SOME POST-WAR DEVELOPMENTS IN NAVAL CONSTRUCTION

BY

SIR ALFRED J. SIMS, K.C.B., O.B.E., R.C.N.C., M.R.I.N.A., M.I.MAR.E.
Director General Ships, Admiralty

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INTRODUCTION

In many respects World War II can be said to have ended an era in naval construction—an era lasting a century in which there were large navies dominated by the battleship and the large-calibre gun. Much of this was made possible by the rapid development of steam machinery to which Andrew Laing made such a notable contribution between the 1870s and the 1930s including the two warships which bore the proud name of *Nelson*—that which was built at Govan from November, 1874 to July, 1881, and that built at Tyneside from December, 1922, to October, 1927.

World War II had a far-reaching effect on naval design. It showed the immense value of air power in naval operations ; it showed a great increase in the scope and destructive power of underwater weapons ; it showed a remarkable increase in scientific developments, particularly in detecting devices in the air, on the surface and under the surface ; scientific developments were applied to collecting and processing information in a form to fight a ship to much greater advantage ; the traditional conception of submarine operation was radically changed ; the development of atomic energy as a method of destruction gave hopes that it could be tamed as a method of ship propulsion.

These and other effects were to change the size and shape of navies. The battleship became of very limited value, the aircraft carrier became the capital ship of the immediate post-war era, cruisers declined in importance and their duties were shared between aircraft carriers and new types of frigates, attention was directed away from the gun to the guided weapon, the true submarine was at last in sight.

The advent of nuclear propulsion and more complex weapon systems, radio, radar and communications has greatly increased the cost of warships so that their size has to be severely restricted if reasonable numbers at sea are to be obtained. All navies tend, therefore, to be of smaller ships than formerly.

In the straining after maximum performance in warship designs, a valuable by-product is the stimulus given to technical features in merchant ships and shipbuilding. It is appropriate, therefore, that some of these features should be summarized from time to time and this lecture—in reviewing post World War II developments—has this purpose in view. Many of them will have been dealt with in more detail in papers before our learned Institutions and appropriate references will be given so far as practicable.

The next section will therefore give a quick survey of some aspects of warship design developments since World War II.

SELECTED WARSHIP DEVELOPMENTS

Ship Hydromechanics

The importance attached by the great maritime nations to developments in this field can be judged by the tremendous growth since the war of major hydromechanic facilities.[1] The British Admiralty has not been slow to appreciate the dividends which can be reaped by such research, despite the heavy initial cost entailed. Post-war developments in this field will, therefore, be summarized by describing the objectives of the new facilities provided in the last decade.

It is perhaps even today not fully realized that while the main parameters of hydrodynamics can be clearly defined, their inter-relation, the segregation of their individual effects and their scale effects have yet to be fully rationalized by fundamental investigation. It was partly to fulfil this need for fundamental research that the rotating-beam channel and cavitation tunnel were installed at the Admiralty Research Laboratory, Teddington, in November, 1955.[2] A considerable portion of the research programme at this establishment covers fundamental investigations which are inseparably linked to general ship hydrodynamics ; for instance, the stability and control of underwater bodies, boundary-layer investigations, the mechanics of the phenomenon of cavitation, and the stability, ventilation and performance characteristics of underwater foil configurations.

Special requirements need special and individual attention both as regards fundamental and applied research and mention must be made of other Admiralty Establishments engaged in the hydrodynamic field, namely, the Underwater Detection Establishment and Underwater Weapons Establishment at Portland. Naturally there is a strong liaison between these Establishments and the long-standing Admiralty Experiment Works at Haslar,[3] where the overall problem of ship hydrodynamics is dealt with both theoretically and empirically. In many cases items of research are carried out by two or more of these hydrodynamics establishments in close association.

The naval operations of World War II made abundantly clear the need for close attention to three main fields of investigation—seaworthiness, manœuvrability and—in the case of submarines—general hydrodynamic design for high submerged speed. Some tentative approaches, theoretical and empirical, had been made towards the solution of the many complex problems in all three fields, but were severely restricted by the lack of suitable facilities. Ship motion studies with the exception of the well-established work on the rolling of ships had been confined to experiments to measure pitch and heave in regular head seas, and no methodical attempt had been made to ascertain the effect of changes in above-water form on motion or such qualities as wetness. Manœuvrability was generally taken to mean ' turnability ' in terms of the geometry of the turning circle as affected by the dimensions of the ship, her rudder(s), and underwater profile. In the design of submarines, some sacrifice had to be made in submerged qualities in order to secure adequate surface qualities until the last stages of the war.[4]

The new manœuvring tank at Haslar will combine, under one roof, all the necessary facilities to extend our knowledge in these fields : indeed, it has already begun to make real contributions in some of them.[5 & 6]

Seaworthiness

For the weapons and defence equipment of a modern warship to be effective it is necessary for the ship to be able to maintain relatively high speed (compared with pre-war standards) in inclement weather conditions and, while doing so, to provide a reasonably dry and steady platform. By suitable choice of hull

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[1] Numerals refer to list of References at the end of the paper.

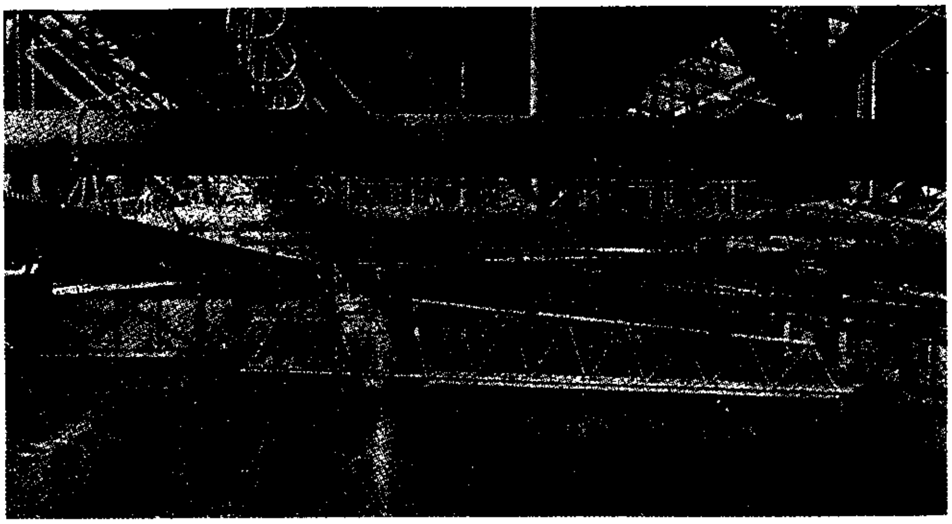

FIG. 1—NEW MANOEUVRING TANK AT ADMIRALTY EXPERIMENTAL WORKS, HASLAR, SHOWING ROTATING ARM

shape, i.e. fine bow waterlines and low prismatic coefficient, the sustained speed in heavy weather can be increased. Calm-water performance or performance at cruising speed must, however, not be greatly prejudiced. The best hull shapes for all such requirements often conflict and the relative importance of each must be considered in the light of the primary functions of the ship.

Rolling motion can be controlled by fitting active fin stabilizers and the present trend in warships is to use a number of fins of low aspect ratio in order to restrict outreach. Such fins are fitted in the plane of the bilge keel and can be fixed, thereby eliminating weight, space and the retracting machinery necessary with high aspect ratio fins.

Investigations carried out in recent years with models in regular waves in the ship tanks have already provided reliable guidance and have produced much success in our modern frigates. An original lead towards the assignment of freeboard and flare to achieve dryness has been given by similar 'regular wave' technique combined with simple statistical assessment of sea spectra.[7] The task now before us is to extend these restricted approaches into more realistic scaled-down versions of the irregular sea conditions met in service. The wave-making installation of the manœuvring tank is designed to do this, but the problem cannot be solved by model experiment and theory alone. Correlation of the response of the model with that of the full-scale ship in similar conditions is essential and this in turn requires simultaneous measurement of actual sea spectra and ship motion. This is currently being done in a *Whitby* Class frigate, and it is aimed to repeat the operation with an aircraft carrier.

Among all the problems confronting the hydrodynamicist of today this one offers the greatest challenge and yet perhaps is the most attractive. It calls for a combination of theory and experiment and co-operation between all authorities possessing similar facilities. Yet it promises no quick solution even though it must employ computers and automatic analysis methods.

Manœuvrability

For many years this term was taken to refer to the tightness of the turning circle for a given approach speed and rudder angle. The parameters affecting the manœuvrability in this sense were well established and it was known that change in some parameters could have opposite effects on directional stability and controllability, the two other important qualities embraced by the term. For example, an increase in the vertical area under the cut-up was known to reduce the tactical diameter but with a consequential reduction of directional stability and an improvement in controllability, or response to rudder.

In new designs different requirements arise according to the operational function which the completed ship has to fulfil and inevitably a compromise has to be struck between tactical diameter, controllability, and directional stability. To do this it is necessary to establish standards and this requires the development of theory and associated experiments employing new techniques. Some indication of the nature of the directional stability can be obtained from spiral manœuvres and a measure of the controllability, or response to rudder, from zig-zag manœuvres. This technique has already been introduced for full-scale ships and is about to be introduced for models in the manœuvring tanks (FIG. 1), the latter field involving no easy problem in the instrumentation required for good correlation.

To establish standards or criteria, however, as regards stability and response it is necessary to conduct model experiments in which the forces and couples at different speeds, turning radii and drift angles are measured. This is one purpose of the rotating arm.

Another advance which has taken place in the manœuvring tank is the measurement of rudder forces and moments under more realistic conditions in remotely controlled free models as opposed to the constrained model technique previously used in the ship tanks. Consequently, correlation with full scale should be more realistic. First tests indicate that the two methods give similar results up to angles of rudder of about ten degrees but beyond this there is a wide disparity in both magnitude and sense of the force and couple. At the same time the maximum values, as measured, are comparable.

Submarine Hydrodynamic Design

The submerged top speed of war-time operational submarines averaged 8 to 9 knots, associated with maximum surface speeds up to 20 knots. The change to submerged speeds of two to three times that of the war-time classes with the consequent greatly increased hydrodynamic hull forces and couples (proportional to the square of the speed) is the primary reason for the development of theory and experiments on dynamic stability. Above about 10 knots these greatly increased dynamic forces override the hydrostatic stability forces which are independent of speed. Broadly speaking the modern submarine has to be able to operate in a depth of water of about three times her length at three times the speed of war-time submarines, so that the time available for corrective measures is only about one-third of that previously available.

The need for automatic gear for control in depth and azimuth is at once apparent and considerable progress has been made. The latest submarines are being fitted with automatic control gear, the development of which again involves theory, analogue computer studies and full-scale trials for correlation. An analogue computer specially installed for this purpose and for the general study of dynamic and directional stability has been in use at the Admiralty Experiment Works at Haslar for two years.

For model work and in the absence of a rotating arm it has been necessary to determine the dynamic stability of the submarine by approximate methods employing models deliberately curved to specified radii and measure the stability derivatives when traversed on a straight path. This device has met with no small measure of success and fair correlation with full scale has been achieved. Investigations using straight models on the rotating arm, in both planes of reference have already been carried out and the earlier work has provided useful guidance. The results are being analysed and are expected to provide much more accurate correlation with the full scale. As previously pointed out a very high degree of accuracy is vital in this case of the submarine with its strictly limited range in operating depth. FIG. 2 illustrates a submarine

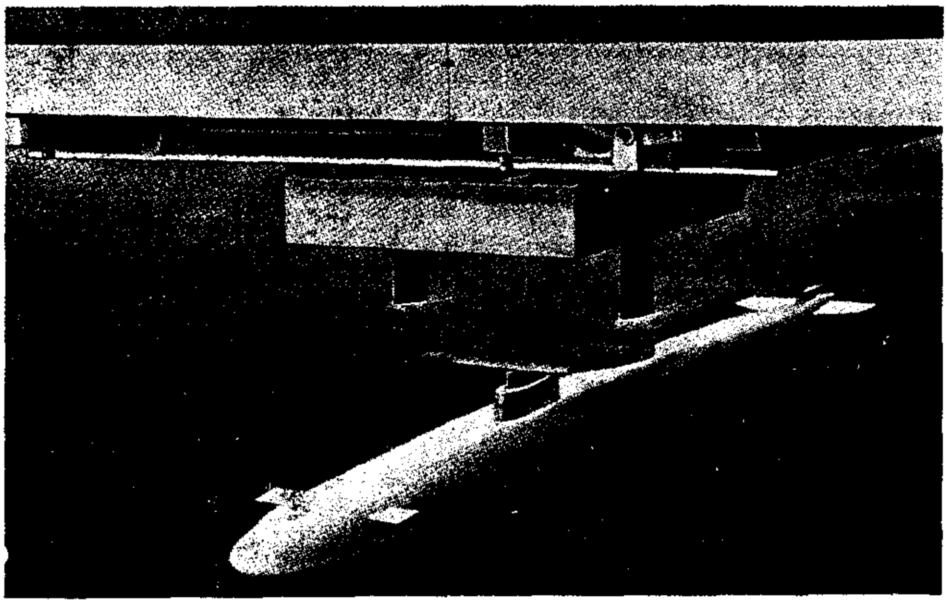

FIG. 2—SUBMARINE MODEL UNDER THE CARRIAGE IN MANOEUVRING TANK RIGGED FOR DYNAMIC STABILITY TESTS IN HORIZONTAL PLANE

model supported from the carriage on the arm, rigged for dynamic stability tests in the horizontal plane. In this case the model is rotated in the upright position while for tests of stability in the vertical plane it is rotated on its side in the horizontal plane.

To achieve the highest possible speed and make full use of the higher powers now becoming available, two radical changes in hull design have become necessary. First the external form of the ship has been designed completely for submerged performance, which means choosing a symmetrical shape of the minimum practical resistance consistent with accommodating all the machinery and equipment and at the same time obtaining a structurally smooth surface covered by a durable and smooth outer bottom composition. As regards hull form the problem of approaching the optimum form within practical limits presents little difficulty and the next step is to obtain the highest propulsive efficiency. Additionally only those appendages absolutely essential to the control and navigation of the vessel must be fitted, i.e. the bridge fin and casings, stabilizing fin, hydroplanes and rudders, and all of these must be reduced to the minimum size and smoothly shaped to reduce their resistance consistent with other factors.

The second change, and one for which much evidence existed at the end of the World War I with the ' R ' Class submarines, has been the adoption of a single- instead of twin-screw drive.

General

The foregoing notes describe the major advances in the ship hydrodynamic field since World War II, but there are others which are worthy of mention. Apart from the inconvenience of heavy hull vibration, the complex and in some ways delicate control systems associated with modern weapons and defensive equipment can be seriously affected by general hull vibration or by local vibration. Much progress has been made in the problem of suppressing vibration and, in particular, through the design of the propeller or propellers and their clearance from the hull.[8]

With another new facility—the large No. 2 Cavitation Tunnel at the Admiralty Experiment Works—the ability to test propellers behind actual large-scale hull

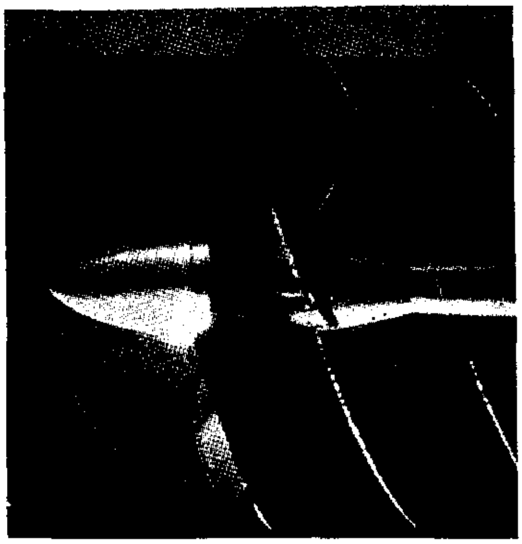

FIG. 3—FIVE-BLADED PROPELLER IN CAVITATION TUNNEL AT A.E.W., HASLAR

forms—known as hull/propeller combinations—has become possible. By this process the theoretical design of wake-adapted propellers is being proved by model experiments and first results appear to be fairly successful. It should be noted here that the size of tunnel necessary for such experiments is very large in comparison with the normal size in use. The new tunnel has a working section 8 ft wide and 4 ft deep and is thus adequate for the purpose (FIG. 3).

In the propeller-design field also, attention is still being given to the old menace of cavitation erosion which, quite apart from the damage caused to the propellers, can often necessitate dry-docking the ship to change them. Experiments are currently programmed to ascertain what changes in section shape in the affected areas are necessary to achieve a worthwhile reduction and whether, in fact, such changes will unduly affect the performance of the propeller as regards propulsion.

There is one other rather interesting case of development which at first sight might be regarded as not falling within the general field of ship hydromechanics; this is the improvement in the design of anchors.[9] Research in this field at the Admiralty Experiment Works has been rewarding and new designs of anchors are being introduced in all new construction ships.

Propulsion

Reference has already been made to the high operational standards required in modern warships and careful design of propellers plays an important part towards achieving these standards. Not only must the propeller be capable of exerting the necessary thrust to achieve the required speeds but the problems of cavitation, erosion and vibration must be solved. Understanding of these problems has been enhanced as more research facilities have become available at the Admiralty Experiment Works at Haslar and elsewhere.[10] Much has been achieved by careful correlation of results of experiments with model propellers with those of full-scale propellers, including observation of the latter through viewing ports in the ship's hull. Much, however, remains to be done.

Thanks to the co-operation of propeller manufacturers, higher standards of finish are being achieved in propellers, the propellers being made to closer tolerances with the object of approaching the standard of finish already possible with model propellers. There are no grounds for complacency in this field, and all concerned are co-operating with this in mind.

Vibration

The sensitivity of the equipment and the many instruments required in modern warships require a much lower degree of vibration than formerly in these vessels. Most vibration in H.M. ships is propeller excited and experience shows that by careful propeller design, followed by precision manufacture, effective reduction in vibration can be achieved. Appreciable success has attended the use of four- and five-bladed propellers, and it is now possible, through investigations carried out in the cavitation tunnels, to design multi-bladed propellers for high-speed ships without loss of efficiency.

Erosion

Although individual cases of erosion exist, the procedures in the design of present-day propellers are all aimed at reducing cavitation and, therefore, contribute to reducing erosion. The theoretical solution to the problem of cavitation erosion still remains unsolved although much research work has been, and continues to be, devoted to the problem by workers in various research organizations.

Controllable-Pitch Propellers

Since the end of World War II increasing use has been made of controllable-pitch propellers in H.M. ships with the result that frigates, minesweepers and tugs have been fitted with this type of propeller.

The widespread application of controllable-pitch propellers in H.M. ships has been limited—among other considerations—by difficult engineering problems in the design of boss necessary to accommodate the blade operating mechanism, problems which are aggravated by the more frequent use of four- and five-bladed propellers to reduce vibration. Another feature which tends to preclude the use of controllable-pitch propellers is the high blade area ratio of propellers in high-speed ships which may prove to be beyond the capacity of controllable-pitch propellers for satisfactory operation.

Materials

Progress in the materials used for manufacture has been made to give greater strength with reduction in weight. The high-tensile brass that was almost universally used ten years ago has been replaced in large vessels with nickel aluminium bronze. Nylon may overcome the serious erosion troubles usually experienced in small boat propellers and may have application to propellers up to 5 ft diameter.

Structural Design

An account of the post-war developments in structural design and the work of the Naval Construction Research Establishment at Rosyth was given by Sir Victor G. Shepheard in his 1956 Andrew Laing Lecture.[13] Present remarks will, therefore, be confined to later developments into :

(*a*) Research into underwater explosions and shock protection ;

(*b*) Development in structural analysis and testing.

(*a*) *Shock Protection*

Extensive trials against warship targets, supported by experimental and theoretical studies of underwater explosions, have shown that the resistance to shock is vitally dependent not only on the energy-absorbing capacity of the outer skin of the ship—and this demands particular attention to details with avoidance of stress-raising features, etc.—but also on the design of internal bulkheads. In order to contain the effects of underwater damage, these bulkheads must withstand the effects of an explosion which would rupture an adjacent compartment.

From the fully instrumented trials in target ships, it has been possible to deduce the correct strength to be given to bulkheads under edge loading so that they are neither too weak to permit excessive deformation, nor so strong as to cause premature failure of the bottom plating. Rules have thus been developed to aid rational design when taking into account the several different functions which bulkheads are called upon to perform.

Target trials on surface ships and submarines have shown the extensive damage which can be caused to machinery and equipment from shock waves. Data are now available which allow the severity of the accelerations and decelerations to be estimated for equipment situated in any part of the ship and

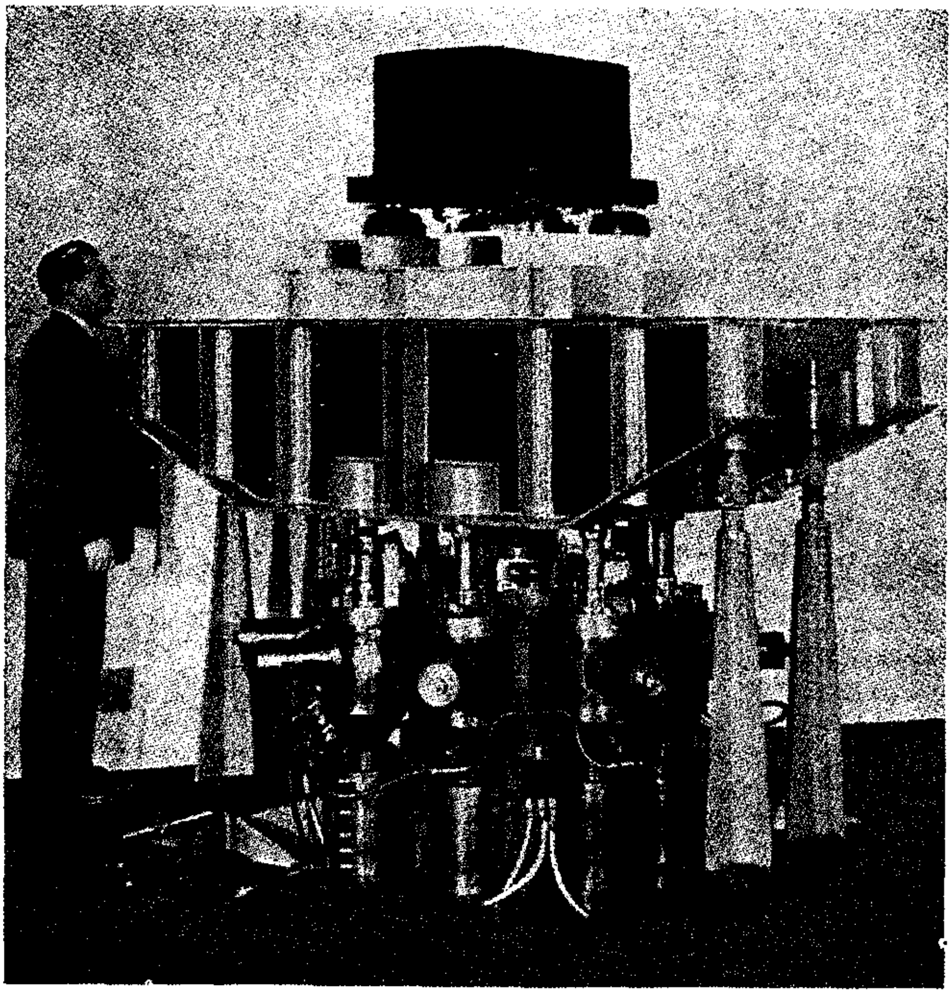

FIG. 4—LARGE SHOCK TESTING MACHINE AT THE NAVAL CONSTRUCTION RESEARCH ESTABLISHMENT, ROSYTH

these figures are taken into account in design. Effort has gone into the development of suitable shock-attenuating mountings to alleviate these effects and this work is still continuing. Many conflicting requirements have to be satisfied, including the effects of such mountings in reducing noise transmission and in controlling vibration.

Some equipment is not amenable to simple design against shock and only trials can prove whether it is satisfactory. Such trials could obviously take place by subjecting ships containing the equipment to underwater explosions, but this is both expensive and difficult to control. A new type of shock-testing machine has therefore been installed at the Naval Construction Research Establishment (FIG. 4). This enables equipment weighing about 4,000 lb to be subjected to accelerations and decelerations delivered by a special piston to the table to which the item is secured. Accelerations up to several hundred times gravity can be generated and the machine has proved invaluable, both for proof testing and for research into mountings.

(*b*) *Structural Analysis*

Probably the major developments in warship structural design have stemmed from our researches into the structural mechanics of ships. Much fundamental work has been done on the behaviour under load of panels of stiffened plating. Two aspects of this work may be distinguished : the study of individual plate panels bounded by stiffeners ; and the overall response of the stiffened panel or grillage. It has been shown, for example, that elastic design of plating may often be unduly conservative and wasteful of weight ; some of the great reserve of strength beyond the elastic limit may well be utilized in design, and this has necessitated new theories of elasto-plastic plate behaviour.

A typical grillage problem is encountered in designing decks for aircraft or helicopter carriers. Here it is important to avoid permanent distortion of the structure under load. In this case elastic analysis is applicable, and a comprehensive series of design data sheets has therefore been compiled, with the aid of a digital computer, for the elastic analysis of flat grillages under both local and uniform loads.

The study has proceeded from flat grillages to that of an assembly of flat and curved grillages which constitutes a ship's hull. An account of this most ambitious investigation has recently been given elsewhere,[11] and this new theory of transverse strength is now being used to examine whether the structural efficiency of warships might be improved.

The application to ships of plastic-design methods—advocated by Professor Baker in a previous Andrew Laing lecture—is also being studied.[12] Tests have been made of the plastic behaviour of stiffeners on plating which have confirmed the applicability of conventional plastic analysis. Such methods are now in regular use for certain structures, such as subdivision bulkheads, where the loading is well defined, and ultimate strength is of primary importance.

Developments in submarine structural design have been rapid in recent years. The Naval Construction Research Establishment has made notable contributions to knowledge of the behaviour of cylinders under external pressure, and this has led to improvements in design methods and in standards of construction. Detailed strength calculations are now made for every part of the submarine, and particular attention is paid to discontinuity problems arising from sudden changes in profile of the pressure hull, or from openings such as hatches and sea inlets. The strength of flat and domed bulkheads has been investigated theoretically and by tests on full scale. Digital computers have helped considerably in this work. Certain problems remain as, for example, that of low-cycle fatigue in high-strength steels.

Steels

The Andrew Laing[13] lecture delivered by Sir Victor G. Shepheard in 1956 dealt at length with the development of Admiralty steels. In this section, therefore, developments since 1956 are considered.

By 1956 the development of the new ' A' and ' B ' quality, notch-ductile steels had been practically completed. It may, however, be of interest to re-state the chemical analysis and mechanical properties of these two steels.

	'A' Quality	*'B' Quality*
C	0·17 per cent maximum	0·19 per cent maximum
Si	0·10—0·35 per cent	0·10—0·35 per cent
S	0·05 per cent maximum	0·05 per cent maximum
P	0·05 per cent maximum	0·05 per cent maximum
Mn.	0·80—1·50 per cent	1·2—1·70 per cent
Yield stress	16 tons/sq in.	20 tons/sq in.
U.t.s.	28–32 tons/sq in.	31–38 tons/sq in.
Elongation on 8 in.	22 per cent	17 per cent
Charpy V Notch at—30°C.	30 ft lb	30 ft lb

The ' A ' quality steel has a yield stress and u.t.s. similar to mild-steel but, unlike mild-steel, has guaranteed notch toughness. Very little ' A ' quality steel has been used to date but it is intended to use it in ship designs where low stresses are acceptable and where the thickness of plating is greater than ½ in.

' B ' quality steel has replaced the now obsolete S, D, and D.W. steels. It is used for ships where weight saving and high design stresses are important, and has been worked extensively in the latest new construction and in non-pressure hull structure of submarines.

'B' quality steel is fully killed and grain controlled with aluminium, and hence tends to be dirtier than ordinary mild-steel. Small, finely dispersed inclusions are present but do not result in any significant reduction in mechanical properties. Occasionally, however, segregations of inclusions or laminations are present. In the absence of ultrasonic testing, such a defect may not be found until the plate has been worked into the hull and the lamination is opened up by welding stresses or is observed during the cutting of openings. Considerable delays to production occur when it is necessary to replace such plates. Fortunately it is only in the thicker steels, i.e. 1 in.-3 in. thick that much of this trouble has arisen, and it is essential to check these plates ultrasonically. The trend on the part of steelmakers to carry out such tests before delivery of the plates to the shipyard is very welcome.

One of the main objects of the introduction of 'A' and 'B' quality steel has been to eliminate the need for riveted crack arresters. Riveted crack arresters have been fitted in all welded surface ships since World War II as a precaution against the unknown crack propagation properties of the mild-steel used. Future new construction ships which are not built throughout of notch tough steel will be fitted with welded 'A' or 'B' quality strakes of plating at the sheer, stringer and bilge keel, and no riveted crack arresters will be required. Tests of six-feet wide plates at the Naval Construction Research Establishment have shown that 'B' quality steel will arrest a fast running crack at —40 degrees C. in a general stress level of 12 ton/sq in.

There have been a number of important developments in high-yield steels since 1956. At that time a manganese molybdenum steel referred to as UXW and supplied in the normalized and tempered condition was in use, but this was being supplanted by a quenched and tempered steel, now known as Q.T.28. The steel is clean, being only semi-killed, and due to its low chemistry has been found very easy to weld. The principal properties of Q.T.28 are as follows :—

Carbon	0·17 per cent maximum	
Silicon	0·10 per cent maximum	
Manganese	1·30 per cent maximum	Together not to exceed 2·20 per cent
Nickel	0·50 per cent maximum	
Chromium	0·30 per cent maximum	
Molybdenum	0·30 per cent maximum	
Elongation on 2 in.	20 per cent minimum	
Charpy V notch	45 ft lb at —20 degrees C.	
Thickness	0·35 in.—1·0 in.	

A further advance has been made with the development of steel 'D' of the B.W.R.A. F.M.8 Committee which has been found to have good weldability. Carbon is about 0·15 per cent while manganese, nickel and chromium are each of the order of 1 per cent. Several steelmakers make trial casts to an Admiralty specification closely resembling this steel and plates were made for an experimental fabrication after which the following specification for Q.T.35 steel plates up to 1½ in. thick was agreed :—

Carbon	0·15 per cent maximum	
Silicon	0·30 per cent maximum	
Manganese	1·20 per cent maximum	Together not to exceed 2·20 per cent
Nickel	1·20 per cent maximum	
Chromium	1·00 per cent maximum	
Molybdenum	0·50 per cent maximum	
Vanadium	0·12 per cent maximum	
0·2 per cent proof stress	36—44 tons/sq in.	
U.t.s.	not specified	
Elongation on 2 in.	20 per cent minimum	
Charpy V notch	40 ft lb at —40 degrees C.	

This steel is fully killed, but not grain controlled, and ultrasonic testing is employed to exclude plates containing laminations or numerous inclusions. It must be appreciated that a steel of this type must require special precautions when welding but great attention has been given to reduce these to a minimum under shipyard conditions. Rules have been established which together with adequate and uniform pre-heating of the plating keep the percentage of repairs and rejections low.

Non-ferrous Metals

Aluminium Alloys

Prior to 1939 the use of aluminium alloys had been restricted to non-structural work. Aluminium-silicon alloys in the wrought and cast forms had been employed but, owing to lack of experience with these alloys and in connecting dissimilar metals, the results were disappointing and corrosion troubles were common.

Subsequently aluminium was only used for minor internal fittings until portions of the superstructure of the *Weapons* and *Daring* Class destroyers were fabricated in clad sheet with 5 per cent Mg aluminium alloy rivets and HE 10—WP sections.

Once again the performance was poor, the sheared edges of the sheets corroding very rapidly, the surfaces lasting only slightly longer until the cladding was damaged in spots by general misuse or by the use of chipping hammers prior to repainting. At these damage spots corrosion was extremely rapid until complete perforation occurred.

The first all-aluminium-alloy experimental M.T.B. was built in 1948 using 5 per cent Mg alloy and employing techniques and designs based on flying boat construction. At this time there was no Admiralty specification laying down the rules for aluminium structures, e.g. spacing of rivets, shape of rivet heads and points of insert materials to be placed between the faying surfaces of joints. Consequently considerable difficulty was experienced in maintaining water-tightness and this continued as a source of weakness throughout the life of the craft.

In 1949 ' Notes for Guidance in the use of Aluminium Alloys in H.M. Ships ' were produced after extensive consultation with the aluminium industry and boatbuilders and, with only minor alterations, the same instructions apply today.

At this time some ex-wartime destroyers were converted into frigates and the fo'c'sle deck was extended from one-third the length of the ship to within a short distance of the stern. The whole of this additional structure and the new superstructure was made in aluminium (5 per cent Mg) alloy. In general, aluminium alloy rivets were used for aluminium/steel joints but steel rivets were fitted at the connexion between the new structure and the old break of fo'c'sle. Again the main troubles in these ships have been corrosion due to stress corrosion of the aluminium alloy rivet material and inefficient joints between dissimilar metals. To overcome the stress erosion problem in the rivets, all those which fail are being replaced by rivets containing less magnesium ($3\frac{1}{2}$ per cent).

In the following year work commenced on the minesweeper programme. The low magnetic permeability of aluminium makes it an ideal material for these ships and many of them are of composite construction with frames, bulkheads and decks of aluminium and outer skin of wood planking.

Development work on new welding processes for aluminium alloy had been progressing rapidly in the United States and a number of ' Aircomatic ' sets were purchased and distributed to the shipbuilders employed on this project. At first the quality of the welding left much to be desired but several reports advising on operating techniques have been produced by the Naval Construction Research Establishment and these form the basis of present practice.

With all-positional welding of aluminium alloys now available, the policy of standardizing on the non-heat-treatable 5 per cent Mg alloy for sections as well as sheets and plates was fully vindicated and the heat-treatable alloys are now only used for guard-wire stanchions, ladderways, etc.

In the early '50s it was general policy to employ aluminium for all minor bulkheads and superstructures but by far the biggest and most ambitious use of the material was in the building of the all-welded fast patrol boat *Dark Scout* at Saunders Roe, Anglesey. She has $\frac{1}{4}$ in. bottom plating, $\frac{3}{16}$ in. side plating and $\frac{1}{8}$ in. deck plating and special keel, chine and gunwale extrusions. Large units of plating and stiffeners were welded by the inert gas-shielded self-adjusting metal arc equipment mounted on a motorized carriage. Extreme care was taken in making the connexions between dissimilar metals and no corrosion troubles have been experienced.

Immediately following the completion of the *Dark Scout* work commenced at Vosper Ltd., Portchester, on two more fast patrol boats, *Brave Borderer* and *Brave Swordsman.* In these the deck, bulkheads and framing are all-welded auminium with wood-planked hulls, and egg-box type of construction being used with great success to facilitate fabrication.

In addition to its use in surface ships aluminium alloy has been used extensively in submarines, first for riveted casings built from conventional sections and later for welded casings incorporating the bridge fin and employing special sections which greatly simplified fabrication and resulted in considerable labour saving.

It is doubtful whether aluminium alloy will be used more extensively in the future as the increased risk of fire in war-time in H.M. ships is a serious hazard. In addition, its use for superstructure is limited by the large deflexions of structure in wake of the blast of guns and by its inefficiency in protection against bomb splinters and small arms attack.

Copper Alloys

Until 1954 the copper alloys used in H.M. ships were mainly limited to brasses, phosphor bronzes and gunmetals. Dezincification has led to banning of the high-tensile brasses and their replacement by the aluminium bronzes, manganese aluminium bronzes and the nickel gunmetals. With nickel now in greater supply the 90/10 and 70/30 copper-nickels are finding new applications, particularly in nuclear ships. Copper and copper-nickel-iron have also been used practically without exception for the fresh and salt water systems in surface ships since 1945 but it was not until the minesweeper programme that the aluminium bronzes were used to any great extent. In these boats the rudders, anchors and chain cables are some of the numerous applications for which aluminium bronze, being virtually non-magnetic, proved ideal.

Welding

The emphasis in post-war years has been on the development of welding techniques, i.e. the evaluation of suitable welding processes and techniques of non-destructive examination to find the means whereby consistently high-quality welds can be obtained in the new steels under average shipyard conditions. The building of *Dreadnought* could not have been contemplated unless a fair measure of success had been achieved in this development work.

These developments could not have been completed without the assistance obtained from the results of other investigations. The work of the British Welding Research Association and reports of American research have been most valuable. In addition, much assistance has been rendered by the manufacturers of electrodes and welding equipment.

The Welding Development Laboratory at the Naval Construction Research Establishment has been equipped with various welding processes and other equipment to carry out tests to assess weldability and to determine the performance of welded joints and to examine and check electrodes. Weldability is assessed initially by controlled thermal severity and the restrained butt cracking tests. The percentage moisture content of the electrode coating in the as-received conditions and after baking at various temperatures and times is also measured using the Gayley Wooding apparatus. From the results of these tests the degree of preheat, the limitation of the cross sectional area of single runs and the temperature and time of baking of the electrodes is established to give crack-free welds. These requirements are then checked on larger assemblies to confirm that the electrode is usable in all positions and produces radiographically clean welds under the required conditions, and to determine the effect of applied restraint on the tendency to cracking. Unfortunately, the limitations of manpower and material do not always permit very large test fabrications.

Close contact is maintained between the welding and metallurgical laboratories where more fundamental research into the factors affecting weldability are studied. Particular effort is applied to the role of hydrogen and other gases and to the temperatures at which the parent plate and weld transform during cooling.

The importance of moisture-free electrodes has led to trials being carried out with electrodes packed at the manufacturer's works straight from the drying ovens into vacuum sealed aluminium containers. If these trials prove successful the requirements of baking the electrodes at the shipyard may be relaxed. The containers have been designed to be robust enough for repeated usage.

In addition to these tests mentioned above, the drop-weight and bulge explosion tests developed by the U.S. Naval Research Laboratory are extensively used. The drop-weight test indicates a temperature of nil-ductility and the bulge explosion test measures overall performance under explosive loading. Some details of this valuable test were included in Sir Victor Shepheard's lecture in 1956.[13] All the bulge-explosion test plates are examined both by radiography and by ultrasonics prior to testing so as to establish if necessary the cause of any premature failure.

As a result of this work, the Naval Construction Research Establishment has accumulated a great deal of information regarding the effect of weld defects. The condition of the surface of a weld has been shown to have a considerable effect on performance under explosive loading and for this reason certain welds in submarine pressure hulls are now required to be ground flush and it is preferred not to speak of weld build-up as' reinforcement '. The information has also been useful when considering the required standards of welding.

In addition to the testing of electrode and plate combinations the potentialities of every new welding process have been examined. The inert-gas-shielded metallic arc process has been used extensively for the welding of quenched and tempered steels. Further work is progressing in conjunction with several firms into other gas-shielded and fluxed processes. The gas-shielded process using either carbon dioxide or a mixture of this gas and argon is particularly promising since positional welding can be carried out using semi-automatic equipment.

Particular combinations of wire and granulated flux for submerged arc welding with a multi-run technique have also given promising results. One of these combinations is at present being used on Q.T.28 steel.

Although most effort has been expended on the welding of the higher strength steels, every opportunity has been taken to improve the quality of welding on the normal structural steels. Many of the processes which have been examined for the welding of the higher strength steels have been found suitable for welding the plain carbon-manganese steels and have been approved for this purpose. In addition, the extent of non-destructive examination has increased considerably, and this in itself has been responsible for improved quality of welding.

In the field of non-destructive examination considerable progress has been made in the application of ultrasonic equipment. Techniques which have been checked by the subsequent destructive examination of many specimens have been established whereby it is now possible to examine for internal defects joints which by virtue of their geometry are impossible to examine by radiography. These had previously had to be accepted solely on the basis of the absence of surface defects. These techniques are being used extensively during the construction of submarine pressure hulls. All butts and seams in the pressure hull are now subjected to 100 per cent ultrasonic examination prior to selective radiographic examination.

Propulsion Machinery

The First Ten Years

The rapid advances made in propulsion machinery design in the first ten years after the war are covered by Vice-Admiral Sir Frank Mason,[14] then Engineer-in-Chief of the Fleet, in his Charles Parsons Memorial Lecture to this Institution in 1956. Some of the more important advances in this period will be highlighted.

The end of the war found the Royal Navy for very good reasons behind the U.S. Navy in propulsion machinery design. The immediate solution was to build and test the *Daring* Class machinery on basic design information supplied by U.S. Navy Department. In order to obtain the maximum support from British industry and to spread the benefits likely to accrue from significant advance, three major variants in the design were permitted. This was only a convenient expedient, and it was fully realized that a long-term development programme was necessary.

To formulate this programme an organization designated YE.47A, and comprising members of Yarrow & Co. Ltd., The English Electric Co. Ltd., and the Engineer-in-Chief's Department was set up in December, 1946. They were charged with the duty of reviewing, on a world-wide basis, the position of naval machinery development and formulating specific recommendations for future policy armed at achieving improved performance.

The YE.47A Committee reported in January, 1949, and, arising from their recommendations, much basic research was put in hand, ranging from investigations into heat transfer in condensers to the development of high-speed turbo-auxiliaries, and a set of YEAD.I prototype propulsion machinery was designed, built, and tested at Pametrada.

A futher recommendation to design, build and shore test YEAD.II (an advance on YEAD.I) which was to benefit from the lessons of YEAD.I was not proceeded with, since it was considered that the gas turbine boost principle showed greater promise.

Although not strictly in the above line of development, which was devoted to powers of 30,000 s.h.p. per shaft designed to meet the requirements of large destroyers, cruisers and aircraft carriers, the requirement for improved machinery for the projected new frigates resulted in the highly successful Y.100 machinery. Because of the Korean War this was designed and built in a great hurry, but in spite of this it is a great advance on previous frigate machinery and has given good performance in service.

In the Diesel field, the introduction of the Admiralty Standard Ranges has been very beneficial. The power range from 2,000 b.h.p. per engine down to 1½ b.h.p. can be met from five basic types of engines, thus considerably simplifying the maintenance and spares problems. Outside these ranges, as a special project, the very successful Deltic engine has been developed, largely at Admiralty instigation and cost.

With regard to gas turbines, although the one complex design (R.M.60) was technically successful, gas turbines of simple design will now be employed both for main propulsion and auxiliary purposes.

The Next Five Years—1956 *to* 1960

(*a*) *Boost Machinery*

The most important single naval machinery development in the last five years has been the introduction of gas-turbine boost. In 1955 it was in the project stage ; today with H.M.S. *Ashanti* about to go on sea trials it is a fact. Later this year H.M.S. *Devonshire*, the first of the new guided missile destroyers, will be on her sea trials.

The term ' gas-turbine boost ' in the context of these two ships is really a misnomer. They have combined machinery plants, and it would be more correct to borrow the American descriptive term COSAG (combined steam and gas) for them. In other words, the gas turbine as well as being used for ' boost ' purposes can also be used for propelling (including manœuvring) the ship with the steam plant shut down.

The chief advantages of boost machinery are :—

(i) Less machinery space height is required vis-á-vis an all-steam plant
(ii) Improved fuel consumption at cruising powers, since the turbine design point is at a relatively higher power
(iii) Ability to leave harbours and anchorages at short notice.

Gas turbine boost machinery has not yet been fully tried and proved, but every care has been taken by prototype trials to make it as reliable as its more conventional counterparts.

(*b*) *Steam Turbine Machinery*

The 30,000 s.h.p. YEAD.I prototype set completed its trials at Pametrada early in 1958. Although YEAD.I has not been earmarked for any new construction the trials proved most valuable, not only in the development of a highly advanced design main propulsion unit, but also because YEAD.I was used for the testing and development of many different items of equipment—particularly for automatic and remote control—which have since been incorporated in new construction.

(*c*) *Gas Turbines*

Big advances have been made in the gas turbine field since 1955, not only for main propulsion purposes, but also for the generation of electricity. For the former the G.6 gas turbine has been developed by Metropolitan-Vickers for the boost plants of the *County* Class G.M. destroyers, and the *Tribal* Class G.P. frigates, and in addition, the Bristol Proteus aero-engine has been successfully adapted for marine purposes, and has been used to propel the *Brave* Class fast patrol boats.

With regard to the generation of electricity, two types of gas-turbine have been developed. First, a design suitable for base-load operation for the boost-plant ships, incorporating a rather complex cycle to give improved fuel consumption at part loads and, secondly, a simple-cycle design suitable for emergency purposes.

(*d*) *Diesels*

No great advances have been made in the Diesel field since 1955. Here the emphasis has been on progressive development to improve the reliability, and increase the periods between overhauls of existing engines.

(*e*) *Free Piston Gas Generators*

Although no active steps have been taken in the field of free-piston gas generators, interest in this project continues. Developments both in this country and abroad (particularly in the French Navy) are being watched with great interest and a more active part may be taken when the time is appropriate.

(*f*) *Automatic and Remote Controls*

Automatic and remote controls for machinery operation are being fitted in new construction. There are three main reasons for this :—

(i) It may be necessary on occasions in future to shut all means of ingress to the machinery spaces (apart from combustion air for boilers, etc.). This means no machinery space ventilation from the open air ; personnel must, therefore, be positioned in a space capable of being ventilated by a closed-cycle system, i.e. a control room.

(ii) Improved habitability standards in ships means increased accommodation space requirements. Any device that reduces the requirement for watchkeepers is to be welcomed, although one must be careful to see that the complexity of the automatic equipment does not necessitate a proportionately higher number of skilled men to maintain it.

(iii) Modern combustion equipment which has to be designed to meet the requirements of remote control (i.e. wide range burner systems) is better operated automatically than by hand since the responses of the automatic controls are so much faster than those of humans.

In the last five years various types of automatic and remote control equipment have been tried at sea, and after some teething troubles, confidence is felt that all the major problems have been overcome.

(*g*) *Noise*

The question of noise reduction will be discussed later in more detail. Much work has been, and is being done, by means of better balancing of machinery, improved mountings, etc., to reduce the noise of machinery to acceptable limits.

(*h*) *Reliability*

Two important steps have been taken to ensure that future machinery will be even more reliable. First, a detailed investigation is being carried out into exactly what does cause lack of reliability and the need for maintenance in the Fleet, and the best ways of remedying these shortcomings. Secondly, the facilities at the Admiralty Fuel Experimental Station at Haslar are being extended to cover the endurance testing of auxiliaries, as far as possible under shipboard conditions, for new construction ships. By this means a lot of the design problems will be removed before the ship goes to sea.

Nuclear Propulsion

The first nuclear submarine, *Dreadnought*, is now launched and is being fitted out. She will have a complete set of American designed and supplied propulsion plant, both the nuclear and conventional components being similar to those fitted in the U.S. submarine *Skipjack*. This will enable full advantage to be taken of the outstanding American success in this field, and give the greatest

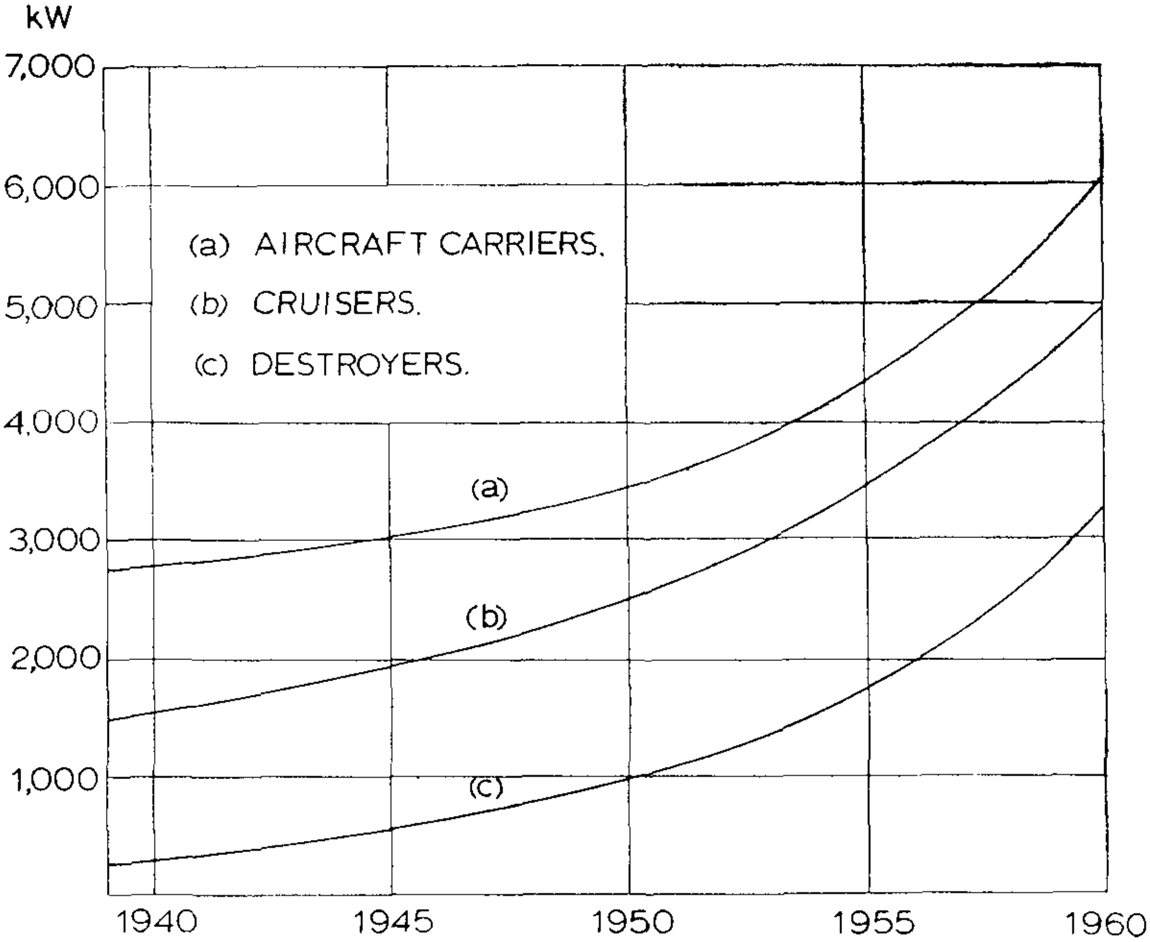

FIG. 5—GROWTH OF GENERATOR CAPACITY IN TYPICAL H.M. SHIPS (TAKEN FROM SIR HAMISH MACLAREN'S PRESIDENTIAL ADDRESS, 1960, TO THE INSTITUTION OF ELECTRICAL ENGINEERS)

chance of a reliable nuclear submarine for the Royal Navy being at sea at a very early date.

In parallel with this, a pressurized-water reactor and propulsion system of British manufacture are being installed for shore trials at Dounreay, and a similar plant will be installed in the second British nuclear submarine.

Attention has been given to possible surface warship applications of nuclear propulsion.

Electrical Engineering

A detailed account of post-war developments in warship electrical engineering has been included in his recent Presidential address to the Institution of Electrical Engineers by Sir Hamish D. MacLaren, formerly Director of Electrical Engineering at the Admiralty.[15]

The development of electrical engineering in the Royal Navy after the war was influenced by two important factors. The first was the greatly increased demand for electrical power during the war with the advent of new weapons and devices such as radar and degaussing, and the evidence that this growth would continue as these devices were developed. FIG. 5 shows how the promise of continued growth was fulfilled and indicates that growth will continue. The second factor was the pattern of action damage experienced in ships which gave rise to doubts whether the direct current ring main which had been in use in large warships since 1908 was now the best system of distribution.

The largest electrical generators in use with the ring main system were of 500 kW capacity and it was evident that 1,000 kW generators and larger would be needed in future aircraft carriers and cruisers. To deal with these larger powers it was necessary to consider the use of a voltage higher than 220 and to decide whether it should be direct current or alternating current.

The possibility of using alternating current in warships had been considered for many years and the new factors strengthened the case in its favour. After a thorough investigation it was decided in 1946 to install an alternating current system in four of the *Daring* Class. H.M.S. *Diamond*, completed in 1950, was the first ship in the Royal Navy to have such an installation.

The two main reasons for changing from D.C. to A.C. were :—

(*a*) An increase in voltage was practicable because lower voltages where necessary would then be obtained from transformers and the higher voltage resulted in a reduction in weight of the electrical system and permitted the use of larger generators.

(*b*) A considerable reduction in maintenance effort on motors resulted from the use of induction motors with direct on-line starting—there are over 1,000 electrical motors in a large aircraft carrier.

A 440 volt 60 c/s 3-phase system with a 115-volt lighting system, which is similar to that in the U.S. Navy, was adopted in the *Daring* Class and it was decided all future warships, with minor exceptions, should have such systems.

The choice of the frequency of 60 c/s—which is different from that used on shore—was made after due consideration of the possible difficulties of obtaining electrical supplies from shore, and was largely governed by the fact that the motor speed of 1,800 r.p.m., obtained with a 60 c/s system, results in auxiliaries lighter in weight than those for a 50 c/s system with a motor speed of 1,500 r.p.m.

Since the decision to change to A.C. was made, a comprehensive programme has been carried out for providing shore supplies at 440 volts, 60 c/s 3-phase in all Royal Dockyards.

The first large ships to have an A.C. system were the three *Tiger* Class cruisers, the construction of which had been suspended at the end of hostilities. When it was decided to complete these ships, the electrical power required for modern armament and other equipment made it necessary to substitute four 1,000 kW A.C. generators for the four 500 kW D.C. generators included in their original design. The recently completed aircraft carrier H.M.S. *Hermes* was dealt with in a similar way and the total generator capacity has been nearly doubled in this ship as compared with the original D.C. system.

In all ships completed with A.C. a switchboard distribution system has been adopted because such a system with its interconnected units comprising closely integrated generators and switchboards is more likely to survive, if only in part, the type of damage which a warship may experience with modern weapons.

Apart from the saving in weight which results from changing from D.C. to A.C., a major contribution to saving in weight was made after 1945 by replacing the lead alloy sheathing of cables by neoprene. As an example, 30 tons was saved in a destroyer by doing this. A more recent change resulting in a further saving in weight and space has been the introduction of silicone rubber as the insulant for all cables.

Consequent upon the ever increasing numbers of cables which have to be installed in modern warships, a new form of watertight bulkhead gland has been developed to permit more cables to pass through a given area of bulkhead. This new gland is a box welded into the bulkhead through which the cables pass. The box is sealed up solid by filling it with a quick-setting rubber-like compound.

These improvements in the design and installation of cables are only a part of a continuing effort to save weight and reduce the size of electrical equipment while still maintaining the high standard of performance demanded of such equipment in H.M. ships.

Electronics

The growth of electronics in warships, begun during the war, has been continued at an ever quickening pace. From being mainly confined to comparatively simple radio, radar and asdics equipment, electronics now play a vital part in every kind of control, detection and communication system in the modern warship. The applications are too numerous to list but the following examples will serve to illustrate the wideness of the field :—control of gun mountings and directors, missile control systems, internal communications, voltage and frequency regulation gear, special static power supplies, servo-follow-ups and remote controls, nucleonic and radiac gear, amplifiers for general instrumentation and monitoring, apart from an enormous increase in radio, radar and asdics of all kinds. The Navy's guided missiles and all the complex test, control, and guidance equipment accompanying them are packed with electronic circuits, as are modern naval aircraft. In little more than ten years the cost of electronic equipment in most classes of ship has increased by over ten times.

The vast increase in the quantity of electronics used has, of necessity, been accompanied by a very considerable improvement in the dependability of electronic equipment, mainly stemming from the better components available to the designers.

Although electronic valves, and particularly the highly specialized types, will have an important part to play for many years to come, a high proportion of the Navy's future electronic developments will be based on transistors and associated semiconductor devices. Limits of frequency have moved upwards steadily to a present limit of 200 or 300 mc/s, but with a promise of several thousands of mc/s at low power levels from newer devices such as the tunnel diode, now becoming available. Power handling capabilities have changed rapidly from milliamps and volts to tens of amps and hundreds of volts. One application of these power semiconductor devices is to static inverters, which may one day take the place of rotary conversion machinery.

The use of transductors and magnetic amplifiers deserves mention. These have found wide application to power controls where utmost reliability is called for, and have lived up to expectations. Their role may in the future be taken over by another semiconductor device, the s.c.r. or silicon controlled rectifier, also known by names such as solid state thyratron, trinistor and thyristor.

Modern electronic equipment is far smaller than its earlier counterpart and it throws less ' wild heat ' into its compartment, so easing ventilation problems. It also demands less power. Had it been necessary to cram the same amount of equipment using the old techniques and components into the modern warship the ship-designer would indeed be faced with a very difficult problem.

Weapons

Conventional Surface-to-Surface and Surface-to-Air Armament

The aims have been to obtain longer range, greater accuracy, faster rates of fire, automaticity and integrated gun direction and fire control. The armament developed since the war and now in service comprises the following :—

The Q.F. 6-in. Mark 26 dual-purpose twin mounting

This weapon constitutes the main armament of the *Tiger* Class cruiser.

The Q.F. 3-in. A.A. mark 6 mounting

This mounting which is fully automatic and capable of a very high rate of fire, forms the secondary armament of the *Tiger* Class cruisers.

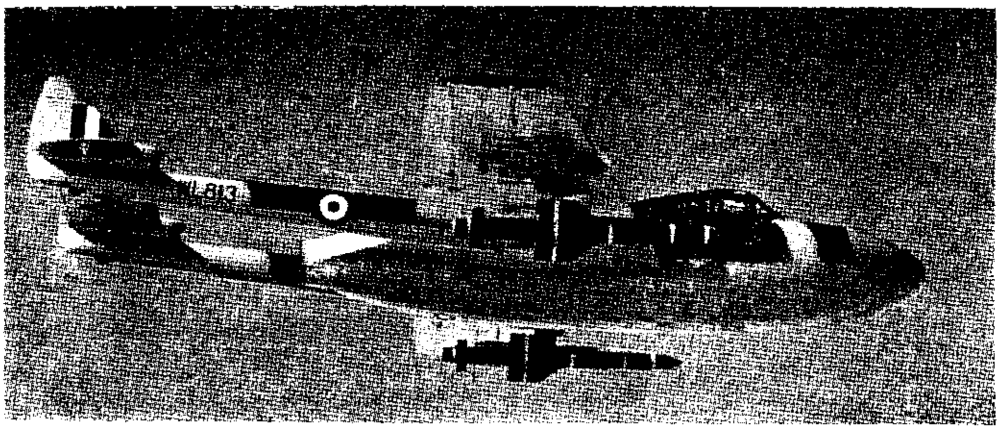

FIG. 6—FIRESTREAK—AIR-TO-AIR MISSILE

The Q.F. 4·5-in. mark 6 mounting
This dual-purpose mounting is the main armament of destroyers and the larger frigates.

Q.F. 40mm. twin and multiple barrel close range A.A. mountings
These weapons have been the close range anti-aircraft armament of most warships completed since the war.

With the introduction of guided missiles into ships of the Fleet it appears unlikely that there will be any further major development in conventional naval guns and mountings.

Guided Missiles
Conventional armament, even of the most advanced type, cannot cope adequately with high-speed, high-flying and manœuvring aircraft targets and to meet the situation there is a guided missile development programme for the Royal Navy which is now coming to fruition.

The post-war naval conception of defence against aircraft attack is to intercept enemy aircraft at long range by carrier-based aircraft followed by engagement with medium-range guided missiles and finally to attack with close-range guns and missiles.

Guided weapons have been developed for each phase, the first family of which comprises :—

(i) *Firestreak*—This weapon is an infra-red homing, air-to-air missile launched from naval intercept aircraft such as the *Sea Vixen*. The size of the missile is of the order of 10 ft 6 in. long with 29½-in. wing span. FIG. 6 shows a missile housed beneath the wing of a naval aircraft.

(ii) *Seaslug*—This is a radar beam riding, surface-to-air missile for use from surface vessels and will form the primary anti-aircraft armament of the *County* Class destroyers now under construction. Seaslug has four wrap-round boosts and an internal sustainer motor, all burning solid cordite type fuel. Overall length is about 20 ft and body diameter about 18 in. Boosts are about 12 ft long. Many Seaslugs have been fired both from shore base and from H.M.S. *Girdle Ness* and a variety of targets have been successfully engaged.
Stowage, handling and testing of the missile demands a large aggregate space per missile and the number that can be stowed in a warship is far fewer than could be desired. Whereas weight has, until recent years, been the biggest single problem in warships, the problem tends to shift to space in guided missile ships. Other difficulties facing the ship designer are stringent safety precautions, provision of complicated

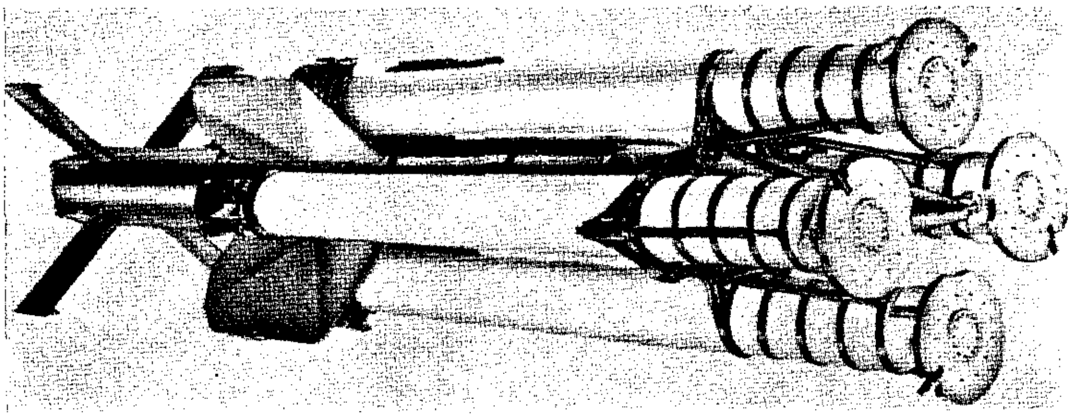

FIG. 7—SEASLUG—SURFACE-TO-AIR MISSILE

mechanized handling and transfer equipment and the siting of large launchers and direction requiring stiff supports in positions free from vibration.

FIG. 7 shows a Seaslug Missile with boosts.

(iii) *Seacat*—This missile is under development for the Royal Navy as a replacement for close range 40mm. conventional anti-aircraft mountings.

Anti-submarine Armament

Ahead throwing mortars controlled by asdics which came into service towards the end of the war have been further developed and form the standard short range anti-submarine armament for frigates and destroyers. There are two types of mortar in service, Squid, and the anti-submarine mortar Mark 10, sometimes referred to as ' Limbo '.

The mountings are stabilized and carry three barrels. Squid can only be fired straight ahead so that the anti-submarine vessel must be pointed at the target. The anti-submarine mortar Mark 10, however, has all-round training. Fire control is similar in principle to gunnery fire control. There are asdics for obtaining initial detection bearing and range, of a submarine which enables fire control and depth determining asdics to be put onto the target. When within range these asdics feed range and depth data into computers and the mortars are ultimately fired automatically.

For long-range attack of submarines, homing torpedoes associated with long-range asdic and dipping sonar equipments have been developed for use from anti-submarine frigates and from aircraft and helicopters.

Torpedoes

Post-war development has tended to concentrate on the homing torpedo for undersurface warfare as distinct from the former conventional weapon used primarily against surface craft, which are, however, still carried in H.M. destroyers and fast patrol boats. H.M. submarines are equipped with a modern version of the Mk. 8** conventional torpedo in addition to the homing weapon. The homing weapons are controlled by a control system in conjunction with the listening device.

A recent innovation into the Fleet is the light-weight active homing torpedo carried by helicopters for use against submarines. The helicopters and weapons are stowed in H.M. frigates and aircraft carriers.

Mines and Mine Countermeasures

The mines to which the greatest attention has been paid in the post-war period are the family of influence mines, i.e. mines designed to be actuated by magnetic, pressure or acoustic influences, or by a combination of these. Mines

TABLE I

Aircraft	*Year*	*Role*
Blackburn Firebrand	1945	Torpedo-strike fighter
Hawker Sea Fury	1947	Fighter-bomber
De Havilland Sea Hornet F.20	1947	Strike-fighter
De Havilland Sea Hornet NF.21	1949	Night and all weather strike fighter
Hawker Sea Hawk	1953	Ground attack fighter
Westland Wyvern	1953	Strike aircraft
De Havilland Sea Venom	1954	All weather and strike fighter
Fairey Gannet	1955	Anti-submarine search and strike
De Havilland Sea Vixen	1958	All weather interceptor fighter
Supermarine Scimitar	1958	Strike and reconnaissance fighter
Blackburn NA.39 (Buccaneer)		All weather search and strike aircraft
Helicopters		
Westland Sikorsky Dragonfly	1950	Air-sea rescue and communications helicopter
Westland Sikorsky Wessex	1958	Anti-submarine, search and rescue helicopter

of this type have been developed for use both in shallow water and in deep water. The types used for shallow water are laid on the sea bed and are known as ground mines. Those suitable for deep water are buoyant and require mooring in the desired position.

Radar and Communications

In the field of radar there has been great progress in the development of specialized radars for armament and aircraft direction, fire control, missile direction, navigation and long range aircraft detection. Conspicuous among these is the so-called 3-D radar fitted in the aircraft carriers *Victorious* and *Hermes*. This single set provides long-range aircraft warning, height, range and bearing data which are processed by an advanced display system for the purpose of aircraft direction and control.

Included in the post-war progress in naval communications is the change-over to ultra-high frequency voice communication between ships and between ships and aircraft. A further notable advance has been the introduction of automatic teletyping equipment for reception of messages.

In order to handle the mass of information made available to shipborne radar, communications, asdics, etc., and to relate it to intelligence, signals, etc., from other sources, the action-information organization in ships has been expanded and perfected. The function of this ship organization may be defined as the collection, display and evaluation of action information and its dissemination to enable the command to appreciate the situation and take appropriate action.

Aircraft

There has been continuous development in naval aircraft. The monoplane has replaced the biplane and the piston engine has been superseded by the turbo-prop and pure jet engines. Operating speeds have increased although stalling speeds have been kept within manageable limits. Aircraft fuels have changed from petrol to kerosene types of fuel. Tricycle undercarriages have been adopted. Weapons and equipment carried have become increasingly complicated and varied. The all-up weight of aircraft has greatly increased and the cost of corresponding types is many times greater.

Types of aircraft and helicopters brought into service since 1945 are shown in Table I.

Noise Reduction

Noise is undesirable in warships for a number of reasons. High airborne noise levels inside the ship, for example, can lead to fatigue and reduced efficiency of personnel, in addition to hampering communications and passing of orders. Since the operational efficiency of a ship depends on the efficiency of the men in it, any high noise level is undesirable operationally.

There are three main sources of airborne noise :—ventilation systems ; machinery ; and, in aircraft carriers, jet aircraft. The last-named is becoming an increasing problem as aircraft increase in speed, weight and complexity, and consequently in power.

Ventilation Noise

Up to the end of World War II, comparatively little attention had been paid to the problem of ventilation noise. The problem was not, in fact, a severe one since most ships were ventilated by a large number of fairly small centrifugal fans. Towards the end of the war, however, the ‘ group ’ system of ventilation was introduced. This incorporated a much smaller number of large fans (usually of axial-flow type), with a consequent reduction in the number of fresh-air intakes and exhausts.

The group system was introduced primarly because of its better overall efficiency and greater facility for shutting down against certain forms of attack. Unfortunately, the size of fans involved and the large water gauge required, tended to make them noisy. The problem was further aggravated by the large amount of additional heat-producing equipment being put into ships, for which adequate supply of cooling air and removal of the waste heat, were essential.

The need to keep trunking sizes down to a minimum, and the impossibility in many cases of avoiding tortuous runs of trunking, make effective noise-reduction measures rather difficult. There are, however, a number of measures which have been taken and which have materially assisted in maintaining acceptably low noise levels, without encroaching too much on limited space. Examples are as follows and these can be taken as summarizing present policy :—

(*a*) All large axial-flow fans are, where possible, sited in acoustically lined fan chambers away from operational and living spaces. Where the fan chambers are adjacent to such spaces the fans are resiliently mounted, with flexible connexions to the ventilation trunking.

(*b*) Fans are mounted on adequately rigid structure. For example, heavy axial flow fans are not sited in the middle of light, flexible decks.

(*c*) Runs of trunking are designed with increased care, the most important need being the provision of a straight run upstream of the fan. Non-uniform flow caused by a bend immediately upstream of the fan increases both the noise level of the fan and the vibration forces that it produces. Sharp bends and abrupt changes of section are avoided anywhere in the system, since the ensuing air turbulence gives rise to increased noise and can also cause ‘ drumming ’ in light trunking.

(*d*) Where a compartment is supplied (or exhausted) by a main trunk running through the compartment, a branch trunk is fitted, with an adjustable baffle. This allows the correct air flow to the compartment to be obtained and also minimizes the noise escaping from the main trunk via the supply or exhaust terminals.

It has been found that if the principles listed above are adhered to, the noise levels in the majority of ventilation systems are acceptable. In exceptional cases, where, on ship trials, noise levels are found to be unacceptable further palliative measures as appropriate are introduced. These include damping treatments (a filled plastic emulsion compound is normally used) on vibrating trunking, use of sound absorbent splitters, and internal acoustic treatment of trunking. The comparatively small number of cases in which these more elaborate treatments prove necessary justifies the *ad hoc* approach as far as these refinements are concerned. In any case, the weight and space involved in fully treating every ventilation system would be prohibitive.

For the future, it is expected that the advent of full air conditioning (with the consequent reduction in fresh air intakes, coupled with the use of a comparatively large number of smaller fans and units for circulating air on messdecks, etc.) will ease the noise problem considerably. Meanwhile, research programmes aimed at producing quieter fans (both axial and centrifugal) are being actively pursued.

Machinery Noise

As out-of-balance forces are a major offender in causing noise, naval machinery must be more accurately balanced than is necessary or economic for most commercial applications. Care is taken to ensure—so far as possible—that noisy machinery is not sited near spaces which for operational or habitability requirements have to be quiet. Where, unavoidably, noisy auxiliary machinery is sited adjacent to such a space, it is general practice to resiliently mount the machinery and apply acoustic treatment to the compartment boundaries. In the case of submarine auxiliary machinery, acceptable levels of airborne noise are laid down for both manned and unmanned compartments.

In main machinery spaces, the airborne noise has to be accepted, with ear defenders and acoustic telephone booths used as necessary. This problem has been eased considerably by the advent of separate machinery control rooms, which are acoustically insulated from adjacent machinery spaces.

Paints, Plastics, Ropes, Cordage, Insulation Materials

Paints

During the war shortage of raw materials, principally linseed oils, made it necessary to look for paints based on synthetic resins. Such paints have since been developed to a stage at which they are much better than the pre-war paints.

The principal change which has occurred in paint systems generally is the introduction of a quick-drying red-lead graphite primer instead of the former slow-drying red lead. For the undercoat of paints an alkyd-resin-based paint is used but this is too sensitive to water-soaked conditions. Consequently a new undercoat based on phenolic resins is being tried. For top coats a formulation based on an oil modified alkyd resin varnish, with rutile titanium oxide and antimony oxide is used. These compositions give excellent results if carefully applied under good conditions. Such conditions cannot be guaranteed, however, and a single-coat weatherwork paint has been developed which does not require an undercoat. This is a phenolic-based paint.

The waterline area is always a problem because it is exposed to wind and water alternately and is also liable to severe mechanical damage when ships are lying alongside. Trials to find the best answer continue and currently under investigation are cold-cured epoxy resins, coal-tar epoxy paints, rubber-modified epoxy paints and neoprene coatings. Cold-cured epoxy resin has given very promising results when applied to rudders and shaft brackets.

Interior paints have to be fire resistant and it is difficult to achieve this and at the same time to retain a good gloss finish. Paints based on an oil modified alkyd or phenolic alkyd resin media into which gum dammar varnish medium is introduced to improve the gloss are used.

A more recent development to save the effort of repainting certain bulkheads and to give improved appearance is the application of p.v.c. cloth which is stuck neatly on to these surfaces.

Plastics

These generally are not suitable for structure but are being increasingly used during fitting out. Their use, however, has to be restricted to non-essential services because of the inability of plastics to survive in a fire.

As mentioned above p.v.c. cloth is now used fairly extensively for covering certain bulkheads. Glass-reinforced fibre has been used for submarine casings.

P.v.c. linoleum has been tried as a deck covering but its use has been abandoned because it is easily marked by cigarette ends and it absorbs dirt. Cork linoleum has now been reintroduced. Trials are, however, in hand of p.v.c. tiles and these so far have given promising results.

The traditional wood decks are now fitted less frequently but no wholly satisfactory substitute has been found. Trials are being carried out with a thin laminated wood deck which should be appreciably lighter. Wood decks are now caulked with a polysulphide or neoprene-based material instead of pitch and oakum.

A number of trials have been carried out with boats of glass-reinforced plastic construction. Various methods of construction have been tried including a plastic-foam sandwiched between layers of glass-reinforced plastic. Such plastic craft have been found to have many advantages over conventional wooden boats, but their development is limited by such factors as cost, problems of maintenance in a smart condition and difficulty of repair.

A warship problem is to reduce the maintenance necessary to keep upper-deck fittings in a smart condition. Trials are in hand of guard rail and awning stanchions, door clips, etc., that have been dip-coated in plastics, e.g. nylon, terylene and polythene. The results with nylon have been by far the best and it is likely that this procedure will be adopted.

Terylene awnings have been on trials for several years and have given excellent results. They have to be proofed with silicones and are expensive, but the additional cost is more than offset by the longer life. One disadvantage is that they are difficult to keep clean and consequently their presentable life may be less than their durability.

Weatherdeck covers are now made of p.v.c. coated mock leno-weave nylon fabrics. This lasts much longer than flax canvas and is easier to de-ice on ships operating under Arctic conditions. These covers are, however, not without disadvantage in that they stain easily and are therefore difficult to maintain in a smart condition. A new material—chlorosulfonated polyethylene—which it is claimed will not stain so easily, is now being tried.

Recent experiments indicate that nylon duck coated with vinyl paint and stuck with resorcinal glue is likely to be a very efficient means of protecting wooden craft from teredo gribble attack in tropical waters.

Ropes and Cordage

One of the chief disadvantages of ropes made from natural fibres is that they deteriorate under the action of sunlight, marine organisms, bacteria, etc. If they are chemically treated for protection their strength is liable to be impaired, particularly in hot climates. Ropes made from artificial fibres are proof against such attack and are far stronger.

The principal fibres used for ropes are nylon, terylene and polythene. Nylon seems to be the most suitable for general use and is likely to be used extensively in the Royal Navy. Terylene is best for towing in enclosed waters because it is less extensible than nylon. Polythene, though not as strong as terylene, and nylon can be used when a floating rope is required.

Insulation

Several types of insulation materials have been used, including sprayed asbestos, resin-bonded glass fibre and resin-bonded mineral fibre. The latter has been found to be the best and is used for both sound and heat insulation. Foamed plastics have been considered but have not been used to any great extent because they are liable to produce dense and possibly toxic fumes in the event of fire. Foamed plastics of expanded polystyrene are used for life buoys and buoyancy blocks.

Ventilation and Air Conditioning

The ventilation arrangements fitted in pre-war ships were based on a rate of air change of 2,000 cubic feet per man per hour and in general were satisfactory for the equipment and complements carried. This situation, however, changed rapidly under war conditions when ships operated for prolonged periods under closed-down conditions. Complements increased considerably without additions to ventilation and the introduction of increasing amounts of heat-producing radar and electric conversion equipment in ships aggravated the situation. The war also made great demands on the capabilities of ships to operate efficiently in contrasting theatres of war. The prolonged periods of steaming at high power released large amounts of wild heat into the ship which, under tropical conditions, made matters worse.

With the end of the war it was realized that the method of assessment of ventilation requirements based on rate of air change in compartments would no longer provide the conditions required, ignoring as it did the heat dissipated by equipment. A completely new approach was made on the basis of airborne removal of the total heat load dissipated in the compartment which took account of solar radiation on boundary structure, heat transfers from adjacent hot compartments and heat radiated by personnel, equipment, etc.

The design requirement decided upon was that the compartment should be maintained at not more than 10 degrees F. above outside temperatures. It was necessary to accept higher figures for hot compartments such as galleys and machinery spaces. Where compartments were ventilated only, i.e. not air-conditioned, a minimum air quantity of 30 cubic feet per man per minute was supplied.

These requirements form the basis for present-day ventilation in H.M. ships, the main essentials of which are:—

(*a*) The provision of sufficient fresh air.

(*b*) The distribution of air without causing discomfort from draughts or noise. In cold climates little air movement is required ; in hot climates, especially if there is a high degree of humidity, air movement is essential, so that a combined jet/diffuser type of terminal is usually fitted.

(*c*) The maintenance of suitable temperature and humidity.

(*d*) The reduction of wild heat, methods to reduce which are :—
    Lagging
    Fan motors not to be sited in living or operational spaces
    Power supply outfits—trunked exhaust from machines which should be sited outside living spaces
    Fluorescent lighting
    Machinery spaces provided with exhaust fans having a capacity of 20 per cent in excess of supply to ensure a partial vacuum
    Heat exchangers—water cooled.

Full air-conditioning provides the only means of ensuring maximum efficiency of personnel under the widely varying climatic conditions that a ship is likely to meet. The majority of existing ships, however, have normal ventilation only to habitability spaces. Practical considerations of weight, space and cost have limited the extensive application of full air-conditioning and in general air-conditioning (cooling) facilities have been confined to vital action compartments and a few special compartments such as sick bays. The air-heating feature of air-conditioning is incorporated in all normal ventilation systems.

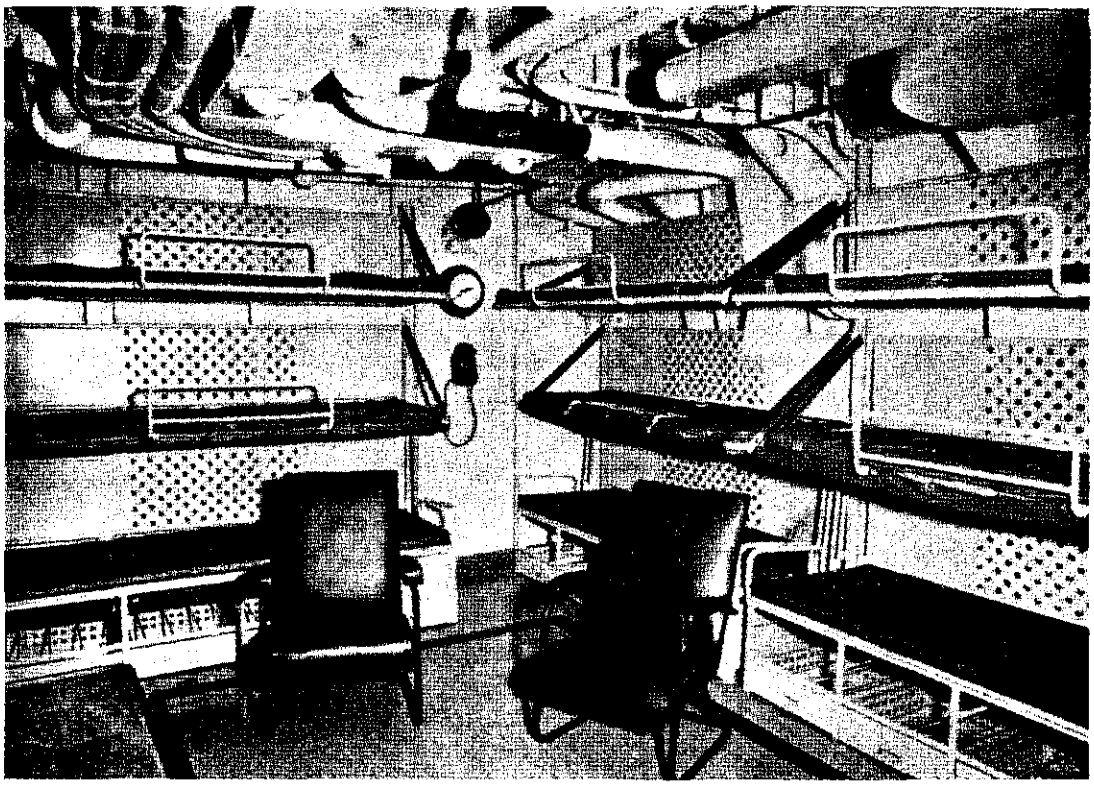

FIG. 8—C.P.O.S' MESS

In modern ships, control of temperature is essential if maximum efficiency is to be maintained and air cooling is now applied to living and working spaces as well as vital action compartments.

In order to reduce the size and capacity of equipment to a minimum consistent with reasonable living conditions, the most severe ambient temperatures assumed to be generally experienced at sea are 88 degrees F. dry bulb and 80 degrees F. wet bulb. More severe conditions may be experienced in harbour and exceptionally at sea but the corresponding rise in internal conditions is accepted. With these outside conditions the internal conditions aimed for are 85 degrees F. d.b. and 71 degrees F. w.b. In special circumstances, the assumed outside conditions may be those of average Persian Gulf conditions, namely : 94 degrees F. d.b. and 86 degrees F. w.b.

A substantial proportion of the conditioned air is recirculated, but provision is made for the introduction into the system of a minimum quantity of fresh air, namely, 10 cubic feet per man per minute. To diffuse the air and so assist distribution and eliminate draughts, slotted trunks have been introduced.

In future fully air-conditioned ships it will be possible to include dust filtration facilities.

In the earliest systems the refrigeration plants of around $\frac{1}{2}$ to 1 million B.T.U./hr. capacity were of the steam-injection vacuum type and presented some maintenance difficulties. For later installations freon compressor-type machines were adopted and were found to be generally more reliable for continuous running.

Present and future programmes for naval vessels will provide for the complete air-conditioning of all spaces where the crew work or rest. Electrical and electronic equipment may be air cooled by means of chilled water or freon cooling coils. Compartments containing special stores, and other equipment will be maintained in ambient air temperature conditions within prescribed limits of temperature and humidity. It is intended that all spaces will be maintained at the desired conditions by means of automatic thermostatic control of steam, air or water flow rates.

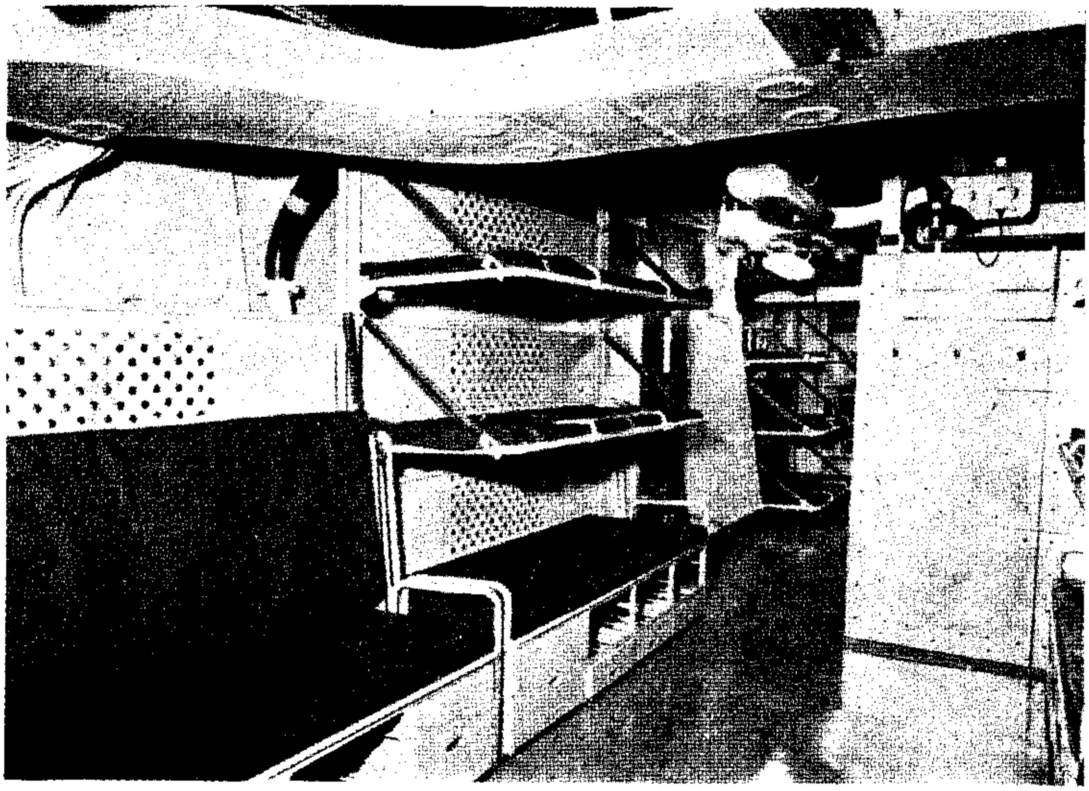

FIG. 9—SEAMEN'S MESS

The growth in air volume requirements has coincided also with growth in extent of trunk systems. This has led to higher air speeds in the trunks to minimize space demands and consequent increase in pressure demanded from the fans which in turn has led to higher noise levels emanating from the fans air outlets.

Initially some sound insulation was introduced into fan chambers and trunk systems, but more recently successful redesign of both centrifugal and axial fans has resulted in overall noise reduction of the order of 10 to 15 decibels with the same performance.

Habitability

Prior to the last war, accommodation spaces in H.M. ships were arranged on traditional lines. The messes were used for eating as well as sleeping in hammocks, and in the older ships washing up and clothes washing were carried out in the same spaces. Considerable advances have been made in the post-war years. Air conditioning of living quarters and centralized messing is current policy. Meals are served in separate dining halls (used also as cinemas) from easily cleaned plastic-topped tables. Within the mess proper, settee bunks are arranged for sleeping and hammocks are gradually disappearing from H.M. ships. In addition, kit lockers of greatly improved standard and other stowages are arranged together with occasional tables and stacking chairs so that a portion of the mess can be set aside for recreation (FIGS. 8 and 9).

Efforts are also made to facilitate cleaning to the maximum extent by building in stowages, blanking off inaccessible corners and ensuring that equipment such as fans, ammunition hoists, etc., are sited outside the mess. Laundries with modern facilities make the washing of clothes on the mess deck unnecessary. Bathrooms are sited in easily cleaned compartments and are fitted with stainless-steel washbasins and the latest pattern showers.

Senior ratings have increased space and improved furniture, including easy chairs, curtains and fireplaces and, in addition, carpets for the C.P.O.s.

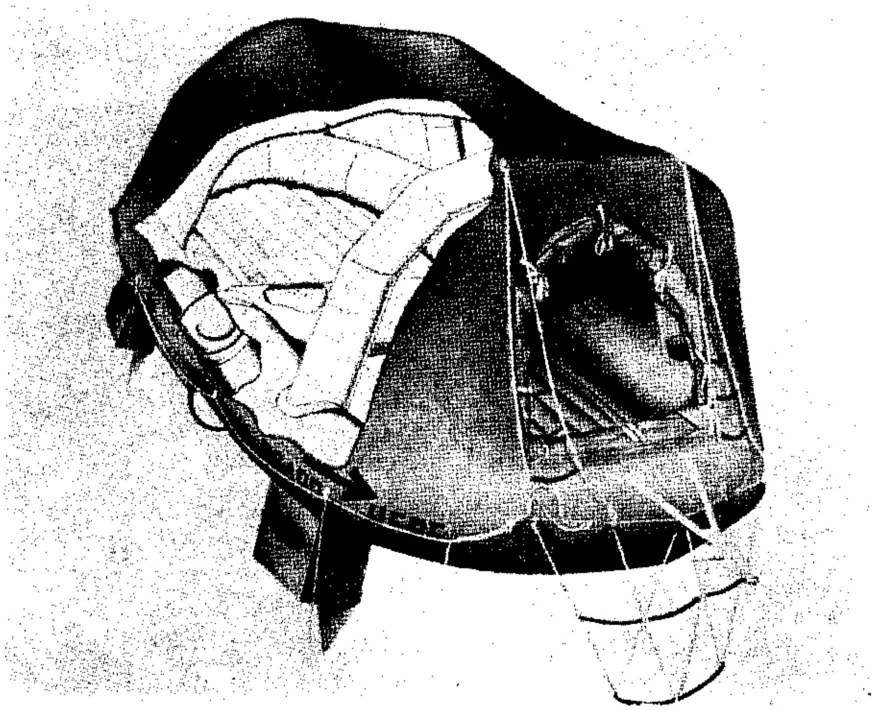

FIG. 10—TWENTY-MAN INFLATABLE RAFT

Galleys have been brought into line, with modern electric-cooking equipment, which is built-in to preserve hygiene, and the bulkheads in the galleys and preparing spaces are lined for the same object. Preparing rooms are equipped with the latest mechanized aids in the preparation of food, and serveries are arranged to facilitate the rapid distribution of hot meals. Special sculleries with washing-up machines are also fitted.

Officers' accommodation has also been improved, including panelled walls and deckheads, and multiple cabins are avoided as far as possible.

Further improvements are contemplated in all fields, particularly in C.P.O.s' accommodation.

Life-Saving Equipment

Considerable study has been given to experience with life-saving equipment in World War II and subsequently with a view to securing the most up-to-date appliances possible with present knowledge. The following information supplements that already published and describes some recent developments :—

Life-Jackets

The naval inflatable life-jacket consists essentially of a stole of 2-ply rubber-proofed cotton fabric which is inflated through a mouth tube fitted with a non-return valve. The mouthpiece is of rigid nylon so as to prevent freezing to the lips in cold weather. The stole is designed so as to provide most buoyancy on the chest. This automatically brings an unconscious survivor face upwards, with his breathing orifices clear of the water. Support is also provided around the neck so as to prevent the head lolling and a marker light with sea-activated cell of four-hours' duration is mounted high on the jacket.

This jacket is supplied to H.M. ships in commission and operational reserve in quantities equal to 110 per cent of the authorized war complement, plus a number sufficient to equip all boats.

Submarine crews are provided with a similar life-jacket incorporating a relief valve to take account of the varying pressures when ascending from a sunken submarine.

Self-Inflating Life-Jacket

A self-inflating life-jacket with water-activated gas cylinder has been developed for use by upper-deck crews. Should the wearer fall into the water the gas cylinder is released immediately and complete inflation is effected within a few seconds.

Life-rafts

Two sizes are used, a twenty-man, with overload capacity of twenty-seven, (FIG. 10), and an eight-man, with overload capacity of ten. Supply is on the basis of raft seats for the full war complement, plus 10 per cent rafts spare. The life-rafts incorporate two main buoyancy systems and are arranged so that if one system is punctured the other will provide flotation and protection for the full complement. The stowage is arranged for ease of launch under abandoning-ship conditions. Hydrostatic release gear which will ensure the rafts' floating free, should the ship sink before the rafts can be launched manually, is under trial.

Trials have shown that 250 lb is about the heaviest load which can be conveniently manhandled on shipboard. The weight of the raft has therefore been kept to within this figure. The rafts carry a limited amount of equipment and survival rations are provided for five days. A first day adrift is spent without rations. Unless the circumstances are exceptional, it is considered that rescue will take place within the six days.

The biggest danger to life in the raft is dehydration and solar stills are provided to ensure some supply of drinking water when the can rations are exhausted. Rain can be collected on the roof of the raft in plastic rainwater packs and, should further storage be required, the inflatable life-jacket can be used.

Survival Pack

As with the life-raft, the survival pack has been kept within a weight of 250 lb. In the case of the twenty-man raft the pack has to be a separate item, but with the eight-man raft the pack can be contained within the raft.

Materials

Naval inflatable life-saving equipment is made of cotton proofed with natural rubber. 3-ply is used for rafts and 2-ply for life-jackets (as already stated). Alternative materials, which are home produced, are under consideration.

Lifebuoys

Plastics of varying density have been considered in place of the cork used in Admiralty Lifebuoy Pattern 307. Trials show that the optimum weight of the lifebuoy is about 7 lb. Further trials under varying climatic conditions are proceeding with lifebuoys of plastic materials.

Lifebuoy Marker

A lifebuoy smoke marker which, unlike the calcium flares used hitherto will not ignite oil on the surface of the water, has been developed and ship evaluation trials are proceeding. A light marker is available in the form of buoyant lights with dry batteries or sea-activated batteries. A marker which combines both the smoke and the light is now under consideration.

A 27-ft motor whaler is being introduced as the standard sea-boat and is replacing the 27-ft Montague whaler and the 32-ft motor cutter which have hitherto been carried as sea-boats.

Survival Suits

A ' once only ' survival suit, made of lightweight material is under trial.

An ' occasional wear ' suit, of thicker material for use by weather deck personnel who may find themselves in the water without warning, is also under development.

Radio Equipment

Medium-frequency/high-frequency radio sets with hand generator are supplied for use in naval boats and inflatable life-rafts. Beacons with sea-activated battery will in due course be supplied and fitted in some naval inflatable life-rafts.

Naval Life-Saving Committee

Life-saving equipment is under continuous review by the Naval Life-Saving Committee. The Ministry of Aviation, the Ministry of Transport, Medical Research Council, and other bodies concerned with life-saving at sea are associated with the work of this Committee.

CONCLUSION

The upsurge in warship development during the last two decades has been astonishing and there is no indication that the rate of progress is slowing down. The designer has been faced with the situation since World War II where almost every aspect of the warship is undergoing fundamental change. With the restrictions on the number of ships, progress cannot be in such relatively gentle steps as formerly.

This calls for even greater standards of technical skill and wisdom from all staffs concerned in ensuring that the many more steps which now have to be taken with each new design are well chosen and directed.

It also calls for the greatest co-operation between designer and builder—whether it be of the warship itself or of the propulsion plant or of any of the complex items which form the modern fighting unit. Thus, modern techniques and discoveries can be harnessed to the Navy's benefit with maximum efficiency and at reasonable cost. They are objectives which are an increasing challenge to all of us at this time if the Navy is to be well served with new material.

Acknowledgment is made of valuable contributions to this lecture by members of the Ship Department of the Admiralty and of the co-operation of other Director Generals of material departments; also of the efforts of Mr. F. G. Bogie, Assistant Director of Naval Construction, in the preparation of this lecture.

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