MARINE BOILER TUBE FAILURES

BY

R. D. BARER, B.A.Sc. S.M.

Pacific Naval Laboratory, Defence Research Board of Canada

The following article is reproduced by permission of the Author and the Editor of the Journal of the Royal Naval Scientific Service, *in which it first appeared in May,* 1961.

ABSTRACT

Three instructive examples of boiler tube failures are described. An instance of local overheating early in the life of a healthy boiler tube resulted in a ballooning burst. There was metallurgical evidence of temperatures of 1,700–1,800 degrees F. prior to the rupture. Freedom from unsoundness in the metal was demonstrated. Failure was attributed to an unknown impedance to normal flow of steam and water in the tube.

Failures by stress-corrosion cracking of marine boiler tubes are commonly the result of a concentrated caustic solution in contact with stressed boiler metal. Usually the concentration of the caustic results from leakage between seams and around rivets, or capillary action and subsequent evaporation. A rare example of the same type of failure is one where no seams or crevices exist for concentrating the boiler solution by leakage ; that is, failure resulting from concentration of the boiler solution right on the steam generating surface of the boiler tube. Details of such a failure are discussed.

It was shown how stress and corrosive environment together result in severe cracking. That this was an example of stress-corrosion cracking, i.e., electrochemical action aided by stress, is indicated. The particular conditions leading to this failure were channelling of hot gases and subsequent concentration of caustic in the boiler water.

An investigation of three cracked tubes from a converted minesweeper is described. Although there were differences in detail in the type of cracking in the most severely cracked of the three tubes, it was established that failures were by corrosion fatigue. Metallurgical evidence established that the tube metal in these three had been subjected to temperatures above normal for considerable periods of time. In only these three tubes was there ' spheroidization ' —a change that normally requires several hours exposure at 1,200 degrees F. Contributing factors were an undesirable oil spray pattern, excessive internal deposits, and especially, a less than normal flow through the three tubes. Radiography indicated that no other tubes were affected in spite of the fact that several were subjected to the same factors, with the exception of flow interference. It was indicated that adjustment of fuel nozzles and internal chemical cleaning of the boilers would be beneficial in ensuring that no additional cracking occurred.

Boiler tube failures hold the power to incapacitate or seriously hamper a vital unit in a defence force or a commercial fleet, and, possibly, endanger life. They are not frequent occurrences. When they do occur, however, accurate diagnosis is a necessity to ensure that conditions leading to a repetition are minimized or eliminated. In this article, three instances of boiler tube failures are described. These instances are chosen particularly because it is believed that not only the assessment of causes, but the steps involved in arriving at conclusions, are rather instructive. These three case histories are accordingly set down in hopes they will prove of value to others.

FIRST CASE HISTORY

This was a failure of a 2 in. fire row tube in a destroyer escort which resulted in flooding of the furnace in several feet of water. The incident occurred during ship trials after a total steaming time of 7 hours. The tube burst open, as shown in FIG. 1, just below the bend on the way to the steam drum. This tube was number 6 from the back wall, in ' A ' row.

Visual examination showed several features of interest :

(*a*) The split was at the centre line of the tube—facing the fire and was consequently at a high heat input zone

(*b*) The thin edges of the split, practically a knife edge, and the ' stretcher ' marks on the inner surface at the break, as shown in FIG. 2, are indicative of plastic flow of the metal

(*c*) No appreciable thickness of internal deposit was noted in the immediate area of the split.

The defective tube and adjacent ' A ' row tube number 7 from the back wall, were made available for detailed laboratory study.

FIG. 1—LOCATION OF BURST IN TUBE BANK
NOTE THIN EDGES AT CENTRE OF BURST AND ' STRETCHER MARKS ' ON INSIDE SURFACE

Metallurgical Examination

Radiographic examination, as well as subsequent examination of sections under the microscope, failed to indicate any evidence of defective material. The metal of both tubes was sound.

Examinations of specimens well removed from the rupture (approximately 4 ft) and comparison with a specimen from tube number 7 showed that microstructure of both was the same (FIG. 3). Spectrographic analysis also showed that both tubes were plain carbon steel, identical with each other, and containing no appreciable alloying elements.

Small pieces of metal were cut from the location indicated on FIG. 2.

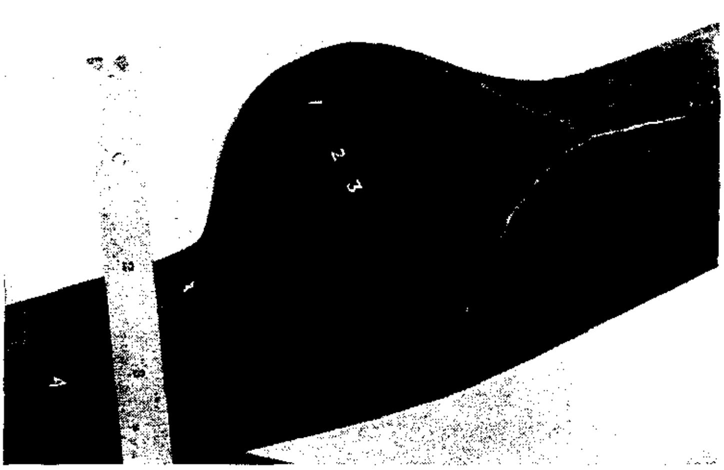

FIG. 2—THE BURST ON THE DESTROYER ESCORT VESSEL

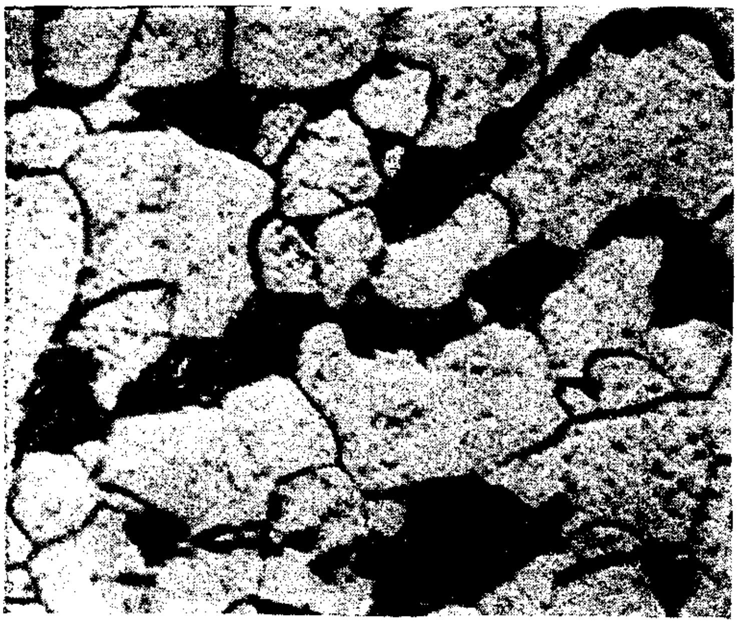

FIG. 3—PHOTOMICROGRAPH OF NORMAL STRUCTURE OF TUBES NOS. 6 AND 7. THIS IS A MIXTURE OF PEARLITE AND FERRITE—USUAL FOR AN APPROXIMATELY 0·25 PER CENT CARBON STEEL (400 ×)

FIG. 4—PHOTOMICROGRAPH OF TYPICAL MICROSTRUCTURE AT LIPS OF BURST. THIS IS MARTENSITE AND COULD ONLY RESULT FROM A DRASTIC QUENCH FROM 1,700-1,800 DEGREES F. (400 ×)

Examination of specimen number 1 at the lip of the split established the fact that metal in this area had been to temperatures of approximately 1,700-1,800 degrees F. before being rapidly quenched by the tremendous flow of steam and water released by the burst. A typical microstructure from specimen number 1 is shown in FIG. 4.

Examination of specimens numbers 2, 3 and 4 showed increasing amounts of bainite and pearlite, at the expense of the martensite. This indicates a decreasingly less drastic quench rate, and to a certain extent that temperatures were a little lower. It was established that the heat-affected zone, as evidenced in microstructural changes, extended well beyond 2 in. past the rupture, both above and below the opening. The heat effect did not extend fully around to the back of the split.

The internal scale was also analysed and measured. It was magnetite and was of negligible thickness on both tubes except within a foot or less of the split, where it became 0·0015 in. thick. There would be little reason for this zone to develop an oxide film greater than elsewhere except as a result of the excessive heat input.

Reviewing all the factors and evidence available, the sequence of events was as follows :

(*a*) Excessive steam generation because of the high heat input at this locality, combined with some temporarily poor circulation (cause unknown), impeded heat transfer.

(*b*) Metal of tube wall became progressively hotter, eventually reaching 1,700-1,800 degrees F. It is anticipated that this overheating took place in a short period of time—probably minutes.

(*c*) At this temperature the metal has approximately one-twentieth of its usual strength and also possesses great ductility. The result was a gentle bulging until the wall became, by stretching, too thin for the internal pressure.

(*d*) At the instant of rupture a great flow of water and steam (much of the water would flash to steam) effectively quenched the overheated metal (proved by the martensitic microstructure).

The exact cause of the initiation of step (*a*) above, could not be determined.

FIG. 5—THE BURST TUBE A25

FIG. 6—RUPTURES ON TUBES B39, B40 AND B41 ALSO FROM R.H. SIDE OF BOILER

CONCLUSIONS

This boiler tube failure was essentially a simple case of local overheating. This overheating probably occurred in a matter of minutes, thereby avoiding the more complicated deterioration (as described later) from prolonged overheating in conjunction with other influences.

This failure presents a picture of a healthy boiler tube metal becoming red hot, and progressively hotter, then ballooning under the influence of internal pressure. The edges of the burst, smoothly tapered to a knife edge, confirmed the soundness of the metal.

Because it was so early in the boiler's life, the possibility was strong that something had been inadvertently left in the boiler, adversely affecting normal water circulation.

It was concluded that a failure of this type was not likely to occur again and the boiler was placed back in service.

SECOND CASE HISTORY

This incident in a light cruiser, involved failure by bursting of one generator tube as well as partial rupture of several others in an Admiralty 3-drum boiler. The ship was steaming steadily at half-load at the time, and records do not indicate anything unusual in operating conditions.

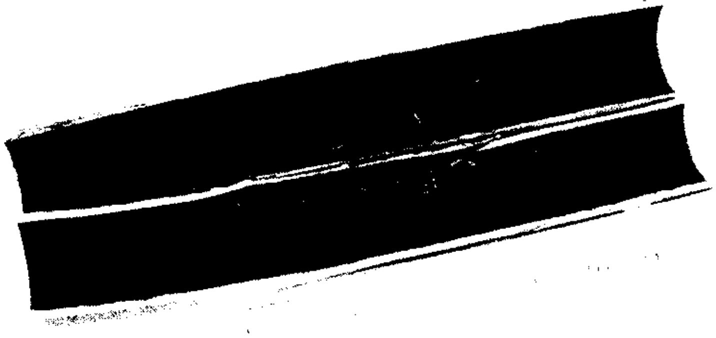

FIG. 7—TUBE B40 SPLIT IN RUPTURED SECTION TO SHOW CRACKING

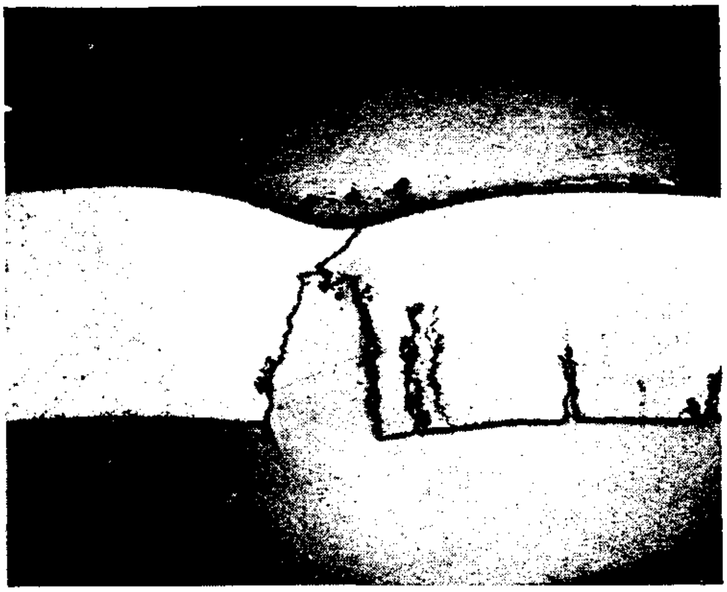

FIG. 8—SECTION THROUGH TUBE WALL NEAR END OF BURST (A25) SHOWING DUCTILE NECKING-DOWN FROM OUTER METAL AND FINAL RUPTURE ON A 45-DEGREE PLANE. ALSO SHOWN ARE THE FIVE ADDITIONAL CRACKS WHICH PROGRESSED IN AN INTERGRANULAR MANNER

Visual Examination

The burst tube, A25, is shown in FIG. 5. There appears to be no metal wastage and this was confirmed by measurement. There was only a minor amount of stretching and the metal had parted along apparent ‘ plates ’. Cracked metal would give a plate-like appearance appearance on fracture. In fact, near the edge of the burst, many fine cracks, $\frac{1}{8}$ in. to $\frac{1}{4}$ in. long, were to be seen.

Among other tubes in which cracking was noted were B39, B40, and B41, shown in FIG. 6. Although these tubes had opened slightly, rather than bursting open, they had apparently been subjected to a similar mechanism. The typical internal cracking is shown in FIG. 7.

The absence of fully ductile breaks was associated with the cracks, and the varied ruptures suggested that a change in operating conditions, presumably overheating, had occurred at a particular instant.

Micro-Examination

Tube A25, whose bursting initiated the investigation, was given a thorough and detailed micro-examination. Sections were cut from the tube near the burst. A particularly interesting section, FIG. 8, shows the presence of several cracks in addition to the main one which is a continuation of the burst. Evidence of normal ductility of the metal may be noted in the outside 25 per cent of the tube wall where the final break was on a 45 degree plane at the necked-down region. FIGS. 9 and 10 show some of the intergranular cracking found in A25, as well as including evidence that the metal had been overheated, and then rapidly cooled.

Tubes B38 to B41 inclusive were also given a detailed examination. An excellent example of the typical intergranular cracking found in practically all sections examined is shown in FIG. 11. This cracking is also indistinguishable from cracking exhibited by the steel of an autoclave exposed to 50 per cent caustic soda at 250 degrees F. and 400 lb/sq in., as reported by Copson⁽¹⁾.

The binocular microscope was then used to examine slices from other

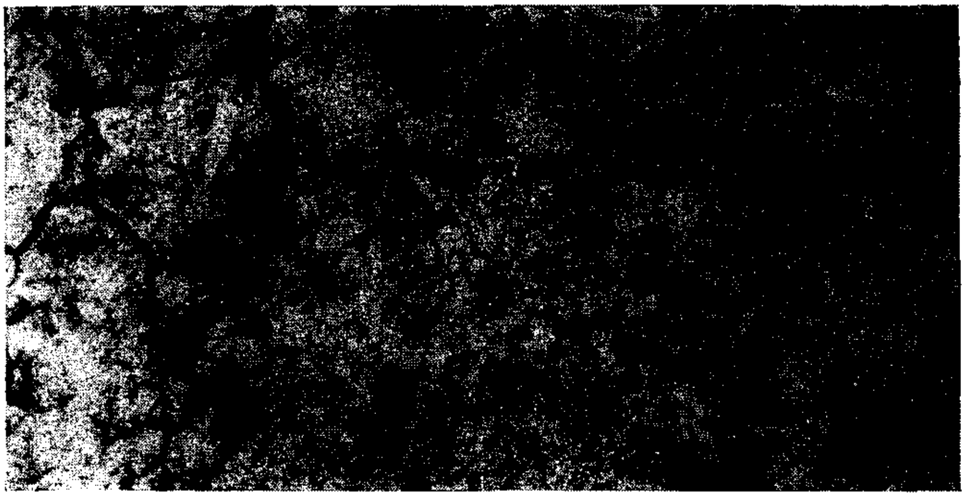

FIG. 9—PHOTOMICROGRAPH SHOWING DEFINITELY INTERGRANULAR NATURE OF CRACKING (240 ×)

FIG. 10—FINE INTERGRANULAR CRACKING ON NON-FIRE, INSIDE SURFACE OF TUBE A25 NEAR THE BURST

randomly selected tubes selected tubes. The cracking was found only in some tubes of ‘ A ’ and ‘ B ’ rows, of either side. Sound tubes were found next to cracked ones. In the defective tubes, the cracking was in a zone approximately centred at two to four feet from the top of the tubes.

Tubes from other boilers on the ship were also examined. Four tubes from each boiler, i.e., A25 and B25, from both left- and right-hand sides, were sectioned at 8-inch intervals down to approximately five feet from the top. No cracking was detected in any of these tubes. This was, of course, a limited sampling.

DISCUSSION OF RESULTS

From the microstructures examined, it was evident that A25 and several other tubes had been severely weakened by intergranular cracking before final failure. This intergranular cracking had been initiated on the water side of the generating tubes.

Many metals and alloys are susceptible to intergranular cracking when they are in a stressed condition and in a specific corrosive environment. It should be emphasized that both stress and corrosive environment are necessary.

In the boiler tubes under discussion the stresses were the normal operating stresses resulting from steam generation at 400 lb/sq in. and 650 degrees F., and

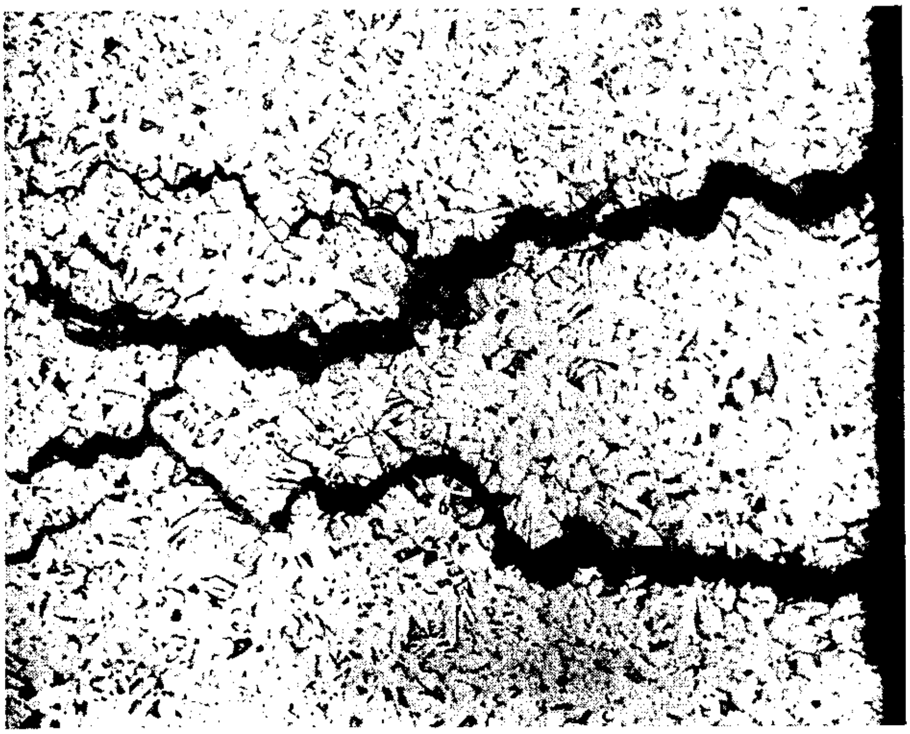

Fig. 11—Section through Tube Wall, B39, showing detail of Intergranular Cracking

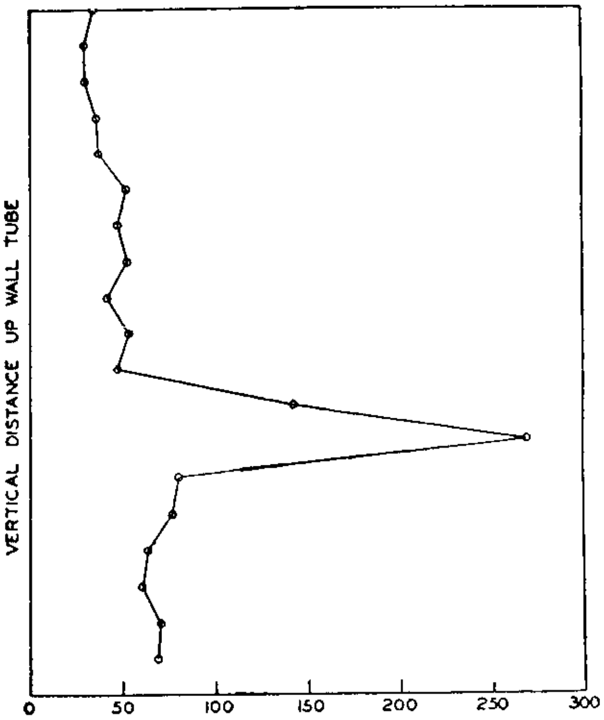

Fig. 12—Evidence of Hot Spot in a 50-ft Vertical Water Wall Tube

the residual stresses. The high residual stresses from fabrication by extrusion and the local stresses from bending the tube would be relatively small after several years' operation, but would still be significant in relation to operating stresses.

The corrosive environment in this case, could only have been caustic from the boiler water. The caustic in this particular instance was by mistake at least twice the usual concentration. However, this increase is not considered too significant. It is true that the caustic concentration in boiler water is usually very low and is expressed in parts per million, commonly 200 p.p.m. This concentration is approximately 0·1 per cent of that required for aggressive attack.

That a hot spot can occur at a particular area on a tube was shown by Davidson and associates(2) who used thermocouples to study various conditions. Their findings of a zone of severe overheating is shown in Fig. 12. They considered this resulted from ' steam blanketing ' following flame impingement.

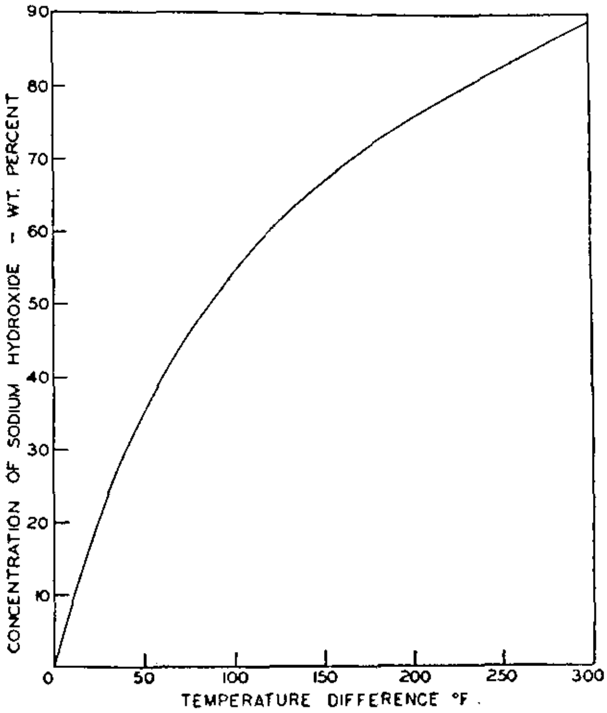

FIG. 13—CAUSTIC CONTENT ATTAINABLE IN CONCENTRATING FILM OF BOILER WATER (BASED ON DATA FROM INTERNATIONAL CRITICAL TABLES, 3, 370 (1928))

FIG. 13 indicates how rapidly the caustic content in the concentrating film boiler water can rise with a small increase of temperature above that of the overall boiler water. A 100 degree F. rise corresponds to 50 per cent caustic in weight per cent. The net effect may be ' equivalent to continuous exposure of the hot steel to a corrosive caustic liquor, even though the main body of boiler water contains but a few parts per million hydroxide '.(3)

The intergranular attack which results from these conditions is commonly known as ' caustic cracking '. Although it is difficult to reproduce operating conditions in the laboratory, instances of cracking taking place in hours rather than days are recorded(4, 5).

The study of boiler-seam cracking by the Joint Research Committee on Boiler Feedwater Studies and the U.S. Bureau of Mines, as reported by Berk and Waldeck(6), indicates a danger zone above 180 degrees F. and 15 to 43 per cent caustic. The probability of crack development in this zone was 40 per cent. Weir(7) reported failure of specimens exposed to solutions of less than 10 per cent caustic, although he states that more concentrated solutions are more effective.

Stress Corrosion Cracking Mechanism

In view of the many statements in the literature that the fundamentals of the caustic cracking phenomenon remain obscure, it may be instructive to assemble a few ideas.

Zapffe(8) made a strong argument that boiler embrittlement is an aspect of intergranular hydrogen attack, and in the consequent vigorous discussion to Zapffe's paper, Mears(9) advanced the opinion that caustic cracking and stress-corrosion cracking are fundamentally the same. The attack in stress-corrosion cracking is electro-chemical, i.e., potential difference between anodic and cathodic areas of the metal causes electro-chemical corrosion which appears, in these instances, as cracking at grain boundaries. Mears indicated that the stress-corrosion cracking of duraluminium-type alloys, the season-cracking of brass and the stress-corrosion cracking of 18-8 stainless steel had either been proved(5), or indications were fairly definite, that the mechanism responsible for all was electrochemical differences in potential causing selective attack at certain planes in the metal. Mears suggested that establishment of the mechanism of caustic cracking might be readily undertaken by attempting to cathodically protect a readily embrittled boiler steel. Investigation of the effect of cathodic protection on cracking was also suggested by a leading technical committee(10).

This confirmation of the true mechanism of caustic cracking has been reported. Pearson and Parkins(11), studying the stress-corrosion of mild steel subjected to boiling nitrates, showed conclusively the electrochemical nature of the action. When a sample of the steel was made the anode in a system subject to

200 ma per/sq in., cracking was produced in one-thirtieth of the time (30 minutes vs. 15 hours) and was much more extensive than cracking in the absence of current. When the mild steel was subject to the same conditions, but as the cathode instead of the anode, no cracking whatsoever was observed.

Wier's(7) detailed study of the fundamentals of caustic cracking also has shown that anodic currents decrease time to failure (this was in 50 per cent sodium hydroxide at 280 degrees C.) and that cathodic polarization is effective protection.

It would appear logical, then, on the basis of the experimental proof cited above, to include caustic cracking among the electrochemical corrosion phenomena known as stress-corrosion cracking.

CONCLUSIONS

An unusual type of failure of marine boiler tubes has been discussed. It is considered the weakening of the tubes prior to the final burst (of tube A25) and partial rupturing of several other tubes was due to caustic cracking.

Caustic cracking, a special case of stress-corrosion cracking, requires that the metal be subject to tensile stresses in a corrosive medium. It has been indicated that stresses were present, and that conditions were such that the necessary concentration of caustic could be attained right on the steam-generating surface of the tubes.

Research by others has shown that stress-corrosion cracking of metals is essentially electrochemical. Application of external current by these investigators has proved the electrochemical nature of stress-corrosion cracking. Samples which were made anodic were cracked extremely rapidly, whereas the cathodically protected samples could not be cracked.

Admittedly, the type of failure here discussed is rare, nevertheless, it can occur.

To prevent a recurrence of this type of failure, attention was directed to avoiding clogging, which can apparently channel hot gases. Some thought was also given to alternative boiler treatments which avoid caustic.

THIRD CASE HISTORY

This failure, in a converted minesweeper, involved the investigation of two leaking tubes and a third tube, sorted out from several others by radiography. The three tubes were, in order detected, A30 R.H., A28 R.H., and A31 L.H. The tubes involved were close to the back wall in an Admiralty 3-drum boiler having 32 tubes in the ' A ' rows.

A first step in this investigation was to determine the location and distribution of cracks in the two tubes known to be leaking. This was accomplished by radiography, with results shown in FIG. 14. An additional five tubes, some of which had been removed from the vicinity of the two leaky tubes, and others from random locations in the 'A' rows, together with 11 tubes from the other

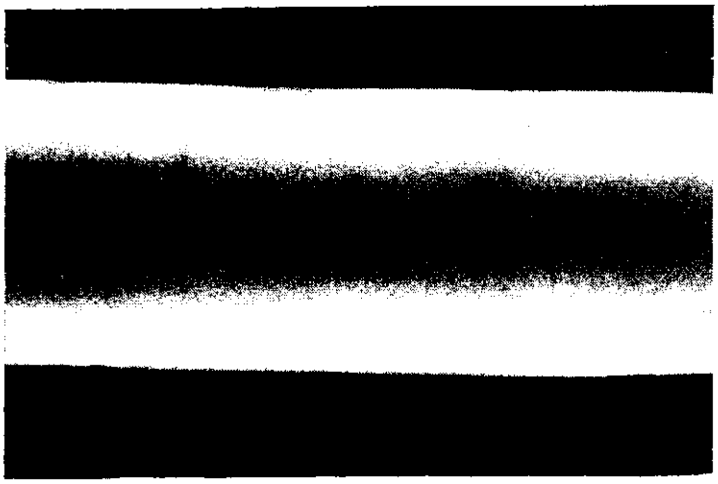
FIG. 14—RADIOGRAPH OF PART OF THE CRACKED ZONE ON A30

Fig. 15—Radiograph showing Fine Cracking on A31. Note that these are all Transverse

Fig. 16—Typical Internal Deposit. This is of A28 where one crack perforated

boiler were also radiographed. This radiography identified the third tube with cracks. In all three tubes the damaged area was confined to the lower two feet. The radiography also indicated that there was a difference in the type of cracking in A30 and that in the other two tubes, A28 and A31 (Fig. 15). In addition, a mottling was noted in the radiographs which, on later splitting of the tubes, was related to the internal deposits shown in Fig. 16.

In view of the information derived from radiography, it was decided to extend its use into both boilers of this ship to ascertain to what extent other fire row tubes were affected. The radiography was confined, for practical reasons, to 'A' rows and was not 100 per cent complete.

It was noted by those engaged in the radiography in the boilers, that a predominantly carbon residue had formed on the lower few feet of the last five to six tubes of all 'A' rows, i.e., in the tubes centred about A29-A30. The distribution of this deposit was strongly suggestive of spray from the fuel nozzles.

No further cracking was detected by radiography in the tubes in the boilers. This was a valuable finding because it obviated an apparent need to re-tube the boilers to ensure freedom from tubes with unknown degrees of cracking.

Metallurgical Examination

Sections were cut from each of the three affected tubes to permit detailed examinations of the nature of the cracking. Sections were also cut from non-affected tubes for comparison.

Although there were basic characteristics among the three tubes which indicated a somewhat similar mechanism, there were variations in detail that suggested it might be useful to deal with A30 R.H. and then with A28 R.H. and A31 L.H. together.

*Tube A*30 *R.H.* A low magnification, longitudinal section (i.e., to show transverse cracks) is shown in Fig. 17. Among the points which may be noted are :—

FIG. 17—SECTION THROUGH WALL OF A30 SHOWING TRANSVERSE CRACKS

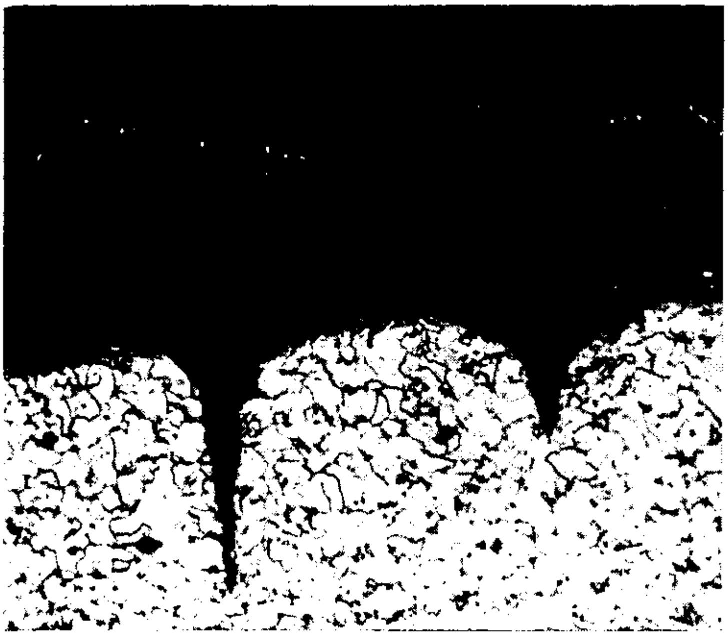

FIG. 18—DETAIL OF FIG. 17. NOTE CRACKS IN OXIDE (BRIGHT PARTICLES ARE COPPER)

(i) The incidence of cracks — rather numerous.

(ii) Great distribution in depth (five cracks, although not shown here, went right through in the 2-ft length affected)

(iii) Negligible penetrating action on the outer surface.

A close-up of one of the cracks is shown in FIG. 18. From this, additional details may be noted :—

(iv) The cracks are generally insensitive to grain boundaries (although an occasional fine branch showed such sensitivity)

(v) There is generally little, if any, oxide in the larger cracks

(vi) There is generally an oxide layer on the tube surface (water side) in which are scattered particles of copper. The layer was thin—approximately 0·0012 in.—and in some areas almost one-third of it was copper particles.

As shown in FIG. 18, there appears to be some correlation between cracks in the oxide layer and the beginnings of a crack in the metal. This is confirmed in FIG. 19, in which are shown ‘ embryo ’ cracks—the earliest stages in corrosion of the tube, the formation of cracks in the oxides, and the apparent pointing-up of the general oxide layer at the location of these cracks—in fact, the initiating points of cracks in the tube wall. There is no copper in this microsection.

The sequence of oxide formation, crack in oxide, and then crack in the metal, was also indicated in sections cut transversely, i.e. showing the longitudinal cracks.

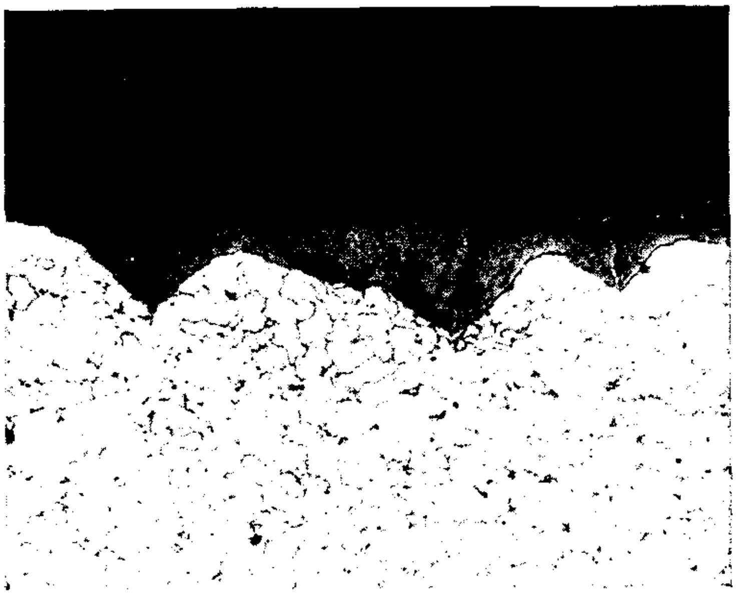

FIG. 19—SIMILAR SECTION TO FIG. 18 SHOWING EARLIER STAGE IN CRACK FORMATION. NOTE CRACKS IN OXIDE LAYER

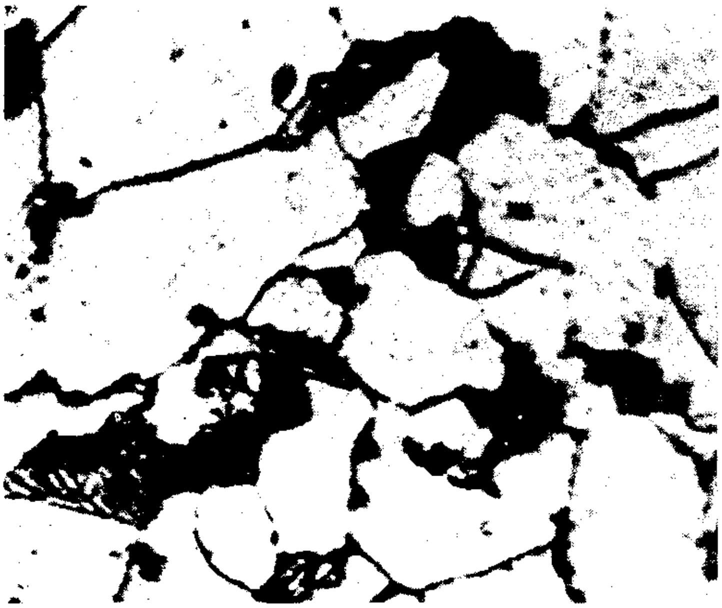

FIG. 20—STRUCTURE OF NON-AFFECTED TUBE A29. DARK AREAS ARE KNOWN AS PEARLITE (650 ×)

An additional factor, to be noted in several of the preceding photomicrographs (e.g., FIG. 19) is :

(vii) The absence of pearlite (a darkly-shaded constituent in steel) and in its place, small particles of ' spheroidized carbide '.

At first this was assumed to be the usual structure, but it soon became apparent when other tubes were examined that they had structures which contained pearlite, as in FIG. 20. Metallurgically this spheroidized structure indicates lengthy exposure to temperatures of 902 degrees F. or higher. For example, approximately 15 hours at 1,200 degrees F. will spheroidize the microstructure in these tubes ; at 1,000 degrees F. it would require a period almost one thousand times as long.

Tubes A28 R.H. and A.31 L.H. A low magnification, longitudinal section (i.e. to show transverse cracks) is shown in FIG. 21. These two tubes, incidentally, were essentially free of longitudinal cracks.

Among points noted were :

(i) At least as many cracks, and possibly more, in some areas than A30

(ii) The distribution is limited to generally shallow cracks (only exception, the major one which perforated in A28). There was no perforation in A31.

(iii) Considerable and practically equivalent cracking on the outer surface (i.e., fire side) in contrast with A30, in which this was almost completely absent.

A close-up of one of the cracks (from A28) is shown in FIG. 22. Although some cracks in A31 and A28 are sharper, there are a number that show these characteristics:

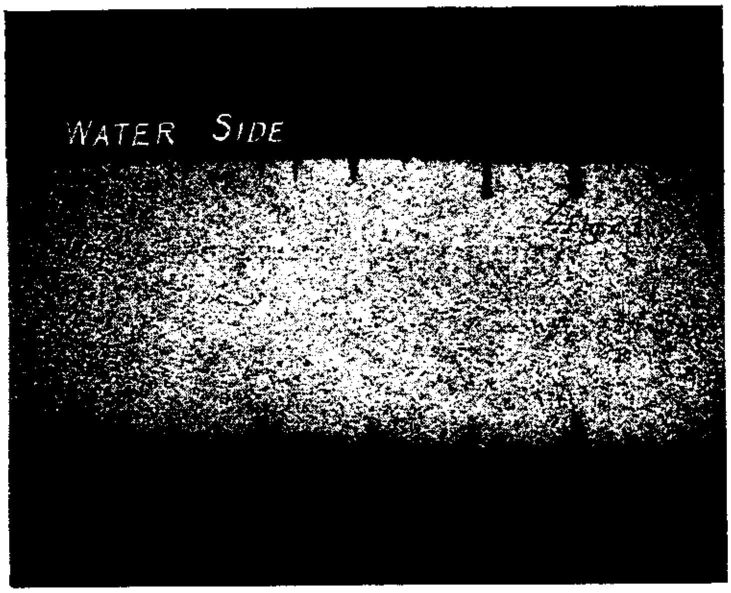

FIG. 21—SECTION THROUGH WALL OF A28 SHOWING TRANSVERSE CRACKS

FIG. 22—TYPICAL CRACK IN A28 SHOWING OXIDE ON SIDES AND ABSENCE OF SHARPNESS NOTED IN FIG. 18. THE SPHEROIDIZED MICROSTRUCTURE MAY BE NOTED

(iv) Generally wider and more oxide on the sides

(v) The rounded bottom suggests a termination of what had already been a more leisurely progress than for cracks in A30. It also indicates a corrosive action at work in enlarging the terminus (particularly FIG. 23).

Additional features noted in sections from these two tubes were :—

(vi) Although not shown in FIG. 22, the oxide layer on the water side was considerably thicker (10 to 15 times) than on A30, and it also contained scattered copper particles

(vii) The spheroidized microstructure readily observed in FIGS. 22 and 23

(viii) External wall cracks are similar to those on the water side.

As noted for tube A30, the cracks in these two tubes were also associated in instances with cracks in the oxide layer.

DISCUSSION

It has been shown that there are some decided differences in detail in the cracking of tube A30 R.H. versus tubes A28 R.H. and A31 L.H. The reasons for these dissimilar characteristics are not clear.

Overheating of these three defective tubes has been established. The initial belief that internal deposits were an important factor in this cracking was modified to a certain extent. Similar deposits were found on other tubes which were free of defects. That the deposits contributed to the overheating and cracking is a reasonable assumption ; that their presence did not necessarily result in cracking was also demonstrated.

lower reversal rate, i.e., 100 cycles/minute, it required 13,000 lb/sq in. to produce cracks—but these were thin, needle-like and not the same as those on the ship. Whether their results can be applied to the boiler tubes is questionable in view of different media, different temperatures, and that the specimens were rotating cantilever rather than long tubes subjected primarily to longitudinal pulsing. They tend to suggest, however, that corrosion fatigue was the phenomenon which caused failure of the tubes in the boiler.

There is little doubt that the cracking in A28 and A31 was a slower process than in A30, as evidenced by FIGS. 22 and 23. It would appear that the mechanical forces partly responsible for the cracking were not present, or only very slightly after a certain stage. At this point the corrosion component had a chance to proceed alone.

An additional factor which may have been influential in the accumulation of the deposits is slight oil contamination. This role of oil is described by Rivers$^{(14)}$: ' Anything that impedes rinsing is bad. Water-permeable deposits of any kind resist rinsing, and it is easy for boiler water to concentrate within the pores of such a deposit. For example, a boiler may remain quite clean under ordinary operating conditions. But suppose a small amount of oil contamination turns up sometime and causes a thin layer of oil-bound sludge to stick to certain steaming surfaces. Evaporation of boiler water within the pores of this adherent sludge might lead to complex silicate scale or even caustic attack of the metal. Similar effects might be produced by dissolved iron in the feedwater or the presence of any other binding substance that can form porous deposits. Failure through overheating or corrosion might thus occur at relatively conservative rates of heat input and in spite of excellent control over boiler water chemical concentration in general.'

The function of copper in these deposits and in the cracking appeared to be incidental. In general, copper particles were scattered randomly and were absent in the ' younger ' oxide layers and in the corrosion products in the cracks. It was noted, in some sections, that there were two oxide structures with a moderate sprinkling of copper particles at the interface between the two layers. This suggests extensive time periods when the chemical environment was different. It does not appear that these changes were harmful aside from the deposits which resulted.

The degree of spheroidization in the three tubes parallel the degree of cracking :

A30 complete, and five cracks which perforated;
A28 practically complete, and one crack which perforated;
A31 almost complete (less than A28) and only shallow cracks.

This may be taken to suggest three different flow rates in the three tubes or onset at three successive times. The net effect is of a non-simultaneous deterioration.

The external cracking in A31 and A28 (FIG. 21) but absent in A30, is a little strange. It probably was the result of a similar mechanism to that which cracked these tubes internally, but high temperature oxidation rather than corrosion was the mechanism by which it progressed from cracks in the oxide scale.

Attention to improving circulation by having cleaner tubes, and to better firing of the oil, by periodic checking of nozzles, seem practical steps to avoid a recurrence.

Considering that the tubes in W2 boiler were 15 years old and were, apparently, good for an indefinite period into the future, particularly so after chemical cleaning, there was reason to consider these three tubes as isolated instances.

CONCLUSIONS

The evidence observed metallurgically indicates that the tubes failed by corrosion fatigue.

Overheating was a common factor and could have been responsible for the following :

(*a*) It changed a non-aggressive environment to an aggressive one. On surfaces with an excessive rate of steam generation the net effect was that of concentrating the boiler water and it was then corrosive to steel(15).

(*b*) With more overheating to the point where steam blanketing resulted, there occurred an additional slowing of mass flow, which in turn was harmful.

(*c*) Expansion and contraction may have produced the cyclic stresses which caused the cracking. Contractions against restraint can produce stresses in the order of several 10,000 lb/sq in.

It was evident that the mechanisms were not exactly the same for A28 and A31 compared with A30. Reasons for this were not established but might be connected with type and intensity of stresses.

It was indicated that the remaining tubes could be expected to give good service, and that chemical cleaning and periodic checking of nozzle adjustment would be beneficial.

Acknowledgement :

The permission of the Defence Research Board of Canada to publish this paper is hereby acknowledged.

References:

(1) Copson, H. R. ' The Influence of Corrosion on the Cracking of Pressure Vessels ', *Welding J.* (Feb., 1953) 75s-91s ; *Corrosion*, **10** 124-139 (1954).

(2) Davidson, W. F. ; Hardie, P. H. ; Humphreys, C. G. R. ; Markson, A. A. ; Mumford, A. R. and Ravese, T. Studies of Heat Transmission Through Boiler Tubing at Pressures from 500 to 3,300 Pounds. *Trans. ASME* (August, 1943) 553-591.

(3) The Corrosion Handbook, John Wiley & Sons (1948) 529.

(4) Symposium on Stress Corrosion Cracking of Metals, ASTM, AIME (1944).

(5) Mears, R. B., Brown, R. H. and Dix, Jr., E. H. A Generalized Theory of the Stress Corrosion of Alloys, ASTM, AIME Symposium (1944) 323-339.

(6) Berk, A. A., Waldeck, W. F. Caustic Danger Zone, *Chem. Eng.* **57** (June, 1950), 235-238.

(7) Weir, C. D. Caustic Cracking : Stress-Corrosion Tests in Sodium Hydroxide Solutions at Elevated Temperatures. *Proc. Inst. Mech. Eng.* (1950) 18-23.

(8) Zapffe, C. A. Boiler Embrittlement. *Trans. ASME.* (Feb., 1944), 81-117.

(9) Mears, R. B. Discussion to Zapffe (8), p. 122.

(10) Stress Corrosion Cracking in Alkaline Solutions. *NACE, T.P. Committee 5C, Corrosion*, **7**, 9 (Sept., 1951), 295-302.

(11) Pearson, C. E. and Parkins, R. N. Stress-Corrosion Cracking in Welded Steel Structures. *Welding Research* **3**, 6 (December, 1949), 95r-106r.

(12) Wescott, B. B. Article, ' Corrosion Fatigue ' in the Corrosion Handbook, Uhlig. John Wiley & Sons (1948), 578-590.

(13) McAdam, D. J. Jr., and Geil, G. W. ' Influence of Cyclic Stresses on Corrosion Pitting of Steels in Fresh Water and Influence of Stress-Corrosion on Fatigue Limits'. *J. Research National Bureau of Standards*, **24** (1940), 685.

(14) Rivers, H. M. ' Concentrating Films : Their Role in Boiler Scale and Corrosion Problems '. Proc. 12th Annual Water Conf. of the Eng. Soc. of Western Pennsylvania (1951), 131-145.

(15) The Corrosion Handbook, Uhlig. John Wiley & Sons (1948), 526-531.

COMMENT BY D.M.E.

The appearance of this article at this particular time is of special interest because in a recent case of two boiler tube failures in an H.M. ship, the first failure showed evidence very similar to that of the second case in the article, and the second boiler, a few hours later, produced the symptoms of the first case.

It is of further interest that the subsequent investigation in association with the Central Dockyard Laboratory produced conclusions in each case very similar to those described in the article, even to the extent of the initial cause of the excessive steam generation in the first case not being clear.

FIG. 23—DETAIL OF ONE OF THE CRACKS SHOWN IN FIG. 21. THE ROUNDED BOTTOM IS UNUSUAL AND SUGGESTS ABSENCE OF STRESS AFTER A TIME

In a similar fashion, the evidence of an external carbon residue on the three tubes indicated a source of extra heat : the quick temperature rise likely from oil being burned right on the tube surface. Certainly the three tubes were from the zone affected, nevertheless other, immediately adjacent tubes were also similarly exposed but were not affected.

It would appear that some additional factor was operating to give these three tubes generally higher temperatures than their neighbours : temperatures sufficiently high and held long enough to produce ‘ spheroidization ’. Only one possibility suggests itself : that circulation of water (and steam) was in some way hampered for considerable periods. If it is assumed that circulation in tubes in the A30 zone was not necessarily as good as in other areas, then it is possible to visualize a situation where, once slightly more than normal steam generation occurred (by slight overheating), an increasingly deteriorating situation would follow.

The extreme example of this state of affairs was tube A30 which was most severely cracked and also had a slight film of white crystalline salts over the affected area. The appearance and distribution of the fine deposit strongly suggested a zone of excessive evaporation. This type of behaviour, i.e., an excessive local rate of steam generation which can result in local supersaturation and deposition of boiler salts, is described by Davidson and associates(2). These investigators established by actual measurement that temperatures as much as 200 degrees F. greater than normal can develop in a local area in an operating boiler. On this hot surface a high rate of steam production gives rise to ‘ steam blanketing ’ which in turn tends to further overheat the tube and also to slow down circulation. The factors here involved suggest that while A30 was subject to much the same conditions as A28 and A31, it must have, in addition, been adversely affected by the further interference with flow resulting from the ‘ steam blanketing ’. During these periods of excessive temperature in A30, the stresses from internal pressure probably resulted in the slight longitudinal bulging and, on other occasions, contributed to the cracking.

Calculations show that stress developed in an 8 ft long tube under restraint, for a 200 degrees F. temperature rise approximates 36,000 lb/sq in. The tubes in this boiler had, of course, considerable flexibility but some development of longitudinal stresses seems feasible.

It may be of some interest to refer briefly to the work on corrosion fatigue of McAdam and Geil(12, 13) who obtained cracking identical with that shown here in FIG. 18. Their work with rotating cantilevered specimens of mild steel in well water produced a great many detailed results. Among these, their photomicrographs show cracks, after a 10-day exposure at 9,000 lb/sq in. to 1,400 cycles/minute, similar to those in the minesweeper's tubes. The fissures reported by McAdam and Geil all started at irregularly rounded corrosion pits. At a