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METALLURGY REPORT 3/53

APPLIED RESEARCH DIVISION

The Effect of Heat Treatment on Shrinkage Stress in Built-up Gun Barrels

H. F. Hall

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Metallurgical Report No. 3/53

The Effect of Heat Treatment on Shrinkage Stress in Built-up Gun Barrels.

by*

H.F. Hall

Summary

The experiments described were the result of collaboration between the Armament Design and the Armament Research Establishments. The work was divided into three parts which related to alternative methods of determining the effects of heat treatment on shrinkage stresses in built-up gun barrels.

Part I, contributed by A.D.E. D.10 Group, described full scale experiments using hydraulic pressure to determine elasticity and permanent set in a 3-inch barrel.

Part II, contributed by A.R.E./S.M.R., described a method of measurement of circumferential stress by the dissection from the barrel wall of thin coaxial rings.

Part III, contributed by A.R.E./S.P.M., described an X-ray technique for the measurement of tangential and radial stresses at any selected points on the transverse section of a barrel.

There was a considerable measure of agreement between the results obtained by the three methods. Heat treatment at 400°C produced no appreciable deleterious effect. With treatment at 500°C decreases in bore stress up to 40 per cent were measured. In the full scale tests at 500°C there was no measurable loss of elasticity but permanent set measurements confirmed that stress relaxation had occurred.

The observed changes in the stress system appeared to be related to creep and the means were thus provided for estimating the type of behaviour to be expected with heat treatment conditions outside the limits of time and temperature investigated.

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47 - 50	- Def. Res. Liaison
51	- Nat. Res. Council
52 - 53	TPA3/TIB - Retention

Stock

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The Effect of Heat Treatment on Shrinkage Stress in Built-up Gun Barrels

by

H.F. Hall

List of Contents

Part I

G9/30/A/

Armament Design Establishment - D.10 Group

An Investigation into the Effect of Heat Treatment on Shrinkage

1. Introduction

During the development of the technique for chromium plating gun bores it has been shown by the A.R.E. that the behaviour of the deposit on firing is improved if the barrel is heated after plating to a temperature in the range 400° - 500°C.

In A.R.E. Metallurgy Report No. 12/51, by Dr. R. H. Greaves, the possible effects of such heat treatment on the mechanical properties of the steel are considered. The main conclusions of the report are that, while the effects of the heating on gun steel are relatively insignificant, an autofrettaged barrel or built-up gun subjected to this treatment is likely to be considerably weakened, owing to the reduction of the favourable internal stress. The report states that "in both cases" (i.e. autofrettaged and built-up) at least 80% of the bore compression is likely to be lost if the gun were heated uniformly at 500°C for 1 hour".

The effect of this statement on current methods of gun design and construction is clearly far-reaching. Thus in guns now under development, such as the 3"/70 cals., where the bore is chromium plated and the barrel is constructed by shrinking a grooved water-cooled liner into a jacket, a loss of shrinkage of this order during heat treatment or due to prolonged firing would be very serious. The present report describes a practical investigation directed to testing the truth of Dr. Greaves's suggestion as affecting built-up guns. A parallel investigation, involving measurement of internal stress in rings parted - off from shrunk-up test cylinders, is in progress in the A.R.E.

2. Method

Tests were carried out on a cylinder which was originally constructed for another purpose. The cylinder, to design D.10(G)4602/163, was built up by shrinking a jacket over a grooved liner and represents a portion of the 3"/70 cals. gun barrel.

Fig. 1 shows the construction of the cylinder and the arrangement for applying hydraulic pressure; the positions on the exterior, at the interface and at the bottom of the cooling grooves at which expansions were measured are also shown.

The cylinder was heated successively to 400°, 450° and 500°C, diameter of bore and at the various exterior positions being measured by C.I.A. before the first heating and before and after each subsequent heating and pressure application.

The heat treatment was specified and supervised by C.S.A.R.(S.M.R.) and was carried out in electric furnaces at R.O.F. Woolwich. The cylinder was put into the cold furnace and the temperature raised at a rate of approximately 75° per hour to the specified maximum. The temperature was then held at the maximum and the cylinder soaked for 1 hour. Power was then shut off and the cylinder cooled in the furnace to 300°C before being removed.

After final cooling and measurement, the cylinder was set up in the autofrettage plant at Woolwich and subjected to hydraulic pressure in the bore. Exterior expansion was plotted against pressure, as in the normal autofrettage procedure. Expansion and pressure were measured with the workshop autofrettage equipment. The maximum hydraulic pressure chosen, viz 31.5 tons/sq. in. was one which the cylinder had previously just withstood without showing permanent set, so that any loss of strength caused by the heat treatment would be detected by a departure from straightness in the pressure-expansion line.

3. Results

(a) Time table

Stage	Details	Date
1	Heating to 400°C	18. 7.51
	1st application of hydraulic pressure	10. 8.51
2	Heating to 450°C	27. 8.51
	2nd application of hydraulic pressure	3. 9.51
3	Heating to 500°C	22.10.51
	3rd application of hydraulic pressure	30.10.51

(b) Table 1 gives the measurements of bore and exterior at the various stages.

A slight tendency for the bore and exterior to contract as the trial progressed is detectable. Exterior measurements at the interface and bottom of grooves show some movement in addition, 0.006" mean contraction being registered at the interface at one stage. It is not known whether these contractions were accompanied by any change in length of the cylinder. The final bore movement is of the order of 0.001", which for practical purposes is insignificant. The changes in the exterior diameters are generally of the same order, viz less than 0.002".

(c) Fig. 2 shows the Pressure-Exterior Expansion curves for the 3rd pressure application, i.e. after heating to 500°C. It will be seen that up to 31.5 tons/sq. in. there is no deviation from the elastic line.

4. Strength calculations

The design shrinkage used for the cylinder was 0.006 inch. The theoretical bore compression was of the order of 12 tons/sq.in.

The actual yield of steel for the liner was approximately 59 tons/sq.in. A strength calculation by the Christopherson method as adapted by Manton, (See A.D.E. Technical Note T1/49/9), shows that under an internal pressure of 31.5 tons/sq.in. a Mises-Hencky stress of 67 tons/sq.in. is produced locally in the bore under the "spokes".

Since the cylinder continued to behave elastically under this pressure and the accuracy of the calculation method is well established, the inference is that slight local yielding occurred so as to relieve this stress. The overstressing and presumed local yielding appear to have no bearing on the point at issue, viz loss of shrinkage force.

5. Conclusions

(a) No loss of shrinkage force due to the heating has been shown after three heatings.

(b) The contractions of bore and exterior produced are of no practical significance.

(c) Judging by the results obtained with this test-cylinder the strength of a gun barrel of similar built-up grooved-liner construction will be unaffected by heating uniformly at temperatures up to 500°C for 1 hour.

Note: This degree of heating could be brought about during heat treatment as part of the manufacturing process. There is only a remote possibility of its occurring in operational use, and then only if the water-cooling system broke down.

Table 1 Test Cylinder to design D.10(G)4602/163

Bore and Exterior Measurements

		POSITION	I BEFORE 1st HEAT TREATMENT	II AFTER 1st HEAT TREATMENT	III AFTER 1st PRESS BEFORE 2nd HEAT TREATMENT	IV AFTER 2nd HEAT TREATMENT BEFORE 2nd PRESS	V AFTER 2nd PRESS BEFORE 3rd HEAT TREATMENT	VI AFTER 3rd HEAT TREATMENT BEFORE 3rd PRESS	VII AFTER 3rd PRESSURE
LEFT "A"	BORE	A	3.0889	3.0889	3.0896	3.0895	3.0895	3.0887	3.0889
		B	3.0889	3.0888	3.0886	3.0885	3.0885	3.0871	3.0875
		C	3.0897	3.0896	3.0893	3.0893	3.0891	3.0883	3.0888
		D	3.0945	3.0945	3.0941	3.0941	3.0941	3.0933	3.0935
		E	3.0898	3.0898	3.0896	3.0896	3.0896	3.0892	3.0894
	EXTERIOR	A	4.3126	4.3135	4.3116	4.3136	4.3133	4.3115	4.3114
		B	10.7967	10.7968	10.7968	10.7968	10.7967	10.7960	10.7962
		C	6.5636	6.5626	6.5558	6.5580	6.5579	6.5584	6.5591
		D	10.7935	10.7935	10.7935	10.7936	10.7934	10.7930	10.7931
		E	10.7954	10.7954	10.7954	10.7954	10.7953	10.7950	10.7951
RIGHT "B"	BORE	A	3.0899	3.0895	3.0896	3.0896	3.0896	3.0885	3.0889
		B	3.0887	3.0887	3.0886	3.0883	3.0884	3.0871	3.0877
		C	3.0893	3.0893	3.0890	3.0890	3.0889	3.0880	3.0884
		D	3.0944	3.0945	3.0941	3.0941	3.0940	3.0931	3.0934
		E	3.0897	3.0897	3.0894	3.0894	3.0894	3.0890	3.0891
	EXTERIOR	A	4.3106	4.3085	4.3097	4.3120	4.3100	4.3086	4.3087
		B	10.7950	10.7951	10.7951	10.7953	10.7954	10.7945	10.7947
		C	6.5631	6.5616	6.5592	6.5590	6.5585	6.5583	6.5590
		D	10.7935	10.7924	10.7924	10.7924	10.7922	10.7918	10.7919
		E	10.7943	10.7943	10.7943	10.7944	10.7943	10.7939	10.7937

Part II

References: A.R.E. MR.4752/15
P & P No. 15F2B

The Effect of Heat Treatment on Stresses in Shrunk-on Gun Barrels as determined by the Dissection of Thin Co-axial Rings

1. Introduction

It has been found that where chromium plating is used to provide the bore surface of gun barrels an annealing treatment will improve the useful life of the coating. If such treatment is to be applied to a shrunk-on barrel after building, consideration must be given to the modifying effects it may have on the building stresses, effects which in general will become more serious with increase of temperature.

For the purpose of determining in some detail how the residual stress system is affected by temperature within the range found to be beneficial to the life of the coating, it was decided to make experiments on three short built-up cylinders representing Ordnance Q.F. 3-inch 70 cal., made in steel to specification E.52, No. 1 analysis.

The proposed experimental method consisted of dissecting a series of narrow concentric rings from the end face of the cylinder and measuring the consequent changes in diameter. The strains thus measured would determine the pre-existing circumferential stresses at the particular locations in the barrel from which the rings were taken and this process could be applied repeatedly to relatively short lengths of cylinder. Several sets of measurements could therefore be made, before and after annealing treatments, on a small sample and the effect of the treatment could be directly observed if similar stress conditions existed initially at all cross sections of the sample.

It will be shown that the degree of uniformity of stress was not entirely satisfactory for this purpose and recourse was had to a system of averaging. The results so obtained conformed fairly closely to those required by theoretical considerations and they were regarded as a satisfactory basis for the conclusions which had been drawn relating to the effects of heat treatments at 400°C, 450°C and 500°C.

2. Description of the Test Cylinders

Dimensions and other details of the test cylinders (Table I) have been taken from C.E.A.D. Drawing D.10(G)7428. The cylinders were supplied by C.E.A.D. and were designated No. 1 (grooved jacket), No. 2 (plain tubes) and No. 3 (grooved liner). Each cylinder was 8 inches exterior diameter, 3.074 inches bore diameter and 18 inches in length. The grooves in cylinders Nos. 1 and 3 formed longitudinal water cooling channels at the interface between jacket and liner (Figs. 3 and 5).

It was recorded that before assembly the jackets of cylinders Nos.2 and 3 were 20 inches in length, whereas the jacket of cylinder No. 1 and each of the three liners were 18 inches in length before building. It should be noted that if the jacket protrudes beyond the end of the liner during the shrinking-on operation the liner compression is increased locally thereby. This is unimportant if conditions everywhere remain elastic, but if the increase is sufficient to cause plastic strain the result is a reduction of the intended shrinkage pressure when the jacket is trimmed flush with the end face of the liner.

The temperatures employed for the shrinkage operations were 295°C (563°F) for No. 1 cylinder, 290°C (554°F) for No. 2 cylinder and 265°C (509°F) for No. 3 cylinder.

The test cylinders were gauged by C.I.N.O. before and after building. Bore measurements (Table 2) were taken at 0.5 inch from each end and at 2 inch intervals along the length; exterior measurements were taken at 3 inch intervals. No record was available of the liner exterior or the jacket interior measurements before building, the difference between which represented the shrinkage at the interface. This was specified (Table 1) as 0.005 inch. A calculation was made of this difference based on the bore and exterior measurements (Table 2) of the built-up cylinders. It was assumed that there was no change in the cross sectional area of the tubes and that therefore after expansion or contraction of a tube the ratio of the changes of exterior and interior diameters was inversely proportional to the diameters themselves, they being large in comparison with the changes. The shrinkages at the interface thus calculated were:- 0.00480 inch (Cylinder No. 1), 0.00613 inch (Cylinder No. 2), and 0.00574 inch (Cylinder No. 3).

3. Method of Stress Measurement

The chosen technique was one previously used (1) (2) for the determination of autofrettage stresses in 3.7 inch and 17-pr. gun barrels. In essence it was perhaps the oldest method and its distinctive feature was complete release of stress in one machining operation. This was in contrast with the better known and more generally applicable Mesnager-Sachs boring-out method in which progressive release and redistribution of stress occurred.

The method now to be described might conveniently be termed the "ring dissection method". A section about 2 inches in length was first parted off from the end of a cylinder and the end of this disc was ground and polished to receive gauge marks. These consisted of small ball impressions and were located, symmetrically about the axis, at intervals along two diameters at right angles to one another. The spacing was selected according to the number of circumferential stress measurements required through the wall of the cylinder. A set of gauge marks with approximately similar spacing was made on a polished stainless steel bar and this was used as the basic standard for all measurements.

Two measuring microscopes with micrometer eyepieces reading to 0.001 mm. were set up on a rigid slide as a comparator, Fig. 6 and by their means the small fortuitous differences between gauge distances on the test disc and those on the standard bar were recorded. A set of thin rings (Figs. 3, 4 and 5), 0.2 inch axial thickness, was then parted off by trepanning from the face of the disc, each ring carrying two pairs of the original gauge marks on two diameters at right angles. The gauge distances on the rings were then measured against the same standard as before and the change was noted. Measurement details are given in Tables 7 - 12.

Rings from the liner showed expansion from a state of compression and those from the jacket showed contraction from a state of tension. The mean of the two diametral measurements at right angles was taken to represent true circumferential strain from which the equivalent circumferential stress was calculated. A complete set of rings all from the same transverse section consisted of three from the liner and seven from the jacket of Cylinders Nos. 1 and 3 with water cooling channels. One additional ring was obtained from the jacket of Cylinder No. 2 with a solid wall. Adjacent rings from liner and jacket still locked together by residual stress are shown in Fig. 4.

After removal of a set of rings, which consumed about 0.3 inch axial length of the disc, the end face was again prepared either for a duplicate test or for heat treatment preparatory to further similar tests to show the effect of such treatment.

4. Heat Treatment of Samples

The identity of each test specimen was denoted by its distance from the original breech face of the cylinder. Heat treatment at 500°C and at 400°C was given to the discs as indicated in the table below. Residues of the discs treated at 400°C, after two sets of test rings had been removed, were then heat treated at 450°C.

Cylinder No.	1	2	3
Temperature of Treatment, °C	Distance from Breech Face, inches		
500	2.5-4.5	2.5-4.5	3.4-5.4
400	6.2-7.9	6.15-7.8	6.05-7.7
450	6.8-7.9	6.7-7.8	6.7-7.7

A Wild-Barfield muffle furnace with forced air circulation was used. Three specimens, one from each cylinder, were treated together but to ensure uniform heating and cooling conditions for each disc they were held apart by distance pieces. The temperature was raised at a rate of 75/80°C per hour from room temperature to the desired maximum temperature, at which it was held for 60/75 minutes. The cooling rate was the same as the heating rate down to about 300°C beyond which it was slower.

Material for the X-ray measurements described in Part III of this Report was also taken from these three cylinders. The discs so used were located at 4.9 - 5.4 inches from the breech end of Cylinders Nos. 1 and 2 and at 2.05 - 2.55 inches from the breech end of Cylinder No. 3. These samples have been designated A5, B5 and C2.5 respectively and were heat treated in the same furnace but separately.

5. Results of Measurement of Test Rings

Particulars of the measurement of the test rings are given in some detail, Tables 7 - 12, as general information on the stress distribution in built-up barrels which may be of some interest outside the main purpose of this investigation. The average results of these measurements are collected in Tables 3-5 from which the graphs, Figs. 7-9 have been plotted. Table 6 shows the proportional stress changes due to heat treatment.

5.1 Possible Sources of Error in the System of Measurement

The two measurements distinguished as 'vertical' and 'horizontal' change of diameter, Tables 7-12, were made in the same orientation in the cylinder throughout the series of tests. Where throughout a set of rings the difference between vertical and horizontal readings tended to be in the same direction it suggested slight ovality of either the liner or the jacket at the interface or the presence of an equivalent internal stress before assembly of the two tubes. In the former case a difference of 25 x 10^{-3}mm. in the readings would represent ± 0.0005 inch deviation from the true circle.

Equality of vertical and horizontal readings was an indication that no serious accidental deformation had occurred during machining operations. The greatest divergence between the vertical and horizontal measurements occurred at the jacket exterior, ring diameter 7.86 inches. In Cylinder No. 1 at 5.87 inches from the breech, Table 7, an expansion of 99 x 10^{-3}mm. in the vertical direction was accompanied by a contraction of 216 x 10^{-3}mm. in the horizontal direction but the mean result was rational. The extreme case occurred in Cylinder No. 3 at 8.02 inches from the breech end, Table 11, where a vertical expansion of 148 x 10^{-3}mm. (0.0058 inch) was associated with a horizontal contraction of 305 x 10^{-3}mm. (0.0120 inch). After duplication and careful checking of these measurements only two possible causes for the discrepancies remained, either the existence of local internal stress in the jacket before assembly or accidental deformation of the ring caused by the machining operation. There is reason to suppose it may have been the latter cause owing to the persistent occurrence of the anomaly in the outermost member of the set of rings at 7.86 inches diameter. However, in the extreme case the effect on the average result was too small to invalidate it, and the occurrence was very rare.

5.2 General Stress Conditions before Heat Treatment

The lack of close agreement in what it was hoped would be duplicate confirmatory tests made it necessary to increase the number of tests to obtain a satisfactory average result. In each cylinder there was a tendency for the bore stress to decrease with increase of distance from the breech end but this did not persist for more than about one inch and greater variations were found elsewhere.

Extreme cases of disagreement between adjacent measurements occurred in Cylinder No. 1, where there was a difference of 6.4 tons per sq. inch between the bore stresses measured at 8.2 and 8.5 inches from the breech (Table 3), and in Cylinder No. 3, where a similar difference existed between liner exterior measurements at 8.0 and 8.3 inches from the breech (Table 5). The initial stress condition was therefore computed from measurements made at six locations in each cylinder.

If certain abnormal values are disregarded the range of variation of liner bore stresses may be taken as 10.0 to 14.5 tons per sq. inch in Cylinder No. 1 (Table 3), 14.0 to 17.0 tons per sq. inch in Cylinder No. 2 (Table 4) and 9.0 to 13.0 tons per sq. inch in Cylinder No. 3 (Table 5). The corresponding ranges of variation in the jacket maximum stresses were 6.4 to 8.3 tons per sq. inch, 5.5 to 8.7 tons per sq. inch and 5.8 to 8.3 tons per sq. inch respectively in Cylinders Nos. 1, 2 and 3. Cylinder No. 2 with plain tubes thus possessed the highest liner stress and Cylinder No. 1 with grooved jacket possessed slightly higher liner stress than Cylinder No. 3 with grooved liner.

Although the jacket stresses were similar in range of values the distribution of stress through the wall was not the same in all cylinders. In Cylinder No. 1 the maximum stress occurred at the jacket interior (i.e. at the bottom of the grooves), but in Cylinders Nos. 2 and 3 the maximum was located nearer mid-wall at many cross sections and this persisted after heat treatment in the case of Cylinder No. 3.

The exceptionally low stress of 1 ton per sq. inch at the jacket interior (4.43 inches diameter), which occurred both at the breech end and at 0.7 inch from the breech end of Cylinder No. 2, can possibly be explained as a consequence of plastic strain during building. This could have occurred, as mentioned earlier, when shrinking on a jacket which protruded beyond the end of the liner. In support of this it may be noted that those innermost jacket rings, when parted from the disc, fell apart freely from the adjacent liner rings (4.15 inches diameter) indicating a very low interface pressure, whereas at all other sections the adjacent jacket and liner rings remained locked together after machining and, for final measurement, had to be forced apart in a press.

5.3 Stress Distribution after Heat Treatment

After each heat treatment two tests were made and there was fairly close agreement between the two measurements of bore stress at each temperature, but large differences at mid-wall in the liner occurred in each cylinder after the 400°C treatment. In each case the first test gave the lower stress (Tables 3, 4 and 5) and this was lower by 9.0 tons per sq. inch in the case of Cylinder No. 1. A feature to be noted was that the average of the two widely different results after the 400°C treatment was, in each cylinder, very similar to the average of the two closely agreeing results after the 450°C treatment. This irregularity which appeared in all three cylinders after the 400°C treatment seemed to be explainable only as a special effect of this heat treatment, such for instance as an 'end' effect, but it has not been possible yet to investigate this further. After treatment at 500°C there was very close agreement between two duplicate tests. The liner stresses showed a smaller gradient through the wall in addition to a reduced minimum value and the jacket stresses sustained a relatively uniform reduction of stress throughout the wall thickness in consequence of this treatment.

5.4 Evaluation of the Total Stress at a Transverse Section

The mean stress through the wall of the liner and the jacket has been calculated for each test location. Only half weight was given to the extreme values at the interior and exterior of the wall in relation to the mid-wall values. In general the mean stress values vary in a manner similar to the maximum stresses. If these measured mean stress values, which are derived from total circumferential strain, were proportional to the hoop stresses the liner to jacket ratio would remain constant because the mean hoop stresses in the liner and jacket must be inversely proportional to the respective wall thicknesses.

In Cylinder No. 2 (Table 4) the liner/jacket thickness ratio or mean hoop stress ratio was 3.064 and the measured mean stress ratio varied between 2.7 and 3.3 in all tests before heat treatment. The effect of heat treatment at 500°C was to reduce this ratio to 2.3. In Cylinders Nos. 1 and 3 (Tables 3 and 5) greater variation was found in the measured mean stress ratio and heat treatment appeared to raise it to the upper limit of these variations which was fairly near to the liner/jacket wall thickness ratio of 2.6.

5.5 The Effect of Heat Treatment at 400°C, 450°C and 500°C

The average results from six tests before heat treatment and two tests after each heat treatment have been used to indicate the changes in stress which heat treatment induced. These changes were almost invariably stress relaxations but in a few cases an increase of stress was noted. Results

(Table 6) have been given for each annular element tested through the wall thickness and from these local changes mean stress values for the whole thickness of liner and jacket have been computed.

The highest liner compressive stress and the lowest mean jacket tensile stress occurred in Cylinder No. 2 which was built with plain tubes. The effect of the heat treatment on the liner compressive stress was greatest where the initial stress was greatest; thus, while the bore stress of 15.2 tons per sq. inch in Cylinder No. 2 was reduced by 13, 20 and 39 per cent after heat treatments at 400°C, 450°C and 500°C respectively, at the liner exterior an initial stress of 10.6 tons per sq. inch was reduced by only 4, 9 and 27 per cent after the same heat treatments.

It would appear therefore that when compressive stress is about 10 tons per sq. inch treatments at 400°C or 450°C have little effect but at 500°C there is an appreciable decrease of stress. This view was supported by the results for the liners of Cylinders Nos. 1 and 3 in which the mean stresses were 10.4 and 9.1 tons per sq. inch respectively. After 500°C treatment the decreases of stress were 13 and 14 per cent respectively but after treatment at the lower temperatures they were negligible. It may also be noted that in Cylinder No. 1 the initial stress was comparatively uniform through the liner wall and that the decrease in stress after the 500°C treatment was likewise uniform, whereas in Cylinder No. 3 where a stress gradient from 11.0 to 7.7 tons per sq. inch occurred, the decrease in stress after treatment at 500°C varied from 22 per cent to 2 per cent.

It was probable that the release of tensile stress in the jacket, owing to the comparatively low value of this stress, was purely elastic and mainly an indirect consequence of the liner contraction which was caused by plastic flow. The percentage decrease in stress after treatment at 500°C was comparatively uniform through the wall of each jacket. The mean stress in Cylinders Nos. 1 and 3 decreased from their initial values of 4.9 and 5.0 tons per sq. inch by 35 and 38 per cent respectively. After treatment at 450°C the corresponding decreases were 22 and 16 per cent and after 400°C treatment they were 14 per cent and nil. In the jacket of Cylinder No. 2 the effect on mean stress was similar for each temperature and it seemed probable that 400°C was sufficient to permit a redistribution of stress involving local changes which were large in relation to the mean decrease. The release of stress after treatments at 400°C and 450° was greatest at mid-wall but after 500°C treatment the decrease was more uniform.

6. Experimental Results in Relationship to Theory

A comparison between the experimental and theoretical results has been made for the case of Cylinder No. 2, this design with plain tubes being the most amenable to theoretical treatment. The stress system corresponding with wholly elastic strain set up by the shrinking process has been used for comparison with the stress conditions experimentally determined both before and after heat treatment.

6.1 Theoretical Stress Conditions

The most important stresses in a shrunk-on barrel are circumferential compression in the liner and circumferential tension in the jacket, each attaining maximum values at the inner wall and minimum values at the outer wall if the liner and jacket were free from internal stress before building. In addition, there exists a radial compressive stress in both liner and jacket which attains a maximum value at the interface between them and falls to zero both at the bore of the liner and at the exterior of the jacket.

These stresses may be calculated for a cylinder built of plain tubes, according to theory due to Lame, from the following formulae in which

R_1 = radius at interface of liner and jacket

R_2 = radius at interior of liner

R_3 = radius at exterior of jacket

d = shrinkage at interface (i.e. original difference between diameters of liner and jacket at interface)

P_1 = pressure at interface

E = Young's modulus

$1/m$ = Poisson's ratio

$$\frac{P_1}{E}\left\{\frac{R_3^2 + R_1^2}{R_3^2 - R_1^2} + \frac{R_1^2 + R_2^2}{R_1^2 - R_2^2}\right\} = \frac{d}{2R_1} \qquad (1)$$

Hoop stress at radius x :-

$$\text{in liner} = -P_1 \frac{R_1^2}{R_1^2 - R_2^2}\left(1 + \frac{R_2^2}{x^2}\right) \qquad (2)$$

$$\text{in jacket} = P_1 \frac{R_1^2}{R_3^2 - R_1^2}\left\{\frac{R_3^2}{x^2} + 1\right\} \qquad (3)$$

These hoop stresses are not directly measured by the present experimental method which determines the total hoop strain. The appropriate formulae for use in direct comparison with the experimental results are given below:-

Stress equivalent to total hoop strain at radius x :-

$$\text{in liner} = \frac{P_1 R_1^2}{mx^2(R_1^2 - R_2^2)}\left[x^2(1-m) - R_2^2(1+m)\right] \qquad (4)$$

$$\text{in jacket} = \frac{P_1 R_1^2}{mx^2(R_3^2 - R_1^2)}\left[R_3^2(m+1) + x^2(m-1)\right] \qquad (5)$$

The stresses in a barrel having the dimensions of Cylinder No. 2 with plain tubes have been computed from those formulae (1) to (5). The results for eight locations in the cylinder wall are shown in the graph, Fig. 10, which extends over a range of values of shrinkage at interface, d, from 0.002 inch to 0.008 inch. This corresponds with a range of interface pressure from 1.23 to 4.93 tons per sq. inch. Values of 13,000 tons per sq. inch and 1/3.5 were assumed for Young's modulus, E, and Poisson's ratio, 1/m, respectively.

Four of the locations for which results are shown (Fig. 10) correspond with test positions, two in the liner and two in the jacket. The relevant shrinkage at interface for comparison with the tests before heat treatment is 0.00613 inch, as calculated from the gauge measurements of Cylinder No. 2. The corresponding interface pressure is 3.78 tons per sq. inch. The theoretical stresses for this shrinkage and pressure at interface are indicated in the table below, which also includes in col. 4 the average experimental results obtained before heat treatment.

(1)	(2)	(3)	(4)
Location in Wall of Cylinder Diameter, inches	Hoop Stress tons per sq.in. Theoretical	Stress Equivalent to Hoop Strain tons per sq. inch	
		Theroretical	Experimental
	Compression		
3.074 (liner interior)	15.56	15.56	-
3.21 (c.f. tests, table 4)	14.92	14.73	15.2
4.15 (" " ")	12.06	11.06	10.6
4.284 (liner exterior)	11.78	10.20	-
	Tension		
4.284 (jacket, interior)	6.82	7.90	-
4.43 (c.f. tests, table 4)	6.48	7.46	6.6
7.86 (" ")	3.10	3.11	2.9
8.0 (jacket, exterior)	3.04	3.04	-
	Compression/Tension		
Liner/jacket, mean stress ratio	2.8	2.4	2.7

It will be noted that at the liner interior and the jacket exterior the hoop stress is equal to the stress equivalent to the hoop strain, i.e. the stress measured in these experiments, and that elsewhere in both liner and jacket the difference increases continuously as the interface is approached. The hoop stress is the greater of the two stresses in the liner and the lesser of the two in the jacket.

6.2 Comparison of Test Results with Theoretical Values

The average stresses measured before heat treatment, given in column (4) of the preceding table, are reasonably close to the theoretical values shown in column (3). The differences however combine to produce a measured stress gradient which is greater in the liner and less in the jacket than is the theoretical gradient. Tests at 8.16 and 8.47 inches from the breech end are the individual results nearest to the calculated values.

After treatment at 400°C there was some release of maximum stress in the liner but practically no change in stress at the exterior of liner (Fig. 8). The result was therefore an approach to the theoretical stress gradient. Only a small change occurred in jacket stress and this was uniformly distributed throughout its thickness. After treatment at 450°C there was a small release of stress throughout the liner wall and approximation to the theoretical gradient persisted. After treatment at 500°C the release of stress was much more marked throughout the liner but very little more in the jacket. The stress gradient in the liner had now become less and that in the jacket greater than was demanded by theory but at the interface the liner and jacket stresses agreed with the theoretical relationship. The experimentally determined stress ratio in liner and jacket tended to decrease to the theoretical value with heat treatment at 500°C.

By means of the graph (Fig. 10) an estimate may be made of the decrease in the interface pressure and shrinkage caused by the heat treatments. Because the measured stress results do not conform exactly with theory slightly differing results are obtained depending on which measured stress is selected as the basis. Four sets of results are shown in the following table derived from the stresses measured at diameters near the interior and exterior of both liner and jacket. The average of the two pre-heat treatment liner shrinkage values, 0.00611 inch, agrees well with the shrinkage of 0.00613' inch calculated from the gauge measurements.

Estimate based on stress measured at diameter	Pressure at interface = P_1 Shrinkage at interface = d	Before heat Treatment	After heat treatment at		
			400°C	450°C	500°C
3.21 ins.	P_1 tons/in^2	3.93	3.42	3.13	2.40
(liner)	d inch	0.00632	0.00550	0.00505	0.00388
4.15 ins.	P_1 tons/in^2	3.67	3.52	3.32	2.66
(liner)	d inch	0.00589	0.00566	0.00532	0.00427
4.43 ins.	P_1 tons/in^2	3.38	3.35	3.12	2.90
(jacket)	d inch	0.00543	0.00537	0.00503	0.00464
7.86 ins.	P_1 tons/in^2	3.51	3.40	3.27	2.92
(jacket)	d inch	0.00564	0.00545	0.00526	0.00468

It will be observed that the estimated pressure and shrinkage at the interface as derived from the measured liner stresses are greater than those derived from the jacket stresses before heat treatment. This relationship however is reversed after treatment at 500°C, the lower temperatures of treatment having produced close agreement.

7. Discussion of Results

Many of the results obtained in this investigation can be explained on the basis that creep properties are the controlling influence. Some interest therefore attaches to published data on this subject which indicates the effects on stress release of varying composition of steel, duration of heating and other variables outside the range of this investigation.

7.1 Mode of Stress Release

In a fully tempered steel no structural change is produced by raising the temperature to any point below its transformation temperature and the room temperature mechanical properties are therefore not affected. The mechanical properties at temperatures within such a range are however reversibly affected by change of temperature.

Those properties which are specially relevant to this investigation are the minimum creep stress and the creep rate at a given stress. Creep may be defined as a plastic strain which increases continuously under the influence of a constant stress. It passes through three phases in succession after the load is applied during which the rate of plastic strain decreases rapidly, remains constant and finally increases until fracture occurs.

Constant stress however is not necessary to the definition of creep but merely a convenience in measuring it. In these experiments therefore the process which accompanies the release of residual stress during heat treatment is considered to be analogous to creep and to be governed by the same principles.

7.2 Some Creep Properties of Carbon and Low-Alloy Steels

The investigation of creep properties has been devoted mainly to materials destined for continuous service at high temperatures. An examination of a normalized 0.17 per cent carbon steel for boilers was carried out by Tapsell.(3) The test temperature was 455°C and the results of tests up to 150 hours duration, reproduced in the adjoining table, indicate a rapid and continuous decrease in the rate of strain over this period at each of the stress levels investigated.

Stress, tons per sq. inch	5	6	7	8
Time Interval after loading	Total Strain, per cent (at 455°C)			
Immediate	.0050	.0075	.0094	.0181
10 hours	.0100	.0150	.0212	.0419
50 hours	.0144	.0225	.0312	.0637
150 hours	.0187	.0287	.0400	.0837

Other short time creep test results for carbon steels (4) have shown the effect of temperature variation over the range used in the present investigation. The conditions required to produce 1 per cent strain have been chosen for purposes of comparison in the adjoining table. On this basis it is shown that an increase in temperature from 400°C to 500°C decreases the equivalent creep stress by about one half. This decrease bears no relationship to the decrease in yield point which was comparatively small.

Temperature of Test	400°C	450°C	500°C
Yield Point, tons/in^2	12.1	11.6	10.3
Duration of Loading	Stress, tons per sq. inch (to produce 1 per cent strain)		
1 hour	20.5	16.5	11.2
10 hours	17.0	13.4	8.0
100 hours	13.4	9.8	6.0

The composition of steel has an important influence both on initial creep rate and on creep stress. An increase in carbon or silicon tends not only to reduce the initial creep rate but the total creep is also reduced. In tests (4) carried out at a temperature of 540°C with a stress of about 2.25 tons per sq. inch the strain rate was reduced from 0.16 to 0.01 per cent per 1000 hours by an increase in the carbon content from 0.012 to 0.160 per cent. High manganese also is beneficial. Aluminium is detrimental in carbon steel but has little influence in alloy steels.

The most important elements for the improvement of creep properties in low alloy steels are molybdenum and vanadium. Taking for example (4) a test temperature of 454°C and a strain rate of 0.1 per cent per 1000 hours the addition of 0.53 per cent molybdenum increased the creep stress from 3.39 to 12.72 tons per sq. inch and this was achieved in spite of a decrease in carbon content from 0.35 to 0.16 per cent. For a strain rate reduced to 0.01 per cent per 1000 hours the corresponding increase in creep stress was from 1.52 to 8.93 tons per sq. inch.

The effect of carbon in a 0.5 per cent molybdenum steel, according to Glen (5), varied with the state of strain. At 550°C with a stress of 9 tons per sq. inch increase in carbon up to at least 0.4 per cent produced increase in creep resistance for 0.1 per cent strain, but for 0.2 to 0.5 per cent strain maximum creep resistance required carbon contents to decrease in the range 0.35 to 0.2 per cent.

The raising of the creep limit with addition of molybdenum was shown in the adjoining table, due to Pohl, Scholz and Juretzek (6), to increase with increase in temperature. The improvement in the nickel steel over the plain carbon steel was probably due to the higher carbon content of the former.

Composition				Creep Limit, tons per sq. inch, at Temperature			
C	Mn	Ni	Mo	350°C	400°C	450°C	500°C
.10	.49	-	-	8.75	5.35	3.6	-
.28	.54	2.0	-	12.7	9.5	5.9	3.2
.15	.50	-	.34	11.1	10.15	9.5	7.1

Creep limits at 450°C are almost invariably below the limit of proportionality, according to results quoted by Guillot, Galibourg and Samsoen (7) some of which are reproduced below. They show in addition the advantage of reducing nickel and increasing molybdenum in a hardened and tempered steel.

Composition				Condition	At 450°C	
C	Ni	Cr	Mo		Limit of Proportionality, tons/in.^{2}	Creep Limit tons/in^2
.115	-	-	-	-	5.75	3.56
.22	-	-	-	-	4.3	4.3
.36	4.58	1.43	-	Hardened and Tempered	21.8	5.7
.33	2.74	0.73	.03	"	17.5	11.8
.30	2.78	0.75	.33	"	24.4	16.9
Ni-Cr Steel				Semi-hard	8.7	9.5

Vanadium was shown by Glen (5) to be a useful addition in combination with molybdenum but when used as a single alloy addition it greatly improved creep resistance. This was shown in the following table of results, due to Cross and Lowther (8), where the creep rates and total creep are quoted for a load of 4.47 tons per sq. inch after 500 hours at a temperature of 454°C.

Composition				Rate of Deformation per cent per hour	Total Deformation per cent
C	Mn	Si	V		
.35	.55	.19	-	0.00058	0.523
.37	.70	.16	.18	0.00006	0.120

The specified per centage composition of the No. 1 gun steel used for the test cylinders was: carbon 0.22/0.35, nickel 2.0/3.4, chromium 0.5/1.0, molybdenum 0.35/0.80, manganese 0.4/0.8, silicon 0.05/0.30, vanadium 0.25. According to some of the creep test results quoted (7) this steel should be capable of sustaining heat treatment at 450°C without stress relaxation provided that the initial stress did not exceed 16.9 tons per sq. inch. This value was equal to the highest stress measured in Cylinder No. 2, located at 5.85 inches from the breech (Table 5), but the bore stress must be put a little higher at about 18 tons per sq. inch after allowing for the stress gradient and therefore some creep was to be expected.

The present experimental results however show an appreciable relaxation at this temperature, an average stress of 15.2 tons per sq. inch having been reduced by 20 per cent. The creep results quoted by another authority (6) for a molybdenum steel containing rather less carbon appeared to be more applicable. Here the creep limit was 9.5 tons per sq. inch at 450°C which together with limits of 10.1 and 7.1 tons per sq. inch quoted for 400°C and 500°C conform closely to the results of the present tests.

7.3 Effects of Thermal Expansion and Creep on Residual Stresses

If the temperature of a built up cylinder is raised uniformly throughout its mass the resulting uniform expansion produces no change in the elastic shrinkage stresses except those consequent on a slight change of modulus.

These stresses are dependent on the ratio of dimensions of the two component tubes in the unstressed condition and this remains the same at all temperatures.

The effect of increasing temperature is continously to decrease the minimum creep stress of the steel; when this has fallen below the maximum stress then existing in the cylinder creep occurs locally in that zone of maximum stress which stress is thereby reduced. The maximum is normally the bore compressive stress which is therefore relieved by plastic flow towards the cylinder axis. The result is a reduction of bore diameter. The greater the excess temperature above that corresponding with the limiting creep stress and the longer it is maintained the greater will be the creep strain; but when, as in this case, creep is attended by stress relief it will cease when the minimum creep stress for that particular temperature is attained, and further treatment at that temperature will have no effect.

If the stress gradient is high enough an immediate result of the reduction of bore compressive stress with contraction of bore is a compensating increase in the elastic compressive stress at the exterior of the liner producing an equalizing effect. An example of this occurred in Cylinder No. 3 after both the 400°C and the 450°C treatments (Table 5), but there was normally enough creep throughout the wall thickness to preclude any increase of stress at the exterior of the liner. This was more decidedly the case at higher temperature when very appreciable stress relief by plastic flow occurred throughout the liner wall. It may be observed in the tests of Cylinders Nos. 1 and 2 after the 500°C treatment (Table 6).

An essential condition for these changes to occur in the liner, which involve a reduction of its diameter, is the maintenance of some tension in the jacket. There will however have been some release of tension in the jacket, owing to contraction of the liner, without the occurrence of any creep in the jacket itself. If however jacket stresses are above the minimum creep stress, there will be additional stress relief by creep strain in the jacket accompanied by expansion of its interior surface and an equalization of stress through the wall similar to that described for the liner. This will allow additional stress relief in the liner by simple elastic expansion. As the initial maximum jacket stresses were less than the minimum liner stresses in the experiments after treatment at 500°C there was probably very little release of stress by creep in the jackets of the test cylinders.

It may be assumed that the condition of stress which exists at the temperature when creep ceases still persists after return to room temperature for the reasons given earlier when discussing the effects of heating the cylinder. Because creep rate diminishes rapidly after initial loading, where stress and temperature conditions are maintained constant, it may be suggested that in a built-up cylinder, heated to a given temperature, the stress conditions soon become relatively stable and that holding it at that temperature for a prolonged period will have little further effect.

8. Conclusions

The residual circumferential stresses in three shrunk-on barrel sections have been determined before and after heat treatment for one hour at temperatures 400°C, 450° and 500°C. The barrel sections were 3.074 inches diameter smooth bore, 8 inches exterior diameter and 18 inches in length. Cylinder No. 1 was made with a grooved jacket, No. 2 with plain tubes and No. 3 with a grooved liner. All were made in Ni-Cr-Mo steel to specification E.52 (No. 1) and hardened and tempered.

Circumferential stresses were determined at various diameters in the walls of both liner and jacket by measuring the change in diameter of narrow rings parted off from the end face of a section of cylinder. The initial tests showed some variation in the stress level along the cylinders. Single determinations before and after heat treatment were therefore considered to be insufficient to indicate the effects of heat treatment. The average figures for groups of six tests before and two tests after the treatments were used for this purpose. (Table 6)

8.1 Cylinders Nos. 1 and 3 (with water cooling channels)

(a) The initial stress levels were similar in Cylinders Nos. 1 and 3, the mean liner stresses being 10.4 tons per sq. inch and 9.1 tons per sq. inch (grooved liner) and the mean jacket stresses being 4.9 tons per sq. inch (grooved jacket) and 5.0 tons per sq. inch respectively.

(b) The stress gradient through the liner wall was greater in Cylinder No. 3 (grooved liner) than it was in Cylinder No. 1. The maximum stress in the jacket of Cylinder No. 3 occurred within the wall at about 0.3 inch from the interior jacket surface.

(c) The decrease in stress with treatment at 400°C was nil in the liners of both Cylinders Nos. 1 and 3 and in the No. 3 (plain) jacket. There was a stress decrease of 14 per cent in the No. 1 (grooved) jacket.

(d) With treatment at 450°C the liner stresses in both Cylinders Nos. 1 and 3 were still not appreciably affected but the jacket stresses decreased by about 20 per cent.

(e) With treatment at 500°C the liner stresses of Cylinders Nos. 1 and 3 decreased by 13 and 14 per cent and the jacket stresses by 35 and 38 per cent respectively.

8.2 Cylinder No. 2 (plain tubes)

(a) The initial mean stresses in Cylinder No. 2 were 12.7 tons per sq. inch in the liner and 4.5 tons per sq. inch in the jacket. These stresses were higher in the liner and lower in the jacket than the corresponding stresses in the cylinders with cooling channels. The greater effective wall thickness of the jacket of Cylinder No. 2 accounted for a different ratio between liner and jacket stresses.

(b) With heat treatment at 400°C the initial steep stress gradient through the liner wall, 15.2 to 10.6 tons per sq. inch, was reduced by decrease of the maximum stress at the bore without appreciable change of stress at the liner exterior and the mean liner stress was decreased by 13 per cent.

(c) With heat treatment at 450°C there was further decrease of maximum stress at the bore and a slight decrease of stress at the exterior, the mean value being decreased by 17 per cent.

(d) Heat treatment at 500°C greatly increased the stress release and decreased the mean stress by 30 per cent.

(e) The decrease of mean jacket stress in Cylinder No. 2 with treatment at 500°C was only 16% but it appeared to be no loss with treatment at 400°C. Decrease of stress at mid-wall was the main effect at the lower temperatures but the decrease was more uniformly distributed with 500°C treatment.

8.3. <u>Comparison of Experimental and Theoretical Stress Values</u>

(a) Theoretical stresses equivalent to circumferential strain were calculated for Cylinder No. 2 (plain tubes). They were based on the calculated interface shrinkage of 0.00613 inch and interface pressure of 3.78 tons per sq. inch. The stress values were 14.73 and 11.06 tons per sq. inch near interior and exterior of liner respectively and 7.46 and 3.11 tons per sq. inch near interior and exterior of jacket.

(b) Experimental stress values corresponding with the preceding theoretical values were 15.2 and 10.6 tons per sq. inch for the liner and 6.6 and 2.9 tons per sq. inch for the jacket.

(c) The shrinkage at interface, calculated from the experimentally determined liner stresses, decreased from 0.00611 inch to 0.00588, 0.00518 and 0.00407 inch respectively with heat treatment temperatures of 400, 450 and 500°C. This represented decreases of 8.2, 15.2 and 33.4 per cent respectively. The interface pressures decreased correspondingly from 3.80 tons per sq. inch to 3.47, 3.23 and 2.53 tons per sq. inch respectively.

(d) The shrinkage at interface, calculated from the experimentally determined jacket stresses, decreased from 0.00553 inch to 0.00541, 0.00514 and 0.00466 inch respectively with heat treatment temperatures of 400°C., 450°C and 500°C. This represented decreases of 2.2, 7 and 16 per cent respectively. The interface pressures decreased correspondingly from 3.45 tons per sq. inch to 3.37, 3.19 and 2.91 tons per sq. inch respectively.

(e) Possible causes of the difference in values between the pressure at interface as determined from the liner and jacket stress measurements are the existence of independent internal stress systems within the component tubes and insufficient data for computing mean stress with the necessary accuracy.

9. Bibliography

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Table 1. Particulars of Test Cylinders used for Shrinkage Investigation of Ordnance Q.F. 3 inch 70 Cal.
Extracted from C.E.A.D. Drawing D.10(G)7428, Sheets 1, 2 and 3.

Cylinder No.	1	2	3
Type of Design	Grooved Jacket	Plain Tubes	Grooved Liner
Length of Cylinder, Inches	18.0	18.0	18.0
Diameter: Bore (Liner), inches	3.074	3.074	3.074
Exterior (Jacket) inches	8.0	8.0	8.0
Interface, inches	4.286	4.286	4.786
Number of Grooves (Water cooling channels)	16	-	16
Width of Grooves at Interface, inch	0.4	-	0.5
Depth of Grooves, inch	0.28	-	0.25
Radius at bottom of Grooves, inch	0.15	-	0.25
Effective Wall Thickness Ratio, Jacket/Liner (i.e. at sections through bottom of grooves)	2.602	3.064	2.653
Shrinkage at Interface, inch	0.005	0.005	0.005
Steel Specification	E52, Analysis 1, Yield 45-55 tons/in^2		

Table 2. Measurement of diameter of Cylinders before and after building.
Data extracted from C.I.N.O. Records.

Distance from Breech End inches	Cylinder No. 1		Cylinder No. 2		Cylinder No. 3	
	Bore diameter Decrease inch	Exterior* diameter Increase inch	Bore diameter Decrease inch	Exterior* diameter Increase inch	Bore diameter Decrease inch	Exterior* diameter Increase inch
0.5	0.0035	0.0010	0.0035	0.0020	0.0035	0.0025
2	.0030	.0015	.0030	.0020	.0030	.0025
4	.0030	.0015	.0030	.0020	.0030	.0025
6	.0030	.0020	.0030	.0020	.0030	.0025
8	.0030	.0010	.0030	.0020	.0030	.0020
10	.0030	.0010	.0035	.0020	.0030	.0020
12	.0030	.0015	.0040	.0020	.0030	.0025
14	.0030	.0010	.0035	.0020	.0025	.0025
16	.0030	.0010	.0035	.0020	.0020	.0025
17.5	.0030	.0010	.0035	.0020	.0020	.0020
Average	0.00305	0.00130	0.00335	0.00200	0.00280	0.00235
Bore Decrease + Exterior Increase in diameter	0.00435		0.00535		0.00515	

* Interpolated from measurements at 3-inch intervals.

Table 3. Summary of Stress Determinations made before and after the Heat Treatments.

Cylinder No. 1 Grooved Jacket

Before Heat Treatment							
Distance from Breech End, ins.	0.0	0.34	0.65	5.87	8.20	8.52	All Locations Average
Mean Diameter of Test Ring, ins.	Stress Equivalent to Hoop Strain tons per sq. inch ($E - 13,000$ tons/in^2)						
3.21	-12.6	-10.5	- 9.9	-14.5	- 7.8	-14.2	-11.6
3.68	-11.7	-10.3	- 7.8	-11.4	- 8.1	-11.1	-10.1
4.15	-11.5	- 9.0	- 9.0	- 8.5	- 9.1	-11.0	- 9.7
4.99	+ 6.5	+ 6.6	+ 6.4	+ 8.3	+ 7.8	+ 6.9	+ 7.1
5.46	+ 5.4	+ 6.6	+ 6.6	+ 6.2	+ 6.4	+ 5.2	+ 6.1
5.94	+ 4.3	+ 5.8	+ 5.3	+ 6.2	+ 5.8	+ 5.5	+ 5.5
6.42	+ 4.4	+ 3.6	+ 4.6	+ 4.9	+ 5.7	+ 3.8	+ 4.5
6.90	+ 3.6	+ 4.7	+ 4.1	+ 4.7	+ 5.3	+ 3.1	+ 4.2
7.38	+ 3.3	+ 4.2	+ 4.2	+ 4.8	+ 4.5	+ 4.0	+ 4.2
7.86	+ 3.8	+ 2.1	+ 1.9	+ 3.8	+ 3.1	+ 3.2	+ 3.0
Liner (mean)	-11.9	-10.0	- 8.6	-11.5	- 8.3	-11.9	-10.4
Jacket (mean)	+ 4.4	+ 5.0	+ 4.8	+ 5.5	+ 5.5	+ 4.4	+ 4.9
Liner/Jacket Ratio	2.7	2.0	1.8	2.1	1.5	2.7	2.1

After Heat Treatment for one hour at:-									
Temperature	400°C			450°C			500°C		
Distance from Breech End, ins.	6.20	6.50	Average	6.80	7.10	Average	2.50	2.83	Average
Mean Diameter of Test Ring, ins.	Stress Equivalent to Hoop Strain tons per sq. inch ($E = 13,000$ tons/in^2)								
3.21	-11.6	-13.9	-12.8	-11.6	- 8.3	-10.0	-10.4	- 8.9	- 9.7
3.68	- 5.6	-14.6	-10.1	-10.1	- 9.9	-10.0	- 8.6	- 9.4	- 9.0
4.15	- 8.9	- 7.5	- 8.2	-10.6	- 9.0	- 9.8	- 7.6	- 9.0	- 8.3
4.99	+ 6.0	+ 7.0	+ 6.5	+ 5.5	+ 6.1	+ 5.8	+ 4.4	+ 3.6	+ 4.0
5.46	+ 5.8	+ 5.5	+ 5.7	+ 3.9	+ 5.1	+ 4.5	+ 4.4	+ 2.9	+ 3.7
5.94	+ 4.8	+ 4.0	+ 4.4	+ 4.2	+ 4.2	+ 4.2	+ 4.5	+ 2.2	+ 3.4
6.42	+ 5.0	+ 4.4	+ 4.7	+ 4.2	+ 4.0	+ 4.1	+ 2.6	+ 2.4	+ 2.5
6.90	+ 4.3	+ 2.9	+ 3.6	+ 3.3	+ 3.0	+ 3.2	+ 4.2	+ 3.4	+ 3.8
7.38	+ 4.2	+ 3.2	+ 3.7	+ 2.9	+ 3.0	+ 3.0	+ 2.9	+ 2.2	+ 2.6
7.86	+ 2.3	+ 0.6	+ 1.5	+ 1.6	+ 2.6	+ 2.1	+ 1.6	+ 2.0	+ 1.8
Liner (mean)	- 7.9	-12.7	-10.3	-10.6	- 9.3	-10.0	- 8.8	- 9.2	- 9.0
Jacket (mean)	+ 4.7	+ 4.0	+ 4.2	+ 3.7	+ 3.9	+ 3.8	+ 3.6	+ 2.7	+ 3.2
Liner/Jacket Ratio	1.7	3.2	2.4	2.9	2.4	2.6	2.4	3.4	2.8

Compressive stress indicated by minus sign
Tensile " " " plus "

Table 4. **Summary of Stress Determinations made before and after the Heat Treatment.**

Cylinder No. 2 Plain Tubes.

Before Heat Treatment							
Distance from Breech End, ins.	0.0	0.35/ 0.70	1.05	5.85	8.16	8.47	All Locations Average
Mean Diameter of Test Ring, ins	Stress Equivalent to Hoop Strain tons per sq. inch (E - 13,000 tons/in^2)						
3.21	-16.4	-14.3	-14.0	-16.9	-15.1	-14.6	-15.2
3.68	-12.4	-11.1	-13.1	-12.6	-12.8	-11.8	-12.3
4.15	-10.2	-11.4	-10.0	- 9.4	-12.3	-10.5	-10.6
4.43	+ 1.0*	+ 1.0*	+ 3.5	+ 7.3	+ 8.7	+ 6.8	+ 6.6
4.92	+ 6.1	+ 4.3	+ 7.8	+ 5.3	+ 6.5	+ 5.2	+ 5.9
5.41	+ 7.0	+ 4.8	+ 4.5	+ 4.3	+ 5.2	+ 5.4	+ 5.2
5.90	+ 4.7	+ 5.5	+ 4.5	+ 4.6	+ 6.0	+ 4.5	+ 5.0
6.39	+ 4.9	+ 2.8	+ 4.4	+ 4.2	+ 3.1	+ 2.8	+ 3.7
6.88	+ 5.3	+ 2.5	+ 2.7	+ 2.3	+ 4.4	+ 4.1	+ 3.6
7.37	+ 3.7	+ 2.5	+ 3.1	+ 2.4	+ 5.0	+ 3.0	+ 3.3
7.86	+ 2.3	+ 4.7	+ 4.0	+ 1.5	+ 2.9	+ 2.1	+ 2.9
Liner (mean)	-12.9	-12.0	-12.6	-12.9	-13.7	-12.2	-12.7
Jacket (Mean)	+ 4.8	+ 3.6	+ 4.4	+ 3.9	+ 5.1	+ 4.2	+ 4.5
Liner/Jacket Ratio	2.7	3.2	2.9	3.3	2.7	2.9	2.8

After Heat Treatment for one hour at:-									
Temperature	400°C			450°C			500°C		
Distance from Breech End, ins.	6.17	6.40	Average	6.80	7.15	Average	2.50	2.83	Average
Mean Diameter of Test Ring, ins.	Stress Equivalent to Hoop Strain tons per sq. inch (E = 13,000 tons/in^2)								
3.21	-12.1	-14.3	-13.2	-11.8	-12.3	-12.1	- 8.3	-10.2	- 9.3
3.68	- 7.6	-13.1	-10.4	-10.7	- 9.7	-10.2	- 9.0	- 9.4	- 9.2
4.15	- 9.2	-11.1	-10.2	-10.5	- 8.6	- 9.6	- 7.5	- 7.8	- 7.7
4.43	+ 7.0	+ 6.0	+ 6.5	+ 5.9	+ 6.2	+ 6.1	+ 5.8	+ 4.5	+ 5.2
4.92	+ 5.5	+ 5.7	+ 5.6	+ 5.2	+ 4.9	+ 5.1	+ 5.2	+ 6.2	+ 5.7
5.41	+ 3.5	+ 3.5	+ 3.5	+ 4.4	+ 4.9	+ 4.7	+ 4.6	+ 4.4	+ 4.5
5.90	+ 4.0	+ 3.5	+ 3.8	+ 3.5	+ 3.8	+ 3.7	+ 4.0	+ 3.5	+ 3.8
6.39	+ 4.2	+ 2.4	+ 3.3	+ 3.4	+ 3.6	+ 3.5	+ 3.4	+ 2.8	+ 3.1
6.88	+ 3.0	+ 2.6	+ 2.8	+ 3.0	+ 2.5	+ 2.8	+ 2.9	+ 3.0	+ 3.0
7.37	+ 2.5	+ 4.0	+ 3.3	+ 3.1	+ 2.8	+ 3.0	+ 2.3	+ 2.4	+ 2.4
7.86	+ 2.8	+ 2.4	+ 2.6	+ 3.5	+ 2.1	+ 2.8	+ 3.1	+ 2.1	+ 2.6
Liner (mean)	- 9.1	-12.9	-11.1	-10.9	-10.1	-10.5	- 8.5	- 9.2	- 8.9
Jacket (mean)	+ 3.9	+ 3.7	+ 3.8	+ 3.9	+ 3.8	+ 3.9	+ 3.8	+ 3.7	+ 3.8
Liner/Jacket Ratio	2.3	3.5	2.9	2.8	2.7	2.7	2.2	2.5	2.3

*** Excluded from calculation of average**
Compressive stress indicated by minus sign
Tensile " " " plus "

Table 5 Summary of Stress Determinations made before and after the Heat Treatments.

Cylinder No. 3 Grooved Liner

Before Heat Treatment							
Distance from Breech End, ins.	0.0	0.53	0.85	5.75	8.02	8.33	All Locations Average
Mean Diameter of Test Ring, ins.	Stress Equivalent to Hoop Strain tons per sq. inch (E = 13,000 tons/in^2)						
3.21	-12.9	-11.6	-10.5	-10.8	-11.0	- 8.9	-11.0
3.68	-10.1	- 6.8	- 8.3	-12.2	- 8.2	- 7.5	- 8.9
4.15	- 9.6	- 6.7	- 7.8	-10.3	- 2.6	- 9.0	- 7.7
4.93	+ 6.9	+ 3.9	+ 6.4	+ 2.0	+ 2.9	+ 4.9	+ 4.5
5.42	+ 6.3	+ 5.7	+ 6.5	+ 4.2	+ 8.3	+ 5.8	+ 6.1
5.91	+ 4.5	+ 6.0	+ 5.6	+ 7.8	+ 6.1	+ 5.9	+ 6.0
6.39	+ 3.4	+ 5.4	+ 4.8	+ 4.9	+ 6.6	+ 4.2	+ 4.9
6.88	+ 4.3	+ 4.7	+ 4.6	+ 5.2	+ 6.2	+ 3.3	+ 4.7
7.37	+ 4.2	+ 4.9	+ 3.8	+ 2.9	+ 4.2	+ 4.3	+ 4.1
7.86	+ 3.1	+ 4.0	+ 5.1	+ 2.7	+ 5.1	+ 3.1	+ 3.9
Liner (mean)	-10.7	- 8.2	- 8.7	-11.4	- 7.5	- 8.2	- 9.1
Jacket (mean)	+ 4.6	+ 5.1	+ 5.2	+ 4.6	+ 5.9	+ 4.6	+ 5.0
Liner/Jacket Ratio	2.3	1.[illegible]	[illegible]	2.5	1.3	1.8	1.8

After Heat Treatment for one hour at:-									
Temperature	400°C			450°C			500°C		
Distance from Breech End, ins.	6.03	6.35	Average	6.65	6.95	Average	3.40	3.67	Average
Mean Diameter of Test Ring, ins.	Stress Equivalent to Hoop Strain tons per sq. inch (E = 13,000 tons/in^2)								
3.21	- 8.3	-11.8	-10.1	-11.8	- 9.7	-10.8	- 9.1	- 8.0	- 8.6
3.68	- 6.8	-11.5	- 9.2	- 9.2	- 9.9	- 9.6	- 8.7	- 7.5	- 8.1
4.15	- 7.3	- 9.2	- 8.3	-10.6	-10.2	-10.4	- 5.2	- 7.6	- 6.4
4.93	+ 3.5	+ 4.6	+ 4.1	+ 3.7	+ 3.5	+ 3.6	+ 2.7	+ 1.3	+ 2.0
5.42	+ 7.9	+ 5.1	+ 6.5	+ 5.0	+ 5.1	+ 5.1	+ 5.0	+ 3.6	+ 4.3
5.91	+ 4.2	+ 5.0	+ 4.6	+ 4.9	+ 4.6	+ 4.8	+ 3.7	+ 2.4	+ 3.1
6.39	+ 5.6	+ 6.1	+ 5.9	+ 4.6	+ 4.2	+ 4.4	+ 2.9	+ 2.6	+ 2.8
6.88	+ 5.2	+ 3.9	+ 4.6	+ 3.9	+ 4.3	+ 4.1	+ 2.7	+ 3.0	+ 2.9
7.37	+ 4.4	+ 8.2	+ 6.3	+ 2.6	+ 3.8	+ 3.2	+ 2.6	+ 3.5	+ 3.1
7.86	+ 3.6	+ 3.9	+ 3.8	+ 3.2	+ 2.9	+ 3.1	+ 1.7	+ 2.7	+ 2.2
Liner (mean)	- 7.3	-11.0	-9.2	-10.2	- 9.9	-10.1	- 7.9	- 7.7	- 7.8
Jacket (mean)	+ 5.1	+ 5.4	+ 5.3	+ 4.1	+ 4.2	+ 4.2	+ 3.2	+ 2.9	+ 3.1
Liner/Jacket Ratio	1.4	2.0	1.7	2.5	2.4	2.4	2.5	2.7	2.5

Compressive stress indicated by minus sign
Tensile " " " plus "

Table 6. **Effect of Heat Treatment on Stress Values.**

Mean Diameter of Test Ring inches	Stress before Treatment tons/in.^{2}	Change of Stress after Treatment for 1 hour at temperature 400°C		450°C		500°C	
		tons/in.^{2}	per cent	tons/in.^{2}	per cent	tons/in.^{2}	per cent
	Cylinder No. 1 (Grooved Jacket)						
3.21	11.6 Compression	+ 1.2	+ 10	- 1.6	- 14	- 1.9	- 16
3.68	10.1 "	0.0	0	- 0.1	- 1	- 1.1	- 11
4.15	9.7 "	- 1.5	- 15	+ 0.1	+ 1	- 1.4	- 14
4.99	7.1 Tension	- 0.6	- 8	- 1.3	- 18	- 3.1	- 44
5.46	6.1 "	- 0.4	- 7	- 1.6	- 26	- 2.4	- 39
5.94	5.5 "	- 1.1	- 20	- 1.3	- 24	- 2.1	- 38
6.42	4.5 "	+ 0.2	+ 4	- 0.4	- 9	- 2.[illegible]	- 44
6.90	4.2 "	- 0.6	- 14	- 1.0	- 24	- 0.4	- 10
7.38	4.2 "	- 0.5	- 12	- 1.2	- 29	- 1.6	- 38
7.86	3.0 "	- 1.5	- 50	- 0.9	- 30	- 1.2	- 40
Liner (mean)	10.4 Compression	- 0.1	- 1	- 0.4	- 4	- 1.4	- 13
Jacket (mean)	4.9 Tension	- 0.7	- 14	- 1.1	- 22	- 1.7	- 35
Liner/Jacket Rati	2.1	+ 0.3	-	+ 0.5	-	+ 0.7	-
	Cylinder No. 2 (Plain Tubes)						
3.21	15.2 Compression	- 2.0	- 13	- 3.1	- 20	- 5.9	- 39
3.68	12.3 "	- 1.9	- 15	- 2.1	- 17	- 3.1	- 25
4.15	10.6 "	- 0.4	- 4	- 1.0	- 9	- 2.9	- 27
4.43	6.6 Tension	- 0.1	- 2	- 0.5	- 8	- 1.4	- 21
4.92	5.9 "	- 0.3	- 5	- 0.8	- 14	- 0.2	- 3
5.41	5.2 "	- 1.7	- 33	- 0.5	- 10	- 0.7	- 13
5.90	5.0 "	- 1.2	- 24	- 1.3	- 26	- 1.2	- 24
6.39	3.7 "	- 0.4	- 11	- 0.2	- 54	- 0.6	- 16
6.88	3.6 "	- 0.8	- 22	- 0.8	- 22	- 0.6	- 17
7.37	3.3 "	0.0	0	- 0.3	- 10	- 0.9	- 27
7.86	2.9 "	- 0.3	- 10	- 0.1	- 3	- 0.3	- 10
Liner (Mean)	12.7 Compression	- 1.6	- 13	- 2.2	- 17	- 3.8	- 30
Jacket (Mean)	4.5 Tension	- 0.7	- 16	- 0.6	- 13	- 0.7	- 16
Liner/Jacket Ratio	2.8	+ 0.1	-	- 0.1	-	- 0.5	-
	Cylinder No. 3 (Grooved Liner)						
3.21	11.0 Compression	- 0.9	- 8	- 0.2	- 2	- 2.4	- 22
3.68	8.9 "	+ 0.3	+ 3	+ 0.7	+ 8	- 0.8	- 9
4.15	7.7 "	+ 0.6	+ 8	+ 2.7	+ 35	- 1.3	- 2
4.93	4.5 Tension	- 0.4	- 9	- 0.9	- 20	- 2.5	- 56
5.42	6.1 "	+ 0.4	+ 7	- 1.0	- 16	- 1.8	- 30
5.91	6.0 "	- 1.4	- 23	- 1.2	- 20	- 2.9	- 48
6.39	4.9 "	+ 1.0	+ 20	- 0.5	- 10	- 2.1	- 43
6.88	4.7 "	- 0.1	- 2	- 0.6	- 13	- 1.8	- 38
7.37	4.1 "	+ 2.2	+ 54	- 0.9	- 22	- 1.0	- 24
7.86	3.9 "	- 0.1	- 3	- 0.8	- 21	- 1.7	- 44
Liner (mean)	9.1 Compression	+ 0.1	+ 1	+ 1.0	+ 11	- 1.3	- 14
Jacket (mean)	5.0 Tension	+ 0.3	+ 6	- 0.8	- 16	- 1.9	- 38
Liner/Jacket Ratio	1.8	- 0.1	-	+ 0.6	-	+ 0.7	-

Table 7 Measurement of Rings for Stress Determination

Cylinder No. 1 Before Heat Treatment

Mean Diameter of Test Ring inches	Change in Diameter of Ring after Parting Off millimetres x 10^3			* Stress equivalent to Hoop Strain tons/in^2	Change in Diameter of Ring after Parting off millimetres x 10^3			* Stress equivalent to Hoop Strain tons/in^2
	Vertical	Horizontal	Mean		Vertical	Horizontal	Mean	
	0.0 inch from Breech End				0.34 inch from Breech End			
3.21	+ 84	+ 74	+ 79	- 12.6	+ 64	+ 61	+ 63	- 10.5
3.68	+ 84	+ 84	+ 84	- 11.7	+ 76	+ 71	+ 74	- 10.3
4.15	+123	+ 64	+ 93	- 11.5	+ 81	+ 64	+ 73	- 9.0
4.99	- 99	- 26	- 63	+ 6.5	- 84	- 44	- 64	+ 6.6
5.46	- 61	- 54	- 58	+ 5.4	- 84	- 55	- 70	+ 6.6
5.94	- 58	- 42	- 50	+ 4.3	- 83	- 51	- 67	+ 5.8
6.42	- 70	- 40	- 55	+ 4.4	- 54	- 35	- 45	+ 3.6
6.90	- 53	- 42	- 48	+ 3.6	- 62	- 66	- 64	+ 4.7
7.38	- 73	- 30	- 51	+ 3.3	- 70	- 50	- 60	+ 4.2
7.86	- 59	-	- 59	+ 3.8	- 64	- 1	- 33	+ 2.1
	0.65 inch from Breech End				5.87 inches from Breech End			
3.21	+ 70	+ 53	+ 62	- 9.9	+ 95	+ 87	+ 91	- 14.5
3.68	+ 60	+ 52	+ 56	- 7.8	+ 78	+ 86	+ 82	- 11.4
4.15	+ 81	+ 66	+ 73	- 9.0	+ 72	+ 66	+ 69	- 8.5
4.99	- 76	- 48	- 62	+ 6.4	- 81	- 80	- 81	+ 8.3
5.46	- 73	- 67	- 70	+ 6.6	- 72	- 60	- 66	+ 6.2
5.94	- 63	- 58	- 61	+ 5.3	- 80	- 63	- 72	+ 6.2
6.42	- 71	- 44	- 58	+ 4.6	- 65	- 58	- 62	+ 4.9
6.90	- 67	- 43	- 55	+ 4.1	- 65	- 62	- 64	+ 4.7
7.38	- 64	- 56	- 60	+ 4.2	- 73	- 64	- 69	+ 4.8
7.86	- 81	+ 21	- 30	+ 1.9	+ 99	-216	- 58	+ 3.8
	8.20 inches from Breech End				8.52 inches from Breech End			
3.21	+ 54	+ 44	+ 49	- 7.8	+100	+ 77	+ 89	- 14.2
3.68	+ 86	+ 29	+ 58	- 8.1	+ 90	+ 69	+ 80	- 11.1
4.15	+111	+ 38	+ 74	- 9.1	+ 96	+ 86	+ 91	- 11.0
4.99	- 69	- 83	- 76	+ 7.8	- 62	- 72	- 67	+ 6.9
5.46	- 77	- 59	- 68	+ 6.4	- 54	- 57	- 56	+ 5.2
5.94	- 70	- 65	- 67	+ 5.8	- 65	- 62	- 64	+ 5.5
6.42	- 57	- 87	- 72	+ 5.7	- 53	- 42	- 48	+ 3.8
6.90	- 76	- 69	- 72	+ 5.3	- 35	- 49	- 42	+ 3.1
7.38	- 71	- 59	- 65	+ 4.5	- 58	- 57	- 58	+ 4.0
7.86	- 51	- 46	- 48	+ 3.1	- 52	- 46	- 49	+ 3.2

*** Assumed Young's Modulus E = 13,000 tons per sq. inch.**
Compressive Stress indicated by minus sign.
Tensile Stress indicated by plus sign.

Table 8. Measurement of Rings for Stress Determination

Cylinder No. 1 After Heat Treatment

Mean Diameter of Test Ring inches	Change in Diameter of Ring after Parting Off millimetres x 10^3 Vertical	Horizontal	Mean	* Stress Equivalent to Hoop Strain tons/in²	Change in Diameter of Ring after Parting Off millimetres x 10^3 Vertical	Horizontal	Mean	* Stress equivalent to Hoop Strain tons/in²
After Treatment for 1 Hour at 400°C								
	6.20 inches from Breech End				6.50 inches from Breech End			
3.21	+102	+ 44	+ 73	- 11.6	+103	+ 71	+ 87	- 13.9
3.68	+ 45	+ 35	+ 40	- 5.6	+121	+ 88	+105	- 14.6
4.15	+101	+ 44	+ 72	- 8.9	+ 80	+ 42	+ 61	- 7.5
4.99	- 57	- 61	- 59	+ 6.0	- 57	- 78	- 68	+ 7.0
5.46	- 72	- 51	- 62	+ 5.8	- 33	- 85	- 59	+ 5.5
5.94	- 43	- 68	- 56	+ 4.8	- 87	- 6	- 47	+ 4.0
6.42	- 22	-104	- 63	+ 5.0	- 53	- 57	- 55	+ 4.4
6.90	-127	+ 11	- 58	+ 4.5	- 56	- 21	- 39	+ 2.9
7.38	- 70	- 52	- 61	+ 4.2	- 49	- 44	- 47	+ 3.2
7.86	- 34	- 38	- 36	+ 2.3	+ 11	- 28	- 9	+ 0.6
After Treatment for 1 Hour at 450°C								
	6.80 inches from Breech End				7.10 inches from Breech End			
3.21	+ 82	+ 64	+ 73	- 11.6	+ 37	+ 66	+ 52	- 8.3
3.68	+ 88	+ 59	+ 73	- 10.1	+ 77	+ 65	+ 71	- 9.9
4.15	+ 75	+ 97	+ 86	- 10.6	+ 81	+ 66	+ 73	- 9.0
4.99	- 50	- 58	- 54	+ 5.5	- 58	- 62	- 60	+ 6.1
5.46	- 23	- 61	- 42	+ 3.9	- 52	- 57	- 55	+ 5.1
5.94	- 34	- 65	- 49	+ 4.2	- 44	- 53	- 49	+ 4.2
6.42	- 32	- 74	- 53	+ 4.2	- 48	- 51	- 50	+ 4.0
6.90	- 67	- 21	- 44	+ 3.3	- 41	- 41	- 41	+ 3.0
7.38	- 39	- 45	- 42	+ 2.9	-133	+ 44	- 44	+ 3.0
7.86	+ 4	- 52	- 24	+ 1.6	- 6	- 74	- 40	+ 2.6
After Treatment for 1 Hour at 500°C								
	2.50 inches from Breech End				2.83 inches from Breech End			
3.21	+ 80	+ 49	+ 65	- 10.4	+ 41	+ 71	+ 56	- 8.9
3.68	+ 63	+ 60	+ 62	- 8.6	+ 71	+ 70	+ 71	- 9.4
4.15	+ 77	+ 46	+ 62	- 7.6	+ 84	+ 62	+ 73	- 9.0
4.99	- 48	- 38	- 43	+ 4.4	- 54	- 15	- 35	+ 3.6
5.46	- 51	- 43	- 47	+ 4.4	- 45	- 17@	- 31	+ 2.9
5.94	- 62	- 42@	- 52	+ 4.5	- 33	- 19	- 26	+ 2.2
6.42	- 37	- 29	- 33	+ 2.6	- 43	- 16	- 30	+ 2.4
6.90	- 67	- 47	- 57	+ 4.2	- 65	- 27	- 46	+ 3.4
7.38	- 50	- 35	- 42	+ 2.9	- 65	+ 1	- 32	+ 2.2
7.86	- 34	- 16	- 25	+ 1.6	- 20	- 43	- 31	+ 2.0

* Assumed Young's Modulus E = 13,000 tons per sq. inch
Compression stress indicated by minus sign
Tensile Stress indicated by plus sign.

@ Interpolated values.

Table 9 Measurement of Rings for Stress Determination

Cylinder No. 2 Before Heat Treatment

Mean Diameter of Test Ring inches	Change in Diameter of Ring after Parting Off millimetres x 10^3 Vertical	Horizontal	Mean	* Stress equivalent to Hoop Strain tons/in^2	Change in Diameter of Ring after Parting Off millimetres x 10^3 Vertical	Horizontal	Mean	* Stress equivalent to Hoop Strain tons/in^2
	0.0 inch from Breech End				∅ 0.35/0.70 inch from Breech End			
3.21	+ 94	+113	+103	- 16.4	+ 90	+ 89	+ 90	- 14.3
3.68	+ 91	+ 87	+ 89	- 12.4	+ 75	+ 84	+ 80	- 11.1
4.15	+ 75	+ 92	+ 83	- 10.2	+ 83	+ 51	+ 67	- 11.4
4.43	- 5	- 13	- 9	+ 1.0	+ 3	- 21	- 9	+ 1.0
4.92	- 58	- 60	- 59	+ 6.1	- 50	- 32	- 41	+ 4.3
5.41	- 75	- 73	- 74	+ 7.0	- 54	- 48	- 51	+ 4.8
5.90	- 52	- 57	- 54	+ 4.7	- 72	- 56	- 64	+ 5.5
6.39	- 68	- 54	- 61	+ 4.9	- 35	- 35	- 35	+ 2.8
6.88	- 79	- 63	- 71	+ 5.3	- 39	- 30	- 34	+ 2.5
7.37	- 58	- 49	- 54	+ 3.7	- 40	- 32	- 36	+ 2.5
7.86	+ 13	- 49	- 36	+ 2.3	-105	- 40	- 72	+ 4.7
	1.05 inches from Breech End				5.85 inches from Breech End			
3.21	+ 87	+ 89	+ 88	- 14.0	+109	+103	+106	- 16.9
3.68	+ 98	+ 91	+ 94	- 13.1	+ 92	+ 89	+ 91	- 12.6
4.15	+ 68	+ 93	+ 81	- 10.0	+ 76	+ 76	+ 76	- 9.4
4.43	- 29	- 30	- 30	+ 3.5	- 51	- 74	- 63	+ 7.3
4.92	- 62	- 87	- 75	+ 7.8	- 61	- 41	- 51	+ 5.3
5.41	- 34	- 62	- 48	+ 4.5	- 42	- 50	- 46	+ 4.3
5.90	- 57	- 38	- 48	+ 4.5	- 56	- 50	- 53	+ 4.6
6.39	- 45	- 64	- 55	+ 4.4	- 50	- 56	- 53	+ 4.2
6.88	- 25	- 48	- 37	+ 2.7	- 31	- 31	- 31	+ 2.3
7.37	- 54	- 35	- 45	+ 3.1	- 28	- 40	- 34	+ 2.4
7.86	- 40	- 83	- 61	+ 4.0	+ 94	-140	- 23	+ 1.5
	8.16 inches from Breech End				8.47 inches from Breech End			
3.21	+102	+ 88	+ 95	- 15.1	+ 91	+ 92	+ 92	- 14.6
3.68	+ 82	+102	+ 92	- 12.8	+ 85	+ 84	+ 85	- 11.8
4.15	+ 96	+103	+100	- 12.3	+ 87	+ 83	+ 85	- 10.5
4.43	- 73	- 76	- 75	+ 8.7	- 55	- 62	- 59	+ 6.8
4.92	- 65	- 60	- 63	+ 6.5	- 53	- 47	- 50	+ 5.2
5.41	- 58	- 51	- 55	+ 5.2	- 58	- 56	- 57	+ 5.4
5.90	- 58	- 81	- 69	+ 6.0	- 49	- 55	- 52	+ 4.5
6.39	- 7	- 70	- 39	+ 3.1	- 41	- 29	- 35	+ 2.8
6.88	-106	- 12	- 59	+ 4.4	- 52	- 58	- 55	+ 4.1
7.37	- 68	- 77	- 72	+ 5.0	- 37	- 50	- 44	+ 3.0
7.86	+ 34	-124	- 45	+ 2.9	- 18	- 48	- 33	+ 2.1

* Assumed Young's Modulus E = 13,000 tons per sq. inch
Compression Stress indicated by minus sign.
Tensile Stress indicated by plus sign.
∅ Results for Liner only at 0.35 inch from Breech End
" " Jacket " " 0.70 " " " "
Complementary results lost owing to machining errors.

Table 10. Measurement of Rings for Stress Determination

Cylinder No. 2 After Heat Treatment

Mean Diameter of Test Ring inches	Change in Diameter of Ring after Parting Off millimetres x 10^3			* Stress equivalent to Hoop Strain tons/in^2	Change in Diameter of Ring after Parting Off millimetres x 10^3			* Stress equivalent to Hoop Strain tons/in^2
	Vertical	Horizontal	Mean		Vertical	Horizontal	Mean	
After Treatment for 1 Hour at 400°C								
	6.17 inches from Breech End				6.40 inches from Breech End			
3.21	+ 68	+ 84	+ 76	- 12.1	+ 90	+ 89	+ 90	- 14.3
3.68	+ 52	+ 57	+ 55	- 7.6	+ 87	+100	+ 94	- 13.1
4.15	+ 74	+ 75	+ 75	- 9.2	+ 83	+ 96	+ 90	- 11.1
4.43	- 40	- 82	- 61	+ 7.0	- 52	- 51	- 52	+ 6.0
4.92	- 49	- 56	- 53	+ 5.5	- 43	- 67	- 55	+ 5.7
5.41	- 21	- 52	- 37	+ 3.5	- 14	- 59	- 37	+ 3.5
5.90	- 52	- 40	- 46	+ 4.0	- 5	- 75	- 40	+ 3.5
6.39	- 41	- 65	- 53	+ 4.2	- 58	- 2	- 30	+ 2.4
6.88	- 47	- 34	- 41	+ 3.0	- 7	- 62	- 35	+ 2.6
7.37	- 33	- 39	- 36	+ 2.5	- 66	- 48	- 57	+ 4.0
7.86	- 36	- 51	- 43	+ 2.8	- 10	- 64	- 37	+ 2.4
After Treatment for 1 Hour at 450°C								
	6.80 inches from Breech End				7.15 inches from Breech End			
3.21	+ 88	+ 60	+ 74	- 11.8	+ 75	+ 79	+ 77	- 12.3
3.68	+ 62	+ 92	+ 77	- 10.7	+ 68	+ 72	+ 70	- 9.7
4.15	+ 90	+ 80	+ 85	- 10.5	+ 70	+ 71	+ 70	- 8.6
4.43	- 35	- 66	- 51	+ 5.9	- 52	- 56	- 54	+ 6.2
4.92	- 60	- 39	- 50	+ 5.2	- 45	- 49	- 47	+ 4.9
5.41	- 36	- 57	- 47	+ 4.4	- 51	- 54	- 52	+ 4.9
5.90	- 40	- 40	- 40	+ 3.5	- 44	- 45	- 44	+ 3.8
6.39	- 63	- 24	- 43	+ 3.4	- 43	- 47	- 45	+ 3.6
6.88	- 13	- 66	- 40	+ 3.0	- 32	- 36	- 34	+ 2.5
7.37	- 27	- 63	- 45	+ 3.1	- 54	- 26	- 40	+ 2.8
7.86	+ 17	-126	- 54	+ 3.5	+ 42	-106	- 32	+ 2.1
After Treatment for 1 Hour at 500°C								
	2.50 inches from Breech End				2.83 inches from Breech End			
3.21	+ 55	+ 50	+ 52	- 8.3	+ 63	+ 64	+ 64	- 10.2
3.68	+ 64	+ 66	+ 65	- 9.0	+ 65	+ 72	+ 68	- 9.4
4.15	+ 67	+ 56	+ 61	- 7.5	+ 73	+ 54	+ 63	- 7.8
4.43	- 52	- 48	- 50	+ 5.8	- 38	- 39	- 39	+ 4.5
4.92	- 46	- 54	- 50	+ 5.2	- 62	- 57	- 60	+ 6.2
5.41	- 42	- 56	- 49	+ 4.6	- 40	- 54	- 47	+ 4.4
5.90	- 41	- 52	- 46	+ 4.0	- 38	- 41	- 40	+ 3.5
6.39	- 45	- 42	- 43	+ 3.4	- 48	- 22	- 35	+ 2.8
6.88	- 30	- 48	- 39	+ 2.9	- 42	- 37	- 40	+ 3.0
7.37	- 25	- 42	- 33	+ 2.3	- 45	- 23	- 34	+ 2.4
7.86	- 55	- 41	- 48	+ 3.1	+ 30	- 97	- 33	+ 2.1

* Assumed Young's Modulus E = 13,000 tons per sq. inch
Compressive Stress indicated by minus sign.
Tensile Stress indicated by plus sign.

Table 11. Measurement of Rings for Stress Determination

Cylinder No. 3 Before Heat Treatment

Mean Diameter of Test Ring inches	Change in Diameter of Ring after Parting Off millimetres x 10^3			* Stress equivalent to Hoop Strain tons/in²	Change in Diameter of Ring after Parting Off millimetres x 10^3			* Stress equivalent to Hoop Strain tons/in²
	Vertical	Horizontal	Mean		Vertical	Horizontal	Mean	
	0.0 inch from Breech End				0.53 inch from Breech End			
3.21	+ 70	+ 92	+ 81	- 12.9	+ 49	+ 96	+ 73	- 11.6
3.68	+ 68	+ 78	+ 73	- 10.1	+ 45	+ 51	+ 48	- 6.8
4.15	+ 74	+ 82	+ 78	- 9.6	+ 33	+ 77	+ 55	- 6.7
4.93	- 58	- 77	- 67	+ 6.9	- 39	- 36	- 38	+ 3.9
5.42	- 70	- 64	- 67	+ 6.[illegible]	- 72	- 47	- 60	+ 5.7
5.91	- 52	-	- 52	+ 4.5	- 84	- 53	- 69	+ 6.0
6.39	- 42	- 41	- 42	+ 3.4	- 78	- 55	- 67	+ 5.4
6.88	- 76	- 40	- 58	+ 4.3	- 64	- 62	- 63	+ 4.7
7.37	- 63	- 58	- 60	+ 4.2	- 74	- 66	- 70	+ 4.9
7.86	-118	+ 21	- 48	+ 3.1	-115	- 7	- 61	+ 4.0
	0.85 inch from Breech End				5.75 inches from Breech End			
3.21	+ 51	+ 80	+ 66	- 10.5	+ 69	+ 66	+ 68	- 10.8
3.68	+ 63	+ 58	+ 60	- 8.3	+ 74	+102	+ 88	- 12.2
4.15	+ 64	+ 61	+ 63	- 7.8	+ 94	+ 74	+ 84	- 10.3
4.93	- 55	- 68	- 62	+ 6.4	- 21	- 16	- 19	+ 2.0
5.42	- 69	- 70	- 69	+ 6.5	- 60	- 30	- 45	+ 4.2
5.91	- 73	- 58	- 65	+ 5.6	-117	- 63	- 90	+ 7.8
6.39	- 62	- 56	- 59	+ 4.8	- 44	- 78	- 61	+ 4.9
6.88	- 63	- 62	- 62	+ 4.6	- 64	- 77	- 70	+ 5.2
7.37	- 60	- 49	- 55	+ 3.8	- 44	- 41	- 42	+ 2.9
7.86	- 83	- 74	- 78	+ 5.1	- 76	- 7	- 41	+ 2.7
	8.02 inches from Breech End				8.33 inches from Breech End			
3.21	+ 74	+ 64	+ 69	- 11.0	+ 72	+ 40	+ 56	- 8.9
3.68	+ 58	+ 60	+ 59	- 8.2	+ 62	+ 46	+ 54	- 7.5
4.15	+ 21	+ 20	+ 21	- 2.6	+ 76	+ 71	+ 73	- 9.0
4.93	- 24	- 31	- 28	+ 2.9	- 34	- 60	- 47	+ 4.9
5.42	- 77	- 98	- 88	- 8.3	- 65	- 58	- 61	+ 5.8
5.91	- 52	- 89	- 70	+ 6.1	- 62	- 75	- 68	+ 5.9
6.39	- 71	- 94	- 82	+ 6.6	- 48	- 55	- 52	+ 4.2
6.88	- 75	- 91	- 83	+ 6.2	- 41	- 47	- 44	+ 3.3
7.37	- 59	- 61	- 60	+ 4.2	- 54	- 70	- 62	+ 4.3
7.86	+148	-305	- 78	+ 5.1	+ 8	-105	- 48	+ 3.1

* Assumed Young's Modulus E = 13,000 tons per sq. inch
Compression Stress indicated by minus sign.
Tensile Stress indicated by plus sign.

Table 12. Measurement of Rings for Stress Determination

Cylinder No. 3 After Heat Treatment

Mean Diameter of Test Ring inches	Change of Diameter of Ring after Parting Off millimetres x 10^3			* Stress equivalent to Hoop Strain tons/in^2	Change in Diameter of Ring after Parting Off millimetres x 10^3			* Stress equivalent to Hoop Strain tons/in^2
	Vertical	Horizontal	Mean		Vertical	Horizontal	Mean	
After Treatment for 1 Hour at 400°C								
	6.03 inches from Breech End				6.35 inches from Breech End			
3.21	+ 58	+ 45	+ 52	- 8.3	+ 70	+ 77	+ 74	- 11.8
3.68	+ 45	+ 53	+ 49	- 6.8	+ 88	+ 77	+ 83	- 11.5
4.15	+ 61	+ 58	+ 59	- 7.3	+ 69	+ 81	+ 75	- 9.2
4.93	- 33	- 34	- 34	+ 3.5	- 42	- 46	- 44	+ 4.6
5.42	- 83	- 85	- 84	+ 7.9	- 49	- 58	- 54	+ 5.1
5.91	- 49	- 47	- 48	+ 4.2	- 40	- 76	- 58	+ 5.0
6.39	- 64	- 77	- 70	+ 5.6	- 27	-125	- 76	+ 6.1
6.88	- 60	- 79	- 70	+ 5.2	- 18	- 86	- 52	+ 3.9
7.37	- 41	- 84	- 62	+ 4.4	- 85	-152	-118	+ 8.2
7.86	- 10	-102	- 56	+ 3.6	- 15	-106	- 60	+ 3.9
After Treatment for 1 Hour at 450°C								
	6.65 inches from Breech End				6.95 inches from Breech End			
3.21	+ 70	+ 77	+ 74	- 11.8	+ 60	+ 61	+ 61	- 9.7
3.68	+ 70	+ 63	+ 66	- 9.2	+ 72	+ 71	+ 71	- 9.9
4.15	+ 91	+ 81	+ 86	- 10.6	+121	+ 45	+ 83	- 10.2
4.93	- 38	- 33	- 36	+ 3.7	- 30	- 38	- 34	+ 3.5
5.42	- 61	- 44	- 53	+ 5.0	- 57	- 51	- 54	+ 5.1
5.91	- 58	- 57	- 57	+ 4.9	- 52	- 54	- 53	+ 4.6
6.39	- 62	- 55	- 58	+ 4.6	- 49	- 58	- 53	+ 4.2
6.88	- 51	- 56	- 53	+ 3.9	- 57	- 60	- 58	+ 4.3
7.37	- 51	- 24	- 38	+ 2.6	- 56	- 55	- 55	+ 3.8
7.86	- 30	- 69	- 49	+ 3.2	+ 88	-179	- 45	+ 2.9
After Treatment for 1 Hour at 500°C								
	3.4 inches from Breech End				3.67 inches from Breech End			
3.21	+ 63	+ 50	+ 57	- 9.1	+ 46	+ 54	+ 50	- 8.0
3.68	+ 75	+ 51	+ 63	- 8.7	+ 50	+ 59	+ 54	- 7.5
4.15	+ 34	+ 50	+ 42	- 5.2	+ 63	+ 61	+ 62	- 7.6
4.93	- 43	- 9	- 26	+ 2.7	- 12	- 13	- 13	+ 1.3
5.42	- 61	- 45	- 53	+ 5.0	- 54	- 21	- 38	+ 3.6
5.91	- 29	- 57	- 43	+ 3.7	- 29	- 27	- 28	+ 2.4
6.39	- 39	- 33	- 36	+ 2.9	- 36	- 28	- 32	+ 2.6
6.88	- 56	- 18	- 37	+ 2.7	- 27	- 52	- 40	+ 3.0
7.37	- 49	- 27	- 38	+ 2.6	- 57	- 45	- 51	+ 3.5
7.86	+ 9	- 60	- 26	+ 1.7	+ 33	-117	- 42	+ 2.7

* Assumed Young's modulus E = 13,000 tons per sq. inch
Compressive stress indicated by minus sign
Tensile stress indicated by plus sign.

Part III

Measurement of relaxation of internal stress by the X-ray method

(Work carried out by the X-ray Section, S.P.M.)

Experimental details

Three sections of compound tubes, marked A5, B5 and C2.5 were received from S.M.R. A5 was a section from the compound tube with channels in the jacket, C2.5 from the tube with channels in the liner, while B5 was a section from the plain compound tube. The flat surfaces had been ground after sectioning. The only other preparation prior to X-ray examination was the polishing and etching of a number of radial strips. Approximately 0.007 inch was removed from each strip in order to eliminate any distortion of the crystal lattice caused by machining and grinding.

Provided the material has not been plastically deformed, the internal strain as measured by the change in the interplanar spacings of the crystal lattice is related to the internal macro-stresses by the normal equations of elastic strain. Measurements of the interplanar spacings can be made with sufficient accuracy only by using the X-ray back-reflection method. By this method the interplanar spacings of those planes which are roughly parallel to the plane surface of the section were measured and the lattice strain values derived by comparison of these spacing values with the unstrained value obtained by measurements on annealed filings of the same material. The method therefore measured the strain in the direction normal to the plane surface of the section, i.e. the axial direction of the tube. Since the axial stress in thin sections is zero, the strain measured was that due to combined radial and circumferential stresses. For this reason the measurements on the outer jacket were not effective since the Poisson strains arising from the tensile tangential stress and the compressive radial stress were in opposition and of the same order, giving little or no net strain in the axial direction. Measurements were thus restricted to the inner tube or liner, where the radial and tangential stresses were both compressions.

Measurements were made along several radii at points distant 1/16, 5/16 and 9/16 inch from the bore surface. The wider annulus of C2.5 permitted an additional measurement between two channels at 13/16 inch. The measurements were repeated after annealing at 400, 450, 500, 550 and 600°C. The specimens were heated and cooled at 75°C per hour and maintained at temperature for one hour.

The sum of the tangential and radial stresses was calculated from the interplanar strains by the equation

$$S_r + S_t = -\frac{E}{m}\,\frac{d_1 - d_o}{d_o}$$

where d_1 and d_o were the stressed and unstressed values of the interplanar spacing. The values of m, Poisson's Ratio, and E, Young's Modulus, were taken from earlier X-ray work as m = 0.3 and E = 12,900 tons/sq. inch for the normal direction of (310) planes.

The accuracy of measurement attained was ± 3 tons/sq. inch.

Observations

The calculated stress values ($S_r + S_t$) are given in tables 1, 2 and 3. Apart from the anomalies discussed below the mean stress level was, within the limits of experimental error, uniform for the liner of the unchannelled tube B5, but for the channelled tubes A5 and C2.5 the stress level ($S_r + S_t$) decreased from the bore surface to the interface. This gradient of stress persisted in A5 after annealing at 600°C., but was eliminated from C2.5 after annealing at 500°C.

Except in B5, where the sum of the principal stresses along radius 1 in the as received condition was markedly lower than that along the other radii, and in A5, where a comparatively low stress value near the interface on radius 4 persisted throughout the annealing treatments, the stress distribution in the as received condition, within the limits of experimental error, was consistent from one radius to another. In B5, further etching along radius 1 failed to raise the measured stress level to conform with the others. This would suggest that the anomaly was not due to residual cold work due to machining and grinding. On the other hand, after an annealing at 400°C the anomaly was removed. It is possible that the lower stress level along this radius may have been due to a slight misfit between the liner and casing or to uneven shrinking when assembling. There is some evidence of a similar effect along radius 2 of the same ring where the stress level after annealing at 400°C was slightly higher and conformed more closely to the values along other radii.

Apart from these anomalies, the stress level in the three rings was not significantly affected by annealing at 400 or 450°C. Annealing at 500°C resulted in a considerable drop in the stress level, continuing at 550°C and falling to less than half the original level at 600°C.

The stress level in C2.5 was lower than in A5 to 450°C both being substantially lower than the stress level in the plain tube B5. After annealing at 500°C the stress level in A5 fell to the same mean value as in C2.5, the equality persisting after annealing at 550° and 600°C.

Conclusions

Satisfactory stress measurements in sections of compound tubes using X-ray interplanar spacing measurements could only be made on the inner components where the radial and tangential stresses were both compressive.

The mean values of the sum of the principal stresses (tangential and radial) after various annealing treatments were as follows:-

	B5	A5	C2.5
As received	22.6 (ignoring radius 1)	17.6	14.6 tons/sq. in.
Annealed 400°C	24.0	17.4	14.8 tons/sq. in.
" 450°C	22.5	16.7	14.8 "
" 500°C	20.5	12.4	12.4 "
" 550°C	17.9	9.8	10.6 "
" 600°C	8.6	6.5	6.3 "

These values are plotted in Fig. 11.

Table 1 - Plain Compound Tube, B.5

Stress distribution in inner tube

Sum of Principal Stresses ($S_r + S_t$) in tons per sq. inch

	As received Position along radius			Annealed at 400°C Position along radius		
	Bore	Mid-way	Inter-face	Bore	Mid-way	Inter-face
Radius 1	11	9	12	23	22	22.5
2	19	19	21	23.5	26	26
3	24	23.5	26.5	23	25	23
4	23	19	25	22	26.5	26.5
5	25	21	22	25	23	23.5
Mean Stress	20.4	18.3	21.3	23.3	24.5	24.3

	Annealed at 450°C Position along radius			Annealed at 500°C Position along radius		
	Bore	Mid-way	Inter-face	Bore	Mid-way	Inter-face
Radius 1	17	17	20	21	16.5	22
2	24	23	21.5	17	22	21
3	25	23	26.5	20.5	21.5	25
4	22.5	22	25	21	21	22
5	24	22.5	25	18	19	20
Mean Stress	22.5	21.5	23.6	19.5	20.0	22.0

	Annealed 550°C Position along radius			Annealed 600°C Position along radius		
	Bore	Mid-way	Inter-face	Bore	Mid-way	Inter-face
Radius 1	17	17	16.5	6.5	9	8
2	17.5	17.5	17	8	8	9
3	19	17.5	20	10	11	9
4	15.5	20	17.5	9	5.5	9
5	18	19	19	8	8	11
Mean Stress	17.4	18.2	18.0	8.3	8.3	9.2

Table 2 - Slotted Compound Tube, A5

Stress distribution in inner tube

Sum of Principal Stresses ($S_r + S_t$) in tons per sq. inch

	As received Position along radius			Annealed at 400°C Position along radius		
	Bore	Mid-way	Inter-face	Bore	Mid-way	Inter-face
Radius 1	21	17	17	22	20.5	18
2	21	16.5	18.5	16.5	17	18.5
3	20.5	15	16	20	14.5	14
4	23	16	10	22.5	15	10
Mean Stress	21.4	16.1	15.4	20.3	16.8	15.1

	Annealed at 450°C Position along radius			Annealed at 500°C Position along radius		
	Bore	Mid-way	Inter-face	Bore	Mid-way	Inter-face
Radius 1	18.5	16.5	22	14	13	15
2	19	16	17	14.5	13	12
3	20	14.5	13	16.5.	12	8
4	20.5	12.5	10.5	12	11	8
Mean Stress	19.5	14.9	15.6	14.3	12.3	10.8

	Annealed at 550°C Position along radius			Annealed at 600°C Position along radius		
	Bore	Mid-way	Inter-face	Bore	Mid-way	Inter-face
Radius 1	14.5	10.5	14	8.5	7	8.5
2	10.5	8.5	9	6	4.5	5
3	10	10	3	8	9	2
4	12.5	8	4.5	8.5	6.5	4
Mean Stress	11.9	9.3	7.6	7.8	6.8	4.9

Table 3 - Slotted Compound Tube, C2.5

Stress distribution in inner tube

Sum of Principal Stresses ($S_r + S_t$) in tons per sq. inch

	As received Position along radius				Annealed at 400°C Position along radius			
	Bore	5/16"	9/16"	Inter-face	Bore	5/16"	9/16"	Inter-face
Radius 1	14.5	16	14.5	12	16	15	15	12.5
2	14	13	13	Slot	16	14	14	Slot
3	16.5	15	15	13	15	15	15	14
4	16	16	16	Slot	16	14.5	15	Slot
Mean Stress	15.3	15.0	14.6	12.5	15.8	14.6	14.8	13.3

	Annealed at 450°C Position along radius				Annealed at 500°C Position along radius			
	Bore	5/16"	9/16"	Inter-face	Bore	5/16"	9/16"	Inter-face
Radius 1	14	14.5	15	13	9	12.5	12	12.5
2	16	15	13	Slot	12	12.5	10	Slot
3	14.5	14.5	15	14	12.5	13	12	13
4	18	14.5	16.5	Slot	16.5	12.5	14	Slot
Mean Stress	15.6	14.6	14.9	13.5	12.5	12.6	12.0	12.8

	Annealed at 550° C Position along radius				Annealed at 600°C Position along radius			
	Bore	5/16"	9/16"	Inter-face	Bore	5/16"	9/16"	Inter-face
Radius 1	10.5	8.5	9	9	4.5	4.5	5	5
2	13	8.5	8.5	Slot	5	6	7	Slot
3	13	11	13	12.5	6.5	9	8	6
4	10.5	12	10	Slot	7	7	7	Slot
Mean Stress	11.8	10.0	10.1	10.8	5.8	6.6	6.8	5.5

General Conclusions

The effect of heat treatment on the shrinkage stresses in built-up barrels has been investigated by means of experiments on test cylinders representing a 3 inch 70 calibre gun barrel. Three different methods of testing were employed in which measurements were made before and after heat treatment to determine (i) any loss of elasticity of the cylinder (ii) any decrease in mean circumferential residual stresses and (iii) any decrease in tangential and radial stresses at selected points.

No loss of elasticity in the cylinder was indicated by a pressure/expansion curve recorded after the heat treatment at 500°C. There was however permanent contraction of 0.001 inch at the bore and 0.0006 inch at the jacket exterior, measured in the grooved portion of the cylinder after the 500°C treatment, but no more than 0.0001 inch contraction at the bore after the 400°C and 450°C treatments. Also permanent expansion of the bore was nil (or negative) in response to the application of 31.5 tons per sq. inch internal pressure after heat treatments at 400°C and 450°C but it was about 0.00035 inch following a similar pressure applied after the 500°C treatment.

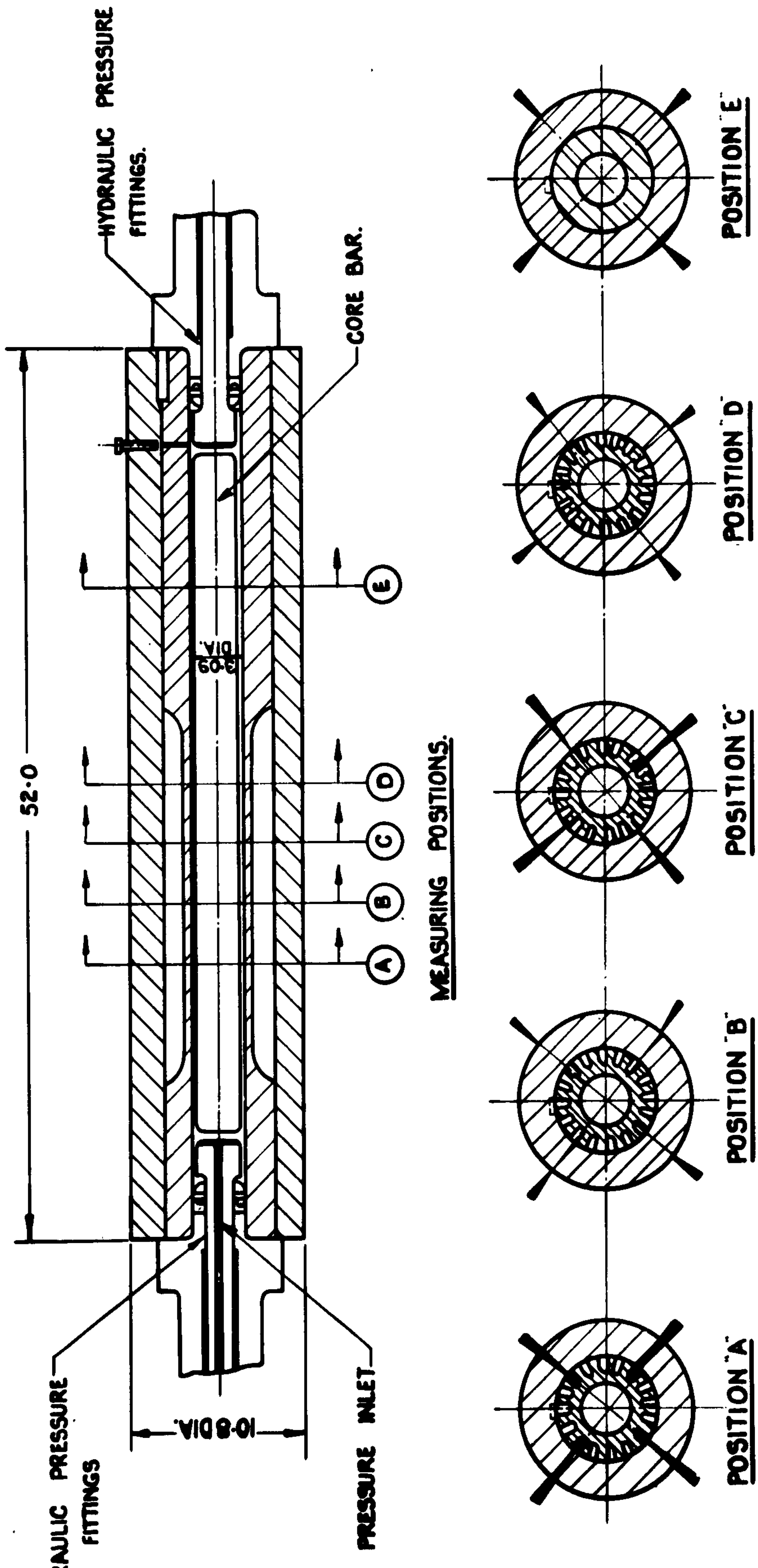
In two cylinders with channelled walls the initial mean liner circumferential stresses were 10.4 and 9.1 tons per sq. inch. These stresses sustained no appreciable decrease with treatments at 400°C and 450°C but decreases of 13 and 14 per cent respectively followed treatment at 500°C. In a more highly stressed cylinder, built-up of plain tubes, the initial mean liner stress of 12.7 tons per sq. inch decreased by 13, 17 and 30 per cent respectively with treatments at 400°C, 450°C and 500°C.

The stress values determined by X-rays, representing the sum of tangential and radial stresses in the liner, showed a similar stability with treatments at 400°C and 450°C. There was a decrease of stress with treatment at 500°C varying from 15 to 30 per cent in the three cylinders tested. This increased to 40 per cent with treatment at 600°C.

Thus the relative effects of different treatment temperatures within the range 400°C to 500°C were confirmed by agreement between the different methods of test in so far as the results could be compared. The behaviour of the cylinders showed that the stress relaxation could be related to creep properties. It was therefore probable that with any given temperature of treatment the maximum stress would decrease, given sufficient time, to the limiting creep stress for that temperature. This limit appeared to be no lower than about 10 tons per sq. inch at 400°C. but below 8 tons per sq. inch at 500°C. These results were not in conflict with the recorded results of creep tests on steels with similar molybdenum content.

M.64/53

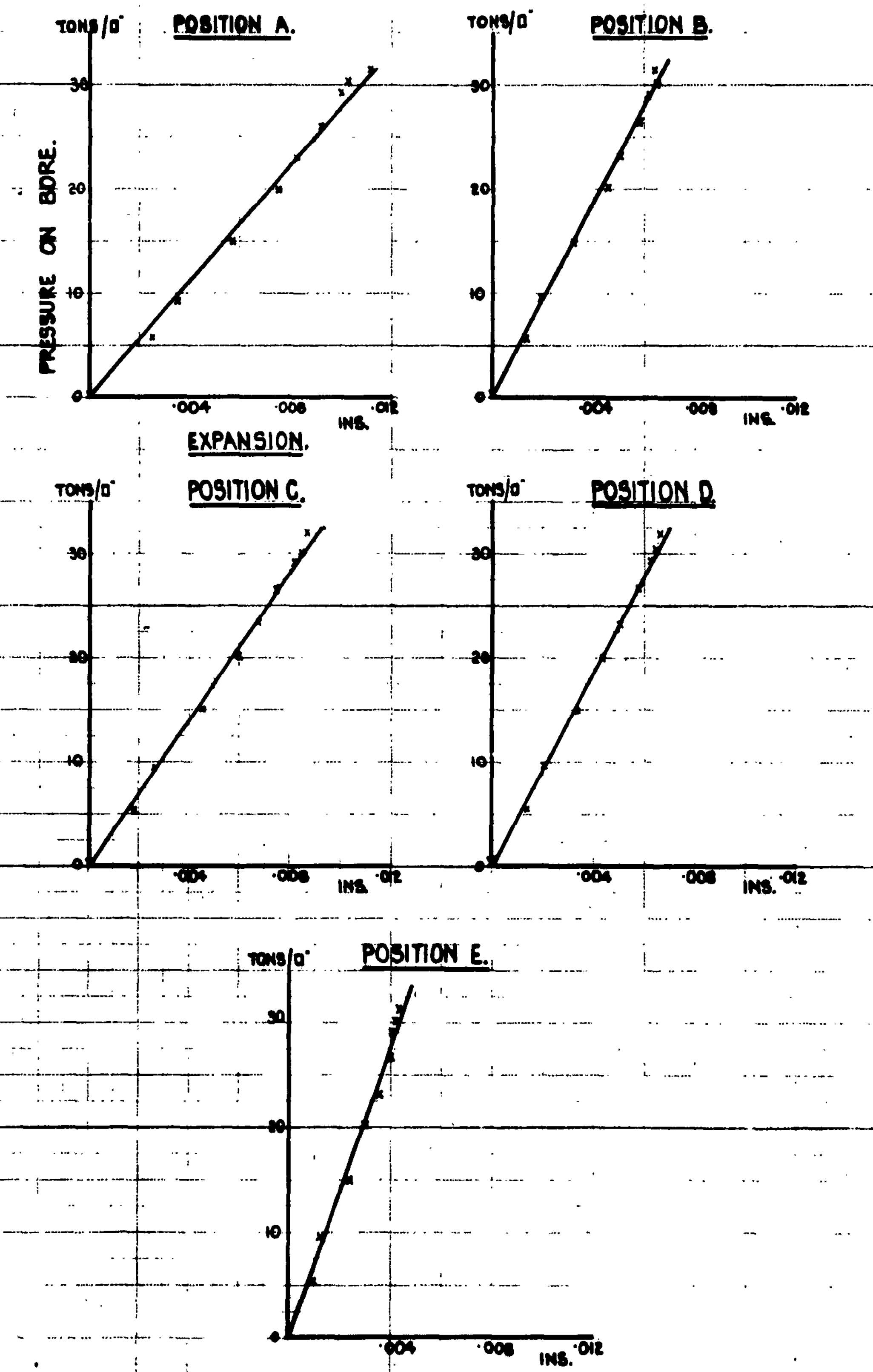
FIG 1.



TEST CYLINDER REPRESENTING 3"/70 GUN BARREL SECTION. (DESIGN D10(G) 4602/163)

APPENDIX 2

MEASURING POSITIONS AS SHOWN ON FIG 1.



TEST CYLINDER DESIGN D 10 (G) 4602/163

PRESSURE EXPANSION CURVES

AFTER HEATING TO 500°C

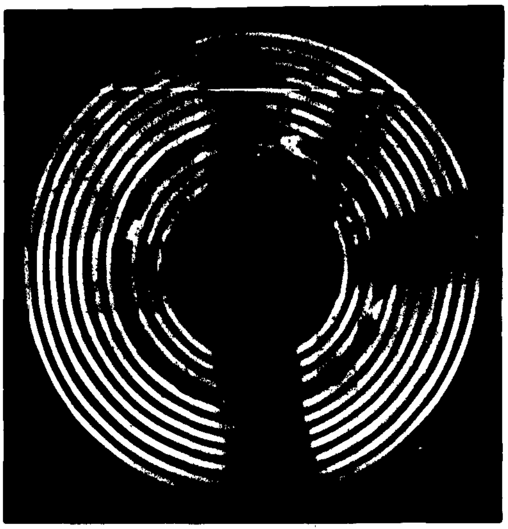


Fig.3 Cylinder No.1

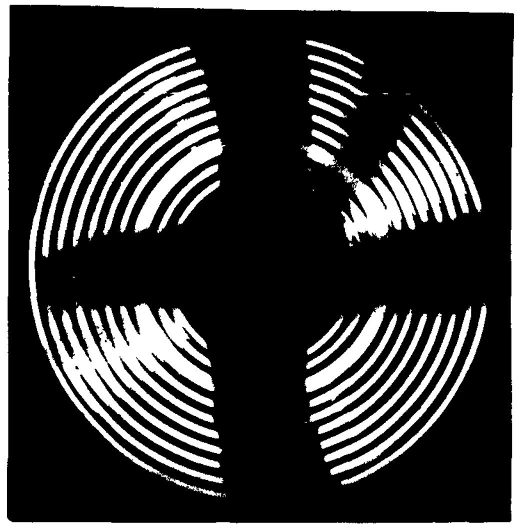


Fig.4 Cylinder No.2

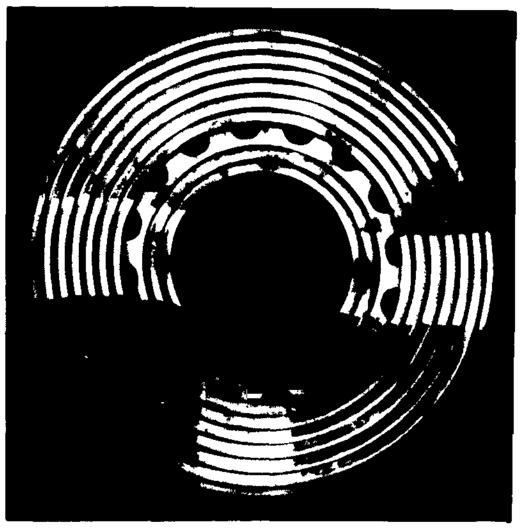


Fig.5 Cylinder No.3

Figs.3 - 5 Sets of dissected rings assembled on the parent discs.

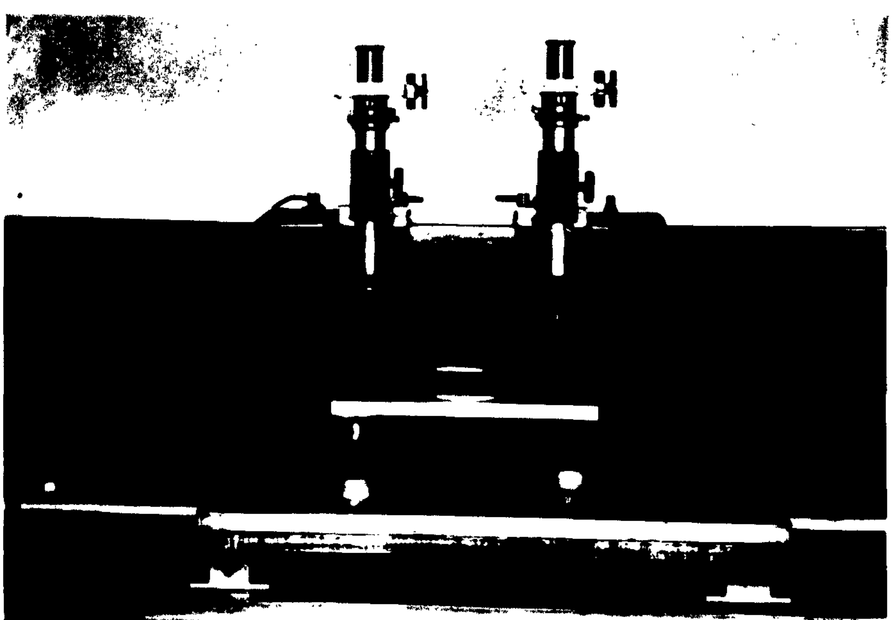


Fig.6 Measuring apparatus for small strains

CYLINDER Nº I (GROOVED JACKET)

RESIDUAL STRESSES BEFORE AND AFTER HEAT TREATMENT.

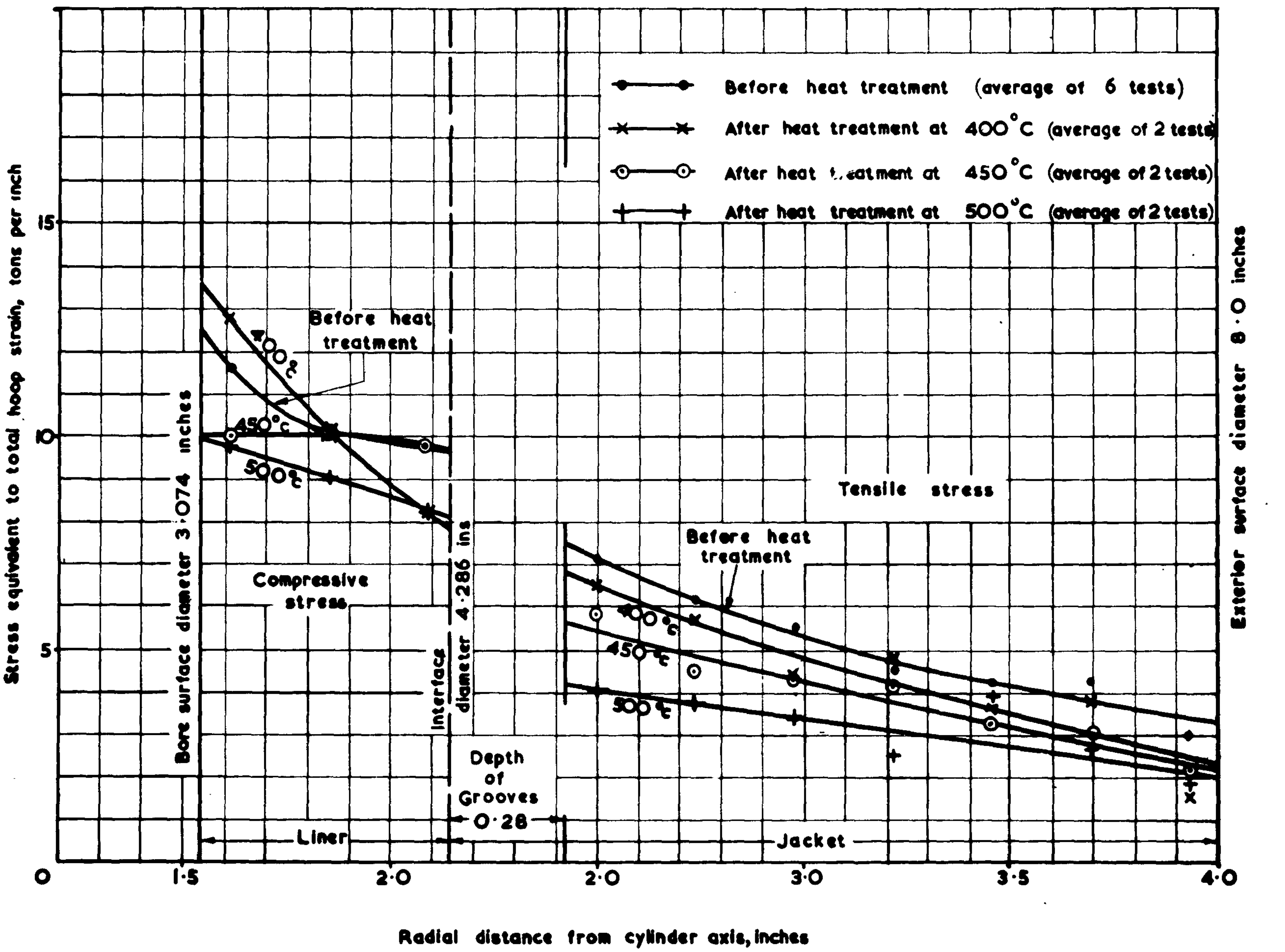


FIG. 7

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CYLINDER Nº 2 (PLAIN TUBES)

RESIDUAL STRESSES BEFORE AND AFTER HEAT TREATMENT.

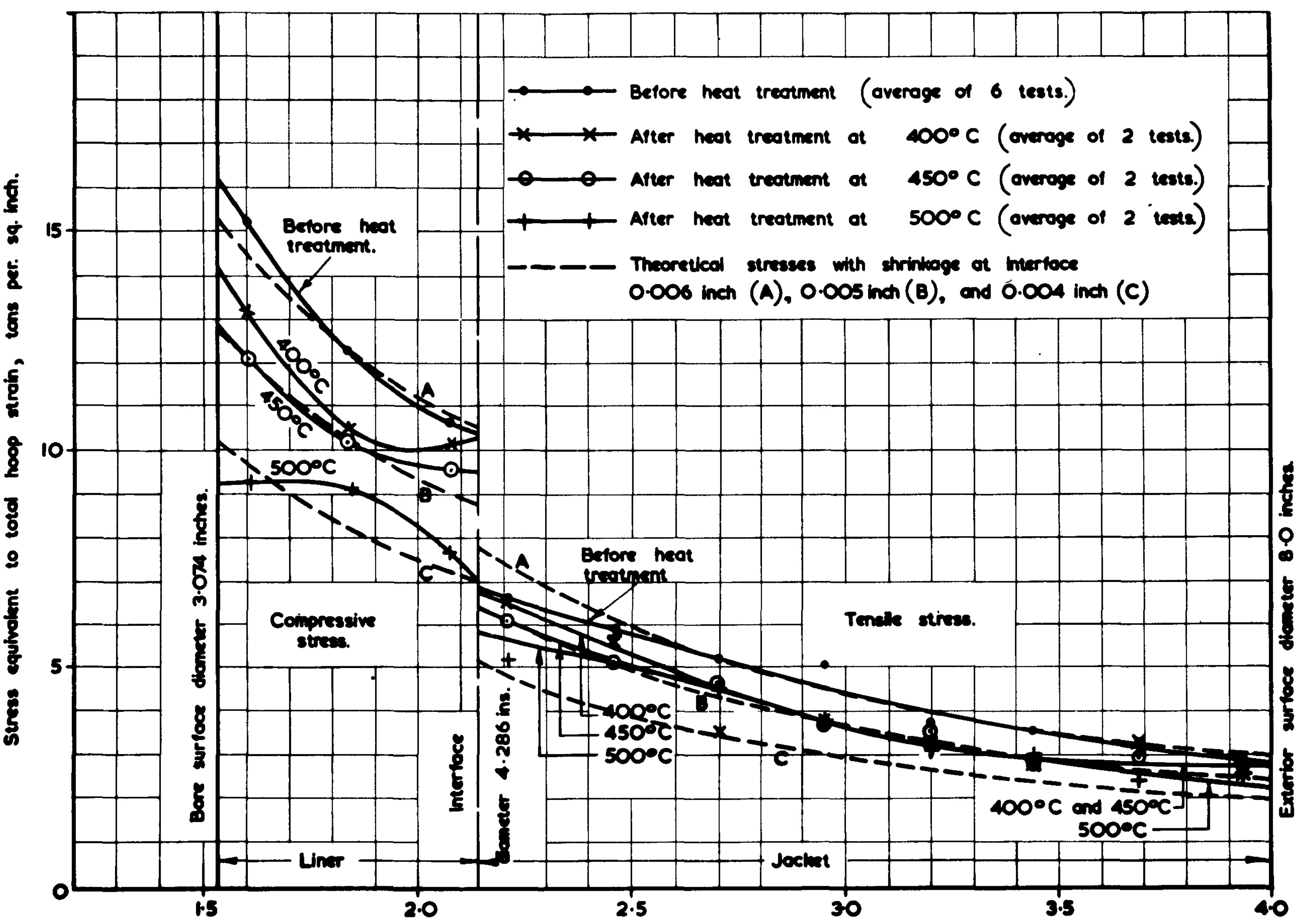

FIG. 8

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CYLINDER Nº 3 (GROOVED LINER)

RESIDUAL STRESSES BEFORE AND AFTER HEAT TREATMENT.

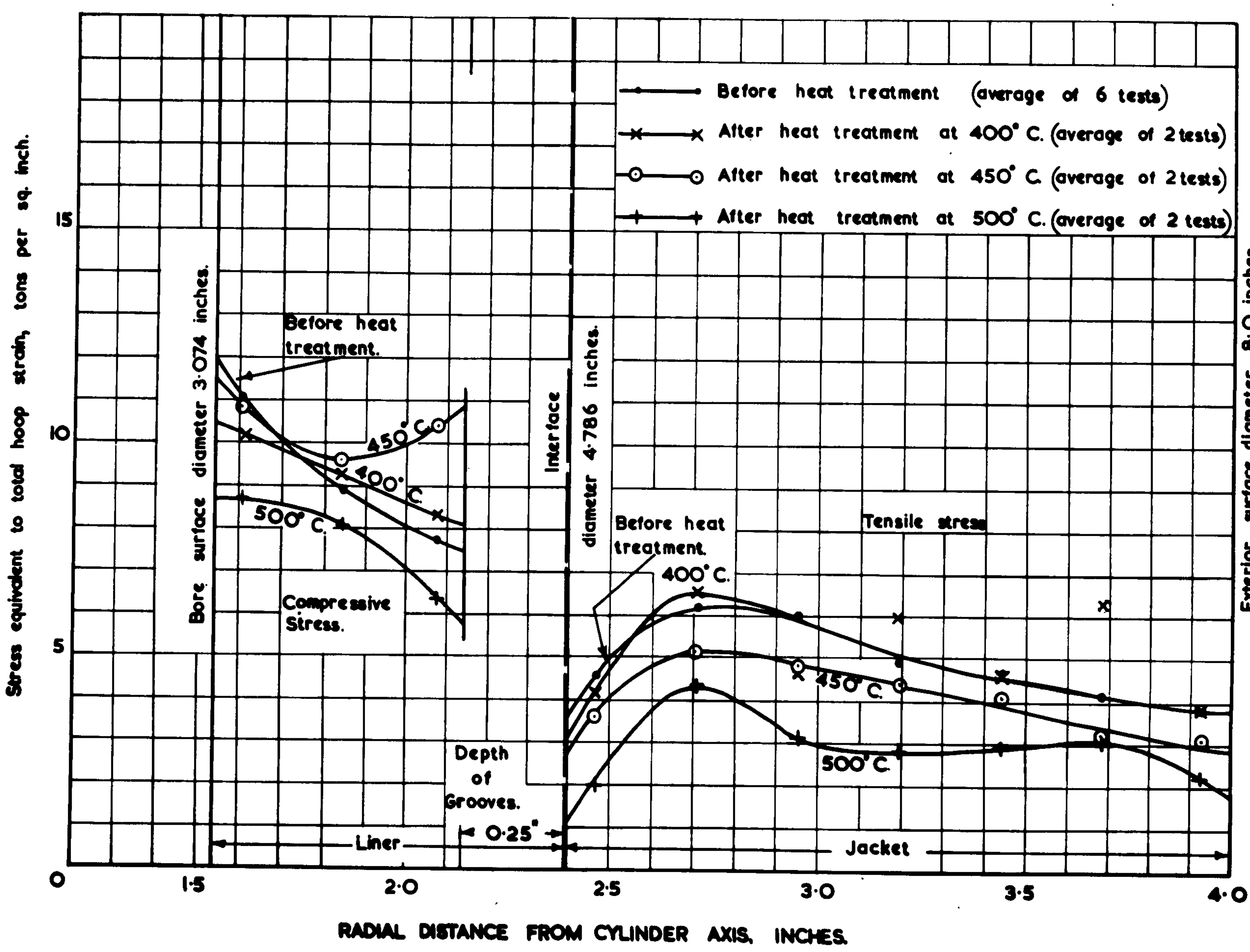

FIG. 9

CYLINDER No 2 (PLAIN TUBES)

MEASURED STRESSES IN RELATIONSHIP TO THEORETICAL STRESS AND STRAIN.

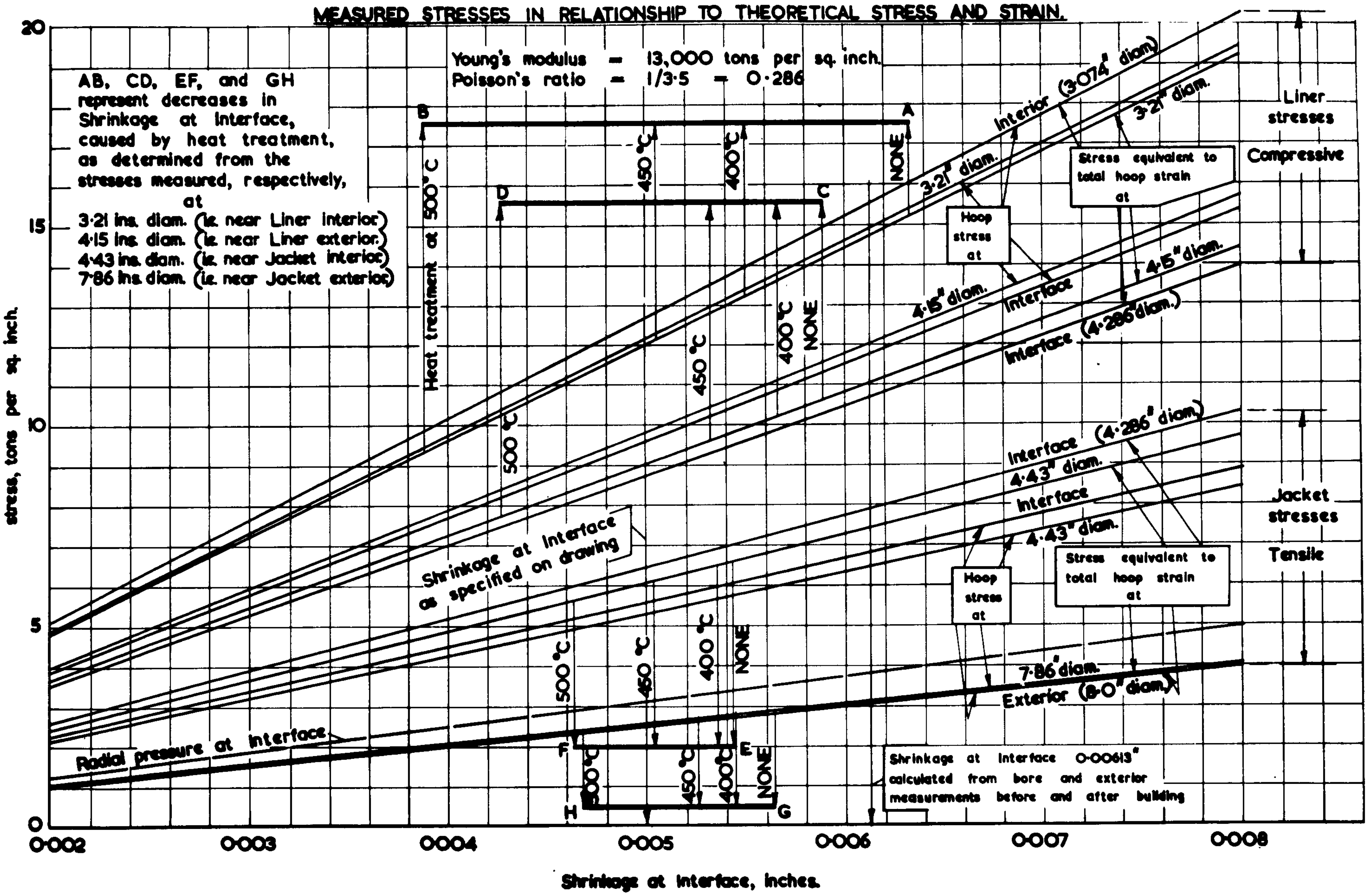

FIG. 10

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RELAXATION OF INTERNAL STRESS WITH ANNEALING

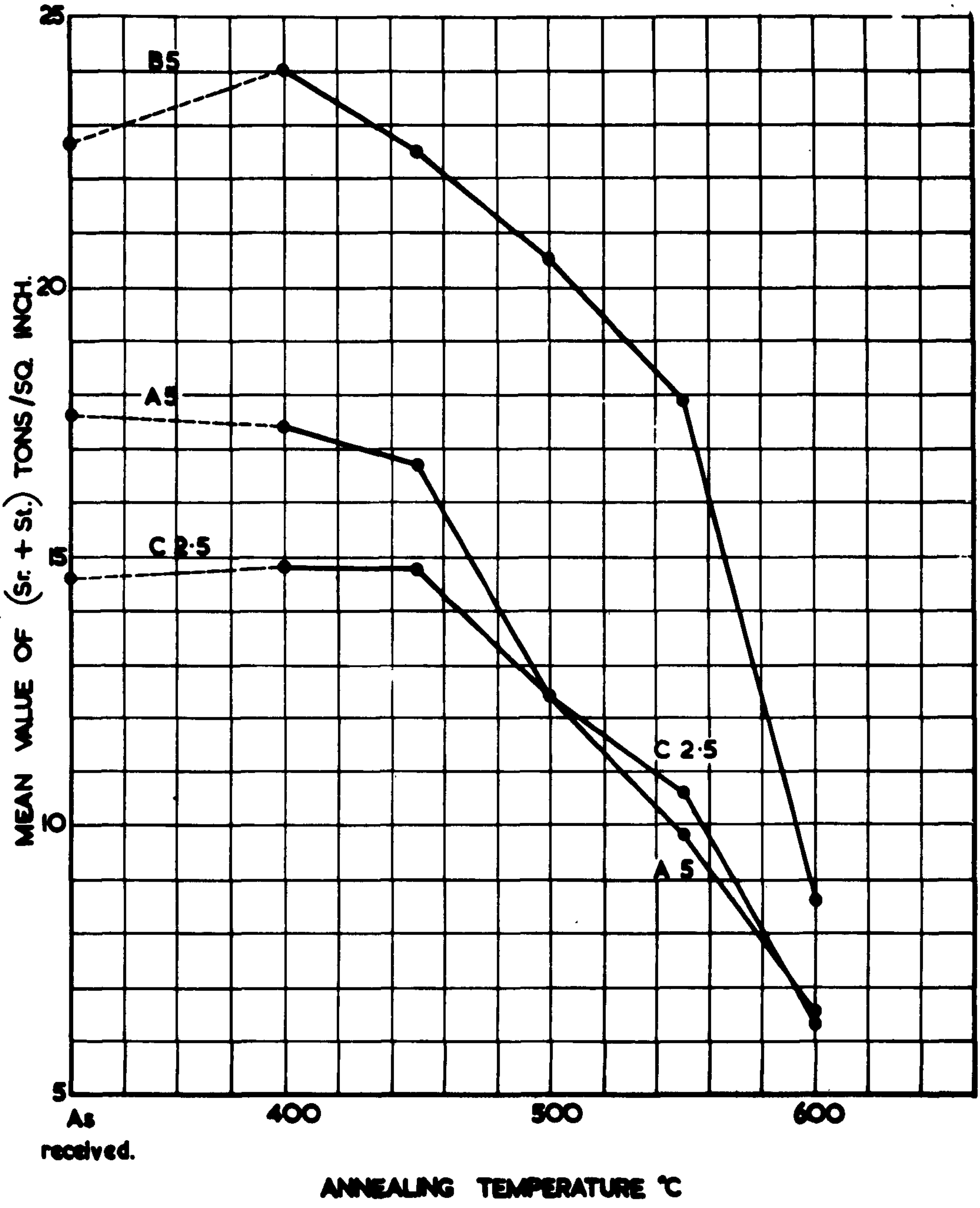

FIG. 11.

For Indexing

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Ministry of Supply

A.R.E. Metallurgy Report No. 3/53

The effect of Heat Treatment on Shrinkage Stress in Built-up Gun Barrels

by

H F. Hall

Summary

The experiments described were the result of collaboration between the Armament Design and the Armament Research Establishments. The work was divided into three parts which related to alternative methods of determining the effects of heat treatment on shrinkage stresses in built-up gun barrels.

Part I, contributed by A.D.E. D.10 Group, described full scale experiments using hydraulic pressure to determine elasticity and permanent set in a 3-inch barrel

Part II, contributed by A.R.E./S.M.R., described a method of measurement of circumferential stress by the dissection from the barrel wall of thin coaxial rings.

Part III, contributed by A.R.E./S.P.M., described an X-ray technique for the measurement of tangential and radial stresses at any selected points on the transverse section of a barrel.

There was a considerable measure of agreement between the results obtained by the three methods. Heat treatment at 400°C produced no appreciable deleterious effect. With treatment at 500°C decreases in bore stress up to 40 per cent were measured. In the full scale tests at 500°C there was no measurable loss of elasticity but permanent set measurements confirmed that stress relaxation had occurred.

The observed changes in the stress system appeared to be related to creep and the means were thus provided for estimating the type of behaviour to be expected with heat treatment conditions outside the limits of time and temperature investigated.

[dstl]

Information Centre
Knowledge Services
[dstl] *Porton Down,*
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SP4 0JQ
22060-6218
Tel: 01980-613753
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Defense Technical Information Center (DTIC)
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