DESIGNING WARSHIPS FOR A COST-EFFECTIVE LIFE

BY

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The Parsons Memorial Lecture was instituted in 1935 and is delivered annually under the auspices of the Royal Society. The range of Sir Charles Parsons' activities was wide and included almost all branches of engineering, and optics, and each Memorial Lecture deals with one of the subjects in which his interests lay and in which his genius played a part.

INTRODUCTION

The problems which faced Sir Charles Parsons in the design and construction of warships in the early part of his career in shipbuilding were mainly those of converting into practical terms the current advances in scientific and engineering theory. While he was himself responsible for many additions to engineering theory, he seems to have been interested in these mainly as aids to the practical achievements in which he delighted.

There are parallels between the developments of his time and present developments in ships being designed for the Royal Navy, such as the controversy then on the relative merits of the current steam plant, the new steam turbine, and the growing advocacy of Diesels, and the present rivalry of steam turbines, Diesels, and gas turbines. Even the argument for mixed plants, such as the reciprocating engine with an exhaust turbine, formed some sort of precedent for the proliferation of choices now available between COSAG, CODOG, or COGOG. But there is one feature particularly which tends to contrast the era of the First World War and the present time. This is the tremendous shift in the role of manpower in the sequence of activities from the conception through development, design, building, trials, and operation until the scrapping of a class of warships. While design decisions have always held the possibility of swinging the balance in war between success and disaster for a ship or class, the performance of ships, their machinery and their weapons, under all conditions, used to depend profoundly upon the performance of the ship's company, their morale, training, and practice in the actual operation of the ship. The guns hit or missed largely according to the merits of the guns' crews. The full speed attained by ships, their ability to stay at sea steaming at high speed and, the reliability of the ships' services depended enormously on the stamina of stokers and the heroic feats of artificers in keeping going machinery whose idiosyncracies and individual cussedness imbued each machine with almost a separate personality. But the advance of technology allows us to relieve the men in ships of these tremendous physical exertions. More and more our effort must be concentrated in the design and drawing offices, to choose the right options, and to satisfy ourselves that we are spending the country's money to the best advantage.

How can we judge this?

Since the Second World War with the increasing complexity of ships and their weapon systems the basis of judgement has become very complex. The tendency is for emphasis to shift from one quality to another according to the current pressures, such as recruiting difficulty, new threats provided by potential enemies, or developments in strategy or tactics within the alliance. In the last few years, there have been increasing efforts in the Western World to devise objective criteria to guide decisions which the designer has to make when trying to reach the best compromise between the many requirements which he is expected to satisfy.

For want of a better currency and because it is the language of Parliamentary Estimates the balance attempted is usually expressed in peace-time in terms of finance. It will be seen, however, that this is far from satisfactory in judging the merits of defence equipment, because the results of naval operations are not readily amenable to expression in terms of financial profit.

Most of our efforts therefore have had to be judged so far by their satisfaction of more crudely expressed demands. Relative military effectiveness, relative availability for operations, and relative capital cost have in general been our guides. Recently emphasis has shifted from advancing the performance of each new ship design to providing designs which aim at better availability. This in naval terms is understood as the percentage of days in the total life of a ship when she is either at sea or fully operational and available to proceed to sea within a stated time such as 4 hours or 48 hours.

Inevitably some requirements are conflicting. The first cost of a warship looms very large in the system of annual estimates, but we are developing the ability to estimate life costs for a ship. This should allow a better judgement of the optimum quality which is justified financially in a new ship or the optimum availability which her life costs can sustain.

Another pressure which looms large and which in fact reinforces our concern with life costs is the difficulty of recruiting men for the Services in peace-time and the familiar squeeze on the Defence Budget which limits these numbers in one way or another. The ship designer is therefore invited to produce a ship which can be operated and maintained at sea for long periods by a minimum number of men. Moreover the jobs these men are required to perform should be consistent with their abilities, rewarding and satisfying. They should also be provided with accommodation and surroundings when off duty which will allow them to rest and relax adequately. The total effect contrived must be to make them wish to continue to serve in the Royal Navy and in these ships. Men are still the greatest single factor in our ability to achieve the sort of sea power we aspire to exert. It is no more by heroic feats of endurance in manual operating tasks that they must achieve success but in the daily feat of keeping all the current sophisticated systems up to peak performance, diagnosing the onset of deterioration, and organizing their work to cover the critical systems and subsystems so that they are never taken by surprise by a failure or fall-off in performance. Feats of endurance are still required of our officers and highly skilled ratings somewhere in some ship every day and night. But now the sort of endurance required of a ship's officer is the mental stamina and strength of character to continue for many hours the search for an unidentified defect in a complex system, the ability to know his men and so to retain their alertness and perseverance as they assist him, and to go on thinking clearly until success is achieved. The Captain, comparatively young in a small-ship Navy, has to know all about the performance of his systems and the management of his men to get the best possible results.

This lecture is an attempt to outline the process of designing a modern warship, to give these people the best possible chance of success in operations. Some of the techniques being developed to improve availability and cost effectiveness are described, but by the very nature of a warship the ultimate proof of success is something one hopes to avoid. However, in continuing to keep the peace we should in a few years' time be able to verify whether our aim of providing more cost-effective ships has been achieved. It is hoped that this account may be of interest to engineers engaged in similar ventures of improving life costs and that we may profit from the experience of others or benefit from their criticism.

THE STAGES IN THE DESIGN AND BUILDING OF WARSHIPS

The warship design process can be conveniently divided into four stages.

Concept formulation. A term coined in the U.S.A. which involves feasibility and design studies of ships to counter various types of threat.

Design development. The formal design stage in the overall design of the ship. Hull form, compartmentation, and layout of weapons systems, machinery spaces, living spaces, and store-rooms are developed, so that the qualities of the ship, her maintainability and so on, can be estimated. Specifications, guidance drawings, and information are prepared.

Preparation of working drawings. Full detailing of the design. Preparation of quality-control documentation, test forms, and shipyard procedures.

Preparation of service documentation. The software required for operating the ship and for her logistic support, fleet maintenance support, and dockyard refit.

CONCEPT FORMULATION

This is the first phase of discussion on the need for a new ship or class of ships. It is set in motion by the creation of a Naval Staff Target. This in turn is backed by the previous long-term planning and operational research on the strategic and tactical force levels and capabilities approved by the Government, on the advice of the Chiefs of Staff. The main discussion which is joined over a new ship concept concerns the balance of qualities in each class. The deployment of a new major weapons system may be the basis of the design, but its combination with other capabilities must also be assessed, for instance whether the class should specialize in meeting or posing one particular threat or have a general-purpose capability and to what extent; whether all the ships of a class should be able to take a Squadron or Fleet Commander with all the necessary communications; whether one should depend on a fleet-maintenance support organization to keep at full efficiency or carry the crew necessary to do all the work needed to maintain all her systems working at peak efficiency for months or years; whether to allow any form of redundancy in systems; how many days or months at sea should her store-rooms provide for; what availability is required or can be justified; what should be her top speed, and endurance at a lower speed? These are some of the elements of the discussion and the bases of a large number of 'design studies' to probe the effect of the various compromises. Attached to each is an order of cost for a new ship.

The justification for the mix of capabilities proposed and the cost will be subjected to a detailed review by the Tri-Service Ministry of Defence Central Committees to ensure that the overall defence requirements are being met in the most cost-effective way.

The design studies are analysed against various threats, against concepts of operations, and the various roles which a ship of this class may be called on to fill. Invariably it will become too expensive unless some restraints are imposed. It is thus likely that the design studies will result in a steady refinement of judgement on the effectiveness which is necessary in a new ship to make her a credible weapon of war to both sides.

There will also emerge a better understanding of the number of ships of such a class which would be needed for them to be effective; and the unit cost for

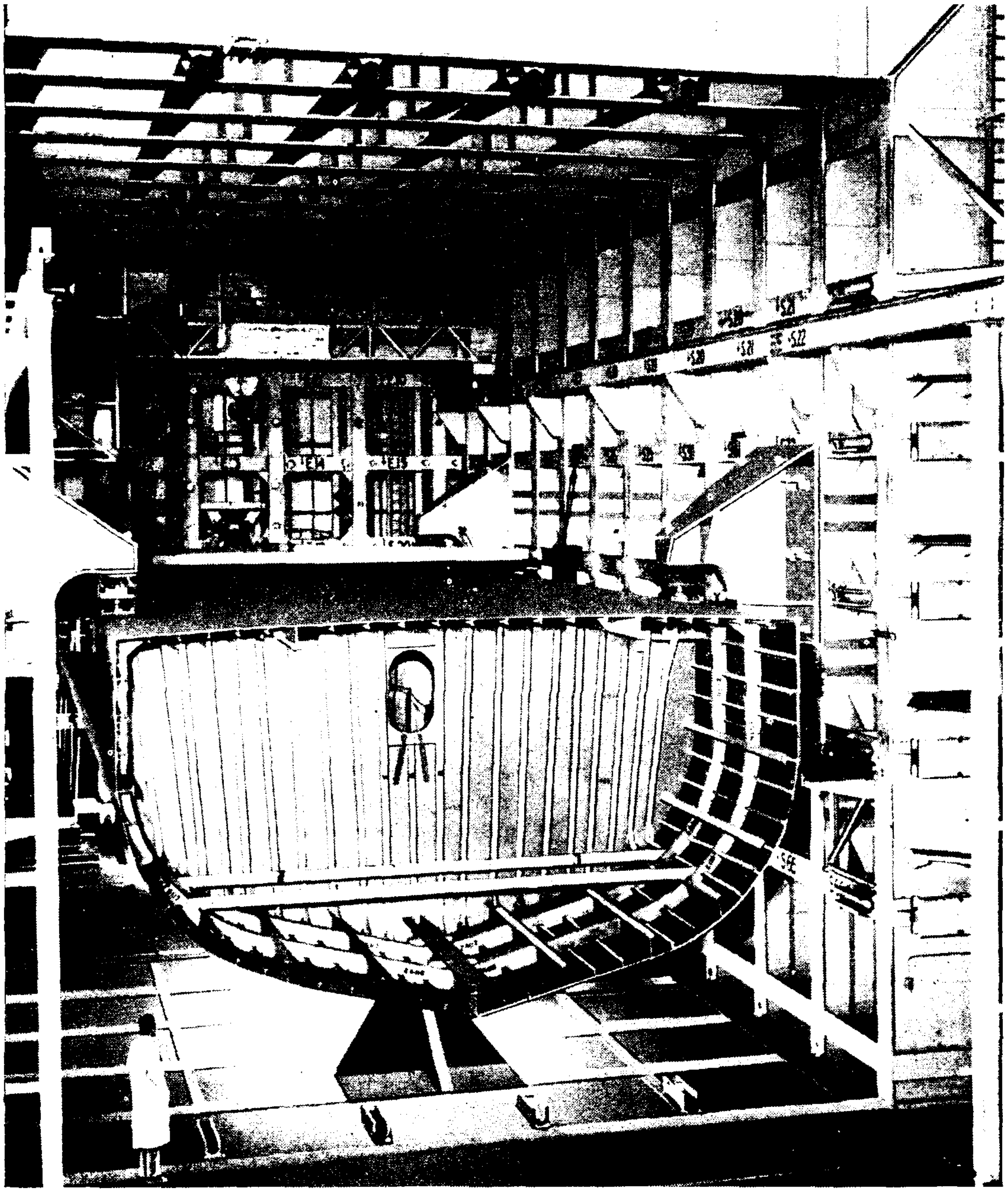

FIG. 2—THE 'FRAME' AT NAVAL CONSTRUCTION RESEARCH ESTABLISHMENT IN WHICH LARGE-SCALE SECTIONS OF A FRIGATE HULL CAN BE SUBJECTED TO STATIC LOADING TO CHECK THE THEORY OF STRUCTURAL STRESS ANALYSIS

each ship, which it is likely that the Naval Estimates can afford in years to come, with other classes in prospect, becomes clearer.

And so the choice is narrowed until a range of options covering a fairly narrow band of unit costs and ship capabilities is evolved. The original Staff Targets are replaced by the more specific Staff Requirements, which are selected as those which can be fulfilled by these designs. These requirements are then put to the Operational Requirements Committee for approval and if they are passed the ship goes into the 'sketch design' stage. This is the development of the design and the initiation of specifications and guidance drawings for the ship and its contents.

So the sketch design proceeds on a hull form worked out on the basis of tank model tests instituted at the Admiralty Experiment Works (FIG. 1), giving resistances at various speeds and evaluating the speed attainable for the horse-

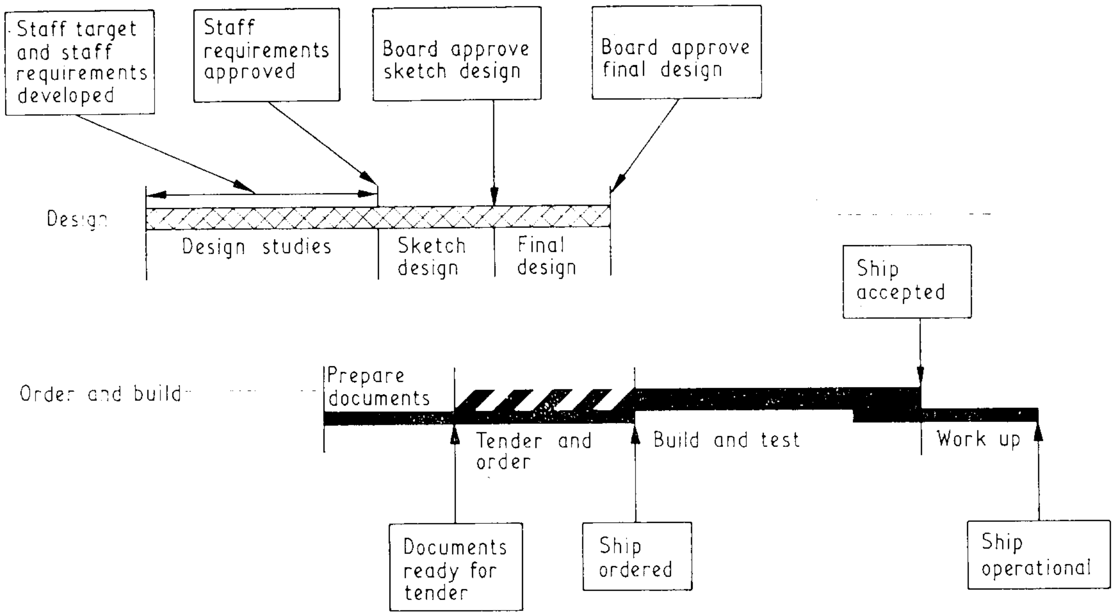

FIG. 3—TYPICAL NEW CONSTRUCTION PROGRAMME

powers available from the selected range of main propulsion plants. The amount of fuel required to be carried to meet the staff requirement 'endurance' is also derived from the resistance curves produced. The hull strength, structure, and materials are checked by reference to work done by the Naval Construction Research Establishment, or directly by them for critical areas (FIG. 2). The weapon, propulsion, and all ship's service and storage systems are worked out. The compartmentation of the ship is devised and the safe firing arcs, radar arcs, antennae, helicopter deck and hangar, and other upper-deck equipment are juggled to try against all odds to get them all fitted with specified clearances, angles of rotation, and safe arcs of fire.

This ultimate iterative process begins and the ship displacement, overall dimensions, cost, speed, endurance, the margins allowed for further additions, the margins for accommodation of men under training, the size of the ship's company, and the standard of accommodation, as well as all the services and systems, are finally settled.

The sketch design goes for approval to the Admiralty Board and then on to the Ministry of Defence Central Committees on Operational Requirements and Weapon Development to approve the ship as cost-effective; the total cost includes the costs of research and development which may be attributed to this class of ship. From this point the specifications, guidance drawings, and ship-structure drawings are refined for issue to shipbuilders who are invited to tender for detailing the design and building the ship (FIG. 3).

At each of these stages (concept studies, design studies, sketch design, detailed design, and construction) new techniques are under development. These are aimed at better judgements of cost-effectiveness, better life-cycle costs, better quality assurance, and better assessment of the resources needed for the operating and upkeep task.

The initial stages of concept formulation are carried out in the Ministry of Defence Navy Department (MOD(N).) Until the sketch design is started there is so much that is speculative and dependent upon weapons-development judgements, so many setbacks and changes of tempo that it is difficult to involve others directly. However, once the sketch design is under way we should like to involve shipbuilders more. They could undertake much of the extra load now imposed in the design stage and this involvement would also give the whole process of detailed design a better start.

Let us now consider in more detail the processes developed in each stage outlined.

Design Study Methods

The systems and components required are covered generally by the following:

Functional systems

Sensors Weapons Control systems and operations room Displays and equipment	each for each of	Anti-submarine Air defence Surface defence
Transmitters Receivers Offices Antennae	each for each of	Electronic warfare Communications Ship to ship shore aircraft satellite

For ship systems

Hull structure (including decks, bulkheads, superstructure, control surfaces, tanks, and compartments).	Structure for stability, sea keeping, manoeuvring.
Machinery, propellers, shafting, controls and auxiliaries.	Propulsion system.

Power generation and distribution, electric, hydraulic, and pneumatic.

Accommodation, bathrooms, sanitary systems.
Store-rooms, refrigeration.
Air-conditioning and ventilation.
Dining halls and galleys.

In each of the weapons systems there are various possibilities, such as a gun or a missile system, a long- or short-range system, the use of shipborne anti-submarine sensors and weapons, or helicopter-borne sensors or weapons. There is a great variety of possible permutations. In order to study the appropriate ship costs, a modelling technique has been devised so that we can see what the inclusion of any given functional system means in terms of cost to the ship as a whole. This will be described later.

The weapons system options can conveniently be examined on this basis, but there are certain ship characteristics which are equally important but more difficult to define as options. These include the ability to float, even after severe damage, to remain stable under a variety of conditions, such as icing-up, hurricane, torpedo, bomb, mine, or missile damage, to have good sea-keeping qualities at good speeds, appropriate habitability standards, and the endurance in the required speed range for long-distance deployment or escort.

It must also be remembered that at the inception of design studies the ship under discussion is unlikely actually to join the Fleet in less than six years' time. Projections of technology and of fleet support policy, therefore, play an important part in deciding ship characteristics and the number and skills of the men needed to operate and maintain her.

Very generally then, once the main weapon system of the ship, for instance surface-to-surface missile, has been decided, her ultimate size and cost will be influenced to a great extent by:

Top speed, i.e. shaft horsepower

Endurance at 15–25 knots, i.e. fuel stowage

Good sea-keeping requirements, i.e. hull form

Defensive anti-air armament and anti-submarine (including a helicopter)

Complement

Availability as a product of system reliability and maintainability.

Apart from the main weapons systems, the main propulsion and the electric generation and distribution systems have a big influence on capital cost, life costs, and the various qualities listed above.

Modelling Costs

The design-study stage requires a number of broad outline studies to show up overall size, cost, and manpower requirements based upon data about systems either historical or predicted, and some indication of the effect on the whole of varying any parts of the staff target. In this way the options are whittled down to perhaps three or four slightly more detailed studies.

This initial process is obviously a case for computer simulation and so we have embarked upon ship-synthesis computer models to give these initial estimates. This is particularly useful because the information required by the Naval Operations Staff differs in pattern from that of interest to the Design and Procurement Departments.

The Naval Operations Staff thinks in terms of roles and functional systems. Each of these functional systems is made up of many material components such as launchers, structural supports, cooling water, electrical power, ventilation, and life-support features for the systems' maintainers and on-board logistic 'tail'.

The elements of the matrix can be reassembled to group together similar components to give to the designers a build-up of material systems including sea-water systems, electrical systems, auxiliary-steam system, chilled-water system, and so on and so on. The Material Departments have to think in terms of such material systems, because this is the logical way in which industry views a ship from the point of view of procuring, fabricating, and assembling material, and installing equipment and systems. It is also the only way in which costs can be properly assessed.

An example of the light shed by the modelling of functional systems is the breakdown of costs for a typical frigate. The traditional way of expressing costs of material systems is as follows (the figures are percentages):—

Armaments	31
Electrics	10
Hull	25
Machinery	27
On costs	7

These costs are the costs of the machinery and equipment, of building the ship's structure, and of installing the equipment in the ship. Accommodation comes under hull costs in this case.

Expressed as costs of functional systems the costs give a clearer indication of the real cost of ownership of the various functional systems within the ship as follows:

Armament	56
Aviation	1
Hull endurance	17
Propulsion	24
Protection	1
Margin	1

To explain this rather more explicitly, each functional system can be made up of a series of sub-systems for each of which we keep account of the total demand it makes for services in a ship. Where these differ significantly with the type of ship this is also logged. Thus for, say, a 4·5 in. gun we log not just the weight, swept radius, and cost of the gun, but the size, weight, and cost of the gun, its control system, its associated radar, its ammunition hoists and magazine, the part of the ship to carry it, the power to run it, the cooling plant to cool it, and the men to man and maintain it (the gun system) and the appropriate proportion of the ship's services for it, plus the on-board logistic tail to accommodate and feed all these men. Provision is also made for logging the maintenance costs and whole-life costs. The sum of the relevant sub-systems integrated in this way will produce each functional system and these again integrated together with hull and propulsion system, and life-support system, etc., will produce a model of the total ship.

The ship design process is thus necessarily iterative, constantly checking the part against the whole, the intermediate answer against the initial assumptions, and so on. For example, the sum of the electrical loads will be checked against the generator numbers and capacity to ensure that the margins for action damage and overload capacity are adequate. If not, the next larger generator will be substituted until the balance is satisfactory and the repercussions upon the machinery plant will be adjusted automatically. In the course of a design development the defined electric-power requirements will usually rise in the course of successive reassessments by at least 25 per cent above those forecast at the outset.

The iteration in this ship synthesis process is performed on both space and weight bases to reconcile the requirements for each with the assumed or progressively computed ship dimensions.

Our main interest at present is with initial cost, complement, and size, but the modelling process is being developed to give maintenance loads and whole-life costs to include support services.

A most valuable outcome of this type of analysis is that it enables attention to be focused on where money is being spent and invites searching examination of whether the result is worth the cost. By correlating functional systems with material systems it becomes possible to examine such questions as 'Do we need to spend all that money on so and so?' and 'Can we not substitute a simpler system manufactured in less expensive materials?'

The validity of the modelling work is much dependent upon the adequacy of information available about the numbers of men required to man and maintain given items of equipment or ship systems and the men required to perform other logistic or communal tasks within the ship. Very close co-operation is needed with the Manpower Departments. Conversely, it will be seen that, given these data, we can provide a complement figure for any concept study by tabulating the study's major characteristics and important equipments and systems, thus helping the Manpower Departments to get an earlier forecast of future needs.

Nevertheless step changes in the ship's structure may well be involved in the inclusion or exclusion of any system and at present it is necessary to stay fairly close to the basic size of ship under discussion if the answers given by the modelling technique are to be trusted.

Life Costing

Although the life costs of some major systems may well influence some of the selections in the design-study stage, their importance is of more widespread significance in the sketch-design stage, where the development of all the systems in the ship takes place and specifications for detailed design and procurement are started.

The elements of whole-life cost are: research and development; design; procurement; personnel; operations; maintenance and refits; modernization; headquarters and administrative costs.

If this list is taken in order the following observations are relevant. Each warship is an amalgamation of equipment of varying obsolescence: in many cases at present the research and development costs are already sunk in capital cost and it is not always possible to produce an acceptable method of retrieving these costs and assigning them accurately against individual ships. The overall cost is, however, not negligible: the annual cost spread over the ships being completed each year amounts to over £3m per ship completed.

Both the research and development and the design costs are intramural and extramural. The present policy is to get industry to take on an increasing proportion of them.

The cost of working drawings carried out by shipbuilders for the first ship of the class, and which are applicable to the subsequent ships, are made part of what are known as the 'First of Class' costs.

Procurement costs account for something under 25 per cent of whole-life costs. Within the procurement cost, we are of course concerned to maximize the military capability of the design and to ensure that this is available for as many days in the year as possible. Various new principles, such as design for repair by replacement and design for upkeep, mentioned later, have been developed with better availability as the objective, but they will increase procurement costs.

Personnel costs, which are largely conditioned by ease of operation and maintenance, reliability, etc., amount to over 40 per cent of the life cost in present warships: hence the continual endeavour to reduce ships' complements and the increasing justification of research and development to do so.

Operating costs include the expenditure on ammunition, fuel, stores, aircraft, etc. and are influenced significantly by changes in availability. The increased complexity of modern warships is reflected in an increase in operating costs as a proportion of the total, this being particularly true of missile-armed ships. A change from furnace fuel oil to Diesel fuel burning does not, however, significantly increase whole-life costs because while it does increase operating costs owing to the higher cost of Diesel fuel the reduction in maintenance and refitting work outweighs this in modern naval boiler plant.

Maintenance and refitting costs depend upon the initial design, its operating cycle and usage. Maintenance is carried out by ships staff at self-maintenance periods with some assistance from Fleet Maintenance Groups and by H.M. Dockyards during 'docking and essential defects' periods and 'refitting' periods. Maintenance and refitting costs amount to some 10 per cent of whole-life costs.

The hull, machinery, and electrics in a warship will last through two generations of military credibility of major sensors and weapons systems. In normal circumstances our life-cost studies show it is cost-effective to modernize the ship by installing new weapon systems at about mid-life and, in effect, to buy time in which to delay the purchase of a new ship, without seriously decreasing the military effectiveness of the Fleet.

Headquarters and administration costs cover all non-assignable costs.

It will be appreciated that there are involved inter-relationships between these various costs and these we are investigating: we believe that the cost of filling a complement billet in one of H.M. ships is higher than the figure we are currently using. It could be as high as £20,000. (The cost of a man in a ship depends on how many there are ashore training to take it over, etc.) We have still to resolve the question of the support costs of helicopters ashore and other support costs in the logistic field. Accepting these cautions we find the percentage life costs for an existing and a future frigate to be as follows:

	Existing	*Future*
Procurement . . .	13·5	21
Complement . . .	50	36
Operations . . .	13·5	22
Refits and modernization .	23	21

On the other side of the cost-effective equation, the elements of effectiveness are: worth; availability; performance.

Worth

Worth is the value to the nation and the Navy of the ship; it is necessary to consider how effective against the potential enemy threat our ships are throughout their lives. The assumptions made regarding the decay of worth with time, of ships or their major systems, have an important effect on overall effectiveness (FIGS. 4 and 5). It would be a great help if a meaningful financial or other value could be placed upon 'worth'. At its lowest level such a method would be of use in conducting trade-off studies between alternative systems and assessing the value of increased availability. At a higher level such a method could influence total-force levels. Reluctantly we have concluded that assessment of naval value in absolute financial terms is not practical; it is impracticable for an important part of naval output and, where it might be possible, it would be misleading. We are therefore pursuing an alternative approach in providing an assessment of the comparative capabilities of different fleets, squadrons and ships within those fleets and developing a method of making comparative assessments of different ship and fleet capabilities.

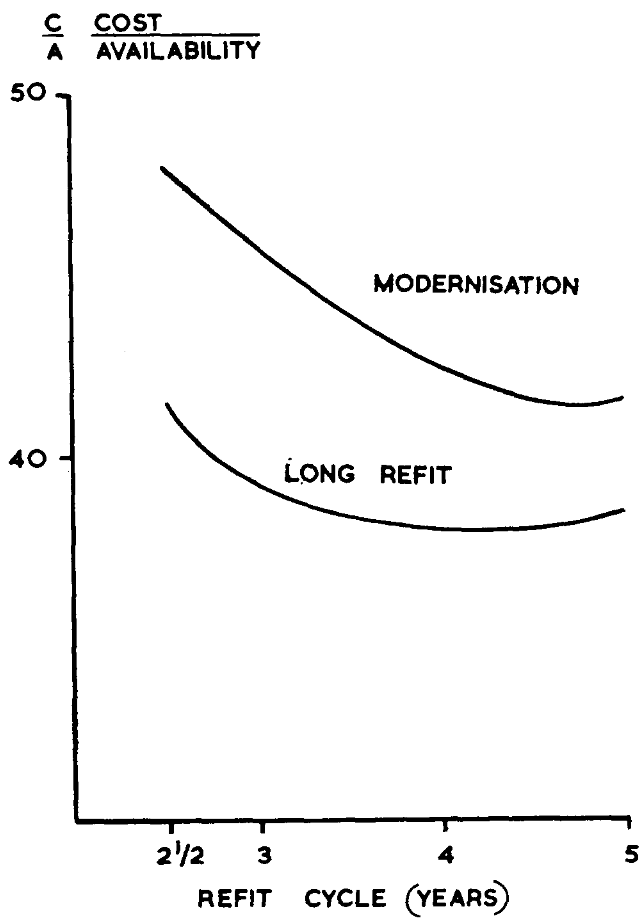

FIG. 4—VARIATION OF COST PER AVAILABLE YEAR WITH TIME BETWEEN REFITS

The worth of a particular class or modification to a class, such as a change in sustained

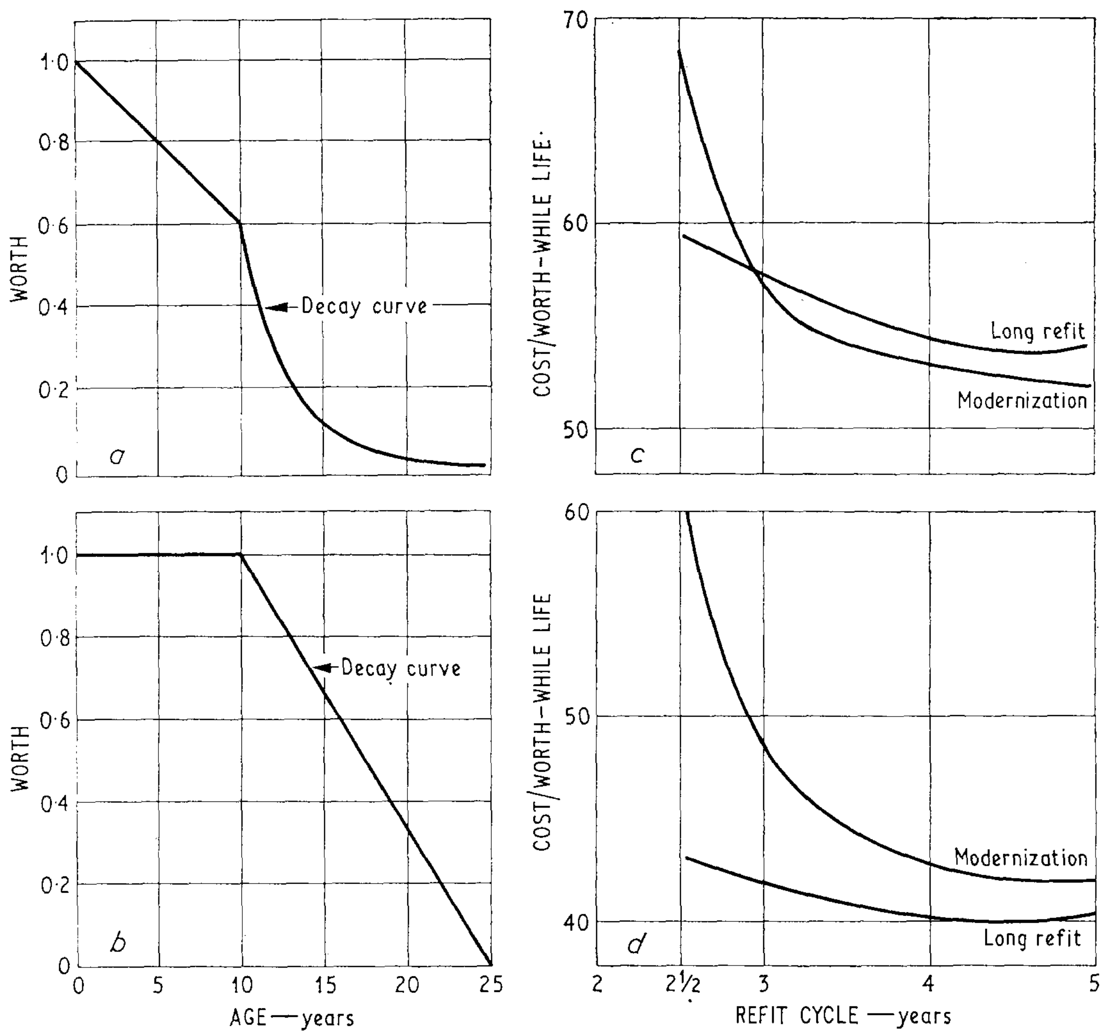

FIG. 5

(a) and (b) ASSUMED DECAY OF MILITARY WORTH OF MAJOR SYSTEMS WITH TIME
(c) VARIATIONS OF COST-EFFECTIVENESS WITH TIME BETWEEN REFITS
(d) FIG. 4 MODIFIED BY FIG. 5*(b)*

top speed or a reduction in overall manpower, could then be judged by its effect on the capability of the entire Fleet.

Availability

Although it is difficult to define in financial terms, the most obvious way in which effectiveness can be increased is to increase the availability of H.M. ships. Some measures being adopted, such as repair by replacement, have been mentioned, but, to be more specific, if we could reduce the time out of action for normal refits by one-third we would increase operational availability by 5 per cent of the ship's total life (i.e. one year in 20). Similarly, if we could reduce modernization times, we would again increase operational availability. Discussion of measures to increase availability must, however, take note of manpower considerations. Over the past 15 years, availability and usage have progressively increased and there are a number of pointers which suggest that present usage is pressing against the upper limit for our present design of ships. One of the factors has been the need for the maintenance staff to stay on board and work at high pressure during the days in harbour, which are becoming scarcer, instead of getting real relaxation. What is therefore needed is increased availability with less strain on men and perhaps a lower percentage of the total availability used up at sea.

Performance

Performance is associated with the durability of the systems fitted. The purpose of maintenance and refitting evolutions in H.M. ships is to maintain the performance of weapons, propulsion, and hull systems at the installed level. Training is associated with performance both in normal and emergency conditions.

A study of the work already done on life costs has given rise to certain specific developments in the design of our future ships which will be described. It also reflects on the policy for research and development work to prepare for future designs and some of these effects will be mentioned later.

DESIGN DEVELOPMENT

It is during the sketch-design stage that it is possible to confirm the effect on this particular ship of introducing changes of design policy or equipment-upkeep policy.

For instance, a change in the volume of space per man or area of deck per man in order to raise standards of accommodation may raise the cost of the ship by £¼m and it has to be decided whether this can be absorbed in the unit cost or justified as an extra to the cost already quoted.

It is during this stage therefore that recent developments in design policy to try to increase availability are fully applied and their effects on the ship design can be gauged.

It is necessary at this stage, too, to define the fleet upkeep policy which will apply to the ship, the operational pattern for the length of period the ship must be capable of operating independently of support, and how often and for how long she will be provided with maintenance support.

Two policies to try to enhance availability which have been applied to our new ship designs for the first time in the Type 42 guided-missile destroyers and Type 21 frigates, now being built, are 'repair by replacement' of machinery and equipment and 'systematic machinery and equipment selection' (SYMES).

Repair by Replacement

The policy of repair by replacement is intended to transfer as much of the upkeep and overhaul work as possible to shore workshops. Fewer men will thus be needed on board. It will also shorten the time a ship is kept in dockyard for refit, provided removal routes are clear and so disruption of the ship is not involved. There are other serious implications. We have to ensure that:

(*i*) Assemblies, and sub-assemblies are truly interchangeable. This in turn means careful tolerancing of manufacturing drawings.

(*ii*) The repair organization meets the need of refit programmes so that reconditioned spares are available. This now means a substantial re-organization of our resources.

(*iii*) The policy of how each machine or equipment is to be refitted is clearly laid down and followed through during the design, e.g., if it is to be refitted *in situ*, the space required round it, the 'maintenance envelope', is kept free of obstruction; if it is to be removed, removal routes must be clearly designated and kept clear, in design, in construction, and during the life of the ship.

(*iv*) Monitoring systems are introduced to ensure rapid diagnosis of deterioration or failure.

In order to contain the cost of this policy it is absolutely essential to reduce the variety of machines and equipments. This is also desirable from other aspects such as training and refitting costs and these have given rise to the policy of SYMES.

SYMES Policy

At present the Fleet is equipped with a large variety of equipments, many of them performing similar functions. For example, there are now 29 different types of fresh-water distilling plant at sea in H.M. ships. There are 47 different air compressors now in service and the story is the same for most of our auxiliary machinery. In general the aim now is to have just three sizes of each type of equipment in the SYMES range, from which the warship designer can select the one that most nearly satisfies his needs. The performance of these three equipments in the SYMES range will be chosen to cover the full spectrum of foreseeable requirements for frigates and larger ships, either singly or as multiple installations.

It is recognized that by limiting his options in this way the warship designer will rarely be able to select an equipment which precisely meets his requirements in all respects, and, in consequence, he may have to install equipments with somewhat greater outputs than he needs, and which are probably slightly larger and heavier than he wants them to be. This penalty is bound to be unwelcome, but it may well enhance reliability by reducing the rated output at which the machine will normally work. Thus the penalty paid in slightly greater size and weight may be partly offset by a greater availability.

This is, of course, only a fringe benefit of the SYMES policy. The main advantages are more direct. Simpler and more certain logistic support provides greater availability: reduced training requirements and the users' familiarity with equipments in the Fleet ensures better maintenance standards: larger and longer production runs invite lower first costs: overhauls can be organized with enough units to give a continuous run and so reduce reconditioning costs: off-the-shelf purchase, if this is developed, would reduce the time scale of building programmes for new construction and, above all, concentration of development effort gives improved reliability. The greater part of our financial and professional resources can be concentrated on proving and improving a limited range of equipments which, once they are established, will, we hope, remain in service for many years in a succession of classes of ship. These established and proved equipments would only be replaced by new designs where a significant technical advance promises an improved performance or reduced life-cycle cost of sufficient magnitude to offset the inevitable penalties and teething troubles of introducing a new equipment into service.

Reliability

Reliability and maintainability clauses are being introduced into contracts for equipment for the SYMES range. Meanwhile, to ensure that our reliability and maintainability specifications are realistic and related to the operational availability requirements of ships in the Fleet, quantified data are being obtained for all SYMES equipment in service. These will enable predictions to be made of system and ship availabilities, areas for necessary improvement to be identified, and reliability and maintainability requirements for new equipments specified to match the required system and ship availability.

We prefer where possible to use commercial equipment because of the manufacturers' greater interest in a larger-than-naval market and because the feedback on reliability and performance is much more extensive. Unfortunately, we are not able to accept commercial practice in many areas owing to shock or noise requirements.

We have also found it necessary to institute a searching set of practical trials to develop reliability in our machinery for the future. The improvement in life and the easement of the maintenance task after ships are in service has been a long detailed slog of elimination of one weakness after another by modifications. Often nothing can be done.

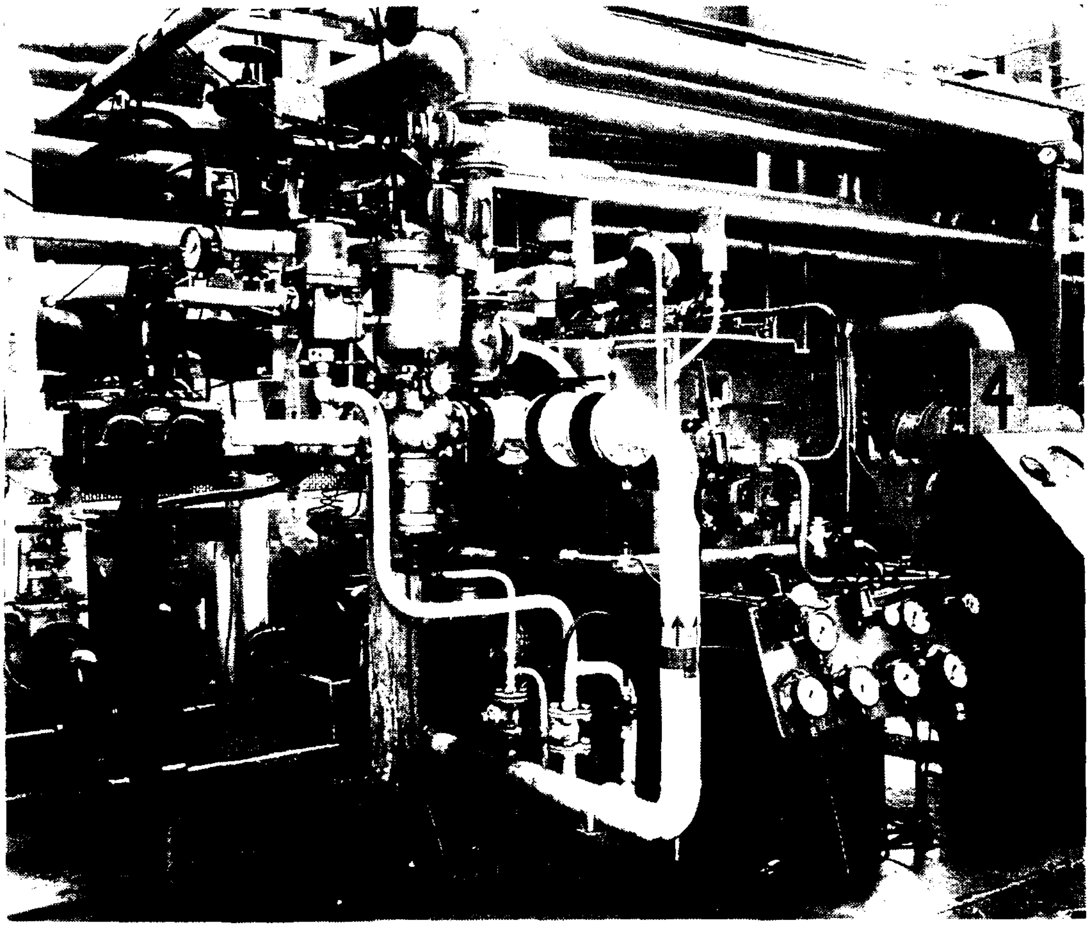

FIG. 6—A RIG AT ADMIRALTY MARINE ENGINEERING ESTABLISHMENT SHOWING A BOILER FUEL PUMP ON TEST. THE ESTABLISHMENT IS FITTED WITH FULL AUTOMATIC DATA-RECORDING FACILITIES. SUBSTANTIAL ALTERATIONS TO THE DESIGN OF THIS PUMP RESULTED FROM THE EXTENSIVE TESTS CARRIED OUT

It is in the field of auxiliary-machinery development therefore that our greatest change has taken place in the last five years.

Gas turbines and Diesels developed for the Navy have in the past been used as main engines of submarines, minesweepers, fast patrol craft, and frigates, and as prime movers for electric generators. It has therefore been natural to tackle seriously their reliability, maintainability and life between overhauls, as an aspect of performance. On occasions we have set up a complete boiler plant or boiler-and-main-turbine set for tests of the whole plant, assuming that the sub-system and individual auxiliary machine's reliability would have been established by the manufacturer. For lack of time and facilities this has often not been the case. Much time has been wasted on the shore trials of our steam plant owing, not to failure of novel features of the system, but to unreliability of equipment designed to normal current principles. Likewise much work arose in ships from a lack of reliability and maintainability which could have been overcome by attention to detailed design and a proper appreciation of environmental conditions.

We have therefore built a test house at the Admiralty Marine Engineering Establishment for the testing of individual auxiliary machines and sub-systems. These include not only steam auxiliaries, pumps, high-pressure valves, and controls but atmospheric-control equipment, refrigerating machinery, and other ship service machinery (FIG. 6).

The work now carried out on each of these auxiliaries is aimed at selection

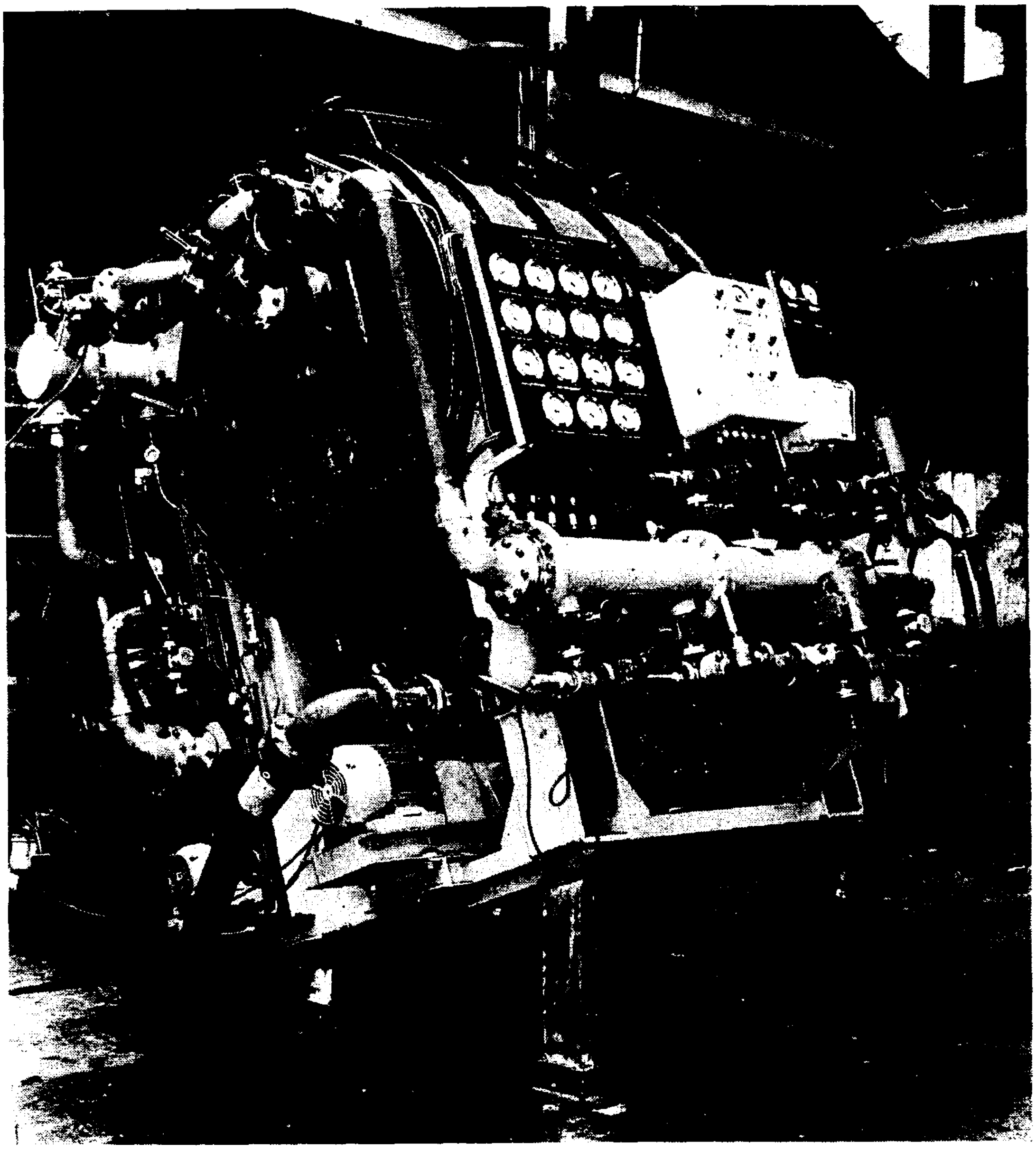

FIG. 7—A DISTILLING PLANT UNDER TEST AT 20 DEGREES HEEL TO PROVE THAT IT WILL MEET THE SPECIFICATION

for our future standard ranges of the most suitable machinery. It is confirmed by test running that the equipment has been developed to give us the reliability and maintainability required (FIG. 7).

The following is a list of the types of test applied:—

(*i*) Detailed series of performance trials at full range of speeds, stops, starts, and variations of speed or power, changes of water temperature, etc.

(*ii*) Vibration and airborne noise tests.

(*iii*) Shock tests.

(*iv*) Maintenance evaluation. The manufacturer's maintenance routines are probed and all anticipated modes of breakdown-repair and normal maintenance routines are carried out by naval ratings. (Not major overhauls.) The draft instructions for maintenance are evaluated, special tools, time taken, level of skills required, and the envelope of space required are all considered, checked, and fed back to the installation designer and the manufacturer.

(*v*) Endurance running on a basis of cycling between starts, stops, and operation at anticipated speeds or outputs. This also includes periodical performance checks or 'condition monitoring' in an effort to develop this art, to supply ships with basic data about their machinery and to save work in ships. The methods used and being tried include:

(*a*) Noting changes of normal indications of pressure and temperature;

(*b*) The use of aids for visual inspection of internals, e.g., intrascope viewing;

(*c*) Variations in vibration levels overall or of discrete frequencies at particular points;

(*d*) Sampling and analysis of lubricating oil or other working fluids;

(*e*) The effects on these parameters of deliberately induced wear.

The use of such instrumentation may well be possible only by providing special fittings and access points for probes and viewing devices through casings in the design.

After this work the design is finally frozen and the auxiliary accepted into the standard range. Our ability to prevent subsequent alterations and preserve real standardization is always in doubt, and we depend on the co-operation of industry to preserve interchangeability of our standard-range machines over the years.

System Reliability

In order to study system reliability or dependability a study is being carried out on Type 42 systems under contracts involving three contractors. The object is to carry out detailed evaluations of system reliability, to study whether system interfaces are adequately covered, whether our organization or the organization of the main and sub-contractors fails to provide the necessary cover, what are the critical areas and how these should be tackled in future designs.

PREPARATION OF WORKING DRAWINGS

Our policies outlined above are aimed at achieving a substantial reduction in the present complexity of logistic and maintenance support, and also at reducing the variety of equipments for whose operation and maintenance men have to be trained. The value of these policies can be seriously undermined, however, unless systems are designed with the same care and the information available to the ships' companies about their equipment is adequate and accurate.

It is therefore in this stage of the detailing of the designs, the recording of information, the analysis of systems operation and reliability, and the documentation provided to the ship and dockyards, that the greatest additional burden is thrown on drawing offices and on planning and quality-control offices for new classes of ship.

Quality-control documentation is now prepared by the shipbuilder to provide his quality control staff with means of checking everything as the building proceeds. This is now part of the contract requirements for new warships. The creation of dockside test teams and a programme for their tasks is also specified. This idea, adopted from the building of nuclear submarines, involves combined teams of the shipyard quality-control team, the naval crew standing by their ship under construction, and the naval overseers at the shipyard. These teams jointly test installed equipment, sub-systems, and systems as the work progresses to avoid the scramble at trials period, when a large number of small defects are apt to be revealed all together. The reduction of defects during trials and deficiencies on completion has been quite impressive in ships so far completed to what is now known as GRAQS (general requirements for the assurance of quality in ships).

In order to produce satisfactory compartment layouts in the congested spaces which characterize the modern complex warships, more extensive use is now made of mock-ups in which all fittings and pipes are represented. From these the working drawings are derived, the model being the master reference. The mock-ups are used to check access for maintenance, removal routes, and the elimination of blind corners where maintenance of the structure would be too difficult. This is part of the First of Class costs paid to the shipbuilder of the lead ship, who will then be required to up-date the mock-up as further ships are built. The cost may well be about £¼m for a ship costing £10m or a class costing, say, £80m or £100m.

PREPARATION OF SERVICE DOCUMENTATION

It is during this stage of detailing therefore that the documentation is prepared to simplify and define the subsequent upkeep task for the whole life of the ship.

Firstly, the ship's company as well as Headquarters and the dockyard should have in a readily retrievable form a list of all that is fitted in the ship. This sounds simple and obvious, but it certainly is not and we have now adopted a system called Configuration Control in order to achieve this end.

Secondly, the detailed design having been prepared to meet newly defined upkeep policies and the maintenance methods for each machine having been developed, these must be recorded and made readily available to the ship and maintenance bases for its support. The removal routes, where applicable, the component breakdown for maintenance, or items to be renewed and the old discarded must be clearly defined.

Thirdly, the optimum division of maintenance work between the ships staff and the fleet-maintenance support organization and dockyards will be worked out during the design and the different organizations will be given a forecast of the extent of the task which will fall upon them, any special equipment required and so on, well in advance.

Fourthly, spare gear required, divided between afloat and ashore and consistent with upkeep policy, must be defined and provisioned and finally the ship must be provided with clear and accurate instructions on operation, upkeep, and diagnosis of faults in all the systems and equipment installed.

In order to ensure that the first three of these tasks are performed for future ship designs to a consistent standard a *Design for Upkeep Code of Practice* is under preparation for use by future First of Class shipbuilders. In the meantime valuable lessons are being learnt in the development of these practices for ships of Types 21 and 42.

Configuration Control

Configuration control is concerned with the management of changes which will be made to the ship, its systems and equipment, throughout the life of the ship. To manage change it is first necessary to establish a datum which records the precise state of the ship and its systems at the time it is accepted into the Navy. To do this, the shipbuilder is required to feed into a computer data bank all the basic information about components, equipments, systems, and the test equipment and tools to support them. The only way we have found to do this is to use drawings as the definitive document. It is therefore necessary to seek out from shipbuilders, and their sub-contractors, adequate drawing references which will give a precise and unique definition of the hardware fitted in the ship. This information for a frigate amounts to a computer input of between 100 000 and 150 000 punch-cards of information. This index is virtually infinitely expandable and we are going to keep this dossier updated as the master record of the material configuration of each ship throughout the life of the class.

One purpose of such records is to enable the maximum degree of commonality to be achieved in the building of repeat ships of the class. In the context of support after entering service the records are required specially to keep a detailed record of all types of modifications to the ship, its systems and equipments.

After a ship enters service it is necessary to have feed-back from the ships themselves, from fleet-maintenance bases and from the refitting dockyards to record the accomplishment of modifications and any other scheduled or unscheduled changes to the ship, or to its systems and equipments. This feedback will include the modification status of drawings, handbooks, test procedures, etc. For these post-construction requirements reliance will be placed on the feedback system being developed for the Ship Upkeep Information System (SUIS) which is now being introduced into the Royal Navy.

It is the intention to implement these support-management and configuration-control concepts on all new major classes of warship. The data banks so established will be integrated to the maximum extent with the data/information banks and files required for other warship design, maintenance, and provisioning activities.

Handbooks

The old-fashioned naval handbook or manual is being replaced by a publication produced to a joint service standard using an agreed eight categories of information. The British Standards Institution has adopted a similar standard for industry using the same eight categories.

The categories are as follows:

(1) Tactical and planning information ..	What it is for
(2) Operator information	How to use it
(3) Technical description	How it works
(4) Installation information	How to fit it
(5) Upkeep information	How to look after it
(6) Work schedules	Who does what and when
(7) Parts catalogues	What spares you can get
(8) Modification Instructions	Afterthoughts

Section 5: The upkeep information will be presented in such a way that it also forms the job information card.

Instead of written descriptions a more pictorial method of information presentation will be provided in the Fleet. The narrative text is condensed into blocks around an illustration. This method is being developed in the Ship Department for some of our existing equipment.

Another technique, FIMM (functionally identified maintenance manual), is based on a form of dependency chart which shows how each part of the system depends upon incoming signals and what signal outputs are produced. This information is produced at various levels from the most general to the most particular. The number of levels depends upon the system complexity.

The FIMM technique can be used by design management as a design disclosure system (DDS). Designers are required to record their work in a formal and disciplined manner by the FIMM technique. The DDS is then used to produce the diagrams, text, and dependency chart required for the maintenance manual.

The aim is to produce technical publications which will consist mainly of illustrations and diagrams supported by a small amount of text. Such books should be less bulky.

THE EFFECTS ON NEWLY DESIGNED WARSHIPS

What has all this meant in practical terms in our new warship designs? Firstly, an effort to double the intervals between dockings and also refits.

The adoption of aircraft gas turbines adapted for naval use is perhaps the most profound single change. These allow of refit by replacement and reduce the on-board maintenance task and hence manpower. They also automatically provide routes for replacement via their own air intakes.

Other trunks are provided for the withdrawal of auxiliary machinery.

Salt-water systems are being constructed of copper-nickel-iron alloys proved to be the least susceptible to corrosion and erosion although costing two or three times as much as the galvanized steel pipes used commercially.

The number of salt-water intakes or sea tubes through the hull, which proved to be difficult to preserve and maintain, has been reduced to about one-quarter of the number in our previous classes of frigates. The present inlets will be big enough for access by divers.

The provision of removal routes and maintenance envelopes has inevitably made the ship slightly larger, but this has not produced an increase in first cost likely to come anywhere near the life-cost savings.

Much more attention is being paid to underwater materials, such as rudder pintles and bearings, for which an experiment is being carried out with stellite in the hope of lengthening life.

More work has also been put in hand at our research and development establishments on further improvements designed to lengthen life. The Central Dockyard Laboratory continues work on paints, cathodic protection systems, and the depositing of non-ferrous materials such as 70–30 copper-nickel or stainless steel on structural steels. The developments of the technique for copper-nickel deposit is established and is of great use for lining critical areas or for repairs. The Admiralty Materials Laboratory continues to study the materials and design of valves and fittings for long life in higher water speeds in salt-water systems. The Naval Construction Research Establishment developments in structural-design methods and in the use of tough steels of high tensile strength and the associated welding techniques have direct application in our new ships.

The Admiralty Experiment Works work on hull resistance with different painted surfaces with different degrees of fouling, in conjunction with the Central Dockyard Laboratory, is also capable of direct application. The measurement and study of hull roughness and resistance will enable better forecasts to be made of performance over longer docking periods.

New materials for propellers are under trial for longer life against erosion and one stainless steel in particular is very promising.

Trials with titanium-tubed heat exchangers have proved the many virtues of this material in high-velocity salt-water flows. The extra expense has already paid for itself by eliminating the need for frequent replacements.

The Admiralty Engineering Laboratory has been engaged in the development of new automatic watchkeeping devices for diesel-electric alternators. This covers both the need for accurate voltage and frequency control and also the introduction of devices for automatic starting-system checks and shutdown in case of malfunction which will eliminate the need for watchkeepers. A fluidic

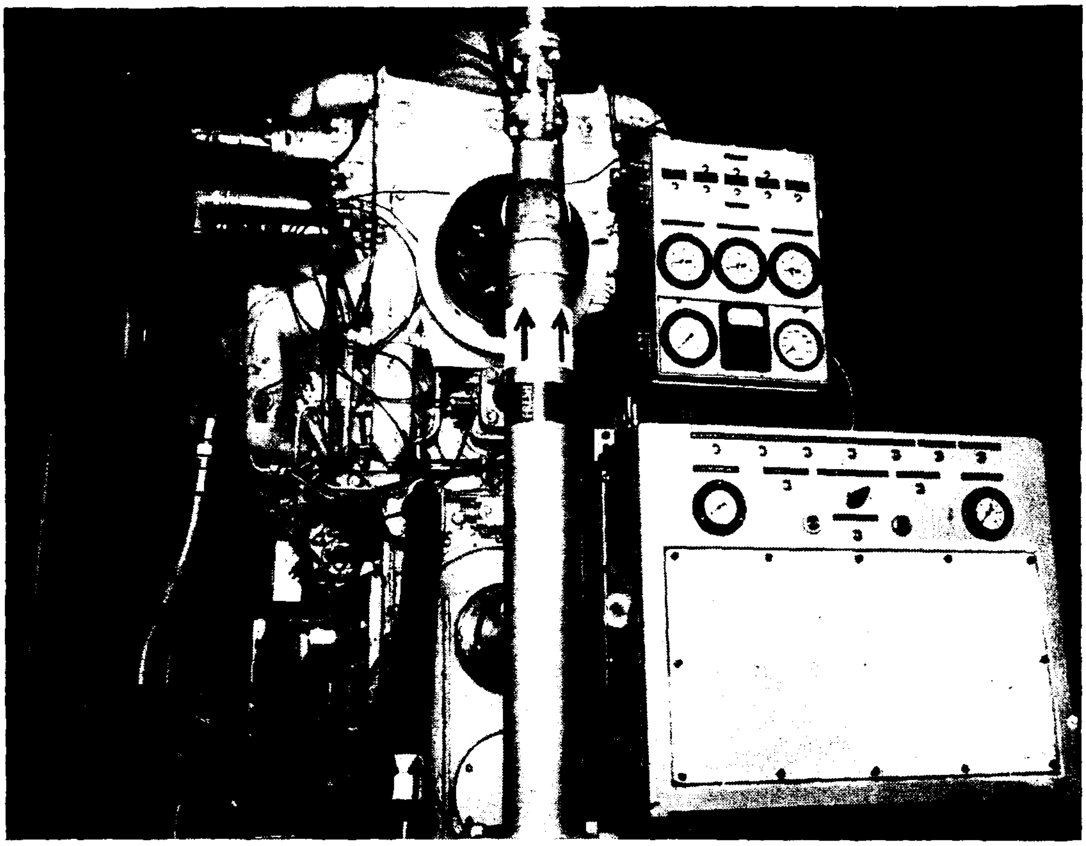

FIG. 8—THIS SHOWS A DIESEL GENERATOR WITH THE ORIGINAL PROTOTYPE SET OF FLUID CONTROLS FOR SYSTEM CHECKS AND AUTOMATIC STARTING AND STOPPING ROUTINES. A LATER VERSION HAS SIGNIFICANTLY REDUCED THE SIZE OF THE CONTROL PANEL

control system is now going to sea under trial after successful shore trials (FIG. 8).

In the 1950s the pressure to keep down the size and first cost of ships, as well as growth of loads on air conditioning and electric power as newer equipment was fitted in succeeding classes, resulted in ship service systems having small or no margins. In the new generation, in order to enhance system dependability, enough margin in capacity and in the number of units fitted has been introduced to allow for shutting down one unit while still keeping adequate output for the whole system. This ability to shut down a plant without impairing system capability enables the equipment to be maintained at sea so that the ships staff is used more productively.

It is inevitable that there should be wide variation of ship's speed, of electric-power requirements, of requirements for cooling of electronics, of messdecks, and of the loads on all systems during the daily routines or exercises in a ship. For this reason a number of artificers and mechanics have always been employed in watchkeeping on main propulsion and auxiliary systems in our present ships.

These will now be reduced to a petty officer mechanic in the control room, an artificer in general charge of all machinery, and two or three mechanics going rounds.

It will be possible to carry out maintenance on ship service machinery and other auxiliaries at sea as well as in harbour. The number of people can therefore be reduced; those in the ship should have fewer random failures to cope with, and the improved instrumentation and better instruction books should allow easier diagnosis of failure.

CONCLUSION

It is therefore anticipated that a substantial improvement in availability will be achieved; that the need for reduced manpower will be met; that the staff of the engine-room department will feel that they have moved into a modern world where they are dealing with better-engineered systems and equipment; and that proper forethought will have gone into providing the means of upkeep to a high standard of reliability through the life of our future ships.

Until we know the true difference in worth to the nation between a warship at sea and one in a dockyard it is not possible to demonstrate the extent of the improvements in cost-effectiveness which may be achieved. However, I believe that the effort to achieve better availability and reduced manpower has put into much sharper focus the need to improve the quality of the employment of our officers and ratings.

If we succeed in this respect, it alone is the best possible justification of our efforts.