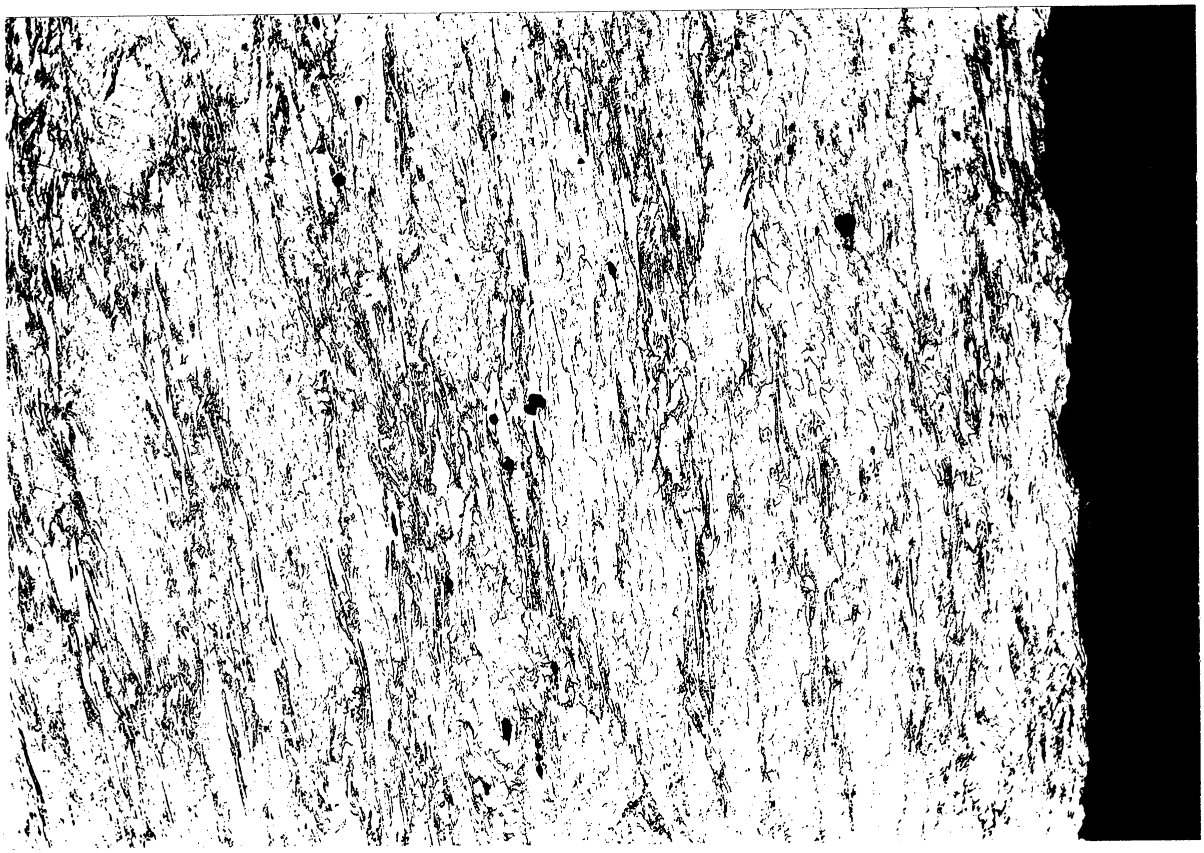


X1000D

Plate 14. - Original Microstructure of 3 Cr - 1 Mo Steel Pipe (RT-4) from Sewaren Generating Station, No. 3 Unit, Main Steam Piping. No Time in Service.



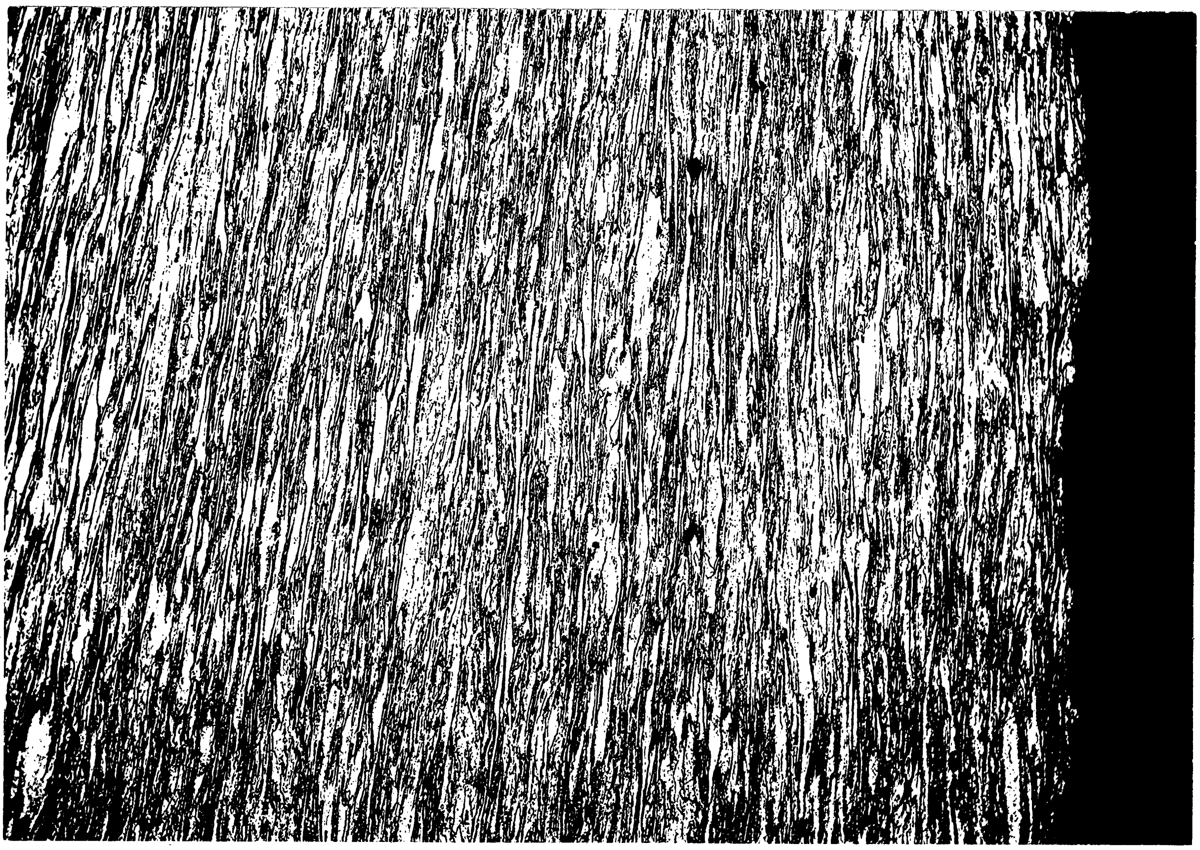
X100D - Fracture



X100D - Surface

Plate 15. - Microstructure of Stress-Rupture Specimen from 3 Cr - 1 Mo Steel Pipe (RT-4) Fractured in 780 Hours Under 17,000 Psi at 1050°F.

X100D - Fracture



X100D - Surface

Plate 16. - Microstructure of Stress-Rupture Specimen from 3 Cr - 1 Mo Steel Pipe (RT-4) Fractured in 1108 Hours Under 12,500 Psi at 1100°F.

PART V

SEWAREN GENERATING STATION NUMBER 2 UNIT MAIN 1050°F STEAM PIPING

Type 347 Stainless Steel after 22,716 Hours of Service.

Sample RT5

Rupture tests were conducted at 1050° and 1100°F for time periods out to 2000 hours on specimens cut from a length of pipe designated as Sample "RT5". The pipe was made from Type 347 stainless steel and had been in service 22,716 hours at a normal operating temperature and pressure of 1050°F and 1500 psi, respectively. The pipe dimensions were 6.625-inch O.D. x 5.189-inch I.D. x 0.718-inch wall.

Description of Pipe and Service Conditions

A section of pipe ten-inches long with a circumferential length of about 6-inches was submitted for machining into test specimens. The sample was identified as RT5, and the following information regarding the pipe was supplied.

Steel: Type 347 stainless steel (AISI Type 347-G.E. Spec. B50A141)

Location: Main 1050°F steam piping, Number 2 Unit.

Size: 6.625-inch O.D. x 5.189-inch I.D. x 0.718-inch wall

Chemical Composition (percent):

C	Mn	P	S	Si	Ni	Cr	Mo	Cb	Cu
0.052	1.64	0.013	0.013	0.43	12.56	18.57	0.03	0.67	0.08

Mill Heat Treatment: Normalized

Shop Heat Treatment: Stabilizing heat treatment, 4 hours at 1600°F.

Physical Properties:

Tensile Strength (psi)	81,000
Yield Strength (psi)	48,000

Elongation (% in 2 in.)	58.5
Service Condition	
Service hours	22,716
Calculated hoop stress(S=Pd/2t)	5,420 psi
Operating Temperatures	
Normal	1050°F
Maximum (Rating for short swings. Not to exceed 1% of operating time)	1100°F
Operating Pressures:	
Normal	1500 lbs.
Maximum	1770 lbs.

Procedure

Standard 0.505-inch diameter test bars were machined with a 2-inch reduced section parallel to the longitudinal axis of the pipe.

Sufficient tests were conducted to establish the stress-rupture time curves out to 1000 to 2000 hours at 1050° and 1100°F.

Results

The individual rupture test data at 1050° and 1100°F are presented in Table X and plotted as stress-rupture time curves on logarithmic coordinates in Figure 8. Table XI shows the stress-rupture strengths obtained for various time periods from the curves of Figure 8.

Figure 8 shows that for time periods out to about 1500 hours there is no evidence of a change in slope in the stress-rupture time curves at either 1050° or 1100°F. The curves also have about the expected degree of divergence for the difference in temperature.

Table X shows a pronounced decrease in fracture ductility with increased time of testing. The test data indicate that quite low ductility could be anticipated for testing periods in excess of about 10,000 hours.

The microstructure of the as-received material consisted of austenite and columbium carbide with an ASTM grain size of 3 to 5 as shown in Plate 17. Plates 18 and 19 illustrate the microstructures observed after testing at 1050° and 1100°F respectively.

The photomicrographs of the failed specimens show that considerable intergranular cracking occurred in the region near the fracture and that the cracking was somewhat more severe at a testing temperature of 1100°F than at 1050°F.

A relatively fine discontinuous precipitate was observed in the grain boundaries of samples tested at both 1050° and 1100°F. Inasmuch as this precipitate was not present initially after 22,716 hours of service, its formation was apparently accelerated by the high stresses that existed during the rupture tests. This is in agreement with previous experience on similar materials.

Discussion of Results

The rupture strengths obtained were well below the average for annealed material as established in Reference 3. This is shown by the comparison of data in Table XI and Figure 9. Type 347 steel, however, is subject to such wide variations in strength that consideration should also be given to the relation of the values obtained for Sample RT5 to the low side of the range of existing data. Table XI shows that the rupture strengths were still below the range at 100 and 1000 hours but were above minimum values at 10,000 and 100,000 hours.

The values of rupture strength obtained are so far above the calculated hoop stress of 5,420 psi that the amount of rupture life used up in 22,716 hours should be negligible. The rupture strengths measured being on the low side of the range should therefore be due either to initally low strength in the particular lot of steel; or to the influence of the long time exposure to temperatures in the range of 1050° to 1100°F. The general flattening of the stress-rupture time curves in comparison to new material suggests that structural changes due to long time heating was at least partially involved. It is not possible to estimate the original rupture strengths with certainty. The normalizing temperature was not reported. The grain size would seem to indicate treatment above 1900°F, although this is not certain since the grain size could have been as large as is shown by the photomicrographs due to hot-working conditions. No data has been found which show that the 1600°F stabilizing treatment would be expected to give low values. It is suspected, however, that the pipe metal originally had strengths on the low side of the range for Type 347 steel.

It should be noted that the long time exposure to service temperature did not remove the tendency for low elongation to develop at the longer times for rupture. This behavior is characteristic of Type 347 steel with other than a very fine grain size. It is presumed that this is related to the precipitate which forms in the grain boundaries. It is possible that the yielding during loading of the test specimens, as well as the creep during testing, was involved in the appearance of the grain boundary phase. All of the stresses used were near to or above the probable yield strength of the alloy at the test temperature. The accelerating effect of the plastic strain and high stress could account for the development of the phase during the relatively short duration rupture tests and not during the comparatively prolonged service time at about the same temperature.

TABLE X

Stress-Rupture Data for 18-8 + Cb Steel Pipe at 1050° and 1100°F After 22,716 Hours Service at 1050°F at the Sewaren Generating Station

Sample RT5

Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elongation (% in 2 in)	Reduction of Area (%)
1050	40,000	59	44.0	55.3
	36,000	257	34.0	36.2
	33,000	2197	10.0	14.0
1100	35,000	55	39.0	47.0
	32,000	146	24.5	30.5
	28,000	595	17.0	19.0
	26,000	1234	9.0	12.9

TABLE XI

Stress-Rupture Strengths for 18-8 + Cb Steel Pipe at 1050° and 1100°F After 22,716 Hours Service at 1050°F at the Sewaren Generating Station

Sample RT5

Temp. (°F)		Stress for Rupture at Indicated Time Periods (psi) 100-hr	1000-hr	10,000-hr	100,000-hr
1050		40,000	33,500	28,000	23,500
1100		33,000	27,000	21,000	17,000
Comparative Values from ASTM STP No. 124					
1050	Average	50,000	43,000	32,000	26,500
1050	*	42,000	36,000	24,000	18,500
1100	Average	39,000	34,500	26,500	21,500
1100	*	36,000	29,000	19,500	15,000

* Lowside of range shown in STP No. 124

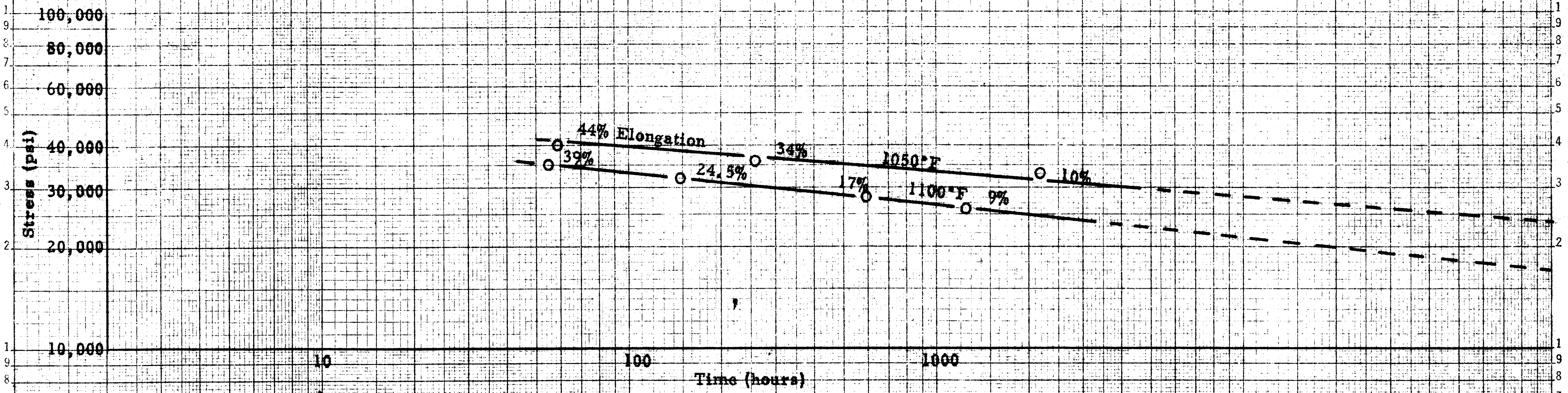


Figure 8. - Stress-Rupture Time Curves at 1050° and 1100°F for 18-8 + Cb Steel from Main 1050°F Steam Piping after 22,716 Hours of Service in the Number 2 Unit, Sewaren Generating Station.

(Sample RT5)

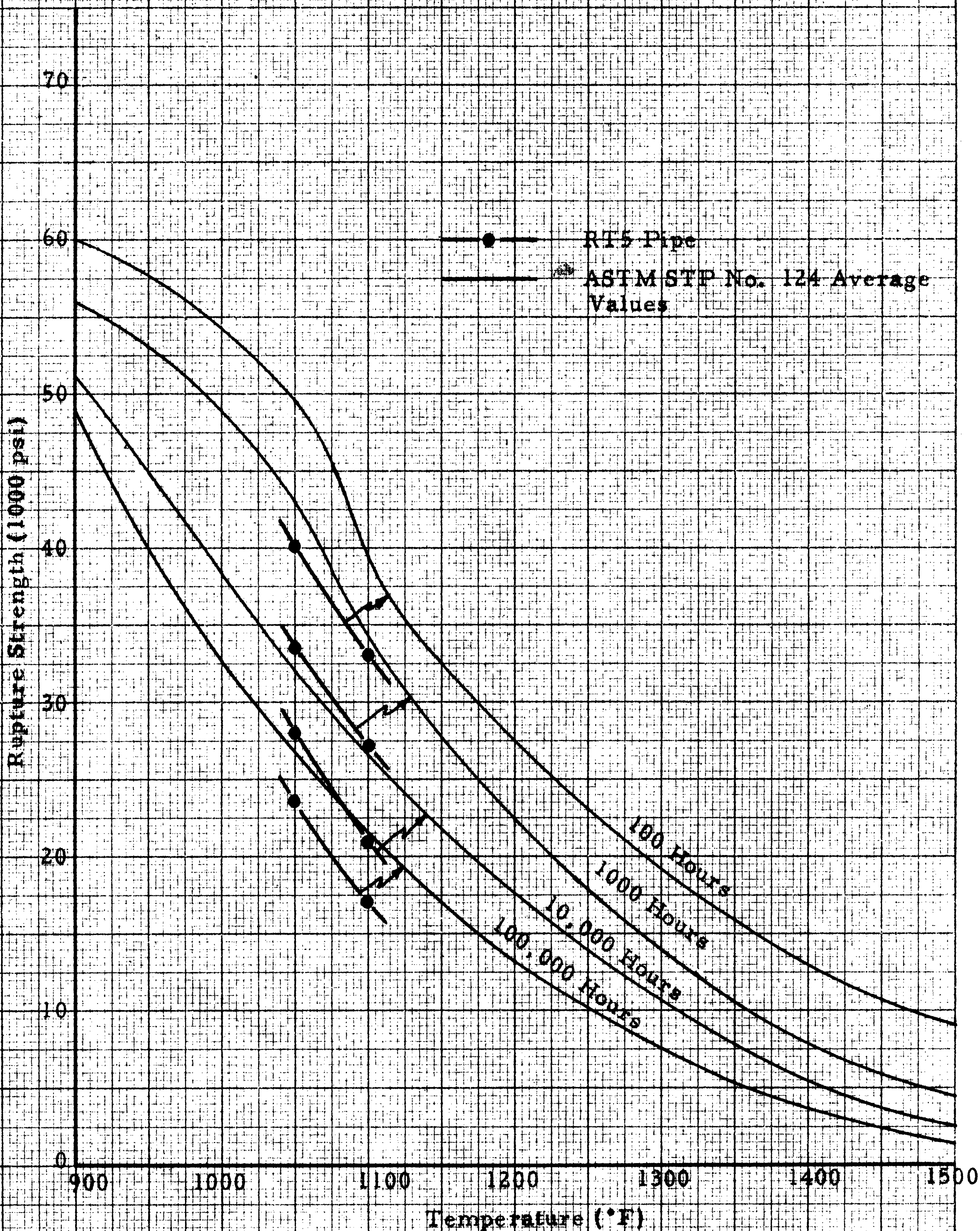
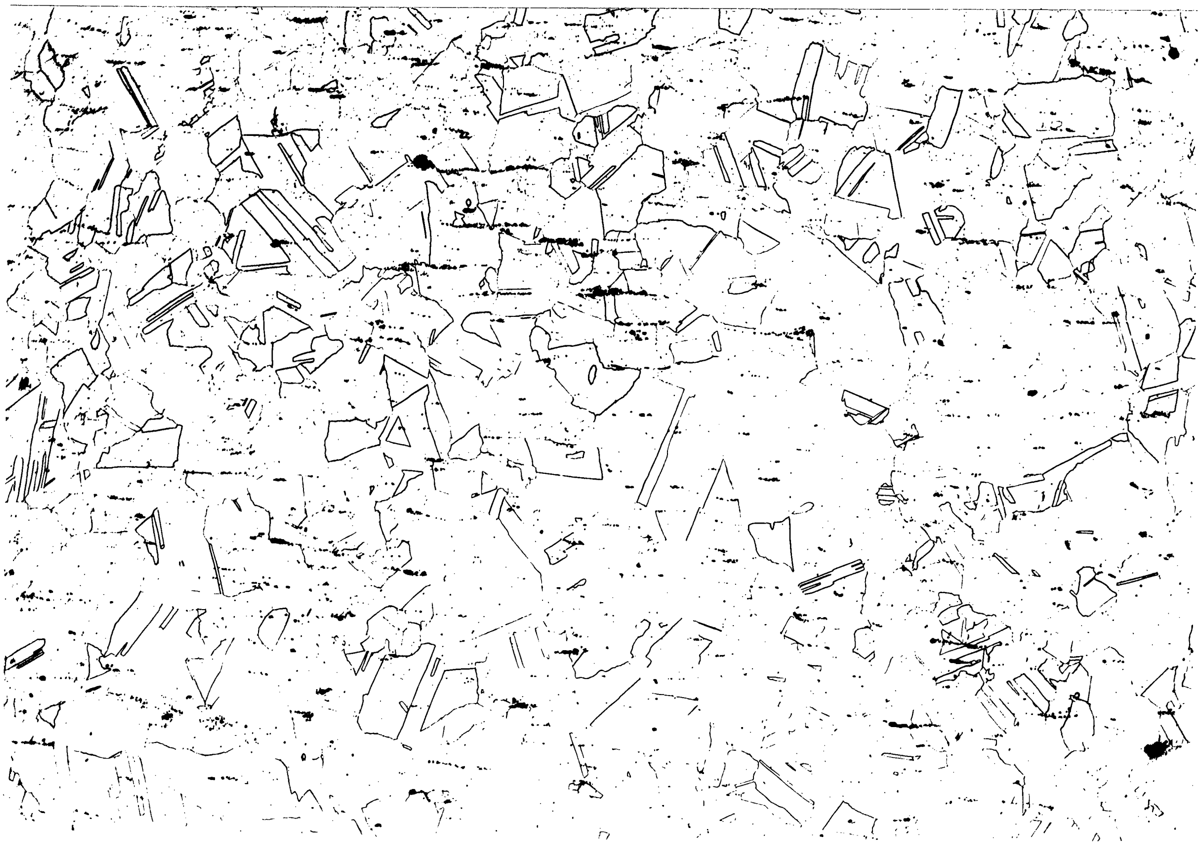
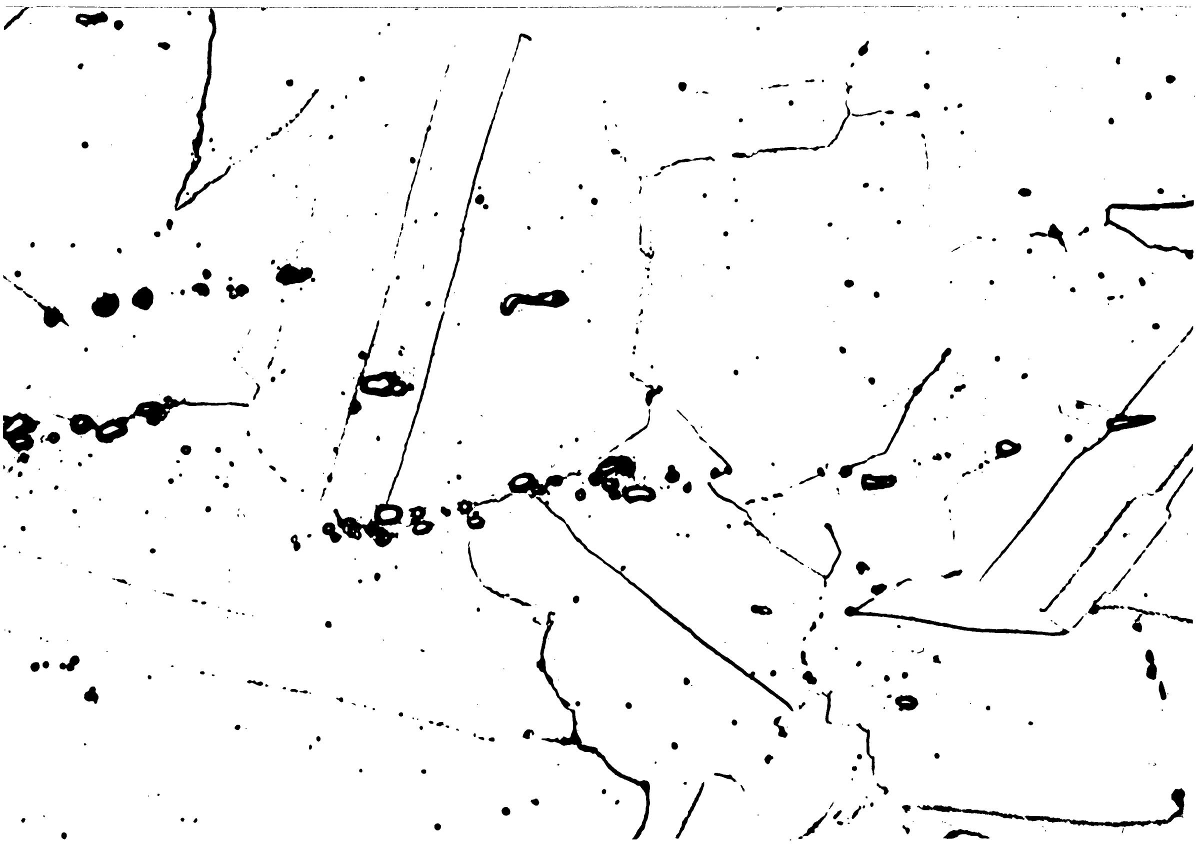


Figure 9. - Comparative Rupture Strengths for 18-8 + Cb Pipe RT5 and Average Values for Annealed 18-8 + Cb Steel

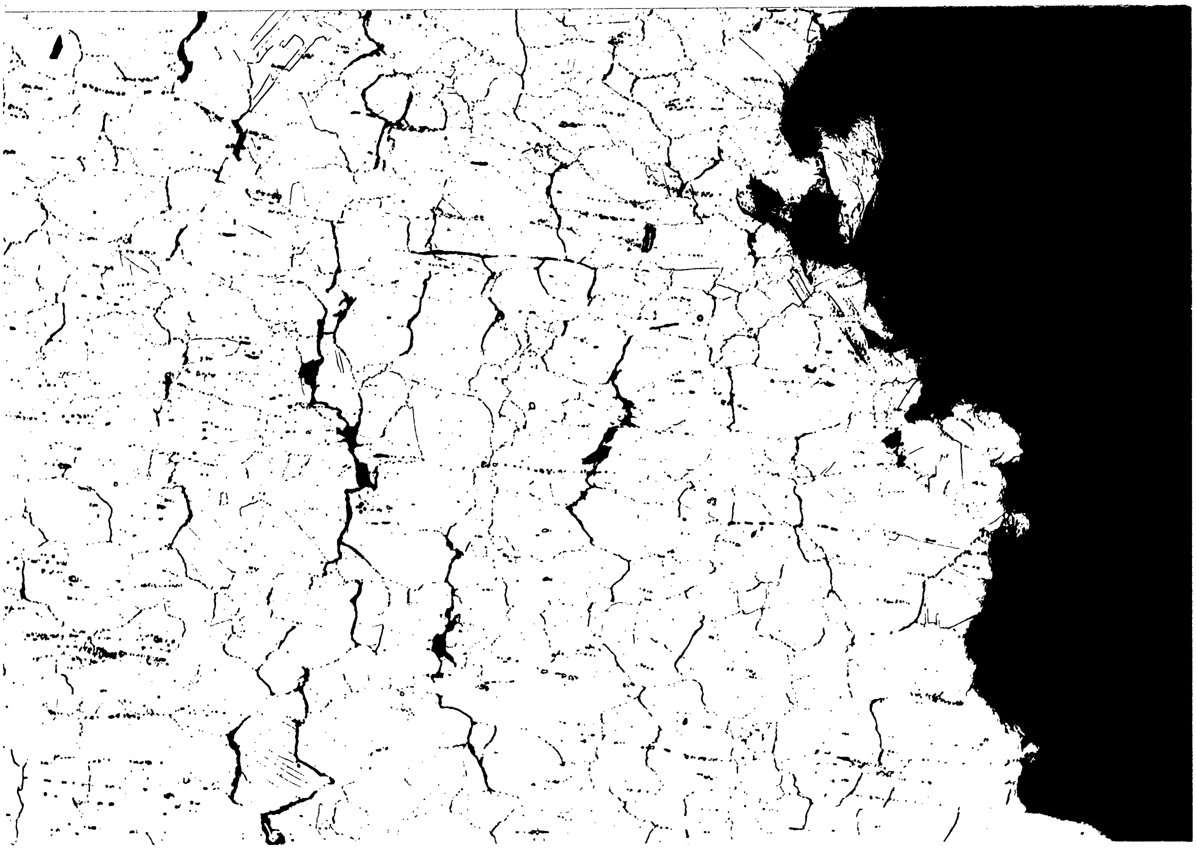


X100D

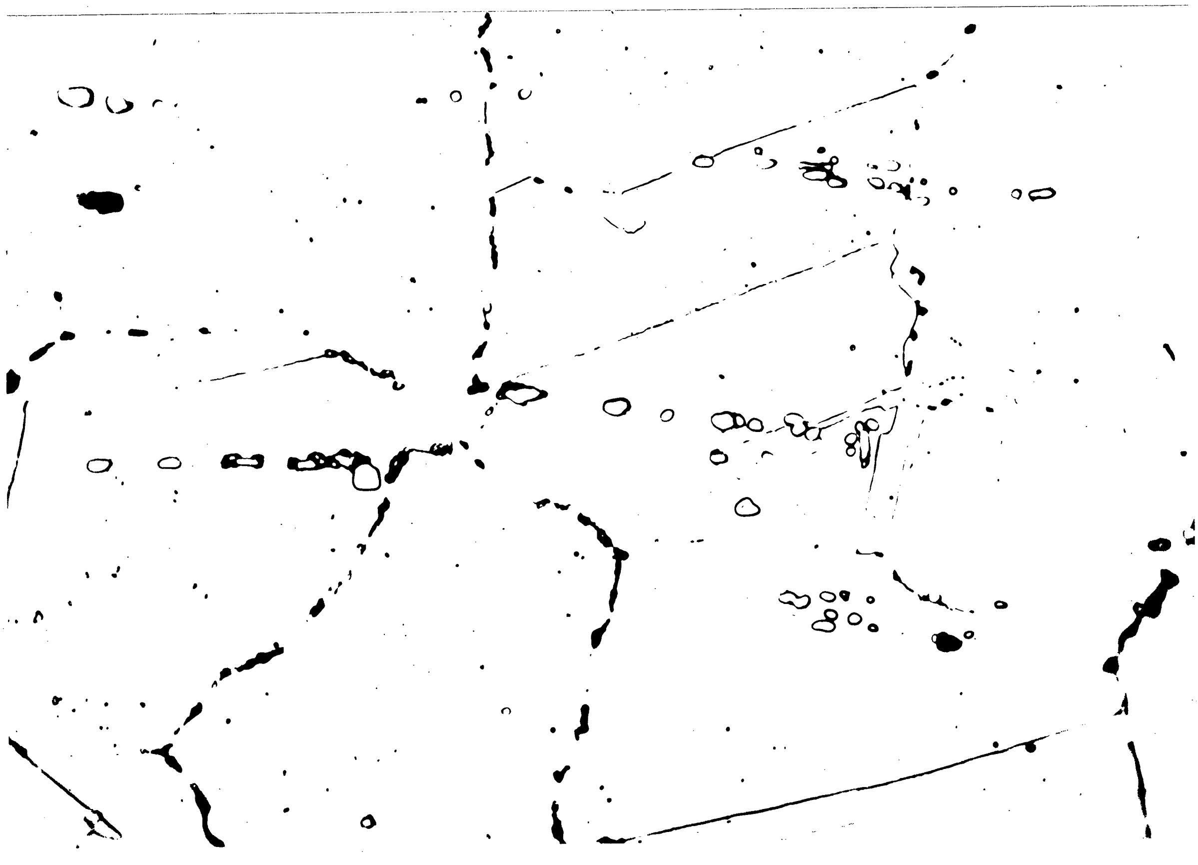


X1000D

Plate 17. - As-Received Microstructure of 18-8 + Cb Steel Pipe (RT-5) after 22,716 Hours Service at 1050°F at Sewaren Generating Station.

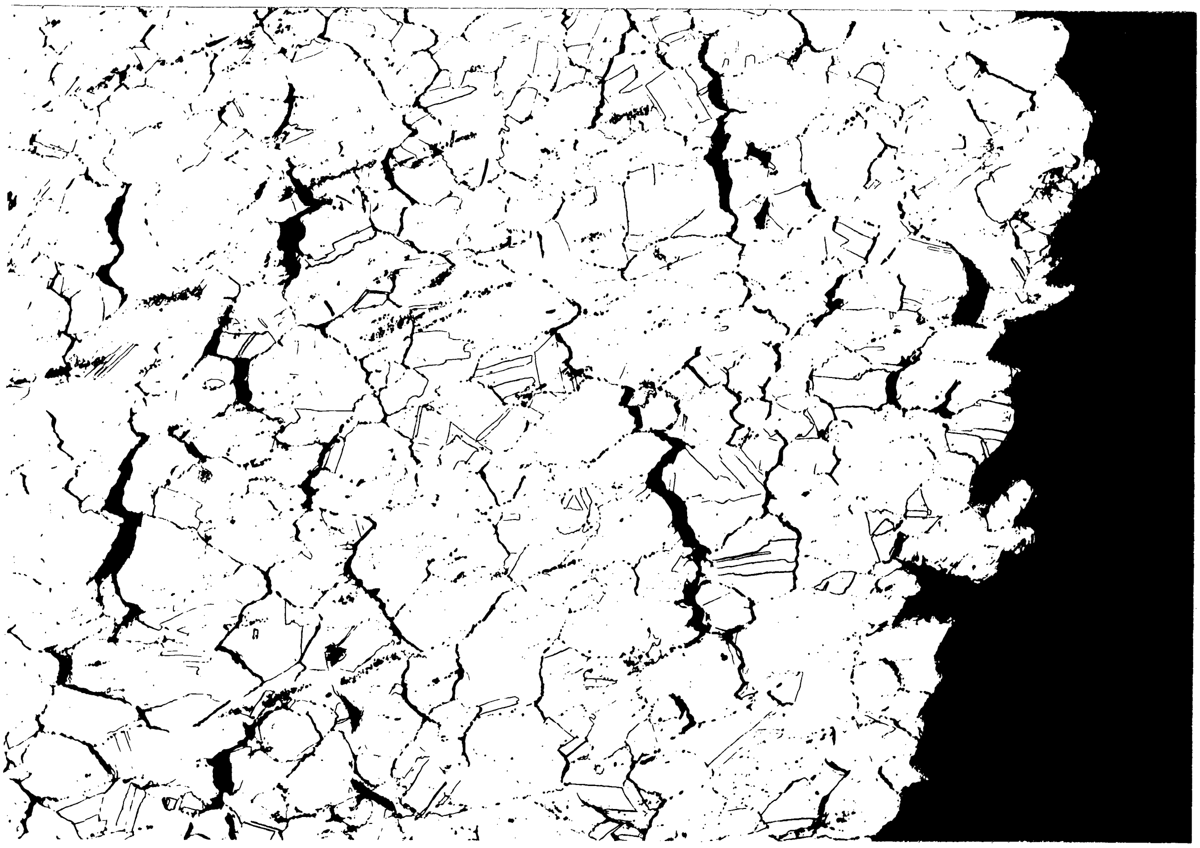


X100D - Fracture

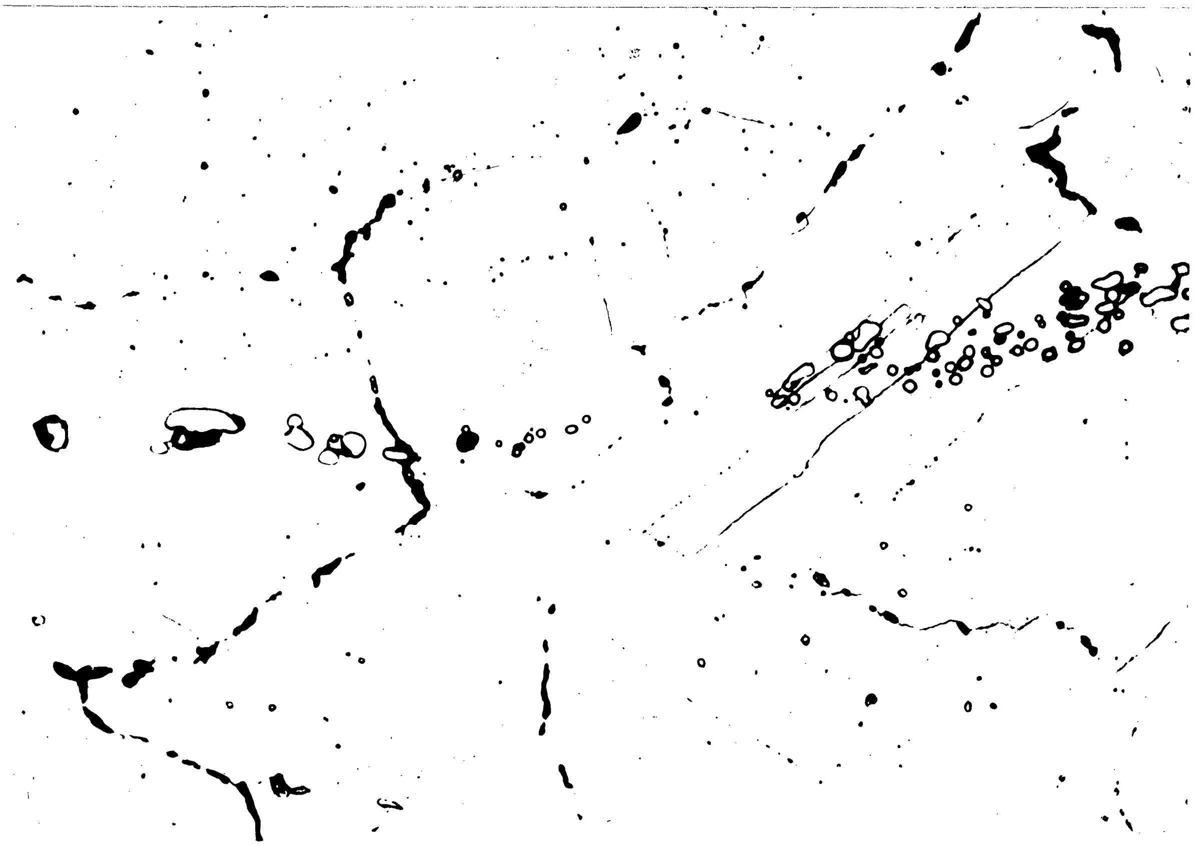


X1000D - Interior

Plate 18. - Microstructure of 18-8 + Cb Steel Pipe (RT-5) Fractured in 2,197 Hours under a Stress of 33,000 Psi at 1050°F.



X100D - Fracture



X1000D - Interior

Plate 19. - Microstructure of 18-8 + Cb Pipe (RT-5) Fractured in 1,233 Hours Under a Stress of 26,000 Psi at 1100°F.

PART VI

SEWAREN GENERATING STATION NUMBER 2 UNIT MAIN 1050°F STEAM PIPING

Weld in Type 347 Stainless Steel After 22,716 Hours of Service

Sample RT6

Rupture tests were conducted on welded samples at 1050°and 1100°F for time periods out to about 1000 to 1500 hours on specimens cut from a length of pipe designated as Sample "RT6". The pipe was made from Type 347 stainless steel reported to be the same as Sample RT5. The weld was made with Arcos 19/9 Cb rod. The pipe was reported to have been in service for 22,716 hours at a normal operating temperature and pressure of 1050°F and 1500 psi, respectively. The pipe dimensions were 6.625-inch O.D. x 5.189-inch I.D. x 0.718-inch wall.

Description of Pipe and Service Conditions

A section of pipe ten-inches long with a circumferential length of about 6-inches was submitted for machining into test bars. The circumferential weld was located approximately in the center of the 10-inch section. The sample was identified as RT6 and was reported to be the same, except for the weld, as sample RT5 described previously. However, for the sake of completeness, that description will be repeated here:

Steel: Type 347 stainless steel (AISI Type 347-G.E. Spec. B50A141)

Weld Material: Arcos 19/9 Cb.

Location: Main 1050°F steam piping, Number 2 unit.

Size: 6.625-inch O.D. x 5.189-inch I.D. x 0.718-inch wall

Chemical Composition (percent):

C	Mn	P	S	Si	Ni	Cr	Mo	Cb	Cu
0.052	1.64	0.013	0.013	0.43	12.56	18.57	0.03	0.67	0.08

Physical Properties:

Tensile Strength (psi)	81,000
Yield Strength (psi)	48,000
Elongation (% in 2 in)	58.5

Service Conditions:

Service hours	22,716
Operating Temperatures	
Normal	1050°F
Maximum (Rating for short swings. Not to exceed 1% of operating time)	1100°F
Operating Pressures:	
Normal	1500 lbs.
Maximum	1770 lbs.

The welding conditions and heat-treatment after welding, if any, were not reported.

Procedure

Standard 0.505-inch diameter test bars with a 2-inch gage length were machined with the longitudinal axis parallel to the length of the pipe. These specimens were located so that the weld metal was in the center of the reduced section.

Sufficient tests were conducted to establish the stress-rupture curve out to about 1500 hours at 1100°F. Because of a scarcity of test material, only two tests were run at 1050°F, establishing the stress-rupture time curve out to about 1000 hours.

Results

The individual stress-rupture test data at 1050° and 1100°F are presented in Table XII, and the stress-rupture time curves are graphed on logarithmic co-ordinates in Figure 10. Table XIII shows the stress-rupture strengths for 100, 1000, 10,000, and 100,000 hours derived from the rupture time curves.

Figure 10 shows that tests out to about 1500 hours duration do not show any evidence of a change in slope for the 1100°F temperature. Since only two tests could be conducted at 1050°F, it is impossible to ascertain whether or not the curve as drawn is correct. More tests might have shown a curve at 1050°F with somewhat more slope.

Table XII shows that a progressive decrease in ductility with increasing time to fracture was observed if only the specimens which failed in the parent metal are considered. This observation is in agreement with the ductility values observed for the parent metal samples, RT5. In fact, the reduction of area values for both RT5 and RT6 were quite similar when fracture occurred in the parent metal. In the two cases where fracture occurred near the weld, the reduction of area was quite low. However, when this type of failure occurred, necking down on both sides of the weld was observed, and the reduction of area in the base metal at these locations was of the order obtained on the base metal samples, RT5.

On the other hand, the elongation values do not accurately reflect the ductility of the metal since apparently very little deformation occurred in the weld metal which made up about 50 percent of the gage length. Thus, the elongation values reported would be expected to be on the low side. Comparison of the values reported here with those shown in the previous section for the base metal (Sample RT5) confirms this conclusion.

The microstructure of the base metal in the as-received condition consisted of austenite grains and columbium carbides. The grain size of ASTM 4-6, Plate 20, was somewhat smaller than the 3 to 5 grain size reported in the previous section for the unwelded sample RT5. However, the photomicrographs of the fractured specimens, Plates 21 and 22, show that apparently the grain size was somewhat variable since Plate 21 indicates a grain size of about 2 to 4 and Plate 22 shows a grain size of 3 to 5.

Plates 23 and 24 illustrate the appearance of the weld metal and heat-affected zone, respectively, in the as-received condition. These plates show the presence of a rather heavy precipitate in the grain boundaries of the weld metal. The precipitate appears to be sigma phase although this supposition has not been verified.

Macroscopic examination of the failed specimens revealed considerable variation in the mode of fracture. Three types of failure were noted:

1. Failure entirely in the base metal about 1/4 to 1/2-inch from the weld bond line. Plates 25a and 26b illustrate this type of fracture at 1050° and 1100°F, respectively.

2. Failure apparently started at the weld bond line or in the weld metal and progressed into the base metal, Plate 25b. Microscopic examination of this specimen revealed small cracks in the weld metal, Plate 27a, near the point where the main fracture apparently started, and cracks in the heat-affected zone, Plate 27b, at a point 180° away.

3. Failure appeared to be entirely in the heat-affected zone as shown in Plate 26a.

4. The macrographs of Figures 25 and 26 appear to show the weld bond-line as being normal to the longitudinal axis of the samples in some instances and at a more acute angle in others. However, these apparent differences are the result of variations in orientation of the polished surface of the sample with respect to the weld metal. The orientation of the weld metal with respect to the longitudinal axis of the test bars was the same in all instances.

The types of failure as described above showed little or no correlation with the duration of testing. The longer of the two tests at 1050°F showed a fracture apparently starting in the weld and extending into the base metal. The shorter time test failed entirely in the base metal. However, at 1100°F, all of the specimens fractured in the parent metal except the intermediate time test, 340 hours, which failed in the heat-affected zone.

Microscopic examination after failure of the longest duration tests showed that the fracture at 1050°F was transgranular, Plate 22, whereas the specimen tested at 1100°F showed a mixed intergranular-transgranular fracture. Considerable intergranular cracking was observed adjacent to the fracture at 1100°F, but only a small amount was observed after testing at 1050°F. However, the difference in testing times, 708 hours at 1050°F as compared to 1444 hours at 1100°F, may account for the difference in type of fracture. It was noted, furthermore, that considerably less of the grain boundary precipitate existed in these specimens than observed previously for the base metal (RT5) material.

Discussion of Results

Figure 10 shows that the samples taken across the weld had slightly lower rupture strength at 1050°F than the pipe metal as established with Sample RT5. At 1100°F, however, the weld samples were slightly stronger for time periods up to 100,000 hours. The comparative rupture strengths for the pipe metal, as established with Sample RT5, are included in Table XIII.

The information supplied stated that the base pipe material was identical for Samples RT5 and for the welded section RT6. Unless there was an unknown difference between the two pipe metals, the observed differences in rupture properties should be due to the presence of the weld-deposited metal and the heat-affected zones of the welds in the gage lengths of the specimens. In all cases, the weld-deposited metal did not show nearly as much reduction of area as the pipe. This, therefore, demonstrates that the weld-deposited metal had higher creep strength than the adjacent pipe metal.

The presence of a stronger section of weld-deposited metal in the center of the gage length leads to certain complications in interpreting results. It is equivalent to dividing the nominal gage length into two approximate short gage lengths. The stronger weld metal should, therefore, result in somewhat higher rupture strengths, if there was any effect. This was observed at 1100°F but not at 1050°F. In the present state of knowledge of these effects it seems as if variation in the strength of the base metal for unidentified reasons is the most probable cause for the differences in the effects at the two temperatures.

There presumably should be a narrow zone adjacent to the weld-deposited metal which has high creep resistance by virtue of heating to high temperature during welding. Presumably there would be little effect on the strength due to the reheating where the temperatures were less than the original heat treatment. The zone heated to temperatures higher than 2000°F should have quite low ductility under creep conditions due to the usual deleterious effects of high solution temperatures on ductility.

The situation, therefore, reduces to a gage length in which there is high creep resistant weld-deposited metal with adjacent zones in the base metal with high creep resistance but low ductility. There should be little change in the parent metal where temperatures were below 2000°F during welding.

Fracture through the heat-affected zone would only be expected when the presumed low ductility initiated failure in spite of higher creep resistance. This should be a function of the angle of the heat-affected zone to the gage length of the specimen. This was reasonably constant in the specimens with all the weld lines being at about the same angle. Apparently, in the tests, chance influences of the angle of the weld-deposit and the stress concentrating effect of the weld-deposit governed the location of fracture. To this, one should add the effect of variation in welding conditions from point to point in the weld. Apparently, all of the factors balanced so that the same stress-rupture time was obtained independent of the location of fracture.

Sufficient background is not available to estimate any effects of the prior service on the test results.

TABLE XII

Stress-Rupture Data For Welded 18-8 + Cb Steel Pipe at 1050 and 1100°F After 22,716 Hours Service at 1050°F at the Sewaren Generating Station

Sample RT6

Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elongation (% in 2 in)	Reduction of Area at Fracture (%)	Location of Fracture
1050	40,000	63	21.5	46.2	Parent Metal
	33,000	708	7.0	11.3	Weld bond line**
1100	35,000	128	19.5	34.0	Parent Metal
	32,000	341	11.5	4.5*	Heat affected zone
	29,000	661	7.0	17.0	Parent Metal
	27,000	1445	4.5	11.5	Parent Metal

* Maximum reduction of area in parent metal was 19.2 percent
** Started at weld bond line and extended into parent metal.

TABLE XIII

Stress-Rupture Strengths for Welded 18-8 + Cb Steel Pipe at 1050° and 1100°F After 22,716 Hours of Service at 1050°F at the Sewaren Generating Station

Sample RT6

Temp. (°F)	Stress for Rupture at Indicated Time Period (psi)			
	100-hr	1000-hr	10,000-hr	100,000-hr
1050	39,000	32,000	27,000	22,000
1100	36,000	28,000	22,000	17,000
Comparative Values Obtained for Base Metal Samples (RT5)				
1050	40,000	33,500	28,000	23,500
1100	33,000	27,000	21,000	17,000

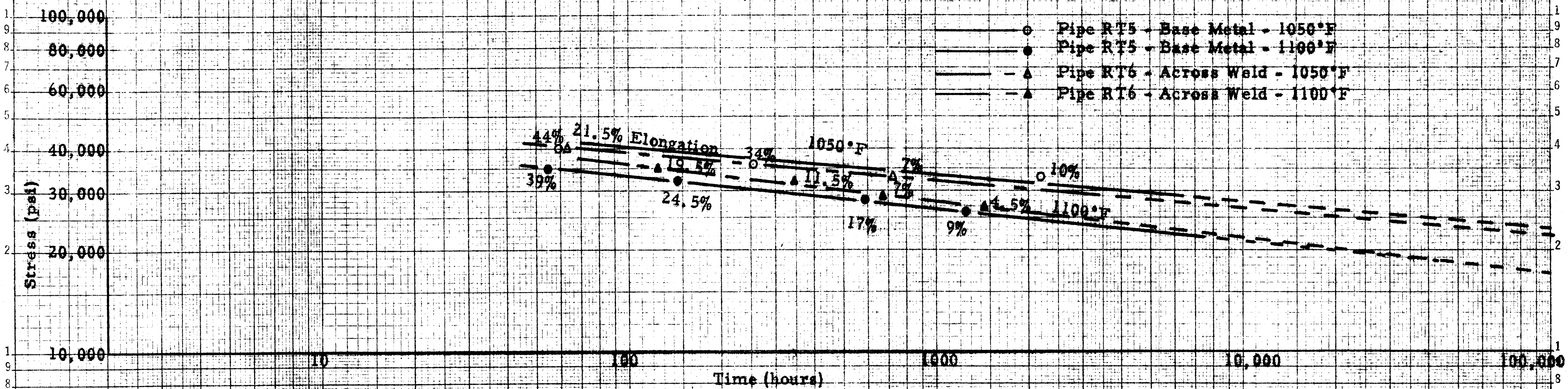
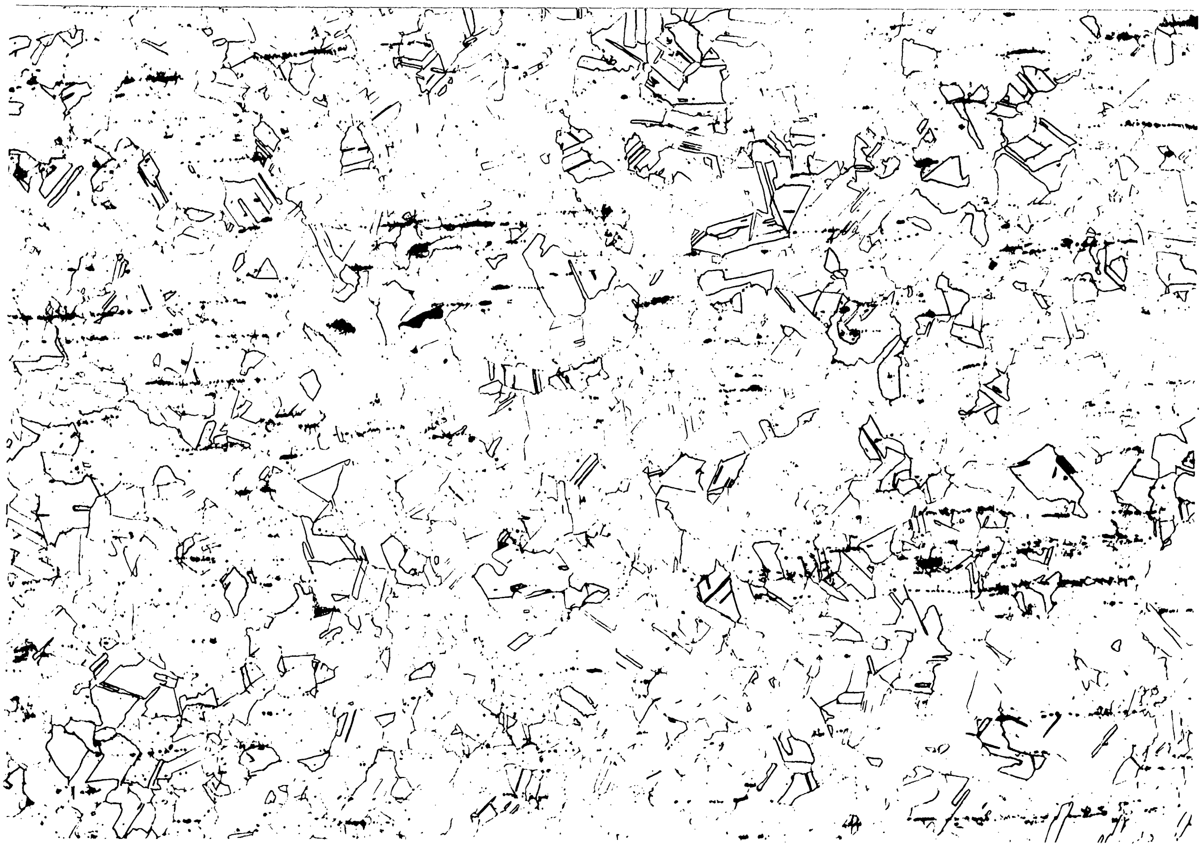
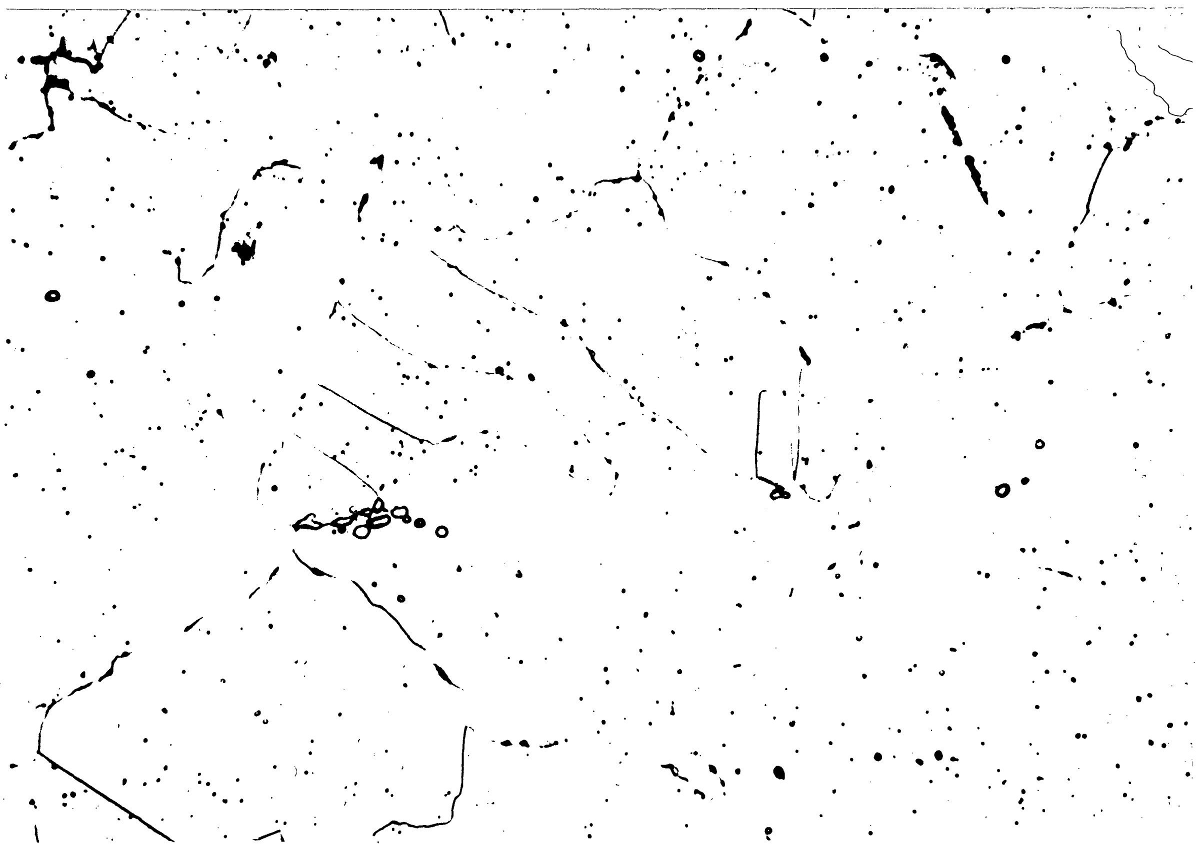


Figure 10. - Stress-Rupture Time Curves at 1050° and 1100°F for 18-8 + Cb Steel Pipe after 22,716 Hours of Service In the Number 2 Unit at the Sewaren Generating Station.

(Sample RT5 and RT6)

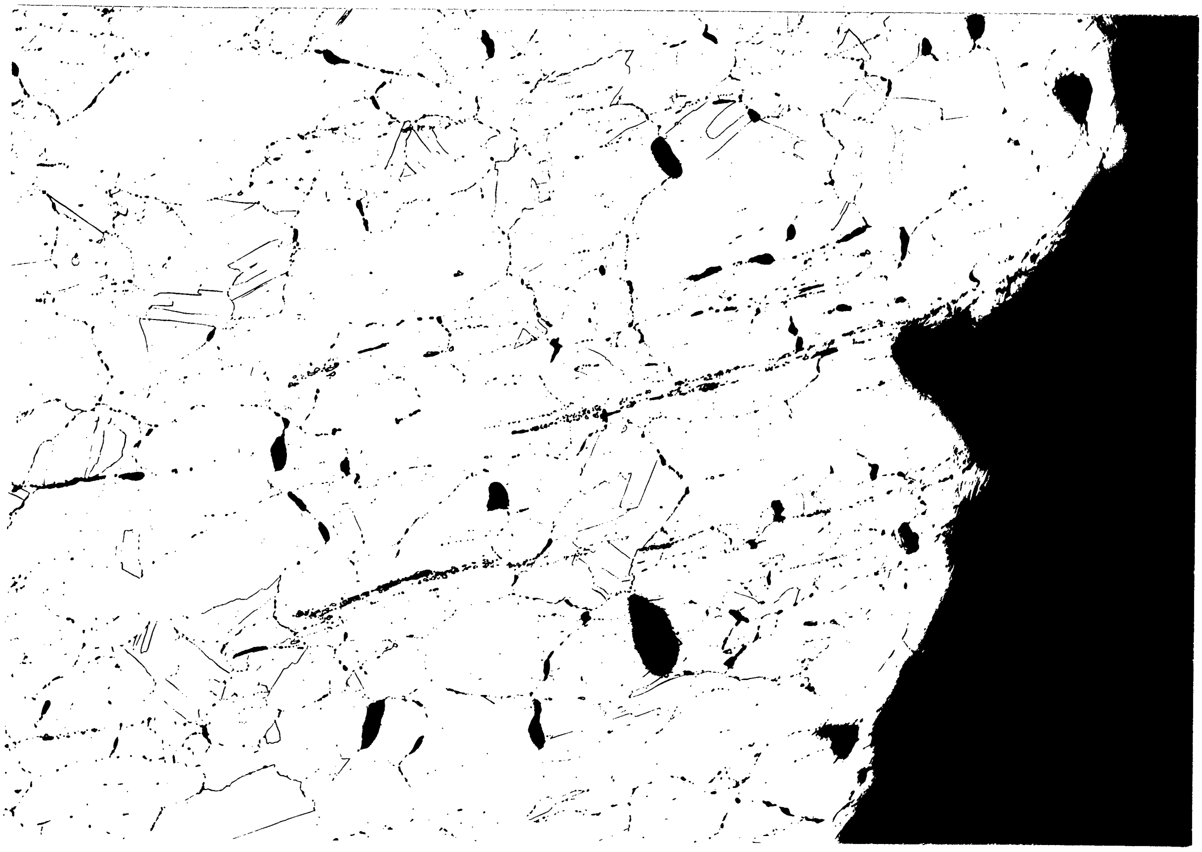


X100D

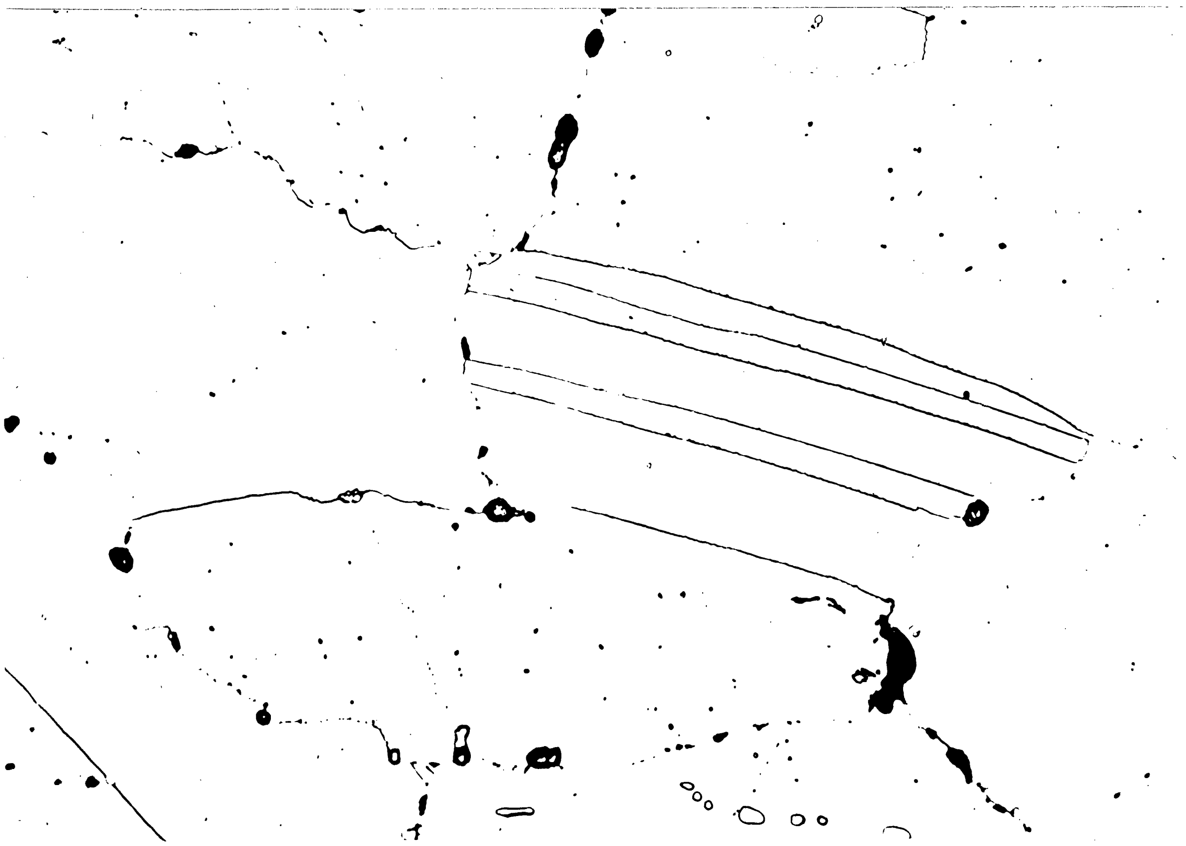


X1000D

Plate 20. - As-Received Microstructure of Base Metal of Welded Sample of 18-8 + Cb Steel Pipe (RT-6) after 22,716 Hours Service at 1050°F at the Sewaren Generating Station.

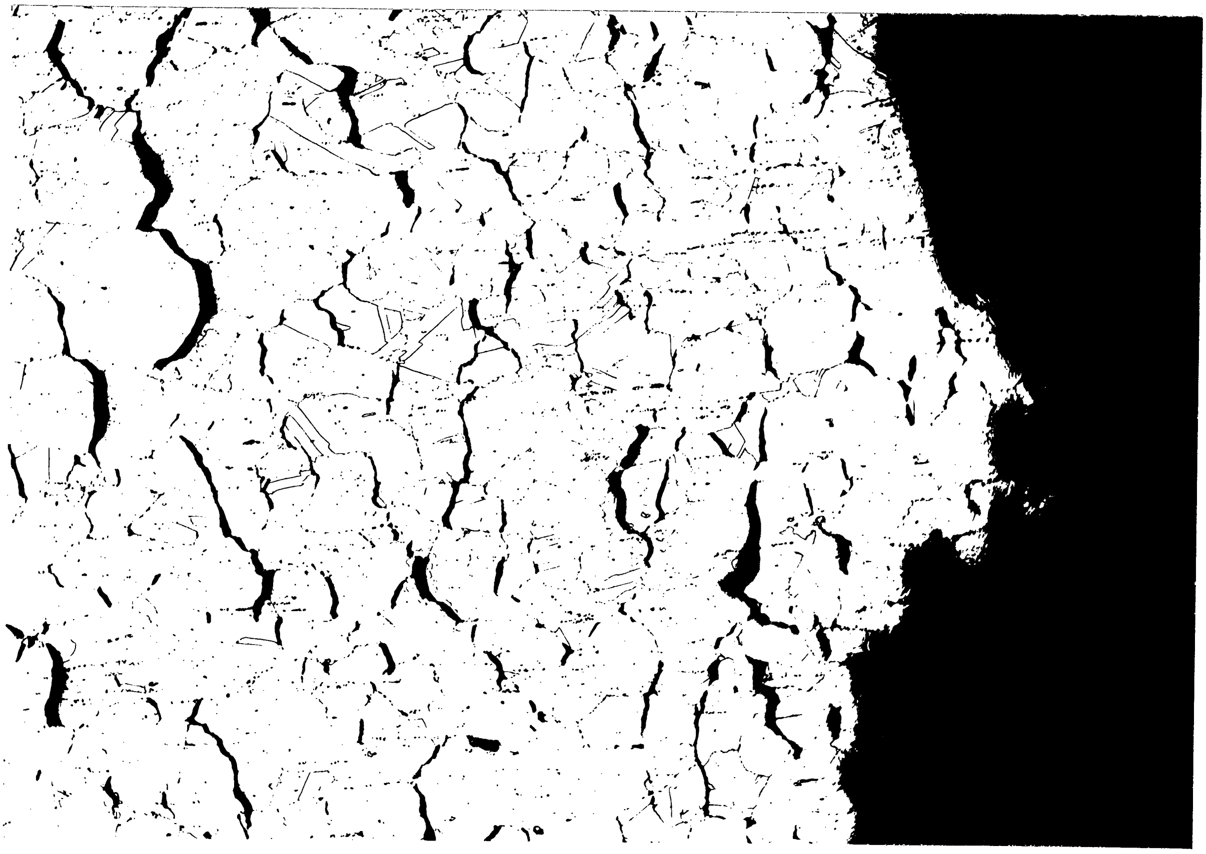


X100D - Fracture

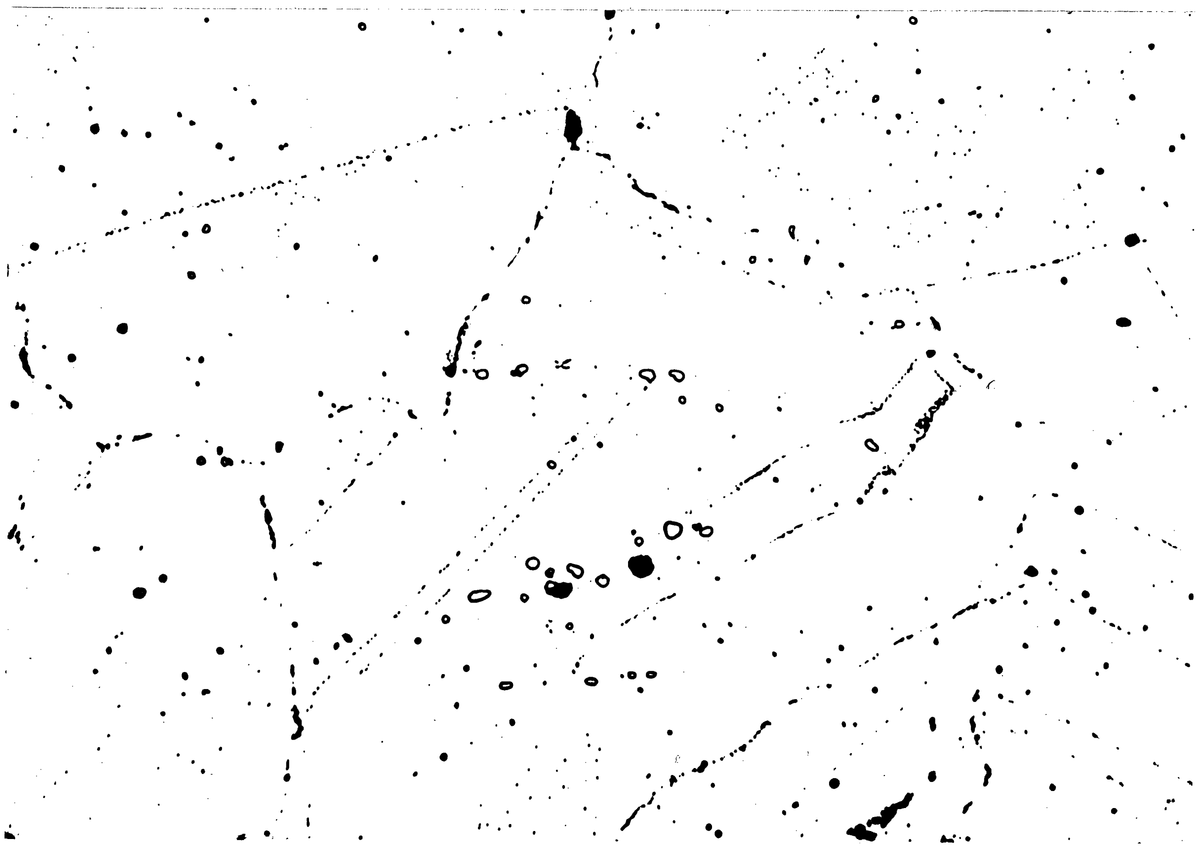


X1000D - Interior

Plate 21. - Microstructure of 18-8 + Cb Steel Pipe (RT-6) Fractured in 708 Hours Under a Stress of 33,000 Psi at 1050°F.

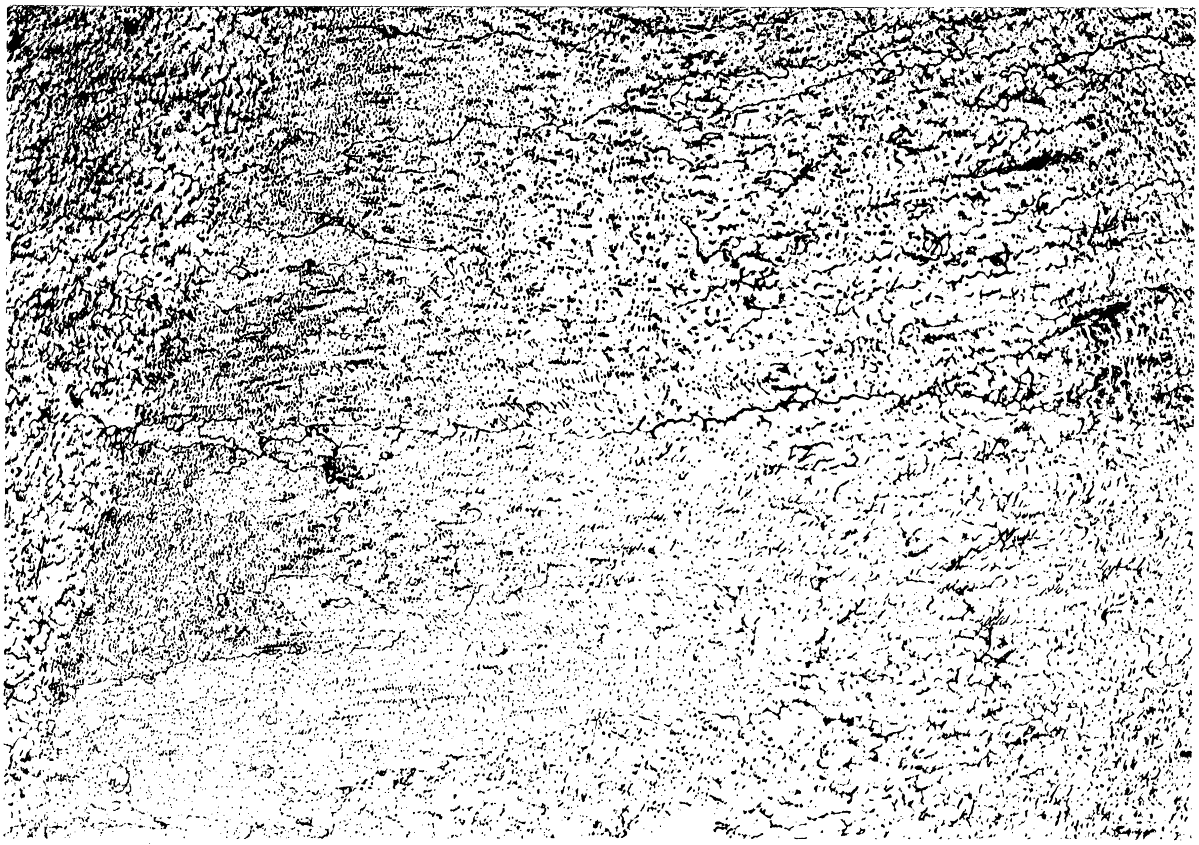


X100D - Fracture

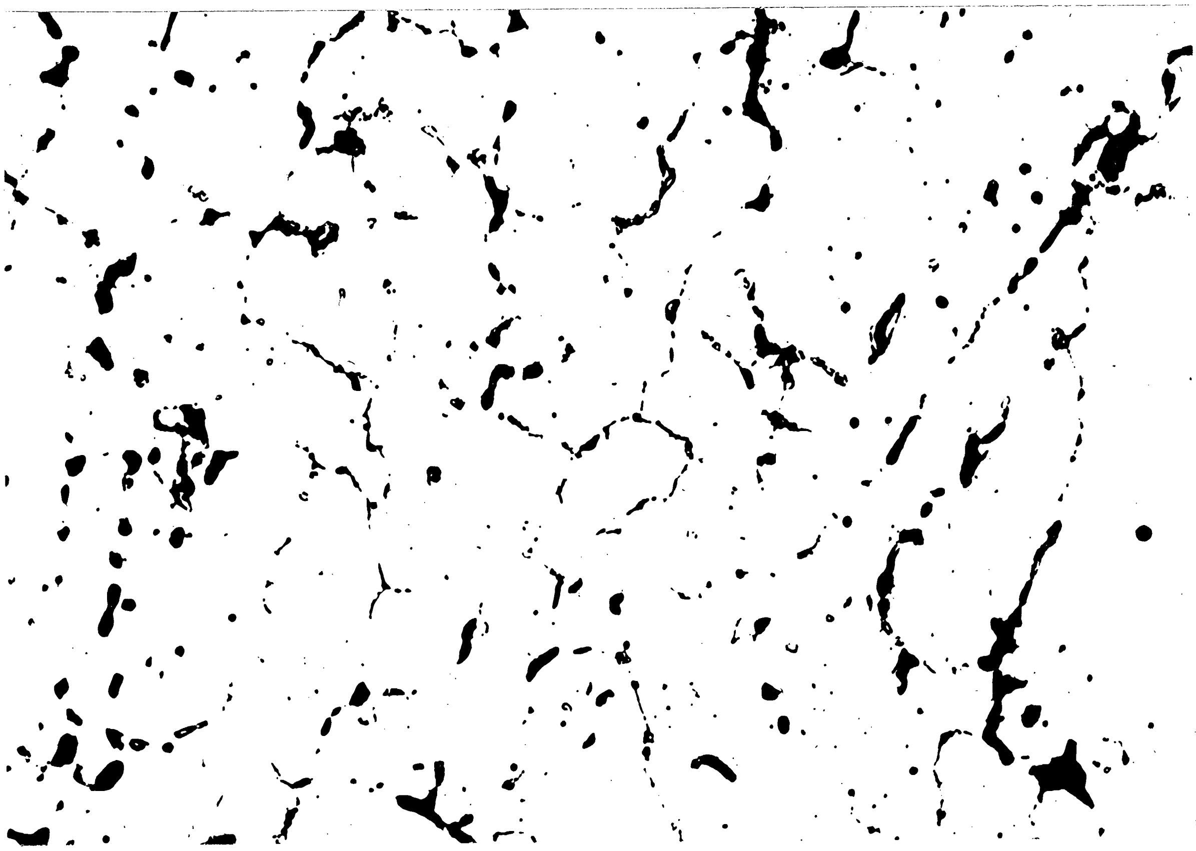


X1000D - Interior

Plate 22. - Microstructure of 18-8 + Cb Steel Pipe (RT-6) Fracture in 1,444 Hours Under a Stress of 27,000 Psi at 1100°F.

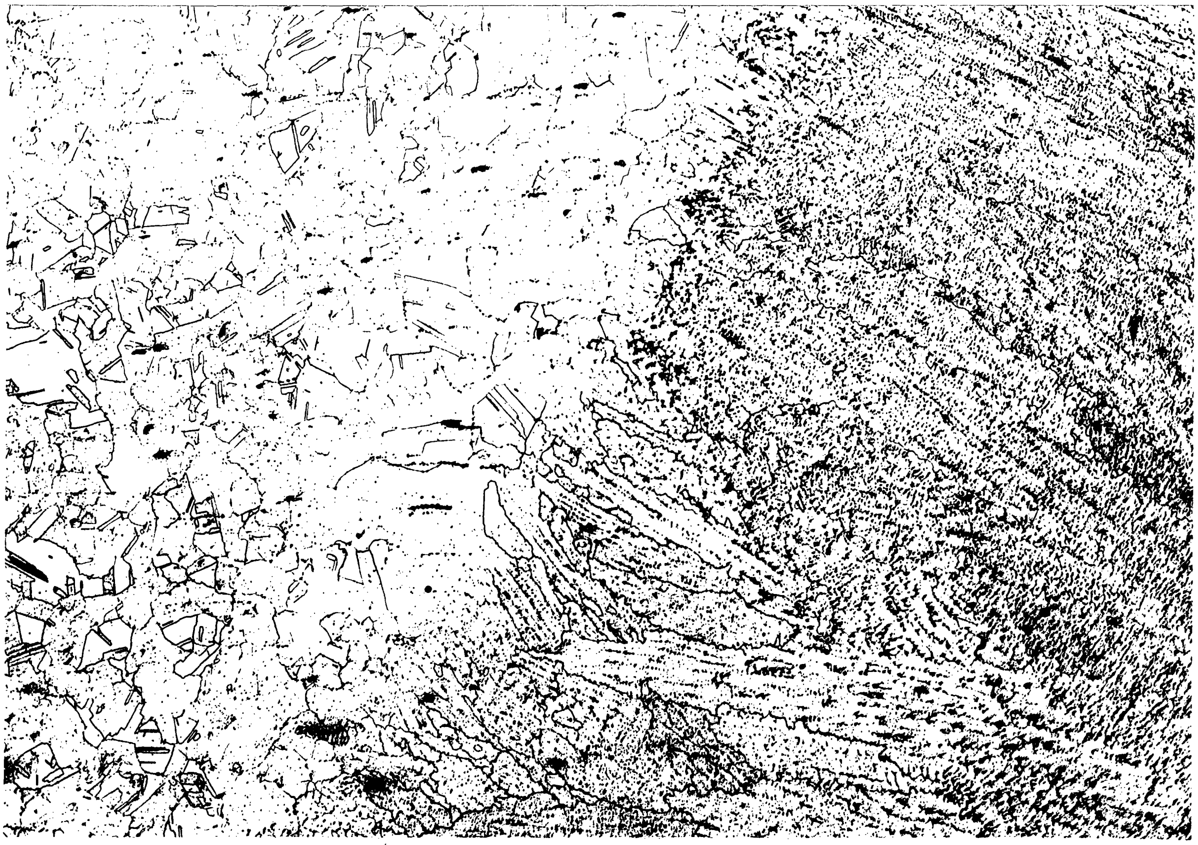


X100D

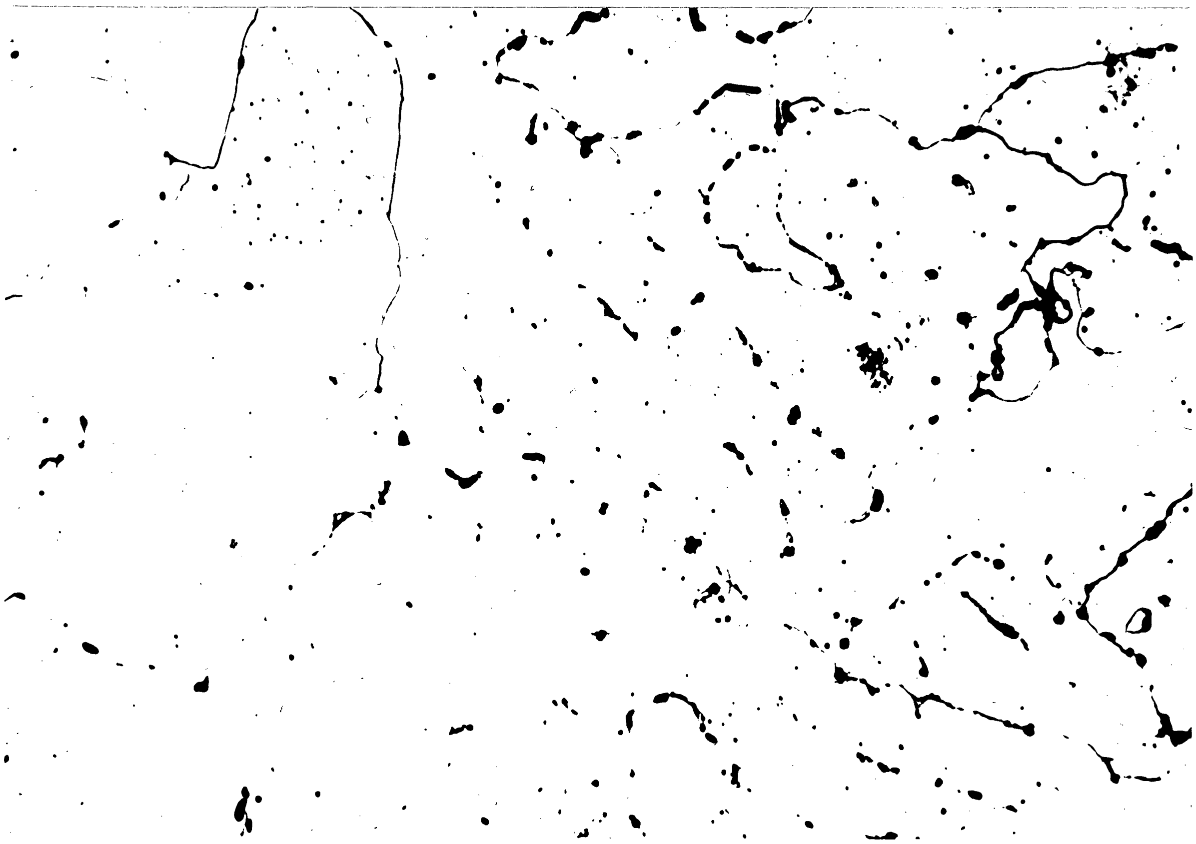


X1000D

Plate 23. - As-Received Microstructure of Weld Metal of Welded Sample of 18-8 + Cb Steel Pipe (RT-6) after 22,716 Hours Service at 1050°F at the Sewaren Generating Station.

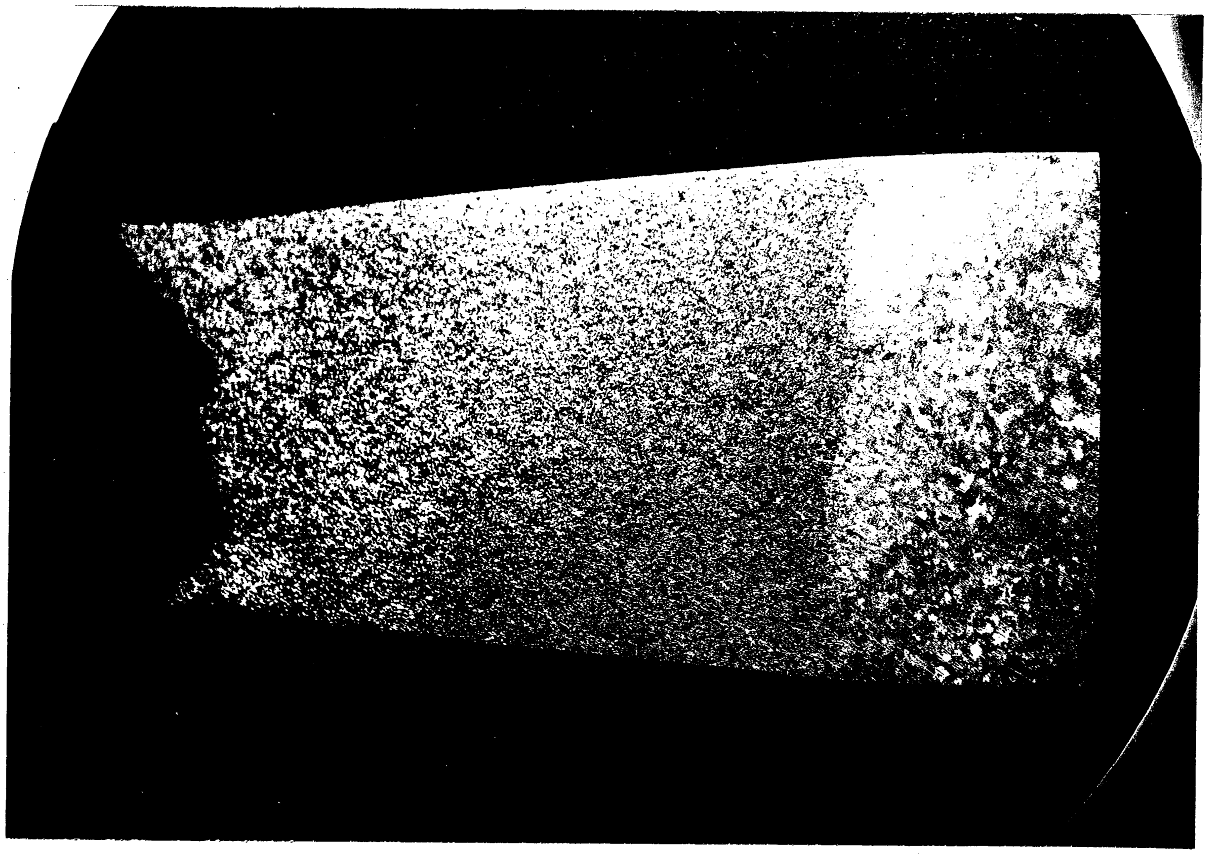


X100D

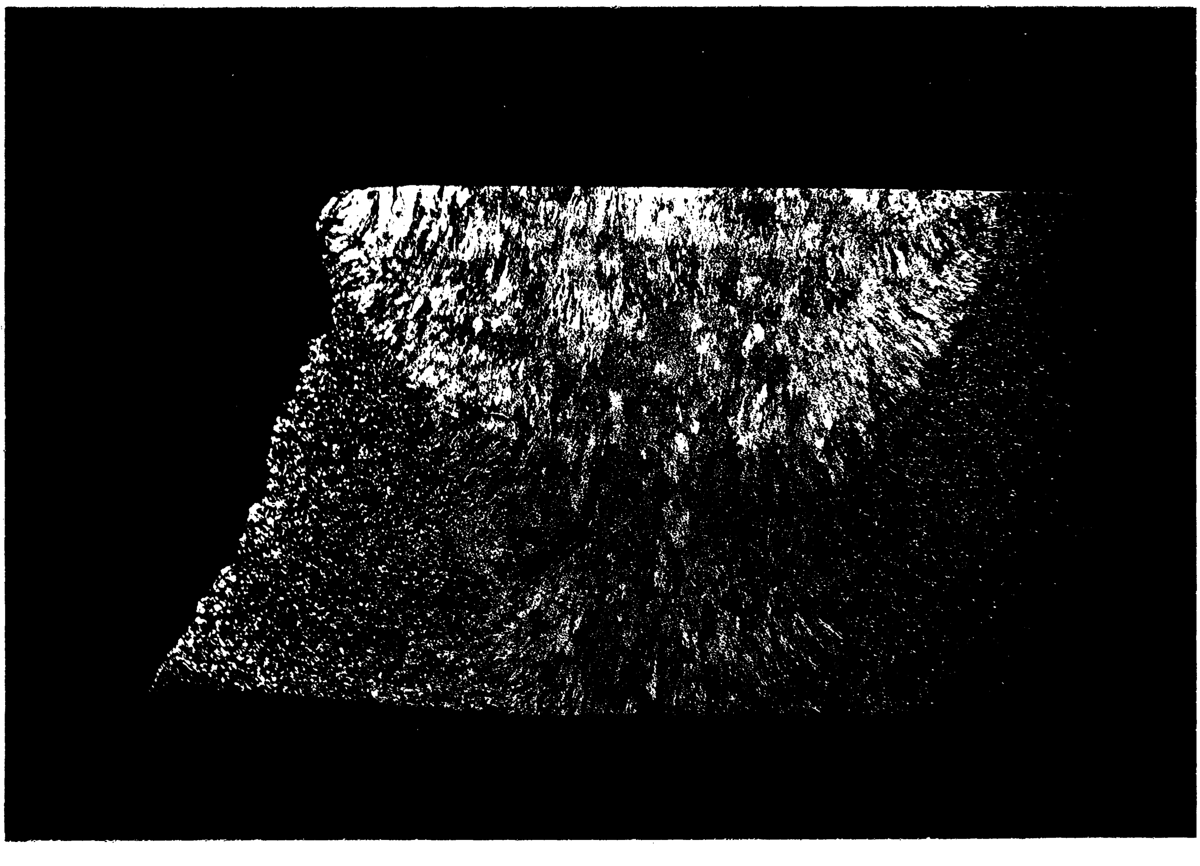


X1000D

Plate 24. - As-Received Microstructure of Heat-Affected-Zone of Weld in 18-8 + Cb Steel Pipe (RT-6) after 22,716 Hours Service at 1050°F at the Sewaren Generating Station.

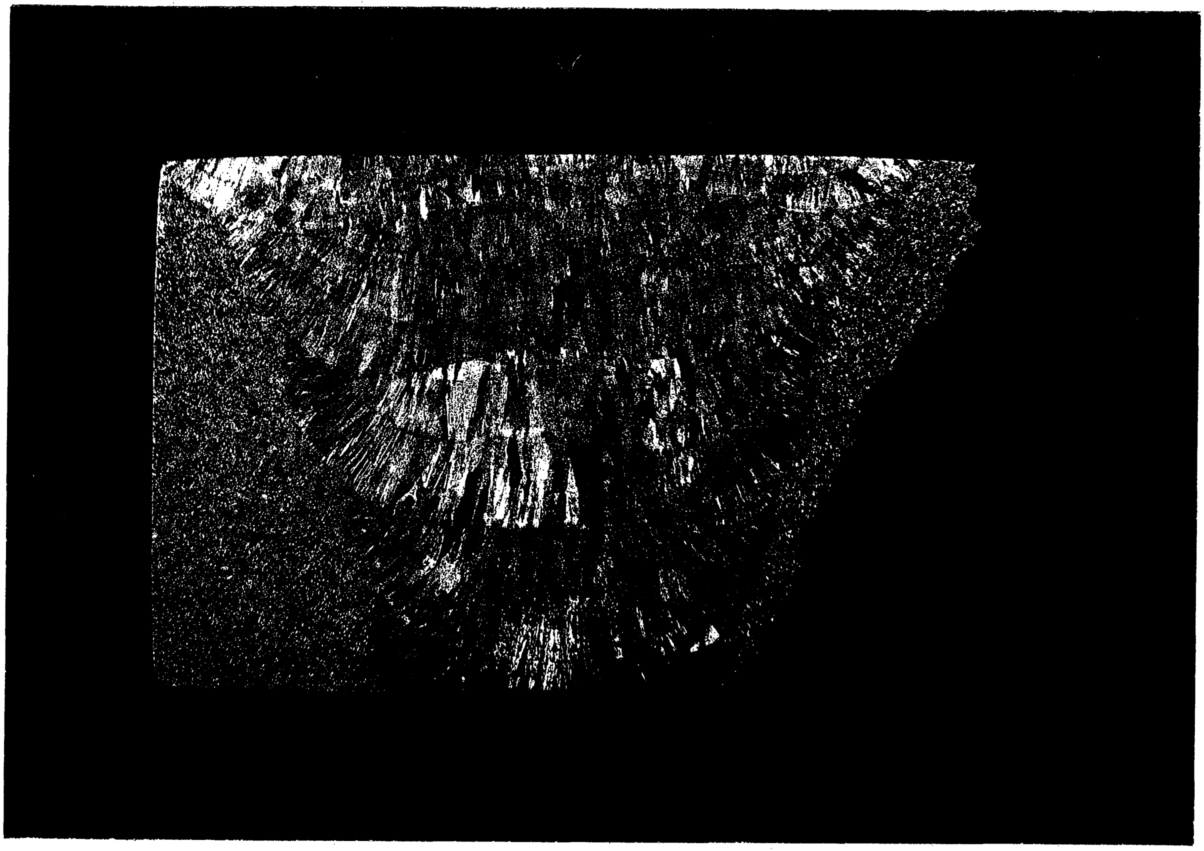


a. Fractured in Base Metal after 63 Hours at 1050°F under Stress of 40,000 Psi

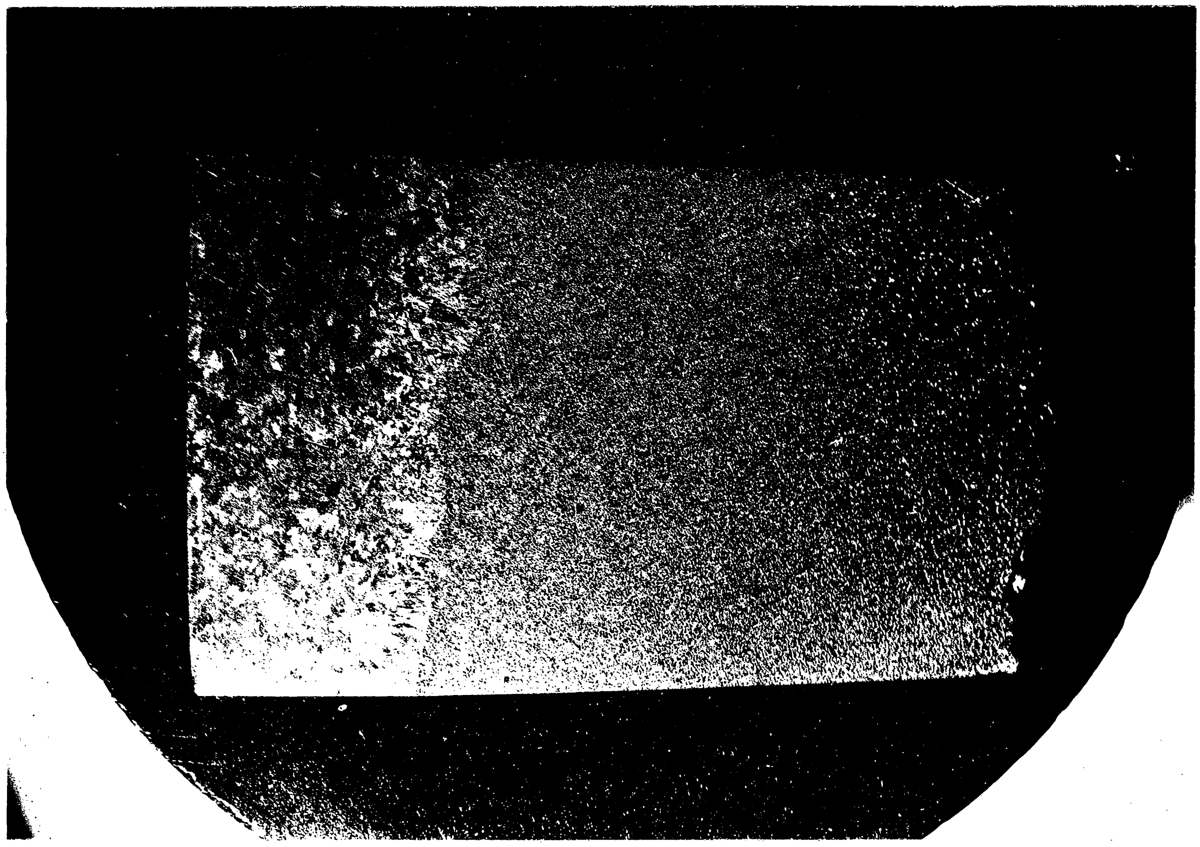


b. Fractured at Weld Bond Line and in Base Metal after 708 Hours at 1050°F under a Stress of 33,000 Psi.

Plate 25. - Macrographs Illustrating Locations of Fracture in Stress-Rupture Tests at 1050°F of Welded Samples of 18-8 + Cb Steel Pipe (RT-6).

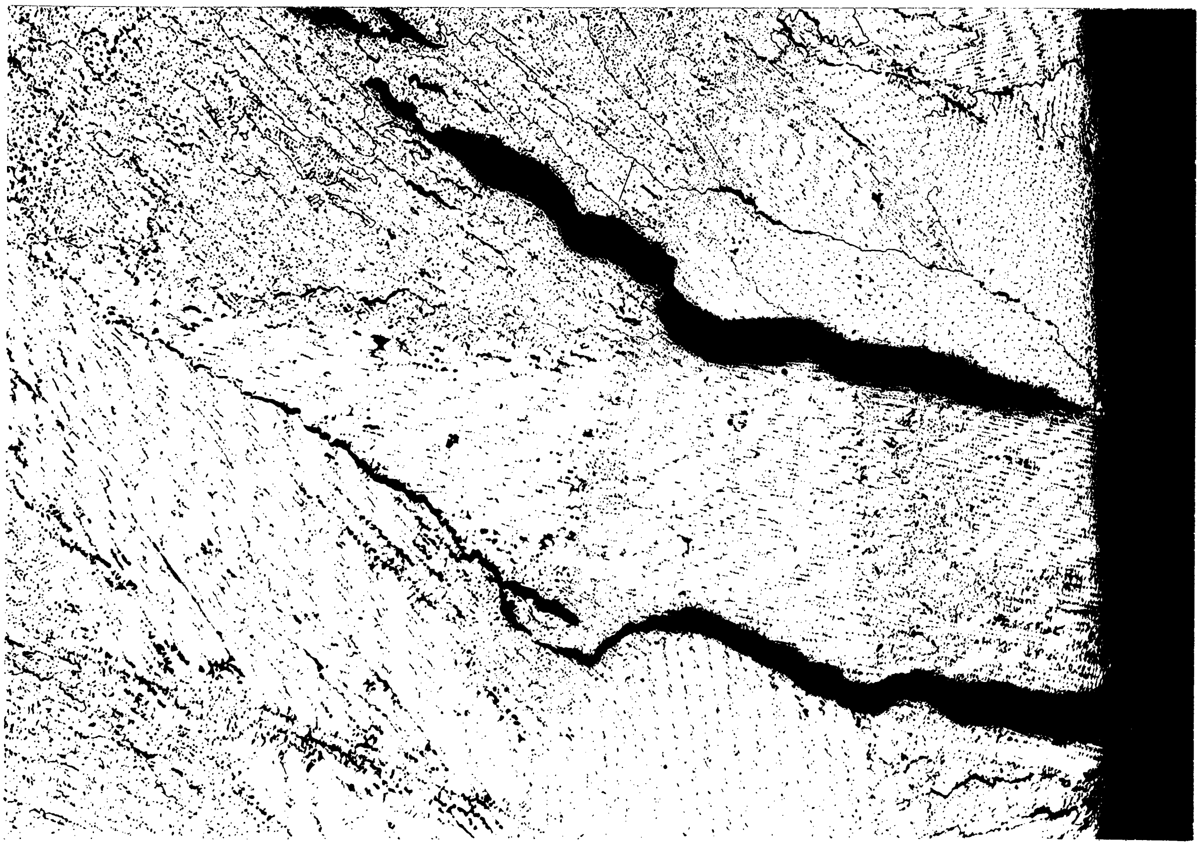


a. Fractured in Heat-Affected Zone of Base Metal after 340 Hours at 1100°F Under a Stress of 32,000 Psi - about 5X.



b. Fractured in Base Metal after 651 Hours at 1100°F Under a Stress of 29,000 Psi - about 5X

Plate 26. - Macrographs Illustrating Locations of Fracture in Stress-Rupture Tests at 1100°F of Welded Samples of 18-8 + Cb Steel Pipe (RT-6).



a. Cracks in Weld Metal of Fractured Stress-Rupture Specimen - X100D

b. Cracks in Base Metal Near Weld Bond Line of Fractured Stress-Rupture Specimen - X100D

Plate 27. - Photomicrographs of Cracks in the 18-8 Cb Steel Specimen (RT-6) Which Fractured in 708 Hours Under a Stress of 33,000 Psi at 1050°F.

PART VII

BURLINGTON GENERATING STATION-NUMBER 13 BOILER HEADER-950°F STEAM LEAD

CMo Pipe After 93,144 Hours of Service

Sample RT7

Rupture tests were conducted at 950° and 1000°F on samples obtained from a length of pipe designated "RT7". The pipe was made of CMo steel and had been in service for 93,144 hours at an average temperature of 933.2°F and a normal operating pressure of 1350 psi. The pipe dimensions were 12.75-inch O.D. x 10.126-inch I.D. x 1.312-inch wall thickness.

Description of Pipe and Service Conditions

A ten-inch half ring sample, identified as RT7, from the Burlington Generating Station was furnished for the machining of test specimens. The following information was supplied regarding the sample:

Steel: CMo steel (ASTM: A-206-39T)

Location: No. 13 Boiler Header Steam Lead, No. 5 Unit

Size: 12.75-inch O.D. x 1.312-inch wall thickness x 10.126-inch I.D.

Chemical Composition:

C	Mn	P	S	Si	Mo
0.10-0.20	0.30-0.60	0.04 max.	0.05 max.	0.10-0.50	0.45-0.65

Mill Heat-treatment: Anneal at 1700°F, Stress relief at 1200°F

Shop Heat-treatment: Stress relief at 1200°F

Physical Properties:

Tensile Strength (psi)	55,000 min.
Yield Strength (psi)	30,000 min.

Elongation (% in 2 in)	30.0 min.
Service Conditions	
Service hours	93,144
Calculated hoop stress(S=Pd/2t)	5,800 psi
Operating Temperatures	
Normal	950°F
Average	933.2°F
Maximum (Rating for short swings. Not to exceed 1% of operating time)	1000°F
Operating Pressures	
Normal	1350 lbs.
Maximum	1500 lbs.

Procedure

Because of the long service life of the pipe, microscopic examination and hardness tests were performed on samples taken at intervals around the circumference of the ring prior to the preparation of test bars to determine whether any non-uniformity of hardness or structure existed.

Longitudinal 0.505-inch diameter tensile bars with a 2-inch gage length were prepared, and sufficient stress-rupture tests were conducted to establish stress-rupture time curves out to 1000 hours at 950° and 1000°F.

Results

The hardness tests and microscopic examination on the as-received pipe did not reveal any evidence of non-uniformity of test material. Uniform hardness values of 123 to 127 Brinell were obtained around the circumference of the half ring. Plate 28 shows the typical as-received structure of ferrite and finely spheroidized pearlite grains with scattered nodules of graphite. The grain size was ASTM 4 to 5.

The individual stress-rupture test data are listed in Table XIV and are plotted on logarithmic coordinates as stress-rupture time curves in Figure 11. The stress-rupture strengths for failure in 10, 100, 1000, 10,000 and 100,000 hours derived from these curves are shown in Table XV.

The stress-rupture time curves of Figure 11 show that the slope of both the 950° and 1000°F curves tends to increase at about 20 to 35 hours and that the curves are virtually parallel for the longer time periods. It is believed that longer duration tests would not substantially change the slope of the curves, and that, therefore, the stress-rupture strengths obtained by extrapolation to 10,000 and 100,000 hours are quite reliable.

The test data of Table XIV shows that the material revealed excellent and quite uniform ductility with only a slight decrease in elongation and reduction of area with increased time to fracture.

Microscopic examination of the longer time stress-rupture test specimens revealed the fractures at 950° and 1000°F to be both intergranular and transgranular in nature with considerable deformation of the grains in the direction of applied stress. The appearance of the metal in the vicinity of the fracture after testing at 1050° and 1100°F is shown in Plates 29a and b and 30 a and b, respectively. Some intergranular cracking occurred adjacent to the fracture and at the surface at both 950° and 1000°F but was more pronounced at the higher temperature. No appreciable spheroidization of the pearlite occurred during testing at either 950° or 1000°F.

The appearance of some of the nodules of graphite after testing is shown in Plates 29c and d and 30 c and d.

These photomicrographs illustrate what is apparently intergranular cracking associated with some of the graphite nodules. However, it was not possible to determine with certainty whether these were intergranular cracks or extension of the graphitization during testing. This condition was noted at locations rather well removed from the stress-rupture fracture.

Discussion of Results

The pipe material would be expected to have its rupture properties altered by the following three factors as a result of the 93,144 hours of service:

1. Loss of life due to creep during service

2. Alteration of strength due to structural alteration from prolonged heating under stress, commonly described as "spheroidization".

3. Influence of scattered nodules of graphite in the structure.

The reported operating stress of 5800 psi is so far below the rupture strength that the percentage of life used up at an average temperature of 933°F would be negligible. It is, therefore, presumed that any measurable changes in properties is due to other causes.

The rupture strengths obtained from Sample RT7 are compared in Table XV with those for average new material. The shorter time strengths are much lower than for new material. The extrapolated stresses for rupture in 100,000 hours are, however, as high or higher than for unused material. The prolonged exposure to temperature and stress resulted in structural alterations that lowered the stress-rupture time curves at short time periods and nearly removed the sharp breaks which lead to the low 100,000 hour strengths for new material. As discussed in Section II for Sample RT2, this is the normal expected result of exposure to temperatures between 900° and 1000°F for prolonged time periods with the accompanying structural changes.

The influence of the graphite nodules cannot be separated from the spheroidization effects. The microstructure of pipe was considerably different from that of Sample RT3 (Part III) in that it had a much larger grain size and the carbides were the spheroidized residue of initially coarse grained pearlite. Also the graphite in Sample RT3 was in the form of stringer of small nodules. These differences in structure would be expected to be a more logical explanation of the differences between RT7 and RT3 than the differences in graphite.

In both Sample RT7 and Sample RT3 the strength and ductility characteristics are in accordance with expectations from spheroidization effects alone and there does not seem to be any outstanding effect of the graphite. In Sample RT3 ductility was low when fracture occurred through the segregated graphite with little effect on strength. In Sample RT7 there was evidence that fracture or extension of the graphite tended to start internally at graphite flakes. This is the first case known to the authors where graphite had exhibited this effect. It seems quite evident that the graphite nodules cause a stress concentration initiating cracks or accelerating graphitization. While the data point to little or no effect on overall properties from the graphite nodules it would appear possible that they could have a detrimental effect if they should be located at a point of stress concentration where considerably creep ductility might be necessary to avoid cracking.

TABLE XIV

Stress-Rupture Data for CMo Steel Pipe at 950° and 1000°F after 93,144 Hours of Service at 950°F in Burlington Generating Station, Number 5 Unit

Sample RT7

Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elongation (% in 2 in)	Reduction of Area (%)
950	38,450	S.T.T.T.	42.5	67.8
	36,000	0.2	43.0	77.6
	29,000	36.4	44.0	74.8
	26,000	149	40.0	64.5
	23,000	821	33.5	48.5
1000	34,500	S.T.T.T.	46.5	81.5
	29,000	1.8	53.0	79.5
	24,000	27.3	52.0	74.6
	19,000	518	34.0	45.0

TABLE XV

Stress-Rupture Strengths for CMo Steel Pipe at 950° and 1000°F after 93,144 Hours of Service at 950°F in the Burlington Generating Station, Number 5 Unit

Sample RT7

Temp. (°F)	Rupture Strength (psi) 10-hr	100-hr	1000-hr	10,000-hr	100,000-hr
950	31,000	27,000	22,500	19,000	16,000
1000	25,500	21,500	18,000	15,000	12,000
Average Values for New C-Mo Steel (from ASTM STP No. 151)					
950	--	42,000	35,000	28,000	10,500*
1000	--	38,000	26,000	16,500	7,000*
Values Obtained from Pipe from Essex Generating Station Number 7 Unit after 75,054 Hours of Service - Sample RT2					
950	31,000	29,500	26,500	21,000	17,000
1000	27,000	24,000	19,500	12,500	8,200
Values Obtained from Pipe from Essex Generating Station Number 26 Boiler Steam Lead after 81,536 Hours of Service - Sample RT3					
950	25,000	21,500	18,500	16,000	13,500
1000	22,000	18,500	14,500	11,500	9,000

*These values are probably low. It is estimated that values of 16,000 and 8,500 psi are probably closer to the real average.

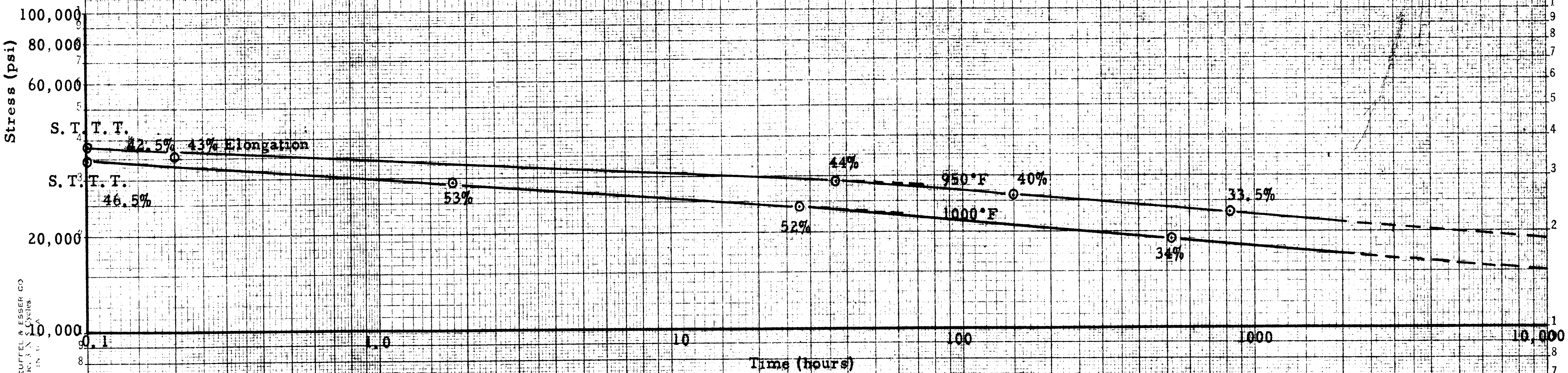
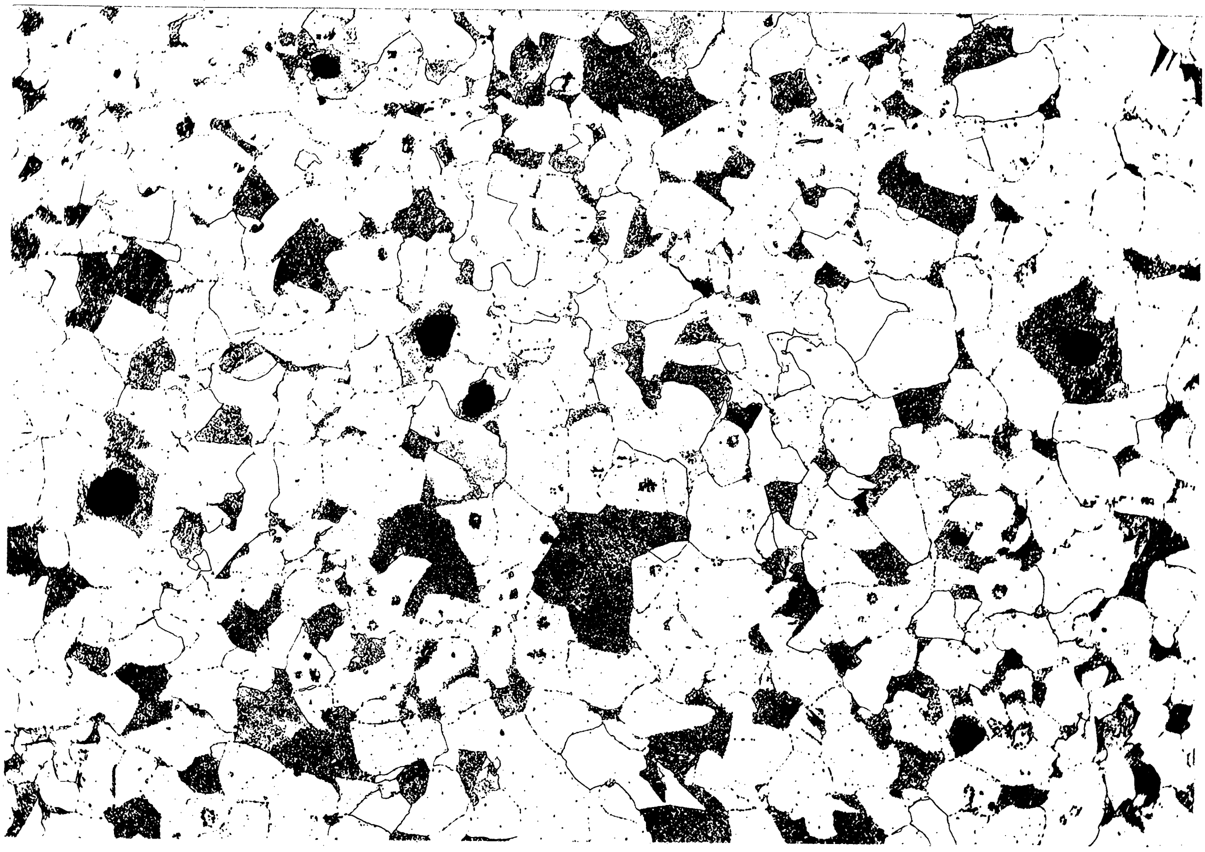
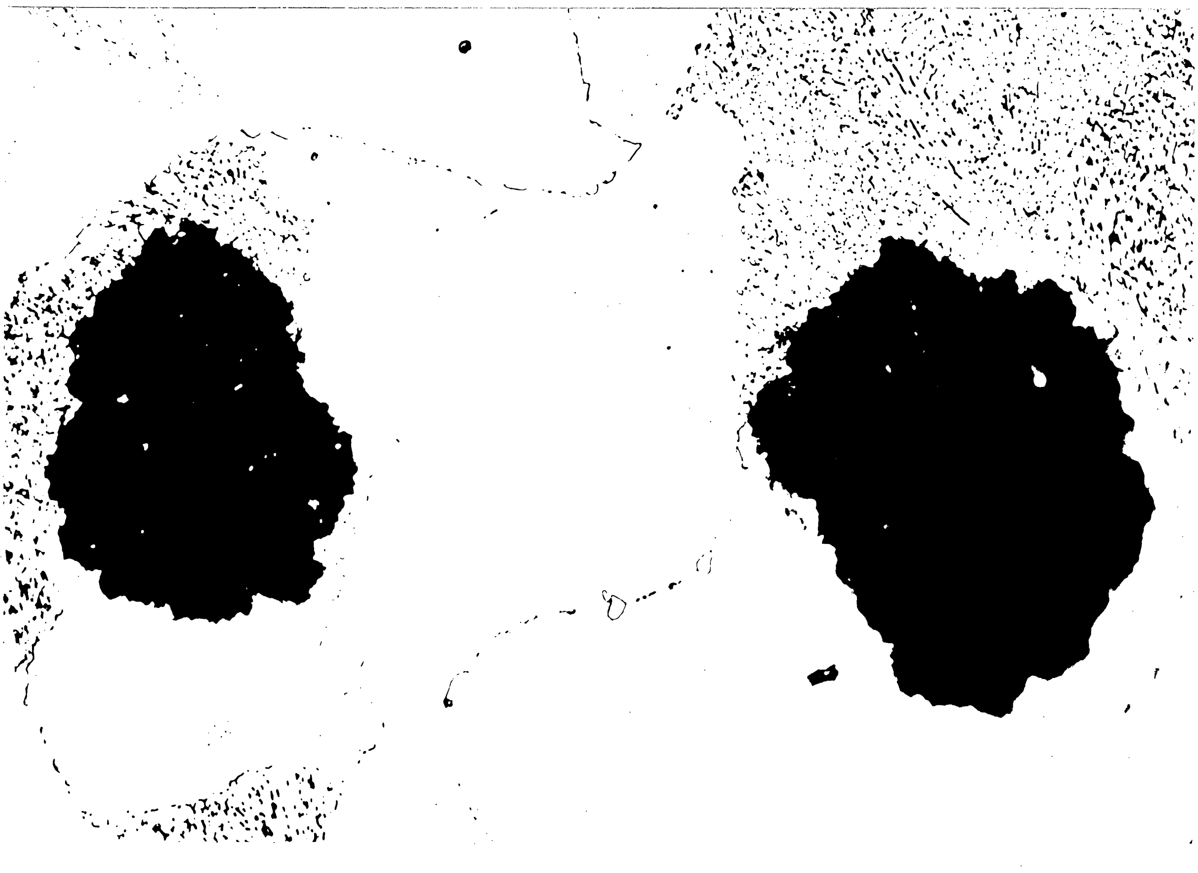


Figure 11. - Stress-Rupture Time Curves at 950° and 1000°F for CMo Steel Steam Pipe after 93,144 Hours of Service in the Number 5 Unit of the Burlington Generating Station.

(Sample RT7)

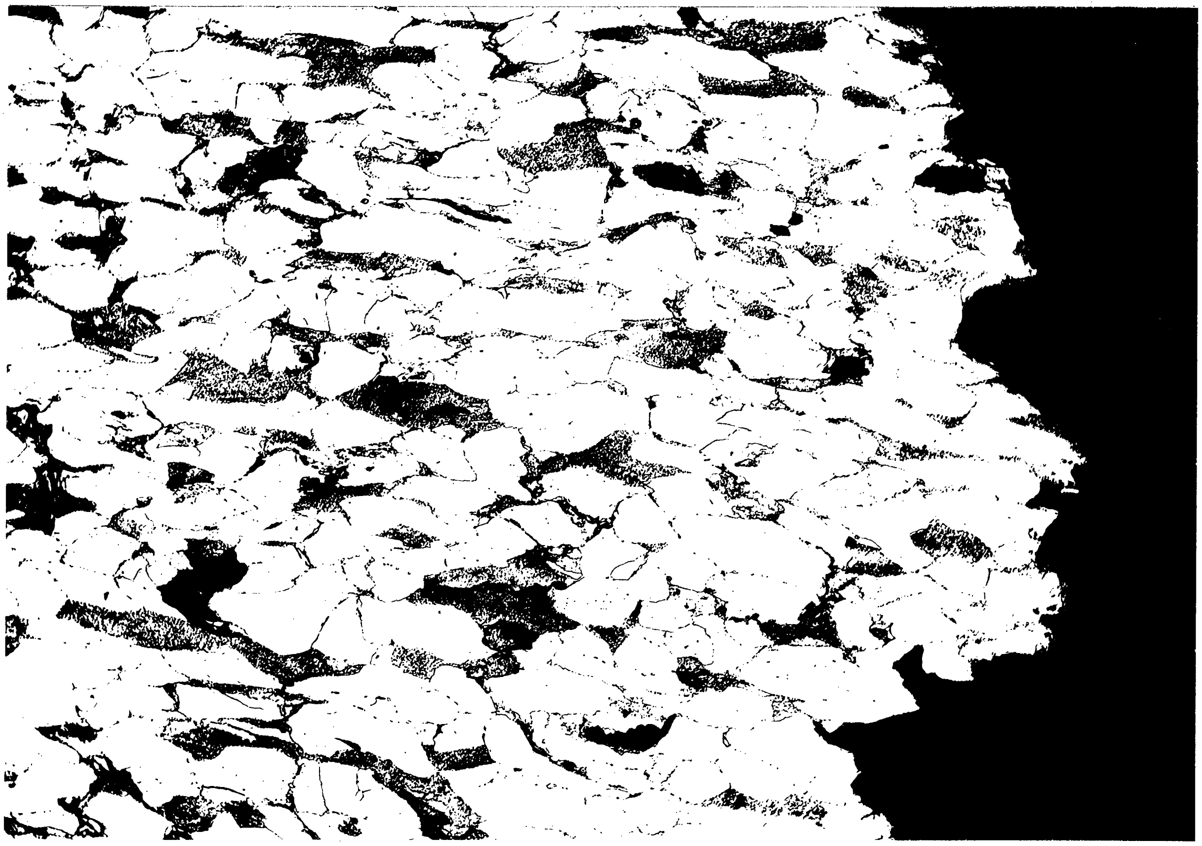


X100D

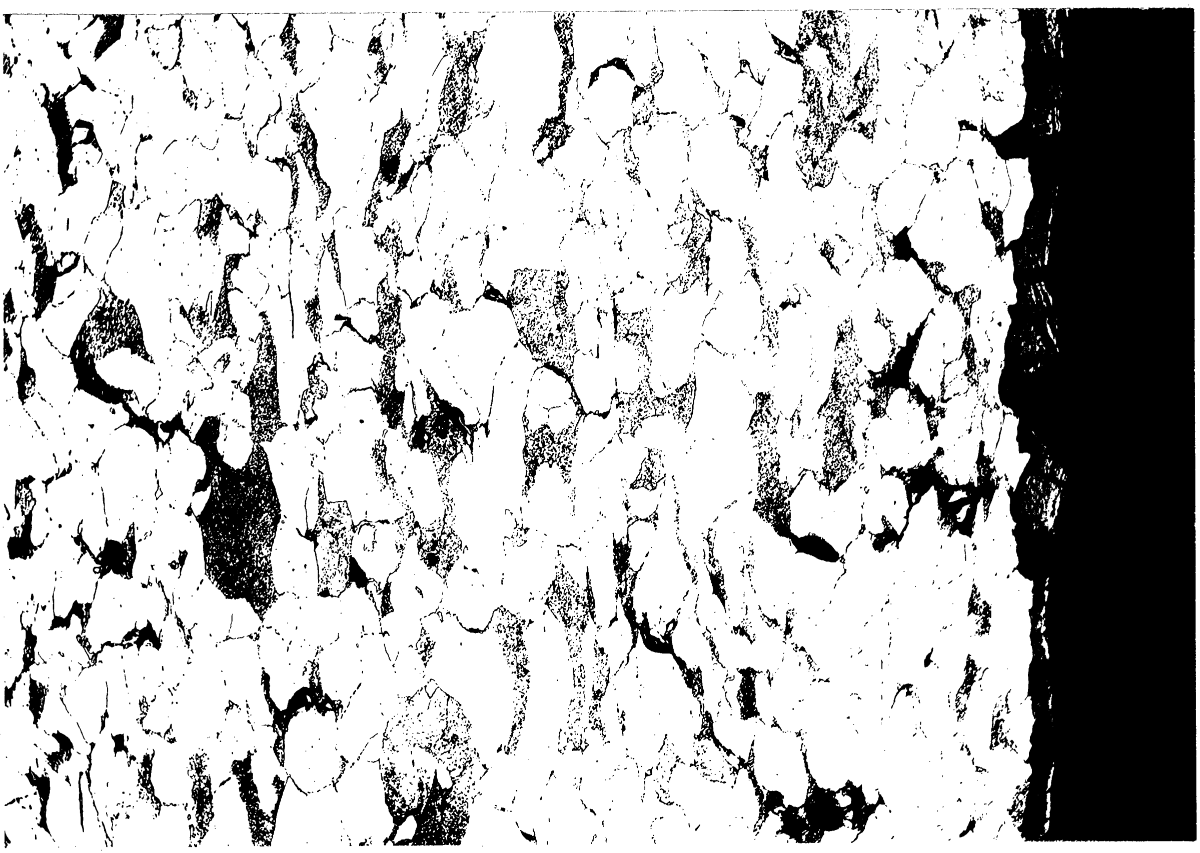


X1000D

Plate 28. - As-Received Microstructure of C-Mo Steel Pipe (RT-7) After 93,144 Hours of Service at 950°F in Burlington Generating Station Number 5.



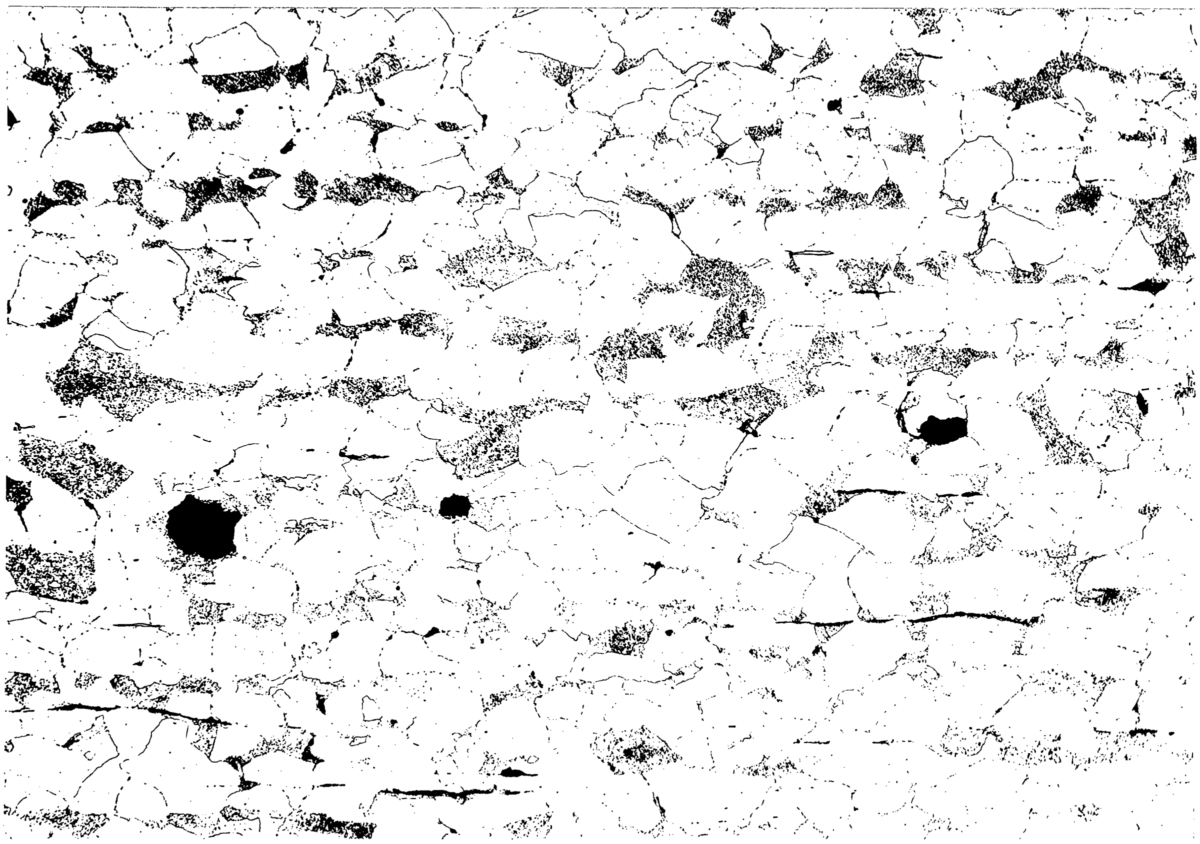
a. X100D - Fracture



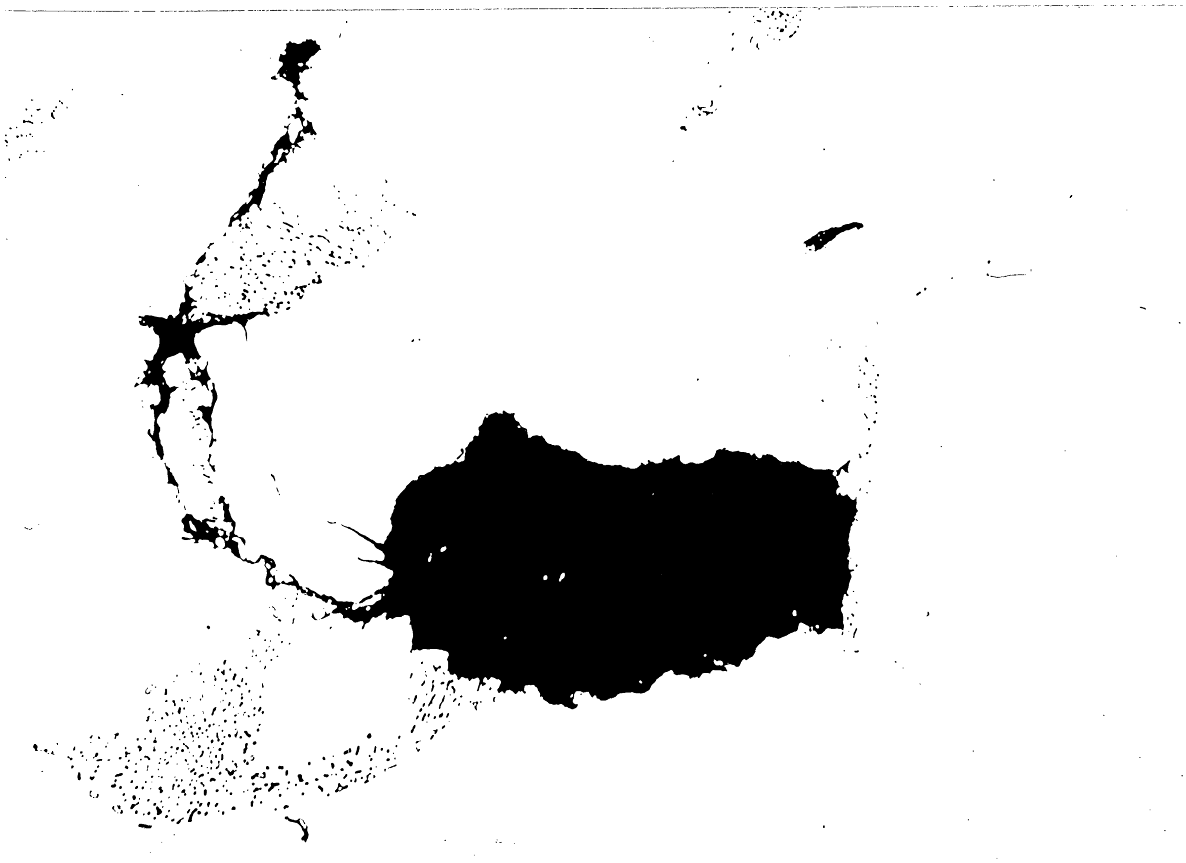
b. X100D - Surface

Plate 29. - Microstructure of C-Mo Steel Pipe (RT-7) Fractured in 820 Hours under a Stress of 23,000 Psi at 950°F.

(Continued on following page).

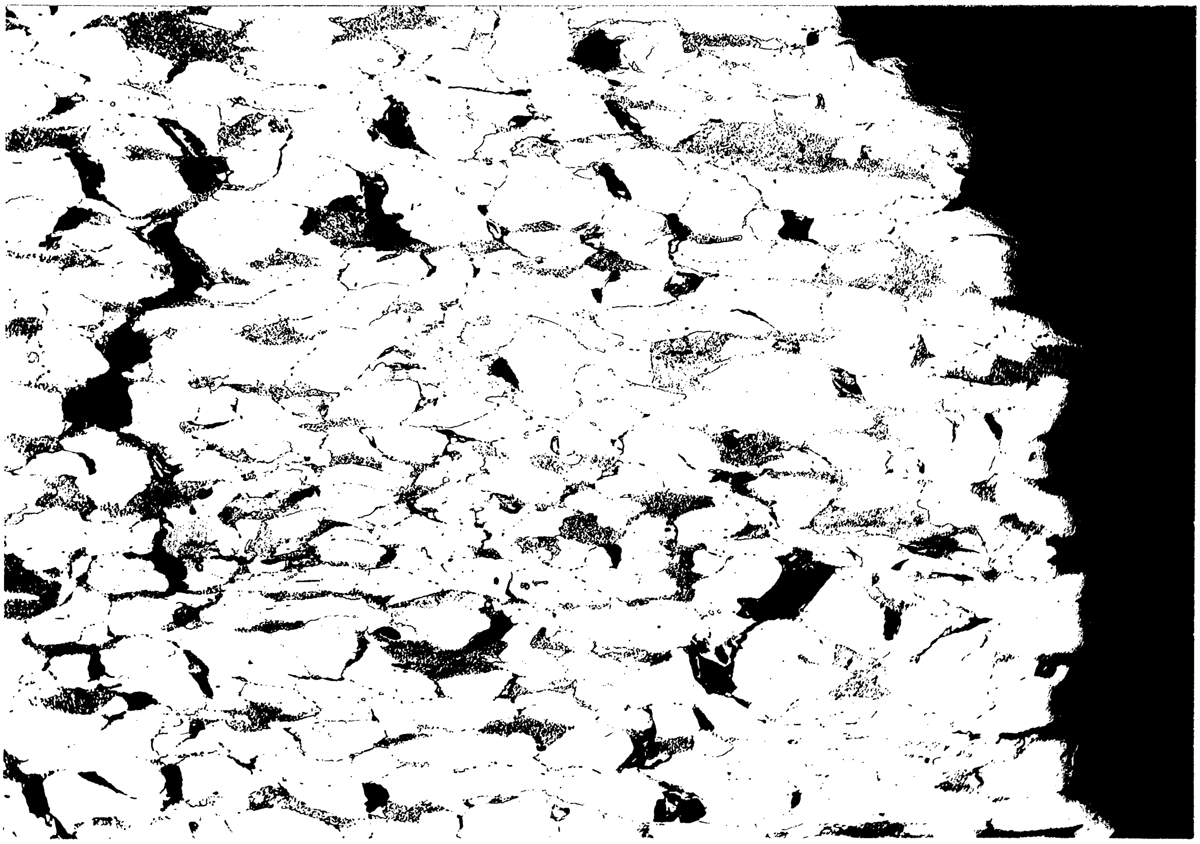


c. X100D - Interior

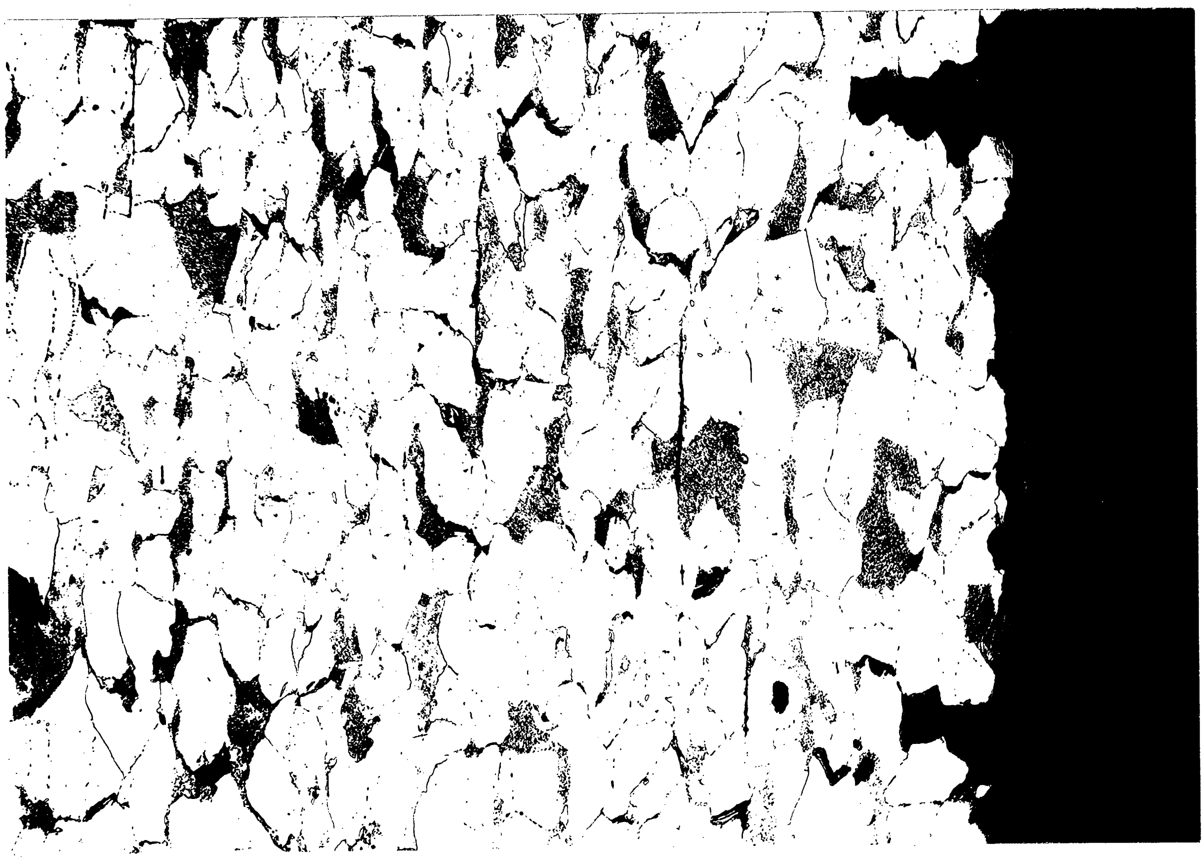


d. X1000D - Interior

Plate 29. - Continued from Preceding Page.



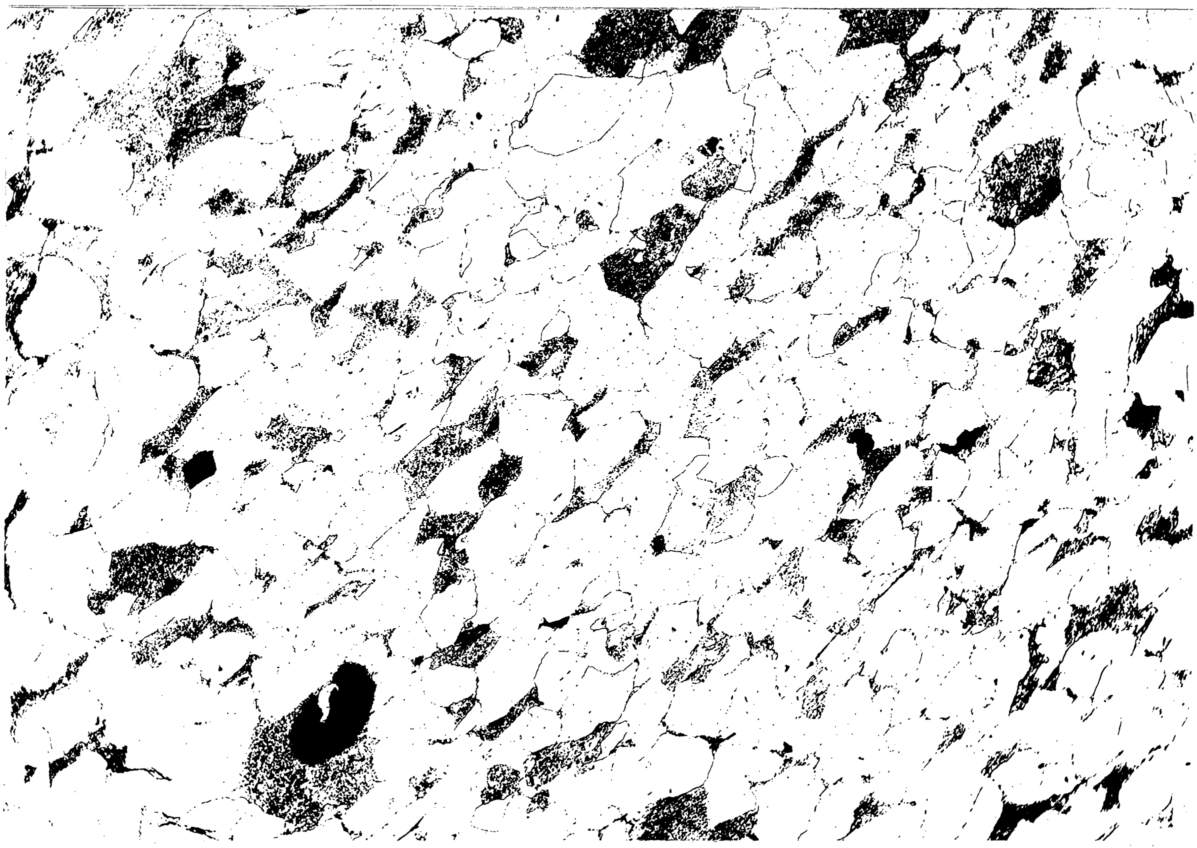
a. X100D - Fracture



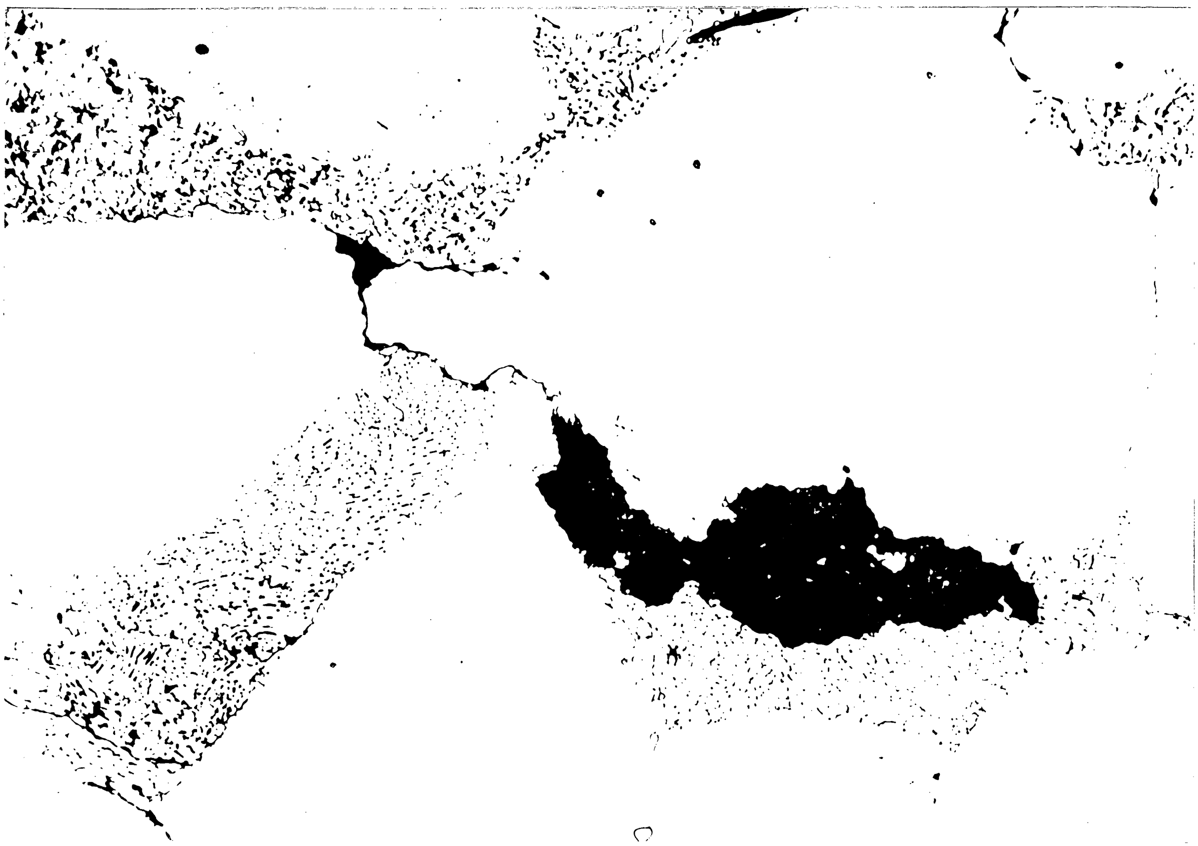
b. X1000D - Surface

Plate 30. - Microstructure of C-Mo Steel Pipe (RT-7) after Fracture in 518 Hours Under a Stress of 19,000 Psi at 1000°F.

(Continued on following page.)



c. X100D - Interior



d. X1000D - Interior

Plate 30. - Continued from Preceding Page.

PART VIII

KEARNY GENERATING STATION NUMBER 7 UNIT STEAM TURBINE LEADS

New Type 347 Stainless Steel Pipe

Sample RT8

Rupture tests were conducted at 1100° and 1150°F on samples cut from a length of pipe submitted under the designation "RT8". The pipe had not been in service and was made of Type 347 stainless steel. The pipe dimensions were 6.625-inch O.D. x 4.705-inch I.D. x 0.960-inch wall. The expected normal operating conditions were reported to be 1100°F and 2350 psi pressure.

Description of Pipe and Service Conditions

An eighteen-inch length of pipe, identified as RT8, from the Kearny Generating Station was submitted for testing. The following information was supplied concerning this sample:

Steel: Type 347 (18-8 + Cb) Stainless steel (G.E. Spec. B50A141-58)

Location: Steam Turbine Leads, Number 7 Unit

Size: 6.625-inch O.D. x 4.705-inch I.D. x 0.960-inch wall thickness

Chemical Composition (percent):

C	Mn	Si	S	P	Cr	Ni	Cb
0.042	1.73	0.37	0.004	0.019	17.33	12.64	0.45

Mill Heat Treatment: Normalized

Shop Heat Treatment: None

Physical Properties

Tensile Strength (psi)	80,000
Yield Strength (psi)	48,000
Elongation (%)	30.0

Service Conditions:

Service hours	None
Calculated hoop stress (S=Pd/2t)	6370 psi
Operating Temperatures	
Normal	1100°F
Maximum	1150°F*
Operating Pressures	
Normal	2350 lbs.
Maximum	2600 lbs.*

(*) Ratings for short swings. Not to exceed 1% of operating time.

Procedure

Prior to the preparation of rupture test bars, a ring cut from one end of the length of pipe was hardness tested and examined metallographically to establish whether or not the pipe was uniform around the circumference.

Following the preliminary examination sufficient stress rupture tests were conducted at 1100° and 1150°F to establish the stress-rupture time curves out to about 1500 hours for both longitudinal and tangential specimens. The longitudinal specimens were standard 0.505-inch diameter tensile bars while the tangential specimens were 0.250-inch diameter with a 1-inch gage length. Four specimens were tested at each temperature for both directions. All specimens were taken at 90° intervals around the pipe so that the stress-rupture time curves are representative of material from the entire circumference of the pipe.

Results

The preliminary examination revealed that the microstructure and hardness of the pipe material were quite uniform. The hardness values around the circumference were 137 to 142 Brinell, and Plate 31 illustrates the structure typical of the entire pipe.

The individual stress-rupture test data are given in Table XVI and are plotted on logarithmic coordinates as stress-rupture time curves in Figure 12. The stress-rupture strengths derived from the curves of Figure 12 for time periods of 100, 1000, 10,000, and 100,000 hours are shown in Table XVII.

The stress-rupture time curves of Figure 12 show that the longitudinal and tangential specimens exhibited very similar strength and ductility properties. With the exception of a small amount of scatter that might be expected from samples taken around the circumference of a pipe, the tangential and longitudinal specimens show excellent agreement and plot on the same stress-rupture time curve at both 1100° and 1150°F.

The tests indicated very good ductility at both 1100° and 1150°F for longitudinal and tangential specimens. A progressive decrease in elongation and reduction of area was observed with increased time to rupture at 1100°F but at 1150°F little change was noted with testing times out to about 1100 hours.

Metallographic examination after testing of the longest duration tests revealed the fractures to be both intergranular and transgranular with considerable intergranular cracking in the vicinity of the fracture at both 1100° and 1150°F as shown in Plates 32 and 33. These plates reveal somewhat more intergranular cracking at 1150°F than at 1100°F. However, the degree of intergranular cracking observed was normal for this material and the testing temperatures involved.

Discussion of Results

The rupture strength obtained from the samples cut from the pipe are very close to average values for Type 347 steel as is shown by the comparative data in Figure 13 and Table XVII. The breaks in the stress-rupture time curves are usually found for this steel in the heat-treated condition. The elongations of the specimens were also quite average for the alloy with the probable heat treatment.

Very little difference between tangential and longitudinal specimens was observed. The lower elongations for the tangential specimens probably reflects differences in specimen shape. The reductions of area were quite similar for both materials. Since this value tends to be more independent of specimen dimensions it is assumed that there likewise was little actual difference in ductility in the rupture tests.

TABLE XVI

Stress-Rupture Test Data for New Type 347 Stainless Steel Pipe Intended for Service in the Kearny Generating Station Number 7 Unit

Samples RT8A and RT8B

Sample No.	Direction	Temp. (°F)	Stress (psi)	Rupture Time (hours)	Elongation (% in 2 in)	Reduction of Area (%)
RT8A	Longitudinal	1100	40,000	44.2	43.0	67.5
			37,500	317	43.5	59.0
			35,000	783	25.5	45.5
			32,500	1355.9	18.0	33.5
		1150	36,000	45.9	55.0	67.0
			33,000	195	30.0	46.5
			30,000	575.3	28.0	37.5
			28,000	1144.5	33.5	35.8
RT8B	Tangential	1100	40,000	78.9	31.0	65.7
			37,500	351.3	32.8	56.5
			35,000	849.2	35.0	49.0
			32,500	1327.7	16.0	44.2
		1150	36,000	85.3	33.3	64.0
			33,000	244.5	33.0	48.3
			30,000	530.0	29.0	44.0
			28,000	779.0	33.0	37.7

TABLE XVII

Stress-Rupture Strengths for 18-8 + Cb Steep Pipe at 1100° and 1150°F

Sample RT8

Sample No.	Direction	Temp. (°F)	Stress Rupture Strength (psi) 100-hr	1000-hr	10,000-hr	100,000-hr
RT8	Longitudinal and Tangential	1100	39,000	34,000	28,000	23,000
		1150	34,500	28,500	23,000	19,000
Average Values for Type 347 Steel (from ASTM STP No. 124)						
		1100	39,000	34,500	26,500	21,500
		1150	32,000	27,500	21,500	17,000

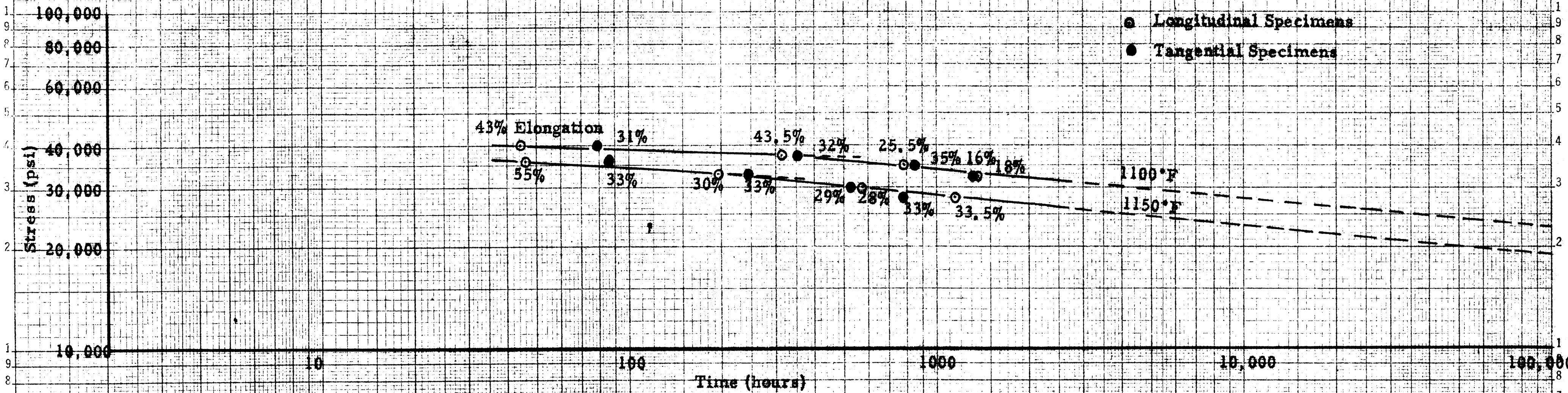


Figure 12. - Stress-Rupture Time Curves at 1100° and 1150°F for 18-8 + Cb Steel Pipe Intended for Service in the Number 7 Unit of the Kearny Generating Station.

(Sample RT8)

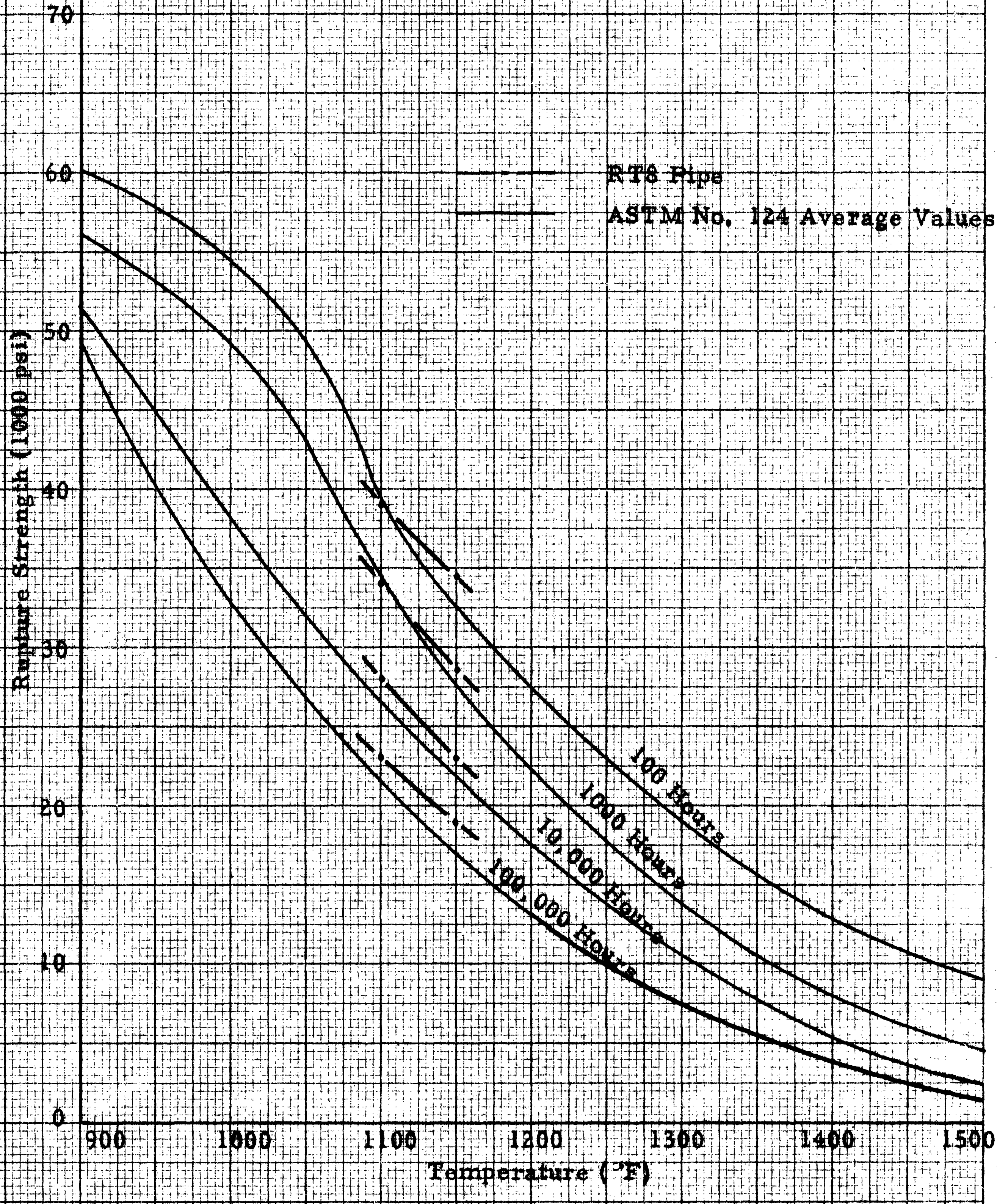
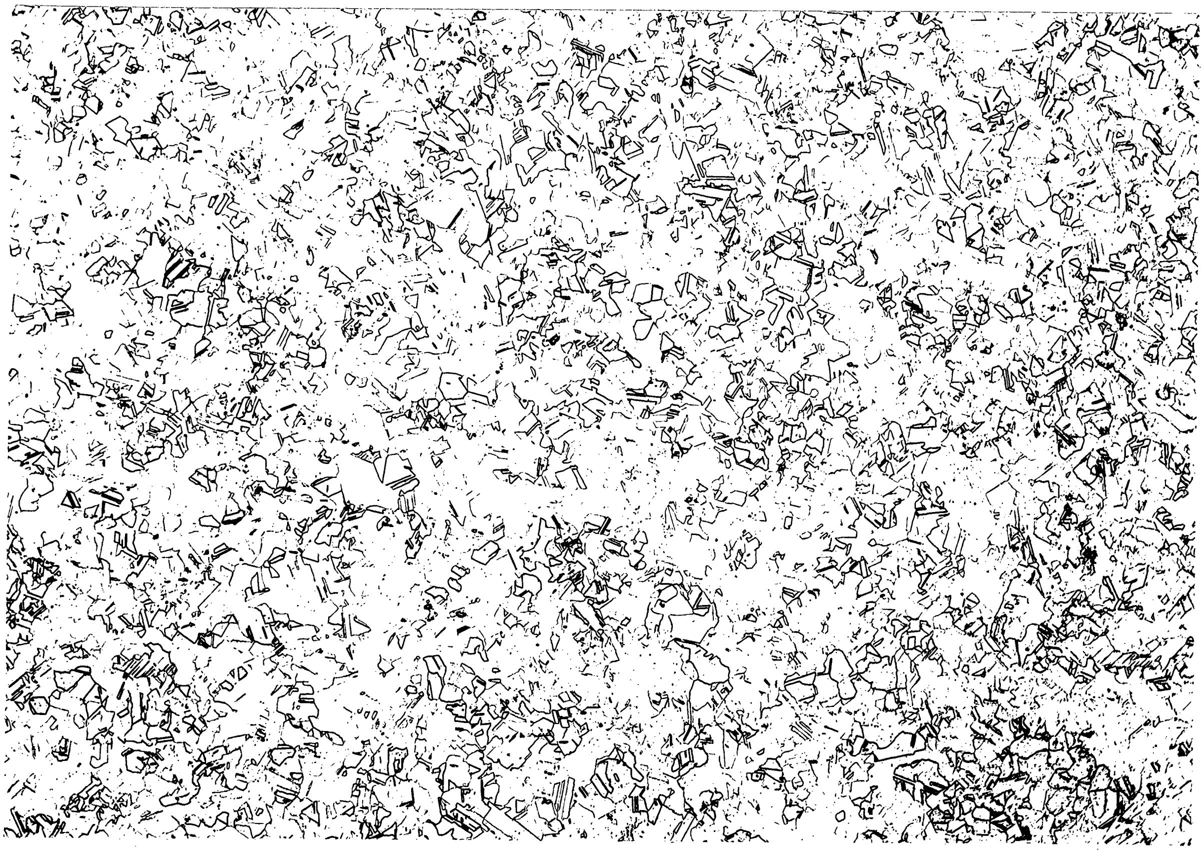
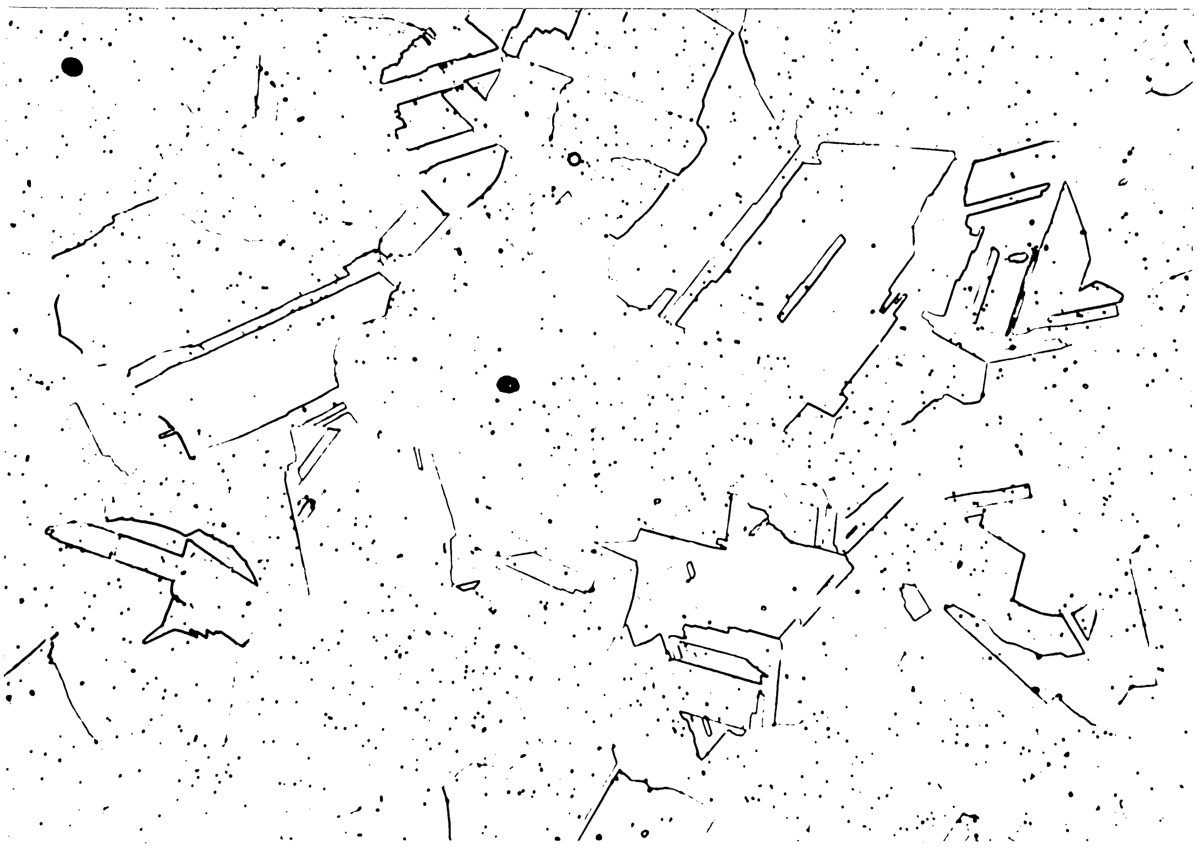


Figure 13. - Comparative Rupture Strengths for 18-8 + Cb Pipe (RT8) and Average Values for Annealed 18-8 + Cb Steel.

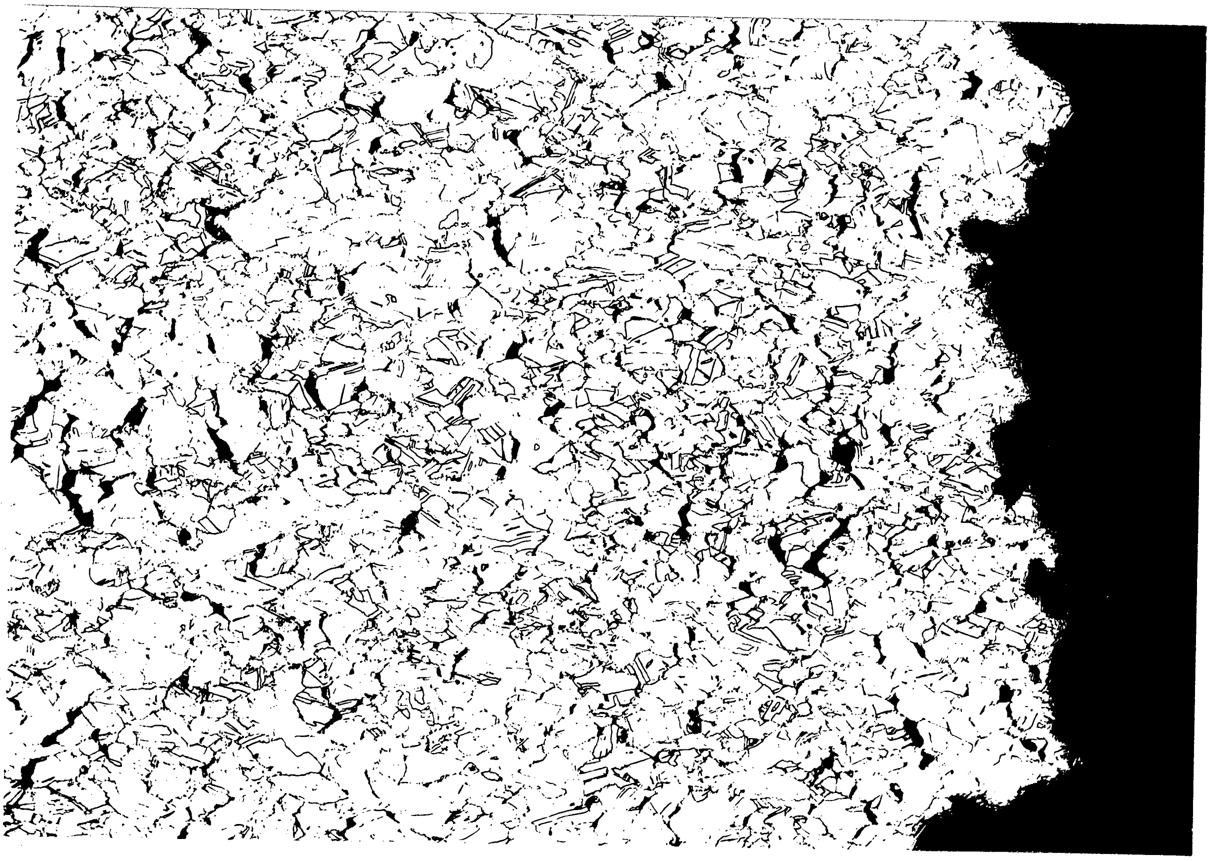


X100D

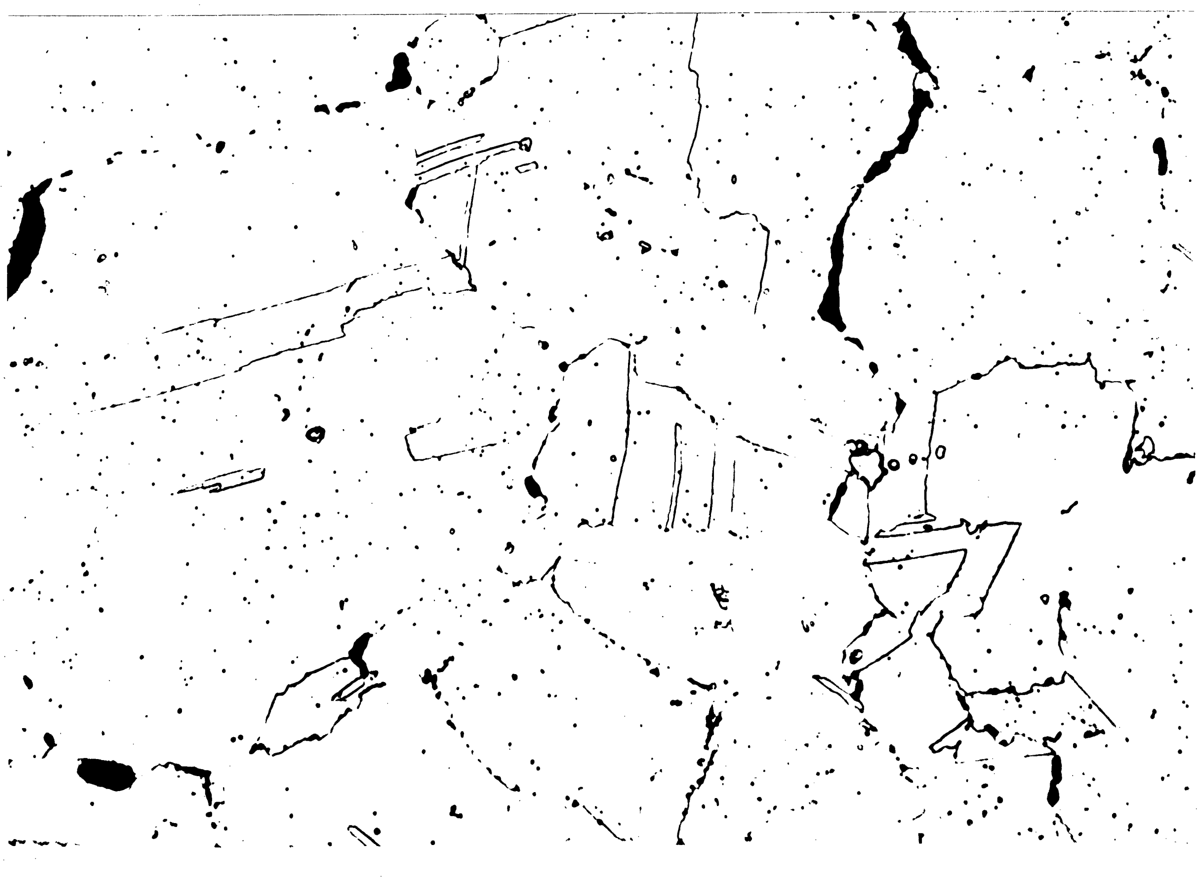


X1000D

Plate 31. - As-Received Microstructure of 18-8 + Cb Steel Pipe(R T-8). Intended for Service in the Kearny Generating Station, Number 7 Unit.

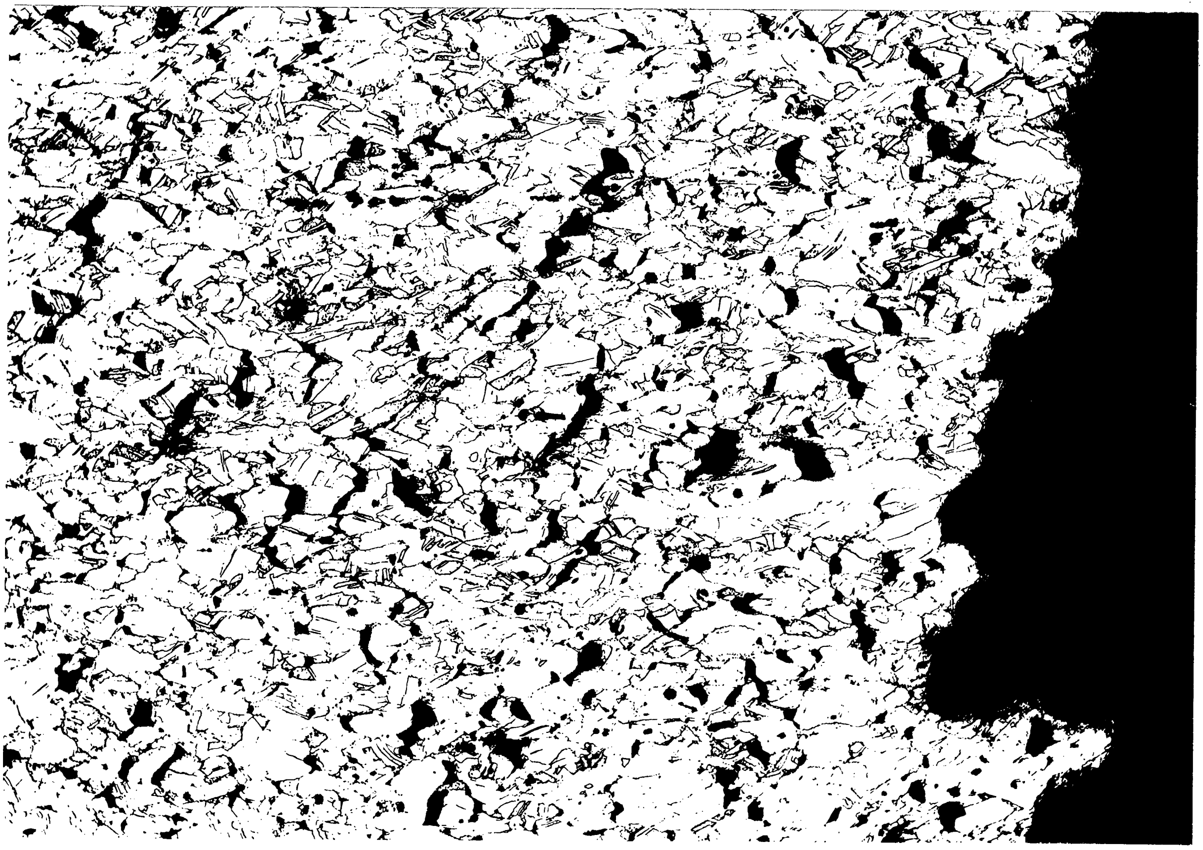


X100D - Fracture

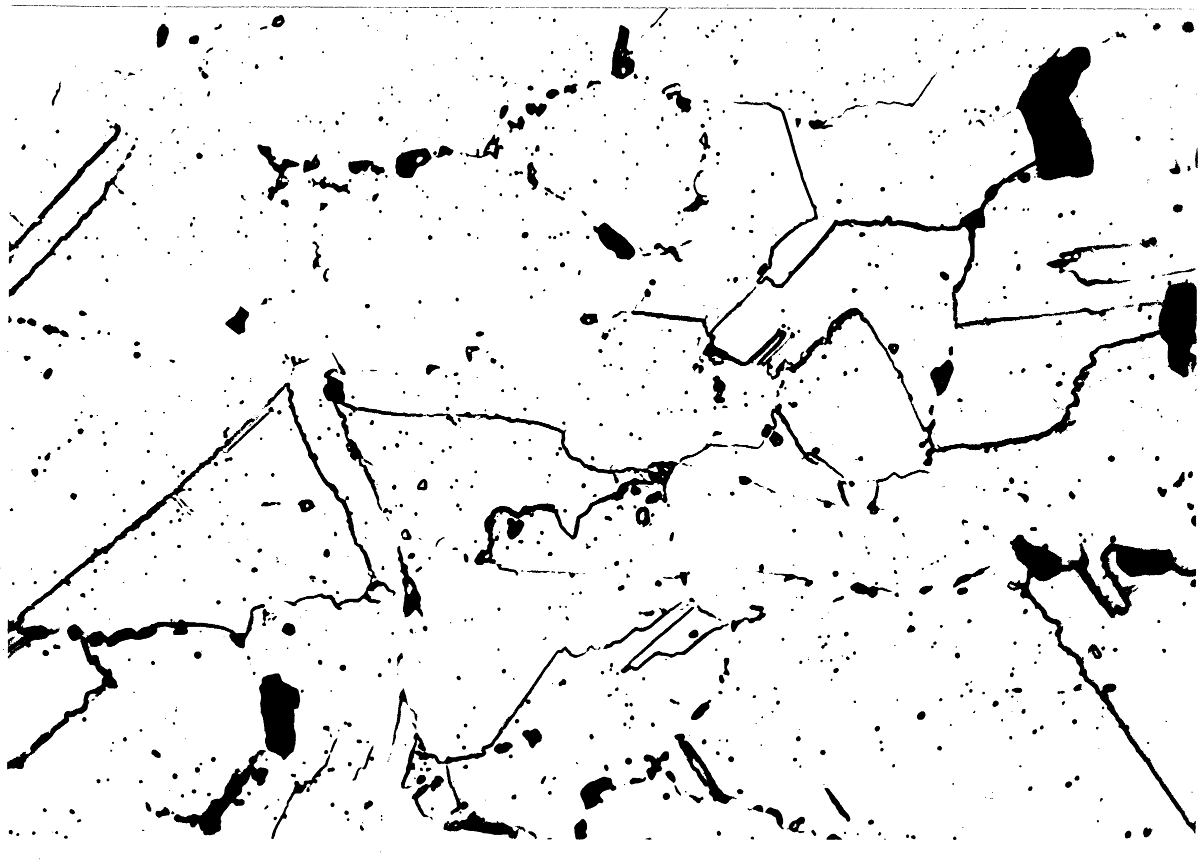


X1000D - Interior

Plate 32. - Microstructure of 18-8 + Cb Steel Pipe (RT-8) Fractured in 1356 Hours Under a Stress of 32,500 Psi at 1100°F.



X100D



X1000D

Plate 33. - Microstructure of 18-8 + Cb Steel (RT-8) Fractured in 1140 Hours Under a Stress of 28,000 Psi at 1150°F.

REFERENCES

1. "Report on the Elevated-Temperatures Properties of Chromium-Molybdenum Steels" ASTM Special Technical Publication Number 151.

2. "The Effect of Carbide Spheroidization upon the Rupture Strength and Elongation of Carbon-Molybdenum Steel" Proc. ASTM Vol. 46.

3. 'Report on the Elevated-Temperature Properties of Stainless Steels" ASTM Special Technical Publication Number 124.