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ESTIMATION OF FUTURE CREEP LIFE OF TYPE 321 18-8+Ti STAINLESS STEEL SUPERHEATER TUBES IN THE SECONDARY SUPERHEATER, NUMBER 3 BOILER, GOULD STREET STATION BALTIMORE GAS AND ELECTRIC COMPANY

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INTRODUCTION

An investigation was carried out to assist in estimating the future creep life of the Type 321 18-8+Ti stainless steel tubing in the secondary superheater of Number 3 Boiler in the Gould Street Station of the Baltimore Gas and Electric Company. Two lengths of tubing removed from the superheater on April 30, 1958 when the service time was 41,566 hours were supplied. The tubes were designed to operate at 1125°F and 5600 psi hoop stress. One of the sections of tubing had undergone about 1-percent creep according to diameter measurements while the other had crept very little.

The widespread difficulties from premature creep failures in Type 321 superheater tubes is well known. Number 3 Superheater was designed to the lower ASME Boiler Code Allowable Stresses in existence prior to 1952. The problem was to determine if the tubes were the low strength fine grain variety that had been associated with premature failures and if so, to estimate the time failures would become a problem in Number 3 Superheater under the old code stress.

The diameters of tubes in the superheater had been measured in 1958 by the Baltimore Gas and Electric Company. The increases in size of a few tubes suggested that as much as 1-percent creep had occurred. Subsequent examination of the tubes in 1959 disclosed a number of cracks where spacer lugs were welded to the tube. In addition, measurements of tube diameters at another location as well as the location measured in 1958 showed more tubes with significant amounts of creep.

CONCLUSIONS

The tubes were found to be the fine grain variety associated with low creep-rupture strength. Rupture tests on specimens cut from the tubes indicated rupture strengths on the low edge of the range of available data for Type 321 steel. There was considerable difference in rupture strength between the two tubes at 1125°F. Tube 89 which had not undergone significant creep according to diameter measurements showed substantially higher rupture strength. Tube 91 which had undergone significant creep was the weakest. The tests at 1200°F, however, showed little difference between the two tubes although Tube 89 was somewhat stronger than Tube 91.

Analysis of the data indicated that the weakest tubes in the superheater should be approaching diametrical creep in straight sections of the order of 1 to 2 percent. Experience has indicated that when this stage of creep is attained, failures could be expected to start to occur at points of stress multiplication, such as tube spacers welded to the tubes. The inspection in 1959 disclosing several cracks at such locations verifies this conclusion.

So far as could be ascertained from the limited data from this investigation, there should not be immediate difficulty in straight sections of tubing from excessive creep. The rupture time under the operating stress of 5600 psi at 1125°F of Tube 91, apparently one of the weakest in the superheater was still about 200,000 hours. Unless the operating temperature would unknownly be higher than 1125°F, the tubes should continue to swell gradually by creep. This assumes that there are no undue stress intensification factors in the straight section of tubes, such as wall reduction by corrosion or uneven creep around the circumference of the tube. Due to the high elongation to fracture swelling should give ample warning for replacement prior to failure in straight sections.

HISTORY OF TUBES

Two 44-inch long lengths of tubing were supplied for the investigation. These were removed from Number 3 Superheater at the Gould Street Station of the Baltimore Gas and Electric Company on April 30, 1958. They were designated as tube numbers 89 and 91 in the third row of tubes downstream from the soot blower aisle. The tubes were 2.0-inch O.D. by 0.260-inch wall.

The operating conditions were as follows:

1. Design steam temperature and pressure - 1080°F and 1700 psi.
2. Calculated mean maximum metal temperature - 1124°F.
3. Calculated hoop stress - 5600 psi.
4. Service hours - 41,566

In addition, operating steam temperatures were measured every hour for five minutes by Baltimore Gas and Electric Company for a seven day period with the following results.

Tube Number	Observed Average Steam Temperature (°F)	Estimated Average Metal Temperature (°F)
89	1090	1134
91	1082	1126

Tube Number	Observed Maximum Steam Temperature (°F)	Estimated Maximum Metal Temperature (°F)
89	1136	1186
91	1122	1166

The measurements did not indicate the relative time at average and maximum temperature.

Baltimore Gas and Electric Company also measured tube diameters and found the following changes:

Tube No. 89 - 0.3% smaller than the nominal diameter.
Tube No. 91 - 0.1% larger than the nominal diameter.

The diameter of Tube 89 was within the tolerance for new tubes. This tube had not undergone significant creep. The diameter of Tube 91 was about 0.5-percent larger than the maximum diameter tolerance for new tubes. Depending on the unknown original diameter, therefore, Tube 91 could have undergone as little as 0.5-percent and as much as 1.5-percent creep.

All of the tubes in the third-row downstream from the soot blower were measured for diametrical increase on April 30, 1958 and again on March 25, 1959 when the service time was 49,000 hours. The measurements made in 1958 were taken at the centerline of the gas pass. In 1959, the measurements were made both at this same location and 6-inches above the top lugs. These measurements are shown graphically by Figure 6.

In general, the measurements of diameter for tubes numbered above 65 agreed quite well at the two locations and in general showed about the amount of increase in creep to be expected in an additional year's service. The measurements of the tubes with lower numbers than 65, however, showed a marked increase in creep from 1958 to 1959 with somewhat more creep above the lugs. There are some discrepancies in measurements made at different times as would be expected due to the difficulties of making such measurements.

More important, however, is the discovery that there were numerous cracks adjacent to the welds fastening the spacer lugs to the tubes.

The steam temperatures of the tubes were measured in 1958 with the results shown in Figure 7. Metal temperatures were calculated from the steam temperatures by adding 44°F. The available information does not give any indication of the time at average and maximum temperature. It will be noted that the temperatures were higher for tubes numbered from about 21 to 51 and from 91 to 125 than for the other tubes. This corresponds to the location of those tubes showing the most increase in diameter from creep.

RESULTS

Rupture tests on the two tubes at 1125° and 1200°F gave the data in Table 1. The stress-rupture time curves, Figure 1, indicate the following extrapolated values for rupture in 100,000 hours.

Tube Number	Temperature (°F)	Stress for Rupture in 100,000 hours (psi)
89	1125	9,500
91	1125	6,600
89	1200	5,000
91	1200	4,800

In drawing the curves of Figure 1, the most conservative values indicated by the data were used. Even then, however, the curve for

Tube 89 at 1125°F indicates a high rupture strength at 1125°F in comparison to the data at 1200°F. More testing would have been necessary to demonstrate whether the value at 1125°F is high or the value at 1200°F is low.

All of the specimens had high elongation in the rupture tests with the specimen from Tube 91 having somewhat higher values than those from Tube 89.

The grain size of the tubes varied to the extent that some samples examined had an ASTM grain size of 7 whereas others were finer than 8. In general, Tube 89 had a somewhat coarser grain size than Tube 91. Figures 2 and 3 show original microstructures of the two tubes. As Figures 4 and 5 indicate, however, the grain size in both tubes varied. Figures 4 and 5 are included to show the grain size of the specimens used for longest duration rupture tests and to indicate to some degree the variation of grain size. Both materials showed extensive formation of a new phase generally considered to be sigma phase. These are the dark larger particles visible in the 1000X photomicrographs of Figure 2 and 3. They formed in the grain boundaries almost like very fine grains separate from the matrix grains. In addition, there were numerous fine precipitates within the matrix grains as well as the grain boundaries.

Four samples at 90° around the circumference showed little variation in grain size when the tubes were originally examined. The variation in grain size was found where the fractured specimens were examined. Consequently, there was in fact some variation either circumferentially or along the length of the tube. The grain size variation may have influenced rupture times and may account for some of the variation observed in rupture times as well as the possible discrepancy between the stress-rupture time curves for Tube 89 at 1125° and 1200°F.

Past experience has indicated that the rupture strength of Type 321 tubing is lower the smaller the grain size. Apparently, the generally finer grain size of Tube 91 was responsible for its lower rupture strength and high ductility. The new phase (probably sigma phase) characteristically forms as shown in the photomicrographs during exposure to elevated temperatures. The amount of the new phase usually increases with decreasing grain size.

Measurements made by Baltimore Gas and Electric Company indicated that Tube 91 had undergone considerable creep whereas Tube 89 showed little or none. It seems probable that this was due to the generally lower creep strength of Tube 91. However, the structures of the two tubes are so nearly the same that it is possible that higher service temperature on Tube 91 could have been responsible for the larger amount of creep and the lower rupture strength.

DISCUSSION

The major objective of the investigation was to obtain data to assist in estimating the future life of the Type 321 tubes in the superheater. The stresses for rupture in 100,000 hours were found to be substantially above the calculated operating stress of 5600 psi at 1125°F. Ductility in the rupture tests was high. The following interpretation can be placed on these findings:

1. If no causes for stress intensification were present and metal operating temperatures are no higher than 1125°F, the rupture life remaining in the tubes should be several hundred thousand hours.
2. The interpretation under Item 1 can be stated another way. If new tubes having the rupture properties measured for the tubes after 41,566 hours of service were placed in service, the anticipated rupture life would be several hundred thousand hours at 1125°F and 5600 psi. There is no metallurgical reason why rupture properties measured for used tubing should be interpreted differently from that of new tubing.
3. It must be recognized, however, that stress intensification or higher than normal operating temperatures can occur. The future life of the superheater tubing must be examined in light of these possibilities. The following interpretations of the data are applied to this problem:
    (a) At points of stress intensification, such as tube spacers and hangers welded to the tubes, the actual stress was higher than the nominal stress due to pressure alone. Failures would be expected to occur first at these points. It is commonly accepted that such failures start to occur in material with high ductility to rupture when the creep

under the nominal stress in straight lengths of tubing reach 1 to 2 percent.

(b) The tube diameter measurements made by Baltimore Gas and Electric Company indicate that the creep in straight sections of some tubes is approaching 1 to 2 percent.

(c) The measured rupture strengths also indicate that the creep in the weaker tubes should be approaching 1 to 2 percent. It is generally found that the ratio of creep strengths to rupture strengths are within certain ranges:

$$\frac{\text{1\% per 10,000-hour creep strength}}{\text{10,000-hour rupture strength}} = 0.7 \text{ to } 0.8$$

$$\frac{\text{1\% per 100,000-hour creep strength}}{\text{100,000-hour rupture strength}} = 0.4 \text{ to } 0.6$$

Applying these ratios to the measured rupture strengths for Tubes 89 and 91 at 1125°F gives the following approximate creep strengths:

	Ratio Factor	Tube Number	
		89	91
10,000 hour rupture strength (psi)		14,000	11,250
Est. 1%/10,000hr creep strength(psi)	0.8	~ 11,200	~ 9,000
Est. 1%/10,000hr creep strength(psi)	0.7	~ 9,800	7,875
100,000 hour rupture strength (psi)		9,500	6,600
Est. 1%/100,000hr creep strength (psi)	0.6	~ 5,700	~ 3,960
Est. 1%/100,000hr creep strength (psi)	0.4	~ 3,800	~ 2,640

The calculated hoop stress was reported to be 5600 psi. A rough interpolation of the estimated creep strengths indicate that the approximate times to reach 1 percent creep for the two tubes would be about:

Ratio Factor	0.8 - 0.6	0.7 - 0.4
Tube 89	100,000 hours	38,000
Tube 91	38,000 hours	20,000

These values suggest that the higher values of the ratio of creep strength to rupture strength come close to the actual service experience. Tube No. 89 had not yet shown measurable creep and Tube 91 was about 1 percent. This statement is based on the measurements of tube diameters made in 1958. The measurements made in 1959 at another location on the tubes showed more creep. This could be due to a higher temperature at the new location or to the metal temperature being closer to 1125°F and lower at the old location. The calculated values, however, seem too low even for the new location and values of ratio of creep strength to rupture strength are probably at least 0.75 and 0.5 for respectively 10,000 and 100,000 hours.

(d) It must be concluded that if failures are to be expected at stress concentrations after 1 to 2 percent of creep in straight sections, such failures could be expected immediately in the weaker tubes.

(e) The probability of failures in the straight sections where no stress concentrations are present would not be expected for many thousands of hours. Available correlation of rupture data for tensile specimens and tubes indicate good agreement in rupture times for tubes of the thickness present in the superheater. Thus shorter life than that predicted by the stress-rupture time curves of Figure 1 would be for cases where creep was localized on one side of the tube with a resultant stress multiplication. This could arise from uneven heating, wall thickness variations from eccentricity, or variations in creep strength around the circumference of the tubes. It should be remembered that grain size variations around the tube circumference were found with consequent probable creep strength variations. Also tube wastage due to corrosion could cause localized stress concentration. So far as this author is aware, however, these factors should not result in straight tube failures for many thousands of hours.

(f) Any failures in straight lengths should be preceded by extensive bulging due to the ductility of the material. Inspection of tubes should indicate impending failures long before they actually occur and allow time for replacement.

(g) Actual operating temperatures are uncertain. The largest single uncertainty in this analysis arises from this source. The marked decrease in rupture strength with increasing temperature would result in marked reduction in rupture life from operating temperatures higher than 1125°F. For instance, rupture in straight lengths of the tubes could be expected in less than 50,000 to 60,000 more hours of service with metal temperatures of 1200°F. One percent more creep would be accumulated in less than a year and even new joints at points of stress concentration such as welded tube spacers would start to fail. Old joints would fail rapidly.

4. Measurements of tube diameters made in 1959, check the above analyses of future life of the tubes. Numerous cracks were found at welded-on spacer lugs. No cases of excessive bulging of straight tube sections were observed as would be expected. The measurements at the new location showed more creep than the measurements made in 1958. Two possible explanations exist. The metal temperatures could be higher than 1125°F at the new location or less than 1125°F at the old location. As discussed under Item 3(c) the analyses of the creep data suggest the latter.

5. There is one feature of the measurements of tube diameters made in 1959, which is disturbing. The amount of increase in diameter of low number tubes at the location measured in 1958 appeared to be more than would have been anticipated from expected normal creep. Although it is possible that the analyses presented is in error in regard to rate of creep, some

alteration of operating conditions leading to more creep is suspected.

In addition to the problem of future life of the tubes in the superheater, tests were carried out at 1200°F so that the properties of the tubes could be compared with the extensive data at 1200°F developed recently for Type 321 steel. The tests for both tubes were slightly below the band for new material presented by the Babcock and Wilcox Company. There seems, therefore, to be little doubt that the Type 321 tubes in the superheater represent the condition of the steel with the lowest rupture strength. This is borne out by the fine grain size and the extensive development of the new phase generally considered to be sigma.

The question of the influence of the 41,566 hours of service on the measured rupture strengths should be considered in relation to the conclusion of the previous paragraph. In all cases with which the author had had experience, it has appeared that the rupture test takes into account the effects of structural changes. Thus the stress for rupture in 100,000 hours based on tests of new material would be similar to that for the same material after prolonged service with structural changes provided that the amount of rupture life used up during service was negligible. This would not be true for rupture in shorter time periods after service. The structural changes during service would result in material with different properties than the new material at the shorter time periods. There would be no difference in long time strengths, however, because both old and new material would have similar structures at long time periods.

Assuming that structural changes are not involved in the stress for rupture at 100,000 hours for the tubes tested after service, the only question is the amount of available rupture life used up in 41,566 hours. The rupture life of the tubes under 5600 psi at 1125°F according to Figure 1 would be (by excessive extrapolation):

Tube 89 ....>1,000,000 hours
Tube 91 .... 200,000 hours

The 41,566 hours of service at 1125°F represents a negligible amount of life for tubes having the strength of Tube 89. For the weaker tubes as represented by Tube 91, the 41,566 hours of prior service represents less than 20 percent of the rupture life. Even 20 percent reduction in rupture life represents only 200 to 400 psi reduction in the stress for rupture in 100,000 hours at 1200°F. Thus, the measured rupture strengths at 1200°F for long time periods probably were reduced at most only slightly by the prior service. Again, it should be recognized that this is not true for shorter time periods where the differences in metal structure due to prior service would be important.

TABLE I

RUPTURE-TEST DATA AT 1125° AND 1200°F FOR TYPE 321 SUPERHEATER TUBES 89 AND 91 FROM THE SECONDARY SUPERHEATER, NUMBER 3 BOILER, GOULD STREET STATION AFTER 41,566 HOURS OF SERVICE

Tube Number	Temperature (°F)	Stress (psi)	Rupture Time (hours)	Elongation (% in 2 in.)
89	1125	35,000	22.4	27.0
		25,000	322.0	33.5
		21,000	923.0	39.5
91	1125	25,000	351.0	46.5
		21,000	674.0	42.5
		18,500	1202.0	37.5
89	1200	24,000	114.0	36.5
		20,000	347.0	35.0
		16,500	710.0	41.0
91	1200	20,000	241.0	43.0
		16,000	605.0	50.5
		14,000	1133.0	55.5