The American Society of Mechanical Engineers
29 W. 39th St., New York 18, N. Y.

Paper No. 54-A-73

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CARBON-MOLYBDENUM STEEL STEAM PIPE

AFTER 100,000 HOURS OF SERVICE

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Advance Copy
Released for general publication upon presentation

Contributed by the Joint ASTM-ASME Committee on Effect of Temperature on Properties of Metals for presentation at the Annual Meeting, New York, N.Y. - November 28 - December 3, 1954 of The American Society of Mechanical Engineers. (Manuscript received at ASME headquarters August 2, 1954.)

Written discussion on this paper will be accepted up to January 10, 1955. Decision on publication of this paper by ASME had not been taken when this preprint was prepared.
Discussion is published only if the paper is published.

Printed in U.S.A. (Preprints will be available until October 1, 1955)

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ABSTRACT

Rarely does the engineer or metallurgist have an opportunity to evaluate design considerations and laboratory data in terms of creep in service. Carbon-molybdenum steam pipe, carefully measured for service creep during 100,000 hr of operation at 900 F, was subjected to laboratory examination after removal from service. The purpose was to check calculated service creep rates, assess creep damage, and to compare long-time performance prediction based on short-time laboratory data. Remarkable correlation was observed between calculated service creep rates and those established by subsequent laboratory creep testing. Full agreement with average values used by the Subgroup on Allowable Stresses for Ferrous Materials of the ASME Boiler Code Committee in setting allowable stresses for this material was established for both creep and stress-rupture properties.

CARBON-MOLYBDENUM STEEL STEAM PIPE AFTER 100,000 HOURS OF SERVICE

By R. J. Sinnott, I. A. Rohrig,
J. W. Freeman, and A. I. Rush

INTRODUCTION

When Unit No. 14 was being erected at the Delray Power Plant of The Detroit Edison Company in 1938, the lack of reliable data on service-life properties of metals subjected to high-temperatures was felt acutely. The practice of basing design on stresses obtained by 1000-hr high-temperature laboratory tests extrapolated to 100,000 or more hours has repeatedly been questioned. Designers accepted such data only because no better method of property prediction of high-temperature characteristics has been available. It is the purpose of this paper to present (a) The results of creep measurements made on carbon-molybdenum pipe subjected to 100,000 hr of actual power-plant service, (b) results of after-service laboratory testing, and (c) a discussion of service results as compared to properties predicted by laboratory testing prior to service.

Service History

With the installation of Unit No. 14, a service creep-measurement program was initiated. Stainless steel-measuring points were arc-welded on the external surfaces of two 10-in. nominal diam. carbon-molybdenum steel pipes connecting the turbine emergency stop valve to the upper and lower steam chests of the turbine. The two Schedule 80 steam leads were designated as "North" and "South" indicating their position with respect to the turbine. The stainless-steel buttons were located to provide both diametral and axial measuring stations and were ground to give accurate measuring surfaces. Fig. 1 illustrates the measuring stations.

Weighted average pressures and temperatures during the operating period are 835 psig and 900 F. Maximum temperature fluctuations of $\pm$ 20 deg F represent normal operating conditions.

Measurements were made at prevailing temperatures during five outage periods and were taken after the unit had cooled down and the thermal insulation removed from the locations undergoing test. Dimensions were measured with an outside micrometer caliper and a special micrometer trammel. Readings taken were corrected to a base temperature of 68 F. The results of these measurements are shown in Table I.

Plotted service creep calculations based on diametral measurements indicated a typical low stress creep versus time curve over the first 67,000 hr of operation; viz, a relatively rapid initial creep rate followed by a reduction in rate of creep, which is characteristic of material operating under stress conditions producing creep at a low rate. Total diametral elongation at this time was observed to be in the order of 0.1 per cent, a relatively low value. The total axial elongation during the 67,000-hr period as determined by axial measurements did not exceed 0.03 per cent and in most cases was considerably less.

After 75,500 hr of operation, weld samples removed from the valve-to-pipe and pipe-to-pipe joints of the South connection indicated the presence of graphite ranging from dispersed nodular in the valve joint to chain type in the pipe-to-pipe joints. At shut-down intervals during the next 5000 hr of operation, all the welded joints in the turbine leads were first normalized at 1725 F, and shortly thereafter all welds were gouged out, rewelded, and normalized. After 100,135 hr of operation, the carbon-molybdenum turbine leads were removed and replaced with chromium-molybdenum pipe, which is highly resistant to graphitization.

Final service creep measurements were made just prior to the removal of the carbon-molybdenum pipe from service. Calculations based on diametral measurements indicated a drastic increase in creep rate over the rate established at the end of the fourth period. Concern over the carbon-molybdenum pipe remaining in service in other portions of the system indicated the advisability of laboratory tests as a check on calculated service creep rates.

Description of Material

The pipe was ASTM A158-36 grade P1, schedule 80, made from National Tube Company's Heat 10043. The reported chemical composition was:

	Per cent
Carbon	0.13
Manganese	0.45
Silicon	0.131-0.135
Molybdenum	0.60-0.62

The pipe was 10.75 in. OD by 0.593 in. wall. After bending and upsetting the ends, it had been given a full anneal at 1900 F for 2 hr. Physical properties were reported as follows:

Tensile strength, psi	60,880
Yield strength, psi	39,730
Elongation in 2 in., per cent	45

EXPERIMENTAL PROCEDURE

Creep Testing

"North Connection". Creep tests were run on both tangential and longitudinal specimens at the operating temperature of 900 F and under the estimated operating stress of 7500 psi. In addition, tests were made under the present 12,500-psi allowable stress of the ASME Boiler Code.

"South Connection". One tangential specimen and one longitudinal specimen were taken from the pipe. Creep tests of these two specimens were run at 900 F under a stress of 7500 psi.

Rupture Testing

"North Connection". A stress-rupture curve was established at 900 F for time periods up to nearly 1800 hr. Longitudinal specimens were used for this test. In addition, a check test was run on a tangential specimen which was tested at 37,000 psi, a stress intended to cause rupture in about 1400 hr.

"South Connection". Tests were run on longitudinal and tangential specimens at a stress of 37,000 psi.

Impact Tests

"North Connection". Charpy V-notch tests were made on both longitudinal and tangential specimens. Similar tests were made on the pipe material after it had been reheated 2 hr at 1900 F and furnace-cooled. All of the Charpy V-notch specimens were tested at 80 F. No impact tests were made on material from the South Connection.

Tensile Tests

"North Connection". Room-temperature tensile tests were run on longitudinal specimens. No tensile tests were made on material from the South Connection.

Hardness Tests

"North Connection". Brinell hardness tests were run on eight sections representing the entire circumference of the pipe section.

"South Connection". The Brinell hardness was determined on one section representing the South Connection.

Metallographic Examination

"North Connection". A metallographic examination was made on sections through the center line of the measuring buttons representing the four quadrants of the North Connection, and, in addition, samples were taken adjacent to all of the test specimens.

"South Connection". Samples were taken at one measuring button and also adjacent to the creep and rupture specimens.

RESULTS

Dimensional Measurements on the North and South Connections

The measurements shown in Table I were made across the diameters of the pipe at the reference buttons. It should be noted that at the time the reference buttons were attached, no attempt was made to keep the height of the measuring buttons uniform. Accurate inside diameter measurement of the pipes was not readily obtainable with the equipment available at the time of installation. Therefore, any initial ellipticity of the pipes which may have existed was not detected, and was not indicated by the diametral measurements made during service. No changes in diameter due to sectioning were observed. The inside diameters were measured at both ends of the pipe ring containing the reference buttons and are recorded also in Table I. Measurements were made on the pipe diameters containing the reference buttons and at diameters between each button. Further, the circumferential length covered by the buttons was determined as a matter of record with the results shown in Table I.

From these data, it was observed that the minimum diameter of the North connection was at the (4-4) axis and at the (1-1) axis of the South connection. These diameters correspond to those showing the greatest increase from creep as judged by the diametral measurements taken during service. Consequently, it must be concluded that the pipes were originally elliptical in shape and were becoming round during service.

The wall-thickness measurements indicated that both sections varied by a maximum of approximately 0.025 to 0.030-in., a variation which was well within the specified allowances for the size of pipe. However, it should be emphasized that these measurements were made after 100,000 hr of service and that original wall thicknesses were unknown.

Creep Rates During Service

The average rates of creep during service were calculated from the measurements taken on the measuring points during service. The results obtained from such measurements were used to calculate the creep rates by two separate and different approaches; namely, changes in diameter of the pipe, and, changes in the perimeter of an ellipse having the dimensions established by the changes in diameter. The latter method is preferred; therefore, the results given for creep during service are based upon changes in the perimeter of an ellipse having the dimensions established by the measurements of the pipe given in Table I. The results of these calculations are given in Table II. Fig. 2 shows graphically the changes in circumference of the pipes as a function of time and service.

The average circumferential creep rates during service show the following:

1 During the first period, the creep rate of both sections was somewhat higher than 0.003 per cent per 1000 hr.

2 During the next three periods, the rates were less than 0.0022 per cent per 1000 hr. However, the minimum creep rates were observed for both sections during the third period.

3 During the fifth period, the average rate for the South connection apparently increased to 0.0047 per cent per 1000 hr, whereas the creep rate for the North section was essentially the same as for the second and fourth periods.

It should be emphasized that the measurements made during service reflected very small changes in the diameters as shown by Table I. Consequently, it would not appear that too much significance should be placed on the minor differences in creep rates observed for the different periods: i.e. the low creep rates calculated for the third period of operation. The somewhat higher average creep rates during the first period might have been expected due to the combined effects of primary creep and possible relief of stress concentrations. The apparent increased creep rate of the South connection during the fifth period is clouded by the effects of the removal of the old welds and the rewelding. It does appear highly significant, however, that in general, the creep rates and total deformations, are of the order expected from the extrapolation of laboratory data.

Tensile and Hardness Properties

Tensile tests conducted at room temperature gave the data shown in Table III. Material from all four quadrants had very uniform tensile strengths and ductility values. Yield strengths and proportional-limit values varied somewhat. There did not, however, appear to be a consistent relationship between specimen location and variation in these values.

Lack of specific comparative data raises the question of whether the low tensile strength was the result of service or if it is characteristic of the somewhat high temperature and slow rate of cooling during the original heat-treatment. This heat-treatment might be expected to give somewhat lower tensile strength than those usually used for reported data for 0.5 Mo steel. For similar reasons, the yield strengths might have been expected to be low. It, therefore, appears that service may have raised the yield points somewhat as would be expected.

Brinell hardness determinations were as follows:

Connection	Location	Brinell hardness Number
North	Top, side and bottom of pipe	103-107
South	Side of pipe	101

There did not appear to be a significant variation in hardness around the pipe circumference. The hardness values, like the tensile strength, appear to be somewhat low for 0.50 Mo steel. Apparently the hardness was characteristic of the original heat-treatment, because reheat-treatment at 1900 F for impact testing resulted in a Brinell hardness of 101 to 106. There is, therefore, no real evidence of softening during service.

Impact Properties

Charpy V-notch tests were made at 80 F on specimens taken from the pipes as removed from service and after sections of the pipe had been given the original heat treatment. The data obtained, Table IV, indicate the following:

1 The impact strength ranged from 8 to 11 ft-lb for the pipe material as-removed from service.

2 Reheat-treatment of the pipe material with the same nominal heat-treatment as the original pipe gave an impact strength of 18 to 22.5 ft-lb.

3 The range in impact strengths was too small for any real significance to be attached to the difference in specimens taken longitudinally and tangentially or from the locations of estimated highest and lowest stress concentrations.

4 The influence of prolonged service at 900 F on the impact strength of 0.50 Mo steel is not well established. Such information as is available would indicate that some deterioration would be expected. At least, that is the usual experience in creep-testing. Consequently, it would seem the observed values of 8 to 11 ft-lb do not appear unusual for material with the original heat-treatment used for the pipe in question. However, if the pipe had been normalized from 1650 F in place of 1900 F, it is probable that the values would have been higher than 8 to 11 ft-lb.

Laboratory Creep-Test Properties

The creep-rate data obtained from the individual tests are shown in Table V, and the log stress-log creep rate curves derived from the creep-test data are shown in Fig. 3. The curves of Fig. 3 indicate that the stress for a creep rate of 0.01-per cent per 1000 hr was 12,500 psi.

Tests were run at two stress levels:

(a) 7500 psi - the stress corresponding to the operating stress during service calculated by The Detroit Edison Company. The measured creep rates ranged from less than 0.001 to 0.002 per cent per 1000 hr. These rates are not considered as precisely established because the sensitivity of the extensometer system, particularly for the 1-in. gage lengths of the tangential specimens, was too low to give exact values. There is no doubt, however, that the creep rates were of the order of 0.001 per cent per 1000 hr.

(b) 12,500 psi - the stress corresponding to the present allowable stress under the ASME Boiler Code. Both a longitudinal and a tangential specimen from the North connection gave final secondary creep rates of 0.01 per cent per 1000 hr.

Tangential, as well as longitudinal, specimens were tested because the creep during service was largely circumferential and it was felt that creep characteristics should be established for material with the same orientation as the service creep. The absence of any substantial difference between the two types of specimens appears somewhat unusual, because specimens taken across the direction of metal flow during working usually have slightly higher creep resistance. The absence of specific data on this point for pipe produced and heat-treated in the same way as the pipe tested, however, make this uncertain for the particular case.

The tangential specimens tested at 7500 psi showed a decrease in length during the first few hours of testing. The reason for this is uncertain. It could have been due to relief of some complex internal stress system or to testing technique variables. Careful review of the testing procedure showed no reason to believe that it was testing technique.

The 7500-psi tests on specimens from the North and South connections did not show a significent difference in creep rate. The creep rates were so low, however, that it is not certain that some difference in creep resistance did not exist.

Rupture-Test Properties

The data obtained from the rupture tests are given in Table VI and are plotted as the usual log stress-log rupture time curve in Fig. 4. From this curve, the following rupture strengths at 900 F have been estimated:

Stress for Rupture in Indicated Time Periods at 900 F (psi)

100-hr	1000-hr	10,000-hr	100,000-hr
37500	37000	33000	29000

The extrapolation to 10,000 and 100,000 hr appears somewhat uncertain in that there seems to be a break in the slope of the stress-rupture curve at about 1000 hr. The tests at longer time periods are insufficient to define the slope of the curve for longer time periods with certainty. The curve has been extended using the greatest slope (lowest strengths) indicated by the available data.

Elongation and reduction-of-area values decreased with rupture time. The short-time elongation was approximately 40 per cent. Tests between 1000 and 2000 hr in duration showed elongations between 30 and 20 per cent. There was no significant difference between longitudinal and tangential specimens or between the two pipe sections.

Metallographic Examination

Test specimens were taken adjacent to or between measuring buttons. The microstructures typical of the test specimens were as follows:

1 The microstructures were ferrite and slightly spheroidized pearlite. In addition, there were apparently fairly massive carbides in the grain boundaries and a light general precipitation throughout the matrix. Scattered graphite nodules were present.

2 The grain size was mainly 5 to 8. No areas of larger grains were observed in the North connection. Occasional nodules of graphite could be found, and it was

noted that the massive carbides were absent in the presence of graphite.

3 No significant variations in structure around the circumference of the North connection was observed. The examination of the South connection was less extensive. All samples were, however, similar to the North connection, except for the occurrence of small patches with grain sizes up to grain size No. 3, ASTM Designation E 19.

4 A rather general graphitization was observed on both the inside and outside wall surfaces of both connections. The graphite was quite fine and appeared to be concentrated in the grain boundaries.

The microstructures beneath the stainless-steel buttons had the following characteristics:

1. Segregated graphite approaching "chain" graphite was present under all buttons. In most instances, the chain graphite was either parallel to the surface of the pipe and approximately half-way between the inside wall and the heat affected zone of weld or progressed diagonally in the wall near one end of the button.

2 Only a few isolated nodules of graphite were observed in the heat-affected zone of the welded stainless-steel buttons.

The microstructure of the material reheat-treated for impact tests revealed the following:

1 The structure of the reheat-treated material was similar to that of the pipe as removed from service except that there was somewhat less spheroidization of the carbides.

2 The massive carbides observed in the grain boundaries of the pipes also were present in the reheat-treated material.

It was concluded from the metallographic examination that where the metal was not influenced by the stainless-steel measuring buttons, little graphitization had occurred. There also seems to be little question, but that the original carbide lamellae in the pearlite had spheroidized slightly. The presence of what appears to be massive carbides in the grain boundaries was somewhat surprising in view of the relatively slight spheroidization of the pearlite and raises some doubt as to whether they are actually carbides. The slight general precipitation in the matrix was characteristic of 0.50 Mo steel after prolonged exposure to stress and temperature. Other than graphitization, the slight spheroidization, "massive carbides," and characteristic general precipitation appear to have been the major structural changes during service. The resistance of the "massive carbides" to removal by heat treatment was interesting and indicates an unusual composition if they are actually carbides.

DISCUSSION

The creep curves, Fig. 2, obtained from the measurements during service are a very unusual set of data. The engineer or metallurgist rarely has an opportunity to evaluate design considerations and laboratory data in terms of actual creep in service.

The exact creep and rupture properties of the particular pipe material at the time it was placed in service were not established. There are, in fact, very few laboratory tests which establish stresses for creep rates as low as those measured in service (less than 0.002 per cent per 1000 hr, Table II). Creep strengths of C Mo steel are rather variable, depending on heat-treatment and melting practice. The exact creep rate for the service stress of 7500 psi at 900 F is therefore not well established. Extrapolation of the available laboratory creep data at higher stresses back to 7500 psi, however, suggests that on an average, rates of the order of 0.001 per cent per 1000 hr might be expected (see Fig. 5). The observed creep in service, therefore, is considered to be in good agreement with the predictions of laboratory data.

The creep rates measured in service and those measured in the laboratory for tests at 7500 psi on coupons cut from the pipes after they were removed from service are in good agreement. This confirms the service creep measurements. It would be expected that, after a brief period of adjustment, the two creep rates ought to agree.

The stress for a creep rate of 0.01 per cent per 1000 hr established in the laboratory, 12,500 psi, and the stress for rupture hours, 29,000 psi, turned out to be in exact agreement with average values for new steel. The observed creep strength is the average value found by Miller and Heger (3) and used by the Subgroup on Allowable Stresses for Ferrous Materials of the ASME Boiler Code Committee in setting the present allowable stress of 12,500 psi. The same group also developed an average value for rupture strength of 29,000 psi.

The average values for strength of the pipe material after prolonged service may appear to be somewhat surprising. Actually, however, this is to be expected if it is assumed that the pipe metal had nearly average properties initially. It is generally considered that exposure to stress and temperature will permanently use up the available life of metals by creep. Consideration of the service conditions, however, indicates that this should have been very small. If the stress-rupture time curve of Fig. 4 was extrapolated to 7500 psi, the indicated rupture time would be many millions of hours. On this basis, 100,000 hr of service was negligible in comparison to the total life available. Certainly the percentage of life used on this basis was too small to alter significantly the rupture-test results.

The laboratory creep data show no evidence of weakening from the 100,000 hr of service. As previously discussed, the creep rates were the same as those existing during service. Creep rates from laboratory tests, however, would be expected to show evidence of structural deterioration only if so-called third-stage creep had started during service. There is no precedent of which the authors are aware for estimating when third-stage creep should become evident in such prolonged time periods and at such low creep rates as existed in service. General laboratory experience indicates that, in the absence of substantial loss of strength by structural alteration due to temperature, third-stage creep would not be expected before the total creep deformation reached 1 per cent. The creep deformation during service, Fig. 2, was of the order of 0.2 per cent and the probability is that the onset of third-stage creep was remote. The test results support this view. The rates observed were average for the steel and there was no indication of increasing creep rates during the tests or in service at either 7500 or 12,500 psi.

The possibility exists that structural alteration under the influence of temperature and stress during the prolonged service could have altered substantially the creep properties from those characteristic of the new pipe. Unfortunately creep data for the particular pipe samples before service are not available. The data obtained from the tests on the pipe after service are compared in Fig. 6 with those presented by Weaver (4) in which he attempted to estimate the effect of spheroidization during service. At 0.01 per cent per 1000 hr, the creep strength was in between that for the annealed condition and for a condition of spheroidization equivalent to 23 years of service at 900 F. Actually the strength indicated is almost exactly that which would be estimated from Weaver's data. The 100,000 hr of service represents about one-half the 23 years estimated by Weaver to attain the degree of spheroidization of his test bars and the creep strength of the pipe material is also about half-way between his two conditions. The microstructure also showed about the degree of spheroidization consistent with the creep strength in comparison to Weaver's data.

The creep strength of the pipe at 7500 psi in both service and laboratory tests did not agree as well with Weaver's data. Both showed a stress for a creep rate of 0.001 per cent per 1000 hr of about 7500 psi or a little less. This corresponded to Weaver's material spheroidized for an equivalent of 23 years of service, rather than to his annealed stock, which showed a stress of 11,600 psi for 0.001 per cent per 1000 hr. Because the pipe showed creep rates from early in its service life of the order of 0.001 per cent per 1000 hr, the indications are that the pipe material had different stress - creep rate relations than Weaver's test stock. Weaver annealed his stock from a lower temperature than was used for the Detroit Edison pipe. White and Crocker (5) reported creep data at 925 F for C Mo pipe given the same heat-treatment but from different heats as the pipe used for the service creep tests. Extrapolation of their data to 900 F indicated strengths of 11,000 and 12,500 psi for 0.01 per cent per 1000 hr. In view of such variation, there seems sufficient precedent to assume that the service creep data reflect initial properties more than changes during service.

The similarity of creep and rupture properties of tangential and longitudinal specimens indicated that there was no great difference from this source in the properties of the pipe after service. Because creep in service was circumferential, it could be expected that any damage effect might be most evident in the tangential specimens. The absence of any difference between the longitudinal and circumferential specimens then could be further support to the indication that the 100,000 hr of creep in service had used up only a small fraction of the available service life of the pipe. Without supporting data on the probable relative strengths of longitudinal and tangential specimens for new pipe or for pipe subjected to creep, there is uncertainty in these conclusions.

The elongation and reduction-of-area values for the rupture-test specimens were not as low as have been observed for C Mo Steel. The change from 40 to 20 per cent elongation as the time for fracture increased to 2000 hr is not at all unusual. Certainly there is nothing in these values to suggest undue deterioration during the 100,000 hr of service.

The impact values after service were low. However, impact values of 10 ft-lb are not at all unusual for C Mo steel, particularly when heat-treated at a relatively high temperature, as was the pipe. The difference in relation to the samples reheat-treated after service does not represent an unexpected change. The absence of any difference between longitudinal and tangential specimens again supports the view that creep damage during service was very slight.

The tensile properties after service possibly show some evidence of structural change during service. There is some uncertainty in this observation, because the comparative data for new material are inadequate. In either event, the properties were satisfactory and the changes were no more than might be expected for 100,000 hr of exposure to 900 F under stress.

SUMMARY AND CONCLUSIONS

A unique set of creep curves is presented for the creep of two C Mo steel steam pipes during 100,000 hr of service at 900 F. Analysis of the data shows that the observed creep rates of 0.002 per cent per 1000 hr or less under an operating stress of 7500 psi were in accordance with the predictions of laboratory creep data.

Laboratory creep and rupture tests were carried out on coupons cut from the pipe after the 100,000 hr of service. The creep rates under 7500 psi agreed with the rates observed in service. The creep strength of 12,500 psi for a rate of 0.01 per cent per 1000 hr and the stress for rupture in 100,000 hr of 29,000 psi are the same as the average values for new C Mo steel.

Analysis of the service conditions indicated that 100,000 hr of service at 900 F under 7500 psi would have been expected to use up only a negligible amount of the available creep - rupture life of the steel. All laboratory test results support this conclusion. Deterioration of creep strength due to structural changes, such as spheroidization, was certainly no greater than might have been expected.

The general conclusion is that the pipes performed in service to a remarkable degree in accordance with the predictions of laboratory data.

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Captions for Illustrations

Fig. 1 Sketch showing location of stainless-steel reference buttons used for axial length and diameter measurements during service of C-MO pipe

Fig. 2 Change in circumference of 10-in. C-MO pipe during 100,000 hr of service at 900 F under an operating stress of 7500 psi

Fig. 3 Stress-creep rate data for 0.5 MO steel steam pipe after 100,000 hr service at 900 F

Fig. 4 Stress rupture-time curve for 0.5 steel steam pipe after 100,000 hr service at 900 F

Fig. 5 Creep data at 900 F from C-MO pipe of Delray Station, Detroit Edison Company, after 100,000 hr of service compared with data for C-MO steel reported by The Timken Roller Bearing Company (2) and the Babcock-Wilcox Tube Company (1)

Fig. 6 Creep data at 900 F for C-MO pipe after 100,000 hr of service compared with data for spheroidized C-MO steel, as reported by Weaver (4)

TABLE I

DIAMETRAL MEASUREMENTS OF 10-INCH SCHEDULE 80 CARBON MOLYBDENUM PIPE DURING AND AFTER 100,000 HOURS OF SERVICE

Location	November 1938	August (12,789 hrs) 1940	March (26,937 hrs) 1942	July (43,832 hrs) 1944	June (66,987 hrs) 1947	August (100,135 hrs) 1951	Tot. Change 5 Periods	Cold relaxed position after removal/line (100,135 hrs)
DIAMETRAL OVER STAINLESS STEEL REFERENCE BUTTONS (INCHES)*								
North Position								
1-1	11.2876	11.2921	11.2933	11.2948	11.2984	11.3046	+0.0170	11.3052
2-2	11.2756	11.2791	11.2808	11.2818	11.2844	11.2887	+0.0131	11.2912
3-3	11.3161	11.3201	11.3213	11.3218	11.3244	11.3277	+0.0116	11.3292
4-4	11.3536	11.3581	11.3608	11.3608	11.3644	11.3734	+0.0198	11.3740
South Position								
1-1	11.2304	11.2453	11.2512	11.2548	11.2593	11.2945	+0.0641	11.2732
2-2	11.3044	11.3103	11.3137	11.3153	11.3193	11.3305	+0.0261	11.3332
3-3	11.4924	11.4873	11.4852	11.4798	11.4783	11.4786	-0.0139	11.4812
4-4	11.3794	11.3813	11.3812	11.3808	11.3823	11.3865	+0.0071	11.3892

INSIDE DIAMETERS AFTER SECTIONING (INCHES)

	1-1	Between 1-2	2-2	Between 2-3	3-3	Between 3-4	4-4	Between 4-1
North Connection	9.665	9.666	9.665	9.659	9.666	9.646	9.646	9.657
	9.666	9.654	9.665	9.658	9.661	9.645	9.653	9.653
South Connection	9.564	9.575	9.598	9.651	9.683	9.678	9.648	9.612
	9.525	9.539	9.611	9.673	9.697	9.676	9.641	9.583

CIRCUMFERENTIAL LENGTH COVERED BY REFERENCE POINTS (INCHES)

North Connection -- 5.090
South Connection -- 5.075

* All measurements corrected to 68 F

TABLE II

CALCULATED CREEP RATES OF SCHEDULE 80 CARBON-MOLYBDENUM PIPE DURING 100,000 HOURS SERVICE AT 900 F UNDER A NOMINAL STRESS OF 7,500 PSI

Period	Duration (hours)	Accumulated Time (hours)	Circumferential Creep Rates %/1000 hours: North Connection	Circumferential Creep Rates %/1000 hours: South Connection
First	12,789	0 to 12,789	0.00315	0.00365
Second	14,148	12,789 to 26,937	0.00165	0.00220
Third	16,895	26,937 to 43,832	0.00020	-0.0015
Fourth	23,155	43,832 to 66,987	0.00140	0.00130
Fifth	33,148	66,987 to 100,135	0.00165	0.00470 (a)

(a) Cutting out welds and rewelding may have influenced measurement and creep during the fifth period.

TABLE III

TENSILE PROPERTIES AT ROOM TEMPERATURE FROM THE NORTH CONNECTION C-Mo PIPE AFTER 100,000 HOURS OF SERVICE AT 900 F

Specimen Location	Tensile Strength (psi)	Yield* Point (psi)	Proportional Limit (psi)	Elongation in 1.5 in. (%)	Reduction of Area (%)
2BT	53,000	35,300	27,500	43.3	71.5
2BB	53,400	32,600	- -	42.0	71.8
4BT	53,400	32,100	27,000	41.3	71.8
4BB	53,900	38,000	32,500	42.0	71.0

* Specimens showed a very sharp yield point so that this value also is the same as the offset-yield strength values.

TABLE IV

CHARPY V-NOTCH IMPACT PROPERTIES AT 80 F FOR PIPE METAL FROM THE NORTH CONNECTION

As Removed From Service	Impact Strength (ft - lb)
Tangential	10, 11
Tangential	7, 8
Longitudinal	11, 9.5
Longitudinal	8, 9
Heated 2 Hours at 1900 F, Furnace Cooled	
Tangential	19, 22.5
Tangential	20, 23
Longitudinal	18, 20.5
Longitudinal	20, 22

Note (1): Specimens were held 16 hours at 200 F after machining. Before testing the specimens were equalized to a temperature of 80 F by holding in a water bath at 80 F.

TABLE V

CREEP TEST DATA AT 900 F FOR 0.50 Mo STEEL PIPE AFTER 100,000 HOURS OF SERVICE

Section	Direction	Stress (psi)	Creep Rate - %/1000 hours at indicated time: 1000-hours	Creep Rate - %/1000 hours at indicated time: 2500-hours
North	Longitudinal	7,500	0.002	--
North	Tangential	7,500	(1)	--
South	Longitudinal	7,500	0.002	--
South	Tangential	7,500	(1)	--
North	Longitudinal	12,500	0.012	0.010
North	Tangential	12,500	0.013	0.010

(1) These specimens showed a decrease in length during the first few hours of testing and no measurable creep thereafter out to 1000 hours.

TABLE VI

RUPTURE-TEST DATA AT 900 F FOR 0.50 MO STEEL PIPE AFTER 100,000 HOURS OF SERVICE

Specimen Location	Stress (psi)	Rupture Time (hours)	Elongation (% in 1.5 in.)	Reduction of Area (%)
North Connection				
2 CB - longitudinal	42,700	S.T.T.T.	38.7	76.8
2 CT - longitudinal	40,000	3.5	44.0	76.2
2 CB - longitudinal	38,000	775	30.0	39.6
2 CT - longitudinal	36,000	1803	21.3	26.2
MA2 B3 - tangential	37,000	1482	25.0*	31.4*
South Connection				
SA3 L2 - longitudinal	37,000	1558	20.0	26.1
SA3 R1 - tangential	37,000	1349	23.0*	29.8*

* Tangential specimens were 0.250-inch in diameter with a 1-inch gage length.

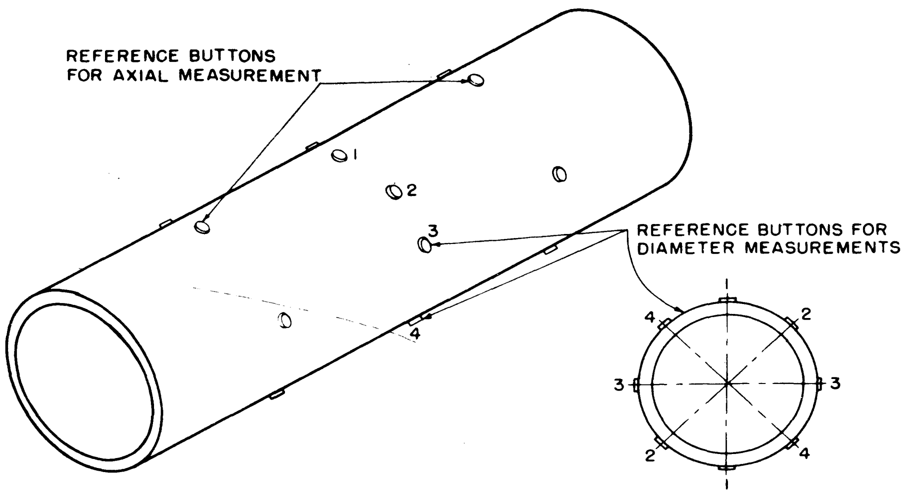

Fig.1

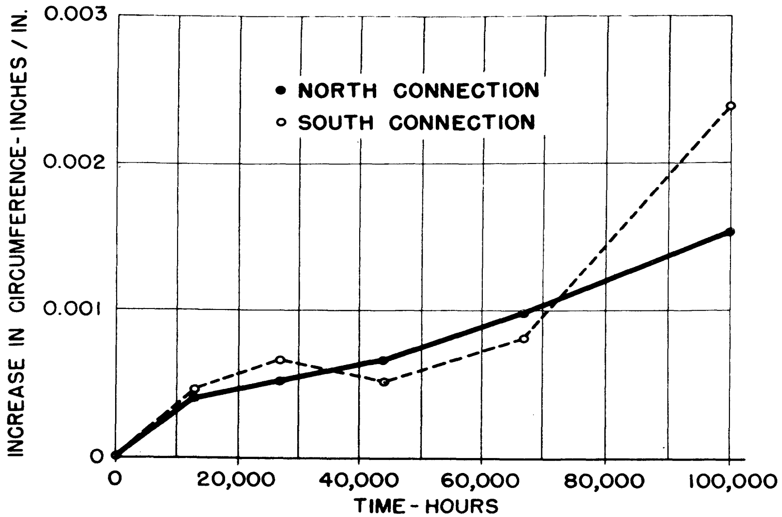

Fig.2

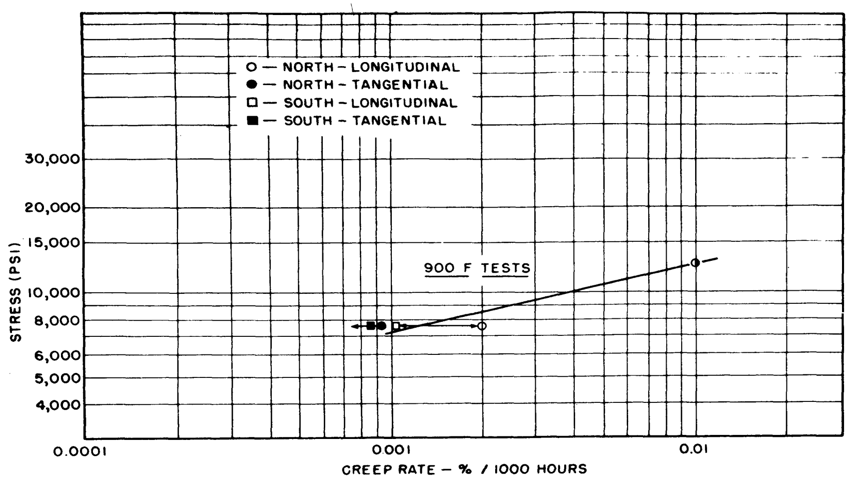

Fig.3

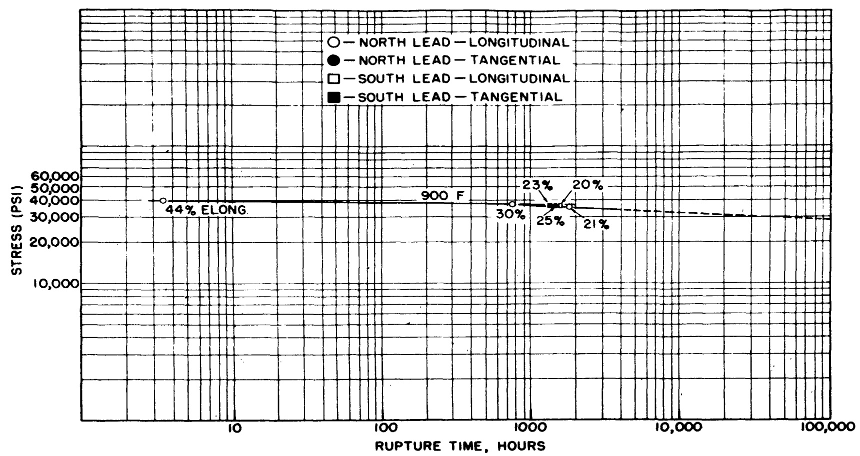

Fig.4

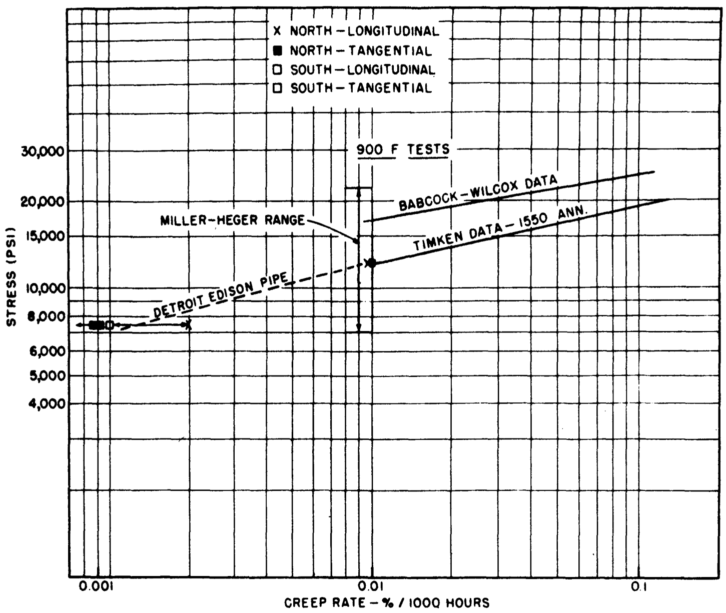
X NORTH – LONGITUDINAL
NORTH – TANGENTIAL
SOUTH – LONGITUDINAL
SOUTH – TANGENTIAL
900 F TESTS
BABCOCK – WILCOX DATA
MILLER–HEGER RANGE
TIMKEN DATA – 1550 ANN.
DETROIT EDISON PIPE
STRESS (PSI)
30,000
20,000
15,000
10,000
8,000
6,000
5,000
4,000
0.001
0.01
0.1
CREEP RATE – % / 1000 HOURS

Fig.5

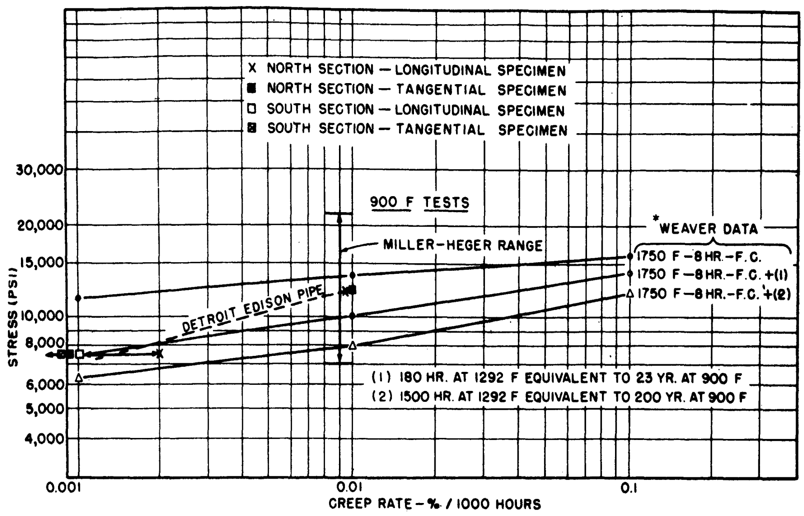
X NORTH SECTION – LONGITUDINAL SPECIMEN
NORTH SECTION – TANGENTIAL SPECIMEN
SOUTH SECTION – LONGITUDINAL SPECIMEN
SOUTH SECTION – TANGENTIAL SPECIMEN
900 F TESTS
MILLER–HEGER RANGE
*WEAVER DATA
1750 F – 8 HR. – F.C.
1750 F – 8 HR. – F.C. + (1)
1750 F – 8 HR. – F.C. + (2)
DETROIT EDISON PIPE
(1) 180 HR. AT 1292 F EQUIVALENT TO 23 YR. AT 900 F
(2) 1500 HR. AT 1292 F EQUIVALENT TO 200 YR. AT 900 F
STRESS (PSI)
30,000
20,000
15,000
10,000
8,000
6,000
5,000
4,000
0.001
0.01
0.1
CREEP RATE – % / 1000 HOURS

Fig.6