the manner already described for the flat fire-boxes of locomotive boilers.

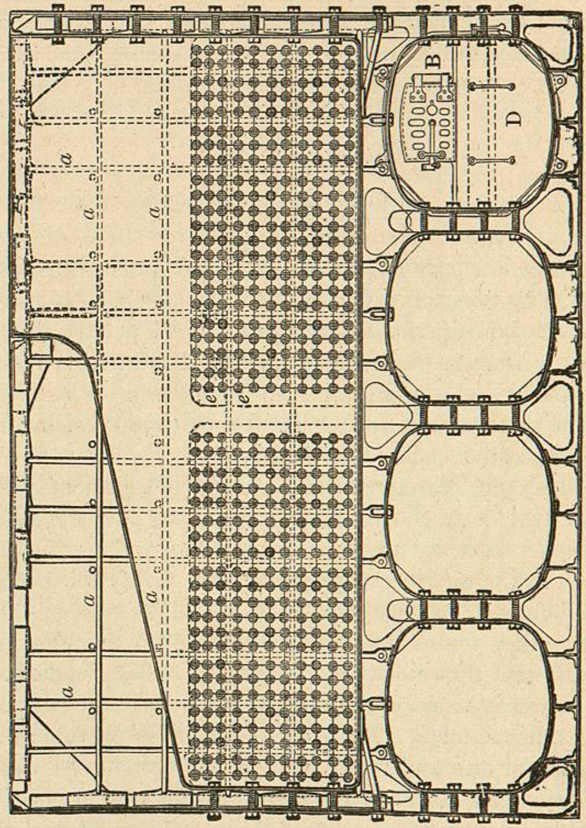

Fig. 166.[1]

The use of high-pressure steam of from 60 to 150 lbs. per square inch in modern marine engines has necessitated the abandonment of the type of boiler just described, as it would not be safe when dealing with such great pressures and large surfaces to depend solely on the strength of the stays. Accordingly we find that modern marine boilers are circular, or nearly so, in cross section, with flat ends.

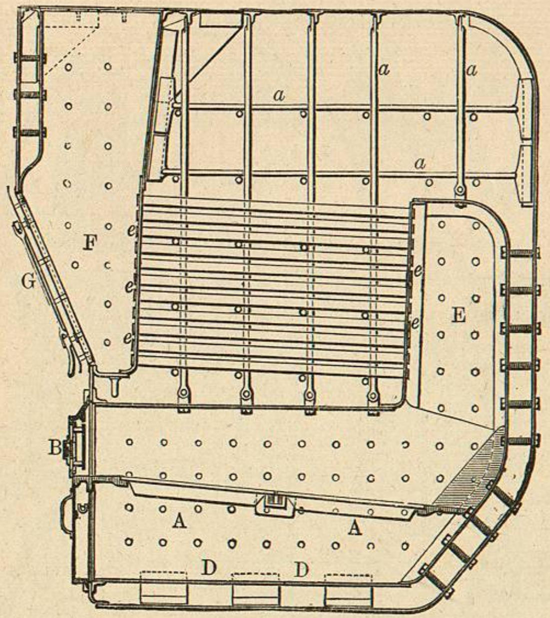

Fig. 167.

Fig. 168 shows a front elevation and partial sections of a pair of such boilers, together with their up-takes, steam-chest, and other fittings; and fig. 169 shows one of them in longitudinal vertical section. It will be seen from these drawings that there are three internal cylindrical furnaces in each end of these boilers, making in all six furnaces per boiler. The firing takes place at both ends. The flame and hot gases from each furnace, after passing over the bridge, enter a flat-sided rectangular combustion chamber, and thence travel through tubes to the front up-take, and so on to the chimney. The sides of the combustion chambers are stayed to each other and to the shell plate of the boiler. The tops

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[1] Figs. 166 and 167 are taken by permission from Mr. R. Sennett's work on the *Marine Steam Engine*.

are strengthened in the same manner as the crowns of locomotive fire-boxes already described. The flat-end plates of the boiler shell are stayed together by means of long bolts,

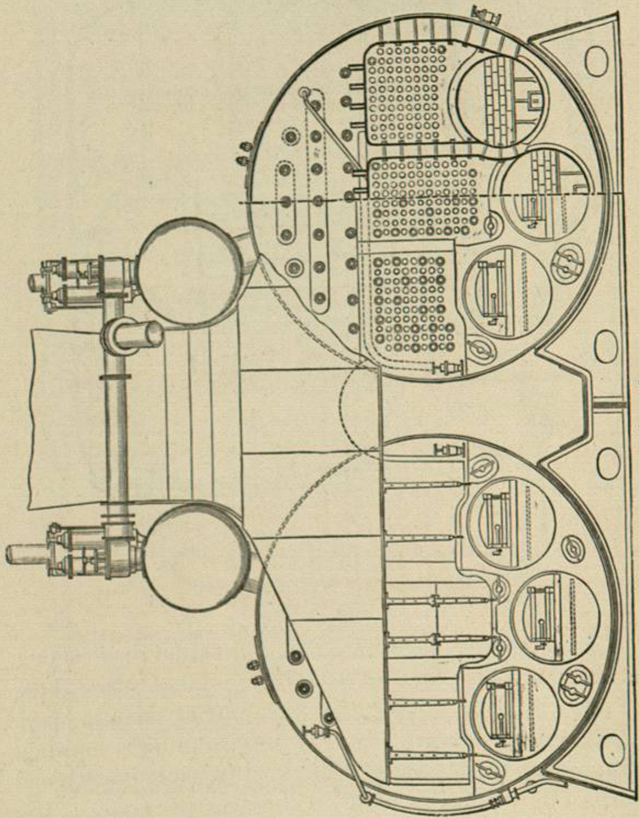

Fig. 108.

which can be tightened up by means of nuts at their ends. Access is gained to the up-takes for purposes of cleaning, repair of tubes, &c. by means of doors on their fronts, just above the furnace doors. The steam is collected in the

large cylindrical receivers shown above each boiler. The material of construction is mild steel.

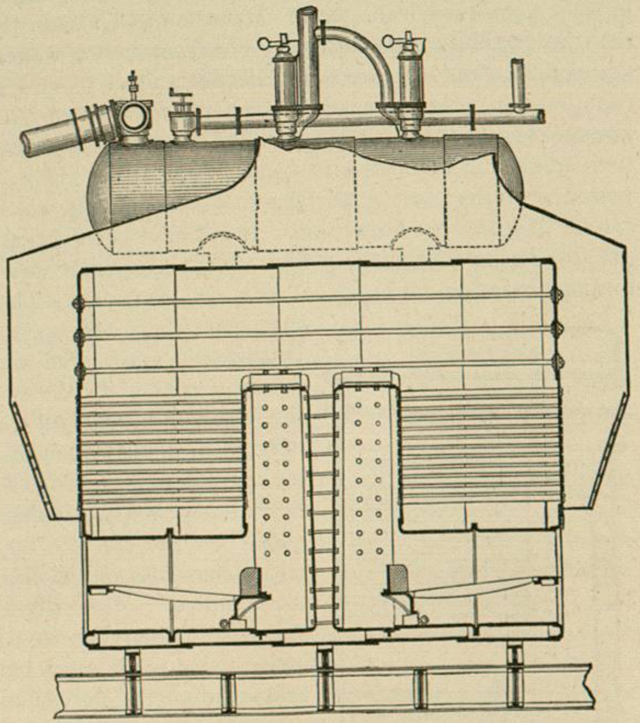

Fig. 169.

The following are the principal dimensions and other particulars of one of these boilers :—

Length from front to back, 20 ft.
Diameter of shell, 15 ft. 6 in.
Length of furnace, 6 ft. 10 in.
Diameter of furnace, 3 ft. 10 in.
Length of tubes, 6 ft. 9 in.
Diameter, 3½ in.

No. of tubes 516.
Thickness of shell plates, $\frac{15}{16}$.
Thickness of tube plates, $\frac{3}{4}$.
Grate area, 126·5 sq. ft.
Heating surface, 4015 sq. ft.
Steam pressure, 80 lbs. per. sq. in.

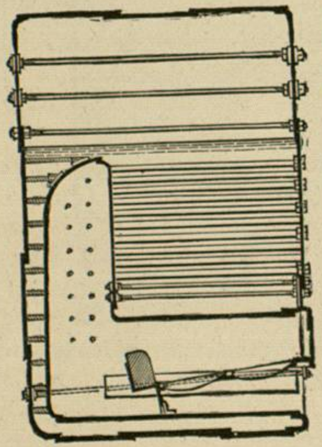

Fig. 170.

There are many varieties of marine boilers, adapted to suit special circumstances. Fig. 170 for instance is a sketch of a modern boiler, which is only fired from one end, and is in consequence much shorter in proportion to its diameter than the type illustrated in fig. 168. The cross section is often not circular. The sides are sometimes flat, and are prevented from bulging by being stayed to each other. The top and bottom are semicircular in shape. This form of section has been adopted in order to save some of the space which is wasted when the true circular shape is adopted, and which can be ill spared on board ship. It will have been noticed that the boiler illustrated in fig. 168 has a separate combustion chamber for each of the six furnaces. This arrangement is very good, because if a tube gives way in one chamber the fires in the other furnaces are not affected by it, but it is nevertheless not always adopted. Sometimes, even in double-ended boilers, all the furnaces have only one chamber in common. The disadvantages of this plan are so serious that it is now but seldom adopted. Very often the two opposite furnaces of a double-ended boiler have a chamber in common, and in single-ended boilers with two furnaces we frequently find the same arrangement. The number of furnaces depends upon the diameter of the boiler shell, and the very confined natural limits, which are set to the diameter of furnaces. If the latter are less than 36 inches, the crown of the furnace is so low that a large proportion of the heating value of the fuel is lost by the process of distillation. On the other hand, if over 48 inches, the thickness of plates necessary to give sufficient strength to the structure is so great, that the metal would be liable to be burnt, and its heat-transmitting powers would be greatly diminished. Boilers over nine feet in diameter have generally two furnaces, those over thirteen to fourteen feet three, while the very largest boilers used on first-class mail steamers, and which often exceed fifteen feet in diameter, have four furnaces.

THE PROPORTIONS OF THE PARTS OF BOILERS.

In designing a boiler of a given type to furnish a certain amount of steam in a given time, it is requisite to know the following things :—

The size of fire-grate necessary to burn the requisite quantity of fuel in a given time with various kinds of blast.

The capacity of different sorts of heating surface to transmit heat.

The area of heating surface required to evaporate the given quantity of water in the given time.

The relative proportions of the cubic contents of the boiler, which should be occupied by steam and water respectively.

The quantity of water which a pound of fuel will convert into steam of a given pressure depends upon the pressure of the steam, the nature of the coal, and the efficiency of the type of boiler. For the purposes of comparison, all rates of evaporation at various pressures and various temperatures of feed are reduced to the corresponding rates at and from 212°. When the above data are known, it is easy to fix the size of fire-grate necessary in order to effect the combustion of the fuel.

Evaporative power of fuel in different types of boilers.—As a general rule, with fair average coal, it may be stated that the following rates of evaporation are obtained with the different types of boilers named :—

	Per lb. of coal
Lancashire boiler using feed heater	9 to 10·5 lbs. of water at and from 212°
Marine boiler of old type . .	8·7 lbs. of water at and from 212°
Marine boiler of new type . .	8·1 lbs. of water at and from 212°
Locomotive boiler . . .	9 to 12 lbs. of water at and from 212°

With bad fuel, such as steamers have often to take in at foreign ports, these figures will have to be reduced about twenty per cent. ; on the other hand, with picked fuel they may all be increased about fifteen per cent.

Fire grate area.—A given grate area will burn very different weights of fuel in a given time according to the nature of the draught. Where the size of the boiler is a matter of no importance, as in most land boilers, a slow rate of combustion is maintained, with a natural draught, on account of the saving in wear and tear of the furnaces. In such cases a common rate is from ten to twenty pounds of fuel per square foot of grate area per hour. On the other hand, when the size of the boiler is limited by the circumstances, as in the case of locomotives and torpedo boats, a rate of from forty to one hundred and twenty pounds per square foot can be maintained by using a forced draught. Most of the following figures are given in Rankine's 'Manual of the Steam Engine.'

	Per sq. ft. per hour
Slowest rate of combustion in Cornish boilers .	4 lbs.
Ordinary rate of combustion in Cornish boilers .	10 lbs.
,, ,, in factory boilers .	12 to 16 lbs.
,, ,, in marine boilers .	15 to 24 lbs.
Quickest rate of complete combustion of dry coal, air coming through grate alone . . .	20 to 23 lbs.
Rate in locomotive boilers with blast-pipe . .	40 to 120 lbs.
Ordinary rate of locomotive boilers with blast-pipe	65 lbs.

The length of fire-grate is limited by the distance to which a stoker can throw the coals back with accuracy. It

is usual to fix six feet as the utmost limit. The breadth of the grate depends chiefly on the breadth or diameter of the boiler, and on the arrangement of the furnaces. In Lancashire boilers with two internal flues the breadth is extremely limited. Narrow furnaces have the great disadvantage that they allow the fire, which is necessarily of small bulk, to be chilled by the proximity of the cold sides of the furnace, and allow but little room above the fuel for the introduction of air to complete the combustion.

Grates of large area are difficult to cover evenly with the fuel. As a consequence the fire is apt to burn through too quickly in the thin places, and the air rushing in most where it finds the easiest entrance, causes the imperfect and slow combustion of the fuel wherever it is piled on too thickly.

Efficiency of heating surface.—The capacity of the heating surface to transmit heat to the water depends on the conductivity and the thickness of the metal, also on the position of the surface, and the difference in temperature between the water in the boiler and the hot gases in the furnace. The metals most commonly used to separate the water from the fuel are wrought iron and steel. These materials are, however, inferior to copper in conducting power, in the ratio of about one to three, and for this reason the latter metal is used to form the sides of furnaces in all cases where it is necessary to obtain a high rate of evaporation from a boiler of limited size. The inner fire-boxes in locomotives form a case in point. For the tubes of locomotive and many marine boilers brass is very generally used, both on account of its high conducting power, and also because of the facility with which tubes can be drawn from this material ; but tubes of steel and wrought iron are also used, especially in the boilers of the mercantile marine. The most effective portions of the heating surface are the sides, and especially the crown of the furnace and combustion chamber, and the first foot or two of the flues or tubes. The reason of this is that the products of combustion are much hotter at these parts than elsewhere, and the effects of radiation are also most strongly felt in these portions of the boiler.

In a boiler with horizontal flues and tubes the lower portions of these latter are considered of no value as heating surface, because of the difficulty with which the steam escapes from them. For this reason the effective value of tube-heating surface is usually estimated to be only three-fourths of the total area of the tubes. In estimating the amount of heating surface in a boiler the surfaces of the furnace below the fire-bars, and of the combustion chamber below the bridge, and also of the tube-plate, farthest from the flame are altogether omitted.

It is impossible to lay down general rules for the evaporating power of a given area of heating surface; for, as has been stated above, so much depends on the temperature which is maintained in the furnace, and also on the position of the surface relatively to the hottest part of the fire. For these reasons the effects of different portions of the heating surface in evaporating the water are widely different, and nothing but an average of effect can be taken. In designing boilers it will, therefore, be safest to follow the proportions of heating surface to grate area, in the various types, which experience has proved to give the best results. The following are the proportions in a few representative cases:—

Lancashire boiler, ratic of grate area to heating surface	1 : 26
Lancashire boiler, including surface of feed-water heater, ratio of grate area to heating surface .	1 : 44
Marine boiler, ratio of grate area to heating surface .	1 : 22 to 35
Locomotive boiler, ratio of grate area to heating surface	1 : 60 to 90

Roughly speaking, it may be said that for every foot of heating surface in a Lancashire boiler 6·8 to 9 lbs. of water can be evaporated per hour, excluding the surface of the feed-heater; in marine boilers from 6 to 8 lbs.; and in locomotives from 10 to 15, for good average coal and ordinary

conditions. The higher figures apply to the case of the boilers being forced. With the locomotive type of boiler applied to torpedo boats 18 lbs. of water have been evaporated per square foot of heating surface, with a forced draught equivalent to six inches of water. The ratio of grate area to heating surface was, however, only 1 : 34, and the water evaporated per pound of coal was consequently very low, having been only about 6 lbs.

As a general rule it may be stated that the proportion of heating surface to fuel burnt is as follows:

	Per lb. of coal burnt per hour
For Lancashire boilers . . .	1·1 to 1·5 sq. ft. of surface
For modern marine boilers . .	1 to 1·5 sq. ft. of surface
For modern locomotive boilers .	·9 to 1·5 sq. ft. of surface

In order to obtain good evaporative results the higher figure should be chosen, but little is gained by any further increase beyond the allowance of 1·5 square ft. per lb. of coal per hour. When the allowance is less than ·7 square ft. per lb. of coal the results are distinctly uneconomical.

Cubic capacities of boilers of different types.—The absolute cubic capacity and the relative capacities of the water and steam rooms in a boiler are determined very much by the nature of the work which is expected to be done. Of course, in the case of boilers of a portable nature the circumstances limit the absolute capacity, but in the case of land boilers, where the bulk is of no particular account, the cubic contents are determined solely by the nature of the work to be done. Thus in cases where steam is only required occasionally, and where, when wanted, it must be raised with great rapidity, the capacity of the boiler is necessarily small, and the heating surface and grate area large, relatively to the cubic contents; but where steady continuous work is required the capacity is always large.

In boilers of small capacity the greatest care must necessarily be bestowed on the feed; otherwise it would be impossible to maintain a uniform steam pressure, and more-over, on account of the rapidity of evaporation, the upper portions of the heating surface are liable to be denuded of water, in which case serious damage is likely to ensue. In boilers of small capacity and great evaporative power it is usual to put a lead plug into the crown of the furnace, in order that, if the water has been allowed to sink below the level of this portion, the plug may melt, and allow the steam to enter the furnace and extinguish the fire.

The absolute capacity of steam and water room in cubic feet, per pound of water evaporated per hour in the boiler, varies greatly in different types of boilers. The following figures give the proportions adopted in a few cases of the best examples.

Lancashire boilers .	1 cubic foot capacity for every 3 lbs. of water to be evaporated per hour
Marine boilers . .	1 cubic foot capacity for every 7 to 10 lbs. of water to be evaporated per hour

In the case of locomotive boilers the rate of evaporation varies within such wide limits in the same boiler according to the work that has to be done, that it is impossible to give any general rule.

The relative cubic capacities of the steam and water rooms also vary very considerably in the different types of boilers. For instance, where high pressure is used, and small quantities of steam are very frequently withdrawn from the boiler, as in the case of locomotives, the steam room need not be relatively so great as when large volumes of steam are slowly withdrawn, in the case, for example, of paddle engines. The effect of withdrawing a large volume of steam from a confined space is to lower the pressure considerably; at the same time the water in the boiler has the temperature due to the higher pressure; consequently, when the pressure falls, the surplus heat in the water at once generates immense volumes of steam, which rushing to the surface carry large quantities of spray with them, and thus give rise to serious priming.

In ordinary practice we find that in Lancashire boilers the water occupies about three-fourths of the diameter of the boiler.

In marine boilers the proportion varies from $\frac{1}{6}$ to $\frac{1}{3}$ of the total shell capacity, according as they supply quick-running short-stroke screw engines, or slow and long stroke paddle engines. It should be borne in mind that when very steady running is required, and comparatively unskilled stoking is all that can be had, it is imperative that there should be not only a large steam room, but also a large water room to back it up with. The importance of a large cubic capacity of water as an equaliser of pressure lies in the fact that the specific heat of water is so high, that whenever the pressure tends to drop through the neglect of the firing, the immense store of heat in the water, at the temperature due to the higher pressure, is at once available for the immediate generation of steam.

THE STRENGTH OF BOILERS.

Hollow cylinder pressed from within.—In considering the strength of boilers the first point to be examined is the case of a hollow cylinder pressed from within. Let the circle (fig. 171) represent the transverse section of such a cylinder, which is supposed to be filled with steam of a pressure of P lbs. to the square inch. It is required to find the stress on the shell of the cylinder at any two points AA, diametrically opposite. It is evident that every inch of the circumference of the shell is subjected to a pressure acting radially outwards from the centre C, so that the total pressure acting on the semi-circumference of a ring one inch wide $=\pi \,.\, r \,.\, P$, where $r=$

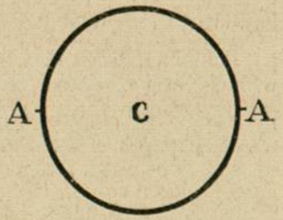

Fig. 171.

the radius in inches. The force, however, which tends to separate the metal at AA is not the whole radial pressure $\pi . r . P$, but the sum of the components of this force resolved in a direction at right angles to the diameter AA. The sum of these components on a ring one inch in width may be proved to be equal to the pressure on an area equal to the diameter of the circle ($2r$) multiplied by the width (one inch). Hence the sum $= 2rP$. The cross section of the metal at AA has, therefore, to sustain a tension $= 2rP$; or at either of these points separately, the tension $= rP$.

Let the thickness of the shell at A be t inches, and let the tensile strength of the metal be W lbs. per square inch; then the total strength of the ring at A per inch run of length of cylinder $= Wt$ lbs.; and when the boiler is on the point of bursting we must have $Wt = rP$, or $P = \frac{Wt}{r}$. In other words, the pressure P, which a cylindrical boiler will support, is directly proportional to the strength and thickness of the metal, and inversely proportional to the diameter. This reasoning applies only to the case of the thickness of the shell being small compared with the diameter; had the thickness at AA been considerable, as in the case of hydraulic presses and heavy guns, we should have had to argue in a different manner.

As an example, take the case of a cylindrical boiler of wrought iron of 6 feet diameter, the plates being $\frac{1}{2}$ an inch thick, and the steam pressure 80 lbs. per square inch, the tensile strength of the iron being 48,000 lbs. per square inch. We have $rP =$ the tension at any point in the circumference of the shell $= 3 \times 12 \times 80 = 2{,}880$ lbs. per inch of length. On the other hand, the strength of a ring one inch in length and half an inch thick is $\frac{48{,}000}{2} = 24{,}000$ lbs.; that is to say, the strength of the boiler in this case is about eight and a half times greater than the stress brought to bear upon it.

In actual practice, however, we could not take the full

strength of the metal, because the riveted joints are much weaker than the solid plate. The tensile strength of a double riveted joint, for such a boiler, would be about 34,000 lbs. per square inch, and consequently the strength of the boiler at the weakest part would be $\frac{34{,}000}{2} = 17{,}000$ lbs. per inch of length; that is to say, the strength would be about six times greater than the stress.

Factors of safety.—The number which expresses the ratio of the strength of a boiler to the working strain is called the factor of safety. Thus in the above example the factor of safety is six. The proper factor of safety is a point not yet fully settled. The number adopted by the Board of Trade for the shells of marine boilers, subject to their inspection, is five for the most favourable cases; that is to say, when materials, construction, and workmanship are all of the best. In Lancashire boilers the factor four is considered sufficient for the weakest strip in the boiler. The French Government has fixed three as the factor in land boilers, and this low number has been found to give perfect security.

In addition to the strength of the longitudinal section of a boiler we must also consider the case of the transverse or ring-shaped section. The stress in this instance is brought to bear by means of the pressure of the steam on the two ends, and tends to pull the shell out like a telescope.

No matter what the shape of the end, the pressure on it tending to pull the boiler in two is exactly the same as if the ends were flat. Taking, therefore, flat ends, and using the same symbols as before,

we have $\pi r^2 =$ the area of the end,

$\pi r^2 P =$ the total pressure on the area,

$2\pi r =$ the circumference of any transverse section,

and $2\pi rt =$ the area of such section.

The area $2\pi rt$ has, therefore, to sustain the pressure $\pi r^2 P$.

When the boiler is on the point of bursting in this manner we must have, therefore,

$\pi r^2 P = 2\pi r t W$. $\therefore P = \frac{2tW}{r}$, or $W = \frac{Pr}{2t}$, whereas in the former case we had $W = \frac{Pr}{t}$; that is to say, W, or the tensile strength of the metal, requires to be only half as great to resist the transverse stress as the longitudinal.

Taking the same example as before, we have the area of the end $= 3{\cdot}14159 \times (3 \times 12)^2 = 4071{\cdot}5$ square inches; while the pressure on the end $= 4071{\cdot}5 \times 80 = 325{,}720$ lbs. Now the area of the transverse section of the boiler to resist this stress$=3{\cdot}14159 \times 6 \times 12 \times \frac{1}{2} = 113{\cdot}1$ square inches, the tensile strength of which is 5,428,800 lbs.; that is to say, the strength is about sixteen and three quarter times greater than the stress brought to bear on it. As before, however, we cannot in practice consider the full strength of the plate, because all boilers are made up of two or more rings riveted together. On account, however, of the comparatively light load which the joints have to bear, it is not considered necessary to double rivet the joints. The strength of a single riveted joint in the above example would be only about 26,000 lbs. per square inch, and consequently the factor of safety would be between eight and nine. The transverse strength of a cylindrical boiler with internal furnaces is of course much greater than in the above example, for while the area of the ends is diminished by the transverse area of the furnace or flue, the section of metal which resists the stress is increased by the area of metal contained in a transverse section of the flue. The way in which the strength is calculated is so apparent from what has gone before that it is unnecessary to give another example. See also pp. 398–9.

Strength of riveted joints.—The principles of the construction of riveted joints are fully explained in the treatise on the 'Elements of Machine Design,' published in this series of text-books.[1] It is here only necessary to state that,

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[1] *Elements of Machine Design.* By W. C. Unwin.

according to Fairbairn's experiments, the strength of a single riveted joint when properly proportioned is 56 per cent. of the strength of the plate, and that of a double riveted joint 70 per cent. Fairbairn's experiments were made on plates $\frac{1}{4}$ inch in thickness, and it seems highly probable that with the much thicker plates now in use, and the consequent alteration in the pitch and proportions of the rivets, his figures can no longer be accepted as correct. They appear to err in representing the strength of the joint as being greater than it really is.

Single Riveted Joints.

Iron Plates, iron Rivets				Steel Plates, iron Rivets			
Thickness of Plates	Diameter of Rivets	Pitch of Rivets	Efficiency of Joints	Thickness of Plates	Diameter of Rivets	Pitch of Rivets	Efficiency of Joints
$\frac{5}{16}$	·670 = $\frac{11}{16}$	1·82 = $1\frac{13}{16}$	·621	$\frac{5}{16}$	$\frac{11}{16}$	1·54 = $1\frac{9}{16}$	·552
$\frac{3}{8}$	·735 = $\frac{3}{4}$	1·87 = $1\frac{7}{8}$	·606	$\frac{3}{8}$	$\frac{3}{4}$	1·58 = $1\frac{9}{16}$	·538
$\frac{7}{16}$	·790 = $\frac{13}{16}$	1·94 = $1\frac{15}{16}$	·598	$\frac{7}{16}$	$\frac{13}{16}$	1·66 = $1\frac{11}{16}$	·512
$\frac{1}{2}$	·849 = $\frac{7}{8}$	1·98 = 2	·571	$\frac{1}{2}$	$\frac{7}{8}$	1·70 = $1\frac{11}{16}$	·501
$\frac{5}{8}$	·949 = $\frac{15}{16}$	2·08 = $2\frac{1}{16}$	·543	$\frac{5}{8}$	$\frac{15}{16}$	1·80 = $1\frac{13}{16}$	·472
$\frac{3}{4}$	1·04 = $1\frac{1}{16}$	2·17 = $2\frac{3}{16}$	·521	$\frac{3}{4}$	$1\frac{1}{16}$	1·89 = $1\frac{7}{8}$	·450
$\frac{7}{8}$	1·12 = $1\frac{1}{8}$	2·25 = $2\frac{1}{4}$	·500	$\frac{7}{8}$	$1\frac{1}{8}$	1·97 = 2	·431
1	1·20 = $1\frac{1}{4}$	2·33 = $2\frac{5}{16}$	·485	1	$1\frac{1}{4}$	2·05 = $2\frac{1}{16}$	·415
Double Riveted Joints.							
$\frac{3}{8}$	$\frac{3}{4}$	3	·75	$\frac{3}{8}$	$\frac{3}{4}$	$2\frac{7}{16}$	·69
$\frac{7}{16}$	$\frac{13}{16}$	$3\frac{1}{16}$	·73	$\frac{7}{16}$	$\frac{13}{16}$	$2\frac{1}{2}$	·67
$\frac{1}{2}$	$\frac{7}{8}$	$3\frac{1}{8}$	·72	$\frac{1}{2}$	$\frac{7}{8}$	$2\frac{9}{16}$	·66
$\frac{9}{16}$	$\frac{7}{8}$	$3\frac{1}{8}$	·72	$\frac{9}{16}$	$\frac{7}{8}$	$2\frac{9}{16}$	·66
$\frac{5}{8}$	$\frac{15}{16}$	$3\frac{3}{16}$	·71	$\frac{5}{8}$	$\frac{15}{16}$	$2\frac{5}{8}$	·64
$\frac{3}{4}$	$1\frac{1}{16}$	$3\frac{5}{16}$	·69	$\frac{3}{4}$	$1\frac{1}{16}$	$2\frac{3}{4}$	·61
$\frac{7}{8}$	$1\frac{1}{8}$	$3\frac{3}{8}$	·66	$\frac{7}{8}$	$1\frac{1}{8}$	$2\frac{13}{16}$	·59
1	$1\frac{1}{4}$	$3\frac{1}{2}$	·64	1	$1\frac{1}{4}$	$2\frac{15}{16}$	·57