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Sir DOUGLAS FOX, Vice-President,
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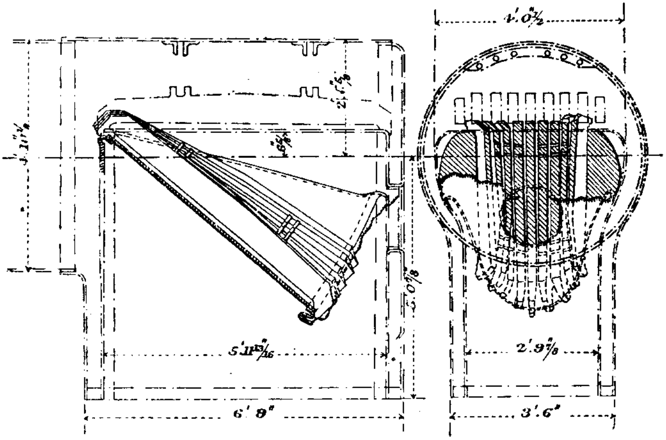
(*Paper No. 3016.*)

"The Security of Some Locomotive Fire-Boxes."

By WILLIAM THOW, M. Inst. C.E.

IN order to ascertain the cause of the failure of a copper fire-box, in a locomotive boiler which had been 6 years at work and which had travelled 210,800 engine-miles, the Author was led to experiment on the strength of copper plates of the kind generally used in the fire-boxes of English locomotives. The fire-box which failed was of ordinary design and modern dimensions, *Figs. 1*, and belonged to one of a set of ten engines constructed in

Figs. 1.



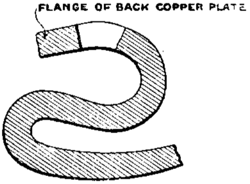
Scale, ¼ inch = 1 foot.

1889. Nine roof stay-bars were employed to support the roof-plate, and they were tied in twelve places by links and pins in the usual way, to angle-bars riveted to the semicircular iron crown-plate. The copper plates in the roof, back and sides, were ½ inch thick and were stayed in the usual manner, the former to the roof-bars by set-screws, and the back- and side-plates to the outer shell by copper stays placed at the ordinary pitch of 4-inch centres. The working pressure in the boiler was 150 lbs. per square inch, and the safety-valves were found, after the collapse, to be in good working order for that pressure. The two lead plugs were found intact, and the plates had not been overheated, nor were there signs of shortness of water. The nature of the fractures in the copper plates distinctly showed the material to have been of good quality. The details, including the foundation-ring and the fire-hole, were of ordinary type, the sides and roof were in one plate, copper rivets were used in the joints of the tube- and back-plates with the usual lap and pitch; there was, in short, no special feature in construction or in proportions to deprive the fire-box of a character thoroughly representative of many locomotive fire-boxes now built or in use. Indeed, those of some modern engines, working at considerably higher pressures, are of larger dimensions, and are not better, if, indeed, as well, stayed to sustain greater loads than this box had to carry.

The boiler and fire-box were examined internally, in the main workshops, after removal of all tubes, 12 months prior to its failure, and were then tested hydraulically and under steam before being passed again into service. A month before the mishap the engine underwent repair in one of the district workshops, and a careful examination was made of the condition of the copper stays; at that time eleven fractured stays were renewed in the side-plates. The immediate defect which permitted the failure was the fracture of several of the copper stays of the two top rows through the fire-hole plates. These stays, if then broken, had not been detected at the monthly examination nor at the ordinary examinations on wash-out days. The copper stays in the boiler are solid, and when not in view—as few are until the boiler is cleared of tubes for internal examination—their condition can only be detected by the sound they emit when tapped on their ends with a hammer. This method is very uncertain, being too dependent on the skill and hearing of the workman. For many years past the Author has used, with the best results, only hollow copper stays, which automatically record their fracture by allowing water and steam to escape. In this case, however, the stays were solid and no such warning was given, and the tests made in the district steam-shed, by sounding the stays, had probably been superficially performed. The copper back plate, when unsupported by efficient copper stays, folded into S-shaped corrugations, *Fig. 2*, under the load which the ends of the nine roof-bars transmitted to it, and which the vertical links and pins between them and the crown-plate angle-bars were not strong enough to restrain. The links and pins were torn apart and sheared in two, some of them at the time of collapse and some previously.

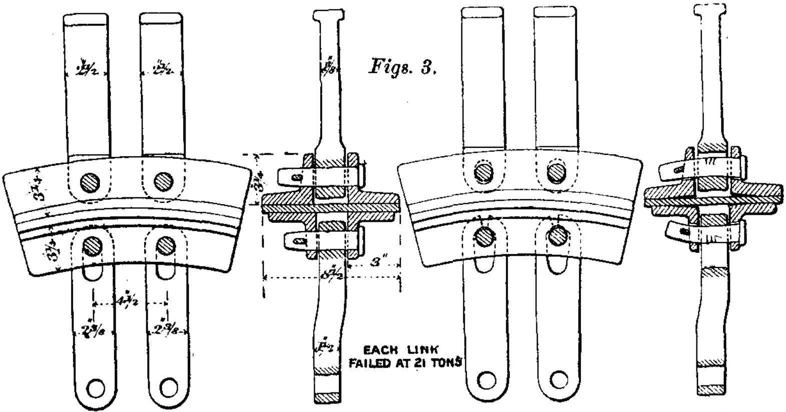
It is manifest that the resistance of the copper tube- and back-plates in their capacity of columns or beams, is the main element in the effective strength of a fire-box, but their resistance is supposed to be aided by the tensional and shearing strength of the connections between the roof-stay bars and the semicircular crown-plate, when such connections are used. These details have to share not only the duty of resisting the load but that of supplying such a surplus of strength as may constitute a satisfactory factor of safety in the structure. The share which each of these elements may be expected to perform is a matter for direct experiment, which the Author believes has not yet received the attention that the subject deserves.

Fig. 2.



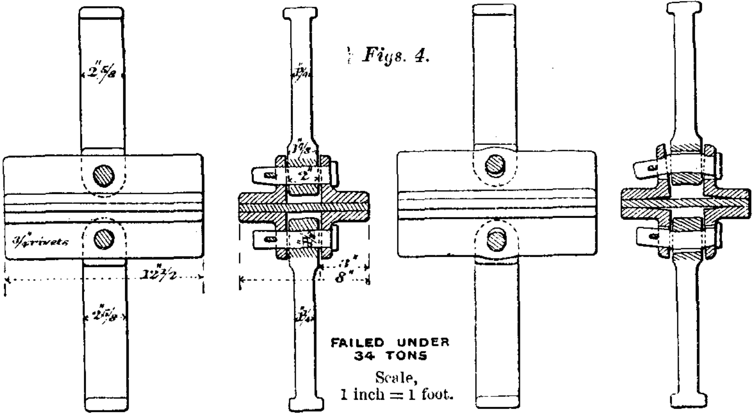
Scale, ¼ full size.

For the purpose of ascertaining the actual resistance opposed to the load on the roof of this copper box, the following experiments were made. The breaking strength of the links, pins, angle-bars and roof-stay jaws, for the case in question, were readily ascertained in the testing-machine; and, deducting their combined ultimate strength from the load imposed on the roof of the fire-box when multiplied by any required factor of safety, the copper tube- and back-plates ought to resist the remainder by their strength as columns or beams. A test-piece made from the original links, pins and angle-bars taken from the boiler which failed is shown in *Figs. 3*; the breaking strength of the connection was 21 tons, the links and pins fracturing at that stress. To discover the ultimate strength of new pieces, made of the best materials and workmanship but still preserving the dimensions originally adopted by the makers, a test-piece, *Figs. 4*, was torn asunder under a load between 33 tons and 34 tons, through the shearing of the pins, the fracture of one eye of the link and the elongation, almost to the point of rupture, of the holes in the angle-bars. That test was repeated with stronger



Figs. 3.

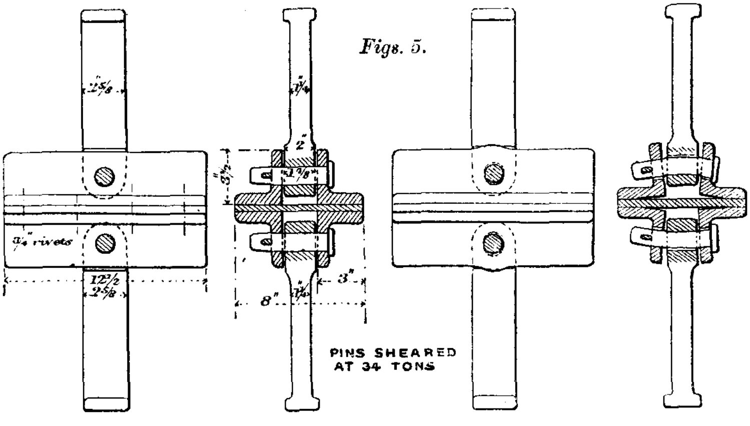
EACH LINK FAILED AT 21 TONS



Figs. 4.

FAILED UNDER 34 TONS

Scale, 1 inch = 1 foot.

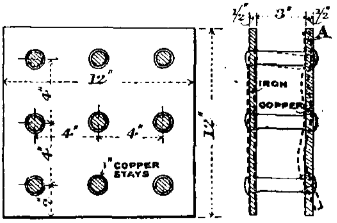


Figs. 5.

PINS SHEARED AT 34 TONS

angle-bars, *Figs. 5*, but the pins again sheared at a load of less than 34 tons. The original strength of each of the connections provided by the makers was, doubtless, considerably less than 33 tons, because the parts were roughly made and proportioned. They are of a character frequently used in contract work in consequence of a want of correctly appreciating their importance and value. It too frequently happens that such links, although of excellent material, have the appearance of having been cut off the merchant bar to the required lengths and used without any of the smithing or forging which is necessary to apply the material most effectively against the stress. Those taken out of the boiler which failed had not 64 per cent. of the strength of the special test connections of similar dimensions shown by *Figs. 4*. Neglecting this inferiority, although important, it is seen that the maximum ultimate strength of the twelve connections, even under the most favourable conditions as to material and workmanship, cannot be greater than 33 × 12 = 396 tons.

Figs. 6.



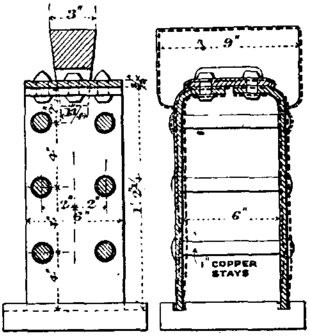
Scale, 1 inch = 1 foot.

The length of the fire-box between the centres of the tube- and back-plates is 72 inches, and the effective width—allowing for the semicircle that joins the roof and sides—is 44 inches; this area multiplied by 150 lbs. per square inch working pressure, gives 212 tons as the load to be resisted. Assuming a factor of safety of four, 848 tons is obtained as the measure of the resistance required in the structure. Deducting the ultimate maximum strength of the twelve connections, 452 tons remains as the resistance required in the two copper plates when considered as abutments for the roof-bars. To determine their capability to perform that duty, the Author made three test-pieces, *Figs. 6, 7* and *8*, and subjected them to crushing stresses, representative of that applied to them in the fire-box.

A square foot of a fire-box back is shown in *Figs. 6*, the iron and copper plates being stayed together in the usual manner. The load was placed directly on the edge of the copper plate, at A, which was ½ inch thick, and represented 6 square inches of section. The iron plate was not loaded, but, like the copper plate, its bottom edge rested on the table of the testing-machine. The main object of these tests was to ascertain, first, the limit of elasticity of copper under a crushing stress, and, secondly, the load per square inch which would permanently distort and buckle a fire-box copper plate between the lines of stays. A load of 8 tons was first imposed on the plate, and careful measurements were taken after each addition of 1 ton to the load up to 25 tons. A slight movement appeared to commence between the 24th and 25th tons, but on releasing the load no permanent change was discovered. The load of 25 tons was again at once imposed on the copper plate, and measurements were taken on the application of each additional ton up to 28 tons, when a shortening of the specimen by a small amount was observed; but on the removal of the load the piece recovered its original length and shape. The load of 28 tons was again imposed, under which the shortening previously detected re-appeared; and, after the addition of 3 tons, by increments of a ton, the specimen shortened $\frac{1}{32}$ inch under 31 tons. This load was removed and the set was found to be permanent. From observations of the behaviour of this specimen, the Author concludes that the limit of elasticity of a copper plate, as commonly stayed to the iron plate in a locomotive fire-box, when the plate is cold, does not exceed 4·7 tons per square inch. The load of 31 tons was again imposed and increments of 1 ton were added, under which the piece gradually changed form and yielded at 53 tons, as shown by dotted lines in *Figs. 6*. Visible distortion set in between the lines of stays when the load reached about 43 tons, and the specimen rapidly changed form after 45 tons were imposed. The final failure of the specimen was due to the bottom edge of the copper plate slipping outwards over the table of the machine. It appears from this experiment that the resistance to buckling between the lines of stays of a $\frac{1}{2}$-inch copper fire-box plate when cold, and when stayed in the usual manner with copper stays at 4-inch centres and loaded directly on the edge of the plate, does not exceed 7 tons per square inch of section.

It was considered that the manner of imposing the load by the ends of roof-stay bars on the curves and horizontal flanges of the tube- and back-plates, was less direct than in the first experiment, and less favourable to the resistance of the upper or flanged portion of such plates; therefore a new test-piece, *Figs. 7*, was constructed, so as to represent more closely the actual conditions. Two vertical plates, flanged to the usual radius, were riveted to a horizontal plate which represented the roof; and a short roof-bar, machined and accurately fitted, was made to span the piece and to impose the load on the curved portions and flanges of the vertical plates, thus resembling the conditions of actual practice. The vertical plates were tied together by horizontal copper stays, pitched at 4-inch centres. To avoid the slipping of the plates on the machine table, which was experienced with the first experiment, the lower edges of the vertical plates, at a distance of 4 inches from the line of nearest copper stays, were inserted into grooves cut to receive them in a base-plate. The top surface of the roof-bar and the bottom surface of the base-plate were parallel. Datum points were carefully laid off on each side of this specimen, giving vertical and triangular distances, and special appliances for detecting movements were employed. A load of 5 tons was first imposed, and was gradually increased by increments of not less than 1 ton, until a load of 20 tons rested on the specimen, when one side of it showed slight shortening. The load was removed and the specimen returned to its original length and shape. A load of 20 tons was again imposed, and the shortening on the same side re-appeared. The load was gradually increased to 25 tons, under which one side shortened $\frac{1}{32}$ inch and the other side less than $\frac{1}{64}$ inch. The load was entirely removed and a permanent set was observed. The limit of elasticity in this piece seemed to be 4 tons per square inch, but the manner in which the specimen behaved under the test justified doubt as to the reliability of such a conclusion. It will be noticed, *Figs. 6*, that the specimen bent over its base-plate towards one side, and it is believed that movement was due to the interposition of a ball-and-socket bed-plate between the bed of the testing-machine and the base-plate of the specimen. It is probable that the centre of pressure on the roof-bar did not coincide with the centre of the ball-and-socket, therefore a diagonal stress would be set up in the specimen, bending it bodily towards one side, and thus interfering with the correctness of the test. The load of 25 tons was reimposed and was gradually increased by 1-ton additions up to 35 tons, when one side showed a shortening of $\frac{3}{32}$ inch and the other of $\frac{1}{16}$ inch. At 37 tons the plates yielded sideways considerably, and the load was removed. Permanent distortion of the plates appeared between 31 tons and 32 tons, and it is assumed that

Figs. 7.

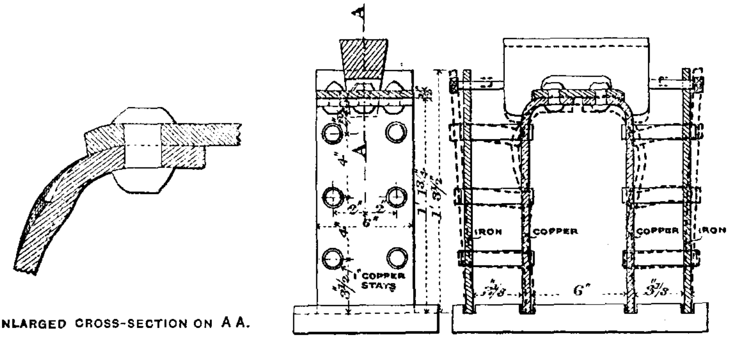


Scale, 1 inch = 1 foot.

in this specimen the ultimate resistance was not greater than 5¼ tons per square inch. The cross-sectional area of this specimen was 6 square inches as in the former case.

With a view to ascertain the effect of adding iron plates outside the latter specimen and staying them to the copper plates—more representative of fire-box conditions—another test-piece was prepared, *Figs. 8*. The arrangements of the copper plates and roof-stay in this case were the same as those in *Figs. 7*, except that the copper plates were stayed to their corresponding iron plates instead of to one another. The area of the cross-section of the copper was, as before, 6 square inches, and the lower edges of all the plates rested in grooves cut in a base-plate, the bottom of which rested directly on the machine bed-plate, without any ball-and-socket refinement between them. This specimen was loaded with 10 tons without showing any movement. Increments of 2 tons were gradually applied up to 18 tons, when a very slight change in its length appeared. Additions of 1 ton were made until a load of 28 tons was reached, when a slight increase in the horizontal distance between the copper plates below the top of copper stays was observed, and a small change also occurred in the shape of the curves joining the vertical sides to the flanges. The load was entirely released, and the specimen returned to its original form and dimensions. It was reloaded with 28 tons in one amount and 1-ton additions up to 33 tons were imposed. Under that load a marked change appeared; the distance apart of the copper plates between the two top rows of stays had increased fully $\frac{1}{32}$ inch, and one of the curves

Figs. 8.



ENLARGED CROSS-SECTION ON A A.

Scale, ¼ full size.

Scale, 1 inch = 1 foot.

under the roof-bar had slightly flattened. The load was again removed, and recovery to the original shape was found to be only partial. The limit of elasticity had been passed at about 31½ tons, or 5¼ tons per square inch of section. The load of 33 tons was replaced and the change of form reappeared. Increments of 1 ton were added, and at 35 tons the distance of the copper plates between the two top rows of stays increased $\frac{1}{16}$ inch. At 40 tons it became fully $\frac{3}{32}$ inch greater than the original measurement. It was manifest that this specimen was weakest between the top and second lines of stays, and that the load on the haunches from the roof-bar had overcome the resistance of the copper plates as columns. Between 40 tons and 42 tons, the haunches began to flatten out; one of them had moved a bare $\frac{1}{16}$ inch and the other a full $\frac{1}{32}$ inch, and at 45 tons the vertical copper plates had spread, in the widest part, $\frac{3}{16}$ inch. At 47 tons this distance increased to ⅜ inch, and the specimen suddenly collapsed and assumed the shape shown by the dotted lines in *Figs. 8*, when the load reached 48 tons. There is no doubt that under a load of 42 tons the ultimate resistance of this specimen was reached, and it was only a matter of time for the distortion, which had then set in, to increase and produce complete collapse. This test confirmed the result obtained in the case of *Figs. 6*, namely, that the ultimate strength or resistance to buckling between the lines of stays of ½-inch copper fire-box plates, when cold, cannot be taken as more than 7 tons per square inch. The elastic limit of this specimen appeared to exceed that obtained from the first test-piece in the ratio of 5·25 to 4·7, but an elastic limit of 5 tons per square inch is all that the experiments made by the Author will justify when the copper plates are loaded as columns and when they are cold.

It is manifest from the results which were obtained by testing the links, pins and angle-bar connections between the roof-bars and crown-plate, *Figs. 3*, even when they are numerous as in the case of the fire-box which failed, that little reliance can be placed on their strength, should sufficient movement in the copper plates impose a load on them. The main reliance has to be placed on the resistance of the copper back- and tube-plates themselves, in most of the cases where roof-bars are used in the longitudinal direction. Indeed, the roof-bar sling-stays are sometimes so loosely and ineffectually applied as to justify the conclusion that they are not considered by their designers as essential to the safety of the structure, but merely as provisions to meet contingencies. They cannot come into play until considerable change of form in the copper plates has taken place; and, in assessing the aid which may be expected from even the most efficient sling-stays, the effect of the difference of the upward expansion due to the temperature of the copper and iron or steel plates must not be overlooked. In consequence of this difference, the sling-stays are often not loaded at all. Such may be the case when raising steam, or when the circulation of the water is sluggish. Indeed, this is recognized and purposely provided for by the general adoption of oblong holes in roof-bar sling-links, by loose stirrups or other similar means, specially designed to permit the free upward expansion of the copper box independently of movement in the outer shell. Such being sometimes the case, the copper plates alone must then sustain the whole of the load from the fire-box roof, and the factor of safety must indeed be very low, especially when consideration is given to the following important feature.

The effect of temperature on copper plates when subject to crushing stress appears not to have been determined. Mr. J. A. F. Aspinall, M. Inst. C.E., has shown[1] that the effect of a temperature of 370° F. (160 lbs. per square inch pressure) on copper bars under tension, was to decrease their ultimate breaking strength when cold, by 3 tons per square inch, or by $20\frac{1}{4}$ per cent. If the strength of copper under crushing or shearing stresses is similarly depreciated by rise of temperature, then the elastic limit and the ultimate strength of copper plates in locomotive fire-boxes, which the Author has assumed to be fair results from his experiments, are seriously affected.

These remarks chiefly apply to the strength of fire-box copper plates when tested as columns, and, in presenting them for consideration, the Author does not overlook the fact that additional support to the crushing strength of locomotive fire-boxes results from their complex construction. He is not aware that the value of such additional support has so far been determined, and is of opinion that it, in itself, presents no great margin of security, but whatever it may be, it ought to be determined by direct and reliable experiment. The tube- and back-plates may be regarded as short beams fixed at both ends to the side-plates of the box, uniformly loaded and stiffened at numerous points where stayed to the outer shell-plates. Even when so regarded, their strength must depend on their capacity to resist change of form by buckling or

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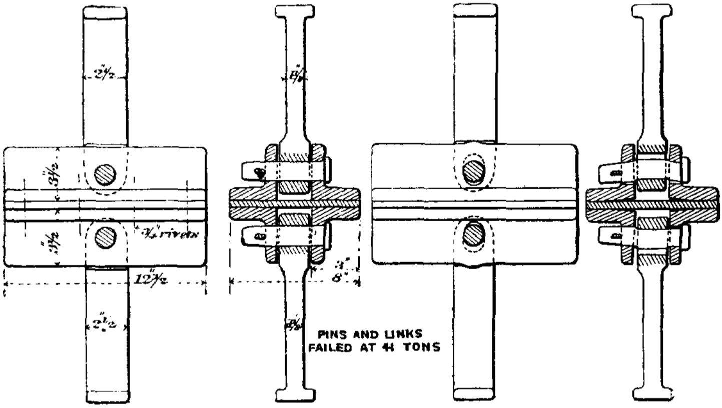
[1] Alloys Research Report, Proceedings of the Institution of Mechanical Engineers 1893, p. 193.

corrugating between the horizontal lines of the copper stays. In the case of the box which failed, it has been shown that if there had been a factor of safety of 4, a total resistance of 848 tons ought to have been opposed to the load of 212 tons due to the working pressure on the roof. Assuming that the sling-stays and their connections act in perfect harmony with the resistance of the copper tube- and back-plates—an assumption which the Author has given important reasons for doubting—452 tons is the resistance which remains for the plates in question. What is the proof that they possess that capacity? Their capacity to resist change of form would appear, from the experiments, to be limited to 5 tons per square inch of cross-section—a resistance far too small in this and many other cases to provide an adequate factor of safety. The fire-box in question had, at the time of its failure, no factor of safety. Whatever it may have previously possessed, when all its copper stays in the top row of the back-plate were sound, vanished when a portion of them broke and left the copper plate free to corrugate and fold. Considering the difficulty and uncertainty generally experienced in detecting the fracture of solid copper stays, the risks involved in present methods of constructing and working some locomotive fire-boxes are too serious to be neglected. It must be regarded as unsatisfactory that a fire-box of ordinary and representative character depended for its safety on the soundness of a few copper stays. As an immediate precautionary measure, in addition to other methods of strengthening, the Author has removed the solid stays from the top two rows

Figs. 9.



Scale, 1 inch = 1 foot.

of the fire-boxes under his charge, and has replaced them with hollow stays. He has also introduced an intermediate row, pitched diagonally between the two upper rows, in all cases where long roof-bars are used, so as to assist the copper back-plates under the ends of the roof-bars to resist bending stresses. In all the engines recently introduced on the New South Wales railways, the Belpaire box is used. The enlarged sling-links and connections, which have been adopted to replace the defective details shown by *Figs. 4*, are indicated in *Figs. 9*; their breaking stress is 41 tons.

The Paper is accompanied by nine tracings and three photographs, from which the *Figs.* in the text have been prepared.

FRICTION OF LOCOMOTIVE SLIDE-VALVES.

Fig: 2.

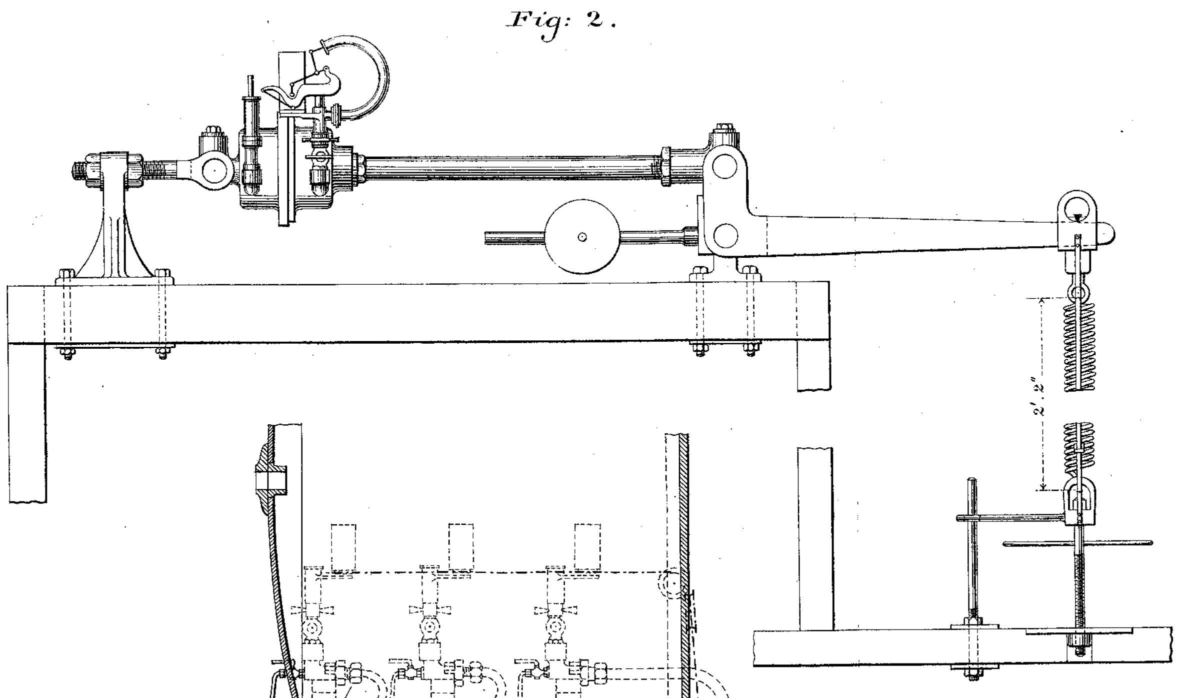


Fig: 1.

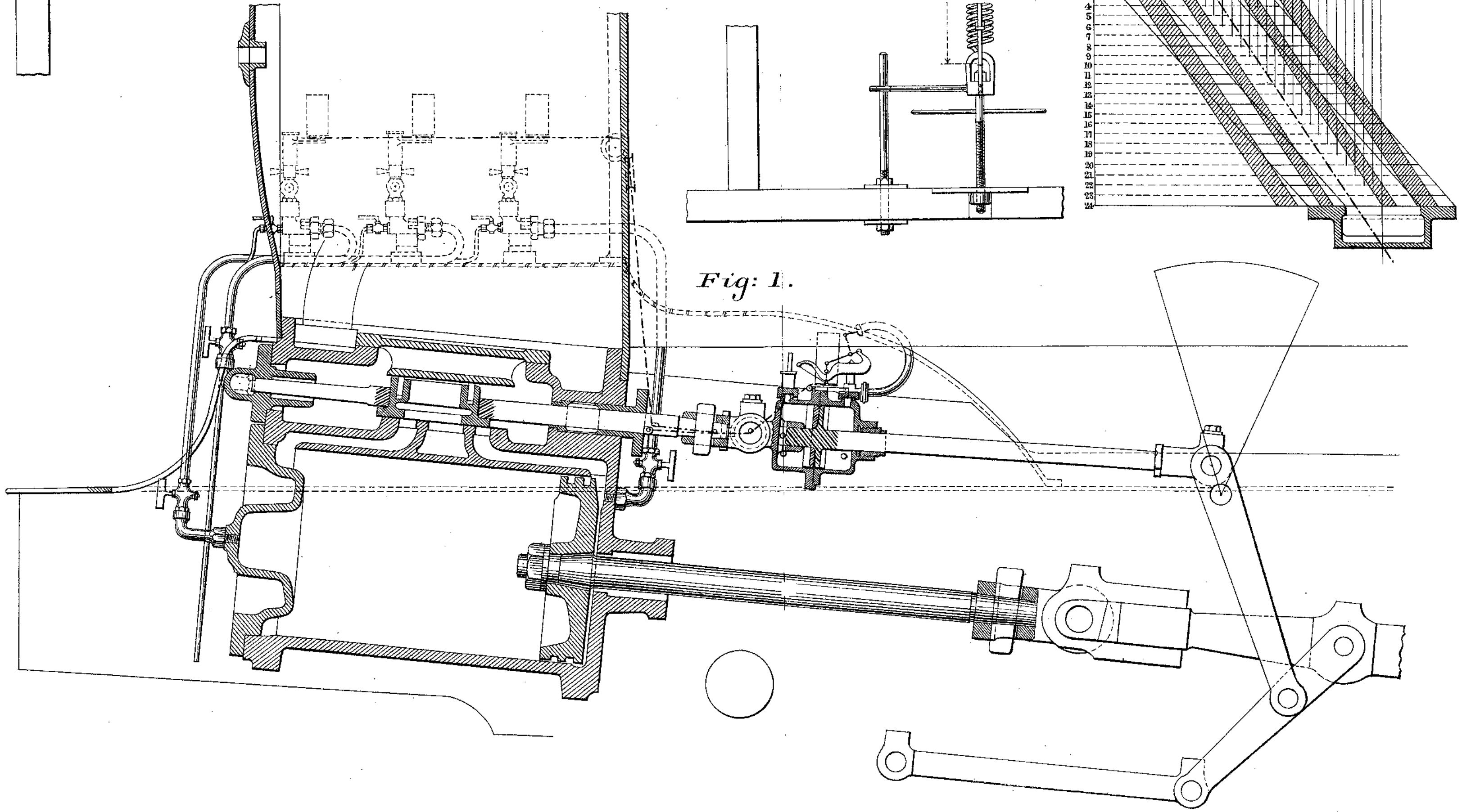
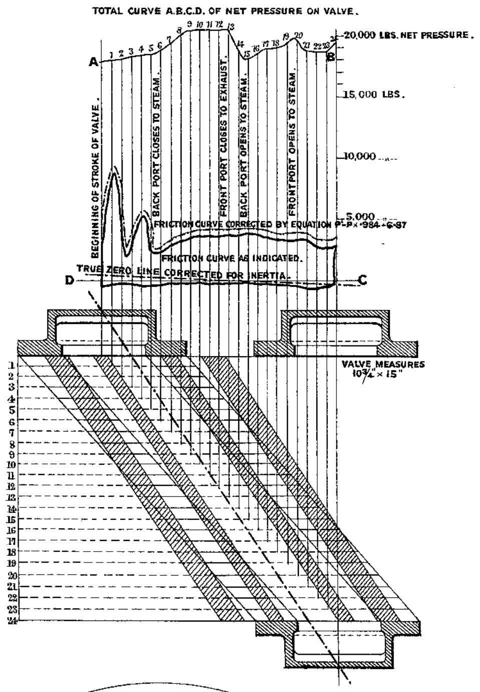
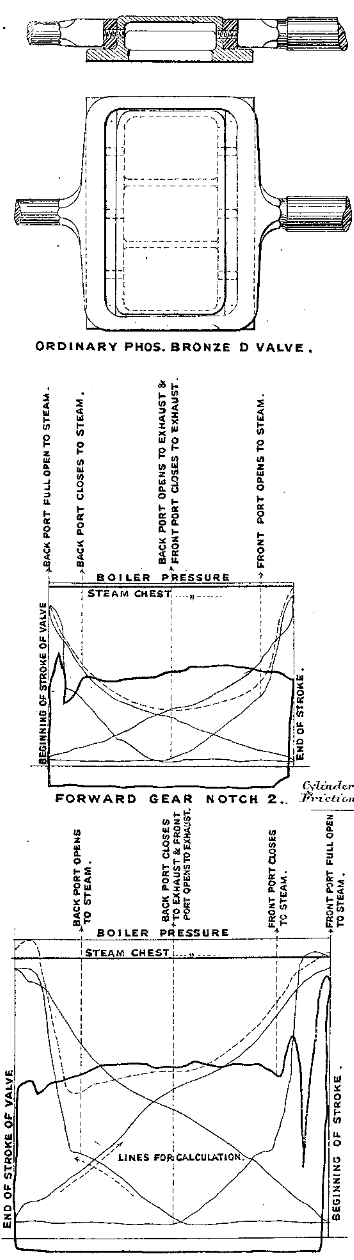


Fig: 3.



Figs 4.



ORDINARY PHOS. BRONZE D VALVE.

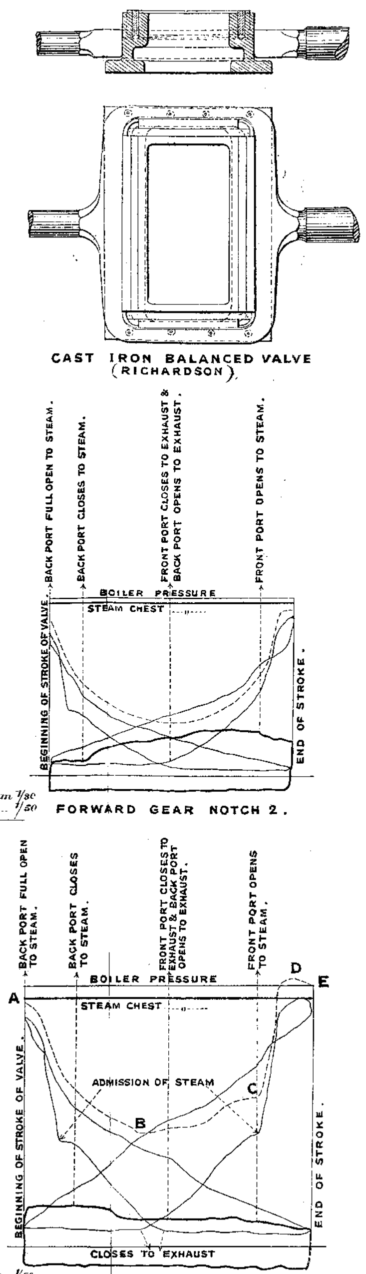
FORWARD GEAR NOTCH 2.

BACK GEAR NOTCH 3.

Cylinder Diagram 1/80
Friction .....do..... 1/50

Cylinder Diagram 1/50
Friction .....do..... 1/50

Figs 5.



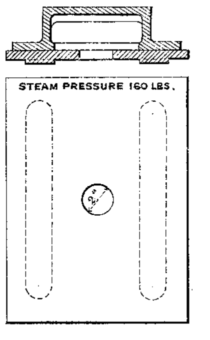
CAST IRON BALANCED VALVE (RICHARDSON).

FORWARD GEAR NOTCH 2.

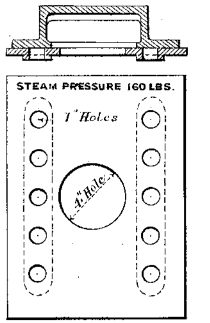
FORWARD GEAR NOTCH 3.

A.B.C.D.E. CURVE OF RELIEVING PRESSURE.

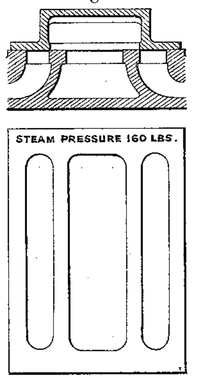
Figs 6.



Figs 7.



Figs 8.



Scale for Figs 1, & 2, 3/4 Inch = 1 Foot.
Inches 12 6 0 1 2 3 Feet.

Scale for Figs 3 — 8, 1 Inch = 1 Foot.
Inches 12 6 0 1 2 Feet.