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Examination of Ruptured Tubing from a Hot Water Generator at Bolling Air Force Base

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Failure Analysis Report

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Naval Facility Engineering Command
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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Acting Director*

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SUMMARY

A failure analysis was carried out on a ruptured hot water generator tube. Scale deposits were found on the inside and outside of the tube. Apparently, these deposits promoted crevice corrosion and pitting corrosion, which resulted in wall thinning. Furthermore, pitting attack created a stress-raising notch. Rupture evidently occurred when generator operating pressure exceeded the remaining strength of the deteriorated tube.

Examination of Ruptured Tubing From A Hot Water Generator At Bolling Air Force Base

1. INTRODUCTION

1.1 Reference

Naval Facilities Engineering Command, Building 57, Washington Navy Yard, Washington, D.C. 20374. This examination was conducted at the request of Mr. George Anadale, Code 511, of the Naval Facilities Engineering Command, under Work Request No. N62477-76-WR00277. The request was dated 25 May 1976 and was received at NBS on 9 June 1976.

1.2 Background Information

Information in this section was supplied on 25 June 1976 by Navy Lt. Paul D. Steinke, C.E.C., who is with the resident engineer in charge of Construction at Bolling Air Force Base. The information was given at the site of the generator at the Base.

Hot water generator (boiler) no. 2, Building No. 18, Bolling Air Force Base was installed and not used for approximately two years before becoming operational. The boiler became operational in November 1975.

The boiler initially operated without chemical treatment of the feed water.

The first of a number of tube failures in this boiler occurred in February 1976. After the failures, tube interiors were cleaned with hydrochloric acid followed by neutralization with soda ash (anhydrous sodium carbonate) and tube exteriors were brushed. Chemical treatment of feed water was also provided at this time.

1.3 Material Submitted

One length of tube from the hot water generator was submitted for examination. According to Lt. Steinke, this length of tube was cut from a tube that failed after the earlier failures. This tube had been subjected to approximately 8 to 10 weeks of continuous operation before the installation of the feed water chemical treatment system. Rupture occurred about two weeks after installation of the system. Thus, the tube had an operational service life of about 10 to 12 weeks.

Rupture of the subject tube occurred midway between tube supports. The supports were approximately six feet apart. The tube sample was flame cut from a section of the tube which was originally straight when installed. Original dimensions were nominally 1.25 inch O.D. and No. 13 guage (0.094 inch) wall thickness.

A sample of scale from the tube labeled "interior" (water-side) and another labeled "exterior" (fire-side) were submitted to NBS for analyses at the same time.

2. PURPOSE

The Naval Facilities Engineering Command requested the NBS Mechanical Properties Section to perform a failure analysis to determine the cause of failure of the tube. The following tasks were specifically requested:

1. Chemical analysis of the tube metal and scale on the inside and outside of the tube.

2. A metallographic and fracture analysis.

3. An examination by Scanning Electron Microscope (SEM) with micrographs.

4. A visit to the boiler site for first-hand observation of the equipment and possible photographs.

3. RESULTS OF EXAMINATIONS, TESTS, AND ANALYSES

3.1 Visual and Macroscopic Examination

Macroscopic examination of the tube sample revealed a tight longitudinal rupture, approximately 0.75 inch long that is shown between arrows B and C in Figure 1. The rupture was in the heated fire-side wall (side on which the flame impinged). The diameter of the tube sample adjacent to the rupture was approximately 1.4 inch. The sample was slightly bowed. An adherent scale was present on the heated-fire-side surface of the tube sample adjacent to the rupture. The sample was flame-cut from the parent tube, which is evident from the irregular contour of the sample end at F, Figure 1. Adherent scale which was found on the water-side of the tube sample is shown in Figures 2a and 2b. Thinning of the tube wall that occurred is shown in Figures 3a and 3b.

3.2 Microscopic Examination

3.2.1 Observations on Water-Side

The original microstructure of the tube wall, as observed in unaffected areas, consisted of pearlite in a ferrite matrix. Some decomposition of the pearlite was found at a metal-scale interface on the tube water-side (see Figure 4a). Crevice corrosion and pitting attack were both revealed in microscopic examination [1]* Crevice corrosion of the water-side of the tube wall is shown in Figure 5a. Pitting attack of the water-side adjacent to the rupture is shown in Figures 5b, 5c and 8.

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* Bracketed numbers refer to references on page 5.

3.2.2 Observations On Fire-Side

In examination of a fire-side area a penetration of oxides and decomposed pearlite were found adjacent to a metal-scale interface. Decarburization was also observed in this area (see Figure 4b). Corrosive attack penetrated into the heated fire-side of the tube wall adjacent to the rupture and decarburization also occurred in this zone (see Figure 6).

3.2.3 Observations On Rupture Surface

An oxide deposit was present over the entire length of the rupture surface. An SEM micrograph, Figure 7, shows the deposit midway along the rupture face.

3.3 Chemical Analyses

The results of a conventional chemical analysis of the steel in the sample are given in Table 1. The results of semi-quantitative and qualitative spectrochemical analyses of the exterior scale and the interior scale are given in Tables 2 and 3, respectively.

4. DISCUSSION

4.1 Visual and Macroscopic Examination

Visual and macroscopic examination of the tube sample revealed that the following damage to the tube occurred in service in addition to rupturing:

a. Bowing and bulging of the tube.

b. Scaling of the fire-side of the tube.

c. Scaling of the water-side of the tube.

d. Thinning of the tube wall.

4.2 Microscopic Examination

4.2.1 Observations On Water-Side

The original microstructure, pearlite in a ferrite matrix, is a normal boiler tube steel microstructure. Decomposition of the pearlite observed at a metal-scale interface adjacent to the rupture is the result of a deterioration of heat transfer characteristics because of scale accumulation. Excessive scaling will create a localized hot spot.

Crevice corrosion and pitting corrosion which were observed both proceed by the same mechanism - galvanic corrosion. Scale or deposits frequently lead to crevice corrosion in boiler tubing by creating anodic and cathodic areas. The anodic areas are subject to relatively rapid attack, mainly because they are small in relation to surrounding cathode areas. The general thinning of the tube wall in the water-side adjacent to the rupture, as shown in Figures 3a and 3b, resulted from crevice corrosion. In pitting corrosion, a small area is attacked because it becomes anodic to the rest of the surface, or because of a highly localized concentration of a corrosive contaminant in the water. Pitting that occurs at relatively few and scattered sites can result in rapid perforation because of the large ratio of cathode-to-anode area. Cracking of the scale, as shown in Figure 2a, is considered to have been conducive to pitting attack of the tube water-side.

From microscopic observations it is evident that crevice corrosion on the water-side greatly reduced tube wall thickness. In addition, pitting attack further reduced tube wall thickness in localized areas and created stress-raising notches.

4.2.2 Observations On Fire-Side

Decarburization observed on the fire-side of the tube indicates that the tube was at some time exposed to an oxidizing atmosphere (flame). This atmosphere reacted with and removed carbon from the pearlite constituent in the steel resulting in a localized weakening of the metal structure. Corrosive attack on the fire-side also reduced tube wall thickness in the rupture zone.

4.2.3 Observations On Rupture Surface

The oxide deposit observed on the fracture surface resulted from the seepage of detritus from within the tube. An S.E.M. fractographic examination of the rupture surface could not be made because of the deposit.

4.3 Chemical Analyses

The chemical composition of the steel in the tube was found to comply with the requirements for ASME SA 178A, Grade A, as reported to be specified by the Naval Facility Engineering Command for this installation. The carbon content of the exterior scale points to an unfavorable operating condition. The high carbon content (about 70%) is indicative of uncombusted fuel. This condition resulted in the accumulation of the fire-side scale that is shown in Figures 4b, 5c and 6. An accumulation of exterior scale on boiler tubes detrimentally affects heat transfer characteristics and can result in localized hot spots. Sulfur, sodium and vanadium found in the exterior scale were apparently derived from the fuel oil in which they are frequently found. These elements are present in complex compounds formed during the combustion of fuel oil. These compounds may have contributed to the corrosive attack shown in Figure 6 [2].

Compounds containing calcium, iron, magnesium, silicon and other cations that were found in analysis of the interior scale are deposited from most untreated water. It could not be determined from this examination whether the interior scale was old (deposited before feed water treatment) or new (deposited after feed water treatment). The contribution of scale to corrosive attack of the tube water-side has been noted in sub-section 4.2.1.

5. CONCLUSIONS

From evidence gathered in this examination, more than one factor was involved in the rupture of the subject boiler tube. These factors were as follows:

1. Scaling of the tube water-side which led to crevice corrosion and thinning of the tube wall.

2. Pitting attack of the tube water-side which created a stress-raising notch.

3. Corrosive attack and deterioration of the fire-side wall.

These factors reduced the thickness and strength of the tube wall in the rupture zone until it could no longer sustain generator operating pressure and finally rupture of the tube occurred. Most of the damage before rupture occurred on the water-side of the tube.

ACKNOWLEDGEMENTS

The metallographic specimens were prepared by Mr. L. C. Smith, Mechanical Properties Section, Metallurgy Division. The photographic prints were also made by Mr. Smith.

REFERENCES

[1] ASM Metals Handbook, Vol. 10, 8th Edition, 1973, American Society for Metals, Metals Park, Ohio 44073; Water-Side Corrosion in Boilers, p. 534.

[2] Ibidem
Oil-Ash Corrosion, p. 537.

Table 1

Chemical Analysis of Steel in Tube Sample

Carbon	0.10%
Manganese	0.36
Phosphorus	<0.005
Sulfur	0.019
Silicon	<0.01
Nickel	0.03
Chromium	0.10
Molybdenum	<0.01
Copper	0.11

Table 2

Chemical Analysis of Exterior Scale

Semi-Quantitative Analysis

Carbon		69.9%
Sulfur		0.109

Qualitative Spectrochemical Analysis and Concentrational Estimates of Detected Constituents

Iron		0.3-3%
Sodium		0.2-2
Calcium, Vanadium, Silicon		0.03-.3 each
Nickel		0.02-.2
Aluminum, Magnesium, Manganese		0.01-.1 each
Strontium, Barium		0.003-.03 each
Zirconium		0.002-.02
Titanium, Copper, Lead		0.0005-.005 each
Cobalt, Molybdenum, Chromium		0.0003-.003 each
Silver		0.00001-.0001
Tin	T	<0.001
Zinc	ND	<0.05
Boron	ND	<0.002

T - Trace

ND - Not Detected

Table 3

Chemical Analysis of Interior Scale

Semi-Quantitative Analysis

Carbon	2.4%
Sulfur	0.98%

Qualitative Spectrochemical Analysis and Concentrational Estimates of Detected Constituents

Calcium	5-50%
Iron	3-30
Magnesium	1-10
Silicon	0.1-1
Copper, Manganese	0.05-.5 each
Sodium, Stontium	0.03-.3 each
Zinc	0.02-.2
Nickel, Vanadium, Aluminum	0.01-.1 each
Chromium	0.005-.05
Zirconium	0.001-.01
Molybdenum, Boron, Tin, Barium and Titanium	0.0005-.005 each
Lead	0.0003-.003
Cobalt	0.0001-.001
Silver	0.00001-.0001

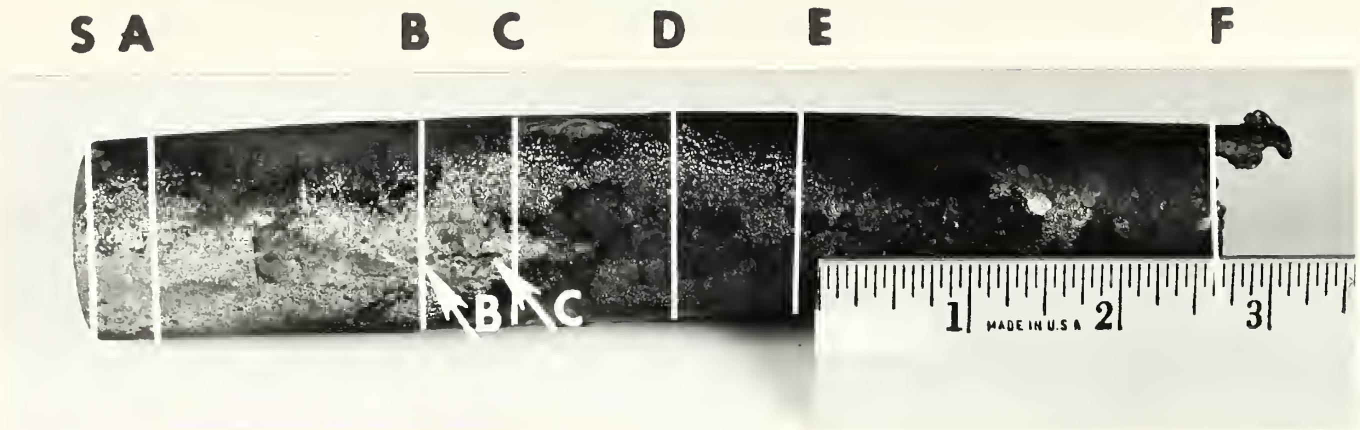


Figure 1. Ruptured Tube Sample Submitted for Examination. Arrows point to rupture. Viewing faces at S, A, B, C, D, E and F are normal to principal axis of sample. X 0.8

S-A - Section used in macroscopic examination of sample interior.

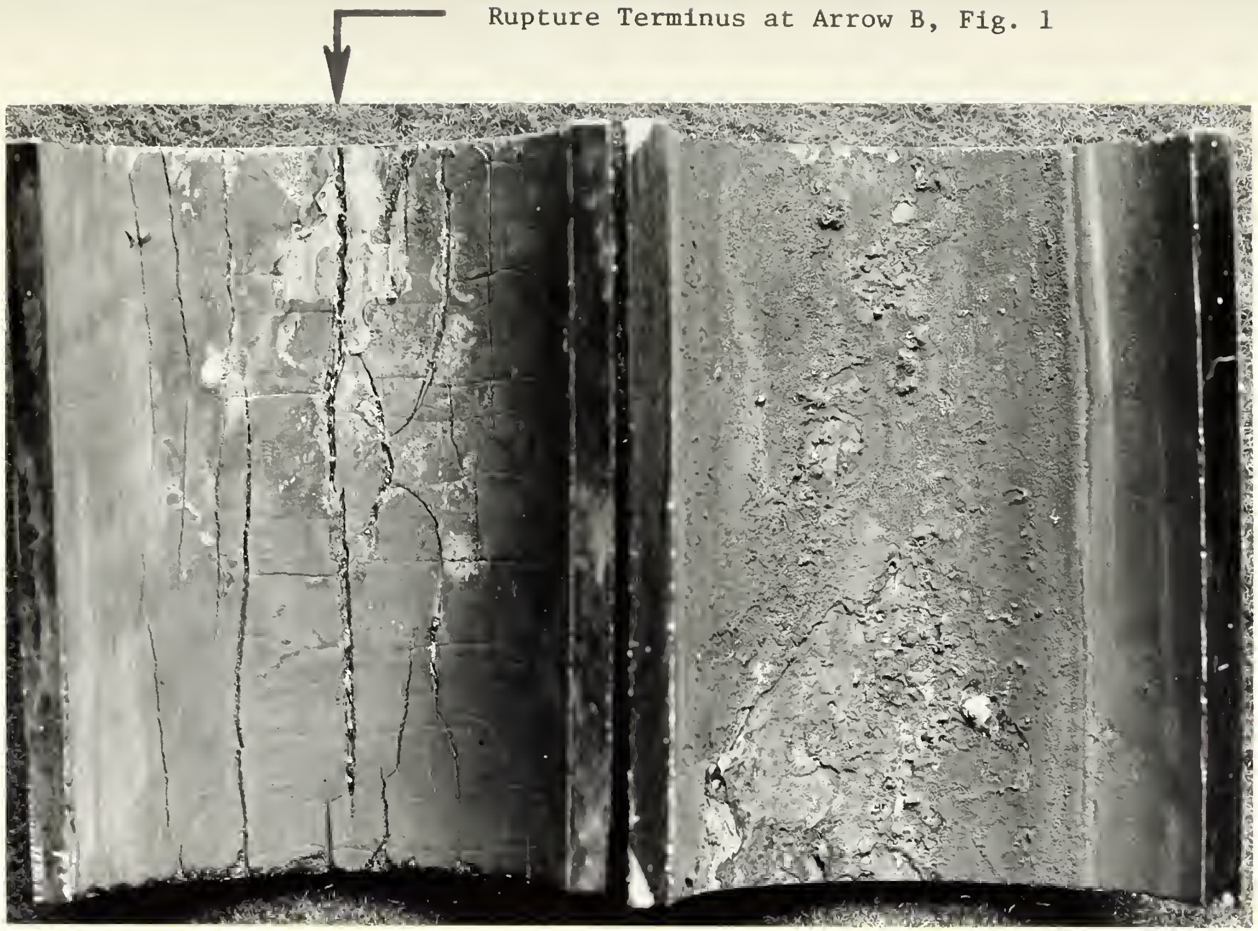
A-B - Section that was split longitudinally for viewing of sample interior.

B-C - A metallographic specimen containing the rupture surface adjacent to arrow B was prepared from section B-C. Another specimen contained one face of the rupture surface and was intended for Scanning Electron Microscope (SEM) examination.

C-D - Section cut to provide specimens for metallographic examination adjacent to the rupture at arrow C.

D-E - Section used as a chemical analysis sample.

E-F - Reserve section.



a b

Figure 2. Views of Section A-B After Splitting. Shows adherent scale on water-side wall of tube X 2.5
a. Heated water-side
b. Shadow water-side
Note the longitudinal cracks in the scale in 2a. Arrow points to terminus of rupture in tube wall.

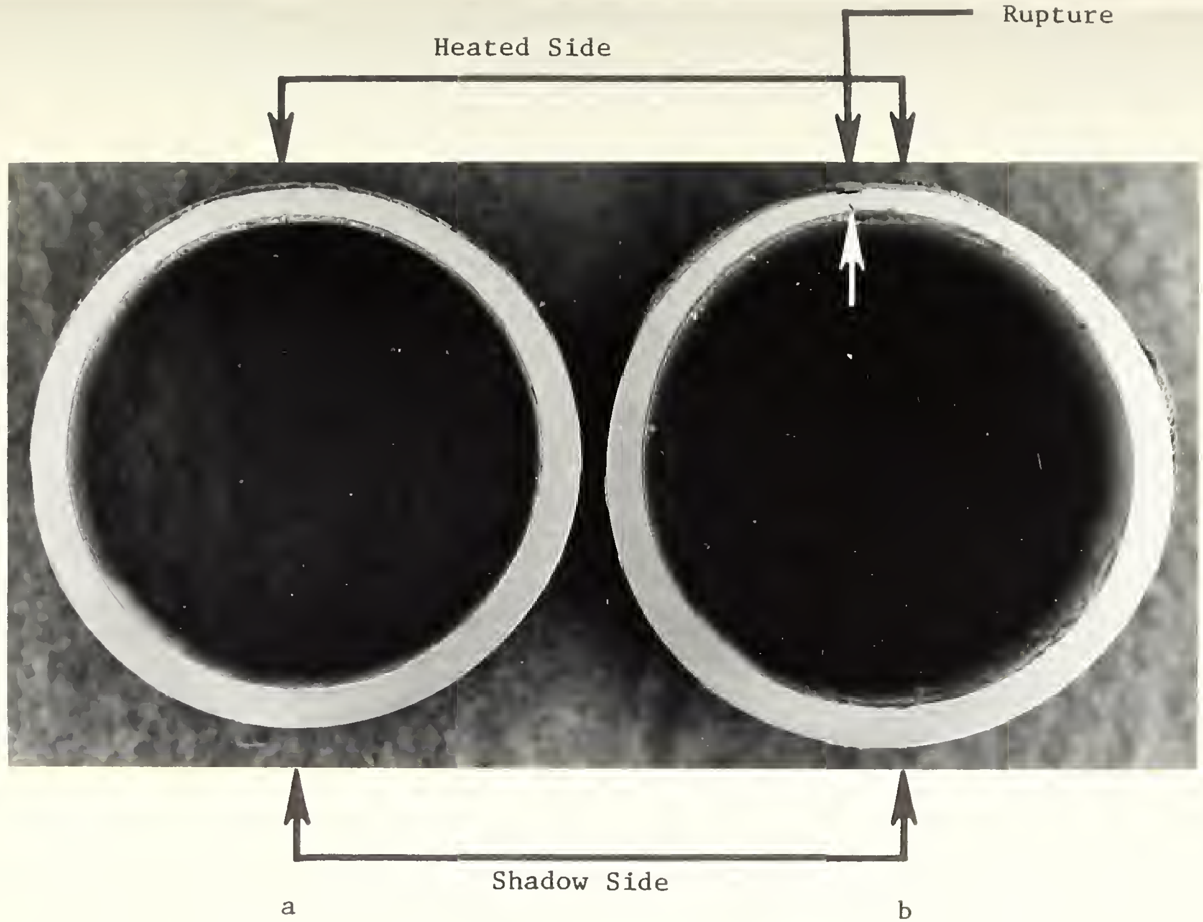
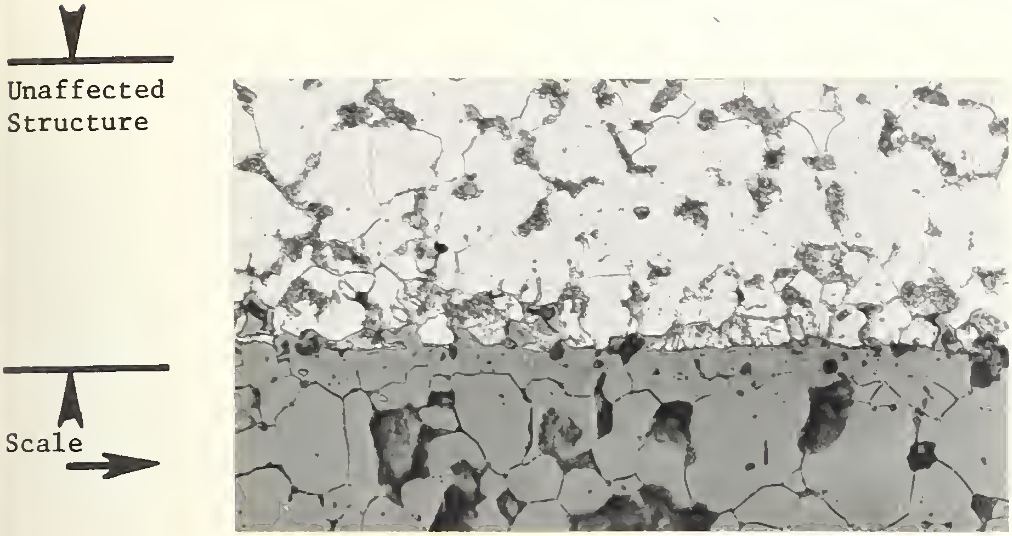


Figure 3. Viewing Faces of Tube Wall Showing Thinning, Bulging and Scale.

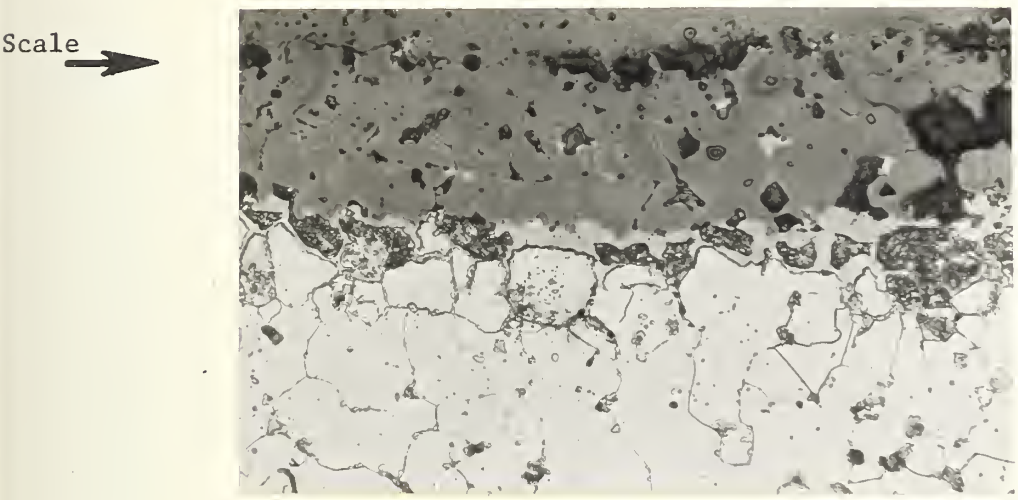
a. Face S of Section S-A

b. Face C of Section B-C

Greatest reduction in wall thickness was observed adjacent to rupture, at arrow, Figure 3b. Bulging - heated side to shadow side axis - was observed to be slightly greater in section B-C than in Section S-A. Note also scale present in both views at heated fire-side and heated water-side areas.



a



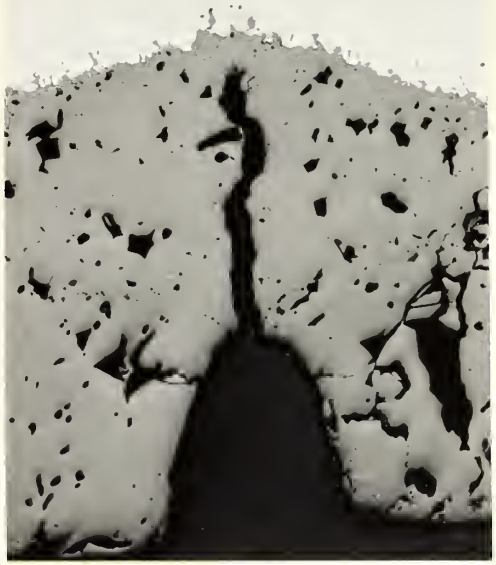
b

Figure 4. Photomicrographs of Structures Adjacent to Rupture in Tube Wall. Transverse. Etched with 1% Nital

X 500

a. Microstructures adjacent to water-side. Upper half shows unaffected structure consisting of pearlite (black) in a ferrite (white) matrix. Some decomposition of the pearlite occurred at the metal-scale interface.

b. Microstructures adjacent to fire-side. Shows a penetration of oxides (grey) and decomposed pearlite (black) in metal adjacent to metal-scale interface. Steel has also been decarburized.



a

b

c

Figure 5. Views of Crevice Corrosion and Pitting Attack of Tube Wall.

a. Crevice corrosion of water-side. Transverse. Unetched. X 100
Corrosion is shown advancing from tip of crack in scale (grey).

b. Pitting attack of water-side adjacent to Rupture. Longitudinal. Unetched. X 200
Penetration into tube wall from break in scale is shown.

c. Crevice corrosion and pitting adjacent to rupture. Transverse. Unetched. X 50
Penetration of pits on fire-side (adjacent to grey scale) and on water-side (large pit) are shown. Crevice corrosion and pitting reduced the tube wall thickness to approximately 0.024 inch from 0.094 inch, the approximate installation thickness.

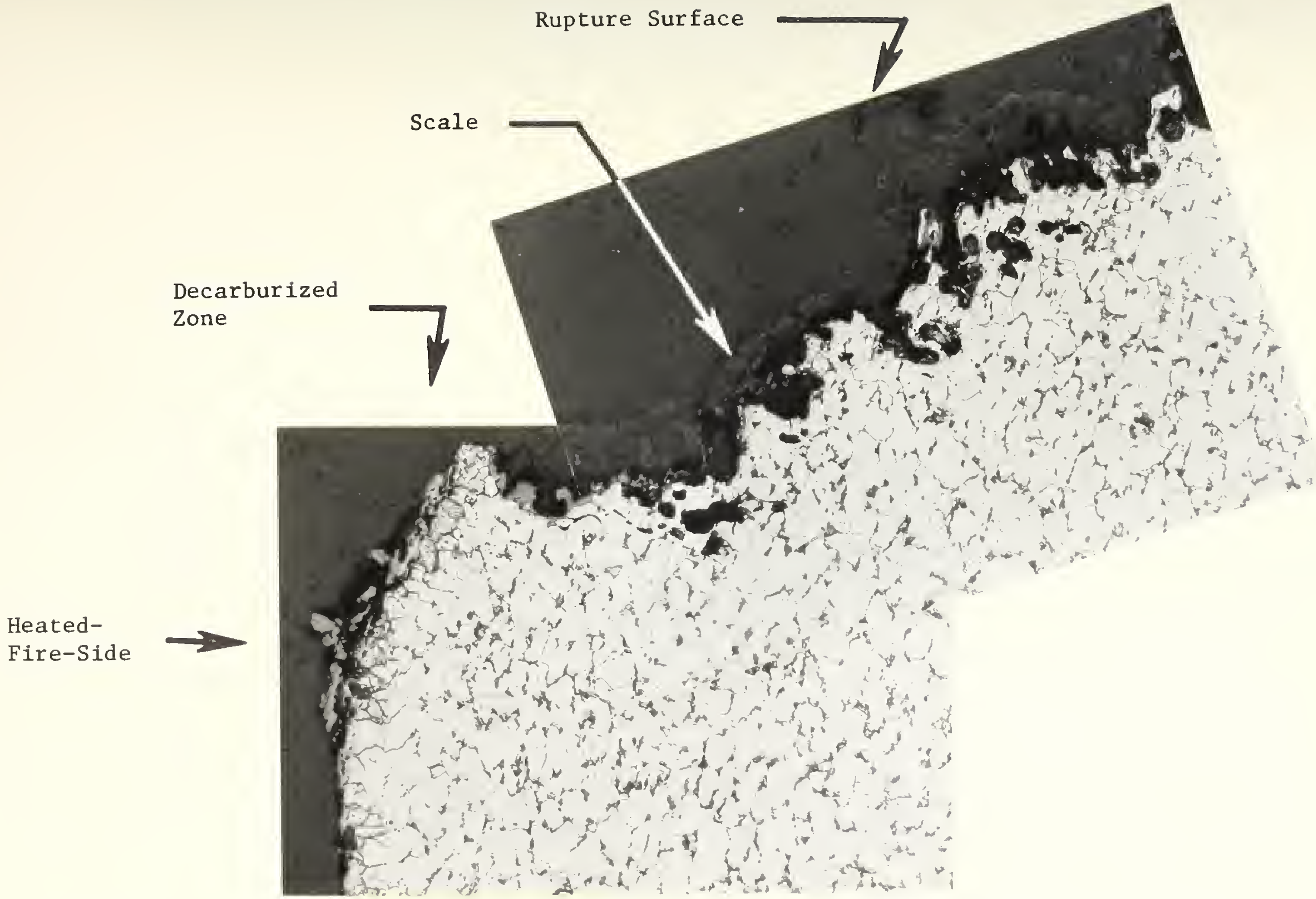
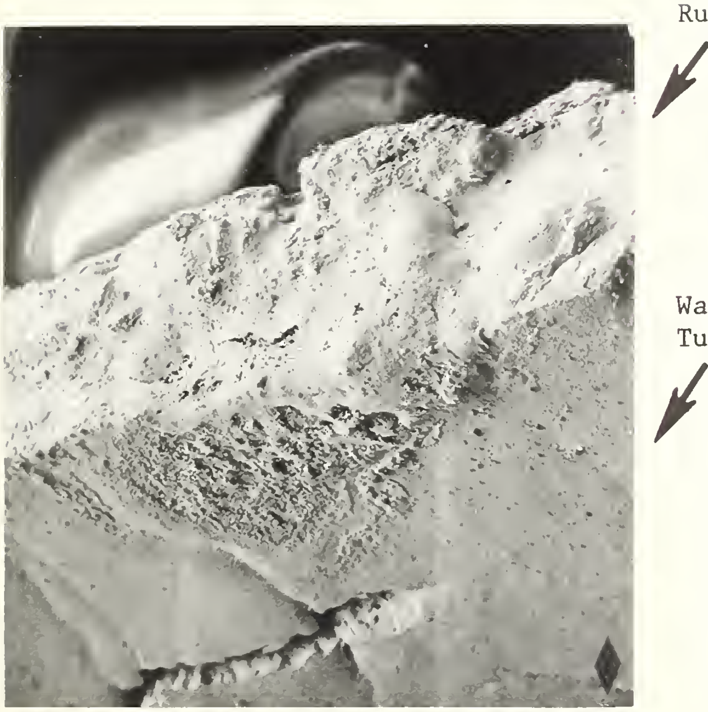


Figure 6. Profile of Rupture in Tube Wall Adjacent to Heated Fire-Side Longitudinal. Etched with 1% Nital. X 200

Shows decarburization adjacent to rupture surface on heated fire-side. Irregularity of rupture surface resulted from corrosive attack penetrating from heated fire-side.



Rupture Face

Water-Side at
Tube Wall

Figure 7. Oxide Deposit Observed Midway Along Rupture Face. SEM X 18.5
Scale on adjacent water-side of tube wall is also shown.

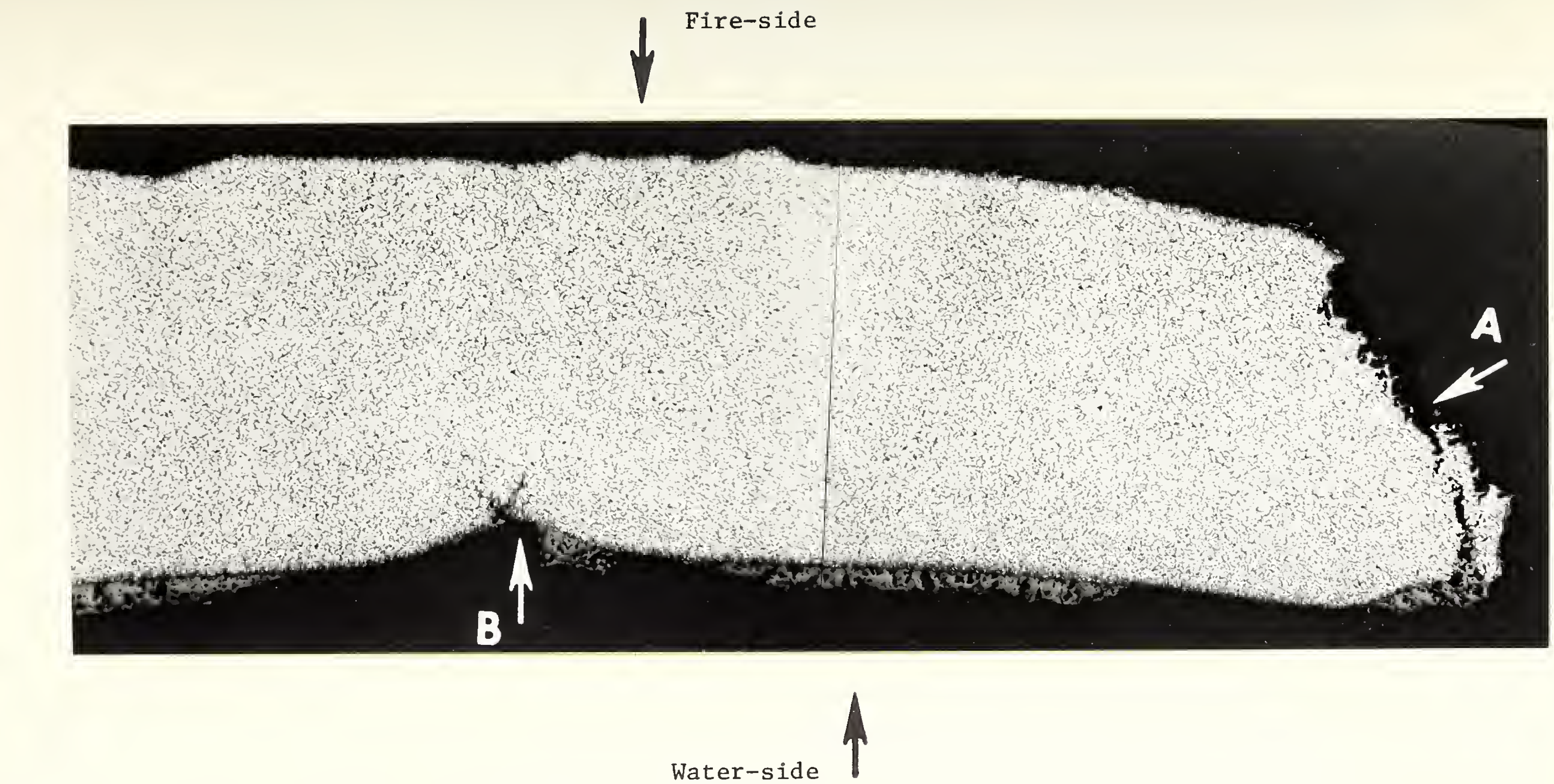


Figure 8. View of Entire Rupture Profile in Tube Wall. Longitudinal. Etchant: 1% Nital X 40

Arrow A. Rupture surface. Note penetration of scale (grey) on water-side adjacent to rupture.

Arrow B. Corrosion pit on water-side.

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. SUPPLEMENTARY NOTES

. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A failure analysis was carried out on a ruptured hot water generator tube. Scale deposits were found on the inside and outside of the tube. Apparently, these deposits promoted crevice corrosion and pitting corrosion, which resulted in wall thinning. Furthermore, pitting attack created a stress-raising notch. Rupture evidently occurred when generator operating pressure exceeded the remaining strength of the deteriorated tube.

. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Boiler; corrosion; crevice; failure; notch; pitting; rupture scale; stress; tube.

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