BOILER DAMAGE EVALUATION

FOLLOWING AN INCIPIENT STEAM-STEEL REACTION

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Introduction

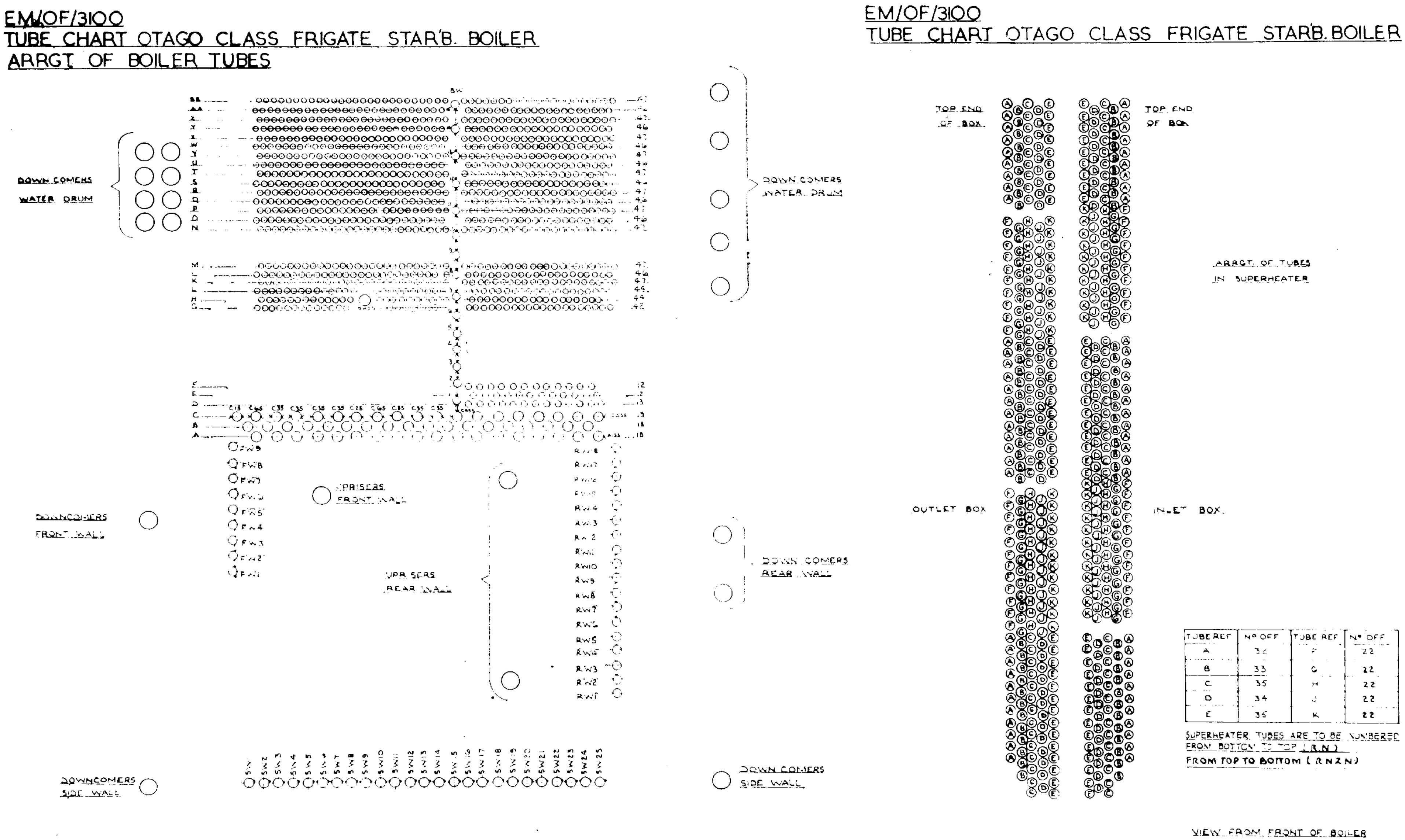
As a result of an unfortunate sequence of events in one of the Royal New Zealand Navy's Type 12 frigates, water starvation conditions in a starboard main Y.100 boiler were created. The consequent catastrophic failure was fully investigated by New Zealand Ministry of Defence Navy marine engineers and metallurgical staff. The findings from the incident are presented in this article which is an abridged version of the original metallurgical report submitted to the Naval Board.

Frequent reference is made to the tube numbering system in accordance with BR 3100, Tube Identification Chart. FIG. 1 was reproduced from BR 3100, with with minor modifications to facilitate the disposition of tubes in a Y. 100 boiler

VISUAL EXAMINATION IN SITU

Preliminary visual investigation gave the impression that the damage was localized to tube A.8 and its nearest neighbours with only superficial damage sustained by some of the other tubes (FIG. 2). However, any thoughts of a short and simple repair plan were dispelled as the investigation progressed.

Examination showed that generator tube A.8 had ruptured and had also been physically forced out of alignment into the tube nest. Tubes A.1 to A.5 and A.11 to A.18 showed clear demarcation lines above which there was deep blue scale; also tubes A.11 to A.15 showed severe blistering on the fire-side surfaces whereas below the line there was a uniform black scale.



TUBE REF	N° OFF	TUBE REF	N° OFF
A	34	F	22
B	33	G	22
C	35	H	22
D	34	J	22
E	35	K	22

SUPERHEATER TUBES ARE TO BE NUMBERED FROM BOTTOM TO TOP (R.N)
FROM TOP TO BOTTOM (RNZN)

FIG. 1—TUBE IDENTIFICATION CHART FOR Y.100 STARBOARD BOILER

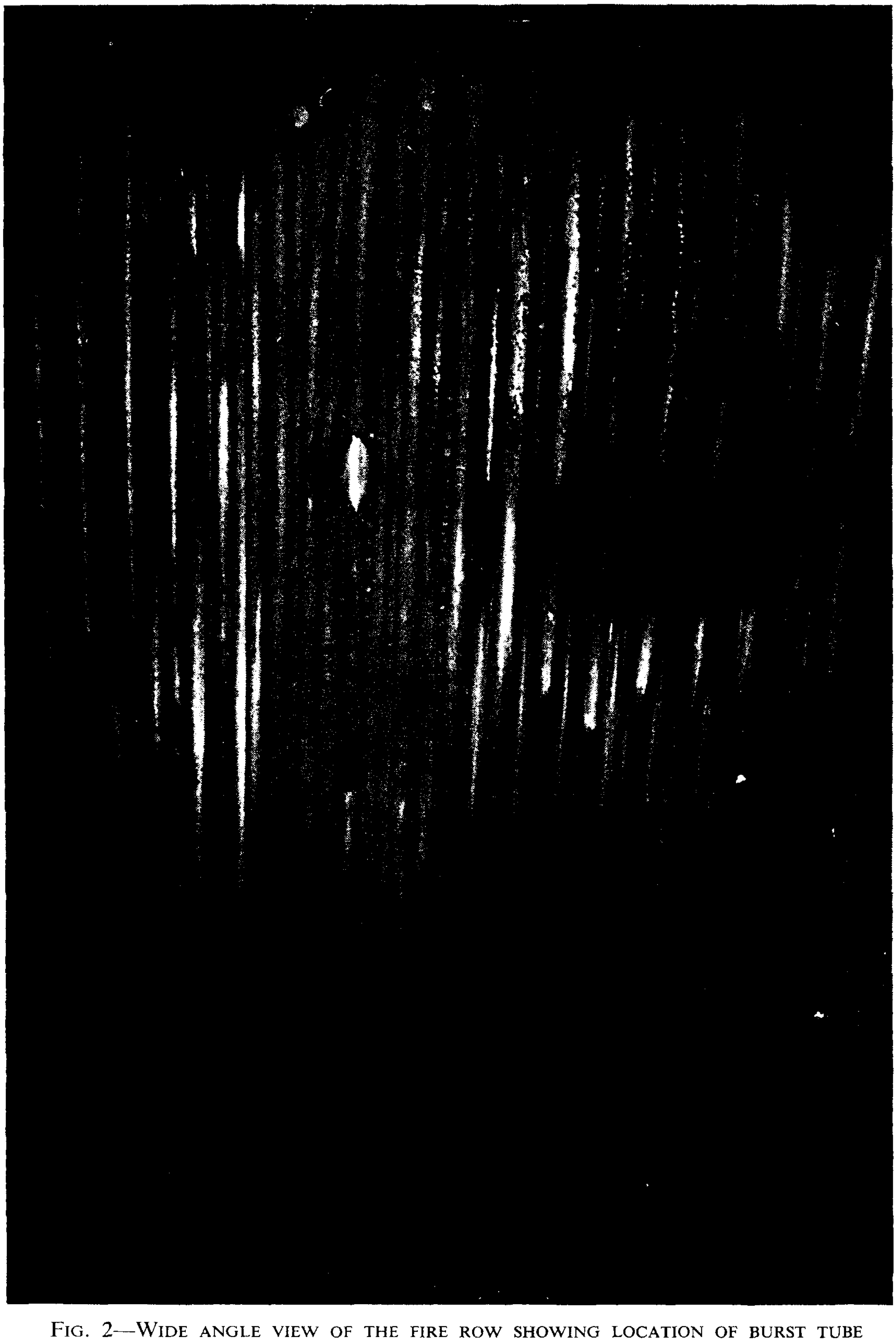


FIG. 2—WIDE ANGLE VIEW OF THE FIRE ROW SHOWING LOCATION OF BURST TUBE

FIG. 3—DETAILED VIEW OF THE BURST TUBE A.8
Note the intergranular disintegration and the heavy scale of the inner surface opposite the split.

Tubes A.6 to A.10 appeared completely clear of scale and were coated with a light brown rust, which appeared newly-formed.

The superheater tubes were clearly visible and the upper banks of these, in the area near the baffle wall, were also coated with a deep blue scale.

The brickwork inside the firebox appeared to be in good condition and was dry. The portion of water wall tubes which were visible appeared to be heavily scaled.

PRELIMINARY EXAMINATION

Tube A.8

The burst tube, A.8, was extracted from the boiler and submitted for detailed metallurgical examination to ascertain if the material complied with the specification and the cause of failure.

A close-up photograph of the failure, taken before any testing, is shown in FIG. 3. The fracture was typical of a high temperature creep failure showing characteristics of inter-granular disintegration of the material, whose creep resistance was reduced by overheating, to a stage when the steam pressure could no longer be supported. Also there was a heavy tenacious scale present on the inner surface of the tube, opposite the split.

Testing Schedule

The lower section of the tube, which had not suffered unduly, was tested and found to comply with the specification for generator tubes, namely DGS 6140A, Type 1, which is based on BSS 3059/2 1958, except for the expanding test where the DGS specification demands a greater increase in diameter.

Tests were carried out as follows:

Tensile test in accordance with BSS 3059/2 1958

Elongation test in accordance with BSS 3059/2 1958

TABLE I—*Physical Tests*

	Tube A.8	*Specification*
Max. tensile stress	23·2 tsi	20·0 min.
Elongation percentage on gauge length $4\sqrt{A}$	46	$\frac{700}{UTS}$ (min 30·2)
Flattening Test	Pass	—
Expanding Test	Pass	—

TABLE II—*Chemical Analysis*

	Tube A.8	*Specification*
Carbon (percentage)	0·14	0·15 max
Manganese (percentage)	0·51	0·30/0·70
Sulphur (percentage)	0·029	0·050 max
Phosphorus (percentage)	0·017	0·050 max

TABLE III

		Below	*Above*	*Increase*
Dimensions	O.D.	2·004	2·064	0·060 in.
	I.D.	1·750	1·825	0·075 in.

Flattening test in accordance with BSS 3059/2 1958
Expanding test in accordance with DGS 6140A, Type 1
Chemical analysis

The results of the physical tests and the chemical analysis are shown in TABLES I and II respectively.

Extended Testing on Tube A.8

Further test pieces were taken at approximately 12 inches above and 12 inches below the burst. These samples were checked for dimensional changes (TABLE III) and were also subjected to the flattening and expanding tests. Additional representative metallographic samples were taken at these locations in the longitudinal and transverse direction with respect to the tube.

The samples failed to pass the flattening and expanding tests and exhibited features in the failures worthy of note. In the sample taken from below the failure, the expanding test showed a discontinuity in the form of an offset along the line of fracture which was indicative of a fault in the material, possibly a non-metallic inclusion or lamination. The expanding test on the sample from above the split revealed a mode of failure characteristic of embrittlement.

The failures are shown in FIGS. 4 and 5.

FIG. 4—FLATTENING TEST RESULT—TUBE A.8

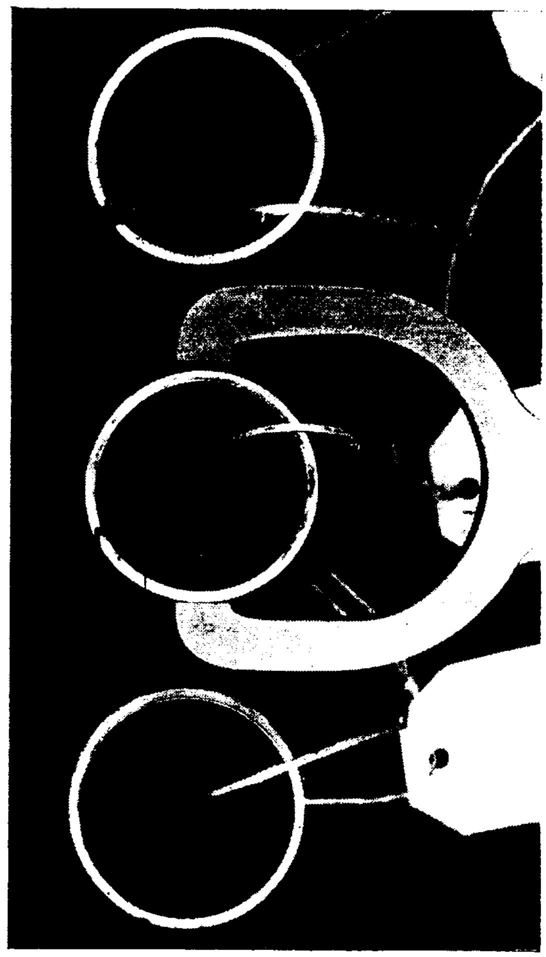


FIG. 5—EXPANDING TEST RESULTS, TUBE A.8, ILLUSTRATING THE DIFFERENT CHARACTERISTICS OF THE FAILURES ABOVE AND BELOW THE BURST

Results of the Microscopic Examinations

Above the fracture the structure was of an acicular nature. (See FIG. 6). This structure can only be achieved by heating this steel to a temperature in the region of 800 degrees C and this must be followed by a severe quench from above 700 degrees C.

There were also some lines of non-metallic inclusions, which are clearly illustrated in FIG. 7.

FIG. 6—PHOTOMICROGRAPH OF THE MICROSTRUCTURE OF TUBE A.8, 12 INCHES ABOVE THE BURST (× 500)

The acicular pattern is typical of heating in the region of 860 degrees C, followed by severe quenching from above 700 degrees C.

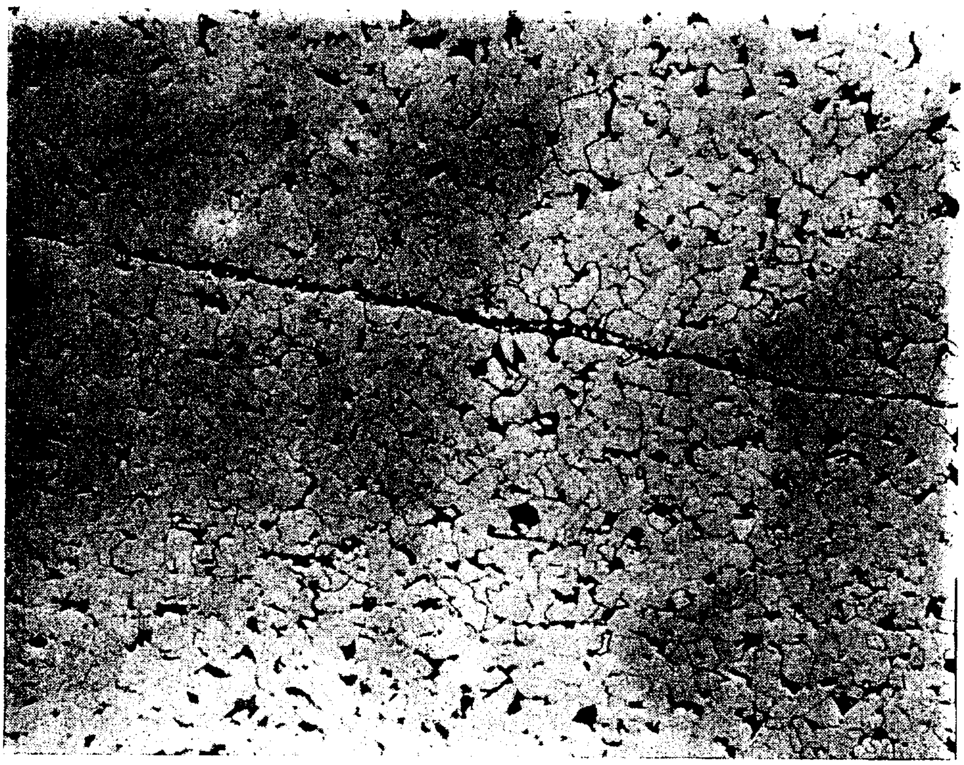


FIG. 7—PHOTOMICROGRAPH SHOWING NON-METALLIC INCLUSION AND THE STRUCTURE OF THE TUBE A.8, 12 INCHES BELOW THE BURST (× 100)

Below the fracture the structure, as expected in this instance, was typical of a normalized steel, with a tendency to banding which is due to the manufacturing processes. However, there were indications of the presence of laminations which have already been described and illustrated in FIG. 7. The presence of the lamination could have contributed towards the failure but micro-examination of a complete cross-section of the tube confirmed that no fracture had propagated from this defect which, in fact, was directly opposite the rupture, and therefore had not influenced the failure in any way whatsoever.

Comments

It was considered at this stage that the tube A.8 had originally complied with specification DGS 6140A and that failure was due to overheating of the tube resulting from water starvation.

This is supported by the facts that:

(*i*) The temperature required to produce the structure found above the failure could not have been achieved if water had been present.

(*ii*) The amount of increase in the dimensions of the tube showed that the temperature reached was sufficient to allow plastic deformation of the metal to take place under normal internal pressure. (The history of the boiler showed no record of steam pressures in excess of nominal working conditions.)

(*iii*) The amount of scale on the bore of the tube in the area of the burst also indicates a lack of water, as scaling to this depth would not be expected under water at normal operating temperatures. Furthermore, the unusually heavy scale was not consistent with the short service life of the tube, which had been renewed at a recent refit and had been under steam for only a few brief trials.

The explanation which fits the evidence strongly suggests that the formation of this scale was due to 'iron burning in steam'. This reaction commences at a temperature of 700 degrees C (1292 degrees F).

The chemical reaction taking place is:

$$3Fe + 4H_2O = Fe_3O_4 + 4H_2$$

This reaction is 'exothermic', i.e., it produces heat and is self-sustained until such time as:

(*a*) The temperature is reduced below 700 degrees C, /or

(*b*) All the iron is oxidized, /or

(*c*) The steam supply ceases.

The liberation of hydrogen also gives cause for concern because of the possibility of hydrogen embrittlement following absorption by the steel. This is aggravated when the hydrogen is in its nascent state at elevated temperatures and pressures.

It was considered that the laminations shown in tube A.8 were originally non-metallic stringers aggravated by hydrogen. Nascent hydrogen can diffuse through solid steel but will tend to migrate into structural imperfections where molecular hydrogen gas is formed, creating extremely high pressure pockets. This can result in the enlargement of cavities occupied by inclusions.

LIMITED SURVEY OF BOILER TUBE SYSTEM

Tubes A.12 and A.17

At this stage it was considered that examinations should be carried out on additional boiler tubes to determine the extent of damage, if any, to other parts

TABLE IV

	A.12		*A.17*	
	Upper	*Lower*	*Upper*	*Lower*
Max tensile stress t.s.i.	27·02	25·74	26·65	25·96
Elongation percentage on 2 in. G.L.	55	60	53	53
Flattening test	Pass	*VSC	Cracked	Pass
Expanding test	Pass	Pass	Pass	Pass
O.D.	2·006	1·989	2·025	1·988
I.D.	1·745	1·725	1·765	1·725

*VSC = Very Slight Cracking

of the boiler. Accordingly tubes A.12 and A.17 were removed and submitted for tests.

Tests were carried out as previously outlined for tube A.8. As the tubes clearly indicated visual differences between the upper and lower sections, samples were taken from these areas for test.

The results obtained from these tests are shown in Table IV.

The fragmentation and breaking away of surface layers during the expanding test made it clearly evident that the upper samples were coated with very heavy scale which was absent at the lower ends of the same tubes. The severity of scaling to a depth of 0·003 in. on the inside of the tube (water-side) is illustrated in FIG. 8. It was also noted from the photomicrograph that initiation of inter-crystalline attack was present and this was attributed to the incipient burning reaction. The changes in the dimensions indicated that ballooning had taken place in the upper regions of the boiler tubes. The micro-structures also indicated that in the upper regions sufficient temperature had been reached to give re-crystallization. The cooling rate in these areas had been less than that experienced by tube A.8 but was sufficient to give a different structure from that of the original tube.

Comments

Examination of tubes A.12 and A.17 showed that:—

(*a*) The temperature attained in the upper portions of the tubes was excessive to the extent that re-crystallization of sound metal occurred and a burning reaction on the water-side as well as the fire-side tube surfaces had commenced.

(*b*) The heavy scale would render these tubes unserviceable because of the consequent decrease in heat transfer characteristics.

(*c*) The scale formation on the bore of the tube was excessive and did not seem to be compatible with either the short time that the furnace had been in service or the normal operating temperatures. However, this heavy scaling effect may be attributed to the steam-iron reaction.

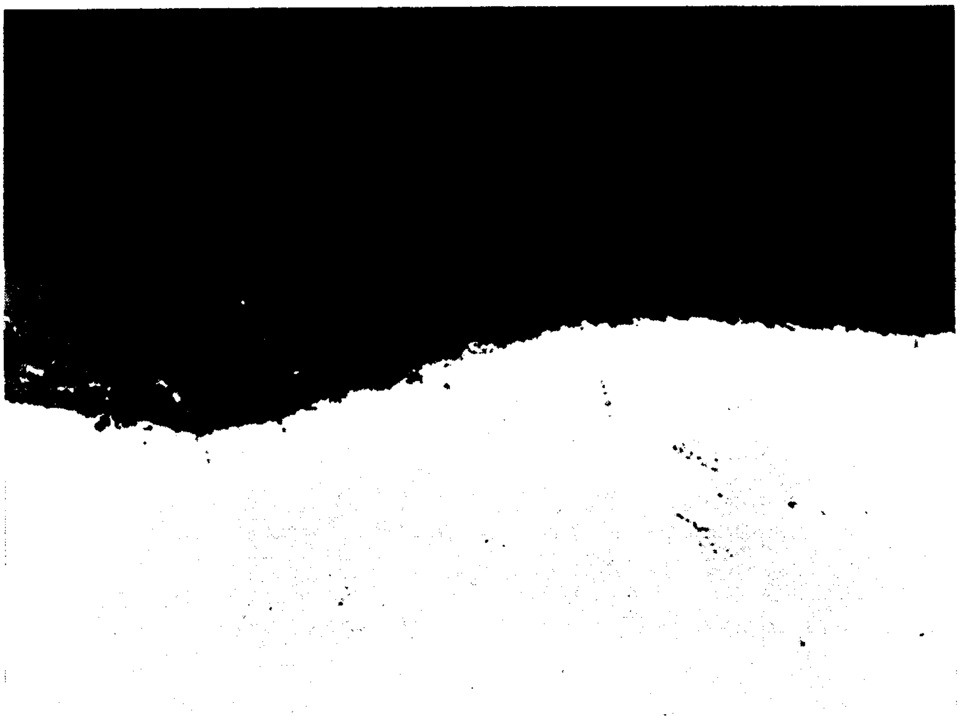


FIG. 8—SCALE ON THE WATER SIDE OF TUBE A.17 SHOWING INTER-CRYSTALLINE ATTACK AND THE HEAVY SCALE (0·003 IN.). SOME UNBURNT METAL CAN STILL BE SEEN ENTRAPPED IN THE SCALE (× 200)

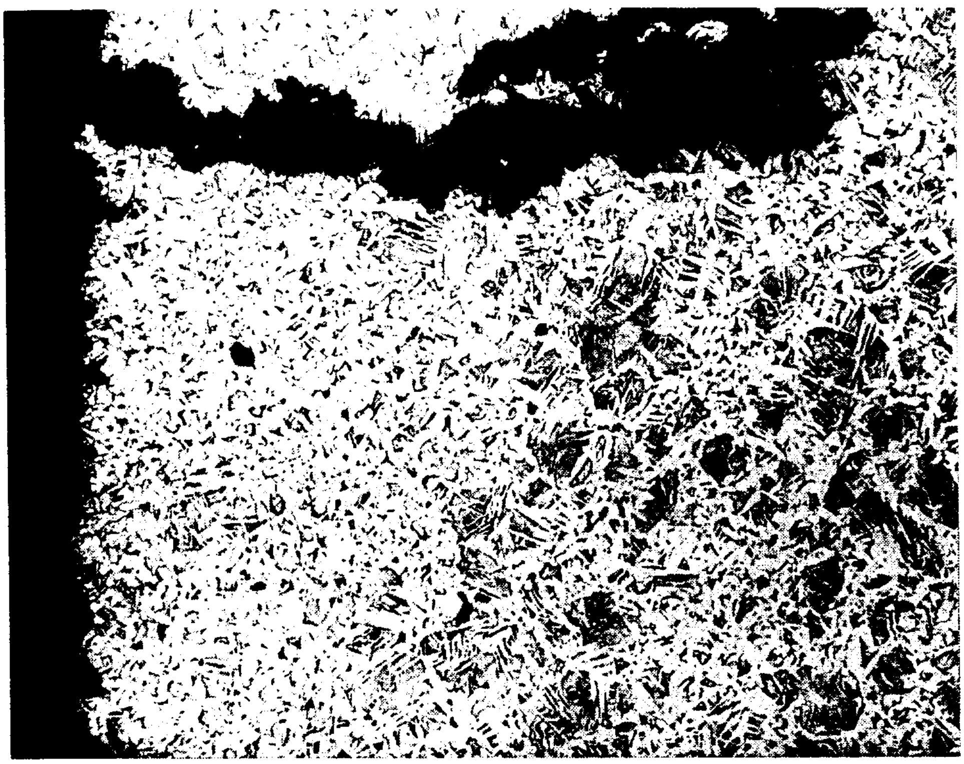


FIG. 9—TUBE A.6 AS QUENCHED STRUCTURE WITH CRACK 0·030 IN. DEEP EMANATING FROM THE BORE OF THE TUBE (× 100)

Tube A.6

At this stage a portion of tube A.6 which had large cracks clearly visible on the bore revealed by wear and waste testing was submitted for micro-examination.

A metallographic sample was taken longitudinally through several of the cracks. The photomicrograph, FIG. 9, illustrates one of the cracks discovered (approximately 0·030 in. in depth) and also shows the change in metallographic structure.

Comment

The structure of A.6 may be considered as representative of the state of tube A.8 immediately prior to rupture. The deep cracks emanating from the bore have been widened by creep and by the burning action as the cracks propagated.

Conclusion

The boiler tubes across the entire fire row had been starved of water resulting in a loss of heat abstraction. The high temperatures so obtained resulted in:

(*a*) Changes in metallographic structure;

(*b*) Formation of iron oxide scale on the outside;

(*c*) Formation of heavy magnetite scale on the bore;

(*d*) Dissociation of steam into oxygen and hydrogen;

(*e*) The possibility of hydrogen embrittlement;

(*f*) A metal burning reaction giving intergranular oxide penetration on all surfaces, the reaction being more severe on the water side.

Based on these facts, it was decided that samples be taken from various positions in the boiler in an attempt to assess the state of each section so that a firm decision could be made on the repair requirements.

OVERALL SURVEY OF BOILER TUBE SYSTEM

Tube SW.17

It was decided that side wall water tube SW.17 should be sampled and considered as representative of the studded water wall tubes of the three walls enclosing the fire-box. This tube was only partially exposed to the combustion gases, there being approximately a 1-inch wide strip of the tube exposed between the chrome ore refractory lining.

Visual examination showed that the surface of the tube which had been exposed was very heavily coated with a rough scale. The edges of the studs nearest to this portion also showed evidence of a severe heating effect. On the bore, a scale formation was clearly seen in the position corresponding with that portion on the outside of the tube which had been exposed to the combustion chamber.

Metallographic sections were prepared from the exposed and unexposed areas of this tube. The results were as follows:

(*i*) (*Exposed area*)
Micro-examination showed the sub-surface structure to be of an 'as quenched' acicular type. There were several deep intercrystalline and some transcrystalline cracks emanating from the bore (FIG. 10).

(*ii*) (*Unexposed area*)
Micro-examination showed the structure to be normal and there was no evidence of any severe scaling on the bore.

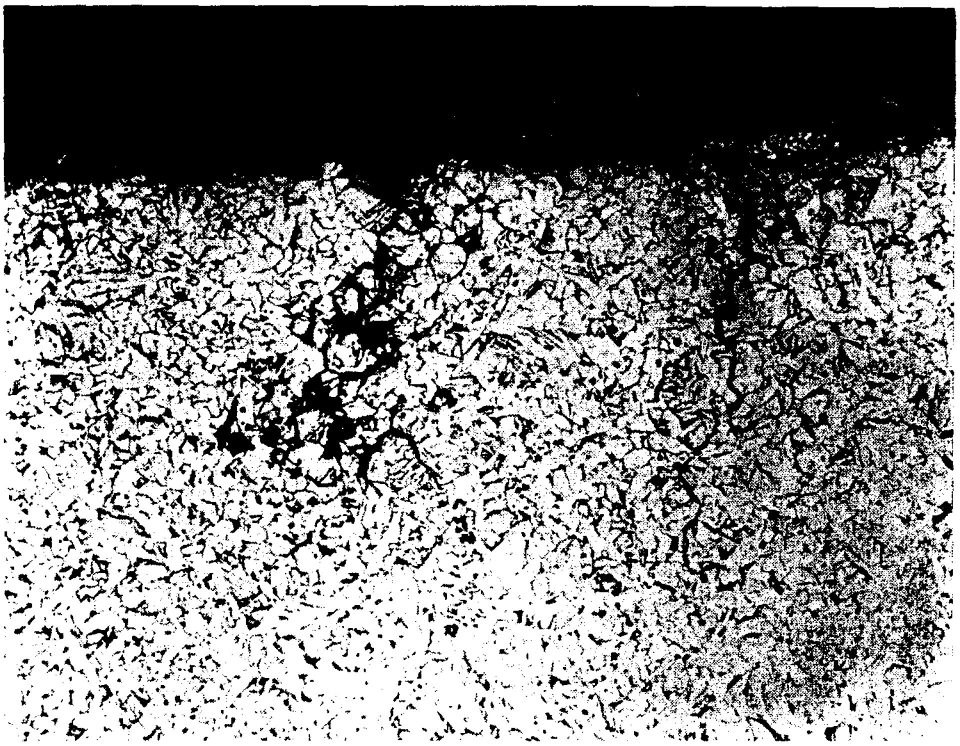


FIG. 10—SECTION THROUGH THE EXPOSED SIDE OF TUBE S.W.17 SHOWING INTER-CRYSTALLINE CRACKS EMANATING FROM THE BORE (× 100)

Comments

From the examination it was clearly seen that the part of the tube exposed to the combustion chamber had been severely overheated and quenched. The tube had been starved of water with resultant burning of iron to give the severe scale and the liberated nascent hydrogen diffused into the metal with eventual inter and transcrystalline cracking.

The following evidence was discovered in tube SW.17;

(*a*) The presence of layers of heavy scale, on the outside surface and on the bore.

(*b*) Variation in the structure with resultant residual stresses from front to rear of tubes.

(*c*) The presence of severe cracking, more than likely associated with embrittlement by hydrogen generated during the burning of iron in steam.

The decision to replace all water-wall studded tubes was based on the consideration that all studded tubes imbedded in the water walls of the fire box had suffered similar or a greater degree of damage.

Saturated Pass

A sample taken from the saturated steam pass, tube No. BB.37, was considered representative of this particular section of the boiler tube system.

Cross-sections which were taken from this tube, revealed that the microstructure was typical for cold drawn seamless low carbon steel, still showing the 'directionality' from the manufacturing processes. However, examination of the surfaces showed that there was some attack on the outside surface resulting in the formation of areas of scale, which were considered excessive for the number of hours steamed. The bore surface also showed distinct signs of intercrystalline attack which can be attributed to incipient burning of the iron in

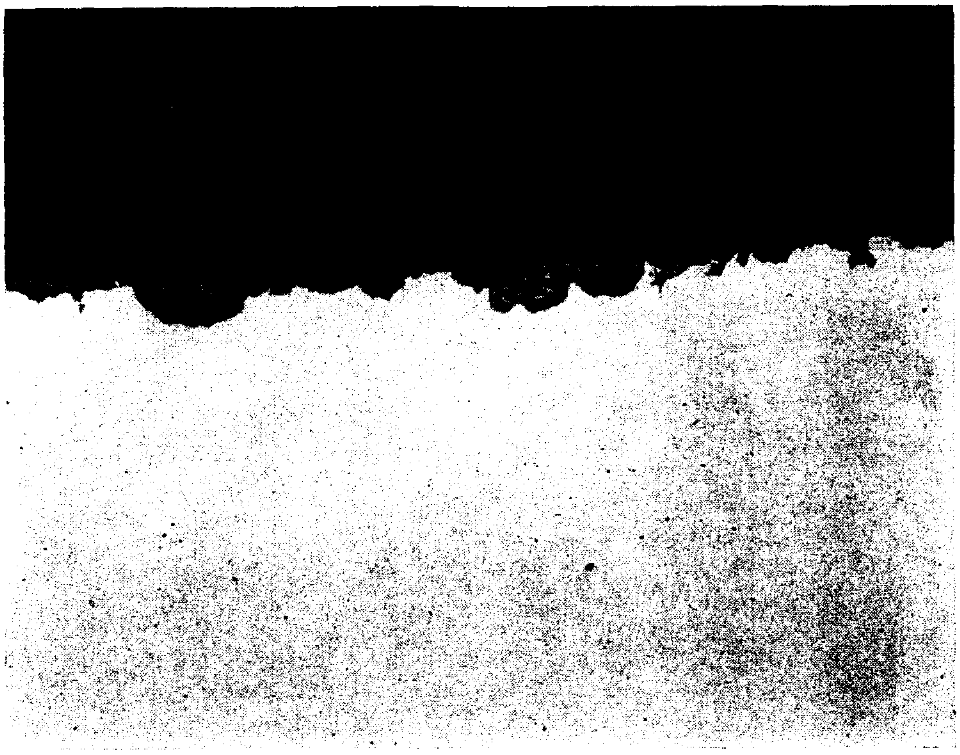


FIG. 11—MICROPHOTOGRAPH ILLUSTRATING THE SCALE AND ATTACK ON THE BORE OF TUBE B.B.37, ATTRIBUTABLE TO THE IRON-STEAM REACTION (× 100)

steam. The temperature attained by this tube must have been in excess of 700 degrees C as shown by the evidence of the steam iron reaction. The attack on the bore is clearly shown in FIG. 11.

Comment

As this tube exhibited internal attack and was also subjected to nascent hydrogen, possibly creating conditions of residual stressing, it was considered that the entire saturated pass was suspect and should be removed.

It was noted during the removal of these tubes, that the stresses set up in individual tubes within the entire bank had been sufficient to cause distortion to the extent that several tubes were touching. Thus, had the tubes not been replaced, localized overheating would have resulted with consequent premature failure.

Superheater Tubes

As soon as practicable, the upper superheater tube (A.1) was carefully removed from the bank and submitted for metallurgical examination. This tube was chosen because it would be possible to effect a replacement without disturbing the complete bank and back refractory wall.

Examination under the microscope showed that the steam-iron reaction had commenced on the bore and had produced the characteristic scale. The microstructure of the material had not been affected. Several specimens were taken from this tube, and it was found that the thickness of scale on the bore varied along its length. As the scale rendered the tube unserviceable, a request was made for further samples to be taken, and subsequent inspection showed that tube F.4 had a far greater degree of scale attack on the outside, as it was situated in the gas lane. The tube was removed, after carefully marking the side facing the source of heat.

A micro-section, taken from the side of tube F.4 facing the source of heat approximately 6 inches from the bend showed that the steel had been excessively heated to give significant grain growth on the inside surface. The bore had been severely scaled by the iron steam reaction, and the scale was measured at 0·0025 in. The outside surface of the tube had also been severely heated and a heavy scale was present. An additional three tubes, K.9, P.10, and C.10, were selected for micro-examination and these exhibited similar defects to those found in tubes F.4 and A.1.

Comments

From the above examination it was considered that the entire superheater bank would have to be removed for the following reasons:

(*i*) The presence of the heavy scale and intercrystalline oxide penetration on the bore of the tubes showed that steam burning had occurred.

(*ii*) The variation from place to place in the microstructure of the tube material indicating localized extreme heating.

(*iii*) The presence of severe scaling on the outside of the tubes showing that the tube material on the fireside had attained extreme temperatures.

As this survey condemned the superheater tubes, it was also considered judicious to replace the adjacent superheater support tube. The superheater support plates showed clear markings of severe heat application followed by steam quenching. As these were required to be returned into service they were stress relieved at 650/700 degrees C for 1 hour.

Superheated Steam Pass

Sampling Rows G to M

At the same time that the uppermost superheater tube was removed, it was possible to remove tubes G.22 and H.23 (generating tubes). These were examined for conditions representative of the G to M section in the superheated steam pass.

Micro-examination showed that the steam burning action on the bore had commenced with some intergranular disintegration and the structure had recrystallized, implying that the tubes had been overheated.

Comment

Because of the damage exhibited by the sample tubes, it was decided that the rows G to M inclusive should be replaced. Again it was found that distortion to the extent that some tubes touched each other had taken place in the centre of the tube nest.

Sampling Row BB

A sample tube for checking from the final row of the superheated steam pass, BB.14, was extracted, as it was considered that this tube should be the least affected in this pass.

Examination revealed that again steam burning had taken place in the bore, with resultant intergranular penetration.

Isolated areas of recrystallization indicated that extreme temperatures had been reached, but the rate of cooling had been sufficiently slow to retain the normalized structure. However, the banding effect from the manufacturing processes had been effaced.

Comment

As the presence of scale on the bore was sufficient to impede heat transfer and the structural attack was intergranular, the decision was made to replace all tubes in the section rows N to BB of the superheated steam pass.

During the removal of tubes from this section, it was again noted that some distortion had taken place with touching of tubes particularly in the centre of the bank. As the BB row tubes from both the saturated and superheated steam pass had been affected by both heat and steam burning, it was considered that the economizers, which are very close to the BB row, should be examined to ascertain if any damage had been sustained.

Economizers

Visual Examination

The outsides were examined from below when it was noted that there was an area immediately above the superheater pass which had a distinct darker appearance. This is clearly shown in FIG. 12. Closer examination showed that this area had been stripped of all the aluminium protective paint and was coated with a light brown rust. Surrounding this area was a white deposit which suggested that boiler compound from escaped boiler water had dried out on the tubes.

The header doors were removed and the bores of the lowest tubes examined using the Endoscope. No definite conclusion could be reached as the Endoscope could not penetrate to the section above the superheater pass, and the bore of the tube appeared to be uniformly coated with scale.

However, as a means for comparison, the port boiler economizer doors were removed, and an internal bore inspection of tubes in both economizers was carried out. From this it was agreed that there was a difference in the scale formations in the bore of the starboard economizer tubes when compared with those of the port economizer.

Comment

A decision was taken to remove a section of only one economizer tube for metallographic examination. No. 4 tube from the starboard side was chosen as it passed through the affected area shown in FIG. 12. Also it was considered that this tube could be replaced with least difficulty should it be discovered that the economizers had not suffered significant damage.

Micro-examination showed that the tube had reached a temperature of at least 700 degrees C, but had not attained 900 degrees C because:—

(*i*) The steam-iron reaction had begun with the formation of scale and intergranular oxide penetration.

(*ii*) The structure of the metal had not assumed an acicular mode.

It was also noted that the steam-iron reaction had only taken place on the bore where the thickness of metal was least. No scale was found on the bore in positions corresponding with fins and studs on the outside of the tube.

From the above evidence, it was decided to replace the economizers.

STEAM DRUM AND SUPERHEATER HEADERS

Steam Drum

At this stage it was considered that an examination of the steam drum and the superheater headers should be carried out to ascertain, if possible, whether or not damage had been sustained, particularly hydrogen embrittlement.

The inner surfaces of the steam drum were inspected visually for the presence of the typical deep blue scale which had been formed in the tubes by steam

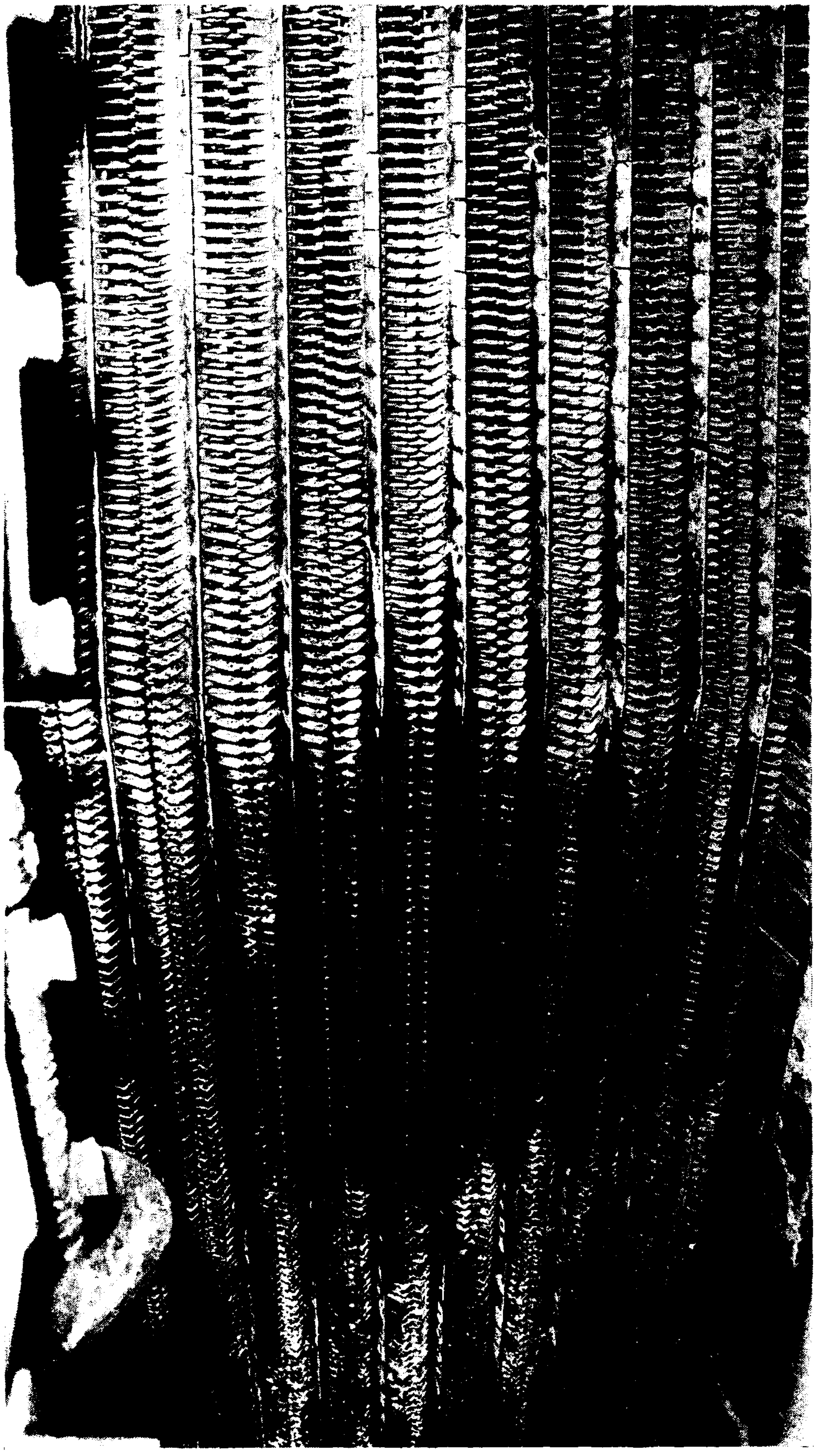


Fig. 12—View of economizers from below showing heat affected zone above the superheated pass

TABLE V

	U.T.S. (tsi)	*Elongation (percentage) Hounsfield No. 12*	*Reduction of Area (percentage)*
Control	29·5	47	61
Door 1	28·5	40	58
Door 2	26·5	43	61

burning. This would indicate the generation of nascent hydrogen, which could be aborbed by the steel. No signs of this scale were detected on the surface of the drum, and it was considered that any action which may have taken place would be very slight, as this mass of metal would hardly have reached the temperature of 700 degrees C considering the large heat sink.

The internal components of the steam drum were visually examined for the presence of scale produced by the burning action but no evidence was found and the parts were considered to be suitable for re-installation into the drum.

Superheater Headers

The superheater headers were examined visually and there were some areas showing scale in zones about the diaphragm plate between the third and fourth pass of the inlet header. This was in line with the hottest part of the superheater bank and the steam would have been at an elevated temperature.

The tube ends from this zone were carefully removed and metallographic sections taken from the portion of tube which protruded into the header. Micro-examination of these showed that there had been some slight steam burning on the inside as well as the outside surfaces of these tubes. Because tube ends had suffered from steam burning serious consideration was given to non-destructive sampling of the superheater header material. It was decided that the handhole doors could be used as representative samples. Examination revealed that some of the doors had been scaled more than others and it was concluded that the affected positions probably corresponded with steam inpingement, jetting out of superheater tubes. Samples of these were micro-examined for the presence of the burning action, which in fact was detected on the two doors sectioned.

Damage which may be sustained by the generation of hydrogen at the steel surface would be primarily in the form of growth of cavities occupied by sulphide or non-metallic inclusions in the metal. After careful examination no evidence of cavity deformation around non-metallic inclusions less than 0.001 in. below the surface in areas where surface attack occurred could be found.

Hydrogen embrittlement would also result in a drop of ductility in the metal. Accordingly, samples from the two affected doors were tested in comparison with material from a door not affected by adverse steaming conditions.

Tensile and elongation tests were conducted on all samples. The results obtained are shown in TABLE V.

Comment

On the strength of the results of the physical tests it was considered that no evidence of embrittlement and lack of ductility had occurred. Therefore the headers did not require to be removed from the boiler room for normalizing or annealing.

Deposit in Boiler Sight Glass

In an effort to establish the cause of water starvation in the boiler a potential contributory factor under suspicion had to be investigated.

An opaque film deposited on the mica shield observed after the incident obscured the view through the steam drum water-level gauge glass and, as the boiler was under manual water tending at the time of break-down, it was imperative to determine whether the film was present before failure and thus impeded the efficient functioning of the boiler room watch.

This initiated a rather interesting side-line investigation. It was decided to subject the sample deposit *in situ*, on the mica, to X-ray diffraction analysis but the backround scatter created by the micaceous material made interpretation almost impossible. A small amount of deposit was then carefully scraped off the mica, on to a glass sample plate, and examined in a diffractometer. Limited identification was possible using this method but more definite results were produced with Debye Scherrer photographs. This investigation was supported by viewing samples under a scanning electron microscope and under conventional visible light microscopes.

Both haematite and magnetite were identified and these were present as layers on the mica. The top layer was magnetite loosely deposited, and responded to a magnetic field, whereas the haematite was a uniform smoke-like deposit adhering tenaciously to the mica.

From a thermodynamic aspect it was quite feasible that haematite fumes could be generated inside the boiler shortly after fire-row tube A.8 burst. The working pressure in the boiler would fall, conditions would pass through atmospheric pressure and as a result of steam condensation partial vacuum may have been created. This reduction in pressure could have fostered a high ratio of oxidizing against reducing agents. (Both oxygen and hydrogen were generated by the steam/steel reaction). The ratio of oxygen to hydrogen in the boiler at the time of failure was quantitatively estimated and at temperatures between 700 and 900 degrees C this concentration has been known to produce brown haematite fumes. It was thus deduced that the accumulation of haematite on the mica shield in the water-level sight glass occurred during the boiler failure incident. Any alternative reasoning for the presence of haematite in a boiler that had been steaming for a considerable number of hours would be difficult to reconcile, as the presence of the correct concentration of boiler compound would have converted all haematite to magnetite.

The surface layer of loosely adhering fragments of magnetite was attributed to the water pressure test carried out subsequent to the failure.

CONCLUSION

Malfunctioning of the boiler manifested itself when a tube in the fire row burst as a result of high temperature creep. Visual examination immediately after this incident suggested that the boiler had been starved of water. Subsequent detailed examination substantiated these findings. The water starvation led to overheating and evidence of steam/iron burning at 700 degrees C was detected.

This reaction produces nascent hydrogen which is capable of migrating into steel and in the process can create high residual stresses leaving the metal in an embrittled state. The presence of the severely blistered scale on the front line of fire-row tubes indicated that hydrogen had been generated and, in its nascent form, had percolated through the metal, creating high pressure gas pockets beneath the scale.

Localized areas of steel re-crystallization and grain growth were also detected. The suspected presence of residual stressing imposed on the tubes as a result of overheating and quenching was substantiated in a number of cases. This was illustrated during metallographic sectioning when it was necessary to split longitudinally short annular tube samples. In a surprising number of cases the ring sections sprang apart at the saw cut.

A complete survey of the tube system revealed such widespread damage that all tubes (including studded tubes such as water walls and economizers) had to be replaced.

The only boiler components which were not seriously affected were the water and steam drums and the headers. However, it was decided to discard the superheater header doors because of the presence of undesirable scale formation on them.

The initial bursting of the fire row tube 'flashed off' the remaining water in the boiler with the result that boiler components in that area were suddenly quenched. The superheater support plates were in this latter environment, and it was decided to give these a stress-relieving heat treatment before re-installation.

From an academic aspect, it was fortuitous that the supply of fuel oil as well as feed water was immediately closed down on failure so that the evidence of reactions were well preserved permitting a full-scale laboratory investigation.

References

(*i*) 'The Burning of Iron in Steam'. *Journal of Naval Engineering*, Vol. 14, No. 3. (Dec. 1963).

(*ii*) 'Marine Boiler Tube Failures—Three Case Histories', by R. D. Barer. *Journal of Naval Engineering*, Vol. 13, No. 2. Dec. 1961).

D.G.S. Departmental Comment

This article is noted with interest.

A similar-looking burst occurred in one boiler tube in H.M.S. *Scylla* at Devonport in August, 1969, and Devonport Metallurgical Laboratory reported the following on the basis of an examination of two tubes, the burst one and an adjacent one:—

(*a*) No compositional abnormalities.

(*b*) No evidence of decarburization.

(*c*) Oxide-filled intergranular cracks and evidence of high temperature oxidation present only in immediate association with the rent in the burst tube.

(*d*) No abnormal inclusions.

(*e*) A 'stain' on the bore of the burst tube, and in a similar position on the adjacent tube, with blue coloration on the fire-side. No microstructural change.

There were no reported abnormalities of operation in *Scylla*, and no obstruction was detected.