XXI. *On the Resistance of Tubes to collapse.*

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THE following experiments were undertaken at the joint request of the Royal Society and the British Association for the Advancement of Science. Their object is to determine the laws which govern the strength of cylindrical vessels exposed to a uniform external force, and their immediate practical application in proportioning more accurately the flues of boilers for raising steam, which have hitherto been constructed on merely empirical data.

It is well known that the immense extension of the application of steam power, and the consequent inducement to economise as far as possible the fuel necessary for its production, together with the growing tendency to employ the expansive principle, has caused a general increase of the working pressure from 10 lbs. to 50 lbs., and even in some cases to 150 lbs. on the square inch. Unfortunately, however, our knowledge of the principles of construction has not kept pace with our desire to economise, and hence the change has been accompanied by an increase of dangerous and fatal accidents from boiler explosions. Investigation has frequently shown these lamentable catastrophes to have arisen from ignorance of the immense elastic power of steam, and from a want of knowledge of the forms of construction best calculated to retain an agent of such potent force; and as explosions become more frequent in proportion as the pressure is increased, it is the more necessary to inquire into the causes of such disasters, and to apply such remedies as may effectually prevent them.

In order to save space and to increase the generative powers of boilers, *internal flues* and tubes have been generally adopted, and that without sufficient attention to proportioning their diameter, length, and thickness of plates, so as to ensure safety on the one hand, and economy of material in its judicious distribution on the other. Hitherto it has been considered an undisputed axiom among practical engineers, that a cylindrical tube, such as a boiler-flue, when subjected to a uniform external pressure, was equally strong in every part, and that the length did not affect the strength of a tube so placed. But although this rule may be true when applied to tubes of indefinite length, or to tubes unsupported by rigid rings at the extremities, it is very far from true where the lengths are restricted within certain apparently constant limits, and where the ends are securely fastened in frames, which prevent their yielding to an external force.

In some experimental tests to prove the efficiency of some large boilers, the author had some misgivings as to the strength of the internal flues to resist a force tending to collapse them. In these experiments it was found that flues 35 feet long were distorted with considerably less force than others of a similar construction 25 feet long. This anomalous result led to further inquiry, which being far from satisfactory, the present series of experiments were instituted, with, it is believed, very conclusive results.

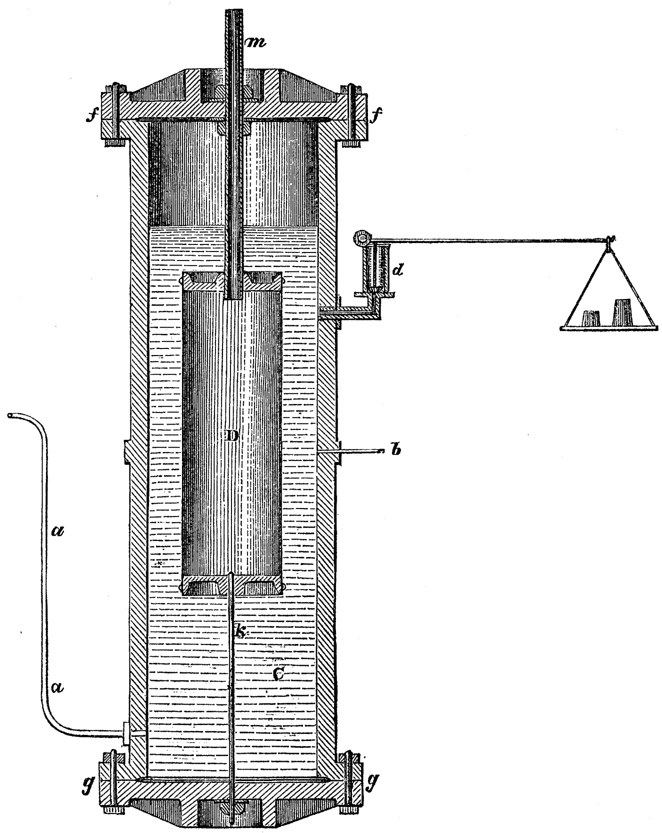
In order to have every facility for conducting these experiments, application was made to the Directors of the North-Eastern Division of the London and North-Western Railway, for permission to conduct them under their large octagonal engine-house at Longsight, near Manchester, where the necessary pumps and cranes were at hand. To this request the Directors gave their cordial assent, and in this position I had the benefit of the suggestions and experience of Mr. J. RAMSBOTTOM, the Company's engineer, and also the constant attendance of Mr. R. B. LONGRIDGE, the engineer and chief inspector to the Association for the Prevention of Boiler Explosions. To both those gentlemen I tender my best acknowledgements for the able and efficient assistance I have received from them during the whole time occupied in conducting the experiments.

To attain the objects of the experiments in a satisfactory manner, it was necessary that the apparatus should be of great strength and of dimensions capable of receiving tubes of considerable length and diameter. For this purpose a cast-iron cylinder was prepared, 8 feet in length, 28 inches in diameter, and 2 inches thick of metal, for the reception of the tubes to be experimented upon. This cylinder, C, Plate XXVIII., was placed upon some balks of timber, in one of the locomotive pits, immediately under the shear-legs A, A, for the convenience of lifting and replacing the heavy cover of the cylinder, which had to be removed at the close of each experiment. A small pipe, *a*, *a*, connected the force-pump, B, with the interior of the cylinder; and another, *b*, *b*, communicated with the steam-pressure gauges at *c*, which exhibited the pressure in the cylinder during the experiment in lbs. per square inch: to ensure accuracy two gauges were employed, one of SCHAEFFER'S and the other of SMITH'S construction, and the indications of these were checked by an accurate safety-valve, *d*. A small cock, *e*, served to let off the air contained in the cylinder when necessary.

Fig. 1 is a section of the large cylinder. The top and bottom covers, *f* and *g*, were made of strength proportionate to that of the cylinder, to which they were secured by 1-inch bolts placed 3 inches apart. In the bottom cover, *g*, a hole was drilled, to receive the rod and screw-nut *k*, which supported the tube D to be experimented upon; and through the top passed a $2\frac{1}{2}$-inch pipe, *m*, inserted in the cast-iron end of the tube D. On the end of this pipe was a large nut, which screwed down upon an indian-rubber washer on the cover of the cylinder, so as to close the opening round the pipe and make it water-tight. The object of this pipe was to allow the air from the interior of the tube D to escape during the collapse, and so to place it, as nearly as possible, under the same circumstances as the flue of a boiler.

The whole of the experiments were effected by means of the hydraulic pump, by which water was forced through the pipe *a a* into the cylinder C; thus driving the air in a highly compressed state to the upper part of the cylinder, whence, when a very high

Fig. 1.—*Vertical section.*



pressure was required, it was deemed advisable to let it escape by the cock *e*, and to effect rupture through the medium of water only. In both these cases a perfectly uniform pressure was ensured upon every part of the tube to be collapsed.

These preparations having been made, and the pressure-gauges carefully adjusted, the experiments proceeded as shown in the following Tables.

The first experiment was upon a tube 4 inches in diameter, and 1 foot 7 inches long between the cast-iron ends, to which it was riveted securely and brazed. It was composed, as in the other experiments, of a single thin plate, bent to the required form upon a mandril, and riveted and also brazed to prevent leakage into the interior. This tube having been fixed to the cylinder covers in the manner described above, the pump was applied and a gradually-increasing force given to its exterior surface, until its powers of resistance were overcome. During the experiments the precaution of allowing the air to escape at high pressures was found absolutely necessary, as the tubes generally collapsed with an explosion of the suddenly-compressed air in the tube D, fig. 1, accompanied by a loud report as it made its escape by the pipe *m*. These explosions give pretty correct indications of what takes place when the internal flues of boilers collapse.

It has long been a desideratum to determine some law by which the engineer could calculate the proportionate strength of the internal flues. Hitherto we have acted upon the principle that the cylindrical flues, as ordinarily constructed, were considerably stronger than the outer shell; but this opinion has in reality no foundation in experiment, excepting only uncertain deductions from occasional explosions and the failure of vessels under high pressures in circumstances of a very variable and doubtful character. There have been no definite rules to guide us hitherto in proportioning the diameter, length, and thickness of plates of the flues, so as to correspond with the strength of the boiler; and even in cases where explosions have taken place from collapse, we have, it is to be feared, too frequently mistaken the actual cause, in consequence of the débris covering the site, and the force which has torn to pieces the outer shell. The anomalous position in which these constructions are placed has greatly retarded the application of science to their improvement, and there appears, in fact, to be no rule known by which to attain uniformity of strength between those parts of a boiler exposed to an internal tensile, and those exposed to an external compressive force.

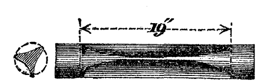
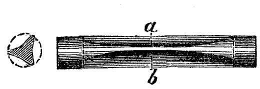
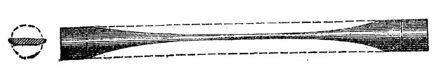
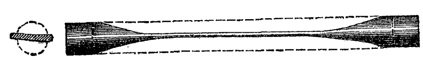
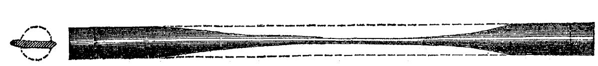
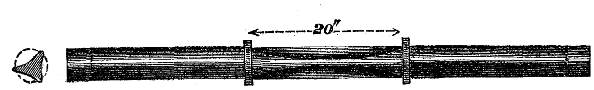
To supply this want, and to remedy certain anomalous results arising from defective forms of construction, it appeared desirable that these vessels should be subjected to direct experiment, and the Laws of Resistance as far as possible ascertained, and the necessary formula deduced for the future guidance of the practical mechanic and engineer. These objects have, it is believed, been attained by the results developed in the experiments enumerated in the following Tables.

EXPERIMENTS.

Resistance of Tubes to Collapse.

In these experiments the tubes were composed of plates of uniform thickness, and of the form and size shown by the figures in the column of remarks. The form after collapse is also indicated by the woodcuts.

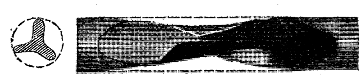
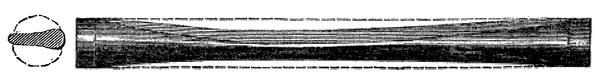
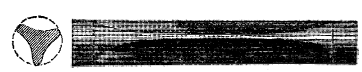
TABLE I. Resistance of 4-inch Tubes.

Mark.	No.	Diameter. inches.	Length. inches.	Thickness of plates. inch.	Pressure of collapse. lbs. per sq. in.	Remarks.
A.	1	4	19	·043	170	 N.B. The figures are drawn to a scale of $\frac{1}{2}$ in. = 1 ft. The cross-sections are taken through the line *a b*, where the collapse was greatest. The dotted lines show their form before they were subjected to experiment.
B.	2	4	19	·043	137	
C.	3	4	40	·043	65	
D.	4	4	38	·043	65	
E.	5	4	60	·043	43	
F.	6	4	60	·043	140	

On consulting the above Table, it appears that tubes of the same diameter and the same thickness of plates vary in strength when of different lengths. The tubes of 19 inches and those of 40 inches differ widely in their powers of resistance. Comparing the results of Experiments 1 and 2 with those of Experiments 3 and 4, we find that the latter, while of twice the length, bear less than half the pressure. Comparing these with Experiment 5, we find that tube E, 5 feet long or three times as long as A and B, exhibits only about one-third of their mean strength. Similarly, E, which is $\frac{5}{3}$ the length of D, bears only about $\frac{3}{5}$ the pressure.

Tube F, Experiment 6, may be considered as composed of three distinct tubes, each 1 foot 7 inches long. It was made with two perfectly rigid rings, soldered to the outside of the tube to keep it in form and prevent collapse at those points. The result of this alteration was to increase the strength of the tube threefold, as is evident on comparing it with tube E.

Table II. Resistance of 6-inch Tubes.

Mark.	No.	Diameter. inches.	Length. inches.	Thickness. inches.	Pressure of collapse. lbs. per sq. in.	Remarks.
G.	7	6	30	·043	48*	
H.	8	6	29	·043	47*	
J.	9	6	59	·043	32	
K.	10	6	30	·043	52	
L.	11	6	30	·043	65	
M.	12	6	30	·043	85†	

This Table gives indications of the same law of resistance as the last. It will be

* On removing the tubes G, H, it was found, that owing to the thinness of the metal, the cast-iron ends of both had been fractured, causing collapse, perhaps, before the outer shell had attained its maximum resistance.

† Tube M had an iron rod down its axis to prevent the ends approaching each other during collapse; a tin ring had also been left in by mistake, which accounts for the increased pressure required to produce collapse.

observed that the tubes being screwed to the covers of the cylinder, were to some extent in a state of tension, owing to the necessity of having to screw up the air-tube tight in order to prevent leakage. This, with the weakness of the ends of the first two tubes, will account for the discrepancies in the Table. Making allowances on this ground and taking the mean of the experiments, we arrive at the conclusion that the results approximate closely to the law that the strengths are inversely as the length; and this, it will be observed, is the result arrived at in the comparison of the 4-inch tubes.

Thus the mean strength of the tubes, 30 inches long, experiments G, H, K, L, is 53 lbs per square inch. Now by the above inverse proportion, we may calculate from this the strength of a tube 59 inches long; thus,

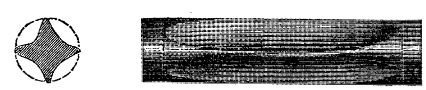
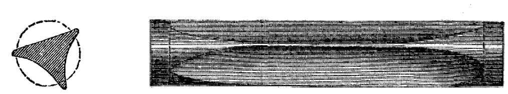
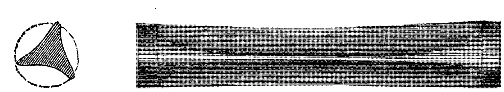
$$59:30::52:x=27,$$

the result being 32 in the above Table, Experiment 9, a difference of 5 lbs. only.

This law receives remarkable confirmation from Experiment 6 on tube F. This tube had, as already explained, two rigid cast-iron rings firmly soldered to it so as to divide its length into three equal parts. The result was to increase the strength threefold, or, in other words, to make it equal in strength to a tube of one-third the length.

The next series of tubes submitted to experiment were 8 inches in diameter, and of the same thickness as the preceding. In these experiments it will be seen that the same law in respect of the length prevails, and is perhaps more strikingly exemplified than in either of the preceding series. Perhaps from their larger size these tubes were less affected by defects of workmanship. Like the last, they had an outlet for the escape of the air, and collapsed with loud reports.

TABLE III. Resistance of 8-inch tubes.

Mark.	No.	Diameter. inches.	Length. inches.	Thickness. inches.	Pressure of collapse. lbs. per sq. in.	Remarks.
N.	13	8	30	·043	39	
O.	14	8	39	·043	32	
P.	15	8	40	·043	31	

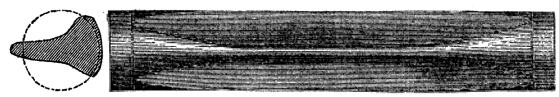
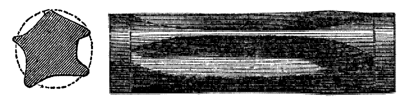
On comparing the above results, it will be found that there is a near approximation to the strengths being inversely as the lengths. Taking the strength of the first tube, 30 inches long, and calculating the force necessary to collapse the 39 and 40-inch tubes, we have, by calculation,

$$39:30::39:x=30 \text{ and } 40:30::39:x=29·25;$$

the difference from the result in the Tables being 2 lbs. in the one case and $1\frac{3}{4}$ lb. in the other.

The following results on 10-inch tubes are also remarkably consistent with the above law.

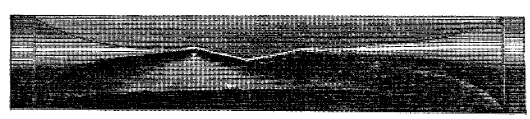
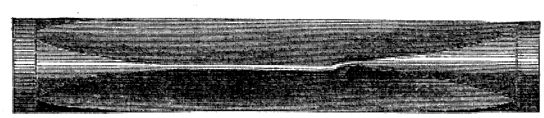
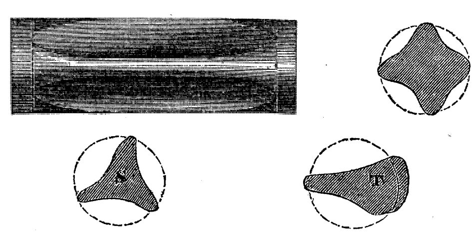
TABLE IV. Resistance of 10-inch tubes.

Mark.	No.	Diameter. inches.	Length. inches.	Thickness. inch.	Pressure of collapse. lbs. per sq. in.	Remarks.
Q.	16	10	50	·043	19	
R.	17	10	30	·043	33	

Both tubes gave way, as in the preceding experiments, with a loud report. Comparing them, we have $50:30::33:x=19\cdot8$; and by experiment (16.) we have 19 lbs.

Equally strong evidence in confirmation of the law respecting the lengths, will be found in the Table of 12-inch tubes. The increase of diameter, without any change in the thickness of metal, does not affect it. On the contrary, this principle of resistance, in the case of tubes with unyielding ends and open for the escape of the contained air, holds true, uniformly, throughout the whole of the experiments on 4, 6, 8, 10, and 12-inch tubes, as nearly as could be expected when due allowance is made for variations in the rigidity of the plates, imperfections in the workmanship, and difference in the tension of the sides.

TABLE V. Resistance of 12-inch tubes.

Mark.	No.	Diameter. inches.	Length. inches.	Thickness. inches.	Pressure of collapse. lbs. per sq. in.	Remarks.
S.	18	12·2	$58\frac{1}{2}$	·043	11·0	
T.	19	12·0	60	·043	12·5	
V.	20	12·0	30	·043	22·0	

Taking Experiment 20 as correct, we have for the collapsing pressure of a similar tube, 5 feet long, $60:30::22:x=11$, or 1·5 lb. less than Experiment 19. Similarly, $58\frac{1}{2}:30::22:x=11{\cdot}2$, or 0·2 lb. more than in Experiment 18. From these results we may reasonably conclude that the law affecting the strength of tubes is, other things being the same, that *the collapsing pressure varies inversely as the length.*

The tube S, when compared with the 6-inch tubes only one-half the length, required a pressure of less than one-fourth to cause collapse. This apparently low pressure, though at first sight anomalous, is confirmed by the result of Experiment 19. Similarly, comparing tubes C and D, Table I., with tubes O and P, Table III., we have,

	Length.	Diameter.	Pressure.
C and D	39	4	65
O and P	39	8	31·5;

that is, whilst the diameters are to one another as 1:2, the pressures of collapse are as 65:31·5, or as 2:1 very nearly. These comparisons, which might be continued, evidently point to a law affecting the diameters similar to that of the lengths.

In order to ascertain the different powers of resistance of tubes composed of thick plates and of different diameters, a strong tube only 9 inches in diameter, and formed of a plate $\frac{1}{4}$-inch thick, was constructed, to match and compare with another tube, also of $\frac{1}{4}$-inch plate, and $18\frac{3}{4}$-inches in diameter. The 9-inch tube was, however, found to be too strong for the retaining powers of the cylinder, which it would not have been safe to have trusted above 500 lbs. per square inch. Finding the strength of the small tube too great for the containing vessel, two new tubes were made, one with a lap-joint as at A in the annexed sketch, and another with a butt-joint as at B. These tubes were made of plates $\frac{1}{8}$th of an inch thick, the object of the difference being two-fold;—*first*, to ascertain to what extent the strength of the tube was reduced by the lap-joint; and *secondly*, to compare with the tube $18\frac{3}{4}$ inches in diameter, and double the thickness of plates. In the construction of boilers the lap-joint is almost invariably in use; and it must at once appear obvious that any such departure from the true circle in cylindrical tubes must injure their powers of resistance to external pressure.

Fig. 2.

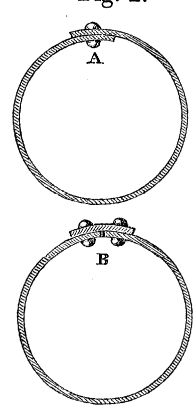
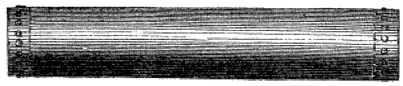
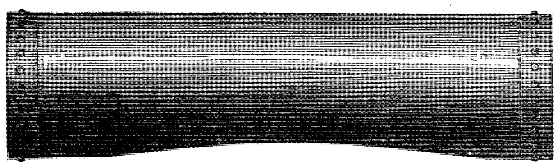
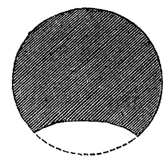
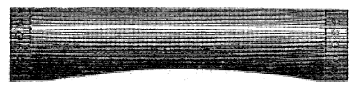
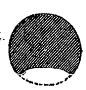
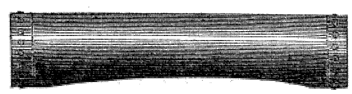


TABLE VI. Resistance of tubes with lap- and butt-joints.

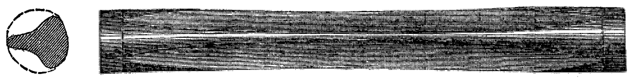
Mark.	No.	Diameter. inches.	Length. inches.	Thickness. inch.	Pressure of collapse. lbs. per. square inch.	Remarks.
W.	21	9	37	·25	(450)	Uncollapsed. 
X.	22	18¾	61	·25	420	 
Y.	23	9	37	·14	262	Lap-joint  
Z.	24	9	37	·14	378	Butt-joint  

The tube Y, Experiment 23, was made with a lap-joint, which caused it to deviate from a true circle in form, to the extent of nearly a quarter of an inch, the double thickness of the plates. In the tube Z, the cylindrical form was better maintained by the butt-joint, and this difference, apparently so small, had a serious effect upon the resisting powers of the tube. According to the results in the Table, there was a loss of more than one-third of the strength in the tube with the lap-joint, the ratio being 69·3 : 100, or 7 : 10 nearly. These facts are conclusive in showing the necessity of adhering in these constructions to the true cylindrical form.

The foregoing experiments were instituted for the purpose of ascertaining the resistance of tubes to collapse, when the ends were securely fixed to unyielding discs (as is the case with the flues of a boiler), and rigidly kept apart to prevent their approaching one another. In this position, the tubes, when submitted to severe collapsing pressures, were to some extent in a state of tension, and in some few cases, when collapse took place, the sides were torn from the cast-iron discs.

The results obtained from tubes of this construction have already been recorded, but we have yet to ascertain to what extent tubes of the same size and form follow the same laws in their resistance to external pressure when their ends are left free to approach each other. To solve this question two tubes were made, similar to those previously experimented upon, of 8 inches diameter and 60 and 30 inches in length. In these tubes there was no rigid bar down the centre, nor were they attached to the cylinder covers; they were simply placed in the cylinder, and water pumped in, in the usual manner, until they collapsed as given in the following Table:—

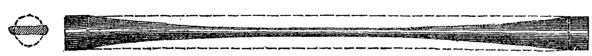
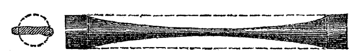
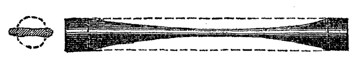
TABLE VII. Resistance of 8-inch Tubes.

Mark.	No.	Diameter. inches.	Length. inches.	Thickness.	Pressure of collapse. lbs. per sq. in.	Remarks.
AA.	25	8	60	·043	22	
BB.	26	8	30	·043	36	

In the above experiments the tubes do not appear to follow precisely the law of "inversely as the length." Had they done so, the tube BB should not have yielded with a less pressure than 44 lbs. on the square inch. It is, however, impossible to manufacture these tubes truly cylindrical, and hence it follows that slight variations may very materially affect the ultimate strength of the tube.

From three experiments on 4-inch tubes, we derive data more in accordance with the law, as will be seen below.

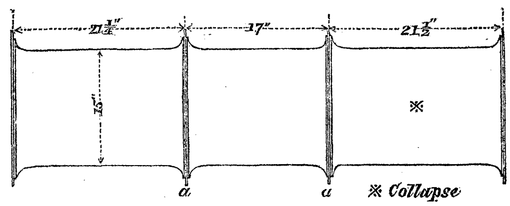
TABLE VIII. Resistance of 4-inch Tubes.

Mark.	No.	Diameter. inches.	Length. inches.	Thickness. inch.	Pressure of collapse. lbs. per sq. in.	Remarks.
CC.	27	4	60	·043	47	
DD.	28	4	30	·043	(195)	
EE.	29	4	30	·043	93	
FF.	30	4	15	·043	147	

In the above experiments, the second on tube DD is lost, in consequence of the ends being fractured and the water obtaining admission, so as to cause a counteracting pressure in the interior. Experiment 29 agrees closely with the law when compared with 27, its strength being correctly double that of the latter. The 15-inch, although not four times the strength of the 60-inch, exhibits high resisting powers. It is probably difficult to reconcile these discrepancies; but we have in these experiments sufficient data to show that these tubes also follow, in their resistance to collapse, some function of the length; and it is important to observe, that we cannot in practice introduce long tubes into constructions exposed to external pressure, without making very considerable allowance for their loss of strength.

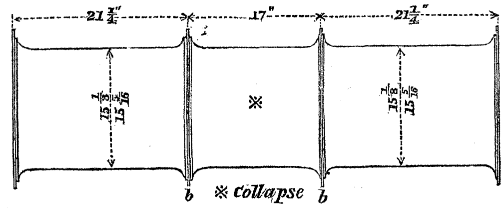
In the earlier experiments the tubes were made of thin wrought-iron plates; but conceiving that it would be of interest to examine how far the laws, which were found to prevail with them, applied also to tubes of other materials, three tubes were made of the following dimensions:—

GG. Iron flue, 15 inches in diameter:—
Plates ·125 inch thick.
Web (*a a*) ·25 inch thick.
Rivets $\frac{1}{4}$ inch, at $1\frac{1}{4}$ inch apart.



HH. Steel flue, diameters $15\frac{3}{16}$ and $15\frac{5}{8}$ inches:—

Plates ·125 inch thick.
Web (*b b*) ·25 inch thick.
Rivets $\frac{1}{4}$ inch, at $1\frac{1}{4}$ inch apart.



JJ. Iron flue, with overlap joints; diameters $14\frac{1}{2}$ and $14\frac{11}{16}$ inches:—
Plates ·125 inch thick.
Ends ·25 inch thick.
Length 5 feet.
Rivets $\frac{1}{4}$ inch, at $1\frac{1}{4}$ inch apart.

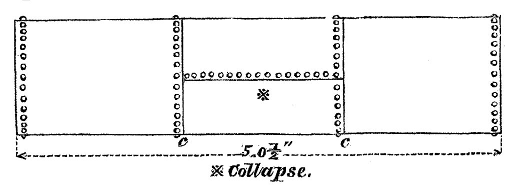


TABLE IX. Resistance of Steel and Iron Flues.

Mark.	No.	Diameters. inches.	Length. inches.	Thickness. inch.	Pressure of collapse. lbs. per sq. in.	Remarks.
GG.	31	15	21	·125	150	Each had an internal longitudinal stay between the ends.
HH.	32	$15\frac{3}{16} \times 15\frac{5}{8}$	17	·125	220	
JJ.	33	$14\frac{1}{2} \times 14\frac{11}{16}$	60	·125	125	

The experiments on these tubes do not at first sight appear to yield very satisfactory results. The first, GG, gave way with a pressure of 150 lbs. on the square inch, when it began to leak so much as to cause its removal from the vessel, to replace some of the rivets which were imperfect. After the necessary repairs, it was again subjected to experiment, when it gave way with a force of 146 lbs., showing how much it had been injured by the previous pressure. On comparing it with the mean results of all the other experiments, we find that it should have borne about 300 lbs.: it evidently failed at the rivets, and cannot be relied upon.

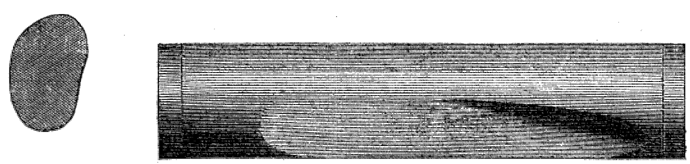
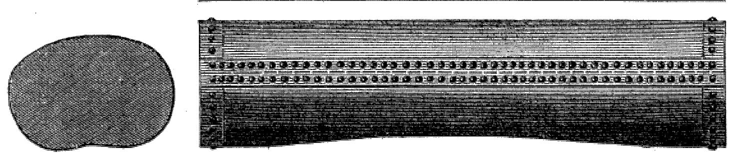
The next experimented upon was a steel tube, of the same form and with similar rigid divisions to those of the iron one. This sustained 220 lbs. on the square inch, when it bulged in or collapsed in the middle division.

The last was a plain tube of similar plates of iron, $14\frac{5}{8}$ inches in diameter, but without ribs. This collapsed with a pressure of 125 lbs. on the square inch; and this agrees nearly with the preceding experiments, as will be seen.

Comparing Experiments 32 and 33, it would appear that the steel tube is not stronger than the iron; but we are not warranted in drawing general conclusions from a single experiment.

The next experiments were of a different character, upon tubes of an elliptical form. The following Table gives the results.

TABLE X. Resistance of Elliptical Tubes.

Mark.	No.	Diameter. inches.	Length. inches.	Thickness. inch.	Pressure of collapse. lbs. per square inch.	Remarks.
A*a*.	34	$14 \times 10\frac{1}{4}$	60	·043	6·5	
B*b*.	35	$20\frac{3}{4} \times 15\frac{1}{2}$	61	·250	127·5	
X.	22	$18\frac{3}{4}$	61	·250	420·0	} Cylindrical.
T.	19	12	60	·043	12·5	

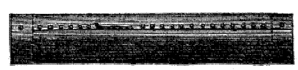
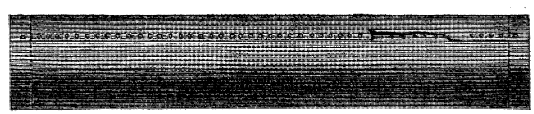
The last two experiments on cylindrical tubes are appended for comparison.

On comparing the elliptical tube B*b* with the cylindrical tube X, which are of the same length and thickness of plates, and only about half a square inch different in sectional area, we have for the collapsing pressure of the former 127·5 lbs., and for that of the latter 420 lbs., where it will be observed there is a loss of about $\frac{5}{7}$ths of the strength, in consequence solely of the flattening of the tube B*b*, or in other words, a cylindrical tube will support nearly three times the pressure which would collapse an elliptical tube of the same weight when proportioned like tube B*b*. A similar deficiency is observable in tube A*a*, when compared with tube T. The change of form, from the cylinder to the ellipse, where the diameter was reduced $1\frac{1}{2}$ inch in one direction and extended as much in another, reduced the bearing powers one-half. The comparative results obtained from the experiments on the thick tube are different from those on the thin one, the loss being much greater in the former than in the latter case, although the ratio of the diameters is about the same. Allowance must, however, be made for inaccuracies of construction, though we might reasonably have expected a nearer approximation in the ratios of the deficiency of strength. From these facts, however, it is obvious that in every construction, where tubes have to sustain a uniform external pressure, the cylindrical is the only form to be relied upon, and any departure from it is attended with danger.

Resistance of Tubes to Internal Pressure.

During the investigation on the comparative resisting powers of tubes to collapse, a question arose as to the relative powers of cylindrical tubes to resist an internal force acting uniformly over their surface. It has already been demonstrated that the resistance of cylindrical vessels to internal pressure varies inversely as the diameters, but what effect the length may have upon the strength has yet to be determined. We have already seen that a cylindrical tube, when subjected to external pressure, loses one-half its strength when the length is doubled, and so on in other cases; hence arose the inquiry, what effect, if any, will an increase of length have upon a tube exposed to *internal* pressure? To solve this problem, three tubes of precisely the same diameter and thickness of plates, but of different lengths, were prepared and submitted to experiment as follows:—

Table XI. Resistance of Tubes to Internal Pressure.

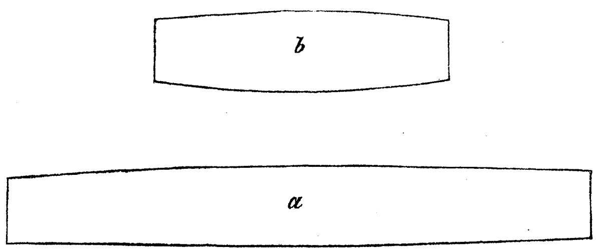
Mark.	No.	Diameter. inches.	Length. inches.	Thickness. inches.	Pressure of rupture. lbs. per square inch.	Remarks.
C*c*.	36	6	12	·043	475	
D*d*.	37	6	24	·043	235	
E*e*.	38	6	30	·043	230	
F*f*.	39	6	48	·043	375	
G*g*.	40	12·13	60	·043	110	

Considerable discrepancies occur in the experiments on internal pressure, as in each case the tube gave way at the riveted joint. Every precaution was taken, by carefully brazing them, to render them as nearly uniform in strength as possible. The weakness of these joints was, however, very apparent, and the results are in accordance with those arrived at several years previously, when it was found that the strengths of riveted plates were as the numbers—

100, for the solid plate;
70, for the double-riveted joint;
56, for the single-riveted joint.

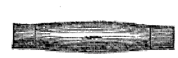
This constant failure at the joints renders the experiments on internal pressure very unsatisfactory, as they do not exhibit the ultimate strength of the plate, but only the strength of the joint; and as boilers invariably present joints, these facts are probably of some significance when applied to them. On a careful examination of the fractures, that of the tube F*f* appeared the most perfect. E*e* was not so well soldered, and burst by tearing off the rivet-heads, and D*d* was torn partly through the plates and partly through the rivets; the plate of which this tube was composed was, however, exceedingly brittle, and broke like cast-iron. Tube G*g* was ruptured in the same way and in the same direction as the others; the rivets were torn through the plates, and the soldering (not very sound) was ripped up for 10 inches along the joint: this tube, as also the others, would have borne a greater pressure had the joints been more perfect and of sounder workmanship.

Comparing the tube C*c*, 1 foot long, with the tube F*f*, 4 feet long, and assuming the joints to be equally perfect in each, it would appear that there is a slight loss of strength when the length is increased; and this again suggests the question, do the rigid ends in short tubes increase the strength of the unsupported portion in proportion to the length of the tube? For example, let us take two tubes of any given diameter, the one 10 feet and the other 20 feet long; it would appear, *primâ facie*, that it was much easier to force the long tube into the form of a barrel, as at *a*, than it would be to produce the same form in the shorter tube, as at *b*; in an elastic material, such as an indian-rubber tube, the extension would certainly take place at the centre, where the particles possess diminished resistance, arising from their respective distances from the ends or points of support.



To ascertain how far this view is correct, two leaden pipes were prepared of 3 inches diameter, and of the lengths of 1 foot $2\frac{1}{2}$ inches, and 2 feet 7 inches respectively, and these were submitted to the following experimental tests:—

TABLE XII. Resistance of Lead Tubes to Internal Pressure.

Mark.	No.	Diameter. inches.	Length. inches.	Thickness. inches.	Pressure of rupture. lbs. per square inch.	Remarks.	
H*h*.	41	3	$14\frac{1}{2}$	·25	374	At 225 lbs. pressure for H*h*, and 325 lbs. for J*j*, the ends were blown out.	
J*j*.	42	3	31	·25	364	After having been taken out and the ends replaced, they burst, as in the Table.	

The tube H*h* ruptured at the thin part of the metal, the water bursting through a narrow slit; *Jj* ruptured similarly; and on measuring the expanded circumferences at the broadest part, it was found that the metal of the former had elongated $1\frac{1}{4}$ inch, and that of the latter $1\frac{1}{2}$ inch.

These experiments seem to show pretty conclusively, that the length has very slight influence on the resisting powers of tubes of *wrought iron* to internal pressure. Beyond the limit of one or two feet in length, it appears to affect the strength so slightly, that it may be almost entirely disregarded in practice.

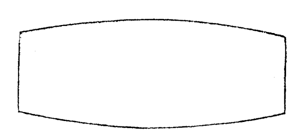
GENERALIZATION OF THE RESULTS OF THE EXPERIMENTS.

In the reduction of the experiments, I have, as on former occasions, been ably assisted by my friend Mr. TATE, whose sound philosophical views and high mathematical attainments are, from his numerous publications, so well known to the public. To that gentleman I am indebted for many services, and among others for an elaborate inquiry into the specific gravity and properties of steam, which I hope will be shortly forthcoming as a new addition to our knowledge, and that more particularly in its application to the wants and necessities of the present high state of civilization.

On this question I am personally gratified to find the subject in such able hands, and aided by the industry, care and perseverance of my own assistant, Mr. W. UNWIN, I entertain hopes of rendering the researches now in progress of such a character as fully to justify the application of the word *useful*, which of all others is probably the best calculated to express the true value of these investigations.

Formulæ of Strength relative to Cylindrical Tubes.

The strain which the material of a cylindrical vessel undergoes, when a uniformly-distributed external pressure is applied to it, is very different from the strain produced when the pressure acts internally. In the latter case the material is equally extended throughout all its parts, and its cylindrical form is preserved at all stages of the pressure, with the exception of a small portion closely bordering upon the inflexible plates closing the extremities. The tube under a high internal pressure will assume the form represented in the annexed diagram, and the relation of the force of rupture to that of resistance will be approximately expressed by



$$P=\frac{2E\times k}{D}, \quad \ldots \ldots \quad (1.)$$

where P represents the pressure requisite to produce rupture, E the ultimate resistance of the material to extension, D the diameter of the tube, and k its thickness; whereas in the former case, the material, being compressed, becomes crumpled in longitudinal lines near the middle; the tube loses its original cylindrical shape at and near to that part, whilst the portions towards the extremities being supported by the inflexible end plates, retain, or nearly retain, their original form; so that, in fact, the material virtually resisting compression is the comparatively small portion at and near the middle, and which, to a certain extent, is independent of the length of the tube, whilst the pressure producing the compression is always approximately proportional to the longitudinal section. Now let us assume for these tubes,—

P' = the external pressure of the fluid in lbs. to produce rupture or collapse;
P = this pressure per square inch;
R = the resistance of the material to compression or to crumpling;
L = the length of the tube in feet;
D = the diameter of the tube in inches;
k = the thickness of the plates in inches;
p = the pressure P reduced to unity of length and diameter, or $=PLD$;
C, α, constants to be determined from the data supplied by the experiments.

Since P', the total pressure on the tube, varies directly as the longitudinal section, that is, as the product of the length by the diameter, we have

$$P'=C'.P.L.D.$$

Now it has been determined by experiment, that the resistance of thin iron plates to a force tending to crush them, or rather to a force tending to crumple them, varies directly as a certain power of their thickness, the number indicating the power lying between 2 and 3; hence we assume,

$$R=C''.k^{\alpha};$$

but when rupture takes place, $P'=R$, and

$$C'.P.L.D=C''.k^{\alpha},$$

$$\therefore \quad P=\frac{Ck^{\alpha}}{LD}. \qquad (2.)$$

For tubes of the same thickness, we readily derive from this equality,

$$P.L.D=P_{,}.L_{,}.D_{,}; \qquad (3.)$$

that is, the continued product of the pressure, the length and the diameter is constant; or in other words, for tubes having the same thickness, the pressures of collapse reduced to unity of length and diameter (p) are equal to one another.

To determine the values of the constants α and C in (2.), we have

$$\frac{PLD}{P_{,}L_{,}D_{,}}=\left(\frac{k}{k_{,}}\right)^{\alpha}.$$

But in order to embrace a range of experiments by taking the mean of their results, we have, putting p for the value of P, when the tube is reduced to unity of length and to unity of diameter,

$$\frac{p}{p_{,}}=\left(\frac{k}{k_{,}}\right)^{\alpha},$$

$$\therefore \quad \alpha=\frac{\log p-\log p_{,}}{\log k-\log k_{,}}; \qquad (4.)$$

and similarly, we find

$$C=\frac{p}{k^{\alpha}}. \qquad (5.)$$

A glance at the results of the experiments recorded in Tables I. II. III. IV. V., where the thickness of the plates composing the tubes is the same, is sufficient to show, —1st, that the strength of the tubes varies nearly inversely as their lengths; 2ndly, that the strength also varies nearly inversely as the diameters. The following reduction of these experiments will not only render these laws apparent, but will also show that in tubes of the same thickness the strength varies inversely as the product of their lengths by their diameters, or, what amounts to the same thing, that PLD $(=p)$ is nearly a constant quantity.

Reduction of the Results of the Experiments on the Collapse of Sheet-iron Tubes ·043 inch thick, to unity of length and diameter.

Experiments 1, 2 and 6, were performed on tubes of the same length and diameter, and also Experiments 7, 10 and 11; hence we have for the mean values of P,—

Mean value of P from Experiments 1, 2 and 6 $=\frac{170+137+140}{3}=149.$

Mean value of P from Experiments 7, 10 and 11 $=\frac{48+52+65}{3}=55.$

4-inch Tubes.

No. of experiment.	D. Diameter in inches.	L. Length in feet.	P. Pressure of collapse in lbs.	P. L. Pressure reduced to unity of L.	P. D. Pressure reduced to unity of D.	p. Pressure reduced to unity of L and D.
1, 2, 6	4	$1\frac{7}{12}$	149	232·5	596	930·0
3	4	$3\frac{1}{3}$	65	216·6	260	866·4
4	4	$3\frac{1}{6}$	65	205·8	260	823·2
5	4	5	43	215·8	172	860·0
27	4	5	47	235·0	188	940·0
29	4	$2\frac{1}{2}$	93	232·5	372	930·0

6)5349·6

Mean value of p...... 891·6

The approximation of the numbers to one another in columns 5 and 7, shows how very nearly the strength varies inversely as the lengths. This observation applies with equal exactness to all the reductions which follow.

6-inch Tubes.

No. of experiment.	D.	L.	P.	P. L.	P. D.	p.
7, 10, 11	6	$2\frac{1}{2}$	55	137·5	330	825
9	6	$4\frac{11}{12}$	32	157·3	192	944

2)1769

Mean value of p ... 884·5

8-inch Tubes.

No. of experiment.	D.	L.	P.	P. L.	P. D.	p.
13	8	$2\frac{1}{2}$	39	97·5	312	780·0
14	8	$3\frac{1}{4}$	32	104·0	256	832·0
15	8	$3\frac{1}{3}$	31	103·3	248	826·4

3)2438·4

Mean value of p ... 812·8

10-inch Tubes.

No. of experiment.	D.	L.	P.	P. L.	P. D.	p.
16	10	$4\frac{1}{6}$	19	79·1	190	791
17	10	$2\frac{1}{2}$	36	90·0	360	900

2)1691

Mean value of p .... 845·5

A comparison of the numbers in the sixth columns with the numbers given by the experiments on tubes of the same length, clearly shows that the strength varies very nearly in the inverse ratio of the diameters; and moreover, since the mean values of p for the different sets of tubes nearly coincide with one another, we infer that the strength varies inversely as the product of the length by the diameter, or that $p=\text{PLD}=$ a constant.

12-inch Tubes.

No. of experiment.	D.	L.	P.	P. L.	P. D.	p.
18	12·2	$4\frac{21}{24}$	11·0	53·6	123·2	654
19	12	5	12·5	62·5	150·0	750
20	12	$2\frac{1}{2}$	22·0	55·0	264·0	660

3)2064

Mean value of p...... 688

Here the mean value of p is somewhat below the value determined from the other tubes. This discrepancy is no doubt owing to the difficulty there is in maintaining such thin tubes of large diameter exactly in the cylindrical form. This circumstance seems to suggest that a small correction, depending on the ratio of the diameter of the tube to its thickness, may be requisite to render formula (2.) mathematically exact. This correction will assume the form of $-\text{E}\times\frac{\text{D}}{k}$, where the constant E remains to be determined from the data of the experiments.

Mean value of p *derived from the foregoing results.*

$$p=\tfrac{1}{5}\{891\cdot6+884\cdot5+812\cdot8+845\cdot5+688\}=824.$$

Reduction of the Results of Experiments 22, 24, 33 on the Collapse of Sheet-iron Tubes to unity of length and diameter.

No. of experiment.	D.	L.	k. Thickness.	P.	p.
22	$18\frac{3}{4}$	$5\frac{1}{12}$	·25	420	40,030
24	9	$3\frac{1}{12}$	·14	378	10,495
33	$14\frac{5}{8}$	5	·125	125	9,140

To find the Value of the Constants α *and* C *in the General Formula.*

In equality (4.), taking $p=40{,}030$, $k=\cdot25$, $p_{\prime}=820$, $k_{\prime}=\cdot043$; we get

$$\alpha=\frac{\log 40{,}030-\log 820}{\log\cdot25-\log\cdot043}=2\cdot23.$$

Similarly, taking $p=40{,}030$, $k=\cdot25$, $p_{\prime}=9140$, and $k_{\prime}=\cdot125$; we get

$$\alpha=\frac{\log 40{,}030-\log 9140}{\log\cdot25-\log\cdot125}=2\cdot14;$$

and taking $p=10{,}495$, $k=\cdot14$, $p_{\prime}=820$, $k_{\prime}=\cdot043$; we get

$$\alpha=\frac{\log 10{,}495-\log 820}{\log\cdot14-\log\cdot043}=2\cdot16;$$

and taking the mean of these values, we get $\alpha=2\cdot19$.

For the value of the constant C, we have from (5.),

$$C=\frac{p}{k^{\alpha}}=\frac{820}{\cdot043^{2\cdot19}}=806{,}300.$$

Substituting these values in (2.), we get

$$P=806{,}300\times\frac{k^{2\cdot19}}{LD}, \quad \ldots \quad (6.)$$

which is the general formula for calculating the strength of wrought-iron tubes subjected to external pressure*, within the limits indicated by the experiments; that is, provided their length is not less than 1·5 foot, and not greater probably than 10 feet.

In order to facilitate calculation, formula (6.) may be written,

$$\log P=1\cdot5265+2\cdot19\log 100\,k-\log(LD);$$

* By taking 2 instead of 2·19 for the index of k, this formula becomes

$$P=806{,}300\times\frac{k^2}{L.D}, \quad \ldots \quad (a.)$$

whence the value of P, the collapsing pressure may be readily calculated by ordinary arithmetic.

For thick tubes of considerable diameter and length, this formula may be regarded as sufficiently exact for practical purposes.

For example, let $k=\frac{1}{2}$ inch, L=10 feet, D=36 inches; then

$$P=806{,}300\times\frac{(\frac{1}{2})^2}{10\times36}=560\text{ lbs.}$$

By formula (6.), $-$ P=1·5265+2·19 log 50 $-$ log 360=502 lbs.

It will be observed that these results do not differ widely from each other.

and by an obvious transformation, we have

$$P=\frac{820}{L.D}.$$

The following Table will show how nearly formula (6.) represents the results of the experiments on the different classes of tubes.

No. of experiment.	D. Diameter. inches.	L. Length. feet.	k. Thickness. inches.	P. By experiment in lbs.	P. By formula (6.).	Proportional error by formula
2	4	$1\frac{7}{12}$	·043	137	130	$-\frac{1}{19}$
5	4	5	·043	43	41	$-\frac{1}{22}$
7, 10, 11	6	$2\frac{1}{2}$	·043	55	54·7	$-\frac{1}{200}$
14	8	$3\frac{1}{4}$	·043	32	31·6	$-\frac{1}{80}$
16	10	$4\frac{1}{6}$	·043	19	19·7	$+\frac{1}{30}$
19	12	5	·043	12·5	13·6	$+\frac{1}{12}$
23	$18\frac{3}{4}$	$5\frac{1}{12}$	·250	420	407	$-\frac{1}{32}$
26	9	$3\frac{1}{12}$	·140	378	392	$+\frac{1}{27}$
33	$14\frac{5}{8}$	5	·125	125	116	$-\frac{1}{15}$

So far as regards practical purposes, this formula appears to possess every desirable precision. As already anticipated, the results derived from the thin 12-inch tubes present the greatest deviation. The value of P, derived from the following formula, gives a still closer approximation to the results of the experiments, viz.—

$$P=806{,}300\times\frac{k^{2\cdot19}}{L.D}-\cdot002\times\frac{D}{k}.$$

It is highly desirable that we should verify the law $P.L.D=P_{\prime}.L_{\prime}.D_{\prime}$, as applied to thick tubes. Now, we know the value of α independently of these experiments, for its value, as determined above, closely approximates to the value derived from the experiments on the compression of sheet-iron plates. Let us, therefore, reduce the collapsing pressure of these plates to unity of thickness, with the view of ascertaining the law of variation of pressure as regards length and diameter.

Let P be the pressure of collapse of a tube k inches thick, and P' the pressure when the tube is ·1 inch thick; then

$$\frac{P'}{P}=\left(\frac{\cdot1}{k}\right)^{\alpha},$$

$$\therefore \quad P'=P\times\left(\frac{1}{10k}\right)^{\alpha}=\frac{P}{(10k)^{\alpha}},$$

and

$$\log P'=\log P-2\cdot19\log(10k).$$

Reducing the values of P by this formula, we derive the following results:—

No. of experiment.	D. Diameter.	L. Length.	k. Thickness.	P. Pressure.	P′, or value of P reduced to unity of thickness, viz. ·1.	Value of P′. L. D.
5	4	5	·043	43	273	5400
22	$18\frac{3}{4}$	$5\frac{1}{12}$	·250	420	57	5400
24	9	$3\frac{1}{12}$	·140	378	190	5300
33	$14\frac{5}{8}$	5	·125	125	76	5600

The remarkable approximation of the numbers in the last column to one another, distinctly establishes the law $(P.L.D=P_{,}.L_{,}.D_{,})$ in relation to tubes composed of thick plates.

Deduction from the Results of the Experiments on the Collapse of Elliptical Tubes.

By comparing the result of experiment (34.) on the elliptical tube with the result of the experiments on the cylindrical tubes, we find that the general formula (6.) will apply approximately to elliptical tubes, by substituting for D in that formula the diameter of the circle of curvature touching the extremity of the minor axis. Thus we have,

$$\text{Diameter of the circle of curvature } =\frac{2a^2}{b}=\frac{2\times 7^2}{5}=20 \text{ nearly.}$$

Now the pressure on this elliptical tube was 6·5 lbs., which reduced to unity of length and diameter, gives 650 lbs., which result nearly agrees with 688 lbs., the mean pressure of the 12-inch tubes also reduced to unity of length and diameter.

Although this deduction is based on merely one experimental result, yet it appears to be confirmed by the following proposition derived from mathematical analysis.

The pressure P per square inch, requisite to flatten equal angular portions of a tube of variable curvature, varies inversely as the diameters of curvature.

Hence it will be observed how very much the strength of a tube subjected to external pressure is deteriorated by a deviation from the cylindrical form.

Strength of Cylindrical Tubes subjected to Internal Pressure.

Taking the mean of the results of Experiments 36 and 39 on iron tubes, we have from formula

$$E=\frac{425\times 6}{2\times \cdot 043}=30{,}000 \text{ nearly.}$$

Hence we find

$$P=\frac{60{,}000\,k}{D}, \quad \ldots\ldots\ldots\ldots \quad (7.)$$

which gives the formula of strength of thin sheet-iron tubes subjected to internal pressure.

Now the tenacity of boiler plates has been found to be 23 tons, or 51,520 lbs. per square inch; hence it appears that a considerable reduction of tenacity must be made for the riveting of the plates. The ratio of reduction is in this case $\frac{3}{5}$.

One remarkable fact distinctly established by these experiments, is the comparative weakness of tubes subjected to external pressure. If p be put for the internal pressure per square inch at which a tube is ruptured, then for tubes of the same thickness and diameter, we find from (6.) and (7.) the following relation of strength:—

$$\frac{p}{P}=\frac{1}{13{\cdot}44}\times\frac{L}{k^{1{\cdot}19}}$$

If $L=2\frac{1}{2}$ and $k={\cdot}043$, then $\frac{p}{P}=7{\cdot}77$; that is to say, in this case the tube subjected to internal pressure will have about $7\frac{1}{2}$ times the strength of a similar tube subjected to external pressure. When

$$p=P,$$

we find

$$L=13{\cdot}44k^{1{\cdot}19}.$$

If $k={\cdot}25$, then we find $L=3\frac{3}{4}$ feet nearly; that is, a tube of this length and thickness will be equally strong whether subjected to external or internal pressure.

Taking the mean of Experiments 41 and 42 on the lead pipes, we have from formula (1.),

$$E=\frac{370\times 3}{2\times{\cdot}25}=2220,$$

which gives us the tenacity of lead per square inch.

Hence we find

$$P=\frac{4440k}{D}, \qquad (8.)$$

which gives the formula of strength of lead tubes subjected to an internal pressure.

Practical Application to Construction of the Results of the Experiments.

Throughout the whole of the experiments enumerated in the preceding pages, it has been proved that the resistance to collapse from a uniform external pressure, in cylindrical tubes, varies in the inverse ratio of the lengths. This law has been tested to lengths not exceeding fifteen diameters of the tube; but the point at which it ceases to hold true is as yet undetermined, and could only be ascertained by a new and laborious series of experiments on tubes of considerably greater length, in which the strength of the material modifies the above law of resistance to collapse. Such experiments are, doubtless, very desirable; but the vessels necessary for the purpose would be most expensive, and the results already obtained appear to supply all the data necessary for calculating the strengths and proportioning the material in all ordinary cases.

If we take a boiler of the ordinary construction, 30 feet long and 7 feet in diameter, with one or more flues 3 feet or 3 feet 6 inches in diameter, we find that the cylindrical external shell is from three to four times stronger in its powers of resistance to the force tending to burst it, than the flues are to resist the same force tending to collapse them. This being the case in boilers of ordinary construction, it is not surprising that so many fatal accidents should have occurred from the collapse of the internal flues, followed immediately by the explosion and rupture of the outer shell. To remedy such evils, and to place the security of vessels so important to the community upon a more certain basis, it is essential that every part should be of *uniform strength* to resist the forces brought to bear upon it. The equalization of the powers of resistance is the more important, as the increased strength of the outer shell is absolutely of no value, so long as the internal flues remain, as at present, liable to be destroyed by collapse, at a pressure of only one-third of that required to burst the envelope which surrounds them.

The following Table, deduced from my own experiments, exhibits the safe working pressure, and the bursting pressure of boilers of different diameters, calculated for an external shell of a thickness of $\frac{3}{8}$ths of an inch.

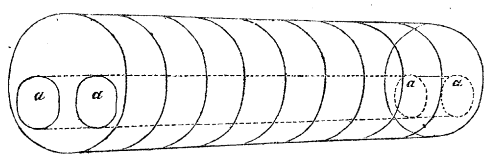
Diameter of boiler.	Working pressure.	Bursting pressure.
ft. in.	lbs.	lbs.
3 0	118	$708\frac{1}{4}$
3 6	101	607
4 0	$88\frac{1}{2}$	531
4 6	$78\frac{3}{4}$	472
5 0	$70\frac{3}{4}$	425
5 6	$64\frac{3}{4}$	$386\frac{1}{4}$
6 0	59	354
6 6	$54\frac{1}{4}$	$326\frac{3}{4}$
7 0	$50\frac{1}{2}$	$303\frac{1}{2}$
7 6	47	$283\frac{1}{4}$
8 0	44	$265\frac{3}{4}$
8 6	$41\frac{1}{2}$	250

Taking from the above Table the strength of a boiler 7 feet in diameter, we find its bursting pressure to be 303 lbs. per square inch. For such a boiler the flues would be ordinarily 3 feet in diameter, and of the same thickness of plates as the shell; and by the formula, $\log P = 1{\cdot}5265 + 2{\cdot}19 \log 100k - \log (L.D.)$, we obtain for their collapsing pressure 87 lbs. per square inch. As, however, the formula does not apply with strictness to tubes of such length, the actual collapsing pressure will be somewhat greater than this. The immense excess of strength in the outer shell is, however, sufficiently apparent; the extra thickness of boiler plate which causes it being so much material thrown away, adding nothing to the strength whilst the flues remain in so dangerously weak a condition.

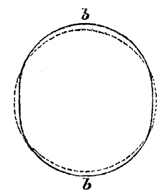
To meet this disparity of strength, the experiments indicate the necessity of *shorter* flues, and one of them shows how this may be obtained, practically and efficiently, without interfering with the present construction of boilers. In Experiment 6, Table I., the tube F was divided into three parts by two rigid rings soldered upon its exterior, and its powers of resistance were thus increased in the ratio of three to one; *virtually*, the length was reduced in this ratio, and the strength was *actually* increased from 43 to 140 lbs. per square inch.

It is proposed to apply a similar construction to the flues of boilers, to equalize their powers of resistance with those of the outer shell, on the supposition that the law of decrease of strength holds true, within no great limits of error, to tubes of much greater length than in the preceding experiments. That this conclusion is not empirical, will be seen by the following experiments upon boilers of full size, where it will be observed that the flues were distorted with one-third the pressure required to rupture the external shell.

These boilers were made for the North-Eastern Division of the London and North-Western Railway Company, and were respectively of 35 and 25 feet in length. They were 7 feet in diameter, and composed of plates $\frac{3}{8}$ths of an inch thick. Each boiler had two cylindrical flues 3 feet 6 inches in diameter, and of the same thickness of plates as the outer shell. They were fixed in the position shown in the annexed



diagram, and were intended to resist an ordinary working pressure of only 40 lbs. upon the square inch. In submitting them to the usual test of double pressure, the flues of the first or longest boiler gave way with 97 lbs. upon the square inch; and those of the shorter boiler required 127 lbs. to effect the same distortion. With these large tubes a complete collapse was not accomplished, but the circular form, indicated by the dotted line, was *distorted*, and the flue became elliptical, as shown at *b b**.



The weakness of the flues in the above experiments is so evident as to need no comment. To remedy it, it has been already stated, we need only resort to a construction so simple, and yet so effective, as to meet at a small expense all the requirements of the case.

* Reducing the above results to unity of length, which with flues of this size should give a nearly constant quantity, we have—

	D.	L.	P.	P.L.
First boiler	42	35	97	3395
Second boiler	42	25	127	3175

The correspondence in the last column shows that these flues obey the law of inversely as the lengths, very nearly, in their powers of resistance.

It may be well to test the accuracy of the formula which has been found to apply to tubes of a length not greater than 10 feet, by determining from it the strength of flues similar to the above, and comparing the results with those derived from experiment.

Here, for the boiler 35 feet long, we have by formula

$$P=806{,}300\frac{k^2}{LD.},$$

$$=78\text{ lbs.};\ \text{by experiment } 97\text{ lbs.}$$

This difference confirms the view already stated, that the formula for short tubes does not apply *strictly* to tubes longer than 10 feet.

For the boiler 25 feet long, we have

$$P=109\text{ lbs.};\ \text{by experiment } 127\text{ lbs.}$$

A less difference between the experimental and calculated result, as would have been anticipated from the shorter length of the flue.

It will be observed, that even these experiments, upon full-sized boilers, are remarkably consistent, and offer no discrepancies which cannot be easily explained consistently with the general formula.

Figure 1, Plate XXIX., exhibits an ordinary boiler flue, 30 feet long and 2 feet 9 inches in diameter, with simple lap-joints, as hitherto invariably constructed. To attain nearly three times the strength of this, it will only be necessary to introduce two strong, rigid, angle-iron ribs, as exhibited in figs. 2 and 3, at *a*, *a*. This arrangement will not only remove all doubts as to the strength of these flues, by bringing them within the limits to which the formula applies with strictness, but will give to flues 30 feet long a strength equivalent to that of flues only 10 feet long, and make them uniform in their powers of resistance with the other parts of the boiler.

The reduction of the strength of flues by the lap-joints has already been stated; the deviation from the true cylindrical form which they cause, lessens, in some cases, seriously the strength of the vessels, as may be seen in Experiments 23 and 24, Table VI. Hence it is also proposed that flues required to resist an external pressure should be formed with double-riveted *butt-joints*, with longitudinal covering plates, as shown at *b*, *b*, *b*, fig. 3, Plate XXIX. It is believed that these alterations will secure ample safety in these important constructions, and in this trust they are commended to the attention of the engineer and the public generally.

FIG. I.

ELEVATION OF

EXPERIMENTAL APPARATUS.

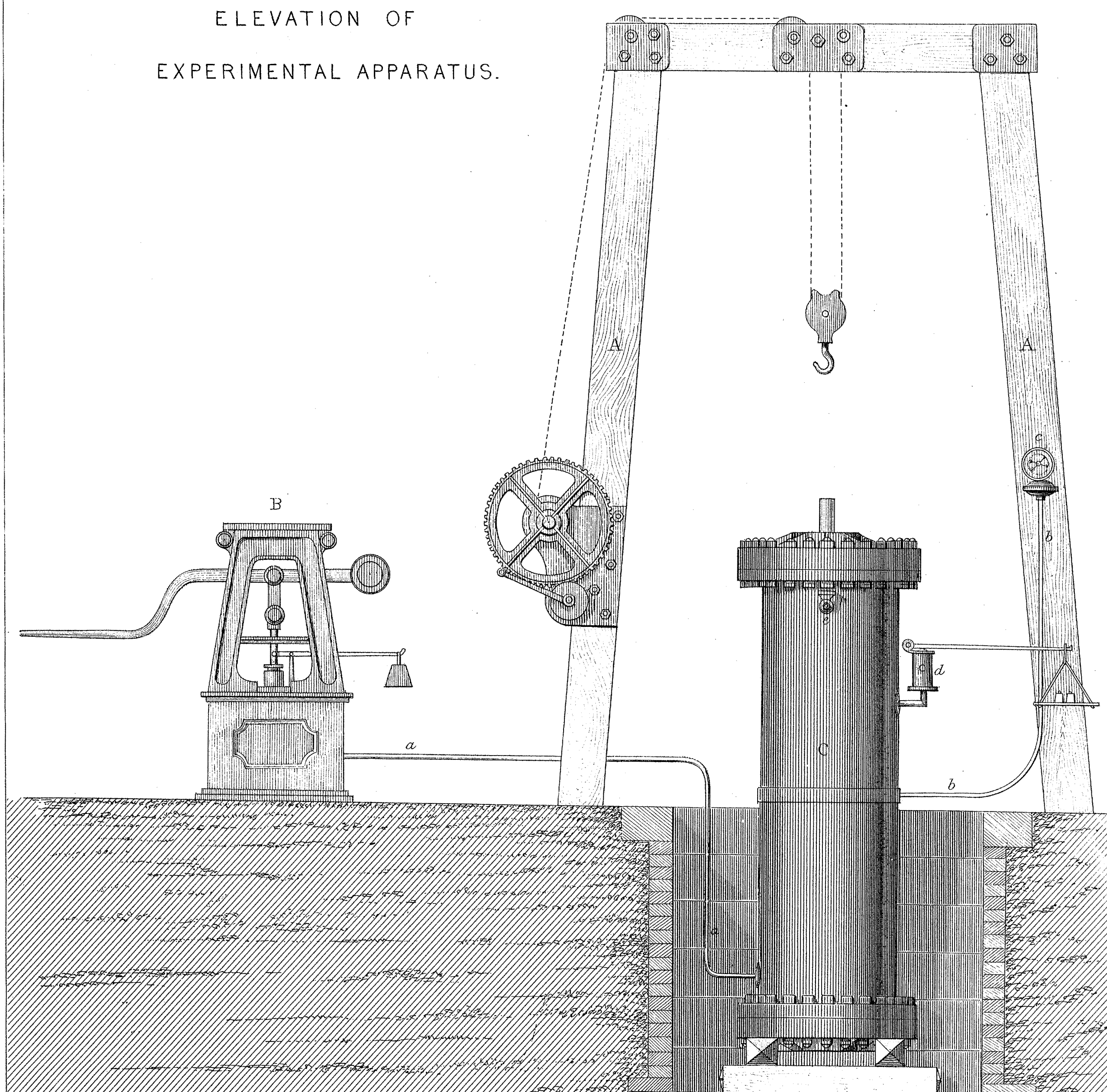


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FIG. 1.

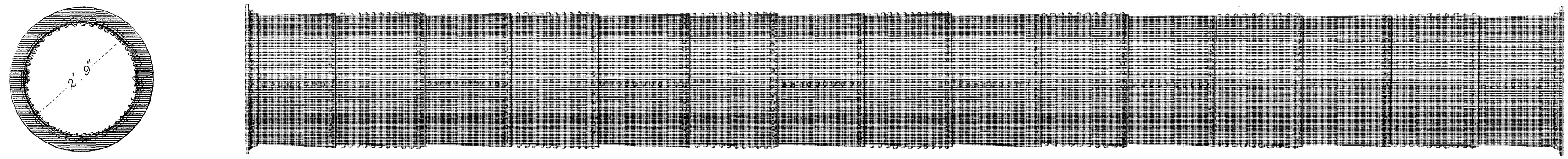


FIG. 2.

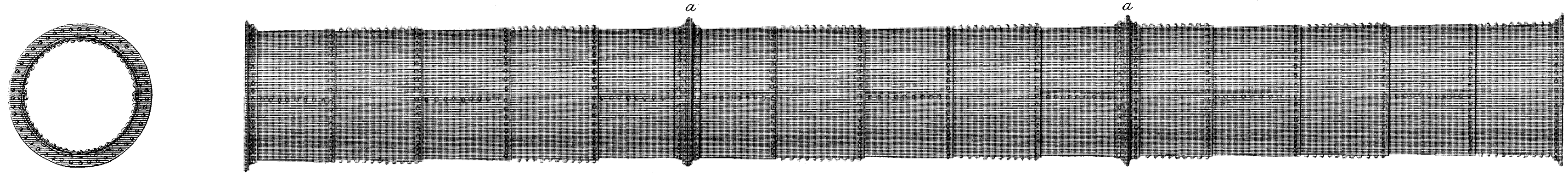
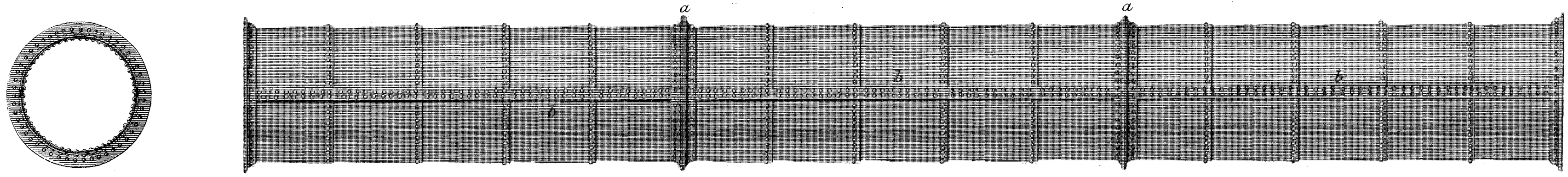
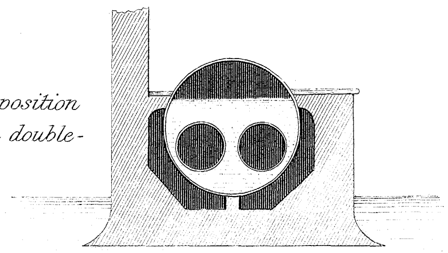


FIG. 3.



Sketch, shewing the position of the flues, in a double-flued Boiler.



PROPOSED IMPROVEMENTS

in the construction of boiler flues, as derived from experiments.

J. Basire, sc.