Marine Boilers for Main Propulsion

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After a brief reference to recent trends and developments in marine steam turbine plants, boiler designs of both the two-drum and the radiant type are presented, the latter being a comparatively recent development in the marine field. Particular emphasis is placed on the importance of correct furnace and superheater design and the effect of various factors involved is discussed. Combustion with low excess air and the inclusion of reheat in marine plants are considered and the results of studies to determine the optimum boiler efficiency are mentioned.

INTRODUCTION

In the last five years considerable effort has been made by designers of marine steam machinery to improve their product. Initial cost, maintenance costs and overall fuel consumption have been reduced and automation has been simplified. The progress has been such that steam machinery can be shown to be more economical than Diesel at very much lower powers than was possible five years ago.

The point at which this occurs cannot be shown precisely as each vessel has its own peculiar trading requirements and the financial backgrounds to initial costs and fuel and running costs vary from company to company. Also, the initial costs will vary from shipyard to shipyard, and the operating experience of available personnel must be considered. However, the trend indicated by recent studies is shown in Fig. 1, but it must be emphasized that this is only a trend and, in any case, there is a degree of overlapping where the advantages of different types of machinery are marginal.

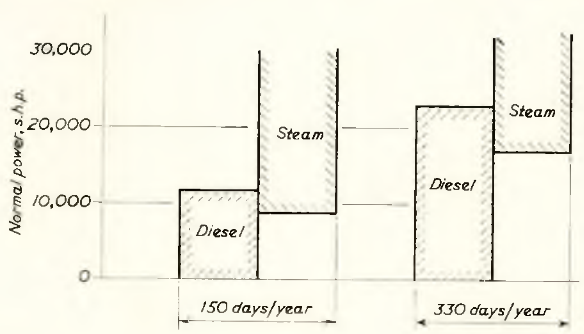

FIG. 1—*Shaded areas indicate range over which steam turbines, alternatively Diesel engines are likely to show a better overall economy when the time spent at normal power is 150 or 330 days/year*

The improvement in the position of steam machinery is due partly to increased efficiency and reduced cost of components, but also to the closer integration of the various parts of the plant, which permits the optimum choice of cycle, steam conditions and efficiency for each proposal. For vessels spending the majority of their life at sea a high efficiency plant is required while, as the proportion of time in port increases, efficiency is sacrificed to give significant reductions in initial cost, space, weight and complexity.

There has been a modest increase in boiler efficiency over recent years and currently boilers are being offered for more advanced steam conditions requiring less maintenance and at a lower cost per s.h.p. The boiler designer also assists in the integration of the machinery design by providing data on the effect of changes in cycle and steam conditions on the price and optimum efficiency of the boiler plant.

For main propulsion, two basic types of boiler are offered, namely, the well-known "Two-drum" type and the "Radiant" type. The radiant boiler has been used for many years in stationary plants but has only recently been developed for marine purposes. A variety of alternative features can be included in both types to suit particular applications.

TWO-DRUM BOILERS

In 1962, a paper(1) reviewing the development of two-drum boilers was presented to the Institute. Since that time, superheater design has been refined and, recently, the use of membrane tube walls has been considered. Also, a more logical approach to furnace design and the importance of improved combustion have become more widely accepted.

It has been thought for some time that any of the following features might help to reduce, remove or eliminate the bonded deposits which can be formed on superheater tubes when burning unfavourable fuels:

1) increase in furnace size;
2) improved combustion equipment;
3) an increase in superheater tube pitch, providing wider gas lanes and lower gas velocities;
4) series superheaters, i.e., a primary superheater arranged immediately after the screen tubes followed by a secondary superheater in the lower gas temperature zone after the primary superheater;
5) a reduction in gas velocity over superheater tubes;
6) use of long retractable soot blowers;
7) reduction in depth of banks of superheater tubes.

Items 1) and 2) would improve combustion at normal load which has been shown to reduce the rate at which the deposits build up. Item 3) would not in itself prevent bonded deposits but, if taken far enough, would prevent them from bridging between adjacent superheater tubes. Item 3) might also increase the effectiveness of the soot blowers unless very wide pitches were used. Items 4) and 5) were expected to reduce, if not eliminate, the problem and items 6) and 7) would assist the removal of any deposits formed.

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Experience in recent years supports these general principles but, while each of these features may, in itself, be advantageous, the combination of them can tend to defeat the object. For example, items 1) and 4) will require more rows of superheater tubes and, therefore, soot blowers will be less effective. Item 3) will also increase the number of rows required and, although the gaps are wider, the net result may also be a reduction in the effectiveness of the soot blowers. These effects are accentuated on the deeper superheaters required for higher steam temperatures. They could be overcome by including more access spaces and soot blowers but, in two-drum boilers, this gives rise to constructional problems and replacement of superheater tubes is more difficult.

Due to the serious troubles experienced some years ago with bonded deposits and still occurring in many ships with older designs, there has been an understandable tendency on the part of boilermakers to "over design" and on the part of owners and consultants to "over specify" with respect to furnace volume and superheater tube pitch, but the importance of the depth of the tube banks has received less attention.

Long Retractable Soot Blowers

The positions where bonded deposits might occur are always associated with high gas temperatures and long retractable soot blowers are essential, as no other type has been shown to be effective and corrosion of soot blower elements and bearings is avoided. Many boilers fitted with long retractable soot blowers are operating on unfavourable fuel for periods of between nine and eighteen months without water washing. Similar units which also have Y-jet steam atomizing burners are steaming indefinitely without water washing. In many cases these boilers have $1\frac{1}{4}$in. o.d. superheater tubes on $1\frac{3}{4}$in. pitch but they are designed for steam temperatures below 860 deg. F. (460 deg. C.) and none has more than three rows of superheater tubes on either side of the soot blowers. In other boilers for similar steam temperatures, but where the soot blowers are required to clean six rows of superheater tubes, the long retractable soot blower has not proved so effective.

Combustion

It has been shown in certain vessels that, by the careful adjustment of registers and burners, to obtain the best combustion, careful selection of high quality mechanical atomizer tips, and the frequent inspection and replacement of these tips to ensure that the high quality is maintained, the periods between water washing are increased, in bad cases, by as much as three times. An even greater improvement is achieved by using Y-jet steam atomizers which are also less sensitive to wear and maltreatment.

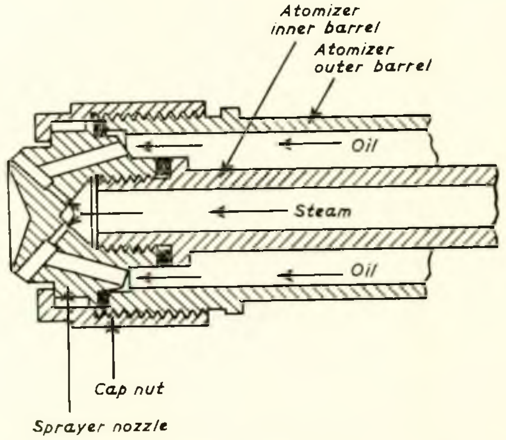

FIG. 3—*"Racer" type Y-jet tip assembly*

If smokeless combustion can be maintained with less than one per cent oxygen in the flue gases, then not only is the efficiency of the plant increased, but also the extent of deposits on all surfaces, and rate of corrosion of low temperature parts are reduced. In addition, there is a saving in cost since less heating surface, fan power and burners are required.

To maintain this quality of combustion in service, the equipment must be carefully chosen and proper consideration given to the arrangement of burners, the gas flow pattern and the combustion control system. The distance between burners should be sufficient to ensure proper air distribution to the registers and avoid undue interference of one flame with its neighbour. The gas path from the burners to the exit from the furnace should give ample residence time for the furnace gases so that combustion is completed before the gases are cooled by convection heating surface. As the burners will be operating close to their smoke limit, the control system, as shown in Fig. 2, should incorporate high and low signal selectors to ensure that sufficient air is always available for combustion. A steam flow transmitter

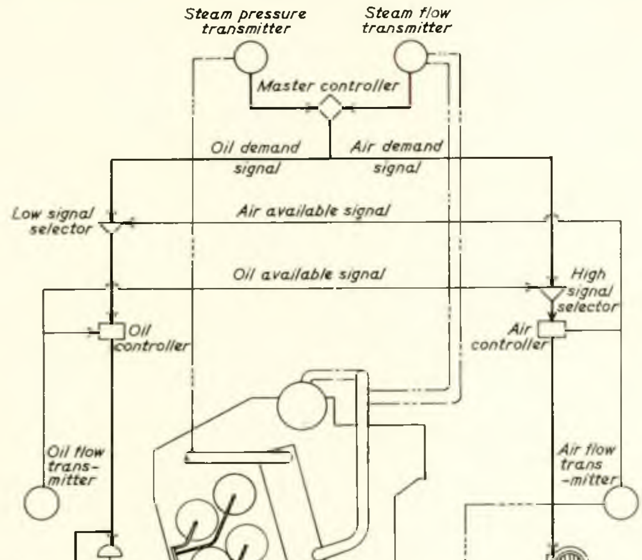

FIG. 2—*Combustion control system*

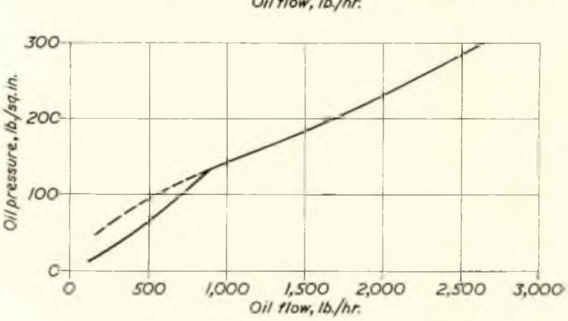

FIG. 4—*"Racer" type Y-jet burner–Output characteristic*

should also be included so that fluctuations in oil flow are reduced. Hand/auto stations would be included at suitable points, but for simplicity these have been omitted from Fig. 2.

The most successful burner at sea today is the well-known Y-jet steam atomizer. The latest version of this atomizer now known as the "Racer" type, was referred to in a paper presented to the Scottish Section of the Institute in 1964[2]. The burner is now available in a range of sizes, and oil quantities as high as 6,000 lb./hr. per burner have been successfully fired in the furnaces of marine boilers with a variety of air registers. The minimum output is difficult to establish accurately as it is so small, but there is no difficulty in turning down to less than 150 lb./hr. of oil per burner in most installations. Details of the "Racer" tip are shown in Fig. 3 and a typical characteristic of oil flow and steam consumption appears in Fig. 4. The maximum oil pressure is 300 lb./sq. in. and steam is supplied at 150 lb./sq. in. A control valve is included to reduce the steam pressure to 20 lb./sq. in. above the oil pressure at low loads. As can be seen from the characteristic, the steam consumption is much lower than in earlier versions of this burner. If steam consumption at lower loads is unimportant, the steam pressure control valve can be omitted and the effect of this is shown by the dotted lines in Fig. 4.

Early in 1965, "Racer" atomizers were installed in the boilers of the *Esso Warwickshire,* together with a control system similar to that shown in Fig. 2. This vessel has now made many voyages and there is no difficulty in maintaining combustion with less than one per cent oxygen. The vessel is fitted with oxygen recorders and these are checked regularly. On several voyages, figures as low as 0·6 per cent and 0·7 per cent oxygen have been maintained and the plant keeps exceptionally clean.

Furnace Rating

The furnace should be designed to satisfy the following criteria:

i) the furnace geometry should be such as to permit adequate burner clearances;
ii) the furnace geometry should give ample residence time for the furnace gases;
iii) the rate of circulation in, and rate of heat absorption by the furnace tubes should be such as to ensure long tube life with correct water conditions;
iv) the furnace exit temperature should be considered in relation to its effect on the superheater design;

Items i) and ii) have been discussed under the heading "Combustion". With regard to item iii), at present the rate of circulation must be left to the integrity of the boiler designer as there is no satisfactory method of specifying this. The rate of heat absorption in B.t.u./hr.-sq. ft. of tube is unsuitable for inclusion in a specification as different boilermakers calculate this figure by different methods. However, the rate at which oil is burnt per unit area of effective water-cooled surface in the furnace is closely related to the rate of heat absorption and can be specified or used for comparison purposes providing a consistent method of calculation is used. The Society of Naval Architects and Marine Engineers' Technical and Research Bulletin No. 3-14 "Boiler Furnace Performance Criteria"[3] gives a method of calculating the effective water-cooled area in the furnace which can be easily applied and the "Firing Rate", R, can then be calculated as:

$$R = \frac{W}{S} \text{ lb./hr.-sq. ft. R.H.S.}$$

where W = oil consumption lb./hr.;
and S = radiant heating surface as defined[3].

The bulletin referred to also indicates the firing rate for certain American ships. These vary from 8·0 to 10·6 lb./hr.-sq. ft. R.H.S. but, as stated in the final paragraph of the bulletin, "Properly designed boilers can, and do, range considerably beyond the tabulated numbers. Naval boilers use much higher values". If a wider selection of American boiler designs is considered then the range is seen to be from 8·0 to 15·0 lb./hr.-sq. ft. R.H.S. European designs fall generally within this range although there are fewer at the lower end of the scale and, in some cases, figures as high as 20 lb./hr.-sq. ft. R.H.S. have been used. Stationary boilers in this country usually have ratings between 5·0 and 7·5 lb./hr.-sq. ft. R.H.S.

It is difficult to recommend a specific value for the firing rate since many naval boilers have ratings in excess of 60 lb./hr.-sq. ft. R.H.S. and give little trouble, providing correct water conditions are maintained. With a well-designed circulation system and adequate burner clearances, the figures currently in use for merchant ships therefore represent a conservative rate of heat transfer through the furnace tube walls, giving a considerable margin of safety. Feed and boiler water conditions should be such that no deposits or scale will form inside the furnace tubes, in which case, the tubes should last indefinitely. If these conditions are not maintained, then tube failures must be anticipated. However, in order to avoid furnace tube replacements, there would appear to be little advantage in specifying a very low rating at normal load since, on what it is hoped would be the rare occasions when adverse water conditions prevail, a similar effect could be achieved by reducing the load on the boilers until correct conditions are re-established.

Item iv), the effect of furnace rating on the configuration of the superheater, is discussed later under the heading "Correlation of Superheater and Furnace Design".

Arrangement of Superheater

Experience with steam temperatures up to 860 deg. F. (460 deg. C.) shows that, with good combustion, long retractable soot blowers and no more than three rows of superheater tubes on either side of the soot blowers, bonded deposits should not be a serious problem. For higher steam temperatures, therefore, a series superheater arrangement can be expected to be satisfactory, providing there are no more than three rows of superheater tubes on the furnace side of the first soot blowers, good combustion is maintained and the steam temperature leaving the primary superheater is no more than 860 deg. F. (460 deg. C.).

The merits of vertical and horizontal superheaters in two-drum boilers have often been discussed. Providing the principles already outlined are followed, either type can be expected to operate for extended periods without water washing. Each design has its own construction and maintenance problems which vary in significance with each application. The choice should, therefore, be made from consideration of the arrangement in the vessel, the arrangement of the superheater tube banks relative to the soot blowers and the ease with which superheater tubes can be replaced, particularly when these are welded to the headers. The diameter and pitch of the superheater tubes is rarely the same as that of the rear bank so that, to facilitate inspection and cleaning, an access space between the superheater and the rear

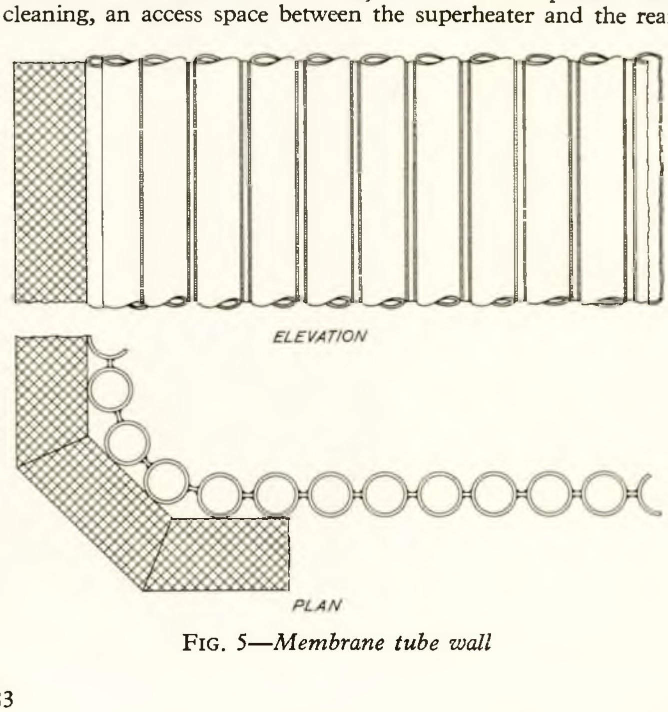

FIG. 5—*Membrane tube wall*

FIG. 6—*Automatic welding of tubes to form a membrane wall*

bank is most desirable with either type. This space also allows all superheater supports and soot blower elements and bearings to be readily accessible.

Membrane Tube Walls

Membrane tube walls are now widely used for stationary boilers and their application to marine units has been discussed[2,4]. In the membrane tube wall, a strip of steel is welded between the water wall tubes throughout their length, as shown in Fig. 5. The manufacturing technique for this type of construction was originally developed in the United States and production commenced in the United Kingdom over three years ago. At present one British boilermaker alone is producing over 6,000 sq. ft. of membrane panels per week by the process shown in Fig. 6 and has received contracts for over 45 boilers using this type of construction, representing a total evaporation of more than 80 million lb./hr. of steam. Fig. 7 illustrates the method by which the completed panels are bent to the correct shape for the particular application.

Repairs to membrane walls are often simpler and quicker than with other types, but experienced welders are required for this work. With improvements in feed water treatment, water level control and the greater use of automatic and supervisory equipment, some marine engineers are looking with favour on this construction, as the tube wall itself can replace both the inner and outer casings and refractories are eliminated. Maintenance is thus reduced and on larger marine units there is a saving in cost.

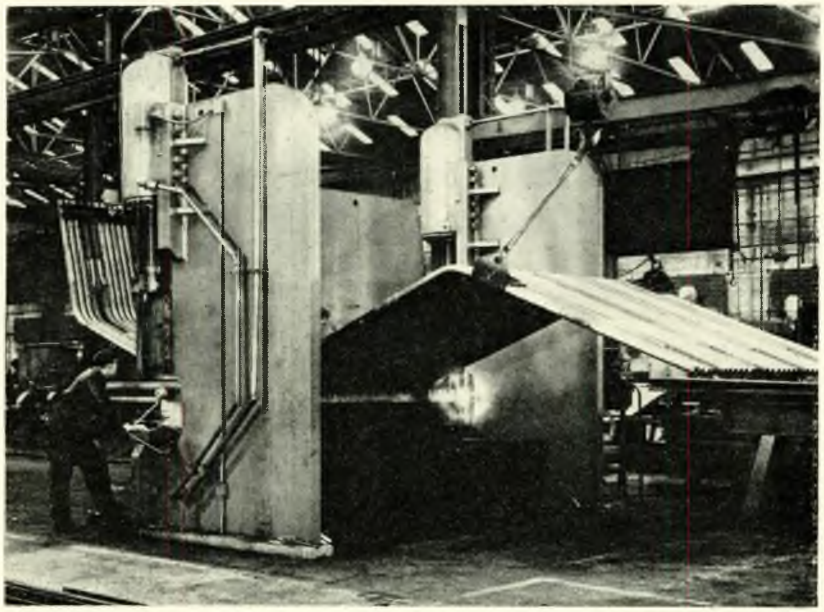

FIG. 7—*Pressing of membrane tube panel to final shape*

Unit Construction

Not all shipyards have boiler shops, and in any case these boiler shops are often some considerable distance from the point at which the vessel is fitted out. Also, in many yards crane facilities at the fitting-out site are limited, so that it may not be possible to lift the boilers into the vessel in one piece. For these reasons, boilers are now often designed for unit construction. The furnace side wall and the superheater screen tubes are connected to headers at both ends so that the furnace and the boiler bank can be built as two separate units which can readily be united alongside, or in, the vessel. In the same way the superheater may be constructed as a third unit or included in either the furnace unit or boiler bank section. With series superheaters it is sometimes convenient to include the primary superheater with the furnace section, while the secondary superheater is included with the boiler bank.

The unit system is particularly attractive when the furnace has membrane tube walls as not all shipyards will have the special equipment required for this type of construction.

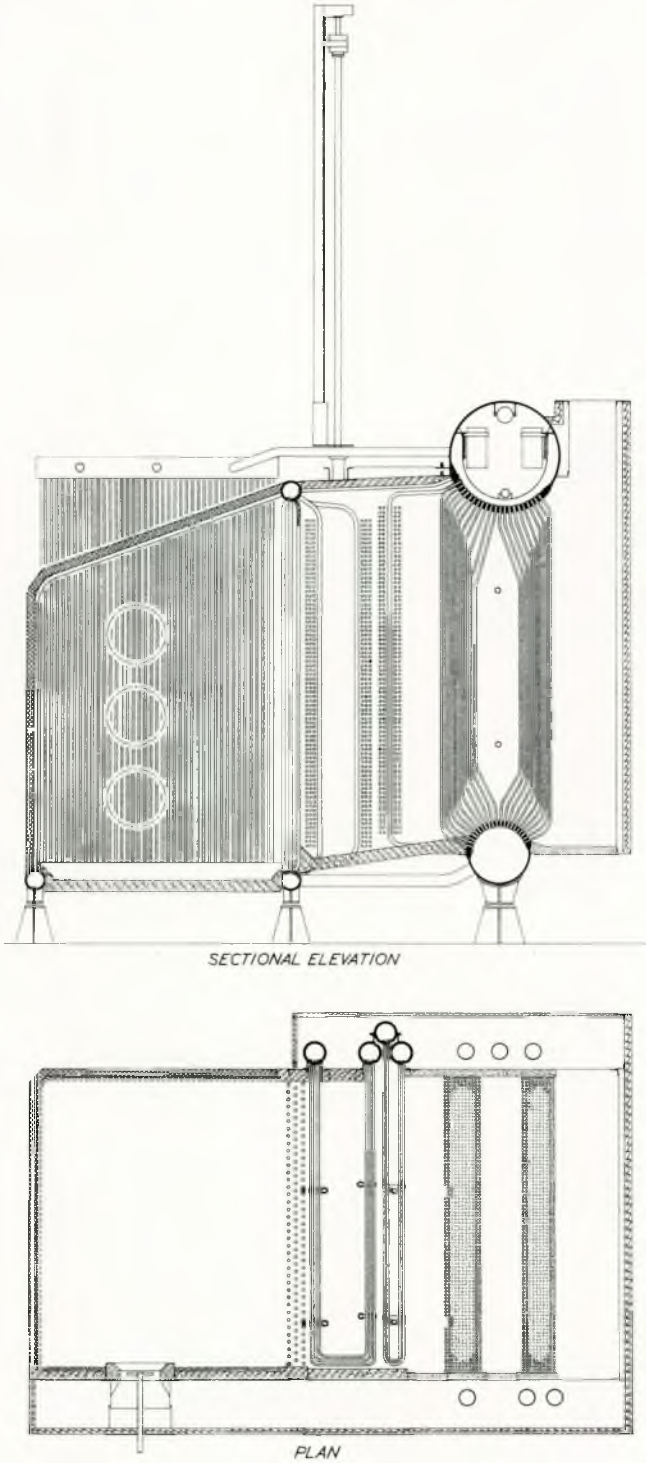

FIG. 8—*Typical modern two-drum boiler with series superheater*

Typical Design

A design of boiler incorporating the foregoing principles is shown in Fig. 8. It is suitable for unit construction and the burners are arranged in the front wall of the furnace. The furnace side, roof and rear wall are of the membrane tube construction, while the front wall is water cooled with bare tubes backed by refractory, thus simplifying the problem of arranging burner openings. On leaving the furnace, the gases pass through three rows of screen tubes to the primary and secondary superheaters and are then further cooled by a bank of generating tubes before passing to the economizers or air-heaters.

The primary and secondary superheaters have six and four rows of tubes respectively and are constructed of horizontal U-loops. Access spaces are provided in the centre of the primary superheater, behind the secondary superheater and in the centre of the bank of generating tubes. Long retractable soot blowers are arranged to operate vertically in the access space of the primary superheater immediately after the first three rows of superheater tubes. Rotating soot blower elements are located in the access space in the centre of the generating bank.

The unit is designed for a normal evaporation of 140,000 lb./hr. of steam at 850 lb./sq. in. gauge and 950 deg. F. (510 deg. C.) from feed water at a temperature of 400 deg. F. (204 deg. C.).

Correlation of Superheater and Furnace Design

An appreciation of the relationships between furnace and superheater design can be obtained from a study of Figs. 9, 10, 11 and 12 which indicate the effect of various changes which can be made to the boiler illustrated in Fig. 8.

Fig. 9 shows that if the same final steam temperature is to be maintained, a reduction in firing rate from $13\frac{1}{2}$ lb./hr-sq. ft. R.H.S. to $8\frac{1}{2}$ lb./hr.-sq. ft. R.H.S. would require the superheater tube pitch to be reduced from $2\frac{1}{4}$in. to $1\frac{3}{4}$in. Alternatively, the pitch can be maintained at $2\frac{1}{4}$in. and the depth of the superheater increased by two rows of tubes, as shown by Fig. 10. Either of these alternatives is undesirable for the following reasons:

1) soot blowers would be less effective;
2) inspection and manual cleaning is more difficult;
3) construction is complicated and costs increased.

If one of the rows of superheater screen tubes were omitted,

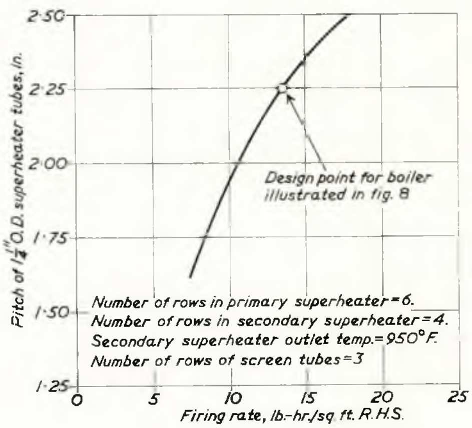

FIG. 9—*Relationship between superheater tube pitch and firing rate*

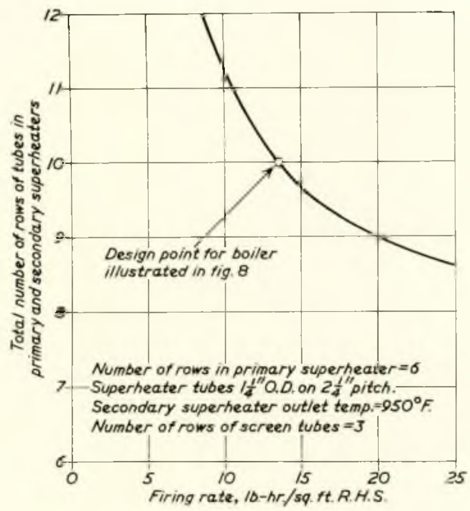

FIG. 10—*Relationship between depth of superheater and firing rate*

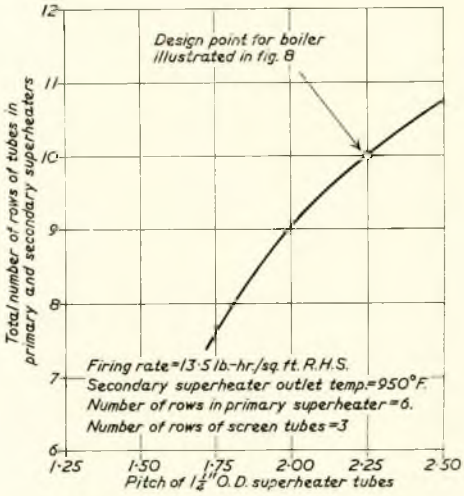

FIG. 12—*Relationship between depth of superheater and superheater tube pitch*

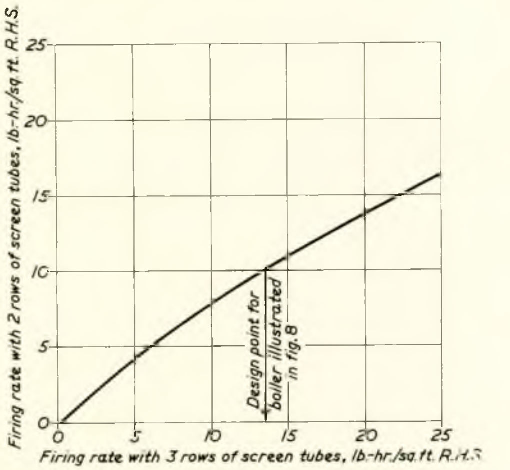

FIG. 11—*Relationship between firing rates to give same superheater construction with different arrangements of screen tubes*

the gas temperature entering the superheater zone would be increased, so that wider pitches or less rows of tubes could be used in the superheater. Alternatively, as shown by Fig. 11, the superheater design could remain unchanged providing the furnace size was increased to give a firing rate of 10 lb./hr.-sq. ft. R.H.S.

Fig. 12 shows the relationship between the depth of the superheater and the tube pitch for a fixed design of furnace and superheater screen. From this curve it can be seen that the combined depth of the superheaters could be reduced to eight rows if the pitch was reduced to 1·8in. The performance of the primary superheater would also be increased so that the depth of this section should be reduced from six rows to four rows to avoid steam temperatures leaving the primary superheater of more than 860 deg. F. (460 deg. C.).

The steam speed in the superheater tubes, and the arrangement of steam passes in the design illustrated in Fig. 8, is such as to permit the burners to be arranged in either the front wall, the side wall or the roof of the furnace without risk of the superheater tubes overheating due to stratification of gas flow. A vertical superheater could also have been included having a similar arrangement of steam passes. The designer is thus free to choose the attitude of the superheater tubes and to select the firing position which will give the best overall arrangement for the particu-

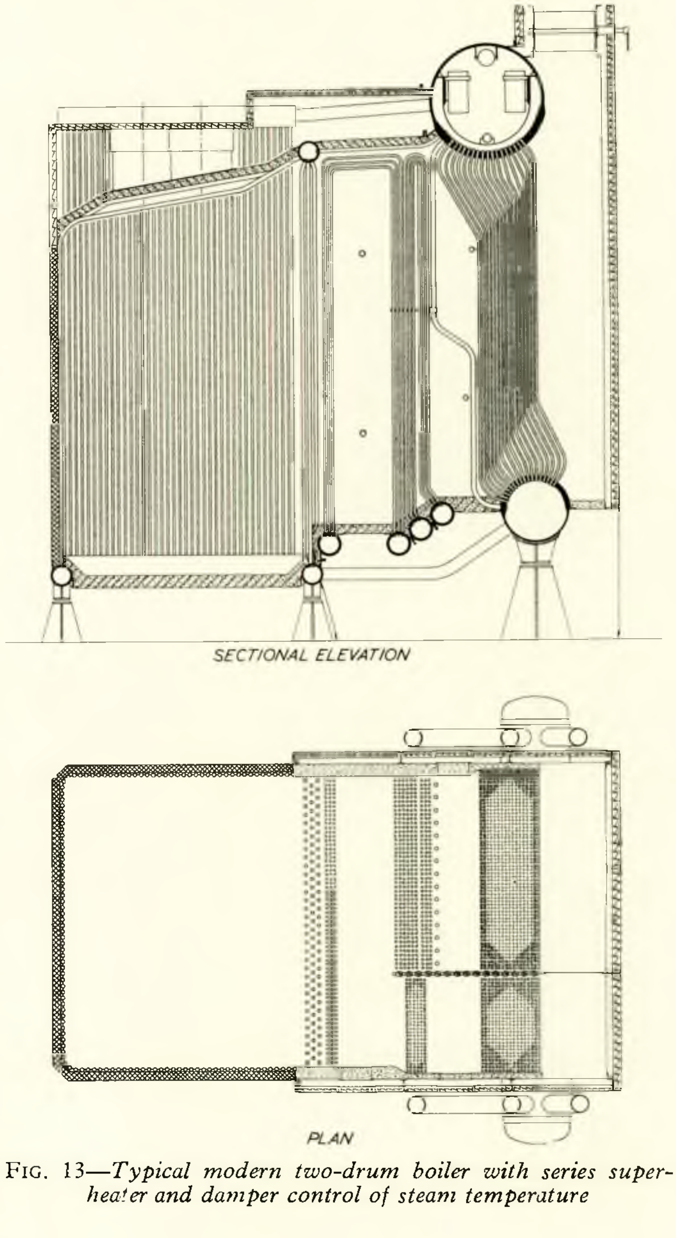

FIG. 13—*Typical modern two-drum boiler with series superheater and damper control of steam temperature*

lar application. Alternative firing positions would, naturally, require some modification to the furnace shape.

There are other permutations and combinations which can be considered, but it is hoped that the data presented will give an indication of the significance of the various points discussed.

Steam Temperature Control

In the designs so far considered, steam temperature control would be achieved by an inter-pass attemperator located in one of the boiler drums. Alternatively, part of the superheater could be arranged so that the gas flow over it, and hence the outlet temperature, can be controlled by dampers as shown in Fig. 13. The boiler illustrated has vertical superheater tubes and the burners are arranged in the furnace roof, but horizontal superheaters could be used and the burners could be arranged in the furnace front or side wall so that once again these features can be selected to suit the particular application. This design follows the general principles already outlined and has ratings and tube pitches similar to Fig. 8.

Damper control has advantages over an attemperator in that the rate of response is more rapid and there are no valves or pipe joints to be maintained. Experience over many years has shown that correctly designed dampers in gas temperatures up to 1,100 deg. F. (593 deg. C.), require little maintenance and, by eliminating the attemperator, access inside the drums is improved. The more rapid rate of response simplifies automatic control.

RADIANT BOILERS

The increases in steam temperatures, feed temperatures, boiler efficiency, and the reduction in the quantity of excess air for combustion which have occurred in recent years, all reduce the amount of boiler heating surface required. The desire in some quarters for lower furnace ratings also has this effect. This reduction in the amount of convection heating surface required has caused boiler designers to study the radiant type boiler similar to that used for large stationary units in which the boiler bank is replaced by economizer surface.

Such a design, illustrated in Fig. 14, is at present under construction for a 170,000-ton tanker having machinery of 30,000 s.h.p., the superheater outlet conditions being 900 lb./sq. in. gauge and 955 deg. F. (513 deg. C.). The burners are located in the roof of the furnace and the furnace is separated from the convection heating surfaces by a division wall of membrane construction. The gases leave the furnace through an opening at the lower end of the division wall and then pass upwards over multi-loop superheaters and an economizer to the airheater. Except where openings are provided to permit the superheater and economizer tubes to be welded to the headers, the walls of the furnace and boiler are entirely of membrane construction. For this particular application, the design illustrated proved cheaper and occupied less floor space than the equivalent two-drum boiler. From a combustion point of view the design is superior since a greater residence time is achieved than is possible in a conventional two-drum boiler.

If higher pressures are required the radiant boiler has advantages since all tubes can be welded to the drum or headers and expanded joints are thus eliminated. The radiant boiler is also readily adapted for a reheat plant, as has been described in detail elsewhere[4] and, since it is relatively simple to arrange for additional rows of superheater tubes and to accommodate extra access spaces and soot blowers, the superheater design is not connected so intimately to the furnace design as in the two-drum boiler.

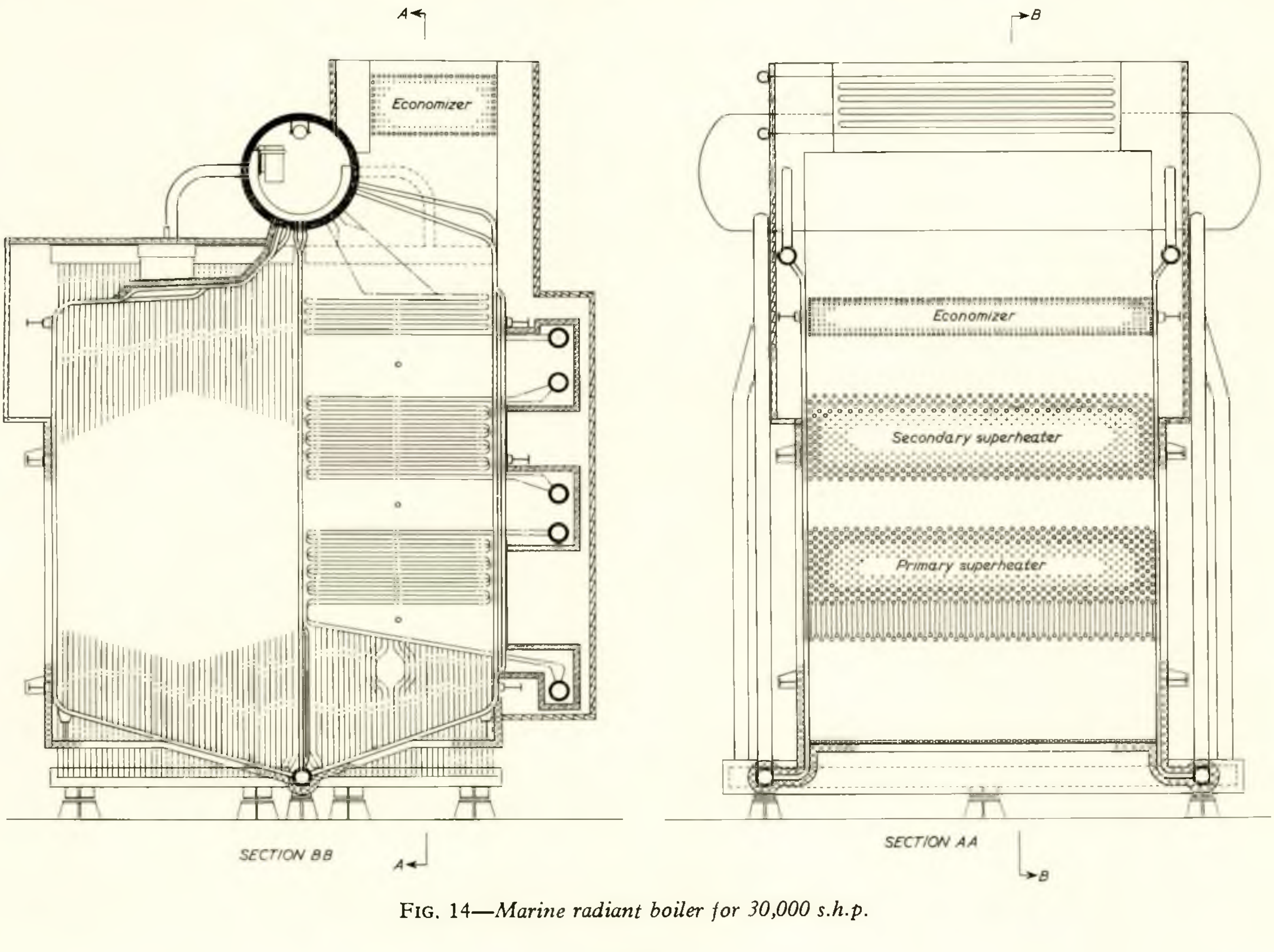

FIG. 14—*Marine radiant boiler for 30,000 s.h.p.*

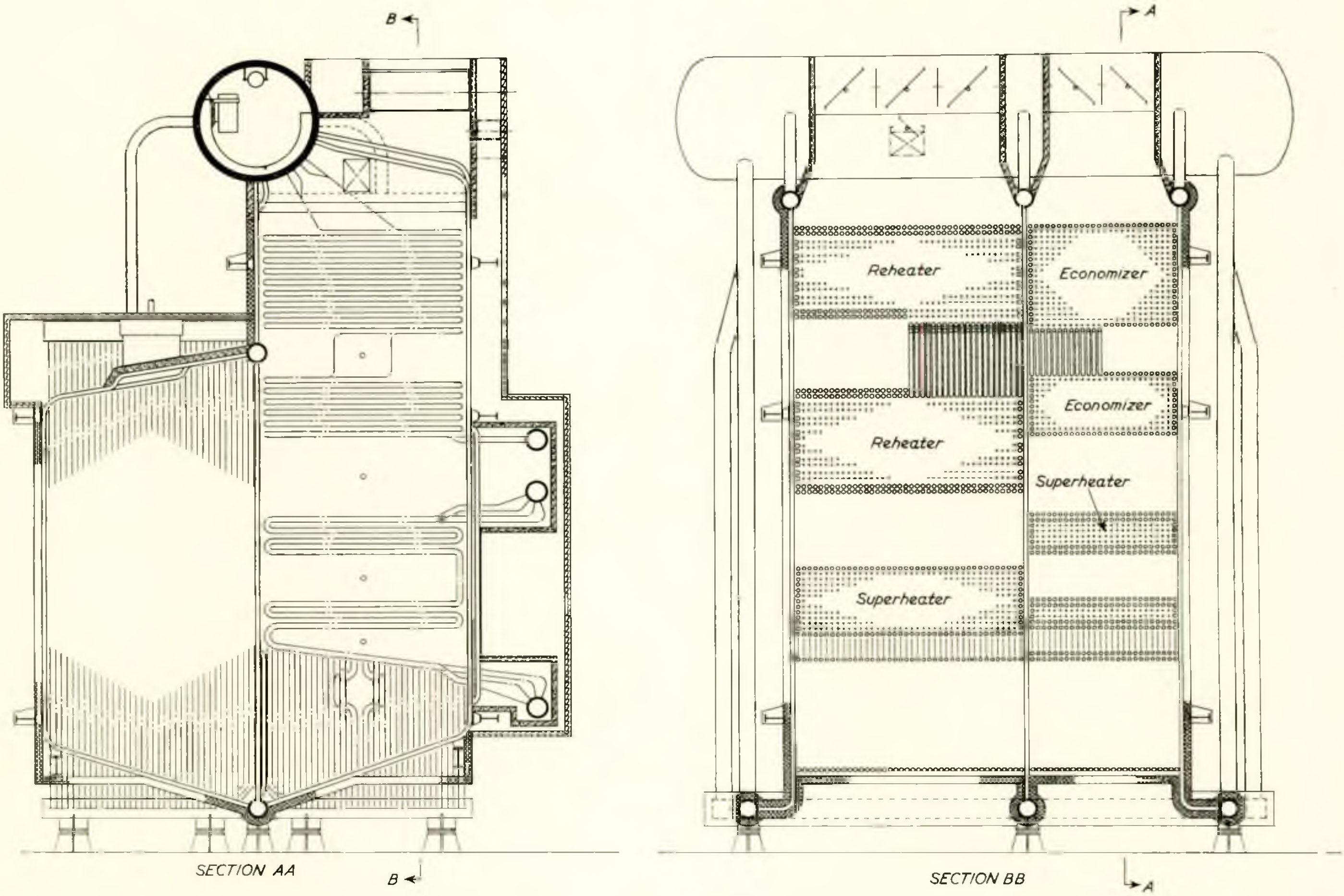

FIG. 15—*Marine radiant reheat boiler with superheat control by attemperator and reheat control by dampers*

There is no problem in providing reheat in a turbo-electric plant or when a controllable pitch propeller is included as uni-directional turbines can be used and the flow through the re-heater can be kept in step with the total load. It is possible to arrange for the flow to be maintained in a reheater even with a reversing turbine, but this usually results in expensive, compli-cated or inefficient arrangements so that with a reversing turbine a better solution is to adopt a boiler such as that shown in Fig. 15, wherein the reheater can be safeguarded. This unit is also de-signed for 30,000 s.h.p. but, to enable the turbine plant to use re-heat to better advantage, the superheater outlet pressure has been raised to 1,450 lb./sq. in. gauge. The steam temperatures from the superheater and reheater are both 955 deg. F. (513 deg. C.). In this unit the gas passage is separated into two parallel paths by a membrane tube wall. One path contains the reheater, while the other has economizer surface. The gas flow over the reheater, and hence the reheated steam temperature, is controlled by dampers above the reheater and economizer sections. A super-heater is arranged in the reheater path and further superheater surface is provided in the path containing the economizer. When running astern, the dampers on the reheater side are closed to re-strict the gas flow over the reheater and there is sufficient super-heater surface below the reheater to ensure that, under these con-ditions, the gas passing to the reheater has been cooled to below the safe metal temperature of the reheater tubes, even when the maximum quantity of oil is fired. The superheater outlet steam temperature is controlled by an inter-pass attemperator.

SINGLE-BOILER INSTALLATIONS

Recently there has been considerable discussion centred around the question of whether one or two boilers should be provided in a single-screw ship and some of the advantages of a single-boiler installation are given here.

Steam for auxiliary purposes can be provided by a steam-to-steam generator. At present most owners would require some emergency arrangement to maintain steerage way in the event of failure of the main boiler. This can be achieved in a variety of ways, all of which offset, at least partially, the advantages out-lined as follows:

Cost, Weight and Space

The cost, weight and space of the boiler plant is reduced. Significant savings can also be made in the cost, weight and space of piping, valves and automatic control equipment, and fitting out and supporting is simplified.

Maintenance

Maintenance should be simplified, as, with the increase in component size, better access to heating surfaces and inside drums can be provided. Less time is required for survey as there is only one unit to be opened up. A further saving in maintenance should result from the reduction in the extent of pipework, valves and control equipment and fewer non-return valves are required.

Efficiency

Since the total surface area of the casings of boiler plant is reduced, there will be a reduction in the radiation loss, with a consequent improvement in boiler efficiency.

Habitability

The reduced radiation loss just referred to also improves the habitability of the machinery space, or permits a reduction in the quantity of ventilating air. The same effect, to a lesser degree, results from a simplification of the piping system.

AIR-HEATERS AND ECONOMIZERS

The main problems with air-heaters and economizers are low temperature corrosion and the choice of an economic feed temperature and final gas temperature.

Corrosion

Unless corrosion-resistant materials are employed, the metal temperature of heat exchanger surfaces should be kept above 280 deg. F. (138 deg. C.) at all loads to avoid corrosion when burning fuels containing 3-4 per cent sulphur, and this requirement is met most economically by using a cycle including mild steel economizers and steam air-heaters with arrangements for keeping the feed temperature at 280 deg. F. (138 deg. C.) or more, under all conditions of operation.

If gas air-heaters are to be used to their full advantage, corrosion-resistant materials are necessary and the problems of uptake corrosion must be considered. Two types of corrosion-resistant tubes are available for air-heaters, namely, steel tubes coated with vitreous enamel by a specially developed technique and tubes made entirely of heat-resistant glass. Glass tubes will not under any circumstances suffer from corrosion, but trouble may be experienced due to cracking, particularly at the tube ends. The vitreous enamelled tubes referred to are robust and have given satisfactory performance in air-heaters having a gas exit temperature as low as 310 deg. F. (154 deg. C.) at normal load. There is no reason to suppose that they will not be equally satisfactory at lower temperatures, but as yet there is no marine experience of such conditions. Fortunately, either type can be installed with the same end-fixing arrangements as shown in Fig. 16 and, providing a suitable diameter is used, they are thus interchangeable.

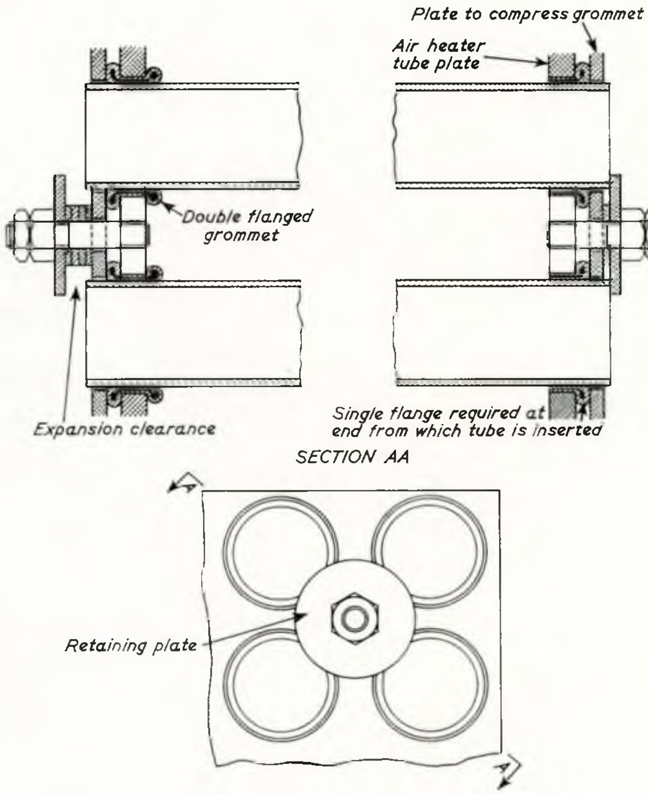

FIG. 16—*Method of securing vitreous-enamelled or glass air-heater tubes*

ECONOMICS

The optimization of a marine boiler plant is complex and a complete study cannot be made without access to data held by the shipowner, the turbine designer, the engine builder, the shipbuilder and sub-contractors since the costs, skills and attitudes of all of these can influence the final conclusion. In addition to the cost of fuel and other financial considerations, the optimum boiler efficiency is influenced by several factors including particularly the power, the operating schedule and the feed temperature.

Although higher or lower values can sometimes be justified the optimum boiler efficiency usually lies between 88·0 per cent and 90·5 per cent based on the higher calorific value of the fuel. In terms of initial cost this represents a very wide range since to increase the boiler efficiency from 88·0 per cent to 90·5 per cent may increase the cost of the boiler plant by over 30 per cent, with a corresponding effect on weight and space.

CONCLUSION

While the problems of bonded deposits on superheaters must not be overlooked, equally they should not be over emphasized or there is a danger that smooth operation may be prejudiced and other maintenance problems may arise.

The introduction of the radiant boiler promises reduced costs and maintenance, particularly for the higher powers, and is also suitable for any increases in pressure which can be foreseen at the present time so that further improvements to fuel consumption can be expected. Reheat can also be provided without serious operational or maintenance difficulties as far as the boiler is concerned.

Although much has been done already there is still scope for improvement in the economics of marine steam turbine plant and this can best be achieved by the close co-ordination of the major parties concerned with the full co-operation of the shipowner.

ACKNOWLEDGEMENT

The author would consider it unfair to mention persons or companies by name as his paper has been influenced throughout by discussions and arguments which he has had with so many marine engineers throughout the world, including all the major turbine designers, many shipowners and engine builders and his colleagues in his own and allied companies abroad. He feels that these people will recognize some of their own views in the paper and hopes that this in itself will be sufficient reward.

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Discussion

Mr. W. H. Falconer (Associate Member), in opening the discussion, stated that the author had provided much food for thought. He had mentioned some of the factors which affected a decision regarding the choice of machinery. As the capital cost was of fundamental importance, interest in steam propulsion could only be sustained if the cost of the complete installation was about the same as that of an equivalent Diesel-engined ship. In recent design studies the Diesel engine had been discounted to the advantage of the turbine. Mr. Falconer had always had the greatest difficulty in reconciling the logic of arguments which enabled one to arrive at such a conclusion.

In discussing the virtues of unit construction, the author had indicated that boilers so designed were easier to erect in the shipyard. This, of course, had obvious economic advantages, but Mr. Falconer hoped that this would not encourage yards to manufacture the boilers themselves. There were considerable advantages to be gained if boilers were manufactured in batches where quality and cost could be effectively controlled.

Membrane tube walls appeared to be particularly attractive as they virtually eliminated refractory on furnace walls. Mr. Falconer, however, had certain reservations regarding repairs to these walls. Presumably techniques for repairing water walls in forced circulation boilers of the La Mont type could be used if a tube failed. In practice, however, one rarely had the opportunity to use these techniques, for two reasons:

1) the defective tube was usually overheated for a considerable length and had to be removed completely in any case;
2) when a tube failed it was good practice to remove the tube and examine it internally from end to end to determine its general condition.

It would therefore appear that the author should consider whether or not it would be better to provide spare tubes with a half-width fin on either side so that, in the event of a tube failure, the wall could be re-sealed, by welding the edges of the fins or membranes together.

In many instances good designs were marred by poorly constructed boiler casings. Mr. Falconer had gained the impression that the casings were designed by less talented people. If boiler maintenance was critically examined, one usually found that a disproportionately large amount of time was spent on repairing boiler casings and refractories, and this therefore had led him to believe that the most talented designers should be given the task of engineering the design in its entirety. Mr. Falconer believed that this subject was very close to the author's heart, and that he was making strenuous efforts to rectify this deficiency.

The author had made some superficial comparisons between naval and merchant ship furnace ratings. It would be helpful if he would compare, in tabular form, the fire row generator tube life at full power with furnace ratings, water condition and intervals between maintenance. Mr. Falconer suspected that the naval boilers did not steam for long periods at the ratings quoted.

Superficially, there appeared to be some merits in a single-boiler installation; however, when due allowance had been made for the emergency services which prudent owners would normally fit, there was little to choose between the cost of a single-boiler installation as compared with a two-boiler plant.

If, as the author had stated, the cost of a boiler plant increased 30 per cent for only a 2½ per cent improvement in performance, there was virtually no incentive to install a boiler in a cargo liner with an efficiency better than 88 per cent. It should be remembered that the cost of boiler repairs was only part of the overall maintenance costs, and that due allowance should be made for the work carried out by the ship's staff. This aspect would be much more significant in future when ships would be operated by a small crew.

Mr. Falconer hoped that boiler designers would continue to publish more information on the prices paid for small improvements in performance. It was the maintenance and reliability of the boiler which would make or break a turbine installation, and not the turbine itself.

The author had commented on the possibility of using enamel-lined or glass air-heater tubes. Mr. Falconer's experience with the latter would indicate that the failure rate might be high, and therefore one wondered whether or not this would ultimately prove to be an acceptable economic solution to a very difficult problem.

Mr. E. A. Bridle, B.Sc. (Associate Member) said that within the last two years a number of exciting new developments in steam propulsion had been announced, and many shipowners were giving serious consideration to turbine machinery for new ships which were originally intended to be Diesel propelled.

One of the principal factors which had deterred, and was still deterring, some owners from adopting steam propulsion, in cases where it was otherwise economically attractive, was their past experience of high boiler maintenance costs. He was sure that Mr. Hutchings' paper would help to dispel their fears. In fact, this paper might well have been entitled "The development of the low maintenance marine boiler", and it was gratifying to see the effort which was being expended towards this end.

The shipowner, however, was a difficult man to convince, and he wondered if Mr. Hutchings could say when he would be able to report on the successful service performance with these new low maintenance features which were undoubtedly revolutionizing marine boiler design. He had in mind the two-drum designs such as the M.10 which had already been in service for a year or two.

Did Mr. Hutchings believe that the obvious advantages of the radiant boiler would ultimately result in its displacing the two-drum design for main propulsion with high steam temperatures—or would it only be suitable for tankers and large bulk carriers where there was always plenty of height available?

He got the impression that Mr. Hutchings did not really like gas air-heaters. If that was so, why was it that so many turbine designers throughout the world were proposing their use in more or less standard installations?

In the section on economics, did the relative costs apply to boilers with similar air-heater designs, or did the lower figure refer to a boiler with steam air-heaters and an economizer?

A third possibility, not mentioned in the paper, was the series feed system with a split economizer. This had been used in nearly all the large tankers built in Britain in the last few years. Some comparative cost figures for all three systems would be very useful.

Mr. Hutchings had made an almost casual reference to reheat, and so much had been said about it recently that it was rather like reading that the Americans had launched another satellite. In other words, it was becoming accepted as an entirely practical proposition. The boiler was undoubtedly the key to a successful reheat installation, and it was worth remembering that the recent world-wide explosion of interest in reheat was the direct result of a practical design by Mr. Hutchings and his colleagues, very similar to that illustrated in Fig. 15.

COMMANDER D. O'HARA, R.N. said that the paper covered a lot of ground and touched on many topics, some of which could be debated at length. He would only touch on a few items, and perhaps stimulate a little thought; many of the Royal Navy problems were peculiar to the Service.

In regard to combustion, he agreed that the choice of steam atomization should enable good combustion figures to be obtained, particularly at the low end of the turn-down, so long as it was used in a suitable register. However, to achieve an oxygen percentage of one per cent or less in the flue gases would require a high standard of air-tightness in the boiler casings, and one which would seem to be ambitious for an ordinary marine boiler. Admittedly, in the Royal Navy they used higher air pressures, but the principle still obtained.

The author asked for ample residence time in the furnace. This required a generously-sized furnace, something not easily achieved in a warship.

He was not sure from the paper whether the author considered that cleaner boilers were solely due to the better combustion at all powers, attributed to the Y-jet, or whether some of the improvement was due to the use of steam as the atomizing fluid. In any case, would the author say whether any comparative analyses had been made of deposits; whether the improvement was notable in ships with steam temperatures greater than, say, 800 deg. F. (426 deg. C.) and whether the improvement was just as apparent with high vanadium fuels?

Concerning controls, in the Royal Navy high response rates were required. Operation of burners near the smoke line required reliable and exacting control of the systems. It was also true to say that the register itself, under these circumstances, must be capable of supporting sub-stoichiometric combustion if the hazards of pulsation were to be avoided. If the air register was to be so capable, at low powers in particular, a sophisticated design might be essential. At Admiralty Fuel Experimental Station, Haslar, they had, during the past year, operated a register in a quarl of 15½-in. diameter between a throughput of 6,000 lb./hr. with a draught loss of 30 in. w.g. and 150 lb./hr. with a draught loss of 0·15 in. w.g., stability being preserved below stoichiometric at both ends of the range and, at the low end, immunity from panting as well.

In spite of this ability to control tightly and to run with low excess-air requirements, particularly at low powers, in the Royal Navy they found themselves in a somewhat unhappy position. The requirements for rapid response rates and violent manœuvrability were such that the limiting factor was the acceleration of which the blower was capable, and a control system, such as was shown in Fig. 2 of the paper, at first appeared to be unsuitable. This did not mean that the system could not be made adequate, but it was unsuitable as it stood. To increase the fuel burnt and let the blower catch up, as well it might, was not the answer, because the heat release was just as dependent on the right amount of air being there as the right amount of fuel. In addition, there was the hazard of black smoke and rapid fouling up of the boiler. The most obvious answer was to make sure that the blower had a head start; i.e. plenty of excess air at low powers. In this way, the fuel could be increased, within limits, instantaneously, and the required response rates would be achieved. However, deliberately to maintain high excess air at low power was inefficient, and did not help to keep down deposits. It might be, therefore, that, except when steaming on passage, it would not be possible to approach the near stoichiometric combustion, so earnestly advocated, unless sluggish reactions could be accepted.

As regards furnace rating, he would prefer to see the designers use heat release rate per square foot of radiant heating surface and so be independent of the fuel; i.e., rate the furnace in B.t.u., rather than pounds of fuel.

Concerning membrane tube walls, he believed that this type of construction represented a notable advance in boiler design; certainly in land boilers it was proving its worth. The Royal Navy was reluctant to adopt it, at present, because of the uncertainty of its behaviour under the high shock conditions which were specified. He did not think that the repair work would be much more difficult than it was with normal construction, provided good welders were available. In fact, it might be easier, because it should be easier to get to the defect itself, the casings being simpler.

The radiant boiler seemed to be a logical development; this had been shown in land boilers. At what point in the increasing pressure and temperature ladder did it become more economical to adopt the radiant design, and why? It would also be an advantage to see a size for size comparison of the two main designs discussed in the paper. It struck him that the radiant type must always be substantially bigger than its equivalent two-drum sister.

In the same context came the question of reheat. The solution for the reversing turbine, i.e., the selective reheat/superheat design, seemed to take up rather more volume than one would like. In addition, the use of an attemperator might have an adverse effect on the reaction time of the boiler, and would therefore not be liked in the Royal Navy.

There was no mention in the paper of internal cleaning. Some of the designs put forward would present difficulties in mechanical cleaning. He presumed that the author had accepted the requirements of chemical cleaning as a standard routine.

Finally, Mr. Falconer had raised the subject of generator tube life in naval boilers. The Royal Navy expected 20 years of life from generator tubes, and usually achieved it.

MR. L. J. CULVER, B.Sc. (Member) said that perhaps working in close proximity to the Science Museum gave him a sense of the historical as well as of the technical aspects of the paper. In 1943 there was a paper by Sampson*, read before the North-East Coast Institution, which showed that the first two-drum boilers used in the Merchant Marine in this country had a 60 per cent radiant duty, and the main bank of generating tubes provided the other 40 per cent. Steam conditions then were 450 lb./sq. in. and 750 deg. F. (399 deg. C.). It was inevitable that, as steam conditions increased, those proportions would change, until currently most of the leading boiler firms were turning to almost 100 per cent radiant steam generation.

It was an inescapable fact that the scale effect had to be contended with. With units now on order for duties of 220,000 lb./hr. and as much as 310,000 lb./hr., it was obvious that marine designs would resemble land boiler equivalents more closely.

Again on a point of history, the evolution of the modern superheater design started in 1951, rather than in 1962, since at that time the contribution by Baker† to a paper read before the Institute referred to steam conditions of 950 deg. F. (510 deg. C.).

On page 282 the author referred to the tendency to over-design and over-specify furnace volumes. Mr. Culver was

*Sampson, W. 1943-44. "Notes on the Design and Performance of Watertube Boilers for Cargo Steamers." *Trans. N.E.C.I.E.S.*, Vol. 60, p. 77.

†Baker, L. 1951. Contribution to the discussion on "Higher Steam Conditions for Ships' Machinery." *Trans. I.Mar.E.*, Vol. 63, p. 261.

sure that the operator would sooner have it this way than find that his boilers resembled solid walls of stone where the superheater ought to be.

The problems of ship-board space and economics must always have a bearing on marine boiler design, but a practical interpretation of past experience was obviously paying dividends in the present day.

The factors which were listed, on page 281, in items 1) to 7), should be coupled with the actual gas temperatures and metal temperature levels in the superheaters.

The author had referred to the depth of the superheater bank as being critical; in the following paragraph, under long retractable soot blowers, he mentioned that the bonded deposits always occurred in high gas temperature zones and, later, that the progressive development of designs showed fairly deep superheater and reheater banks. They shared the problems of keeping boilers free of slag. He believed that success was achieved by avoiding the critical combination of gas temperature and tube metal temperatures. Work at fuel research establishments and seagoing experience with external convection type superheaters served to emphasize these points.

With regard to air distribution to registers, he was sure the author would agree that the air-entry conditions to the wind box were a significant contributory factor to successful air-register performance, particularly with a wide range of turn-down.

The question of membrane walls had already been raised by other speakers, and he would bear out the author's comment that, for larger boilers, there might be economic savings, but if they tried and applied the technique to smaller boilers on a one-off, intricate detail basis, it was not so favourable. Since the linings behind the water walls seldom gave trouble, there was a number of operators who preferred to be independent of special tube shapes or the necessity for special shipboard spares, and preferred to use plain tubes with the universal supply, both in terms of spares and staff of adequate skill to effect repairs.

Unit construction was nothing new, but economic conditions were centralizing boiler manufacture, with more limited numbers of shipyards or engine works engaged in boiler construction, with greater emphasis on construction by the boiler designers.

Radiant boilers had a familiar look. It was interesting to reflect that the boilers referred to by Baker in 1951 would probably have had roof firing if the problem of close pitch registers could have been solved at that time. Roof firing had been applied successfully in the intervening years, and would become more common with the simple air-tube designs of registers now available. Boiler designers might appear to be clever by introducing tall boilers with roof firing, but they did not have much option, because the wide range of control dictated smaller numbers of burners with bigger capacities, and these, in turn, demanded long flame paths to ensure complete combustion with low oxygen contents.

Could the author say why there was an advantage in the interchangeability of ceramic-coated steel tubes with glass tubes for air-heaters? Either one was all right or it was not.

Also, on ceramic steel tubes, there had been a practice of spot welding the tubes through the ceramic to fasten them to steel tube sheets. Had the author left this out for any particular reason?

The mechanical detail for repairing a membrane wall tube *in situ* would be of value, both to cover the emergency repair of one or two tubes, or the technique for replacing a damaged area in more favourable conditions.

It was easy to appreciate the progress recorded by the author in the paper. Mr. Culver hoped that there was sufficient truth in the introductory picture to provide the friendly competition which was an asset to boiler design in this country.

Mr. W. C. Carter, B.Sc. (Member) said that before proceding to detailed comments, he would like to point out that, throughout the paper, the influence of land experience and practice was markedly evident, and this, he considered, was a good sign, despite the general conservatism in the marine fields.

Dealing with the first specific point, combustion and burners, if the boilers were to run at one per cent oxygen, six to seven per cent excess air or less, depending on the oxygen present in the fuel itself, it meant that not only must the air control be such that the distribution to each burner was fully and carefully maintained at all loads, but also that the same control of the actual orifice size must be maintained. For example, in a burner passing a ton of oil per hour with a single orifice, the latter might have a size of 0·200. If this orifice wore to the extent of 0·001 in., it would mean an increase in oil throughput of at least one per cent and this would quite patently affect the six to seven per cent excess air arranged for optimum operation. Thus if the excess air were in fact reduced to five per cent consistently, it would be appreciated that it would be necessary to have a programme of orifice checking to ensure optimum performance throughout, say, a four-month voyage.

On the subject of membrane walls, although the company that the speaker represented was a competitor of Mr. Hutchings' company, he did agree that these could be very satisfactorily accommodated in marine and similar units, and he did not share the misgivings which had been expressed by other speakers relative to tube replacements and other difficulties. He did feel, however, that Mr. Hutchings might have given a few more details regarding construction and, in particular, temperature variations through the tubes and membranes with different forms and distributions of heating.

In fact the foregoing remarks led to another point which did not seem to have been commented on so far, and this was with respect to the down firing proposed on the radiant heat fired unit. He was satisfied that with firing from the top as indicated, better heat distribution should be experienced throughout the furnace, together with an optimum flame length, and this might therefore be considered to be a better form of firing than side wall, front wall, or any other system. However, in the illustrations presented, natural circulation units were shown, and this could mean that at low loads with short flames, all the heating was taking place at the top of the tubes and this was not a particularly desirable feature for natural circulation boilers.

The speaker also wondered whether, in the general heat absorption, the better or expected better, distribution from down firing had been fully exploited?

One of the previous speakers had commented quite extensively regarding the use of reheat and, although certain economy could be substantiated, he would make a simple observation, namely, that the cost and complication of the reheat pipework and possible difficulties associated with astern use, must not be forgotten. This advantage might be more imagined than real.

With regard to the formation of SO_3, it was his company's general experience that operation at some 13 per cent CO_2 with 20 per cent excess air gave an SO_3 concentration of some 25-30 p.p.m. At 14·5 per cent CO_2 and perhaps 10 per cent excess air, the SO_3 concentration might well be reduced to 12-15 p.p.m., while with excess air in the 4-5 per cent region, the SO_3 concentration was reduced to 5-8 p.p.m., and this, while not completely innocuous, did give extremely low rates of corrosion and build-up.

Consequently, one would like to pose the question—had Mr. Hutchings found that, on enamelled tubes with gas temperatures of 310 deg. F. (154 deg. C.) and possibly lower, with operation under the lower excess air conditions which were now prevalent, i.e. one per cent oxygen and below, the amount of SO_3 was really that much lower, and could he therefore go to lower gas temperatures with a consequent improvement in efficiency? This point was obviously quite real in view of the extra costs mentioned for improvements in efficiencies from 88 per cent upwards, with which figures the speaker was in substantial agreement, although he considered that if the improvement could be effected by non-pressure parts, such as a gas air-heater, the costs would not be so great. However, the question of corrosion of uptakes would then require consideration, as of course the metal temperature of any part was the final and real criterion.

Considerable emphasis had been made in the paper on the use of steam atomization and its effect on the general cleanliness of the boilers, presumably with less formation of SO_3. Mr. Carter had never seen any real facts to support this contention. Could Mr. Hutchings, therefore, give any positive figures, namely, that steam atomization reduced by a half or any proportion, the formation of SO_3, when used to burn fuel oil.

Finally, he assumed, regarding the radiant heat boilers, particularly as shown in Figs. 14 and 15, that due to the relatively small combustion chambers with their lower total heat absorption, the economizers were of the steaming type.

Mr. J. A. Bolt said that the section of the paper headed *Combustion* was of interest, since many factors affecting the operation of boiler plant were mentioned in it, and they were of interest to a burner manufacturer—particularly if he did not happen to make the Y-jet burner.

Some two years previously he had been privileged to take part in the discussion when the author gave his paper*, "The Design and Development of Two-drum Marine Boilers." Reference was made in that paper also to the Y-jet burner performance. In reply to his points raised at that time, the author did not produce any figures, but did state that some ships had improved their performance by changing from pressure-jet—presumably of the author's manufacture—to Y-jet burners. This compared with the 3,150 ships fitted with the equipment of Mr. Bolt's firm over the same period. On those vessels, in the last four years, over 88 had been fitted with their steam-assisted burners, 32 of those on the author's boilers. To be statistical, 88 in four years was 22 per year average; 135 in 20 years was approximately seven per year average. Mr. Bolt's company, therefore, had, on average, some 300 per cent more steam-assisted pressure-jet burners of their own manufacture being fitted, than the author's Y-jet burners.

That brought him to the author's remark on page 283 of the paper: "The most successful burner at sea today is the well-known Y-jet steam atomizer." If Mr. Bolt's arithmetic was correct—and it excluded all other burner manufacturers—then the statement regarding the success of the Y-jet could only be one of two things:

a) a misprint—perhaps it should read "Our most successful . . ."
b) a claim to be the most successful burner technically if not numerically.

If he was accused of marketing during a technical paper, he pleaded self-defence.

The author mentioned a new version of the Y-jet called the "Racer". It was stated that the "Racer" had fired 6,000 lb./hr. down one register on marine boilers, utilizing a variety of registers. Could the author state the dimensions of the combustion chambers used, the Δp across the air register, and the steam consumption? It was also stated that the "Racer" could turn down to less than 150 lb./hr. oil flow per burner; was it claimed to turn down to this from 6,000 lb./hr? A previous speaker had mentioned that 6,000 lb./hr. had been achieved with 30 in. w.g. Anybody involved in the normal commercial world would agree that it would be a job to sell that to anybody.

From page 282, Fig. 4, the steam consumption appeared to flatten out at some 40 lb./hr. per burner. Assuming 2,500 lb./hr. of oil per burner, the percentage evaporation used for atomizing steam seemed to be 0·1 per cent. This was about one-fifth of the previous Y-jet steam consumption. From the drawings shown of the "Racer", it appeared to be very similar to its predecessor. Could the author enlarge a little on the new design to account for the remarkable reduction?

There was a reference under the same heading to a paper given to the Scottish Section of the Institute in 1964 (reference (2) of the paper under discussion). That reference read: "The Y-jet atomizer has been used, particularly in German and American ships, for many years, and has proved, without doubt, to be superior to any other burner from the point of view of quality of combustion and the resulting improvement in efficiency and cleanliness of the boiler and reduction in corrosion rates". Mr. Bolt was not aware of the total number of British-built oil burners which at that time had been fitted to German or American-built ships—his firm had only one—but he wondered what the Y-jet was being compared with.

Both in the present paper and that given a year ago in Scotland, the author referred to the *Esso Warwickshire.* In the Scottish paper it was stated that "Racer" type Y-jets were to be fitted on that vessel to "reduce fire-side deposits and corrosion as well as to improve efficiency." It was said that the vessel was now running at 0·6 per cent to 0·7 per cent oxygen and keeping the fire-side (presumably) very clean. The combustion control system was also made more sophisticated at the same time that the new burners were fitted. Could the author answer the following questions:

1) Had the cost of this change paid off?
2) What was the original problem regarding fire-side deposits?
3) What type of burners were originally fitted?
4) What was the source of bunkers utilized before and after the change?
5) What were the combustion chamber dimensions?
6) What was the Δp of the air register and throughput per burner under normal steaming?
7) What was the guaranteed accuracy of the oxygen meter below one per cent?
8) Where was the oxygen sampling point?

Mr. J. H. Milton (Member) said that it appeared that recent development of the marine watertube boiler had been to improve its efficiency and reliability in attempts to make a steam cycle more competitive with the directly-coupled Diesel engine. To this end, during the last year or so, quite a lot had been heard about ships with one large watertube boiler for propulsion purposes, with or without an auxiliary boiler.

The boiler for a single-unit installation must necessarily be as reliable and rugged as possible, and must, in addition, be capable of operating trouble-free under both low and normal steaming conditions.

One read, almost daily in the press, of casualties involving loss of water and burnt-out tubes; in three successive days recently, seven ships were reported with watertube boiler troubles, one of which necessitated stoppage at sea.

The records of Lloyd's Register of Shipping over a five-year period indicated that, out of some 900 turbine-driven ships, there were 142 cases of boilers becoming inoperative for a short or longer period.

The Society had no objection to a single main-boilered installation, but considered it prudent to provide some "get-you-home" arrangement. This might consist of:

1) a shaft generator which might be operated as a motor, the supply coming from a Diesel generator;
2) an auxiliary boiler which could supply steam to some section of the propulsion turbines;
3) emergency gas turbines which could be connected to the main gearing.

In the paper the author showed, on page 281, a chart illustrating how the overall economy of steam turbines compared with that of Diesel engines. It was rather surprising to see that steam compared favourably with Diesels at the lower powers, when the usage was less, and not so favourably when the usage was more; one would have expected the converse to be the case.

In Fig. 14, a radiant boiler was shown. One of the main differences of this design from that shown in Fig. 8 was that, as the author stated, the superheater was not connected so intimately to the furnace. It was, in fact, shielded from radiant heat as in the external superheater design of boiler and, although

*Hutchings, E. G. 1963. "The Design and Development of Two-drum Marine Boilers." *Trans. I.Mar.E.*, Vol. 75, p. 37.

a larger superheater surface would be required for the same result, this position of the superheater would appear preferable as a precaution against excessive metal temperatures and slagging, which could occur under adverse operating conditions. Perhaps the author would enlarge on this, particularly in view of his observations on slagging temperatures, in his previous paper.*

With further regard to this "radiant" boiler, it would be interesting to hear how, in this design, the opening in the membrane wall was made and how the top of it was protected from the intense heat of the combustion gases sweeping through from the furnace.

The author stated, on page 284, that repairs to membrane walls were often simpler and quicker than with other types; this would not, at first thought, appear feasible. It would be interesting to hear how the membrane tubes were connected to the headers and whether the fact that the tubes received most of their heat from one side affected their shape and length of service.

In conclusion, he asked the author why, if one of the reasons for heavy fuels burning cleaner in oil-engine cylinders was presumably the fact that combustion was taking place under pressure, more attention was not being given to highly-pressurized boiler furnaces.

Dr. A. W. Davis (Member of Council) asked that the ingenuity that was going into the design of modern boilers should be directed towards making them ever more rugged, rather than achieving exceptionally high degrees of efficiency. The turbine had suffered quite gravely in the past by reason of the shortcomings of boilers in their practical operation. It was to be hoped that, at this time, when there was obvious scope for some come-back of turbine operation in the range of higher powers, the opportunity should not be spoiled by misplaced endeavours to go to very high efficiencies. He deprecated attempts to claim possible consumption rates below 0·4 lb./s.h.p.-hr. in the hope of attracting a shipowner into a venture which might not reflect the credit that the boiler and turbine installation really deserved. This was in no way to criticize the number of ingenious devices which had been brought forward and to which Mr. Hutchings had referred.

He did not think that Mr. Hutchings had done justice to the reheat boiler in attempting to deal with such an extremely involved problem in one short paragraph. He doubted the wisdom of depending upon dampers to preserve a reheater when going astern. One had to consider the case of an emergency astern movement when all parts were at full power operating temperatures; the dampers were open and suddenly there was no steam going through the reheater; damage could arise very quickly. Experience with reheat boilers at sea showed that, even with generous means of protection, reheater tubes were still more vulnerable to temperature than one would anticipate.

It had been remarked, by another speaker, that the question of the practicability of reheating was to be sought in the pipework rather than the boiler. He believed that the pipework was critical, but this did not minimize difficulties in the boiler, in fact it rather added to them. At high powers, reheating pipes obviously became unwieldy in their size. This forced the designers of such installations into adopting a high working pressure, and this in itself introduced further complications throughout the installation. The unhappy fact must also be considered that, when the reheater was cut out during astern running, a relative inefficiency arose and a greater amount of fuel had to be burnt for full astern than for full ahead power. When he looked at the proportions of the boiler shown in Fig. 15, he wondered if adequate thought had been given to this aspect of the problem.

*Hutchings, E. G. 1963. "The Design and Development of Two-drum Marine Boilers." *Trans. I.Mar.E.*, Vol. 75, p. 37.

Correspondence

Mr. D. J. Williams (Graduate) wrote that, in the paper, the results tabulated and conclusions drawn were obviously the result of the very best in forward thinking with minimum maintenance and economy of operation in mind.

In so far as the problems of deposits on superheaters needed to be considered, by far the main problem was the hard bonded deposit. The friable deposit could be cleaned from the lower gas temperature regions by soot blowers which had been fitted for many years. However, the use of long retractable soot blowers was essential, as pointed out in the paper, to reduce the bonded deposits and, to broaden this point a little further, only long retractable soot blowers, having nozzles of modern design and which were capable of delivering, on an economical basis, the high mass impact values which were necessary for restraining the build-up of these bonded deposits, should be fitted. A modern, long retractable soot blower lent itself extremely well to a fully automatic system, whereas non-retractable soot blowers in high temperature regions would continually give rise to maintenance work. A soot blower design compatible with automatic operation, capable of operating over an extended period of, say twelve to eighteen months, was obviously of the highest priority when the large single-boiler installations were proposed.

The paper indicated that effective long retractable soot blowers had assisted to a considerable degree in maintaining clean superheaters of modern design. It was always encouraging to a soot blower manufacturer, particularly one who had gone to great expense in research and in developing an effective long retractable soot blower, to see his contribution acknowledged in this manner.

Undoubtedly prevention was better than a cure and great emphasis had to be placed on high combustion efficiency and furnace design, and this, together with the continual research and development, by leading soot blower manufacturers, of their products would, it was trusted, give the boiler manufacturer strength to continue with the development of these newest and, in some cases, novel designs of marine boilers.

Commander W. J. R. Thomas, R.N. (Member) wrote that he was particularly interested in the section of the paper devoted to combustion, because he had himself striven to achieve high CO_2 and low oxygen figures in combination with large turn-down on naval boilers for several years. The author had implied that his "Racer" Y-jet burner could achieve a fuel rate turn-down of 6,000—150 or 40 : 1. To achieve good combustion over this range presumably entailed metering both the fuel and air over the same quantity turn-down. If these quantities were sensed, as was normally the case, in terms of pressure drops through orifices, this demanded measurement of those pressure drops, with reasonable accuracy, over a range of 40^2, or 1,600 : 1. The writer would be interested to know how this was achieved, for he himself had always found it very difficult to guarantee sufficiently good measurement, and hence control, of fuel and air to achieve a realistic 16 : 1 fuel input turn-down on spill burners. He had, on occasions, demonstrated 40 : 1 turn-down of these burners, under more or less laboratory conditions, but never under normal automatic control. While spill burners might not produce the exceptional atomization which one might expect of a well-designed steam atomizer, the control problem was surely identical in each case.

Author's Reply

The author replied that he was very pleased with the discussion, particularly since every point in the paper had received comment from at least one of the eminent contributors. Such a response was most gratifying. He was also pleased to hear in the oral, if not in the written, discussion that the majority of the contributors agreed on the following points:

i) the importance of the quality of combustion;

ii) that at present the future prospects for marine steam machinery looked brighter than they had been for some few years;

iii) that, if these prospects were to be realized, it was essential to obtain the correct balance between initial cost, fuel consumption and simplicity, and that the design of machinery should not be over-complicated purely in the search for an exceptionally low fuel consumption;

iv) that membrane tube walls should be attractive for future marine boilers of the larger powers.

He agreed with Mr. Falconer that there were advantages to be gained in concentrating the manufacture of marine boilers in a small number of factories specializing in this type of production. The half-width fin membrane tubes suggested by Mr. Falconer had obvious advantages and, in fact, the author's company were shortly to place in production a machine suitable for producing such tubing. This, as Mr. Falconer had suggested, would further simplify repair work and also reduce production costs. He appreciated Mr. Falconer's desire for more information on prices which would enable him to make a more accurate assessment of the relative merits of possible alternative arrangements of plant. Unfortunately, the fact that, at present, boilers were manufactured by a large number of shipyards reduced the value of any such data since there was naturally a considerable variation in costs between these various manufacturers and possibly an even greater variation in prices for identical equipment, so that comparisons based on one company's figures could be quite misleading.

Mr. Falconer was correct in believing that the author's company took the question of casing design very seriously and considerable improvements had been made in this area in recent years. So much so that, in a modern boiler, the casing leakage should be extremely small while still allowing adequate and simple access and low initial cost. The question of the tightness of the casings had also been raised by Commander O'Hara and the author could assure him that, from the point of view of operating with a low oxygen content in the flue gases, this presented no great problem on a modern boiler. It was true that the casing pressures involved for naval vessels were higher than in merchant ships, but the difference might not be quite as great as Commander O'Hara believed since it was not unusual for the fan design pressure in a tanker to be 25 in. w.g., and in passenger ships higher figures had been used.

Mr. Hutchings said that he was grateful to Commander O'Hara for his remarks on the life of boiler tubes in the Royal Navy which also served to answer Mr. Falconer's queries on this subject.

The number of boilers chosen should depend, to a large extent, on the type of vessel and the service for which it was required, and no hard and fast recommendation could be made to cover all cases. As Mr. Falconer had pointed out, in some vessels a two-boiler solution was more attractive than a one or one and a half boiler scheme from all points of view. The important thing was that the number of boilers should be considered and the right choice be made for the particular vessel, taking into account cost, availability, simplicity of operation, port duties and requirements for an emergency "get-you-home" service.

In answer to Mr. Falconer and Mr. Bridle, the author

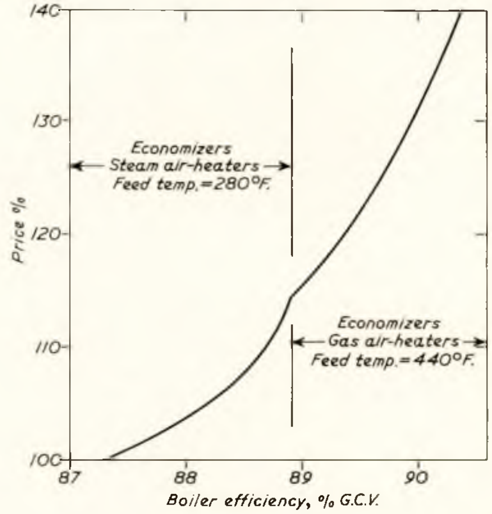

FIG. 17—*Effect of efficiency on total boiler price*

introduced a curve, Fig. 17, showing more explicitly the effect of boiler efficiency on cost, with both air-heaters and economizers, and agreed with these two speakers that reliability and low maintenance were more likely to encourage the more extensive use of steam machinery than any small reductions in fuel consumption. He hastened to add that the curve represented the variation in price in one particular application and the picture might be different for other vessels.

Mr. Bridle had raised some very pertinent questions. The author stated that the experience gained with the M.10 boiler was at present most satisfactory and, after over twelve months service without water washing, the superheaters had been quite clean. He felt that the radiant and two-drum boilers illustrated in the paper would be even better. Mr. Bridle and Commander O'Hara would appreciate that the radiant boiler was a comparatively recent arrival on the scene and at present it was difficult to determine precisely the range over which the radiant boiler had an economic advantage over the two-drum design. They would also appreciate that the "novelty" of the radiant design might cause it to be unattractive to the more conservative owners until considerable sea experience had been obtained, and for this reason alone he did not expect the radiant boiler to completely displace the two-drum unit for some considerable time.

The majority of studies which had been carried out in the past had shown that the "split economizer" system mentioned by Mr. Bridle had little to offer when compared with a gas air-heater system in terms of first cost and fuel consumption. The "split economizer" also required more complicated piping than either the conventional "air-heater" or "economizer" cycle. He was sorry if he had created the impression that he did not like gas air-heaters, as this was quite untrue, and the decision as to whether or not a gas air-heater should be included must depend upon considerations of economics, space and weight, since, with modern design techniques, there should be no problem in producing a reliable gas air-heater requiring little or no maintenance.

As mentioned by both Mr. Bridle and Dr. Davis, reheat had only been given a small space in the paper. This was intentional. In a recent paper by Mr. T. B. Hutchison*, the design illustrated had already been discussed in some detail and, in any case, the author considered that the importance of reheat in the recent advances in marine steam machinery design had been over-exaggerated. As far as he was concerned, reheat could now be applied to steam machinery with greater confidence, greater simplicity and at a lower cost than had been possible in the past, but this did not mean that it should be adopted for all vessels and, generally speaking, reheat should only be used when a sound economic case could be made for its adoption. He doubted whether such a case could be made, except for high-powered vessels operating on long trips and having very little time in port. While on the subject of reheat, he was grateful to Dr. Davis for pointing out that the heat rate required in such an installation for the astern power specified was often equal to, or greater than, the maximum heat rate in the ahead condition. This point was frequently overlooked but, on the other hand, he questioned whether the astern power currently specified was realistic, particularly for large vessels, and felt that a much lower power could be accepted without prejudicing the safety of the ship.

Most of the speakers had introduced the question of oil burning. The comments from Commander O'Hara were particularly valuable as, not only did these introduce the experience of the Royal Navy, but it should be remembered that the combustion-testing facilities operated by the Ministry of Defence were among the most extensive in the country and were closely related to the practical requirements of marine boilers. The residence time required was, to a large extent, a function of the efficiency of the burner/air register combination and the improvements which were currently being effected by the Ministry of Defence in this respect should be of significant advantage to all. The author regretted that he was not fully acquainted with, or permitted to give, full details of this work, but he understood that a large proportion of the available data was likely to be published later this year. In reply to Commander O'Hara and others, the author felt that the real reason for the superiority of the Y-jet was the high quality of atomization, particularly at low loads. It was possible that the introduction of steam also helped, but this had certainly not been proved and, in land boilers, similar experience had been found with Y-jet burners operating with compressed air. In these cases, the improvements were less marked, as the original problems had been less severe than those in some marine boilers. In the author's opinion, the Y-jet was always superior to other oil burners and the degree of superiority increased as the problem of boiler cleanliness increased. As pointed out by Mr. Carter, with pressure atomizing tips, a small degree of wear could produce a large change in output. This was less important with a Y-jet, partly because the orifice sizes were greater and also since there were no sharp-edged orifices, so that the rate of wear was reduced. Also the Y-jet atomizer should not require cleaning as frequently as the pressure jet. Marine boilers should in any case not be so sensitive as large land boilers, from the point of view of air and oil distribution, due to the smaller number of burners. The reduction in corrosion and greater cleanliness experienced with the Y-jet was, in the author's opinion, due partly to the reduced amount of solids in the flue gases and partly to a reduction in the excess air. He regretted that he was unable to give Mr. Carter any exact numerical comparison in the corrosion rates with Y-jets and pressure jet burners, but would refer him to the remarks in the Author's Reply to his earlier paper†.

Any comment on oil burners would, of course, be incomplete without reference to the contribution by Mr. Bolt. He felt that Mr. Bolt's company was to be congratulated on selling such a large number of burners; however, the statement in the paper was not a misprint. The author would repeat that he considered the "Racer" type Y-jet burner to be, without doubt, the most successful in use at sea today, this assessment being made from the point of view of a boilermaker in that less trouble was experienced in boilers due to deposits, corrosion and general fire-side maintenance when Y-jet burners were adopted. Also, in vessels where the oil burning system had been changed over from pressure jets or steam assisted burners to Y-jets there had been a significant reduction in the fire-side maintenance. With regard to Mr. Bolt's query on the ability of the "Racer" burner to operate over a range from 150 lb./hr. of oil to 6,000 lb./hr. of oil, he would firstly refer him to the contribution by Commander O'Hara. This achievement was in a furnace slightly shorter than the well-known *Whitby* Class Frigate boilers. Admittedly in achieving this the total register resistance had approached 30 in. w.g., but similar turn-downs had been possible on other boilers with larger furnaces and with a maximum register resistance of between 12 in. and 15 in. w.g. He agreed with Mr. Bolt that "it would be a job for anyone involved in the commercial world to sell a register with a resistance of 30 in. w.g. to anybody" but he would also suggest to Mr. Bolt that it was unlikely that anybody in the commercial world would expect an oil burner manufacturer to burn 6,000 lb./hr. of oil per burner in a furnace less than 6 ft. 0 in. deep. Further, in the installation referred to by Commander O'Hara, the same burner operated in the same furnace with an oil flow per burner of 3,800 lb./hr. with a resistance of 10 in. w.g., which was comparable to the figures at maximum power in many merchant installations, thus exhibiting a turn-down from 3,800 lb./hr. to 150 lb./hr. He would also mention that the minimum output referred to by Commander O'Hara was the minimum attempted, and lower outputs were both possible and practical on the same burner. The reduction in steam consumption between the Y-jet of a few years ago and the current "Racer" tip was due largely to the elimination of tip leakage and an increase in maximum oil pressure. Older versions operated at maximum output with oil and steam pressures of 100 lb./sq.in. and 150 lb./sq.in. respectively. With the "Racer" tip, the maximum oil pressure could be increased to 300 lb./sq.in. without any increase in the steam pressure.

The author felt obliged to answer the numbered points in Mr. Bolt's contribution as follows:

1) The modifications to the oil-burning equipment and the combustion and remote control system in the *Esso Warwickshire* had been carried out for the purposes of field research so that cost had not been the prime consideration. In fact, the system included certain areas of duplication which would not have been considered if the object of the exercise had merely been to improve combustion and reduce crew. Even so, he believed that the owners were happy with their investment.
2) Prior to the modifications, the *Esso Warwickshire* was not suffering unduly from fire-side deposits, partly due to the inclusion of long retractable soot blowers in the superheater zone, but the improvement in the fire-side condition was very obvious and he understood that the ship's staff considered that the soot blowers need not be used as frequently as before.
3) The *Esso Warwickshire* was originally fitted with conventional pressure atomizers in "Iowa" registers.
4) The *Esso Warwickshire* took her bunkers in the United

*Hutchison, T. B. 1966. "30,000 s.h.p. Unitized Reheat Steam Turbine Propulsion." *Trans. I.Mar.E.*, Vol. 78, p. 109.

†Hutchings, E. G. 1963. "The Design and Development of Two-drum Marine Boilers." *Trans. I.Mar.E.*, Vol. 75, p. 63.

Kingdom and, therefore, had had a variety of fuels both before and after the refit.

5) The combustion chamber dimensions were typical of contemporary marine two-drum boilers and as illustrated in Fig. 9 of the author's previous paper*.
6) At maximum power each register burnt 2,000 lb./hr. of oil with a resistance of 6·5 in. w.g.
7) The accuracy of the oxygen meter was not guaranteed, since this was installed primarily to give seagoing experience with this type of equipment. For this reason, the oxygen meter was repeatedly checked with an "Orsat" apparatus so that the readings obtained could be considered reliable.
8) The oxygen meter was arranged to take its gas sample from below the air-heater directly after the boiler.

The author thanked Mr. Culver for his kind remarks and the useful historical background which he had provided and certainly hoped and believed that the future of marine steam machinery would provide ample opportunity for the healthy and friendly competition, to which Mr. Culver referred and which the author agreed was essential to progress and an asset to boiler design in this country. Referring to some of the specific points raised by Mr. Culver, he agreed that the evolution of superheater design started long before 1962, but the data included in the paper were confined largely to progress subsequent to that date. The author had tried to point out in the paper that, if the furnace rating was reduced to a very low figure, disadvantages would follow which could outweigh the benefits of the low furnace rating and the designer should make every effort to effect the correct balance between the furnace rating and other factors in the design, but, of course, he was bound to agree with Mr. Culver that, if in doubt, it was better to err on the low side when selecting the furnace rating. He was aware that Mr. Culver's company had, in the past, frequently adopted a different solution to the problem of slagging superheaters, and indeed the author had mentioned this in his previous paper*. The well-known ESD boiler had the superheater in a zone of low gas temperature, so that bonded deposits were unlikely, but the superheater characteristic was far less favourable than in a conventional two-drum boiler. The designs being offered currently by most companies were an attempt to produce a successful compromise. To avoid bonded deposits, a high temperature superheater was located in a low temperature gas zone. The primary superheater, which was less susceptible to bonded deposits, was located in a high temperature gas zone before the secondary superheater, thus maintaining the better superheater characteristics associated with a conventional two-drum boiler.

The author wished to point out that he did not consider roof-firing in itself to offer any advantages from the combustion point of view. The radiant boilers illustrated had burners in the roof and this design had been developed as a simple method of providing long flame travel and not specifically to facilitate roof-firing. In a two-drum boiler, the choice of position of the burners was, in the author's opinion, largely a question of arrangement in the ship and probably, from the point of view of combustion and gas distribution, the best choice was to have the burners arranged in a vertical straight line in the front wall of a wide furnace, but the disadvantages of alternative arrangements were probably marginal. If one considered combustion alone, the best solution was probably upward-firing, with burners in the floor as was sometimes used in refineries, but this, so far, had proved unacceptable or unpractical for marine boilers.

With regard to the choice of materials for air-heater tubes, the author had a preference for steel tubes with vitreous enamel coatings, as he was not fully convinced that glass tubes would give satisfactory service in marine boilers, for the reasons stated in the paper. The advantage of having an end fixing which was suitable for either glass or vitreous enamelled air-heater tubes was that the final choice could be left until the contract was well advanced and while, as stated, the author himself would prefer vitreous enamel, he was perfectly aware that certain owners had a strong preference for glass tubes. Mr. Culver was quite correct in stating that vitreous enamelled tubes were often secured to steel tube sheets by spot welding. This method had proved satisfactory, but the author considered the method shown in the paper to be superior, since the sealing arrangements were more effective and tube replacement was easier. It was, of course, intended that vitreous enamelled tubes should avoid the necessity for replacement due to corrosion, but the tubes might become damaged for other reasons.

The author felt that Mr. Milton was unnecessarily pessimistic in his interpretation of the statistics of boiler failures. Taking Mr. Milton's own figures, it could be seen that, over a five-year period, there were 142 cases of boilers becoming inoperative out of a total of 900 ships. Since the majority of these vessels would have had two or more boilers, this therefore represented at least 1,800 boilers. These statistics could be interpreted as implying 142 failures in over 9,000 boiler years, or alternatively, that the chance of a boiler failure was one in every 60 years of its life. When it was borne in mind that these statistics were from older vessels which had in any case been in service for some time, the author would consider that these data were favourable to the adoption of a single boiler. There was an added psychological advantage in that, with only one boiler in the vessel, the operators were likely to be more careful of their water treatment and water level than would be the case in a two-boiler ship and this in turn should reflect in greater reliability. The author was pleased to see, however, that Lloyd's Register of Shipping had no objection in principle to a single main boiler installation and welcomed Mr. Milton's suggestions for alternative "get-you-home" arrangements. Mr. Milton would appreciate that as the usage factor decreased, the importance of the fuel bill also became less and it was for this reason that the break-even power between steam and Diesel was lower with lower usage factors.

The author would like to point out to Mr. Milton that the gas temperature entering the superheater, on the radiant designs shown, was not very much different from that in a corresponding two-drum boiler and, as already explained, slagging of the superheater was avoided by locating only the primary superheater in the hot gas temperature zone which in turn provided a stable superheater characteristic. The opening, at the bottom of the membrane wall separating the furnace from the convection heating surface, was made by omitting the membrane in this area and bending the tubes to form a staggered screen. The rate of heat transfer in this area was conservative compared with the rate of circulation available with this type of boiler.

The author shared Mr. Milton's view that pressure combustion should offer advantages in that better mixing of oil and air could be obtained, combustion would be more rapid and more complete, with corresponding beneficial effects on efficiency and cleanliness. Several studies had been made of this problem and some boilers had been built and operated with varying degrees of success but, so far, nobody had been able to produce a design which was commercially attractive.

The author thanked Dr. Davis for emphasizing the importance of effecting the correct compromise between efficiency, cost and simplicity of operation and installation.

In reply to Commander Thomas, the author said that the turn-down from 6,000 to 150 lb./hr. of oil, which had been demonstrated with a "Racer" tip in a naval boiler, was achieved with hand control, since automatic control was not available. He appreciated Commander Thomas' scepticism about the ability for this to be repeated with automatic control, but, from experience with merchant ships, felt that this was both possible and practical, providing the correct equipment was chosen. Referring to Fig. 2 of the paper, one method of achieving this was to have a large and a small oil fuel control valve in parallel with each other using split range control. The oil flow transmitter was of the "area meter" type. A similar method was required for metering air if the correct air/fuel ratio was to be maintained over the full range, and arrange-

*Hutchings, E. G. 1963. "The Design and Development of Two-drum Marine Boilers." *Trans. I.Mar.E.*, Vol. 75, p. 37.

ments must also be included to reduce the air quantity down to the very low figures required at minimum load. With the usual type of fan used in merchant ships having inlet vane control, this would imply either speed control or the use of an additional discharge damper. Recently a new type of fan had appeared on the market using a combination of inlet vane control and air recirculation within the fan. This design was reputed to give a much wider turn-down of air quantity than had been possible with earlier types.

The author thanked Mr. Williams for his contribution which served to amplify the advantages of long retractable soot blowers. He was, however, rather disappointed to see that Mr. Williams was proud of the fact that his blowers were capable of operating over "an extended period of, say, 12 to 18 months", since the author's company and others were working towards an eventual target of four years boiler operation without maintenance and had already passed the 18 months point in some installations.