[No. 65.]

G.W.R. Mechanics' Institution, Swindon.

JUNIOR ENGINEERING SOCIETY.

TRANSACTIONS, 1905-6.

ORDINARY MEETING.—Tuesday, November 28th, 1905.
Chairman—Mr. G. H. Burrows, A.M.I.Mech.E.

"LOCOMOTIVE BOILER DESIGN,"

BY

H. C. RODDA (Member).

With Discussion.

In opening the meeting, the Chairman congratulated the Society upon its new Lecture Hall, which, through the kindness of the President, Mr. G. J. Churchward, had been furnished and fitted up in a most comfortable manner.

There were other rooms in the building, including an office for the Hon. Sec., a smoke room, lavatories, etc., and he suggested that the Hon. Sec. would show the members round the new premises at the close of the meeting.

The subject they had to consider that evening was a paper on "Locomotive Boiler Design." He reminded them that during last Session Mr. Dyer had read them a paper on the practical side, viz., Boiler Making, and he (the chairman) hoped that taking the two together, they would provide much useful information.

He then called upon Mr. Rodda to read his paper.

LOCOMOTIVE BOILER DESIGN.

The subject of boiler design and construction is a large and varied one, in fact, it has such a wide scope, that under ordinary circumstances it would not be an easy matter to choose a point at which to start. But considering that our chief concern is with the Locomotive Boiler, this paper deals with its design, to the exclusion of all others.

There is a general theory underlying the construction of boilers which is common to all types, and that is, the boiler should be constructed to suit its particular requirement with the greatest possible economy.

Having in view the present day requirements, *i.e.*, high pressure steam of a good quality and enough of it, only the best materials and workmanship obtainable should be employed, together with the strictest supervision. Without these essentials, when working under severe conditions, the boiler soon shows signs of failure, and is generally unreliable, whereas when well constructed it is soon found to be a good article and measures are taken accordingly for its preservation and long life.

The history of steam boilers makes interesting reading, but the purpose of this paper is to discuss the present day affairs of the subject. It should not be deleted from one's study, however, as it is a most valuable stepping stone to use when studying steam generation in all its branches.

The locomotive type boiler is standard for all locomotives, no other form having ever yet competed with it in thorough adaptation for this purpose.

Generally speaking, the structure of the boiler is made up of four parts. The inside firebox, which is usually made of such material as to effect the transfer of the heat of the fire as fully and as quickly as possible. The outside firebox, which, together with the inside firebox, forms one part of the receptacle for the boiling water and steam. The barrel, which is the chief vessel for the retention of the water and steam ; and the tubes, which besides adding considerably to the evaporative power of the boiler, serve as a passage for the products of combustion from the furnace to the chimney. These will be dealt with more fully later.

Since the engineer designs his engine to perform a certain amount, of work at a high economy, there should be no deficiency of steam, or want of heat ; neither should there be too great an excess of steam causing useless expenditure of fuel, but the boiler must be efficient and capable of, doing just a little more work than will be required of it ordinarily.

Whereas the designer of land engines can, generally, please himself as to the amount of room taken up by his engine, the designer of a locomotive is considerably handicapped for want of space wherewith to obtain the necessary power. For instance, there is a load gauge to consider, also the convenient disposal of the weight, of which the boiler is a considerable factor, being something between 20 per cent. to 30 per cent. of the total.

Looking at this from another point of view, these limitations may be called advantages, because the boiler must necessarily be designed on well defined lines, and, therefore, the details become more fully developed.

The chief points of good design can be easily prescribed and defined. They are fairly simple; and although frequent attempts are made to obtain improved results by varying the arrangement and design of heating surface, the best boilers of nearly all makers of acknowledged standing are practically equal in merit, although of such different forms.

The following are some of the points the engineer has to effect to obtain an efficient boiler:—1st to obtain as complete combustion as possible without permitting the products of combustion to become diluted by an excess of air; 2nd, to get the temperature of his furnace as high as possible; 3rd, that by so arranging his heating surfaces the heat available can be most completely taken up and utilised without checking the draught; 4th, the form of the boiler to be such that it can be constructed without mechanical difficulty or excessive expense, and aid the circulation of the water as much as possible; 5th, to withstand all strains put upon it either externally or internally, and the corroding elements of the atmosphere; and eventually not to be rendered useless by local defects; 6th, to make every part easy of access both for repairing and cleaning; 7th, to so proportion the boiler that a high factor of safety is the result; 8th, to provide efficient safety valves, steam gauges, etc., and intelligent and very careful management.

It is evident, then, that effective development, transfer and storage of heat in the best possible combination is what is demanded in the performance of the boiler. Also, as the power developed is derived from the form of energy called heat, and as this heat is obtained by the combustion of a fuel, it is essential that the principles involved and the natural laws relating thereto be clearly understood. This has more often than not been neglected in the past, with consequent inefficiency of the steaming plant. But of late years, engineers are generally waking up to the necessity of having a knowledge of the chemistry of steam raising.

Steam is obtained from water by the formation of bubbles, consequent upon the continued application of heat. These bubbles do not form on the surface of the water or the point of application of the heat only, but throughout the whole mass of boiling water, and rise to the surface. This action is very violent in steam boilers, and bubbles of steam rise so rapidly as often to carry considerable water in mechanical suspension into the steam. It occurs most frequently in poorly designed boilers or those that are forced beyond their capacity, also dirty ones; and is called "priming." The working surface of the water should therefore be placed in as unrestricted a place as possible; in fact, if the boiler were cut into successive horizontal laminations of equal thickness each area thus obtained should be greater than the one next below it, and so obtaining an easy separation of the steam from the water.

The heating surfaces should be so arranged that the whole of the water is got at and kept in motion by circulation, and that there be no "dead spots." The shape and general formation of the boiler should be such that there will be no liability for the formation of "pockets" of steam. This is important, because if not attended to serious damage may be the result, such as a burnt plate, or even an explosion.

In arranging heating surfaces the effort should be to impede the draught as little as possible, and so to place them that the circulation of water within the boiler should be free and rapid at every part reached by the hot gases. The directions of circulation of water on one side and of gas on the other side of the sheet should, wherever possible, be opposite. This, together with velocity, has been found by experiment to be the most effective method of transferring the heat from the fire to the water.

The most effective part of the heating surface is found to be located at and near the firebox tube plate, that is to say, the front and upper part of the firebox and the first two feet of tube surface transfer in the same time more heat than any other part of the heating surface.

This is, undoubtedly, due to the fact of the gases in the firebox impinging on the tube plate through the action of the draught. Thus nearly half the total heat is taken up by the firebox surfaces, and that part of the remainder which is utilised passes through the flues, the heating surfaces of which may be from ten to twenty times the size of the former. Fig. 1 shows the difference of evaporation at different parts of the boiler. As the surfaces in contact with the fire and gases are further away from the firebox, the transmission of heat decreases, following a geometrical progression. The surfaces increase in arithmetical progression. The quantity of heat transferred is proportional to the difference of temperature between the gases and the water, with clean plate surfaces. The diagram is obtained in the following manner: The base line represents the total heating surface. The firebox surface is shown by the first part, the remaining four parts being equal to one another and together representing the tube surface. The total

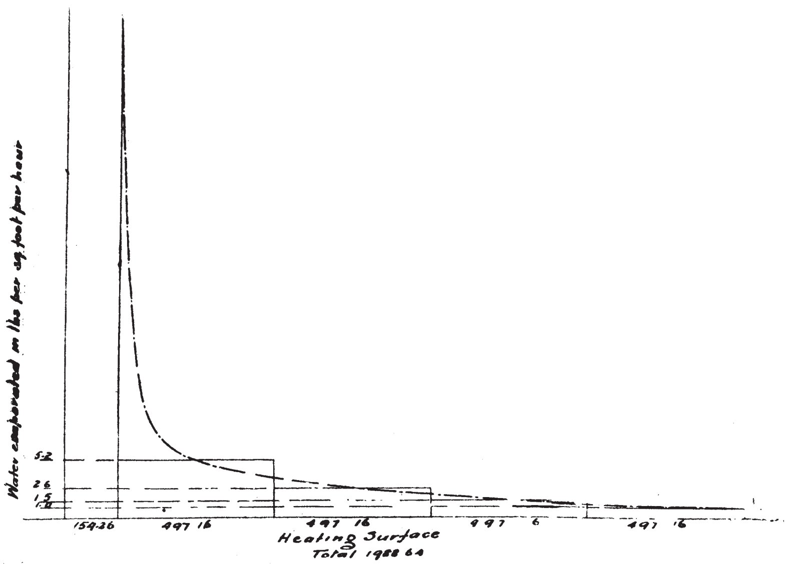

Fig. 1.

water evaporated is divided in a ratio, which was obtained by direct experiment on several locomotive boilers. The heating surface is that of the G.W.R. No. 1 standard boiler (see Fig. 2) and the water evaporated is by that boiler on an ordinary trip of, say, Paddington to Exeter, a distance of 193½ miles, with a cut off of about 25 per cent. The coal used on such a trip would be three tons, about 73lbs. per square foot of grate area per hour, or 6¼ lbs. of water evaporated per. lb. of coal. The total heat of combustion, as given by D. K. Clark in his book on steam (which may be taken as fairly reliable,) from an average of 37 samples of Welsh coal, is 15,123 units of heat per lb. of coal.

If these figures are used in conjunction with the figures on the diagram it will be found that the heat utilised is about 50 per cent., which is, comparatively speaking, a good performance for a locomotive boiler.

The question naturally arises at this point: How can the efficiency of the boiler be increased so that at least the amount of the lost heat is minimised?

This appears to be a difficult matter, but if a sound knowledge of the different stages of the evolution of steam is obtained the difficulty would soon begin to disappear and the necessary experiments then be conducted on scientific principles and their full value obtained and recognised.

In securing complete combustion, an ample supply of air and its thorough intermixture with the combustible elements of the fuel are essential; also for high temperature of furnace it is necessary that the air supply shall not be in excess of that absolutely needed to give complete combustion. It is also necessary to concentrate the heat in order to aid combustion. Concentration of heat in the furnace is secured in some cases by special appliances for heating either the combustible, the air supply, or both. On this particular point, however, detached firebrick furnaces have an advantage over the fireboxes of steam boilers in their higher temperature. Surrounding the fire with non-conducting and highly heated surfaces is an effective method of securing more perfect combustion and high furnace temperature. In the case of furnaces constructed entirely of firebrick surrounding the grate, supposing the material to be absolutely non-conducting, the whole of the heat radiated from the fuel is returned to it by counter radiation, so that the fire is placed in the same condition as if there were no heat radiated. The temperature of the gaseous products leaving the fuel would, therefore, be equal to the maximum temperature of combustion, since they would carry off the whole of the heat that would be generated. Thus it is that extremely high temperatures may be attained. In practice this condition of perfect non-conduction is far from being reached. There is also considerable loss of heat by external radiation.

Such an arrangement of course cannot be recommended for locomotive boilers using fuels which can be burned in an ordinary furnace. The more promptly the heat of combustion can be taken up by the boiler the more efficient is the evaporative performance. The conditions of the furnace in a steam boiler are different than that just stated, the heat that is radiated from the fire is but feebly reciprocated from the plate surfaces of the firebox, since those plates are maintained at a temperature not much higher than the water inside. Under these conditions the heat which is radiated from the fuel upon the plate, together with the heat which is communicated by convection by the heated gases, is rapidly absorbed and carried off. It is, therefore, impossible to maintain in the firebox of a locomotive a temperature even near the maximum temperature of combustion.

The temperature of the complete combustion of the coal of average composition is about 5000°F on the condition that the whole of the atmospheric oxygen admitted is completely used up. It is naturally lower than this when free or surplus air is present and included in the gaseous products. The addition of a brick arch in a furnace is of considerable importance in that the counter-radiation of the heat of the underside to the fire considerably helps combustion and raises the furnace temperature. As to the size and inclination of the brick arch, it will generally be found necessary to obtain these by direct experiment.

By combustion is meant "chemical union," and in general this union is productive of heat. It is a union between a combustible or fuel and a supporter of combustion, and the only one which comes within the sphere of this paper is the oxygen contained in the atmosphere.

The principal fuels are coal, wood, gas and oil. The chief constituents of these fuels are carbon and hydrogen, but their characteristics and modes of entering into combustion are very different. The carbon is oxidised to carbon dioxide, the hydrogen to water or steam, sulphur to sulphurous or sulphuric acid, and any other elements, commonly called impurities, to their respective oxides. A fresh charge of coal when thrown on the fire in an active state becomes a great absorbent of heat. This apparent loss of heat is utilized in volatilizing the bituminous portion, and is a very cooling process due to the change of sensible into latent heat.

While this generation of the gases is taking place the carbonaceous part remains black, or at a low temperature, awaiting the proper time for it to burn. If the bituminous portion be not utilized in the gaseous state for the production of heat, it becomes a total loss, and were better absent, as then all the latent heat would have been available. It is due to this fact that the bituminous coals do not give such an intense heat as the anthracites. In order to effect complete combustion, the particles composing the gaseous and carbonaceous portions of the fuel must be brought into thorough contact with the oxygen of the air supplied. The great difficulty is the proper mixing of the gases.

If all the carbon is burned to carbon dioxide, there must be an excess of air passing through the furnace. If all the carbon is not burned in the short time allowed with a powerful draught such as is usually obtained from the exhaust of an engine, due to a lack of mixture or to a deficiency of air, the carbon is wasted as carbon monoxide, or half burnt carbon, which is commonly called smoke.

If once smoke be produced, it will be a difficult matter to consume it. It is not so difficult to burn coal without producing smoke by a proper admixture of air, introduced in suitable proportions and in a manner to bring the particles of carbon in contact with the oxygen when at high temperature. But under the circumstances of locomotive firing smoke will be produced, no matter how much the fireman tries to prevent it.

This, then, is the real result that should be accomplished. No definite rule can be laid down for the admission of air so as to burn all kinds of coal without producing smoke, as each variety of coal has its peculiar qualities and as so much depends on the design of furnace grate, nearness of heating surfaces, and strength of draught.

What is desired is that the air be thoroughly mixed with the particles of fuel before the latter are too much cooled by contact with the boiler surfaces. For some bituminous coals, a supply of air admitted above the grate and also behind the bridge wall is often desirable and necessary.

Mr. Webb, late Superintendent of the L. & N.W.R., went so far as to split up the length of the tubes into two parts, and placed a combustion chamber between them.

In the intense heat of a fiercely burning fire, the bituminous coals are vaporised with such great rapidity that it is practically impossible to burn all the gaseous portion before it flies to the chimney and passes beyond the reach of combustion. Of all the different kinds of furnaces designed for various purposes the most persistent smoker is that belonging to the locomotive steam boiler.

The reason is obvious, as there are no walls to radiate back the heat and thus aid combustion. The object of the boiler is to rob the fuel of its heat as quickly as possible, therefore every particle of gas and carbon that comes into contact with the plate surfaces is cooled below the temperature of perfect union and must be drawn into the chimney in its unburned condition, surplus air or not, and must add to the volume of smoke. It will now be generally conceded that the firebox or furnace is by far the most important part of the boiler or, in fact, of the engine, therefore it should have the first and foremost attention paid to it in the design.

The efficiency of a furnace burning fuel completely is measured by $E = \frac{T-C}{T-A}$, in which E = efficiency, and represents the ratio of heat utilised to the whole calorific value of the fuel. T is the furnace temperature; C is the temperature of the chimney, and A that of the external air. Hence, the higher the furnace temperature and the lower that of the chimney the greater is the proportion of heat available. It is further evident that, however perfect the combustion, no heat can be utilised if either the temperature of the chimney approximates to that of the furnace, or if the temperature of the furnace is reduced by dilution to approximately that of the chimney. The question of air supply is an important one, as will already have been noted. All engines are provided with an ashpan having a damper or door provided at either end for the regulation of the air to the underside of the fire. It also serves the purpose, as its name implies, of catching the ashes that happen to fall through the grate, and thus prevent them from falling on to and damaging the permanent way.

On some of the older ash pans a pipe was attached, through which water or steam could be admitted. This was supposed to answer the double purpose of cooling the ashes and increasing the efficiency of the furnace. Instead, however, of doing the latter, the steam actually robbed the furnace of some of its heat and passed through the flues without giving all that heat back again. In regard to the design of the grate for the purpose of air regulation, care should be taken that the air can get at every part of the fire, and so prevent dead or stagnated parts. The usual kind of firegrate has about 30 to 40 per cent. of air space to total grate area. The bars are made to rest longitudinally to the firebox on crossbars or racks. The ends of these bars are also thickened, and on either side of the end an amount equal to half the width of the air space is provided, then when the bars are laid side by side the full amount of air space is obtained without any trouble. Some grates are made to fit fairly close to the firebox, only allowing for the usual amount of expansion, and the space left is then plastered up with fire clay. It is a well-known fact that there is a thin layer of air between the furnace gases and the sides of the firebox, so, probably, it is with the idea to prevent this kind of thing that the plastering is done. At any rate, it is an idea that is not generally adopted.

The grate of the No. 1 Boiler has an air space of 55 per cent. out of a total of 27 square feet area. There is no doubt about this being a decided advantage, because, if the engine has to be forced at any time, there will be plenty of room for the air to get through. Perhaps a short description of this grate will not be out of place here. The firebars are of wrought iron, 5 inches deep, $\frac{9}{16}$ inch thick on the top, and $\frac{5}{16}$ inch thick on the bottom. There is a $\frac{7}{16}$ inch air space between the bars. They are carried on crossbars, or racks, which are shaped like a comb. It will be noticed that the teeth of the racks taper towards the point and that they do not reach the tops of the bars by half an inch, being only $4\frac{1}{2}$ inches long. Also, that the ends of the bars do not touch one another, as is usually the case in other grates. The front portion is carried on a shaft, so that it can be dropped down out of the way whenever it is necessary to clean the fire. This is worked by a wheel and screw placed on the right hand side of the engine.

The grate area depends largely on the kind of fuel to be used. For instance, some locomotives in America are used in a district where wood is plentiful, therefore their furnaces are designed to burn wood, which necessitates a large firebox. Hence, the very wide fireboxes which are known as the Wootton type, and which are sometimes supplied with two fire-hole doors.

It remains now to fix the amount of flue area. This is the cross-sectional area of all the flue tubes, and should be of such a size as to cause the gases to have a considerable velocity in their passage through the tubes. There is a reason for this, it having been found by experiment that more heat will be given up at a high velocity than at a low one, especially if the flow of the water on the one side is in an opposite direction to the flow of the gases on the other side. This is owing probably to the increased scrubbing action that takes place. The flue

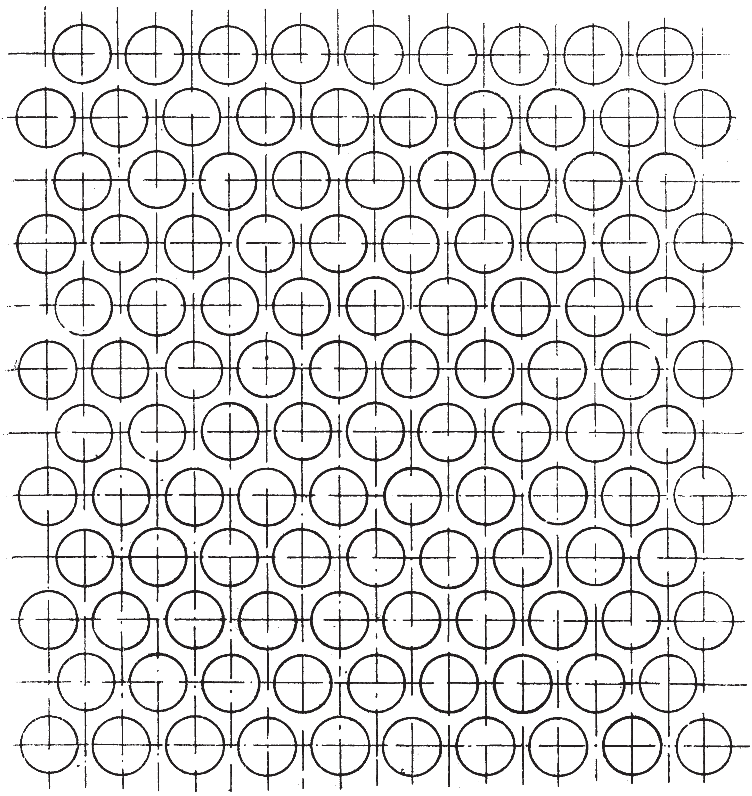

Fig. 3.

area must not be made so small, however, that the draught is checked. The tubes should be about $\frac{1}{60}$th to $\frac{1}{90}$th of their length in diameter. The arrangement of the spacing of the tubes is a subject for considerable diversity of opinion, but in most good types of boiler it is usual to employ the vertical and horizontal spacing. The horizontal spacing is of minor importance compared with the vertical. In the vertical arrangement of spacing the tubes are placed directly over each other in preference to being placed zigzag (see Fig. 3). The latter was once in great favour, the idea probably originating in the belief that an intercepted current would help the water to take up more heat on its way upward than if it proceeded directly to the water surface, as would be the case if the tubes were placed in vertical rows. The tubes should be so spaced that they are farther away from the barrel at the sides than at the bottom. In this way the downward flow of the water is facilitated.

The shape of the perimeter, then, being fixed, together with the length of tube and the distance between the tubes, it is obvious that if an increase in the heating surface is required some other method than altering these must be found. This can be done by decreasing the diameter and increasing the number of tubes down to a certain limit, after which the heating surface will decrease. Serve tubes have been tried with this object in view, and they appear to have found favour with a large number of manufacturers. A Serve tube is merely an ordinary tube with a number of ribs, generally an odd number, running longitudinally for the whole length inside the tubes. They are supposed to take up more heat from the passing gases, because they expose more surface to these gases.

Some people put retarders in the tubes. They are simply flat strips of some metal twisted into a spiral. The idea is to cause the gases to have a greater scouring action on the surfaces of the tubes. The tubes should not be placed so close that the water is restricted in its passage upward, neither should they be placed so far apart that there is too large a mass of water between them, thereby losing some of their effectiveness. They can with advantage be spaced further apart at the firebox end than at the smokebox end, because the circulation is considerably more violent at the former. Some makers give to their tubes an upward camber, probably with the idea of giving the firebox a chance to "breathe."

There are various methods in vogue for fixing the tubes into the tube plates. These are more or less effective. The principal object should be to make them steam tight and keep them so under working conditions; and any method which can be found to satisfy both of these is sure to be widely adopted. A common method of fixing is to fit a ferrule into the tube at the firebox end and then expand it with a tube expander, and merely to expand the smokebox end. Sometimes both ends of the tube are enlarged to enable the tubes to be got out easily, sometimes only one. Another method of fixing or securing is to leave the ferrule out and simply expand both ends and bead at the firebox end. Still another is to bead the tube on either side of the plate as well as expand it. It is necessary in all cases that the firebox end of the tube should be beaded or hammered over, otherwise a ragged edge would be left exposed to the fire, which would quickly burn away, with consequent leakage of the tubes. All these ideas are very well in their way, but it must be remembered that the tubes have to come out again and with little or no damage to the tube plate, which is an expensive article to replace. In past years brass was almost universally used for the boiler tubes. Steel and iron tubes were said to corrode too quickly in boilers that were frequently being emptied. Nowadays, however, probably owing to the improved conditions of manufacture, brass tubes have been almost entirely superseded by solid drawn steel tubes, which are finding a considerable amount of favour.

With regard to the kind of material to be used for the inside firebox, it is the practice in America to use mild steel to the exclusion of every other metal. The reason why had perhaps better be left to the Americans to explain. It was stated before this Society at a previous lecture that two steel fireboxes which were tried on G.W. boilers soon came to grief, owing to unexplained causes. This probably being looked upon as an object lesson, it is worthy of note that copper is now, and has been since then, at any rate, the only material that is used on the G.W.R. In fact it is the common practice with all British firms to use copper. It wears better under the intense heat of the furnace, and gives a higher evaporative efficiency. As is well known, it is very ductile and malleable, and can therefore be worked with great ease; it will also stand a considerable amount of straining action. The rates of the co-efficients of expansion for copper and iron or steel is about three to two respectively, and it is probably due to a knowledge of this that incited many persons to try to overcome the trouble of broken stays by inventing so called flexible stays. There is probably a legion of flexible stays, the majority of which are fixed rigidly to one or the other plate by being screwed into it, the end being then hammered over. Such a stay is perfectly flexible while held in the hand, but when put into place and fixed, it becomes but little better than an ordinary rigid stay. The cause of the breakage of the stays is the unequal expansion of the plates and the short length in the stay to take the consequent bending.

The designer or practical boilermaker has yet to be found who can successfully cope with these difficulties. As regards the pitching or distance apart of the stays, that of course depends on the boiler pressure and the working tensile strength of the material to be used, which should never be exceeded. Care must be taken to place them a short distance from the corners, vertically, of the firebox, to give the firebox a chance to breath. The common form of rigid stay, usually made of copper, but sometimes of iron, is a straight bar screwed into the two plates and the projecting ends hammered over, either by hand or machine according to the facilities afforded in the shop. Perhaps the relative merits of hand over the machine beading will be more fully discussed if left in the hands of practical men who are fully conversant with the matter. The staying of the crown of the firebox is a matter which requires a good deal of attention, owing to the complex nature of the subject.

The crown of the inside firebox is always made flat, so that it shall not become liable to be burnt when the water is getting low, and to increase the heating surface.

The crown of the outside firebox is sometimes round and sometimes flat. With flat or Belpaire fireboxes the two crowns can be stayed to one another with stay bolts or bars in the ordinary way, because the two pressures nearly equalise one another. The distance between the two plates may be anything between one and two feet, so that the horizontal movement of the firebox is easily taken up in the length of the stay. Also it will be noticed that on all Belpaire fireboxes the corners are all made with good large curves. These are a necessity, as they help considerably towards taking up the difference in the vertical movement of the two boxes. With a round topped firebox, however, matters are different. The movement of the inside box cannot be effectually taken up by the round outside crown, unless very elaborate means are provided. This kind of thing is not wanted in a boiler—the simpler method being the better. Therefore, provision has to be made whereby the staying of the inside crown is practically independent of the outside crown, although they are always attached to one another in some way.

The movements of the inside firebox are due to the changes of temperature in the combustion chamber. This temperature varies to a great extent, the variations at times being very sudden and covering a great range. At one moment an engine is dragging a heavy train at a high speed with a fire urged by a fierce blast and fed by a strong draught from below. Under such conditions the furnace is developing the maximum heat it is capable of producing. The next moment steam is shut off and the blast ceases; the damper is shut and there is no draught from below, all possible means being used to check the heat and prevent the generation of steam not then required for working the engine. It is easy to see then that the movements of the inside box will be considerable. There are various ways of securely staying the crown of the box, which are more or less effective. Care must be taken that the circulation of the water is not interrupted, and that the plate itself can be kept thoroughly clean and free from dirt and scale by being washed out. One very common method in use is to support the plate by a series of girders running longitudinally across the firebox and resting on the front and back plate, the plate itself being held to it by a ferrule or distance piece between the girder and plate, and a bolt put through the plate and tapped into the underside of the girder. Two or four of these girders are then attached to the outside firebox with links carried in suitable brackets, the links having long holes in them to allow for the upward movement of the inside box. On some of the older American boilers these girders, or crown bars, were placed transversely across the firebox. It would be interesting to know the reason for this, seeing that it considerably interrupts the passage of the water from the back to the front of the box. In the case of a Belpaire firebox it is also necessary to stay horizontally the rectangular portion above the inside box. This is done by passing stays through the two plates by screwing them and then securing them on the outside with nuts. The back head is treated in the same way, with the exception that the stays and boiler mountings have to be placed with advantage to each other. These stays are fastened at the other end in various ways according to the shape of the boiler. Sometimes they are fastened to the sides of the firebox, being then called palm stays, and sometimes they go right through to the other end of the boiler and support the upper part of the tube plate at that end. This kind of staying is probably better for locomotive boilers than would be the use of gusset stays, which take up a large amount of the room necessary for the boiler mountings. Now as to the size of a boiler required for a certain amount of work. It will be useful here to mention a few suggestions or points to be observed regarding the general proportions of such a boiler. The designer must obtain then: Sufficient grate area to burn the available fuel with the usual draught; suitable combustion space to properly burn the gases; sufficient area of tubes to carry off the products of combustion; sufficient heating surfaces to absorb the heat generated; proper water space to prevent too great a fluctuation of the water level when there is an irregular demand for steam; suitable steam space to prevent too great a fluctuation of steam pressure when steam is taken at intervals, as for the cylinders of a steam engine; sufficient free water area for the disengagement of the steam. A problem for design will perhaps be appreciated here.

Let it be required to determine the main dimensions and some details of a boiler to develop 400 H.P. The American Society of Mechanical Engineers have decided that the evaporation of 34·5 lbs. of water per hour from and at 212°F. is equivalent to the development of 1 H.P. Let the working pressure be 200 lbs. per square inch. Assume that coal of an average quality will be used, and that it will give an equivalent evaporation of 7 lbs. of water per lb. of coal from and at 212°F. Assume further, that 75 lbs. of coal will be burned per square foot of grate per hour. These figures will be evolved after due deliberation, resulting from observation or experiment.

Heating Surface.—The heating surfaces may be made in accordance with an average of 30 boilers of similar type which have been illustrated in the engineering journals within the last twelve months. This will represent up-to-date practice. It is 66 times larger than the grate area. Let 70 times the grate area then be adopted. The diameter of the tubes have already been stated to be from $\frac{1}{60}$th to $\frac{1}{90}$th of their length. The cross-sectional area should be about $\frac{1}{6\cdot5}$ of the grate area.

Grate Area.—The total equivalent evaporation will consequently be

400 H.P. × 34·5 = 13,800 lbs. of water per hour. With an equivalent evaporation of 7 lbs. of water per lb. of coal, the coal burned will be 13,800 ÷ 7 = 1,971·5 lbs. per hour. With a rate of combustion of 75 lbs. of coal per square foot of grate per hour, the grate area must be 1,971·5 ÷ 75 = 263 square feet. The cross-sectional area of the tubes will be 263 ÷ 65 = 4·04 square feet. Now as to the amount of steam space. A good rule for this type of boiler is to allow about ·25 cubic feet of steam space per H.P. A more logical way appears to be to proportion the steam space to the rate of steam consumption by the engine. The capacity of the steam space is sometimes equal to the volume of steam consumed by the engine in 20 secs. It was found in some experiments with marine boilers having a working pressure less than 50 lbs per square inch, that a considerable quantity of water was carried away by the steam when the steam space was made equal to the volume of steam consumed in 12 secs., but that no water was carried into the cylinders when the steam space was made equal to the volume of steam consumed in 15 secs., and that no trouble from water was ever experienced when the steam space was proportioned for 20 secs. A volume equal to a 6 secs. supply is found to be a minimum for locomotive boilers. The working pressure in question is 200 lbs. per square inch. Therefore, under the foregoing conclusions, it will be safe to assume that no trouble will be experienced if the steam space is taken as equal to the volume used in 15 secs.

Diameter of Boiler.—The steam space is commonly made one-third and the water space two-thirds of the contents of the boiler. To this must be added the space occupied by the tubes. Then the total volume, minus a proportion for the firebox ÷ the length = the cross-sectional area, from which the diameter will be found. This will be subject to the structural conditions of the engine, as also the other principal dimensions will be. It had now, perhaps, better be left in the hands of the designer to develop.

DISCUSSION.

In opening the debate, the Chairman said that in the design of a locomotive boiler, one of the most important considerations was the necessary provision for the passage of dry steam to the cylinders.

In the No. 1 standard boiler (Fig 2), it would be noticed that the steam was taken from the space above the top of the firebox, an area of about 45 square feet. The old method was to take steam from the dome, which has a relatively small area, about three square feet. The ratio diameter of the tubes to the length was another important point. A case occurred where a set of boilers which originally had $1\frac{5}{8}''$ tubes were altered to $1\frac{7}{8}''$, but it was found that the boilers would not steam. The ratio was 70 to 1. The boilers were refitted with $1\frac{5}{8}''$ tubes, and the subsequent working was entirely satisfactory, the ratio then being 85 to 1.

Mr. W. O. Chalk then asked the author the ratio to be obtained between the tube heating surface and the grate area. In reply Mr. Rodda said that this particular ratio worked out to about 60 to 1 on the 30 boilers mentioned in his paper. It was a ratio that varied a good deal in different boilers, because the grate area depended on the quality of the coal to be used, and the tube heating surface on the size of the boiler required.

Mr. R. H. Smith referring to the No. 1 boiler, said he had had a considerable amount of experience with it, and found it to be a very efficient boiler. With a train of 350 tons, and running from London to Bristol in two hours, maintaining steam as it did, was considered a fine performance. In this particular run they used a fair quality of coal, which was thrown on to the fire in a proper manner to suit its particular nature. He thought the boiler showed superiority over other boilers, as it was such a good generator of steam. No doubt the French engine had as good a tractive power, but allowing it to take the same weight train, it was found that it did not keep in time and used more water, showing at once the reason to be inferiority in boiler as compared with the G.W.R. No. 1 boiler.

Mr. A. H. Nash referred to the fairly high factor of safety required by the Board of Trade. He considered that since there was such rigid supervision in the selection and inspection of material used in the construction of the boilers, and the workmanship of the best quality, the factor might be something less than five. In reply Mr. Rodda said that the factor of safety was at present in dispute. It must be remembered that the factor required by the Board of Trade was decided years ago, when the manufacture of materials was not nearly so good as it is now.

The necessary calculations should be made on the weakest part of the boiler, which is usually the joint, and not on the shell plating. In the No. 1 boiler they had a fairly high efficiency, viz: 82 per cent at the treble rivetted joints. There were of course several styles of joints. The strongest that had been made was a sextuple rivetted double welted butt joint, the inside plate tapering off till the outside row contained only one rivet. This joint gave an efficiency of 96%. The usual figure for the factor of safety employed by the G.W.R. was between 4·5 and 5. A later idea was to dispense with joints in the barrel by making the plates seamless. This was done by taking a steel ingot of known volume and forcing a hydraulic ram through it, afterwards rolling to the required dimensions. It is claimed that the plate is not so liable to be damaged during the construction, it is stronger and better able to withstand the stresses and, having no joint, the designer is able to calculate on its full strength, and use thinner plates.

Mr. C. T. Cuss, in referring to the drawing of the No. 1 boiler, said he noticed the taper of the barrel ran from one end to the other. Could Mr. Rodda enlighten him as to why this was done in preference to the older method of carrying the taper through the first barrel plate only. Mr. Rodda said that it gave an increased steam and water space.

The Chairman said the principal object of the continuous taper was to obtain a better flow of water to the firebox.

Mr. Rodda, in answer to Mr. Cuss, said the plate is first cut to shape and then rolled, and so well is the cutting and rolling done that the ends are not touched afterwards.

Mr. J. H. Shepherd said the Vanderbilt boiler was largely adopted in America and on the Continent, and asked if there was any advantage in this type over the Locomotive pattern, such as the No. 1. Long and wide fireboxes were being used pretty freely in some parts of America, and he asked if this was an advantage, and if so, why they were not more generally adopted.

Mr. Rodda, replying, said the Vanderbilt boiler was originally built for the purpose of burning oil, and the relative advantage or otherwise would naturally depend on the facility for obtaining the necessary fuel. With regard to the long and wide fireboxes, these boxes were made to suit the different kinds of low grade fuel which was to be found in abundance in various parts of America. Where peat, straw and wood were used, large fireboxes were essential.

Mr. R H. Smith then invited Mr. Rodda to describe an old drawing of one of the original broad gauge boilers. In acceding, the Author said he had placed the drawing of the boiler before them to compare it with the drawing of No. 1 standard boiler, which was also being shown.

The two drawings side by side spoke volumes, not only in design, but in general construction and also in draughtsmanship. The boiler in question had a barrel 10 feet long and made up of one plate. The firebox had a waterspace or diaphragm running transversely across it from the foundation ring to the level of the firehole, which was placed as high as it was possible to get it in the inside firebox. The fuel in use at that time was coke, which necessitated the firehole being placed in such a position. The top of the outside firebox was dome-shaped, from which the steam was taken by a trumpet-shaped pipe enclosed in a perforated plate. The front of the firebox was rigidly fixed to the frames of the engines, as also was the smokebox to the cylinders. The drag gear was also rigidly fixed to the back of the firebox. This would seem rather startling nowadays.

Mr. Chalk: Have hollow steel or bronze stays ever been tried in G.W.R. boilers?

Mr. Rodda, replying to Mr. Chalk, said hollow steel stays had not been tried, but bronze and copper manganese stays had been tried with poor results. Copper manganese stays had been tried in some boilers in the north of France, and appeared to give very satisfactory results, which was quite different to experience here. They were put at the top of the water leg, where the greatest difference in expansion was to be found, and along the bottom, where the stays were most liable to break because of overheating due to excessive incrustation, and it was reported that hardly any of them failed. Mr. Webb of the L. & N.W.R., carried out an exhaustive series of experiments with not very good results. The present G.W.R. practice was to use copper stays exclusively.

Mr. Gabb asked why the brick arch was very seldom used in America?

Mr. Rodda replied that to renew a brick arch a considerable amount of time was taken up, first, in cooling the boiler (which should not be done rapidly,) to enable a person to get inside the firebox to work, and second in allowing the fire-clay to set gradually. This occupied too much time for the Americans who, rather than go to the trouble of renewing or even building a brick arch, preferred to consume a little more fuel, and he was sure that the consumption of fuel was of little importance to them.

Mr. Nash mentioned the experiments made at Wigan, and wished to know whether there was any advantage to be derived from the use of Serve tubes over plain tubes. Mr. Rodda said that although Serve tubes had a much greater heat absorbing surface, they were not so efficient per square foot of heat distributing surface as plain tubes. It is well known that radiant heat is the most effective for transference through the plates and tubes, and for that reason many people put retarders in their tubes. These get hot through contact with the gases, and consequently radiate that heat to the tubes, thereby obtaining increased efficiency. There was one point against Serve tubes and that was their rigidity, they were continually grooving and pitting on the under-side between the ends of the ribs and the plate to which they were fastened owing to expansion and contraction.

In answer to Mr. Bowers, the Author said that melloid plates were a failure; in some cases they had been eaten away to such an extent that the head of the rivet was left standing clear of the plate. In concluding the discussion, the Author gave some interesting figures relating to conductivity. He explained the great difficulty in arriving at a comparative figure, for the relative conductivities of heat of copper, scale and oil. Scale and oil was the chief source of annoyance to engineers in the care and preservation of boilers. Roughly speaking, the comparative figures of scale and oil to copper is as 1·10 and 1·32 respectively, or 1″ of scale is equal to about 70″ to 100″ of copper, according to the former's consistency and $\frac{1}{32}$″ of petroleum is equal to about 10″ of copper.

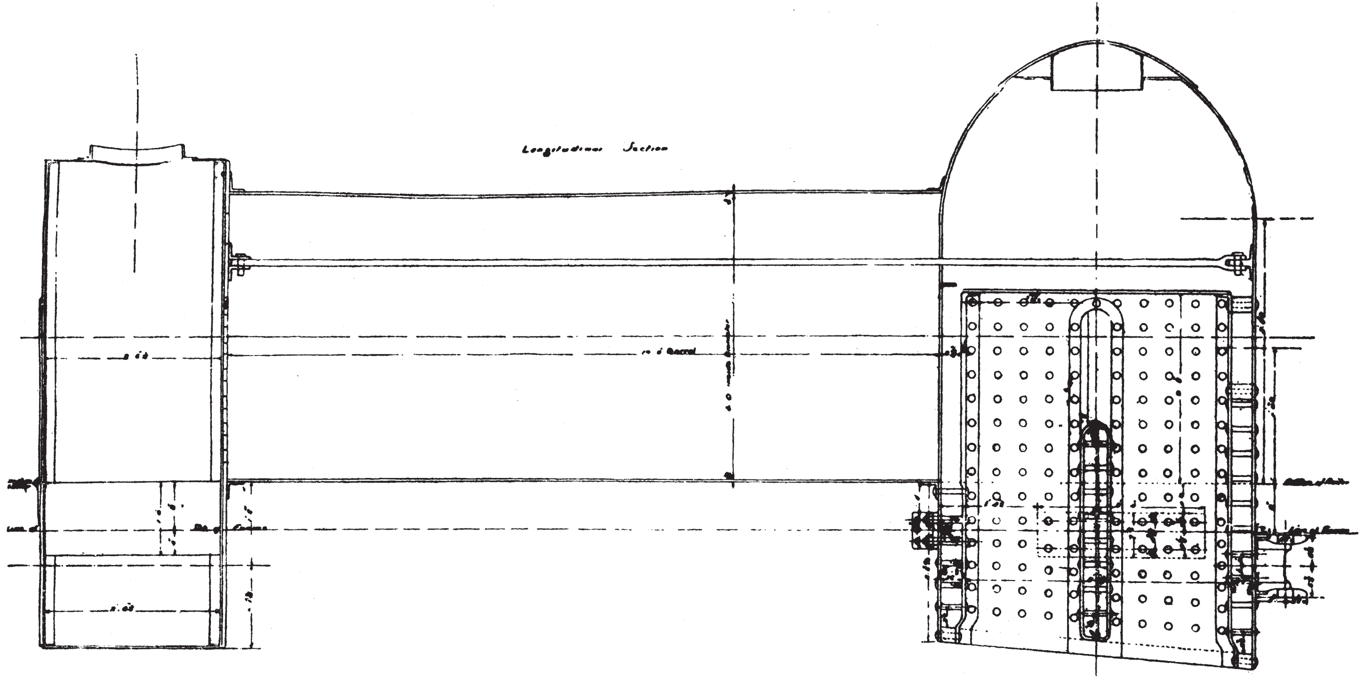

Fig. 4.

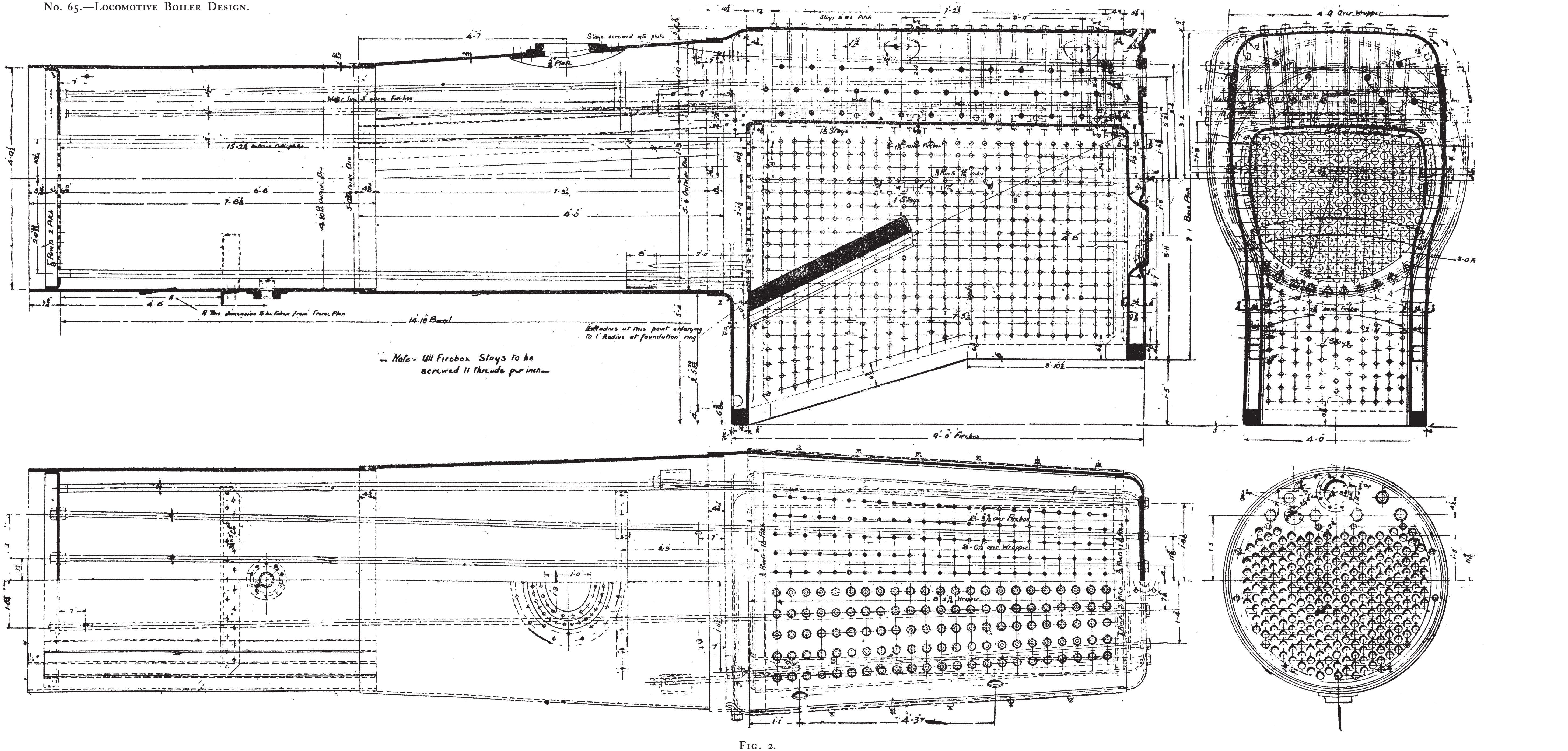
Note:- All Firebox Stays to be screwed 11 threads per inch
14-10 Barrel
9-0 Firebox
4-0
4-9 Over Wrapper
Water line 5" above Firebox
Stays screwed into plate
A This dimension to be taken from Frame Plan

Fig. 2.