Having settled what the maximum stress can be, there remain two other questions of interest, (a) what stresses can we expect in the plate around the rivets? (b) how far back will the bending extend in a joint of an existing boiler where the fixing is rigid and not pin-jointed as was assumed above?

(a) At the mid-point of the joint we can only have a direct tensile stress of magnitude $\frac{P}{bt}$ ÷ efficiency of plate (say 66%) so that at the line of rivets, in a single riveted joint, the plate only has a stress equal to $\frac{1{\cdot}00}{{\cdot}66} = 1{\cdot}51$ times the direct tensile stress in the plate. Those places close to the centre line of rivets will be aided in carrying their small additional Bending Moment by the rivets themselves, and, consequently, the extreme fibre stress will rise fairly uniformly from the mid-point until it reaches its maximum value (nearly $\frac{4P}{bt}$) at the place where the plate just ceases to receive assistance. On the whole, the condition of the mid-point, in spite of reduced section, is very favorable compared with the edges of the joint where the maximum stresses occur.

(b) The second question will depend for its answer on the actual construction of the joint; e.g., consider the lap joint so often put longitudinally in a circular shell; both plates are bent a slight amount out of a true circle (Fig. 5), and since bending can only occur when the neutral axis lies away from the line of tension (curved in this case) it is easy to see that extra stresses, due to bending, will not occur further back than the point at which "joggling" commences. If the plates are not "joggled," the bending will continue until adjacent plates or stays supply a counter-balancing couple, or, failing this assistance, until the plates bend sufficiently to bring them in line with the pull (Fig. 6).

It should also be mentioned that unequal "joggling" of the two plates will impose unequal stresses on the plates; hence, bad workmanship may cause even greater stresses than those appearing in the foregoing calculations. Referring to Fig. 7, J_2 is now greater than $\frac{1}{2}t$; hence, Bending Moment at $B = P.J_2$ and is greater than if the joint were symmetrical, the maximum tensile stress being correspondingly increased.

Conditions similar to those of Fig. 3 were realised in the testing machine, and the result of experiments may be compared with these calculations, by reference to Part II of the paper, where will also be found an account of the modifications introduced when the joint forms part of an actual boiler.

6. *Characteristics of Lap Joint Failures.*—There are repeated references to the disadvantages of the lap joint type of construction in boiler literature of the last 20 or 30 years, and there are numerous accounts of appalling accidents caused by its failure.* The official publications of well-know boiler insurance companies have again and again protested against the use of this form of riveted joint, and in some of the States of America even legislative action has been invoked to prevent its adoption in new boiler construction. Although the joint is probably being slowly abandoned, it having no striking advantage apart from a slightly decreased cost, yet it is doubtless a safe estimate that three quarters of the boilers in use at the present moment employ this type of joint. Its characteristic method of failure is recognised to be by a fracture of one of the plates, starting from the inside of the joint, the fracture following the general course of the joint in such a manner as to be entirely covered by the projecting lap of the unaffected plate. It cannot be seen either from the inside or the outside of the boiler shell until it has penetrated right through the plate or has run into a rivet hole where its presence may possibly be indicated by a small leak.

The cause of the failure is usually ascribed to longitudinal grooving or furrowing caused by the "'working" or "breathing" of the boiler—this "breathing" being a general kind of term to describe the strains or alterations of shape set up in a boiler by the variations of pressure and temperature that accompany its normal working operation. The "breathing," of course, has an effect on all the parts of a

*The explosion of an ordinary horizontal tubular boiler owing to the failure of one of the longitudinal lap joints at Brockton, U.S.A., in 1905, and which caused the loss of 58 lives and injuries to 117 others, and the destruction of much property, attracted very marked attention to this type of joint.—See *Engineering Record*, 17th June, 1905.

boiler, and the authors' object at present is to point out that this action only becomes serious in such places where the surface stresses of the material are not only variable but abnormally high.*

7. *Method of Growth of Cracks and Grooves.*—A close examination of the additional cracks and grooves observed in the fractured plate of the Thornton boiler, casts a good deal of light upon the nature of the action that goes on in these failures. The position of the main line of fracture is indicated on the diagram (Fig. 2, Plate III.) extending from p to q. Throughout its entire length the surface of the fractured material showed two distinct parts, one, the smaller, revealing recently ruptured metal which had been torn by the actual explosion and proving that the thickness of the metal at the instant of rupture was from about 1-32″ up to 1-8″, the average thickness being approximately 1-16″. All the rest of the surface of fracture showed evidence of very considerable age, no doubt extending over several years; indeed, it is possible that the action starts at the beginning of the life of the boiler. When the plate was examined after being removed from the boiler, a few small cracks and groovings were found in the neighbourhood of x and y, on test specimens 12 and 11 respectively. These cracks and grooves are of a very definite form, and subsequent examination proved them to be of considerable age; evidently their appearance indicates what the surface of the plate from p to q looked like just prior to the failure. The marks at y, for example, took the form of a groove about 1-32″ deep and 1-16″ wide, following roughly the edge of the landing of the upper plate and having the appearance of a mark produced on the plate by a blunt chisel, but not looking in any way like a serious crack. But when this groove was laid open it was seen that at the bottom of it was an old crack running through the

*Professor Goodman, in his *Mechanics Applied to Engineering*, draws specific attention to the fact that the stress in the material due to the bending action is as great as, or greater than, the direct stress, and is the cause of the dangerous grooving so often found in lap-riveted boilers. His short treatment of the subject is the only attempt to compute the stresses in lap joints which the authors have found in books on Machine Design. Professor Goodman, however, proceeds with the detailed design of lap joints along traditional lines.

plate about $\frac{1}{3}$ of its thickness. At the part marked px the crack in the plate was not of such a definite nature, exhibiting to the eye more the appearance of a light pitting or slight furrowing. The fact that this marking followed the edge of the landing and terminated in a deep pit hole at the extreme corner of the landing led us to examine it under a stereoscopic microscope of low power* when it was found that the deep cracks evidently had their birth in such pitting or grooving which exhibited everywhere very characteristic features. They appear as grooves with well-rounded edges forming shallow depressions at the bottom of which the fine hair crack occurs. Fig. 8 shows in a diagrammatic way on an exaggerated scale the beginning of the growth of these cracks and the subsequent path they follow as they eat their way through the material of the plate. In one of the pit holes this action was very clearly marked, and a stereoscopic

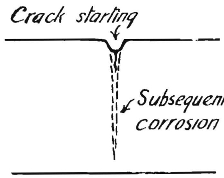

FIG. 8.—Sketch Showing Growth of Crack.

photograph was taken by means of a camera attached to the above-mentioned microscope (see Fig. 9). The photograph shows in a magnified way the fine crack at the bottom of the pit hole, extending longitudinally up towards the edges of the hole where it would gradually break into a similar crack in a neighbouring hole, or join another such crack at the bottom of one of the grooves. What condition it is that determines the precise fibre of the metal which is first going to give way under the combined severe surface strain and the chemical action of the water and the heat, it is impossible, of course, to predict. It may in one case be due to some slight additional strain caused by the caulking

*The authors strongly recommend the use of these low-power stereoscopic microscopes for the examination of cracks and groovings. The double tube portion of the microscope can easily be detached from the stand and supported by one hand when examining the inside of the boiler.

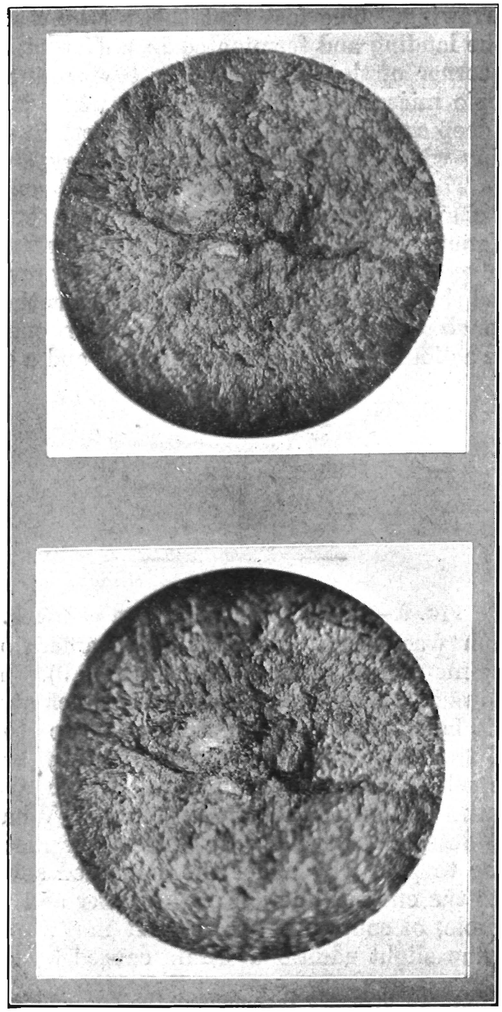

FIG. 9.—Stereoscopic Photograph of Pit Hole.

of the joint; in another the fracture may be localised by some accidental damage done to the surface of the plate during the construction of the boiler—for example, a slight bending during rolling, or, as in the case of the second of the explosions herein described (see § 11) to the cracks caused by punching the holes. It seems reasonable to suppose that the phenomena exhibited by pit holes, cracks and groovings may vary considerably in different materials. It is probable, for instance, that the action here described will be much more characteristically defined in metals with a well-marked fibrous structure than, say, in the case of castings or of forged materials. Further, any such action will be exaggerated by the presence of original defects in the material, understanding by that term defects which are fairly easily discerned or of considerable magnitude—of course, all materials used in construction will show microscopic defects if sufficiently minutely examined.

8. *Investigation of the Corresponding Unfractured Joint on Other Side of Boiler.*—The authors were naturally led to suppose that, assuming their explanation of the cause of the failure to be the correct one, a similar action would be found to have been proceeding in the corresponding joint on the other side of the boiler, although it might, perhaps, not have occurred to the same extent owing to the possibility that most of the " working " or breathing of the boiler would be taken up by the weakening of the joint that actually fractured. This question was investigated in some detail, and the results arrived at are so unusual as to merit a fairly complete statement of them. In the first place, a very minute examination of the other joint was made from the inside of the boiler with a view to determining whether there were any signs of grooving immediately under the joint at the edge of the landing, such as had been discovered in the fractured plate. At the first examination the joint appeared to be in thoroughly good order without the slightest suggestion of any flaw, and it was only after spending a couple of hours on it that a spot was located where a very fine pointed scriber seemed able to enter a minute groove in the inner surface of the outer plate exactly at the edge of the inner crown plate. This seemed to point to the possibility of there being more grooving hidden by the crown

plate, and, in order that the matter might be further examined, the Chief Mechanical Engineer directed the crown plate to be entirely removed so as to leave the side plate quite clear. When this was done, it was seen that there were fine groove marks in one or two spots along the line marked by the edge of the landing; the most prominent of them being the one which had been already located by the scriber point as stated above. The marks, however, were insignificant in appearance and were only such as are commonly seen along the junction line where two plates are riveted together. They were not such as to attract special attention even at this stage, and nine out of ten inspectors examining the plate would have decided, and with considerable justification, that it was quite sound. In fact, it appeared to the authors, although they were, at the time, specifically looking for and expecting a fracture at that spot, that the action could not have proceeded very far, and that the suggestion referred to above, that the failing of the other side of the boiler had relieved this one, was possibly correct.

Fortunately, however, the whole side plate was subsequently removed from the boiler, and the top portion was put under the hydraulic press, when it was found that the plate was fractured from end to end along the afore-mentioned line, and that the fracture had gone right through the plate almost to the outer skin. A photograph of the whole length of plate, and an enlarged view of portion of it are shown in Figs. 10 and 11. The history of this plate illustrates, in a very striking way, the extraordinary difficulty that besets the boiler inspector who is endeavouring to determine the existence of these fractures. Here was a plate nearly severed throughout its entire length; the edges of the fracture were so close together that its surface, even under minute examination, looked almost as good as new; the line of fracture was almost entirely masked by the overlapping crown plate, and the fracturing had gone on so uniformly that it had approached the skin of the plate on the far side throughout its entire length without piercing it at any one point so as to give warning, and yet it was in such a condition that a very slight shock would have sufficed to break it and let out the contents of the boiler.

9. *Statistics of Locomotive Boiler Risks.*—It is, of course, impossible to entirely eliminate the element of risk

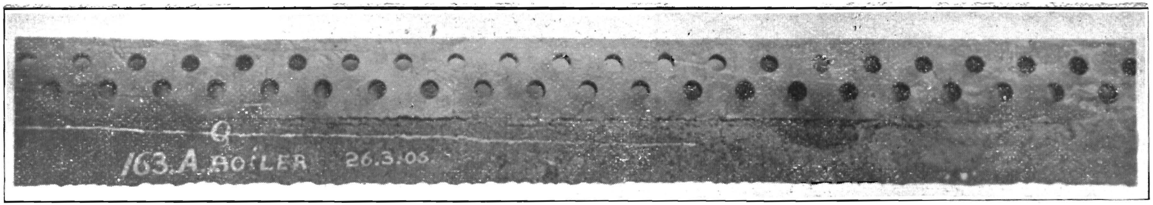

FIG. 10.—View of Upper Portion of Unfractured Plate.

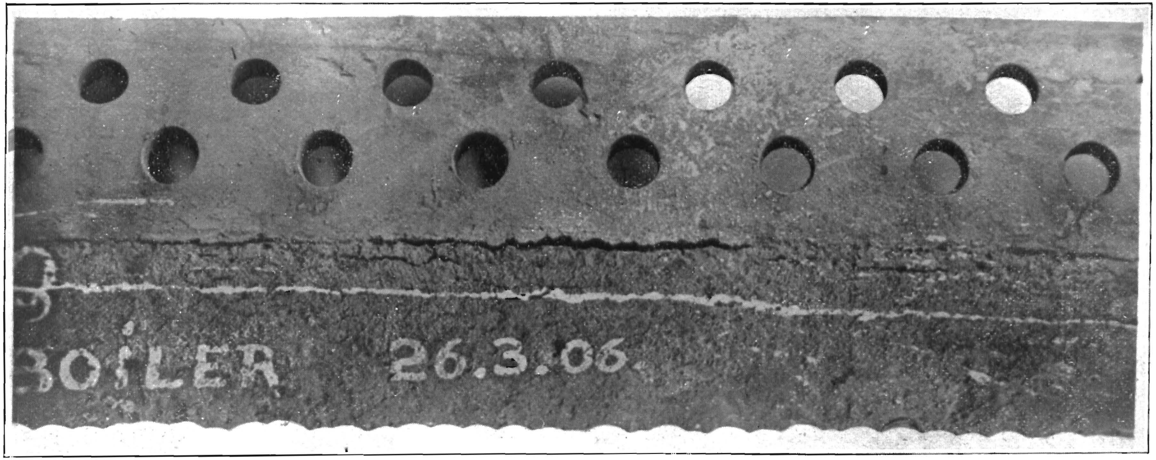

FIG. 11.—Enlarged View of Portion of Unfractured Plate.

in engineering construction, and the lengths to which it is justifiable to go in minimising the risk must be determined by the interests involved in each particular set of circumstances. What should be arrived at, however, is a definite understanding of what the degree of risk is; and this can only be achieved by a careful analysis of the conditions of each case. An important aid in making this determination will naturally be found by studying the statistics of failures or accidents affecting the particular engineering construction under discussion.

Looked at from a statistical point of view, New South Wales railway risks appear to be very small so far as locomotive boilers are concerned, since only three explosions, in addition to the present one, have been recorded. The first was the case of boiler No. 17, made by Stephenson, which was first put into service in 1874. It exploded at Wentworth Falls in December, 1881, one of the barrel rings with the dome on it having given way. The second case was that of the boiler of engine No. 22, made by Vale & Lacy, which exploded when going up the Wallsend bank in 1876. This boiler was only three years old, but no further particulars are available in connection with the accident. The third record is that of engine No. 437 of the "L" class, the fire box of which collapsed when the engine was working a train on the Cooma line in 1896, the boiler being about six years old at the time of the occurrence.

Two other fractures of a somewhat similar nature to the one now under discussion, but smaller in extent, occurred in locomotive boilers, one in 1901 and the other in 1904, but they were observed in time to avert disaster. The only point that seems to be specially worthy of note in connection with these two cases is that the boiler shells were made of iron plate, as was the case in boiler 163, and, further, that the inspecting officer in reporting on the latter of the two, states that there were no indications of groovings or waste on the inside of the boiler, and that the fracture was clean and sharp. These conditions, it will be noticed, correspond to those obtaining in the case of the present boiler failure. The authors have not sufficient data to justify them in saying that these conditions of fracture are specially characteristic of iron plate, although there are one or two indications in that direction.

10. *Methods of Locomotive Boiler Inspection and Proving.*—One of the most obvious and most interesting matters arising out of the foregoing, is a consideration of what methods of boiler inspection will suffice to detect flaws of the character here described. This boiler had been subject to the ordinary inspection of the N.S.W.G.R. Department, and an examination of the regulations (see Appendix II.), shows their method to be satisfactorily stringent and searching, and the statistics referred to in § 9 prove them to have been successful in general. It is quite clear that the application of proof pressures will not help except in an odd case where a boiler was about to fail and the proof pressure, if high enough, might just be sufficient to cause the fracture and so show the presence of the defect. This would be an extremely rare happening, and in the majority of cases it may be safely assumed that the proof pressure would only make things worse. Indeed, an examination of the stresses set up in this type of joint (for the details of which see Part II.) will make it quite clear that the frequent application of high proof pressures is a practice of very questionable utility. There is still a considerable difference of opinion amongst authorities as to the correct proof pressures to apply. Some are still found to recommend a proof pressure for new boilers exceeding twice the normal pressure, and for old boilers up to as much as twice the normal pressure. On the whole, the tendency seems to be towards lowering proof pressures and the authors are of opinion that the Railway Department's system of applying something less than 50% excess of working pressure as the hydraulic test pressure in the case of new boilers, and of about 20 or 30 lbs. over the working pressure in the case of boilers that have been repaired is a sound one. In fact, it seems to the authors that no good grounds exist apart from the most exceptional circumstances, for applying a greater pressure than, say, 50% excess to a new boiler and 25% to one that has been used, and commonly, less than these figures would be prudent.

Some boiler inspectors consider that the hammer test applied by a man with considerable experience affords the best means of determining these fractures before they have gone far enough to be absolutely dangerous. That there are men with special skill in this direction is not to be denied, but when the fractures occur right underneath a double-riveted joint the difficulties of detecting them with any certainty by a hammer test are undoubtedly great.

It is worth noting that the rather rough-handed methods sometimes employed in cleaning the inside of a boiler are to be greatly deprecated. For instance, the practice often witnessed of scaling a boiler with a chipping hammer so vigorously as to mark or sometimes even cut the surface of the plate makes it almost impossible to detect the fine cracks of the character now under discussion. Any information as to what is amiss with the riveted joint is chiefly to be obtained by a minute study of any pittings, grooves or cracks that may exist in its neighbourhood, and these are very readily masked by any rough treatment of the surface of the plate.

It is evident that anyone responsible for inspecting a boiler should be thoroughly acquainted with the nature and characteristics of these pittings and groovings and should be able to tell whether they are merely surface frettings or whether they tend to grow deeper by minute fracturing of the bottom of the pit or groove. Above all things the inspector should be instructed to make the most painstaking scrutiny of every detail—even the apparently most insignificant—in the neighbourhood of a lap joint and of such other parts of a boiler as are similarly subjected to very unsymmetrically distributed stresses. For this purpose the authors are strongly of opinion that a low power stereoscopic microscope is one of the most useful pieces of equipment with which a boiler inspector can be provided.

Of equal difficulty with the question as to how to locate these fractures is that of determining what to do with a lap joint, about the safety of which there may be some little suspicion. No general answer can be given, but it is obvious that inspectors while treating each case on its merits, will do well to err on the side of safety.

11. *General Description of the Burwood Tramway Boiler Explosion.*—The second explosion was that of the boiler on tramway motor No. 82. The accident occurred at a