## 3.

# MACHINERY WEIGHTS IN MODERN WARSHIPS.

The lightness of the machinery in contrast to the power developed has been always a characteristic of Naval designs when compared with those employed in the Mercantile Marine, and this feature is, of course, an essential factor in the constant effort to improve the fighting qualities of warships. The Treaty for the Limitation of Naval Armaments, concluded at Washington in 1921, has served to intensify the demands for the reduction in machinery weights, since, with a strict upper limit to the permissible displacement of each class of ship covered by the Treaty, it is evident that additions to the armour or armament can only be made at the expense of the machinery or of the habitability of the vessel.

The leading characteristics of the vessels built by the principal Powers to these " standard " displacements would be of great interest were such details available, as is unfortunately not the case. Press reports regarding speeds, horse-powers, machinery weights, guns and protection must be accepted with due reserve, bearing in mind always that any apparent marked advantage possessed in one or more features by a particular vessel over another of the same total displacement is probably accompanied by a deficiency in other less obvious directions.

Thus, if two 10,000 tons cruisers have identical speeds and protection, but one carries more guns that the other, then, given equally good design, the former must have sacrificed (say) either reliability and durability of the machinery or some gunnery feature, such as speed of loading or angle of elevation, in order to compensate for the weight of the additional armament. Minor differences can and will appear due to variations in design and workmanship, while the use of special materials may account for small changes in weight as between similar designs: it must, however, be accepted as a fundamental fact that a definite penalty has always to be paid for weight cutting. The main characteristics of a particular warship represent therefore the designer's compromise between the various conflicting requirements, which must be satisfied if the vessel is to carry out adequately her allotted function.

It is obvious that various conceptions may obtain as to the relative importance of speed, armament, and armour in a particular class of vessel, while the proportions of the total available weight allotted to these items may be influenced by such factors as whether the vessel is expected to remain absent from her home ports for prolonged periods, whether she is built with a view to war in distant or in home waters, and many other considerations of a similar nature.

Any just comparison of two vessels must therefore take all such points into account and cannot fairly be made without this knowledge, which is necessarily but seldom available. Broad deductions are, however, very frequently made from statements in the Press, and it may therefore be of general interest to review the various factors which influence the weight of the machinery installation, thus enabling an intelligent opinion to be formed regarding the different directions in which lightness may be sought.

The principal factors governing the machinery weights may best be discussed under the following headings :—

(1) Design of boilers.
(2) Efficiency at full and reduced powers.
(3) Revolutions.
(4) The ship arrangements.
(5) The auxiliary machinery.
(6) Factors of safety and special materials.

(1) **The design of the boilers** depends primarily upon the class of fuel to be burned and upon the type of boiler employed. Modern requirements can best be met by the adoption of small tube boilers, burning oil fuel, and the following remarks are confined to units of this type.

The weight of the boilers in an installation of given power may be reduced in three principal ways, the effects of varying each of these being treated separately.

(a) *Increasing the size* of individual units results in a definite saving in weight, but the possible increase is limited mainly by the maximum length of the flame from an oil fuel sprayer, and this limit has already been closely approached. The maximum length of a boiler in existing designs is also restricted by the necessity for providing sufficient room in which to withdraw the superheaters, any increase being thus accompanied by a similar addition to the stokehold dimensions if the degree of superheat is to remain unaltered. The length of the boiler compartment is in turn limited by considerations regarding the maximum dimensions of any individual compartment in a given ship, in view of the effect upon stability should flooding occur.

The heights and widths of individual boilers are similarly restricted by ship space considerations, and on this account alone it is not, in general, possible greatly to exceed the present dimensions. The height is in any case limited by the length of boiler tube which can be fitted without risk of overheating in highly forced boilers—here again the limit appears to have been reached with tubes of the present standard diameters. Both height and width alike are influenced by the slope of the boiler tubes, a factor which has a definite bearing upon the circulation of the feed water and thus upon the maximum safe rate of forcing.

The existing designs, however, by no means mark finality, and new developments, such as double-ended types, arrangements not requiring large spaces for the withdrawal of superheater elements, or even radical changes in the disposition of the heating surfaces, may be necessary in order to fulfil future requirements. The foregoing remarks must thus be read as applying to existing designs only, but will serve to indicate some of the improvements which are being sought after.

(b) *Increasing the rate at which fuel is burned* per sq. foot of heating surface will lead to a reduction in boiler weights but not to the extent that would be anticipated. Increased forcing involves a reduction in the efficiency of the boilers and is further accompanied by increased steam expenditure for the fans and fuel pumps, together with the necessity for either increasing the size of these units or for accepting reduced reliability if these auxiliaries are more severely pressed. The military qualities of the vessel will be also affected in so much as the endurance for a given fuel stowage is reduced.

The most important consideration from the engineering maintenance aspect is that the life of the boilers is directly affected by the rate of forcing, which primarily concerns the conditions of heat transference at the rows of tubes exposed to the flame. Experience indicates that the limiting rate has been closely approached in boilers of the T.B.D. Class, where both the reliability and life are markedly less than in the case of the boilers of the less highly forced units in the larger ships.

A comparison between the boiler weights per S.H.P. in the various classes of vessel is afforded by the Table on p. 16, from which it will be seen that in passing from a rate of burning oil of 1·0 lbs./ft./H.S. per hour in the cruiser to one of 1·3 to 1·4 in the T.B.D. a saving in weight of only 1·0 lbs./S.H.P. or 2·0 per cent. of the total weights is effected : a trivial reduction when compared with the attendant disadvantages, and one which can only be legitimately adopted in vessels where high speed is a paramount requirement and where the machinery weight comprises a large percentage of the total weight of the vessel.

The smallness of this reduction is due to the fact that the heating surfaces proper account for only a fraction of the total weight of a modern water-tube boiler and that savings made in this manner are not accompanied by proportionally similar benefits as regards the steam drums and the brickwork.

The brickwork accounts for no small proportion of the total weight of the boilers, and it is evident therefore that, if means can be found whereby greater quantities of fuel can be burned in a given combustion chamber without unduly stressing the fire row tubes, a welcome reduction in weight may be achieved even if the actual boiler heating surfaces have to be increased. Alternatively, it is possible that these relatively heavy refractory walls, which serve no useful purpose in heat transmission, may eventually be displaced by useful heating surfaces, as has been successfully carried out in power station practice. It should be observed, however, that the glowing brickwork is of value in ensuring ignition of the oil fuel, and that the operation of a completely water-cooled furnace may be somewhat different to that of one of normal type. The principal barrier to such an

TABLE.

| Item. | Battleship. Revs./min., 160. | | Battle Cruiser. Revs./min., 210. | | Cruiser. Revs./min., 300. | | T.B.D. Leader. Revs./min., 360. | | "P." Boat. S.H.P., 4,000. Revs./min., 300. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Weight. Lbs./ S.H.P. | Per cent. Total Weight. | Weight. Lbs./ S.H.P. | Per cent. Total Weight. | Weight. Lbs./ S.H.P. | Per cent. Total Weight. | Weight. Lbs./ S.H.P. | Per cent. Total Weight. | Weight. Lbs./ S.H.P. | Per cent. Total Weight. |
| 1. Turbines - - - - | 10·4 | 10·1 | 8·6 | 10·2 | 5·0 | 10·8 | 5·2* | 15·0 | 9·7 | 10·3 |
| 2. Gearing - - - - | 11·0 | 10·7 | 7·4 | 8·8 | 4·0 | 8·7 | 3·5 | 10·0 | 6·7 | 7·1 |
| 3. Main condensers - - | 4·9 | 4·8 | 4·3 | 5·1 | 2·5 | 5·5 | 2·0 | 5·8 | 5·7 | 6·0 |
| 4. Propellers and shafting - | 13·2 | 12·9 | 13·1 | 15·5 | 4·5 | 9·7 | 2·8 | 8·2 | 9·9 | 10·4 |
| 5. Boilers - - - - | 18·3 | 17·9 | 17·0 | 20·2 | 13·1 | 28·5 | 12·1 | 35·2 | 27·6 | 29·2 |
| 6. Uptake and funnels - - | 4·3 | 4·2 | 4·3 | 5·1 | 2·5 | 5·4 | 0·7 | 2·1 | 1·1 | 1·2 |
| 7. Steam and exhaust pipes - | 7·8 | 7·6 | 7·4 | 8·8 | 3·7 | 8·1 | 2·5 | 7·2 | 7·0 | 7·4 |
| 8. Water and oil pipes - - | 6·7 | 6·6 | 5·9 | 7·0 | 3·8 | 8·4 | 1·0 | 2·9 | 4·9 | 5·2 |
| 9. Steering gear - - - | 1·6 | 1·6 | 0·5 | 0·6 | 0·6 | 1·4 | 0·2 | 0·7 | 3·1 | 3·2 |
| 10. Evaporators - - - | 1·9 | 1·8 | 0·9 | 1·1 | 0·6 | 1·3 | 0·2 | 0·5 | 1·2 | 1·3 |
| 11. Workshop machines - | 1·7 | 1·7 | 0·7 | 0·8 | 0·3 | 0·6 | — | — | — | — |
| 12. Auxiliary machinery and fittings - - - - | 18·7 | 18·2 | 13·0 | 15·4 | 4·9 | 10·6 | 4·0 | 11·6 | 15·0 | 15·8 |
| 13. Floor plates, ladders, &c. - | 1·9 | 1·9 | 1·3 | 1·5 | 0·5 | 1·0 | 0·3 | 0·8 | 2·8 | 2·9 |
| Total - - - | 102·4 | — | 84·4 | — | 46·0 | — | 34·5 | — | 94·7 | — |

* Separate cruising turbines.

arrangement for marine work lies in the difficulties associated with ensuring a proper circulation of the feed water in such units under conditions of very rapid variations of output. These difficulties should not, however, be insuperable, and the course of boiler development may well be along some such avenue.

(c) *Reduction in the scantlings of the pressure parts.*—The thickness of the pressure parts of the boilers is decided by three main requirements, namely, strength, reasonable life under the influence of corrosion and, in the case of the tube plates, the necessity for providing the required length of contact to ensure an efficient rolled joint between the tubes and the plate.

Modern investigations of the causes of corrosion and the application of devices for minimising this action have now advanced sufficiently to render it probable that the thicknesses of the tubes may be reduced in future without a corresponding reduction in the life of these parts. The stresses due to heat (arising from the difference of temperature between the inner and outer walls) are, in the case of tubes near the furnace, much in excess of that due to the internal steam pressure: accordingly, the total stress on a thin tube may be less than that in one of thicker gauge.

The other requirements are, however, less susceptible to arbitrary treatment, although some small reduction in tube plate thickness may be anticipated from a slight rearrangement of the tubes. So far as thickness is decided by the strength necessary to prevent bursting, the only methods of effecting a reduction are by accepting a lower factor of safety or by the employment of special steels: the former alternative is evidently not acceptable, while the latter is dependent upon the results of the experience with these materials in shore station practice, since the possible savings do not justify experiments of this nature in naval boilers.

It has been suggested by some designers that the scantlings of the boiler pressure parts may perhaps be beneficially reduced in order to give increased flexibility. This proposal rests upon the probability that deterioration of the plates of the boiler drums and the like may be due to fatigue owing to "working" of the plates at positions where considerable changes of section occur; this action is made evident by the occurrence of grooves or cracks: if such changes of section were avoided by reducing the thicker parts, then this action might not occur and failure might thereby be avoided, despite the increased nominal stresses in the plating. As, however, the scantlings of the thicker plates in a water-tube boiler are determined entirely by considerations of properly securing the tubes, it would appear that but little prospect of altering these dimensions can be held out unless new methods of tube attachment are developed.

### (2) **Efficiency at Full and Reduced Powers.**

The dimensions of the turbines themselves, of the steam and other piping and of the boilers are necessarily determined by the total steam consumption at full power, and thus the efficiency under these conditions has a considerable bearing upon the over-all weight. To improve this efficiency in any modern design, it is necessary to employ larger turbines and to make use of special features such as heating the feed to high temperatures, preheating the air supply, etc., all of which can only be provided at the cost of additional weight. It is therefore a matter of no small difficulty to strike a proper balance between these conflicting factors, especially in view of the fact that the limitations on displacement decided by the Washington Conference do not include the weight of the fuel carried.

Efficiency at low powers on the other hand can be obtained with comparatively small additions to the over-all machinery weight, since in general it merely entails the use of a few special auxiliaries of small size, together with comparatively light cruising turbines or two or three additional stages in the main turbines.

The maximum output of the installation has some bearing upon the efficiency since small units are inevitably more expensive as regards steam consumption than large ones, certain losses being nearly constant whatever the output.

(3) **Revolutions.**

The revolutions of the propellers affect not only the weight of the reduction gearing, the propeller shafting, A brackets and stern tube bushes and that of the propellers themselves, but may also influence the weight of the turbines since gearing considerations may prevent the use of high-speed turbines in conjunction with low-speed propellers. Some 40 per cent. of the total machinery weight is affected directly by the revolutions, and it is estimated that in a modern cruiser a variation of 16 per cent. in the R.P.M. is attended by one of 30 per cent. in the weight.

The propeller revolutions are, however, intimately concerned with the propulsive efficiency and the adoption of high propeller speeds may be attended by an undue reduction in over-all efficiency, thus adding to the power and weight of machinery required to produce a given speed. High revolutions may also be accompanied by cavitation and pitting of the propellers, together with undesirable vibration of the ship's structure. Finally, the diameter of the propeller is influenced by the shape of the hull and the draught of the vessel, all of which must therefore be taken into account when settling the revolutions, since it is not practicable to increase greatly the tip speed of the propellers.

(4) **The Arrangement of the Machinery** in the ship is one of the principal factors influencing the over-all weight of the machinery, and, although in many cases somewhat arbitrary, any substantial alteration of the existing practice would involve departure from well-tried principles which are not only logical but which war experience has proved to be sound.

The type of vessel in general governs the degree of subdivision of the machinery compartments and duplication of the auxiliaries. It is the practice to provide these to a fair extent in the capital ships, in view of the evident importance of safeguarding the performance of these very important fighting units. The principle is followed to a much lesser extent in cruisers, while in T.B.D.'s there is practically none, all the machinery and fittings being required at Full Power.

Comparatively large numbers of small boilers and engines are fitted in capital ships, leading to a high weight per horsepower. Further, in such vessels, the floor spaces can be more generous, and the compartments are larger, thus entailing increased weight as regards piping, floor plates, ladders, etc. Owing to the size of the vessels of this class and to the number of power-worked appliances warranted by their high military value, auxiliaries are provided in parts of the ship remote from the machinery spaces, thus further adding to the weight. Finally the uptakes and funnels are necessarily heavier than in the smaller classes of vessel. The degree of subdivision of the machinery spaces also exercises its influence upon weight, a 4-shaft arrangement being in general heavier than one with two shafts. There are, however, advantages in the greater subdivision of a four-shaft design for a warship, and the difficulties which are introduced with the propellers when very large powers are transmitted by a single shaft have led to the general adoption of four-shaft designs for the larger cruisers.

(5) **The Auxiliary Machinery** exercises a sensible effect upon the weight, since although very light units are available, their adoption involves a sacrifice of efficiency and of reliability. Here again the tendency is to accept reduced reliability in the less valuable vessels and so to obtain a reduction in weight. As regards the steam consumption of the auxiliaries themselves, it is obvious that a compromise must be sought between this factor and that of weight.

The weight allotted to the auxiliaries will not necessarily follow the horse-power ratio, not only on account of the factors mentioned previously, but also because many of these units are dependent upon considerations other than the horse-power of the main turbines. For example, the capacity of the distilling plant depends chiefly upon the number of men carried, the steering gear is proportioned according to the speed of the ship, while its degree of duplication depends upon the class of ship. Electric generating machinery is more extensive in the larger vessels than in small ones, and, although the weight of this plant is not conventionally included in that of the machinery, yet it will exercise a definite effect upon the latter (*i.e.*, auxiliary condensers, boiler margin, piping, etc.).

The weight of the condensing plant is largely determined by the margin provided to meet adverse conditions, such as dirty tubes or high temperature of sea water. A past tendency has been to arrange the design so that the vessels can only realise their contract horse-power under the most favourable conditions; it is preferred, however, to design the larger ships at least for a power which they can be relied upon to obtain in any climate and when condensers and boilers are not clean. This requirement evidently can only be met at the cost of weight.

### (6) Factors of Safety and Special Materials.

The acceptance of lower factors of safety is an obvious method of reducing weight, and is at the same time the most difficult field in which to make rapid advances. Factors of safety cover the unknown or incalculable stresses which may arise in any structure or moving part, and are thus almost entirely empirical and can only be departed from with safety by a slow and gradual process of evolution. Advances in this direction are continuous and are made initially in the less important vessels, being gradually adopted in the larger units of the fleet as experience proves their value.

The use of special materials is dependent upon the progress of metallurgical knowledge and experience with the fruits thereof. Very light alloys are of comparatively recent introduction and their adoption is at present limited to parts which are not subjected to stress.

The use of special alloy steels with the object of taking advantage of their improved physical qualities is somewhat restricted by the difficulties which have been found in providing reliable articles of large size when made of such materials. Many of these alloys are dependent for their superiority upon the results of heat treatment, which it has been found impossible to apply with the certainty of obtaining uniformity of product in large masses.

The tendency is now towards the production of alloy steels in which superior qualities are obtainable without the application of heat treatment. Thus, pending development along these lines, or failing practical methods of surmounting the "mass effect" in heat treatment, the use of materials of this type will be chiefly restricted to small parts of the machinery exercising but little effect upon the overall weight. The use of cast steel in the place of cast iron for important parts of the machinery installation is gradually increasing, but has been retarded by the small progress achieved in the art of producing satisfactory castings of the desired thinness.

The statement is sometimes made that machinery weights have been considerably reduced in a particular vessel by the use of special high grade materials, but it will be evident from the foregoing that in such cases there will be an element of uncertainty introduced and the reliability of the machinery may have been prejudiced. Such a practice may be justified by particular circumstances, but in general cannot be upheld for valuable fighting ships, especially where these may be required for extended service on stations remote from modern engineering shops.

*Summing up*, therefore, it may be taken as certain that any general advances in Naval designs, in the direction of reducing the factors of safety or of employing special materials, must necessarily be slow, in order that the prime virtue of reliability may not be prejudiced. Reliability cannot be directly measured, but can only be judged by the results of prolonged experience, and it therefore follows that any departure from established practice should be subjected to the same acid test of time before it is widely adopted.