with joggled plates of the form shown in Fig. 16B, and the observations were treated and the strain curves obtained in a similar manner to that employed in the case of the joint with straight plates*. These results, which are shown graphically in Fig. 22, indicate a diminution in the value of the bending moment in consequence of the joggling, for the maximum fibre stress never exceeded twice the value which it would have reached if the joint had been subject only to a direct load.

Although it is thus seen that the stress in the plates of a joggled lap joint does not approach the same maximum value found in joints constructed with straight plates, the

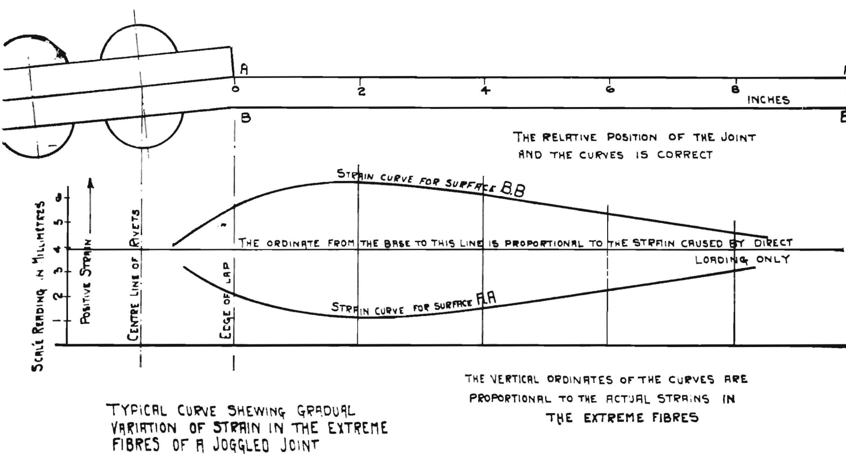


FIG. 22.—Strain Curves for Joggled Joints

fact does not constitute a final argument as to the superiority of one joint over the other, for it can be seen that additional and increasing stresses are set up in the already indeterminately stressed rivets as the load upon the joint increases. Workmanship and the mechanical treatment during the joggling of the plates, in addition to the fact that

* This was the only joggled joint tested, and an effort was made in its construction to reproduce the exact conditions indicated in the drawing (Fig. 16B), but it should be noted that small variations in the set of the plates, would probably considerably affect the distribution of stress.

the rivets are put in tension when the joint is under load, must always be kept in mind.

27. *Suggestion of an Alternative Method of Measurement by Fixed Mirrors.*—While the observations taken by means of the extensometer mirrors and fixed mirrors were being interpreted, it was noticed that the readings from the fixed mirrors did not show uniformity, but varied according to the position of the fixed mirror upon the joint. This fact suggested that a comparison should be made between the mirrored scale differences obtained

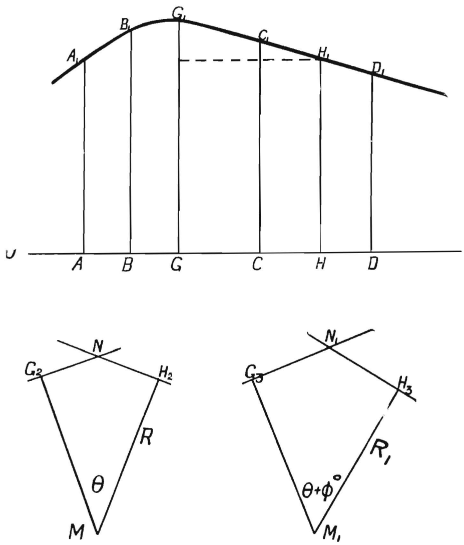


FIG. 23.

from the fixed mirrors at various points along the joint; upon this being done it was noticed that they gradually increased as the point of attachment of the fixed mirror to the plate approached the point of maximum bending moment. A general movement in the plate as a whole would have produced a uniform change in the "mirrored" scale differences from the fixed mirrors, and since such did not exist, it was argued that the observed variation was produced by local curvature of the plate as a result of the varying bending moment present. It then became evident that the magnitude of the fibre stress might be determined by interpreting the results obtained from the fixed mirrors alone.

If a mirror rotate through λ radians, any ray reflected by that mirror has its direction turned through 2λ radians. Using a telescope in the manner already described, any angle through which the fixed mirror may have turned will be measured (in radians) by

$$\frac{1}{2} \times \frac{\text{Difference of ``Mirrored'' scale reading.}}{\text{Distance of scale from Mirror.}}$$

Let the points G_2 H_2 (see Fig. 23) represent two points in a test line upon the specimen under any condition of loading, and let G_3 H_3 represent the same points with an increased load. Suppose that the ordinates AA_1 BB_1 etc., are drawn equal to the "mirrored" scale differences obtained from mirrors attached at intervals along the surface ABCD of the test piece under observation, and that these observed differences are entirely due to the effect of the additional load. The two points G_2 H_2 are taken sufficiently close to one another that the surface of the test piece between them may be considered as a portion of a circular arc.

With these assumptions

$G_2 M = H_2 M = R =$ the initial radius of curvature

similarly $G_3 M_1 = H_3 M_1 = R_1 =$ the final radius of curvature

Assuming that the initial curvature of the specimen is caused by a bending moment,

Let M units = the initial cause of curvature,
And M_1 = the additional bending moment imposed on the specimen between the points G and H.

If the position of the neutral axis be known, then the radius of curvature of the neutral axis may be obtained under both conditions of loading from the values of the radius of curvature of the outer surface.

Assuming that no appreciable error is introduced by ignoring the difference in the radius of the outer surface, and that of the neutral axis, and if

E = Modulus of Elasticity
I = The Moment of Inertia of the Section

$$\text{then } R = \frac{EI}{M} \text{ or } M = \frac{EI}{R}$$

$$\text{and } R_1 = \frac{EI}{M+M_1} \text{ or } M + M_1 = \frac{EI}{R_1}$$

$$\therefore M_1 = \frac{EI}{R_1} - \frac{EI}{R} = EI\left(\frac{I}{R_1} - \frac{I}{R}\right)$$

Let f = the additional extreme fibre stress caused by the additional bending moment M_1

y = the distance of the extreme fibre (where f is measured) from the neutral axis.

$$\text{then } f\frac{I}{y} = M_1 = EI\left(\frac{1}{R_1} - \frac{1}{R}\right)$$

$$\therefore f = Ey\left(\frac{1}{R_1} - \frac{1}{R}\right)$$

but from Fig. 23

$$R = \frac{Arc\ G_2\ H_2 \times 360^0}{2\ \pi\ \theta}$$

$$\text{and } R_1 = \frac{Arc\ G_3\ H_3 \times 360^0}{2\ \pi\ (\theta + \Phi)}$$

$$\therefore \left(\frac{1}{R_1} - \frac{1}{R}\right) = \frac{2\ \pi\ \Phi}{Arc\ G_2\ H_2 \times 360^0}$$

But if GG_1 and HH_1 represent the mirrored scale differences that would be obtained from fixed mirrors situated at the two points G_2 and H_2. then

$$\Phi = \frac{1}{2}\left\{\frac{(GG_1 - HH_1)}{\text{distance of scale from mirror}} \times \frac{180^0}{\pi}\right\}$$

and by substitution

$$f = Ey\left\{\frac{(GG_1 - HH_1)}{2(\text{distance of scale from mirror})(Arc\ G_2\ H_2)}\right\}$$

but in the limit

$$\frac{GG_1 - HH_1}{Arc\ G_2H_2} = $$ the tangent of the angle of slope of the plotted mirrored scale differences, at the point under consideration, when the curve is drawn to a natural scale.

hence $f = \dfrac{E\ y\ tan\ \beta}{2k}$

where β = angle of slope of the plotted mirrored scale differences.

k = the distance of the scale from the mirror.

From the above it is seen that the magnitude of the extreme fibre stresses set up by a bending moment only may be determined by referring to the mirrored scale differences obtained from fixed mirrors. This method of determining extreme fibre stresses is hereinafter referred to as the "Fixed Mirror" method of measurement.

SECOND SERIES OF TESTS.*

28. *Application of the Fixed Mirror Method to Boilers.*— The relative values of the extreme fibre stresses in the vicinity of lap joints as they actually exist in boilers were next investigated, and as no method of using the Martens' mirror extensometer proved practicable at this stage, the results during this series were obtained by measuring the additional extreme fibre stresses caused by bending moments, by the "fixed mirror method" above described. To the result so obtained the computed values of the extreme fibre stress caused by direct loading only, were added, and thus the total stress in the extreme fibres under consideration was determined.

The fixed mirrors were attached at various points along the test lines by means of beeswax, the surface of the plate being previously scraped in order to secure a satisfactory attachment.

The test lines on which observations were made are shown on Fig. 24, and from the results of the tests the

* The authors are indebted to Mr. G. F. Davidson, B.E. for he observations and much of the work of this series.

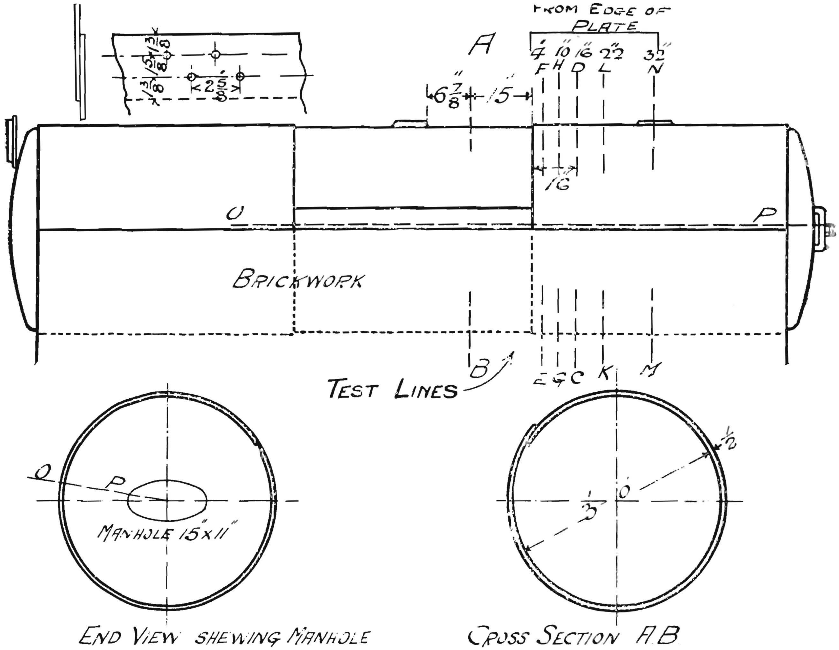
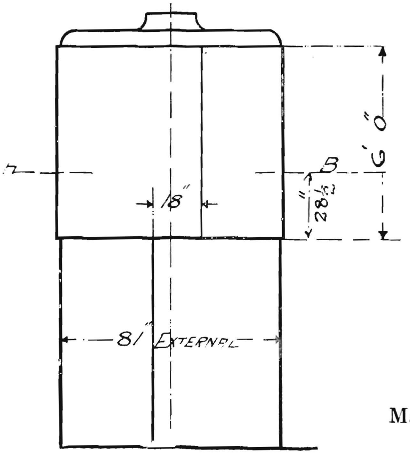


FIG. 24A.—Boiler Drum (B. & W. type).



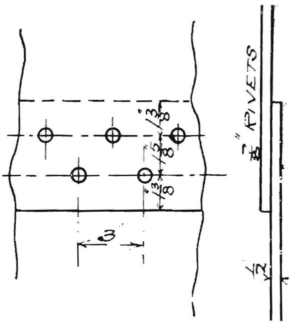


FIG. 24B.—Vertical Boiler,
Made by G. & C. Hoskins, Sydney.

FIG. 24.—Diagrams of Boilers with Test Lines.

"Sections of Stress" shown later in the paper are deduced.

29. *Description of Boilers.*—The majority of the experimental observations upon the stresses in boiler plates were made upon a new Babcock and Wilcox boiler which is part of the equipment of the Engineering Department of the University of Sydney. At the time of the second series of tests this boiler had never been under steam, and in consequence no corrosion or pitting of any kind had developed in its plates.

The general appearance of the boiler is shown in Fig. 24A. Its circumferential barrel plates were half-an-inch in thickness, and were connected together by means of double-riveted longitudinal and single riveted circular lap joints.

Some observations were also made upon a new vertical boiler of the ordinary type (Fig. 24B), and a tubular boiler of the Colonial type, which were kindly loaned for the purpose of experiment by the firm of Messrs. G. and C. Hoskins, of this city (see Fig. 24). These observations were entirely confirmatory of those taken on the B. and W. boiler.

30. *Actual Observations taken from Boiler Plates.*—In order to determine the strain in the extreme fibres of the barrel plates in the vicinity of the longitudinal joints of the B. and W. boiler above referred to, a test line A.B. was chosen, and fixed mirrors were placed at various points along that line. The gauge pressure within the boiler was varied from 0 to 140 lbs. per square inch by a small hydraulic pump; the water used for that purpose was at the same temperature as the plates of the boiler themselves in order to eliminate any dimensional changes caused by unequal expansion.

The "mirrored" scale differences were obtained after the same manner as those in the first series of experiments; that is to say, for every twenty pounds of increase or decrease of pressure an observation was made from each mirror. The series of "mirrored" scale differences obtained from each mirror were then plotted against the corresponding pressures, and a fair curve drawn to represent graphically the "mirrored" scale differences for all pressures, less than the maximum of 140 lbs. per square inch.

From the set of observations thus graphically recorded,

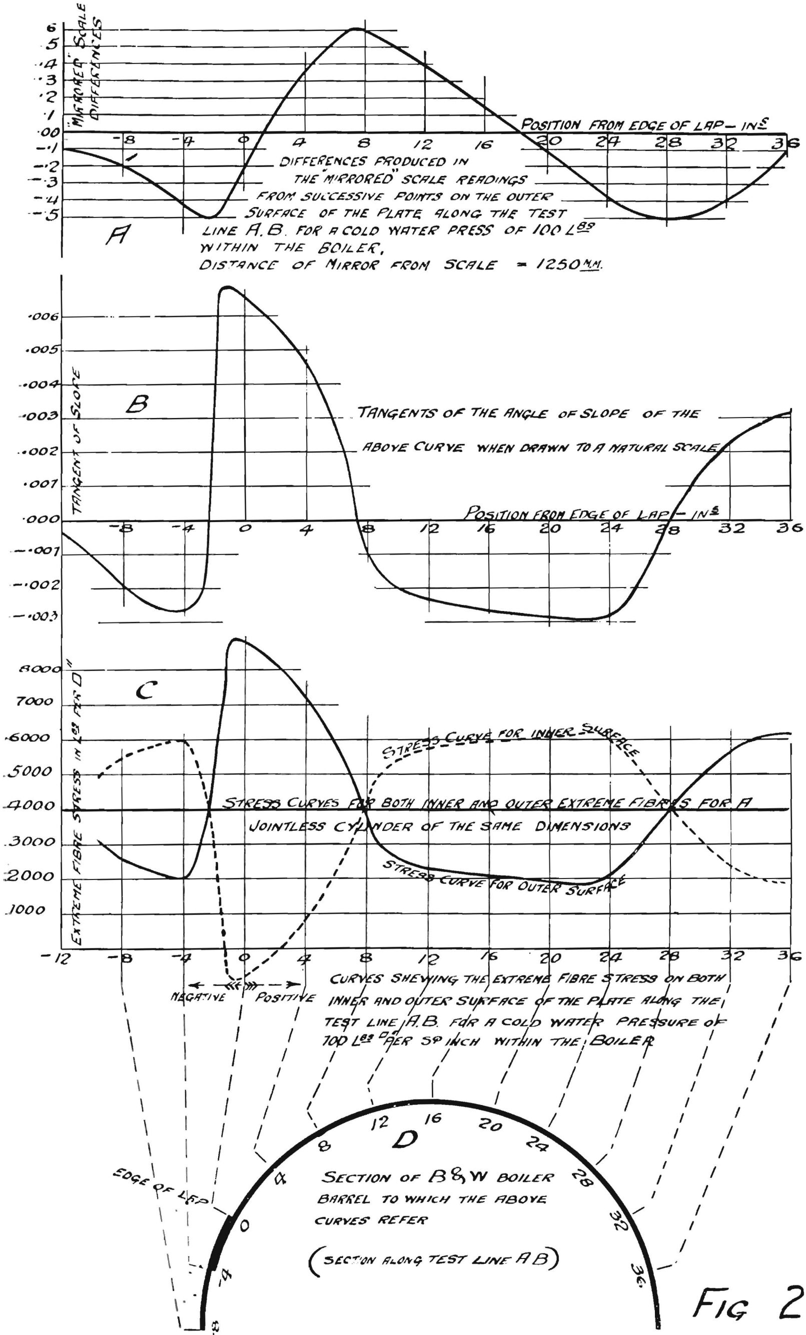


FIG 25

TYPICAL METHOD OF DEDUCING RESULTS.

the "mirrored" scale differences corresponding to those which would have been obtained from each mirror when the cold water pressure within the boiler was 100 lbs. per square inch were taken, and are shown plotted in Fig. 25A. Observations were also taken in the same way on the test lines C.D., E.F . . . . . . O.P., and the deductions from the results are dealt with later in the paper.

31. *Interpretation of Results.*—From this curve, the tangents of the angle of slope, when drawn to a natural scale, were directly measured, and their values graphically represented in Fig. 25B.

Knowing the tangents to the curve of mirrored scale differences at any point, the stress at that point due to bending is readily obtained for, from above—

$$f = \frac{E.\, y \tan \beta}{2k}$$

where in the boiler plate under test—

$E = 29,000,000$ lbs. per sq. inch (Young's Modulus)

y=half the thickness $= \frac{1}{4}''$

k=Scale distance $= 1250$ m.m.

i.e. $f = \tan \beta \times 73600$ lbs. per sq in.

Using the values of the tangents shown graphically in Fig. 25B, and multiplying their respective values by the numerical constant 73600,—the magnitude of the stresses caused by bending alone was obtained for all points upon the surface of the plate along the test line A.B.

By calculation, it was found that the stress per square inch, which would have been caused by a cold water pressure of 100 lbs. per square inch in a jointless cylinder of the same dimensions as that under test

=4020 lbs. per square inch,

and therefore the stress in the extreme fibres, at that pressure, is the algebraic sum of

(4020 + fibre stress due to bending).

The curves giving the extreme fibre stress in the inner and outer surface of the boiler plate, along the test line A.B., obtained in this manner, are shown in Fig. 25C.

The four diagrams, Fig. 25, indicate clearly the method of arriving at results where the "fixed mirror method" alone is employed. For instance, Fig. 25D represents a crosssection of the boiler upon which the actual positions of the fixed mirrors are shown. Fig. 25A, is a graphic record of the mirrored scale readings obtained from those mirrors under any one condition of loading; Fig. 25B represents the values of the tangents of the angle of slope of the curve previously mentioned when drawn to a natural scale; Fig. 25C shows the calculated stress caused by direct loading to which is added the stress caused by bending moment.

The same results are shown plotted directly round the boiler shell in Fig. 26A.

32. *Experiments on the Shell of a Vertical Boiler.* —Experimental observations were next carried out along the test line AB upon a new vertical boiler previously referred to (see Fig. 24B). The observed results were analysed in a manner similar to the above, and the resulting curve (see Fig. 26B) is shown for a cold water pressure of fifty pounds per square inch within the boiler. On making a comparison between the curves obtained along the test lines on the two boilers experimented upon, it will be observed that the same characteristics are exhibited in both; that is to say, in each case the extreme fibre stress in the vicinity of the lap joints is increased considerably above what would occur in a jointless cylinder of the same dimensions. It is clear, however, that the ratio between the maximum extreme fibre stress existing within the plates and the extreme fibre stress that would have existed if the joint had been absent reaches only a value of two in each case, and from this it may be argued that a lap joint action is not as severe when the lap joint occurs within the plates of a boiler as it is in the experimental joints dealt with in the first series of tests. An explanation of this is not very hard to find, for on referring to the curve of the extreme fibre stress obtained from the Babcock and Wilcox boiler, along the test line AB (see Fig. 24A), it will be seen that the extreme fibre stresses show signs of a similar action occurring at a point in which no lap joint is present within the actual plate, but which is in a position corresponding to that of the longitudinal joint in the adjacent plate (Fig. 26A)*. This indicates therefore

* See also Fig. 32, Plate IV., where the same action is indicated at x and y.

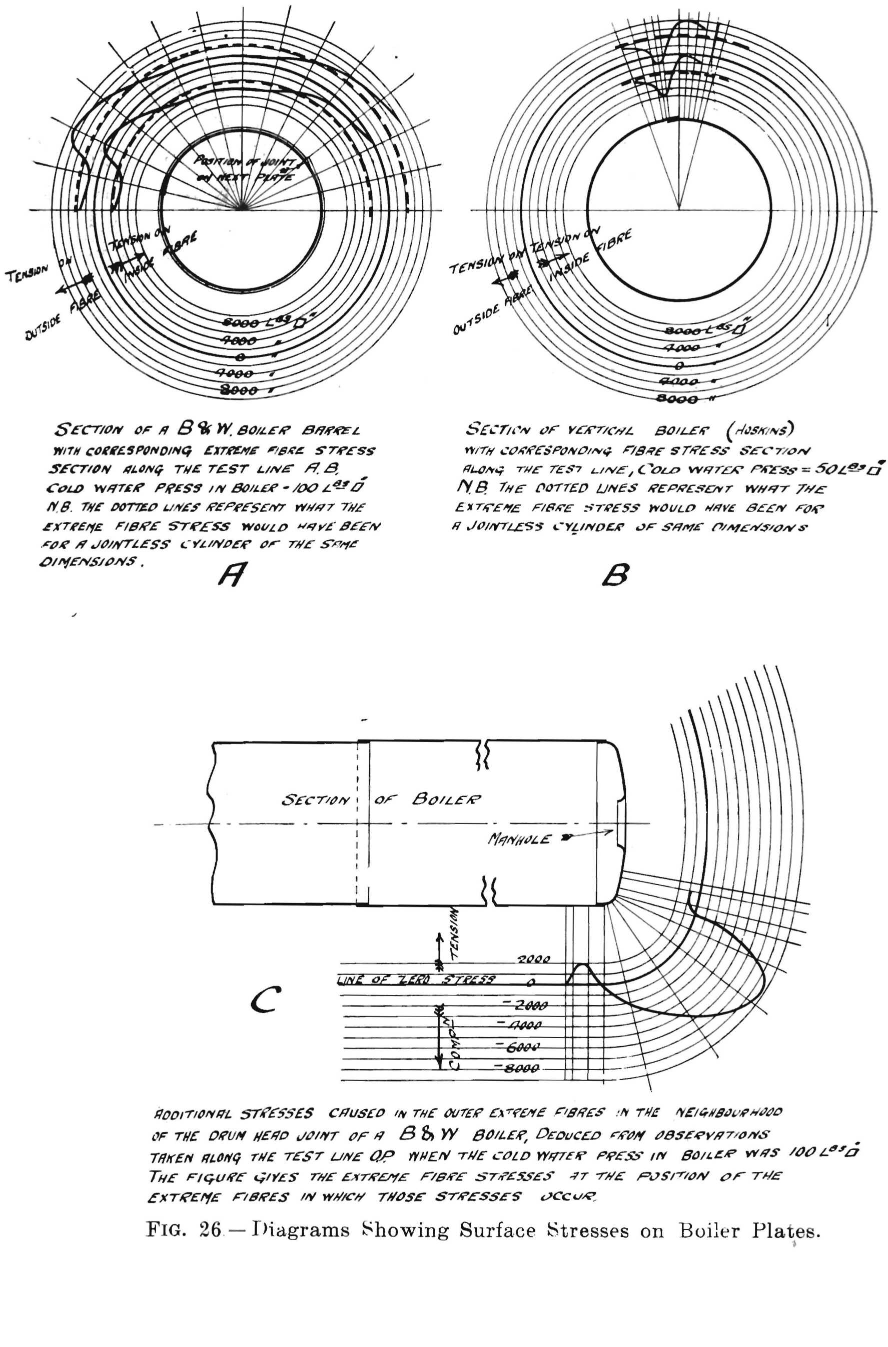


FIG. 26.—Diagrams Showing Surface Stresses on Boiler Plates.

that the construction of the boiler tends to stiffen the various parts, and, as a result, to modify the effect of want of symmetry in the design of the joint.

33. *Experiments on the Dished End of the B. and W. Boiler.*—About this time the report of an enquiry into the cause of an explosion of a thermal storage drum which occurred at Greenwich (England) became available. In this explosion the end of a cylindrical drum, whose diameter was about five feet, and length about 24 feet, was blown out as a result of a fracture which extended circumferentially along the flanged portion of the end of the drum, the fracture being slightly removed from the edge of the rivet holes (see Fig. 27). The report of the committee appointed to investigate this explosion considered that the

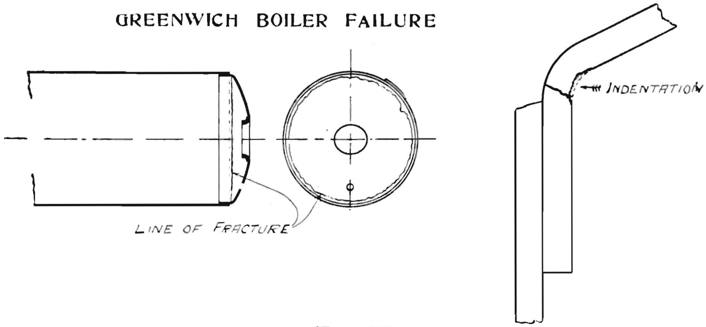


FIG. 27.

failure was due entirely to inferior workmanship, for the plate had been severely injured during the course of construction. The experimental results, to be described later, however, will clearly show that the faulty workmanship which was noticed was not entirely responsible for the failure, although it certainly caused it to happen at a much earlier date than would otherwise have been the case. The occurrence of this explosion, even though inferior workmanship was regarded as its immediate cause, naturally directed the experimental work towards the determination of the extreme fibre stresses in the vicinity of the flanged portion of the end plate in the Babcock and Wilcox boiler previously described. For that purpose a test line OP (see Fig. 24A) was taken, and the extreme fibre strain caused by the bend-