

29 January, 1895.

JOHN WOLFE BARRY, C.B., Vice-President,
in the Chair.

(Paper No. 2769.)

(Abridged.)

“Boiler Explosions.”

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It is proposed to deal in this Paper with the subject of boiler explosions in its broad engineering aspect; and before entering upon the consideration of it, some of the old theories of boiler explosions may well be recapitulated, although it is not now worth while to refute them. The theories alluded to are those of (1) deferred ebullition; (2) dissociation and sudden recombination of the oxygen and hydrogen of the water; and (3) spheroidal condition of water in contact with overheated plates, and sudden excessive increase of pressure when water is admitted.¹

The importance of clearly understanding the causes of boiler explosions is evident when the destructive effects of which they are often the origin are considered. As it is not universally understood that it is not so much the steam as the hot water which is the destructive agent, a brief enquiry as to where the energy is stored is an important preliminary to the general study of the question. When it became recognised that a boiler-shell was normally in a state of high tension, and that when once a rupture was produced by the action of the static stresses on a locally weak spot, the stored-up energy was capable not only of enlarging it into a complicated series of rents extending through the sound portions of the structure, but of producing all the other destructive effects observed in such cases, the investigation of these disasters was

¹ Report of the Chief Engineer of the Manchester Steam Users Association, January and February, 1867; also Report on a Series of Red-hot Furnace-crown Experiments, by the same Author, 1889.

placed on a satisfactory basis and a long step was taken towards their elucidation. The amount of energy stored in the hot water and the steam of a boiler, and capable of being expended in the event of explosion, is readily calculable by well-known thermodynamic methods. The question was investigated concurrently by Airy¹ and Rankine² in 1863. Into the details of the reasoning it is scarcely necessary to enter, since they can be found in most treatises on thermo-dynamics. It is sufficient for the Author's present purpose to give the numerical results contained in Table I.³

TABLE I.

Absolute Pressure.	Initial Temperature.	Total Energy Liberated on Reduction of the Pressure to Atmospheric Pressure, and of the Temperature to 212° F.	
		By 1 lb. of Water.	By 1 lb. of Steam.
Lbs. per Sq. Inch.	° F.	Foot-pounds.	Foot-pounds.
25	240	440	29,596
50	281	2,550	68,164
75	307	4,816	90,739
100	327	6,885	106,673
150	358	10,536	129,004
200	381	14,153	145,121
250	401	17,314	157,830

From this Table it will be seen that the available energy stored in any body of hot water will suffice to raise it to a height of 2 miles when the pressure is 150 lbs. per square inch, and to more than 3 miles when the pressure is 250 lbs. per square inch. In an explosion, only part of this energy is expended in tearing up the boiler and hurling the fragments about, but even a small fraction of it will suffice to do enormous damage. A few actual cases are stated in Table II, and a comparison is there drawn between the energy stored in boilers and the weight of gunpowder which is capable of producing an equivalent effect.

¹ Philosophical Magazine, vol. xxvi., 1863, p. 329.

² *Ibid.*, p. 388.

³ These results are abstracted from a Table given on pp. 656 and 657 of Prof. R. H. Thurston's "Manual of Steam Boilers," New York, 1888.

TABLE II.

Type of Boiler.	Dimensions of Boiler.	Working Pressure by Gauge.	Approximate Weight.			Available Energy.			Height to which Energy would lift Boiler.	Gunpowder equivalent to Total Available Energy.
			Boiler.	Water.	Steam.	Water.	Steam.	Total.		
	Length. Dia. Feet. Feet.	Lbs. per sq. in.	Tons.	Tons.	Lbs.	Foot-tons.	Foot-tons.	Foot-tons.	Feet.	Lbs.
Lancashire	27 × 7	100	12½	11½	46	93,000	2,351	95,351	7,628	795
„	30 × 8	150	24½	17	110	200,991	6,606	207,597	8,473	1,730
Egg-ended	30 × 6	80	5½	10	88	64,740	4,083	68,823	12,513	574
Marine .	15 × 13	150	39	24½	100	289,663	6,005	295,668	7,581	2,464*

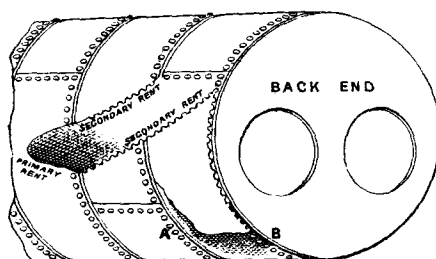
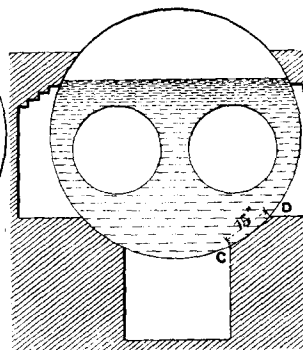
In considering the principal causes of explosions which have occurred, each group will be dealt with separately, and will be illustrated as far as possible by actual cases in which there can be little doubt as to the primary cause of the explosions.

FAILURE OF BOILER-SHELLS.

External Corrosion of the Shells.—Some of the most disastrous explosions have been due to the external corrosion of boiler-shells. Such corrosion is nearly always due to dampness of the brickwork, and this dampness again may be due to leaky rivets, pipes or cisterns, or to drainage when the boiler is situated below the level of the surrounding ground. But whatever the original cause of the dampness, its action is aggravated by defective boiler-settings.

Case I is presented by an ordinary Lancashire boiler which burst near the back end at the right-hand side of the shell, *Fig. 1*. The rupture occurred in the first instance along the longitudinal line A B, where the plate had been eaten away by external corrosion for a length of about 3 feet, until it was as thin as a sixpence and too weak to resist the ordinary working-pressure. The position and extent of the corroded portion are roughly indicated by the shading, *Fig. 1*, while the manner in which secondary rents were developed from the primary one, a portion of the last belt of plating being opened out and torn through the sound plating at the adjacent circumferential seams, will be understood from the view given in the *Fig.* Fortunately, in this instance the secondary rents did not extend far, and

the case is a simple one; not only as to the relationship between the cause and the effect, but also in regard to the manner in which the corrosion was brought about. Turning to *Fig. 2*, which shows a cross-section of the external flues, it will be observed that the brickwork seating C D, upon which the boiler rested, was as much as 15 inches in width, so that corrosion of the plates at this part could take place to a considerable extent unobserved. Further, any moisture which leaked into the side-flue would naturally have drained to the point D, and thus have come into contact with the plates; while the great width of the bearing-surface afforded a secure lodgement for the water, and rendered it difficult for the heat passing through the flues when the boiler was working to drive it away. When it is added that subsequent enquiry elicited the fact that at the back end of the

Fig. 1.*Fig. 2.*

boiler, close to the part where the corrosion occurred, there was a jack-well, the water-level in which was above the floor of the side flue, the chain of causes leading to the explosion is completed. When the primary rupture in a boiler-shell is in a longitudinal direction and of serious dimensions, it is not often that the secondary circumferential rents which start from it stop within such moderate limits as in the case just considered; more frequently they start from each side of the initial rupture and run completely round the shell, occasionally forking and branching off in an irregular manner.

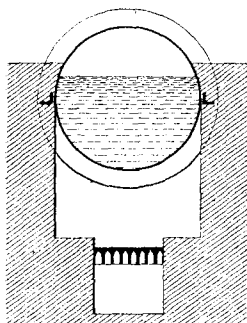
In some cases corrosion has occurred at the bottom of the shell where it rests on a broad mid-feather wall. This is a method of seating boilers which has been very fruitful of explosions, since the mid-feather is situated just at the part to which any moisture

on the shell, arising from leakage or other causes, naturally drains, while the excessive bearing-surface often allowed renders the mid-feather an objectionable receptacle for water, and permits the insidious work of corrosion to proceed unseen.

Case II, *Fig. 3*, shows a defective method of setting externally-fired boilers which frequently gives rise to trouble from corrosion

—the sides of the boiler being swathed in brickwork to such an extent that as much as one-third of the entire circumference of the shell is hidden from view. The result in the instance illustrated was that leakage at a longitudinal seam kept the brickwork in the vicinity damp, and thereby set up the corrosion which led to the rupture of the shell. It will be noticed that the secondary rents do not always follow the seams of rivets or lines of natural weakness, but apparently rip through the solid plates with apparent facility.

Fig. 3.



External corrosion is comparatively slow in its action, at most about $\frac{1}{16}$ inch in twelve months; and, provided the boiler possesses an adequate factor of safety, a searching periodical inspection, at intervals of about a year, affords ample opportunity of detecting the ravages of external corrosion before it attains serious dimensions. To this end, therefore, the flues should be sufficiently capacious to admit of the passage of a man through them with ease, and the concealment of large areas of plating by brickwork should, as far as possible, be avoided. Broad seating-walls or mid-feathers are unnecessary. A bearing-surface of 4 to 5 inches is ample, even for the largest land boilers, and this surface should be afforded by fire-clay blocks specially made for the purpose, so as to raise the surface of contact above the floor of the side-flue and to keep it as dry as possible. The crowns of the side-flues should also be closed in with curved fire-clay tiles, having not more than two courses of bricks laid over them so as to hide as little of the plating as possible. Further, the jointing-material between the boiler and setting should be of fire-clay throughout, and not of common lime mortar, owing to the hygroscopic character of the latter material. Again, the longitudinal seams should be arranged, if possible, on the upper part of the boiler, clear of the brickwork, so as to be easily accessible for inspection or caulking. With small iron plates

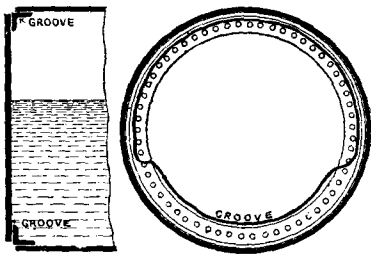
this was not formerly feasible, but with the introduction of steel plates of almost any size, no difficulty need now be experienced on this score. These points may perhaps appear somewhat trivial, but experience proves that they are too often ignored, and the consequences occasionally entailed by their neglect are very serious.

Internal Corrosion of the Shell.—Next in importance to external corrosion of the plates in contact with the boiler-seating, is the internal wasting of boilers from the action of the feed-water. The effects produced by this agency differ considerably in character, inasmuch as the points attacked and the nature of the corrosion vary. In some instances the plates are wasted away over their entire surface, in others the corrosion assumes the form of pits, varying in diameter between $\frac{1}{2}$ inch and 2 inches, which may appear in groups or be widely scattered. The wasting due to internal corrosion is occasionally far more rapid than that due to external corrosion, and instances have occurred in which the metal has been so much reduced in the space of three years that no margin of safety remained.

From the foregoing it will be inferred that those explosions which, either directly or indirectly, owe their origin to internal corrosion, are not of a well-defined type. Reference may, however, be here made to a fact often revealed by explosions, viz., that external and internal corrosion sometimes run in parallel lines; as, for instance, in the vicinity of brickwork whose heat, when the water has been let out of the boiler, loosens the internal scale and exposes the bare plates to the action of warm moisture.

Combined Corrosion and Mechanical Action: Grooving.—When corrosion is accompanied by bending movements in the plates of a boiler, its wasting action is markedly intensified and a specific defect is developed of the character technically termed “grooving” or “channelling.” An example of the failures arising from this cause frequently met with amongst cylindrical flat-ended boilers, is illustrated in *Figs. 4*. Sometimes these grooves form in the end-plate, sometimes at the root of the angle-bar ring or flange attachment. The groove results from the breathing action which often takes place in unstayed circular end-plates of this kind, in

Figs. 4.



consequence of variations of the steam-pressure. This gives rise to a local fretting action at the circumferential attachment, which, by splitting off the scale and oxide as fast as it is formed and exposing the raw plate to the action of the water or steam, greatly accelerates corrosion. The position of the groove depends upon the relative weakness of the end-plate and the attachment. If the end-plate is elastic while the angle-bar is stiff, the groove will be in the former, and *vice versâ*; or it may happen that the groove is formed in both at the same time, as in the particular case considered. The breathing and fretting action increases with the growth of the groove, which, when once started, develops with considerable rapidity, especially if the steam-pressure be subject to wide and frequent fluctuation. That the formation of these grooves is more the result of mechanical movement than of corrosive action will be evident from the fact that they form in the steam-space with almost as much rapidity as below the water-line, and they occasionally eat their way through the plate before other parts of the boiler exhibit any serious signs of wasting. In the cases considered, the grooving may be regarded as due primarily to weakness, and the failures would probably not have occurred had the ends been strengthened with bolt-stays or by other suitable means. It frequently happens, however, that grooving occurs as a consequence of excessive stiffness of the end-plates, particularly in Lancashire and Cornish boilers; and, though the defect is rarely in such cases a source of danger, a few words in reference to it may be not out of place. Such grooves are almost invariably situated near the crown of the furnace and follow the circle of the tube, sometimes in the end-plate and sometimes in the angle-bar or flange attachment, while the defect is always most severe at the front or furnace ends of the tubes. The grooving in these cases arises from lack of elasticity in the end-plates for the expansion and contraction of the furnace-tubes, and relief is often afforded, and further mischief prevented, by removing one or two of the lower rivets in the gusset wet-plates, so as to allow greater freedom of movement and to distribute the bending action over a wider area. In *Figs. 5* is shown a typical case of failure of a vertical boiler from grooving at the junction of the uptake with the crown of the fire-box. The uptake, it will be evident, acts as a strong central stay to the crown-plate, and in this instance when the stay, becoming insufficient to resist the working pressure, fractured, the fire-box crown proved incapable of bearing the additional load thrown upon it and collapsed, with the result that the boiler was shot up like a rocket and thrown to a considerable distance. It

should be mentioned that the attachment of the base of the fire-box to the shell was weak, and to this fact the grooving was in all probability largely due. *Fig. 6* represents a rather peculiar case of grooving in connection with another vertical boiler which exploded. In this case, the waste heat and gases were discharged through an opening in the side of the fire-box. There was no uptake, and the cambered crown-plate became, in consequence of its excessive pliability, grooved as shown at the convex corner of the flange which unites it to the vertical sides of the fire-box.

Grooving at Riveted Seams between the Shell and Tubes.—Grooving or channelling is occasionally found at the edges of the overlaps of the longitudinal or circular seams both of shells and of furnace-tubes. In the case of the longitudinal seams, the defect arises from the bending action due to the fact that the shell is not truly circular and that the couple set up by the stress in the plates tends to deflect the joint, the amount of deflection varying with the steam-pressure. The action is more pronounced in boilers of small diameter with a narrow single-riveted overlap than in those of large diameter having double-riveted overlap seams; it is also, as in other cases, promoted by wide and frequent fluctuations of steam-pressure; and in some instances is doubtless started by the injudicious use of caulking-tools. In the case of the ring-seams, the bending action which gives rise to grooving arises from arching of

Figs. 5.

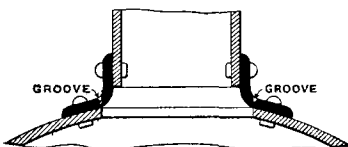
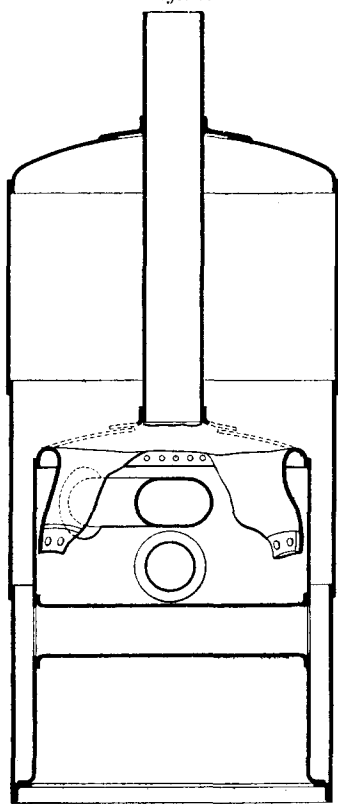


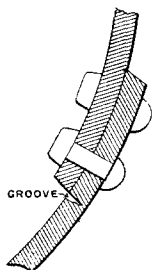
Fig. 6.



the shell or of the furnace-tube in consequence of unequal expansion.

Grooving in Locomotive Boilers.—It seldom occurs that grooving at the riveted seams of stationary boilers is of a very serious character or gives rise to an explosion. In locomotive boilers, however, it assumes such an aggravated form as to constitute a specific defect of a dangerous kind. A larger number of disastrous explosions of locomotive boilers have arisen from grooving than from all other causes put together. In locomotives, the grooving is confined almost exclusively to the longitudinal seams, and its active character is due to the fact that the barrels are of small diameter and that the steam-pressure is liable to large and sudden fluctuations; while the deformation at the joint is intensified by the jolting to which the boiler is subjected in its transit over the permanent way. Grooving is not confined to single-riveted

Fig. 7.



seams, and double-riveted seams do not afford absolute security. In a few instances on the North Eastern Railway, the groove, Fig. 7, was so fine that it must have been almost invisible before the explosion; and its appearance even suggested that it might be a fracture of a brittle plate. That, however, was not the case, nor could the grooving have been started by careless caulking, as all the seams were caulked outside only.¹ In all the cases of explosions of locomotive boilers from longitudinal grooving, the defect has invariably been associated with riveted joints of the ordinary overlap

form, and no case of grooving has been met with where the joints were of the double butt-strap type. With a view to the detection of this defect the longitudinal seams should always be placed in the steam-space, so as to be easily accessible for examination.

Stresses arising from unequal Expansion and Contraction, in externally-fired Boilers.—The severity of the stresses produced by differences of temperature may be inferred from the fact that long plain cylindrical boilers will occasionally rend at a circumferential seam with hardly any premonitory warning. The tendency of boilers which are only heated along the bottom of their shells is to curl up at their ends, while the introduction of cold feed-water, which naturally gravitates towards the bottom, produces severe stresses in an opposite direction. Fractures consequent thereon are sometimes found to run from the rivet-holes to the edge of the

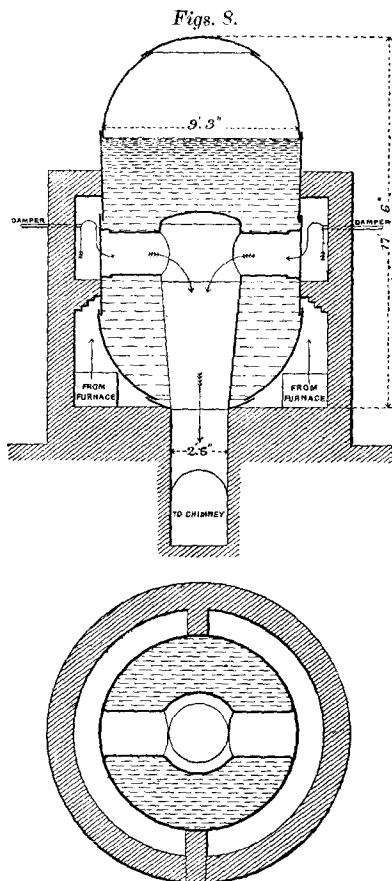
¹ For further particulars, see Report of the Chief Engineer of the Manchester Steam Users Association, December, 1880.

overlap, and sometimes from hole to hole. In the latter case they are rapidly developed into "seam-rips" when the boiler is subjected to the racking stresses of actual work.

Rastrick Boilers.—The remarks as to the dangers of externally-fired boilers are also applicable to a large extent to boilers of the Rastrick type, which are often adopted at ironworks for utilizing the waste heat of puddling-furnaces and which have been productive of some of the most disastrous explosions on record. *Figs. 8* show the general arrangement of this type of boiler. The shell is practically of the plain egg-ended type set upright, and the flames, after playing on this in the first instance, pass through two, and sometimes through four, short cross-tubes (according to the number of furnaces) into a central descending flue-tube, whence they are led to the chimney. The quantity of heat passed off from puddling-furnaces is not great but it is of an intense character, and its local impingement on the vertical plates of the shell, which are necessarily thick on account of its large diameter (ranging in some cases up to nearly 10 feet), gives rise to over-heating and to serious distress at the riveted joints, which suffer much from lap-fractures and occasionally from seam-rip. The sulphurous fumes which are passed off with the gases from the furnaces also prove destructive, by causing a rapid corrosion of the plates over their entire surface. This corrosion is often not apparent to the untrained eye, and is only capable of being detected by careful examination of the rivet-heads and of the edges of the overlaps.

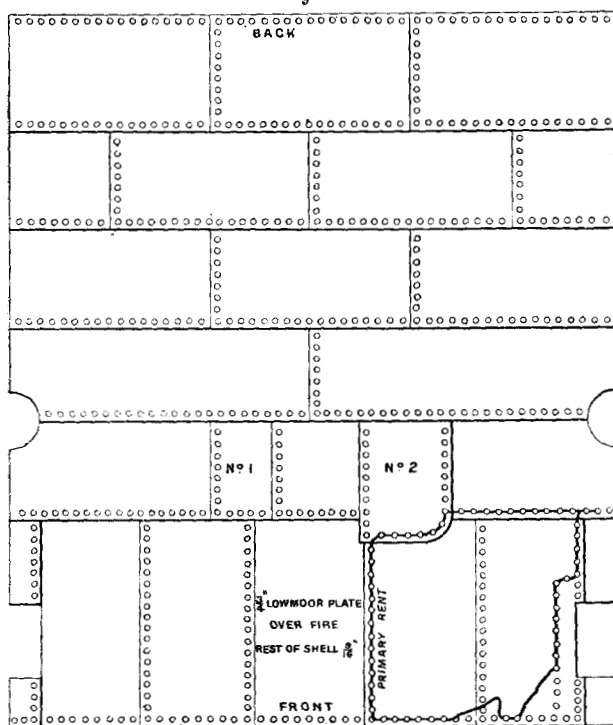
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A brief reference may here be made to a specially interesting case of failure of an externally-fired boiler, which presented a unique feature, inasmuch as the explosion occurred two hours after the fire had been drawn and while the pressure was considerably below its maximum. The boiler was fired under the bottom, and the waste gases were ultimately led through two internal flue-tubes. The feed-water produced a sediment, and three months after the boiler had been set to work, leakages at the ring-seam over the bridge

Fig. 9.

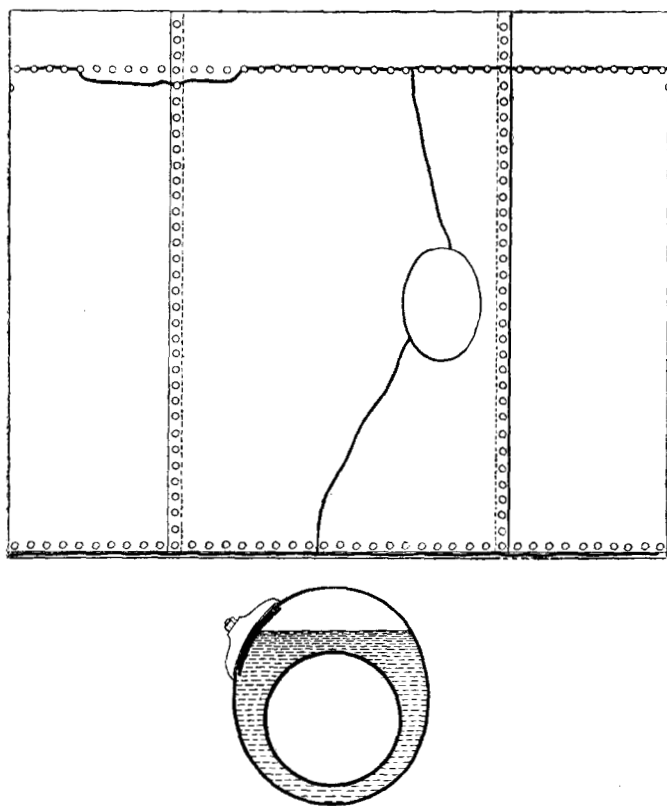


became so serious that patch No. 1, *Fig. 9*, had to be fitted. Shortly afterwards patch No. 2 had to be added; but this did not stop the leakage of the seams between the thick and the thin plates, one of which ultimately tore as shown in the *Fig.* when the boiler was only two years old.

Insufficiently Strengthened Holes in Shells.—Many explosions owe their origin to local weakness caused by large man-holes or dome-holes being cut through boiler-shells and the omission of com-

pensating rings or the provision of inefficient ones, see *Figs. 10*. The weakness thus produced was clearly demonstrated in hydraulic experiments carried out in 1874-76 by the Manchester Steam Users Association,¹ when a Lancashire boiler gave way at the man-hole under a pressure of 200 lbs. per square inch, although the estimated

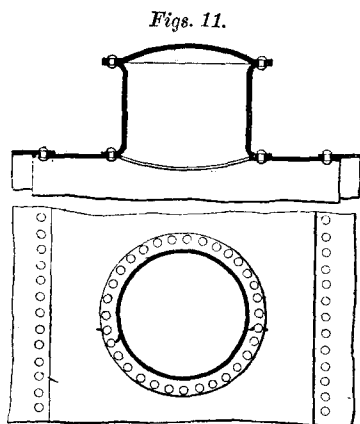
Figs. 10.



bursting-pressure for a seamless shell without the hole was 466 lbs. per square inch. On this occasion, the mean circumferential stress did not exceed 8·6 tons, whereas the material had been proved capable of withstanding a stress of 20·6 tons per square inch. Another test was made with a small wrought-iron neck

¹ See also *Engineering*, vol. xxi., 1876, p. 237.

riveted round a 17-inch circular opening, *Figs. 11*; but the boiler gave way at that point when the pressure had only reached 250 lbs. per square inch, which is very low having regard to the



sectional-area of the compensating material. From this it is evident that the sides of a dome cannot be depended upon to add materially to the strength of a boiler-shell which has been locally weakened by a large hole; and even where the opening is small, the presence of a dome seriously affects the strains in the boiler-shell. Another experiment was carried out with a cast-iron mouthpiece fitted round a hole 20 inches in diameter, but although its sectional-area was 30 square inches, as against $8\frac{3}{4}$

square inches of the removed boiler-shell plate, this part gave way at a pressure of 200 lbs. per square inch, proving that cast-iron is an unsuitable material for man-hole mouthpieces.

COLLAPSE OF BOILER-FLUES.

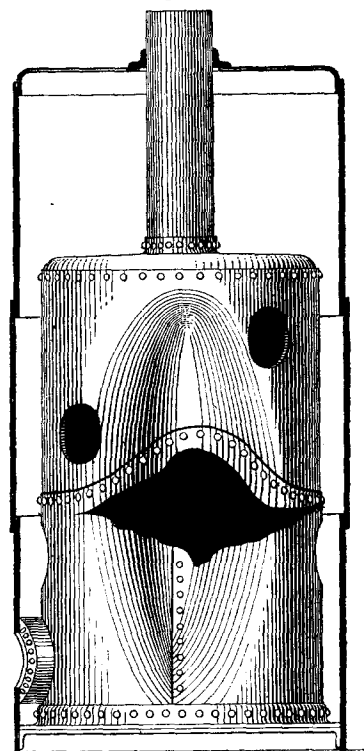
Until Sir W. Fairbairn made his well-known experiments on boiler-flues, little was known about the strength of flues; and, although it had been previously shown mathematically that a departure from the cylindrical shape seriously weakened them, he was the first to demonstrate experimentally that the length of flues was an important factor in estimating their resistance to collapse. Nearly all boiler-flues are now fitted with strengthening rings, and the best manufacturers ensure a perfect cylindrical shape, either by welding the longitudinal seams or by making them with double butt-straps. In the tests conducted by Sir W. Fairbairn, the experimental tubes bent during collapse until their cross-sections assumed star-shaped forms.¹ Professor W. C. Unwin has shown that the number of depressions in the circumference of the tube increases as the ratio between its length and its diameter diminishes.²

¹ "On the Resistance of Tubes to Collapse," *Phil. Trans. Roy. Soc.* 1858, p. 389.

² "On the Resistance of Boiler-Flues to Collapse," *Minutes of Proceedings Inst. C.E.*, vol. xlv. p. 225.

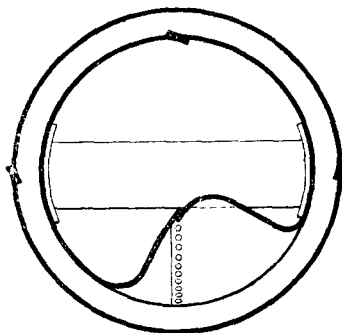
In actual practice, however, the collapse nearly always consists of a flattening of one or two sides. Generally the top of the furnace gives way, the crown of the tube is crushed down until it follows more or less the sweep of the lower portion. The prevalence of this kind of collapse is due to the fact that the crown of the tube is usually the part most seriously affected by the fire as well as by corrosion. Occasionally the bottom of the flue is crushed upwards, the crown remaining convex; and sometimes the crushing affects the sides. *Figs. 12* show a typical example of collapse often met with in boilers of the small vertical type; and similar effects are sometimes produced in vertical chimney boilers, the flues of which should always be strengthened by hoops. Cases have been noticed where such rings having been originally fitted have been removed during repair of the boiler, or perhaps have been replaced by a few stays.

Figs. 12.



COLLAPSE OF FURNACES.

Overheating through Shortness of Water.—To whatever cause shortness of water may be due, its effect is always the same. As the water-level is lowered, the furnace-crowns are exposed to the weakening influence of a gradually-increasing temperature and ultimately bulge down. Such collapses usually occur in one furnace only of a pair, as might be expected; since



the fires, unless mechanically stoked, are never charged simultaneously. The results of such collapses are rarely of so serious a nature as those previously mentioned; and the Author can remember only one case, during the last twenty years, in which shortness of water in Lancashire or Cornish boilers has led to the destruction of the shell. The risk of serious rupture in the event of collapse from overheating is much diminished when the tube is strengthened by encircling rings; and cases have occurred in which the tubes have been seriously overheated and even crushed, but were prevented from tearing by their strengthening rings.

Whilst referring to the diminution of risk of rupture, a word or two may be not out of place with respect to one or two precautionary measures against shortness of water. Chief of these is the fitting of duplicate water-gauges, so that one may serve as a check on the other, and diminish the chances of misreading. Valuable supplements are a low-water safety-valve and a fusible plug. Carelessness will account for some mishaps, and the water has repeatedly been accidentally run out of a boiler by the blow-off cock being opened; such cocks should always be fitted with a safety-guard to prevent the removal of the key except when the cock is closed.

When several boilers are fed from one pump, particularly when there is a difference of pressure in the various boilers, and one of the check-valves becomes accidentally jammed, the water will readily be siphoned from one boiler into another; and to prevent this, the feed-pipes which supply a group of boilers should be placed so as to deliver 3 inches or 4 inches above the furnace-level.

Whether overheating be the result of slow evaporation or of rapid exposure of the furnace-crowns through some misapplication of the feed or blow-off, the character of the collapse is practically identical, and shows the same local peculiarities. If the boiler is of the Lancashire type, both furnaces generally show marks of overheating—a distinct purple bloom being generally visible on the fire side of the collapsed part, showing the level to which the water has sunk and the extent to which the plates have been overheated. If the overheating be excessive, this is corroborated by discoloration of the plates on the water side also, though seldom to the same extent. The only reliable experiments relating to the strength of overheated flues are those conducted by the Manchester Steam Users Association, and to which reference has already been made. In one of these tests, which was conducted under a pressure of 40 lbs. per square inch, the water-level was lowered by opening the blow-out tap until nearly half the circumference

of each furnace-tube was laid bare.¹ The time occupied in exposing an arc of the tube having a versed sine of 15 inches was four minutes, and in six minutes after this, *i.e.*, ten minutes from the time of the water being level with the crowns, one tube collapsed. What was the precise temperature attained by the furnace it is impossible to say, but there can be little doubt that it was red-hot, since some fusible disks attached to the furnace-crowns, as well as some lead strips laid loosely across them, were fused. Some gauges attached to the furnaces afforded a means of watching the rapidity with which the collapse took place; and observation showed that under the conditions of the test, with a large extent of surface quickly exposed and heavy fires, there is very little warning, and when once bulging begins it is followed by complete collapse in the course of two or three seconds.

In a subsequent test, the water-level was lowered and the crowns of the furnace-tubes were laid bare by the action of evaporation, in a manner approximating to that which generally occurs in practice in cases of scarcity of water. With a view to form some estimate of the temperature attained by the plates over the fire, fusible gauges of tin, lead, and zinc were attached to each furnace-crown, while lead strips were also bound in position at intervals throughout the length of each tube. In this experiment the water was brought down to the level of the furnace-crowns by opening the blow-out tap. The tap was then shut, the fires were heavily charged, and the furnace-crowns were permitted to become exposed by evaporation. In twenty-three and a half minutes, all the fusible gauges attached to the furnace-crowns having melted, the feed was turned on through a pipe fixed immediately over the furnace-crown, and perforated on the under side so as to play in a series of fine jets upon the overheated plates, the injection of the feed being at the rate of about 28 gallons per minute. The only effect of this was to reduce the pressure, which fell in two and a half minutes from $28\frac{1}{2}$ lbs. to 26 lbs. per square inch. The whole bearing of these, as well as of the other tests of the series, showed that the popular notion with respect to the danger of turning on the feed in the event of shortness of water is erroneous.²

Reference has been made to the effect of shortness of water in

¹ The boiler was of the Lancashire type, 27 feet 9 inches long and 7 feet in diameter, with plain tubes measuring 3 feet in diameter and $\frac{1}{8}$ inch in thickness.

² For a complete record of these tests and explanatory illustrations, see "Report on a Series of Red-hot Furnace-crown Experiments," by the Chief Engineer of the Manchester Steam Users Association, 1889.

boilers of the Lancashire and Cornish types only; but failures from this cause are not exclusively confined to such boilers. Collapse of locomotive-boiler fire-boxes sometimes occurs, though happily rarely—a fact due partly to the superior attention which boilers of this class receive, and partly to the efficient manner in which the roofs of the fire-boxes are supported, in consequence of which a warning of overheating is generally afforded before the danger becomes serious. In boilers of the multi-tubular marine type the furnace-tubes are in a somewhat similar way protected against collapse; since it would be almost impossible to lower the water-level to such an extent as to lay bare the furnace-crowns without attention being drawn to the fact. In such an event the whole of the smoke-tubes would be first uncovered, and even before this, serious trouble would be experienced with the crown of the combustion-chamber and the smoke-tube ends in the tube-plates. Nevertheless, the furnace-tubes of marine boilers occasionally collapse through overheating, which does not, however, arise in these cases from deficiency of the water-supply.

Again, in boilers of the small vertical type, deficiency of the water-supply is generally revealed by collapse and rupture of the uptake before the water-level can be so far reduced as to jeopardise the safety of the fire-box; although, as the uptake acts as a substantial stay, its failure in some instances causes the crown of the fire-box to collapse downwards in its turn. In boilers of the plain egg-ended type, the water may fall to a very low level without risk of serious overheating; and failures from shortness of water pure and simple are seldom met with, since the straining and leakage at the seams of rivets afford warning of the danger. A few instances, however, have come under the Author's notice, and their characteristics may be briefly referred to. One of these showed discoloration on each side of the shell over the fire, indicating that the water in the boiler had been boiled away until there was only a depth of about 6 inches at the time of rupture; when the left-hand side ripped for a length of 4 feet 6 inches, forming an opening about $2\frac{1}{2}$ inches wide in the middle with distinct lips on each side, which showed it had been produced while the plate was in a plastic condition. As an illustration of the statement that the water is the main factor in the work of destruction, it may be noted that in this case the boiler was not stirred from its seat, its contents consisting almost entirely of steam, which escaped through the opening as from a fractured pipe. Had the boiler been filled with hot water to its normal level, a rupture of such magnitude would in all probability have

resulted in the complete destruction of the boiler and its seating. It may be well to add, however, that the rapid lowering of the water-level, say, from fracture of the blow-out pipe or other similar cause, may, in the case of a boiler of this type, which is fired hard and severely strained, precipitate a disastrous explosion; and the Author has met with one very striking instance of this.

Cases of overheating and rupture often result from the presence of soluble salts or mechanical impurities, grease, &c., in the water, and occasionally even from imperfect circulation due to improper design. In marine boilers using salt water, the neglect to blow out is often the cause of collapsed furnace-crowns, the density of the water gradually increasing until it reaches a maximum, when salt is precipitated upon the plates in a solid state. This, being a bad conductor of heat, soon interferes with its transmission to such an extent as to cause the plates to soften and collapse under the ordinary working pressure, even although there may be a copious supply of water in the boiler, and although the structure may possess a fair factor of safety.

In some vertical boilers the effects of overheating are most visible at the bottom of the fire-boxes, which are bulged inwards all round their circumference, forming a series of pockets at the level of the fire-bars.

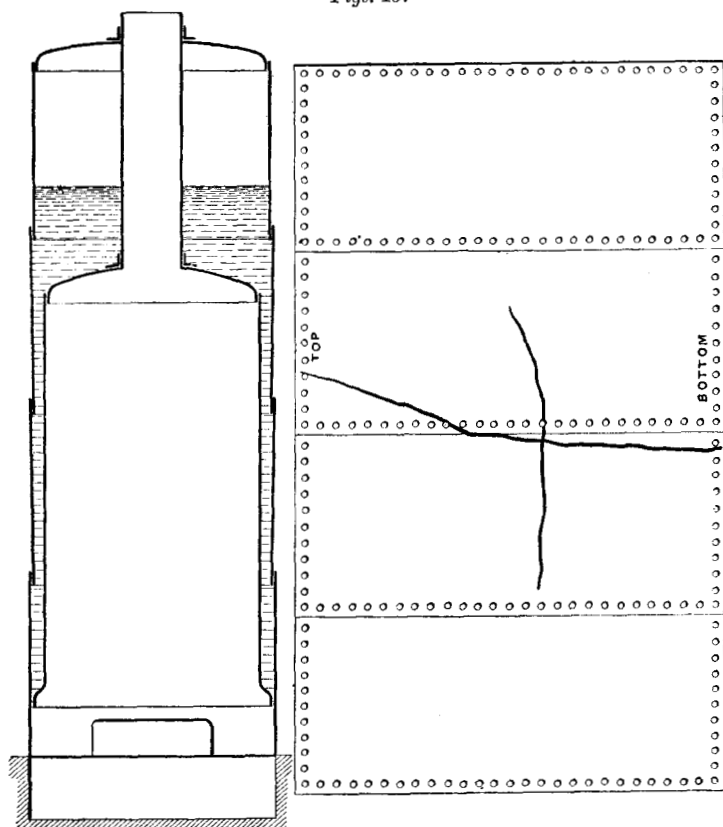
In land boilers, the carbonates and sulphates of lime and magnesia are the most frequent source of overheating of the kind described, especially when those salts are associated with grease. Considerable attention has been directed to the action of these impurities in consequence of the numerous and puzzling cases of failure of the furnaces of high-pressure marine boilers, using fresh water and supplying steam to surface-condensing engines. Professor Vivian B. Lewes¹, however, has shown that the trouble arose mainly from the presence of oily matter in the water carried over from the engines. A point to be noticed in such cases of overheating is its gradual character compared with overheating from shortness of water. In the case of furnace-tubes, the point of maximum heating occurs oftener at the haunches than at the crown, so that the cross-section of the collapsed tube presents two points of depression instead of one. This peculiarity does not however invariably occur, and is more noticeable in the early stages of distortion than after complete collapse and rupture have occurred.

As already remarked, overheating may occur as the result of in-

¹ Transactions Inst. of Naval Architects, 1891, p. 67.

adequate circulation from defective design of the boiler. As an example, the Author cites the case of a boiler of the ordinary vertical type, *Figs. 13*, in which the annular water-space surrounding the fire-box was exceedingly narrow, viz., 2 inches to 3 inches for a depth of 9 feet 6 inches. This space was insufficient to permit of satisfactory circulation, the consequence being that when the

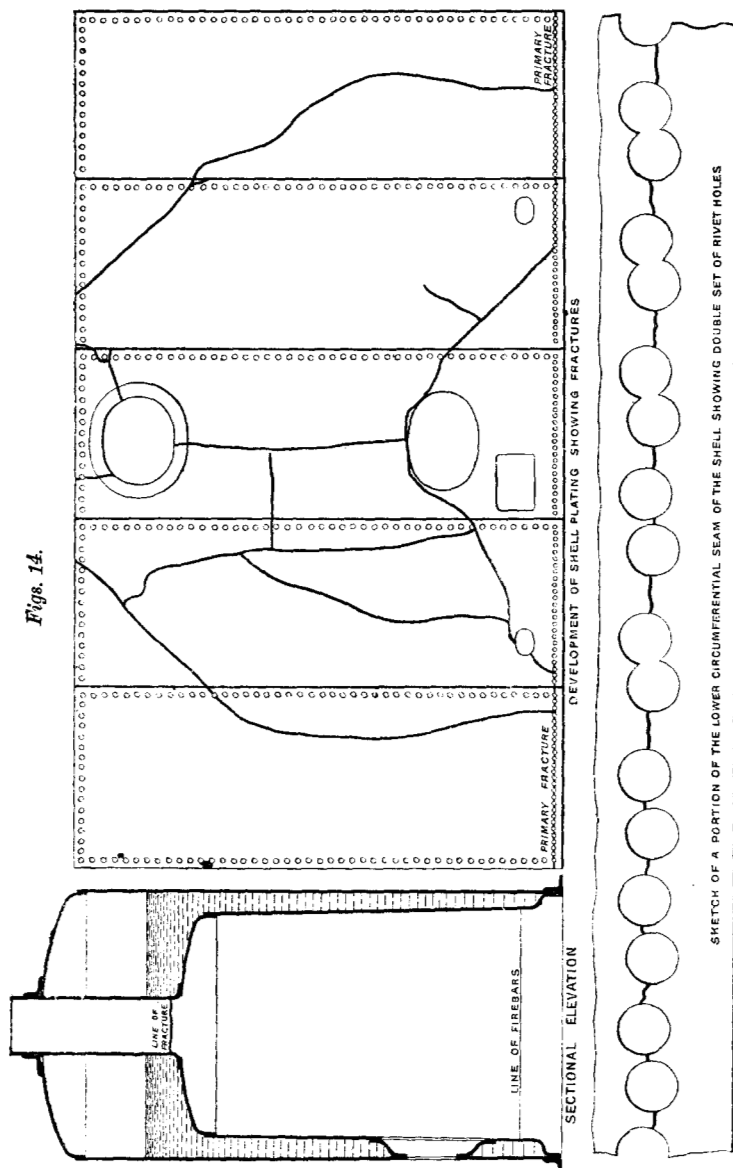
Figs. 13.



boiler was at all forced, the up-cast current of steam, which was generated in the lower part of the boiler, interfered seriously with the current of water flowing downwards to take its place. The fire-box was consequently surrounded by foam rather than by water, and, as might have been expected, the plates became overheated. The boiler gave trouble from the commencement, and soon after being set to work bulges or pockets began to be formed inside the

fire-box at the fire-bar level. Stud-stays were inserted across the annular space at this part, with a view to prevent the formation of the pockets, but the attempt proved unsuccessful, and the fire-box eventually collapsed and was torn open from top to bottom. Numerous cases of overheating from a similar cause have been recorded in connection with certain types of sectional tubular boilers. The boiler formerly known as the Howard sectional boiler was very defective in this respect, especially in its earlier form. Considerable improvement has during recent years been made in the design of tubular boilers, but, taken as a class, their employment is not desirable when the water is heavily charged with lime salts or other impurities.

Over-pressure.—Explosions due to the pressure in the boiler becoming, from any cause, greatly in excess of the ordinary working pressure are in all cases associated with the defective operation of the safety-valve. This fitting is defective if it is capable of being overloaded, either by accident or design, or if the valve may become jammed down upon its seat by the insertion of a wedge between the upper side of the lever and the top of its guide, or by the spindle, in cases where there is a waste-pipe above the valve, becoming rusted in the hole of the cover. Valves of the pendulous dead-weight type are much to be preferred to those of the lever type. For locomotive boilers, valves loaded by the direct action of a spring are preferable to those in which levers and spring-balances are employed. These latter valves have been productive of more explosions from excessive pressure than have occurred from all other causes combined. Their action provides for the variation of the pressure on the valve by increase of tension in the spring. This is effected by a thumb-nut upon a screw, and there is nothing to prevent either this nut being screwed on until after the spring has become fully extended, or the insertion of a plug between the pointer and the top of its guide, by both of which means it is possible to jam the valve firmly down upon its seat. The grouping of the safety-valve and the stop-valve upon a common outlet, especially if the boiler be one of a series, is to be avoided, on account of the ease with which the plugging of the hole in the shell from the inside, when the boiler is under repair, may pass undetected. Two very disastrous explosions have arisen in this way. Even in cases of boilers in which the pressure is little if at all above the atmospheric pressure, safety-valves should not be omitted, as provision should be made for an accumulation of pressure which may occur at any time, due to the outlet becoming choked or to some other cause.



FAULTY MATERIAL AND CONSTRUCTION.

In regard to an explosion which occurred within six months of its being first put to work, of a Lancashire boiler, built of "Best" iron (which, as is well known, is of poor quality), in which the holes were punched before the plates were bent, the nature of the fracture showed that they had been partially cracked along a line of rivet-holes in one of the longitudinal seams. Mild steel has now almost entirely superseded inferior iron, and in most works the plates are drilled after being bent. In another case in which a boiler-shell burst from over-pressure, a case of gross carelessness of construction was revealed, the seam which gave way having at first been punched in at the wrong points, and subsequently punched again along the same line, *Figs. 14*. The defect was then covered by an iron angle-bar. In both of these cases a searching hydraulic test would probably have revealed the defective construction.

CONCLUSION.

In presenting this account of the scientific and engineering features of boiler-explosions, the Author feels that he has imperfectly accomplished his task. The subject is so wide, and is so intimately linked with every detail of the design and construction of boilers, that its exhaustive treatment is impossible within the limits of a single Paper. Many details of importance have necessarily been passed over, but the Author trusts that the facts and statements contained in the Paper, which have been collated during the course of a somewhat unique experience, may possess sufficient interest to the Institution to warrant the attempt he has made.

The Paper is accompanied by numerous drawings and tracings, from a selection of which the *Figs.* have been prepared.

[DISCUSSION.