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Marine Engineering in the Royal Navy: A Review of Progress during the Last Twenty-five Years*

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INTRODUCTION

Just nineteen years ago, Engineer Vice-Admiral Sir Reginald Skelton delivered the Third Thomas Lowe Gray Lecture and gave a most interesting account of marine engineering in the Royal Navy, from about 1815 to just after the end of the 1914-18 war. He described the developments which had occurred during that period, from the earliest side-lever engine and jet condenser, to the geared turbine and surface condenser; from the flue boiler supplying low-pressure saturated steam, to the water-tube boiler supplying high-pressure superheated steam; from the paddle wheel to the screw propeller; and from coal to oil fuel. I shall endeavour to continue the account for the quarter-century commencing in 1922, when the first post-war designs were under consideration.

At the beginning of this period, marine engineering really meant steam engineering; in the Royal Navy the use of internal combustion engines for propulsion purposes was limited to submarines, small craft, and a few minor war vessels; even in the Merchant Navy only about 4 per cent of the total tonnage of shipping was propelled by internal combustion engines, although their growing popularity was shown by the fact that about 9 per cent of the tonnage of new construction was to be fitted with these engines and the percentage was increasing each year. By 1947 the challenge of the internal combustion engine had been strengthened by its fine performance during the 1939-45 war, and it had become a fully accepted competitor with the steam engine in merchant ships, but in the Navy the steam engine still predominated; a new competitor, the gas turbine, was in the field, and in this year the first gas turbine ever to be fitted in a naval vessel carried out successful sea trials.

On the conclusion of the 1914-18 war, there was an almost complete stoppage of naval new construction; design departments were mainly concerned in studying the lessons of the war, and in planning future designs in the light of engineering progress during the war years. Consideration was also given to the future programmes of the two research establishments, namely the Admiralty Fuel Experimental Station (A.F.E.S.) at Haslar, and the Admiralty Engineering Laboratory (A.E.L.) at West Drayton.

Naval machinery had stood up well to the test of war conditions, and there were only two major mechanical troubles, namely, the failure of the D-shaped water drums of boilers, and the failure of brass condenser tubes. These problems were soon solved, the former by the adoption of circular water drums, and the latter by the adoption of cupro-nickel tubes. Another trouble, the almost complete immobilization of one of our battle cruisers by one unlucky hit, took longer to solve, although the first steps in this direction were apparent in the design of the "Kent" class cruisers.

DESIGN REQUIREMENTS

In all marine designs there are three essential requirements; reliability, economy at full power, and durability. The naval

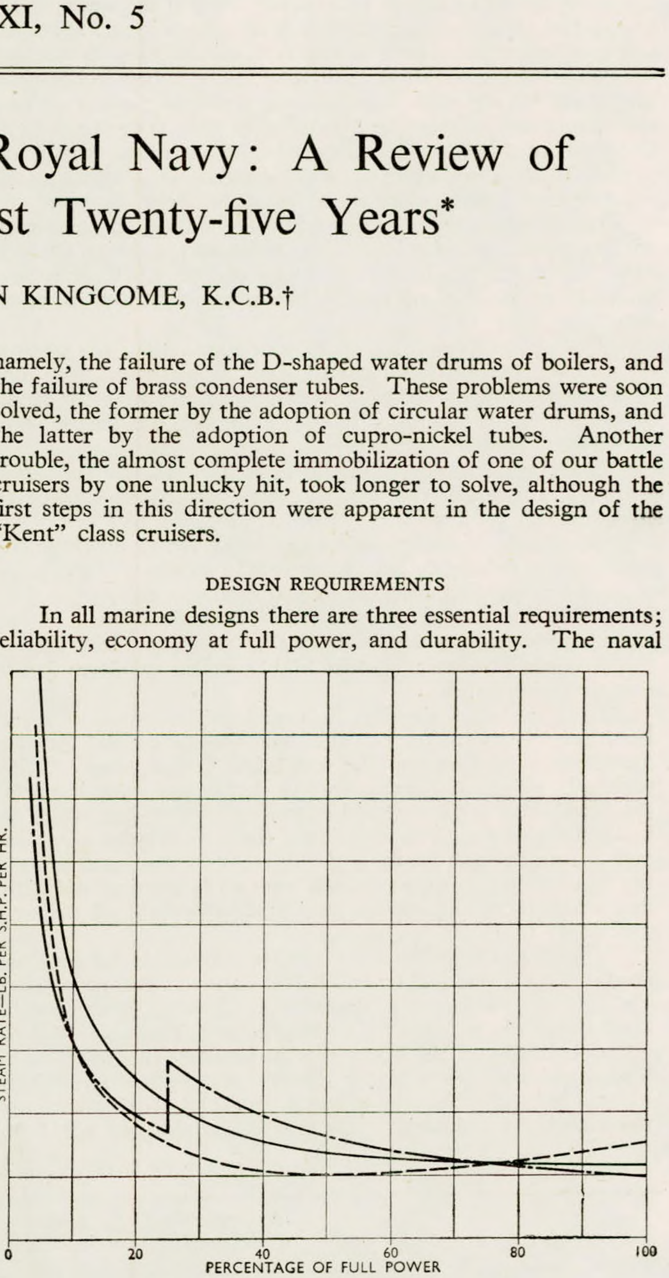

FIG. 1—*Steam consumption curves*

Unit with cruising turbine —— · ——
Unit with impulse wheel at inlet to high pressure turbine
(*a*) *with maximum efficiency at full power* ————
(*b*) *with maximum efficiency at half-power* — — — —

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designer must, however, obtain these with minimum weight and in the minimum space, and, in addition, the design must provide good economy at all powers, endurance, and flexibility combined with simplicity in handling and maintenance.

The need for economy at all powers raises many problems. Economy at full power is of major importance to the designer as it affects the overall weight and space of the machinery but, from the operational aspect, it is of less importance in warships than in merchant ships, as the former seldom steam at high power for long periods. In peace time, most passages are made at the most economical speed, in order to save fuel. In war time, warships proceed at various speeds, depending on the circumstances of the naval war, e.g., at high speed in a dash at night through a danger zone, or at low speed when escorting slow convoys. Most of the time is, however, spent at moderate speeds, and as fuel economy enables the ship to remain longer at sea, the war cruising-speed is kept as low as is consistent with safety.

Thus there are three main conditions where economy is important: at the peace-time cruising speed, at the war cruising speed, and at full speed, and these have to be considered in the development of the design. Owing to the overriding importance placed on weight-saving in naval designs, as a result of the Washington Treaty, British ships have been designed for maximum efficiency at full power. By aiming for maximum efficiency at some point lower than full power, a design could be obtained which would give a better overall result as regards economy at the cruising speeds, but at some sacrifice in weight and space (Fig. 1).

The ability to increase or decrease speed rapidly is essential in warship designs. Originally this requirement was more applicable to small ships such as destroyers, but with the advent of aircraft it is now equally important for the bigger ships, particularly aircraft carriers.

Endurance, or the ability to remain at sea, for the service intended, for prolonged periods was fully tested during the operations in the Pacific.

Simplicity of design and accessibility are of major importance, as warships may have to operate in any part of the world, and they must, therefore, be able to maintain themselves for a reasonable time without assistance. The majority of our ships are equipped with a small number of machine tools, and the engine-room personnel contain highly skilled artificers for the task of maintenance.

In a warship there is a varied collection of auxiliary machinery, both ancillary to the main machinery and for other duties; most of these are now turbo-driven, and, owing to limitations in weight and space, only the larger and more important are fitted with separate condensers—e.g., turbo-generators and hydraulic pumps. The remaining turbo-auxiliaries are, therefore, uneconomical units, and the recovery and utilization of the heat rejected in their exhausts form an interesting and highly important factor in the economical development of the naval machinery unit.

In 1922, conditions were most unfavourable for progress: the first world war had ended, Naval estimates had been heavily cut, and the staff of the Engineer-in-Chief's Department had been drastically reduced. The Washington Treaty of 1921 had set such limits on the Navy that weight-saving was given the highest priority—even higher than technical efficiency. Owing to the lack of adequate research facilities, both Admiralty-controlled and industrial, most new design features could only be tried out in operational ships, and this naturally delayed progress. Nevertheless, steady progress has been made throughout the period as shown by Sir Stanley Goodall in a paper read before the Institution of Naval Architects (1946). He referred to the reconditioning of the "Queen Elizabeth" class, and said that reconstruction of such a drastic nature was only rendered possible by the advances in marine engineering practice during the previous quarter of a century, as could be seen from the comparison in Table 1.

Table 1. Advances in propelling machinery of 80,000 s.h.p.

	As originally designed	As completed in 1940
Weight of main engines and boilers, tons	3,080	1,570
Floor space occupied by main engines and boilers, sq. ft. ...	13,150	8,610
Steam consumption at full power, lb. per s.h.p.-hr.	12·8	9·4

The weight of the machinery was nearly halved, the space reduced by a third, and the steam consumption at full power reduced by a quarter.

The machinery of the "Queen Elizabeth" class battleships was particularly suitable for conversion as it was designed in 1914 before the adoption of superheated steam and geared turbines, whereas the conversion design embodied both these features and the further advances made during the between-war years. Reduction in the weight of machinery is of importance to the shipbuilder, as any savings can be used for more fuel or other items of military importance, but, for the engineer-designer, weight reduction must not be carried out at the expense of reliability, and the degree to which weight-cutting can be achieved should depend on the importance of the ship considered as a military unit. Further, the margins to be allowed between the various classes of ships can only be assessed by experience and by a thorough knowledge of the types of machinery being installed.

Table 2 draws a comparison between the various classes of ships and shows the advances made in each class. The figures represent s.h.p. per ton of main engines and boilers.

Table 2. Advances in Output (s.h.p.) per ton of main engines and boilers

Capital ships		Cruisers		Destroyers
		Large	Small	
Queen Elizabeth (original design)	26			
Hood	34	*Hawkins* 39	"D" class 48	"Vee" class 77
Queen Elizabeth (conversion)	51			
Modern big ship	60	Modern cruiser 75		Modern destroyer 95

This not inconsiderable achievement was largely produced by a slow step-by-step method in which each new advance could only be tried out in the next year's new construction programme.

STEAM MACHINERY

Steam Conditions. The basic factors in steam machinery available for variation are the pressure and temperature of the steam generated by the boilers. Raising the pressure and temperature increases the thermodynamic potential and, if advantage can be taken of it, the overall efficiency of the installation.

In 1922, British ships were using saturated steam at 220lb. per sq. in., but superheated steam was being introduced in all new construction; the steam conditions in the "Nelson" class were 250lb. per sq. in. and 575 deg. F. By 1928, pressures and temperatures had risen to 300lb. per sq. in. and 625 deg. F., and it was apparent that higher temperatures would present new and unfamiliar problems. At this time, steam conditions in land plant were 330lb. per sq. in. and 720 deg. F. on average, with a maximum of 620lb. per sq. in. and 840 deg. F., and it was evident that higher steam conditions would soon be in use.

An experimental unit using steam at 500 lb. per sq. in. and 750 deg. F. was installed in the destroyer *Acheron*. Successful trials were carried out on completion, the fuel consumption for all purposes being 0·608lb. per s.h.p. per hr., as compared with 0·81lb. per s.h.p. per hr. of her sister ships using steam at 300lb. per sq. in. and 625 deg. F. Naturally, there were teething troubles, and it was most unfortunate that *Acheron* was transferred to the Mediterranean with the rest of her flotilla. Normal duties may be the best way to find out the weaknesses in a design, but with so novel a design it would have paid to retain this ship in home waters and run her hard, but under the control of the Engineer-in-Charge of the Fleet. On the whole, the boilers and auxiliaries were fairly satisfactory, and we learnt a great deal which was of value in later designs. The high-pressure turbines gave continuous trouble, which could undoubtedly have been overcome by development testing ashore had facilities been available. Unfortunately, by this time the country was going through a financial crisis, and no money was available for the changes necessary to complete the trial.

By 1935, the war clouds were blowing up over Europe, and a policy had to be adopted in the big reconstruction programme which began in 1936. The steam conditions in land plants were by this time up to 400lb. per sq. in. and 750 deg. F. on average, with a maximum of 1,800lb. per sq. in. and 900 deg. F., and it was known that certain foreign navies were using higher steam conditions; in view of our experience in *Acheron,* it was decided to take no risks and to revert to our method of step-by-step advances. As a result, at the outbreak of the 1939-45 war our large ships were using steam at 400lb. per sq. in. and 700 deg. F.; destroyers were, however, still using 300lb. per sq. in. and 650 deg. F. for production and maintenance reasons; this was a complete reversal of our usual practice, which was to incorporate the more advanced designs in destroyers and only to adopt them in the bigger ships after they had been thoroughly proved under the severer conditions of the destroyer.

The *Acheron* trial was a great disappointment and stressed the need for an Admiralty research establishment and for facilities for the full-scale testing ashore of ships' machinery and equipment.

The fact that the steam conditions in British ships were lower than those in the United States and German navies has given cause for criticism, and it may be of interest to consider how the higher steam conditions were developed in the two countries respectively.

The United States Navy decided to carry out a test similar to that on *Acheron,* but in a flotilla of destroyers, not just one ship. They tackled the problem differently, however; they made use of their land engineering industry, which already had experience of higher steam conditions, and set it the problem of producing a design for destroyer machinery to meet two alternative conditions: 42,000 s.h.p. with steam at 385lb. per sq. in. and 620 deg. F., or 52,000 s.h.p. with steam at 375lb. per sq. in. and 825 deg. F., both at the turbine throttle. The Navy's decision about future policy did not have to be made until 1938, by which time most of the teething troubles of the original destroyer design had been overcome. Even so, it is understood there was a good deal of discussion before these steam conditions were extended to bigger ships, but their subsequent adoption was fully justified by war experience. The item which probably contributed most to this successful development was the locked-train double-reduction gearing, which had been developed in the United States in the between-war years.

In Germany, where the trend was to use even higher pressures and temperatures, the development was carried out in merchant ships, an early example being the *Uckermark* which was fitted with a high-pressure Benson boiler as early as 1932. Further marine experience was obtained in the liners *Scharnhorst* and *Gneisenau* (650lb. per sq. in. and 850 deg. F.), and *Potsdam* (1,300lb. per sq. in. and 875 deg. F.), the latter being fitted with Benson boilers. A "Narvik" class destroyer which came to the United Kingdom after the surrender of Germany in 1945, was fitted with single-reduction geared turbines using steam at 1,100lb. per sq. in. at 930 deg. F. Possibly this high pressure was used to reduce steam pipe sizes and to save machinery space; actually the machinery spaces, though very congested, were longer than in the corresponding British destroyer and the steam consumption was higher.

Towards the end of the 1939-45 war, the steam conditions in British destroyers were raised and a design was prepared using steam at 650lb. per sq. in. at 850 deg. F. For this new design, and for further work in the high-pressure, high-temperature steam field, great advances will be required in the technique of turbine detail design and manufacture, in the production of high precision gearing, in steam-valve and steam-pipe manufacture, in the development of auxiliary machinery, and in many other directions, but I feel confident that the marine engineering industry will tackle these problems with their usual skill and energy. The firms in the industry have already shown that they have appreciated their lack of research facilities and have taken the first step to rectify the position by setting up Pametrada (Parsons and Marine Engineering Turbine Research and Development Association). This establishment includes a test house where high-powered marine sets can be tested at full power. This is a good beginning, but much research work remains to be done, not only on advanced designs, but also on production technique, without which any big step forward in the design will be hampered by the lag in production. Given the whole-hearted support of the firms themselves and of the Admiralty, there seems to be every possibility that the next decade will see a very real advance in the field of marine steam engineering.

Boilers. Advances in boiler design have undoubtedly made the major contribution to the large saving in weight and space of naval machinery over the last twenty-five years. The two main reasons for these advances are that facilities have been available at the makers' works for full-scale testing of boilers, and that the Admiralty research establishment at Haslar has been able to carry out continuous research and development work on boiler designs and on the closely related subject of fuel combustion.

The priority task assigned to the A.F.E.S. on the conclusion of the 1914-18 war was the development of a superheater suitable for warships. A design was prepared with the superheater tubes behind the fourth row of generating tubes, so overcoming the disadvantages of the uptake type of superheater previously fitted. Trials of this new design were carried out in the test house at Messrs. Babcock and Wilcox works at Renfrew and were satisfactorily completed in time for superheaters of this type to be fitted in *Nelson*, the first new ship of the post-war period. This type of superheater with minor modifications was fitted in subsequent ships until it was replaced by the Melesco design.

During the 1914-18 war, the oil-fired, small-tube boiler had given good service in cruisers and destroyers, but the change from coal to oil in the big ships had only taken place towards the end of the war. With this change, there was no longer any reason for retaining the large tube boilers previously fitted in our big ships, and *Hood,* completed just after the 1914-18 war, had twenty-four oil-fired, small-tube boilers for her 144,000 s.h.p., whereas *Tiger* of 108,000 s.h.p. had thirty-nine coal-fired, large-tube boilers. The resultant saving in weight and space of machinery and in personnel pointed the way to the adoption of a smaller number of larger boilers in future designs. With this end in view, much work was done at the A.F.E.S. on the development of larger oil-fuel sprayers; at the beginning of the period, the largest fuel sprayer had an output of 900lb. per hour, but new designs with outputs up to about 1 ton per hour have since been developed. Work on improving the oil burning arrangements continued at the A.F.E.S. throughout the period, but was intensified during the 1939-45 war with very satisfactory results.

The development work on boilers has been mainly progressed by full-output shore trials of actual ship boilers; but, owing to the unfortunate position of the A.F.E.S. at Haslar, where the duration of trials are limited by the tide, most of these trials have been carried out at makers' works at Birkenhead, and on the Tyne and Clyde. These arrangements were not entirely satisfactory and, during the war years, an Admiralty test house was erected at Clydebank, and a number of our latest boilers have been tested there. The shortcomings of the Haslar site have now been recognized, and Admiralty approval has

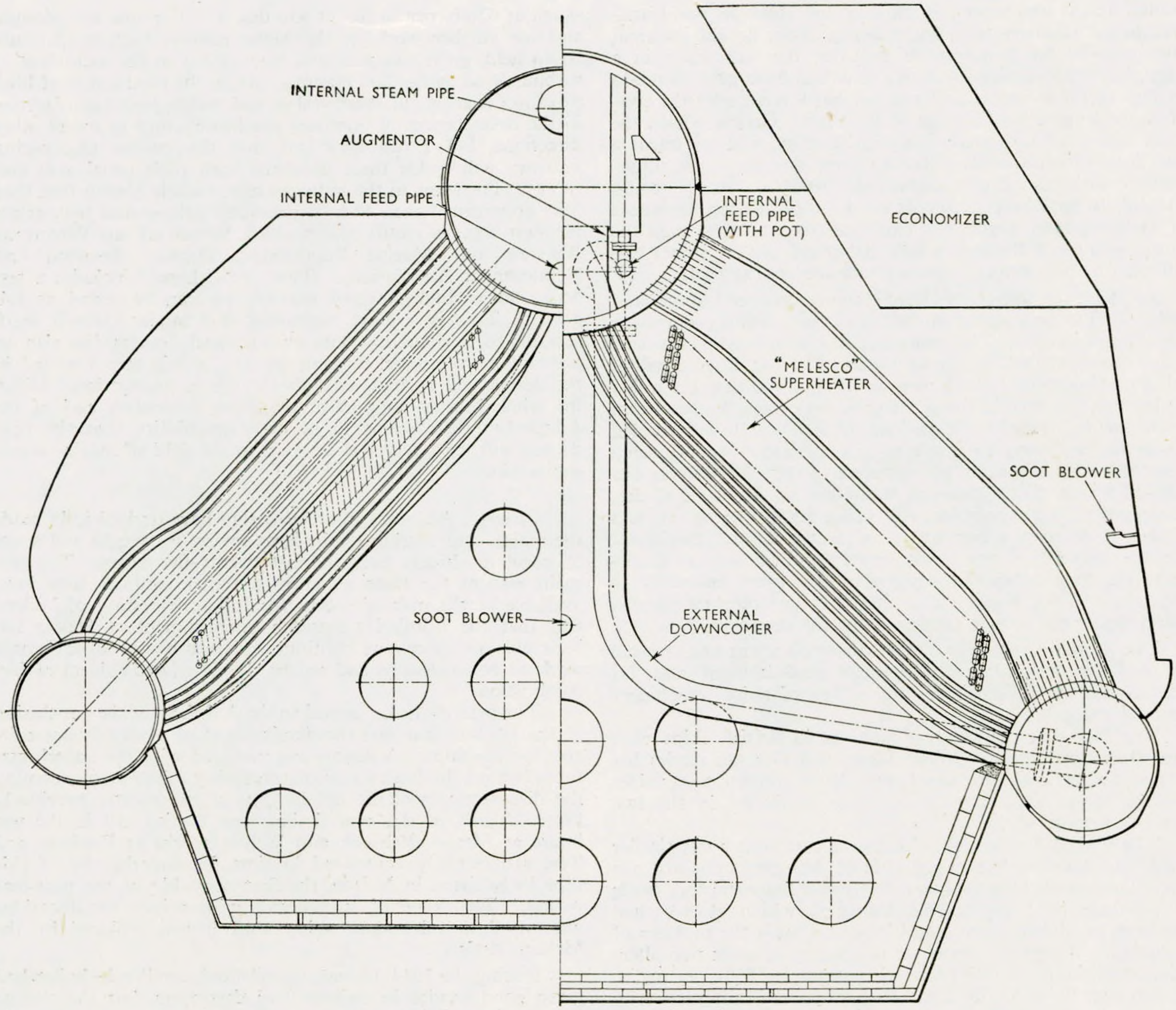


FIG. 3—*Admiralty boilers*
On left—"Kent" class. On right—Modern cruiser

been obtained for setting up a new and better equipped establishment on the Tyne, as soon as money and building labour are available.

Progress in reaching higher boiler efficiencies was hampered by the ever pressing need for decreases in weight and space; for example, the addition of air preheaters and economizers would certainly have resulted in a big increase in boiler efficiencies, but only at the expense of a considerable increase in weight and space. The merits of these two items were compared and it was mainly owing to weight considerations that the air preheater was chosen. Satisfactory trials were carried out in a cruiser in 1931, and air preheaters have since been fitted in most cruisers and bigger ships; they were also fitted in a few destroyers, but space limitations are so severe in this class that their general adoption has not been possible. The fitting of air preheaters necessitated a change in the fuel burning arrangements, with the consequent development of the "closed front" for boilers; this was so successful that it was fitted in subsequent boilers even where no air preheaters were fitted (Fig. 2, Plate 1). The possible uses of economizers were always kept in mind, and with the lighter weight of the modern designs they would probably have been fitted for trial during the late nineteen-thirties but for the international situation, and the need to standardize designs when production becomes the most important requirement. Economizers have, however, been fitted on some of our latest boilers. Fig. 3 shows the development of the Admiralty boiler over this period; some of the main changes included:—

(*a*) The elimination of the straight tubes of the Yarrow design and their replacement by bent tubes, so providing a convenient space for the superheater. Attention is drawn to the curvature of the tubes: this system was adopted to save weight by reducing the number of spare tubes carried on board and is a good example of the extreme lengths to which we went to meet the requirements of the Washington Treaty.

(*b*) The deepening of the tube nest from seventeen or eighteen rows to twenty or twenty-one. The old method of assessing the forcing rate of a boiler in pounds of fuel burnt per square foot of heating surface would be sound if each row of generator tubes extracted the same amount of heat from the gases, but, with fire rows taking so much more than the outer rows, it could be misleading. By adding some additional rows at the back of the nest and retaining the same forcing rate on the old basis, we should be subjecting the fire rows to a much higher loading. As the fire-row tubes are the most heavily loaded in the boiler, a new forcing-rate figure was evolved:

Table 3. Advances in boiler performance

	Nelson	"I" class destroyer	Modern destroyer	Modern capital ship	
				With air preheater	With economizer
Length of fire-row tube	9 ft. 6 in.	10 ft. 0 in.	11 ft. 8 in.	11 ft. 0 in.	10 ft. 3 in.
Length of furnace	8 ft. 9 in.	9 ft. 8 in.	15 ft. 1 in.	11 ft. 1 in.	10 ft. 3 in.
Evaporation from and at 212 deg. F., lb. per hr.	104,000	136,000	290,000	222,000	200,000
Fuel per sq. ft. wall area, lb. per hr.	44	48	59	55	55
Fuel per cu. ft. combustion chamber, lb. per hr.	9·2	11·6	12·6	12·7	11·6
Fuel per sq. ft. of:—					
(*a*) Generating heating surface, lb. per hr.	1·18	1·34	1·4	1·6	1·6
(*b*) Total heating surface, lb. per hr.	1·02	1·14	1·26	0·74	0·71
Efficiency, per cent	73	78	75	80	85
Evaporation from and at 212 deg. F. per lb. of boiler weight, lb. per hr.	0·92	1·34	1·64	1·74	1·24

pounds of fuel per square foot of tube wall, i.e., the flat area of the tube nest exposed to the radiant heat of the furnace.

(*c*) The change in tube bores from 1½ inches to 1¾ inches for the fire-row tubes and from 1⅛ inches to 1 inch for the tubes outside the superheater. The former change was necessitated by the higher forcing rates and longer fire-row tubes of the modern boiler; the latter was made with the object of increasing efficiency without any appreciable increase in weight.

(*d*) The increase of the steam drum diameter from 50 inches to 56 inches to give adequate tube-plate arc for the increased number of rows of tubes. This change had the added advantages of providing a greater water-line area and a larger steam space.

(*e*) The adoption of feed augmentors to improve the circulation. These were developed at Haslar and they tided us over the first increases in forcing rates.

(*f*) The adoption of external downcomers to ensure circulation at the higher forcing rates.

(*g*) The fitting of two internal feed pipes, with pots. The two pipes were necessitated by the use of augmentors, but their adoption was followed by hunting in the water level in the boilers (Hillier 1947). This trouble was cured by the fitting of pots.

(*h*) The use of welded or forged drums instead of riveted drums. All-forged drums were used in the *Acheron's* boilers with the pressure of 500lb. per sq. in.; forged drums with riveted ends were used for lower pressures (300-400lb. per sq. in.) but, with the advance in welding technique, the present practice is to use riveted drums up to 300lb. per sq. in. and welded drums for higher pressures.

The advances resulting from these changes in the pressure parts of the boiler are shown in Table 3.

Concurrently with these developments much work has been done at Haslar on refractories. Furnace temperatures rose with the increased forcing rates, necessitating the use of better quality bricks in order to meet the more severe conditions without unduly increasing the weight of the boiler.

Contact has also been maintained with developments in other types of boilers both at home and abroad: various designs have been fitted from time to time for comparative trials with the Admiralty boiler—for example, the Babcock and Wilcox "Express" boiler; the Yarrow five-drum boiler, both front- and side-fired; the Thornycroft "Grafton" boiler; the Lamont boiler; the Johnson boiler; the Foster Wheeler boiler, both single- and double-furnace. A Yarrow controlled superheat boiler was built for a "Weapons" class destroyer and satisfactorily tested at Yarrow's own test house, but was not fitted —owing to the cancellation of the order for the vessel. A Babcock and Wilcox two-furnace boiler is under construction for our latest destroyer design. A small Velox unit was installed at the A.F.E.S., but difficulty was experienced with the automatic controls and work was handicapped by lack of staff and the unsuitability of the establishment. In general, the Admiralty boiler has held its own in these trials except in the case of the controlled superheat or two-furnace boilers, in which the superheat characteristic is much better than can be obtained from the standard Admiralty boiler.

Turbines. At the end of the 1914-18 war, we were fitting both Parsons and Brown Curtis turbines (for convenience I will refer to these as reaction and impulse respectively), with a preference towards the latter, and impulse turbines were fitted in the first four ships of the post-war programme. Unfortunately, serious blade failures occurred, some due to blade vibration and some to wheel flap. In consequence, opinion swung over to the reaction type, and these have been fitted in all subsequent ships with a few exceptions. The relative merits of the two types have again come up for consideration in connexion with our latest destroyer design, and it has been decided to fit three different designs in order to get direct service experience in both types; these are:—

1. with reaction high-pressure and low-pressure turbines;
2. with impulse high-pressure and reaction low-pressure turbines, and
3. with impulse high-pressure and low-pressure turbines.

Turbines have generally been designed for maximum efficiency at or about full power, and special arrangements have had to be made to meet the requirements of economy at the peace and war cruising speed. In some ships, separate cruising turbines have been fitted, coupled either direct or through gearing to the high-pressure turbines. Quite apart from the additional weight and space involved, these entail additional and undesirable complications in pipe arrangements and in operation; moreover, if operational requirements call for speeds just above the range given by the cruising turbines, they become redundant, and the main turbines have to be used under unfavourable conditions as regards economy (Fig. 1). In other ships, cruising stages have been fitted in the high-pressure turbines; these were not very satisfactory as there was a tendency for overheating to occur owing to the lack of steam flow under high-power steaming conditions. Probably the simplest arrangement is the provision of an impulse wheel at the inlet end of the high-pressure turbine with groups of nozzles controlled by valves, as fitted in the latest designs; but efficient operation is dependent on the manual opening and closing of the nozzle group control valves in order to maintain the minimum number of nozzles in use for the power required. Unfortunately there was a tendency to keep more valves open than necessary with consequent loss of efficiency, and. in order to overcome this human weakness, the United States Navy method of operating all nozzle group control valves in sequence by the movement of the main manœuvring valve is being adopted in the latest designs.

Although the blading in the impulse wheels is of 39-ton austenitic steel, several failures have occurred; it has been established that the failures are due to vibratory stresses set up by resonance of the blade in its fundamental natural frequency with the frequency of the steam impulses from the nozzle jets.

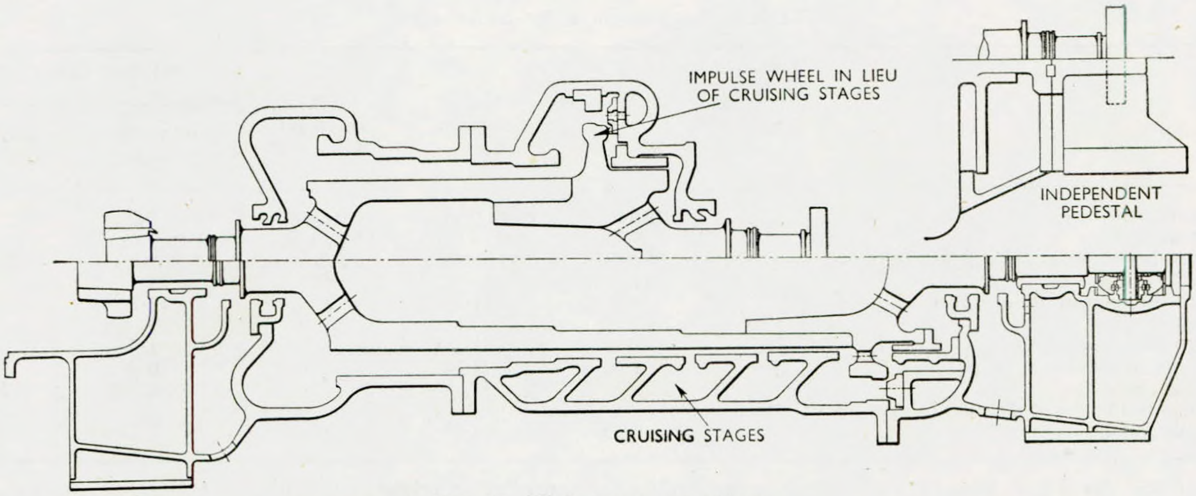


FIG. 4—*High-pressure turbines*
Bottom half—"Kent" class. Top half—Modern cruiser of same power

Once the cause of the failure was known, it was relatively easy to take the necessary corrective measures. Inaccuracies in the assembly of the earlier cast-in nozzle plates complicated the problem and accurately machined nozzle plate assemblies are now being fitted. Very little other mechanical trouble has been experienced with turbine blading, but under war conditions there were some corrosive troubles with stainless iron blading in the low-pressure turbines of some destroyers; as no such trouble was experienced in the larger ships, the corrosion was probably caused by priming of the boiler resulting from salt water contamination of the feed.

Although there have been no outstanding changes, various detail improvements have been made in turbine design either to improve efficiency (by the use of end tightened blading in the high-pressure turbine), or to simplify production (by the use of side-locked segmental blading instead of the original individual blades and packing pieces), or to meet the requirements of rising temperatures (by the adoption of stainless iron or monel blades instead of bronze), or to save weight or to overcome specific defects.

Figs. 4 and 5 give a comparison between the turbines of a "Kent" class cruiser and a modern-cruiser turbine unit of the same power. The high-pressure turbine-bearing pedestals were originally cast integral with the bottom-half turbine casing, but with rising steam temperatures, cocking of the turbine feet occurred: separate pedestals are now fitted, secured to the turbine castings by bolts in clearance holes; alignment is maintained by horizontal keys near the horizontal joint, and a vertical key at the centre line near the bottom of the pedestal.

The higher steam temperatures also raised a problem in connexion with the astern turbines which, as shown in Fig. 5, are fitted at one end of the low-pressure turbine casings. Under prolonged astern steaming, overheating occurred in the ahead blading of the low-pressure turbine, owing to some of the exhaust steam from the astern turbine passing through both flows of the ahead turbine blading to the exhaust annulus at the far end of the turbine. This difficulty can be overcome in new designs by fitting astern turbines at both ends of the low-pressure casing, but to overcome the difficulty in existing ships desuperheaters had sometimes to be fitted on the astern steam supply.

War experience proved the weakness of cast iron to shock, and quite early in the 1939-45 war we were faced with the problem of changing all designs with cast-iron turbine casings. A change to cast steel was not possible, as the steel foundries could not possibly have met so large a demand. Welding appeared to offer the only solution, although at that time there were not enough firms in the country with sufficient welding experience to meet all the requirements, nor was there much knowledge on the design of such large welded structures. Requirements were finally met by using cast steel high-pressure and astern turbine casings and welded low-pressure turbine

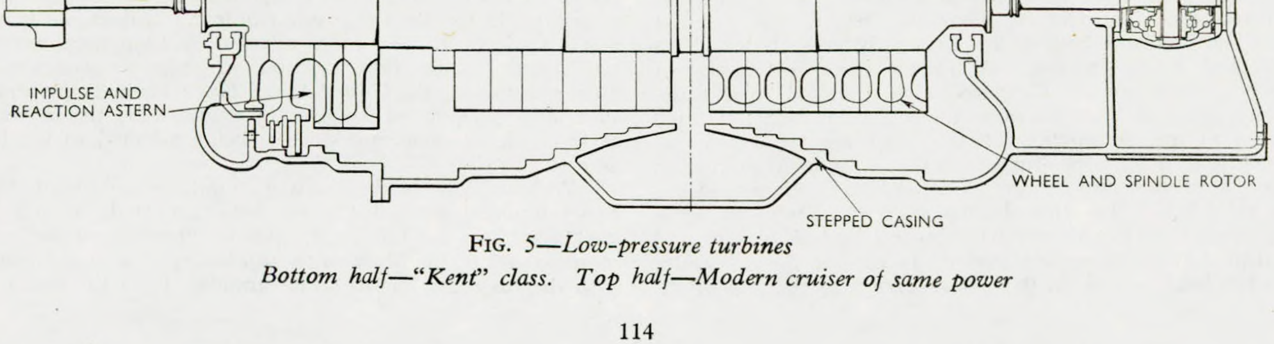


FIG. 5—*Low-pressure turbines*
Bottom half—"Kent" class. Top half—Modern cruiser of same power

casings. The number of defects in steel castings was rather disturbing, and although many defective castings were saved by the use of radiological examination and welding, it is evident that casting designs must be simplified and foundry control and technique improved if such defects are to be avoided. It may be that the problem will only be solved by the greater use of welded casings or of composite units consisting of simple castings and welding.

The effect of the various changes in turbine design on weight and space are shown in Table 4.

Table 4. Advances in turbine design

	High pressure		Low pressure	
	"Kent" class	Modern cruiser	"Kent" class	Modern cruiser
Length between bearings	10 ft. 11 in.	8 ft. 6 in.	12 ft. 3 in.	11 ft. 3 in.
Speed, r.p.m.	3,000	3,474	2,100	2,446
Weight of turbine, tons	13½	10	30½	25

Correct operation of the turbine glands, which is essential for efficient operation, entails much work for the engine room watchkeepers in warships, where changes of speed are frequently made. The operation has, however, been greatly simplified by the adoption of the "pot" system; suitably sized pipes are led from each turbine gland to a pot reservoir which is fitted with a steam supply and a leak off to condenser; by manipulation of the control valves on these two leads, one watchkeeper can maintain a pressure of about ½lb. per sq. in. in the pot, and so pack all glands. This system has worked well, but there is still some steam leakage into the engine rooms, which adds to the heat in these spaces. To improve the habitability of the engine rooms, which in the tropics become uncomfortably hot, the latest practice is to fit a gland evacuation system, small steam ejectors being fitted to the outer gland pockets, whilst the pot system packs the inner gland pockets, the pressure in the pot being raised to about 3 or 4lb. per sq. in.

Main Gearing. The main reduction gears in warships have, since their introduction during the 1914-18 war, been of the double-helical single-reduction type; reduction ratios were between 7 and 9 for the high-pressure stage and 5 and 7 for the low-pressure stage, but went up to between 8½ and 12, and 6½ and 8½ respectively, when turbine speeds were increased. The original sets fitted were very noisy and various modifications in the helix angle and tooth form were tried, but without much success, and by 1922 the design had been standardized with a helix angle of 30 deg., a pressure angle of 14½ deg., a tooth pitch normal to the tooth of 7/12 inch, and an involute form of tooth with well-rounded fillets. The length of each helix was about 2½ times the pitch-circle diameter of the high-pressure pinion, and a centre bearing was necessary between the two helices to keep the distortion due to bending and torsion within acceptable limits.

The first step towards modification of the tooth form, so as to enable the teeth to carry a heavier load, was taken by Messrs. Vickers with their V.B.B. gear. After test in some cruis-

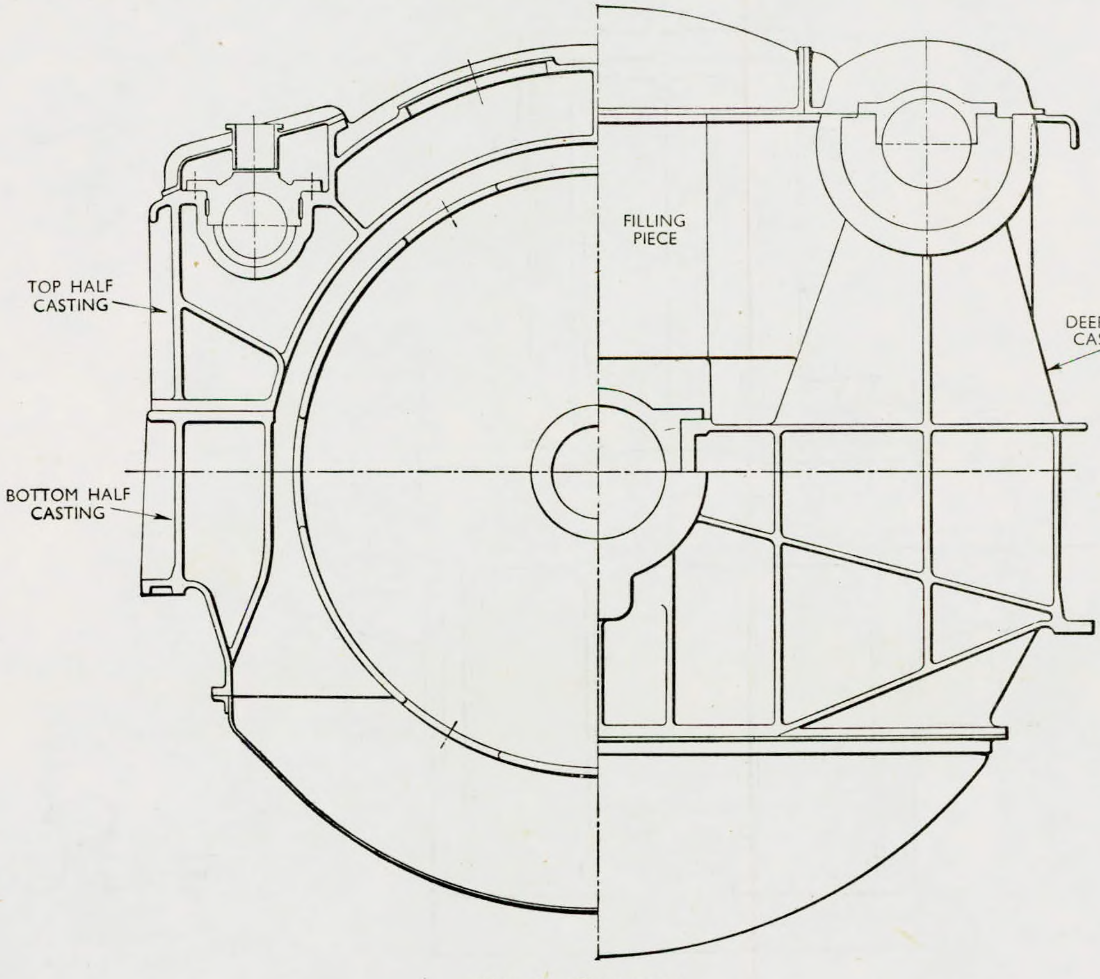


Fig. 7—*Gear cases*
On left—"Kent" class. On right—Modern cruiser

ing gears in 1927, V.B.B. gearing was accepted for main units in a repair ship, and in some cruisers and destroyers. The gearing in the repair ship, which had a loading factor approximately equal to that of the standard involute gearing, gave no trouble, but tooth fractures due to fatigue failures at the roots of the teeth occurred in all the other ships. Complete breakdown of the V.B.B. gears during the trials of a cruiser in 1935 was attributed to absorption of backlash and consequential distortion, and led to the rejection of this tooth form for warships. Soon after the adoption of the V.B.B. gear, the Parsons improved involute tooth form, commonly called the A.A. or all-addendum gear (although it is only the pinion teeth which are all-addendum, the gear wheel teeth being all-dedendum), was introduced. This gear was satisfactorily tested in a destroyer in 1930, and became the standard gear for all main and cruising gears, the helix angle and normal pitch remaining at 30 deg. and 7/12 inch respectively, but the pressure angle was increased from 14½ deg. to 22½ deg. With the higher loading factor of these teeth, the length of each helix came down to below 1½ times the pitch-circle diameter of the high-pressure pinion, and we were able to omit the centre bearing and yet keep the distortion due to torsion and bending within acceptable limits.

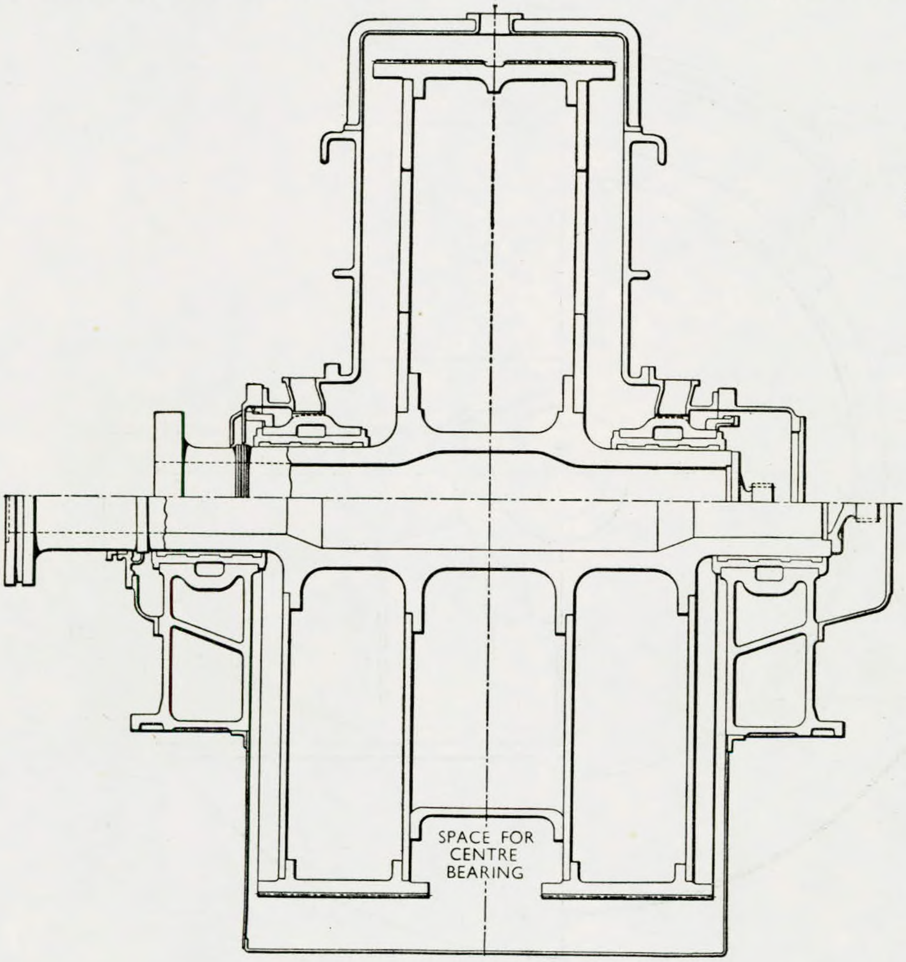
Although many of the earlier involute gears have given excellent service, as evidenced by the fact that gears installed during the 1914-18 war were still running at the end of the 1939-45 war, they were very noisy and pitting on the tooth surfaces, particularly in the region of the pitch line, was a common defect.

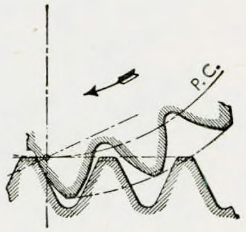
The need for improving our gear-cutting technique was fully appreciated both by the contractors and the Admiralty. The National Physical Laboratory gave every assistance in developing instruments for checking the accuracy of the gears, and all gear cutting machines and hobs had to pass N.P.L. tests before being used for cutting naval gears. As a result of these measures, and of the efforts of the contractors, the standard of gear cutting has risen, but it is evident from contacts with the United States Navy that it is not as high as that in America, where all gears are subjected to post-hobbing processes of shaving or lapping, and are then run ashore under torque to correct errors.

The specifications for the double-reduction gears to be fitted in the latest destroyers have been stiffened up; this measure should tide us over the immediate future, but there is still much to be learnt about the production of gears. An Admiralty Vickers Gearing Research Association (A.V.G.R.A.) has been set up to undertake investigations and tests of gear-cutting machines and methods. It is hoped that this association, working in close co-operation with Pametrada (on design problems) and the N.P.L. will put British gears in the van once more.

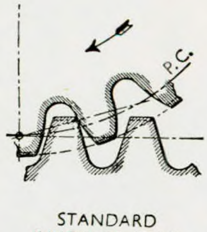
The A.A. gears have given excellent service but the need for reduction in noise is still the chief problem. Defects in the teeth themselves have not been serious enough to cause any real anxiety, although there have been fractures of teeth in gears of high power, and surface defects or scuffing in small gears.

The first double-reduction gears in the British navy were fitted in two frigates in 1946 (Fig. 6, Plate 1); they were designed and manufactured by British Thomson-Houston, and running experience to date has been satisfactory.





AA GEAR



STANDARD INVOLUTE GEAR

FIG. 8—*Gearing*

Bottom half—"Kent" class. Top half—Modern cruiser

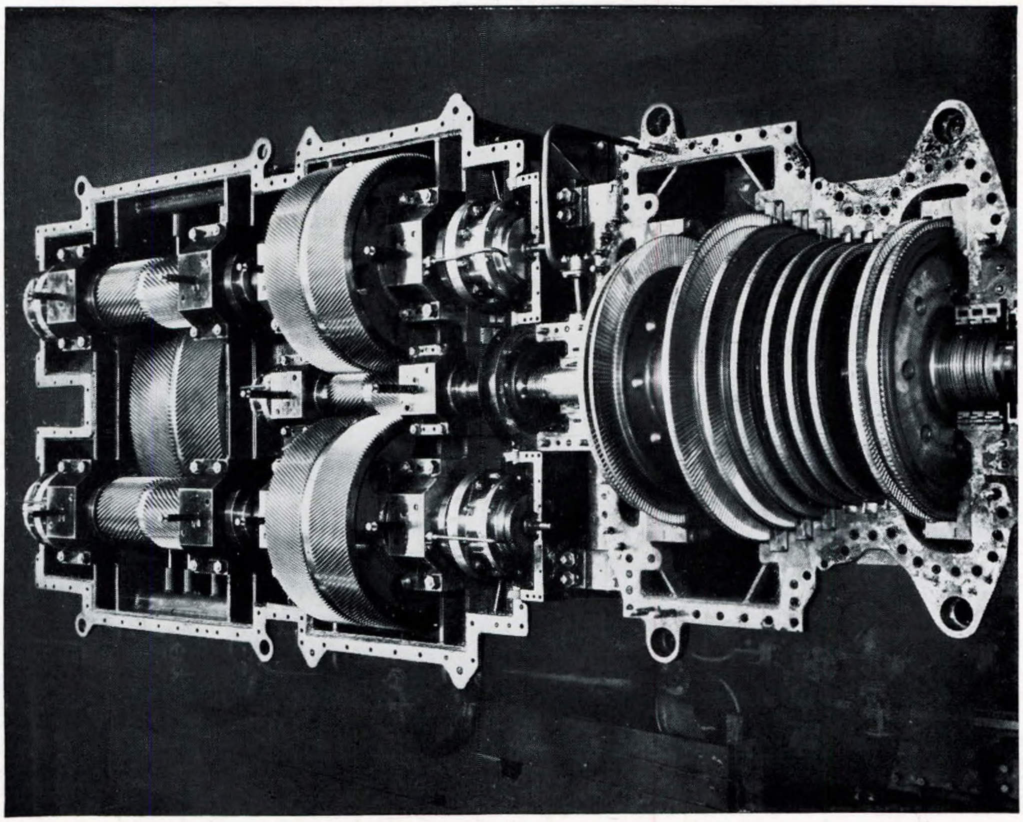


FIG. 6—*Double-reduction gear for frigate*

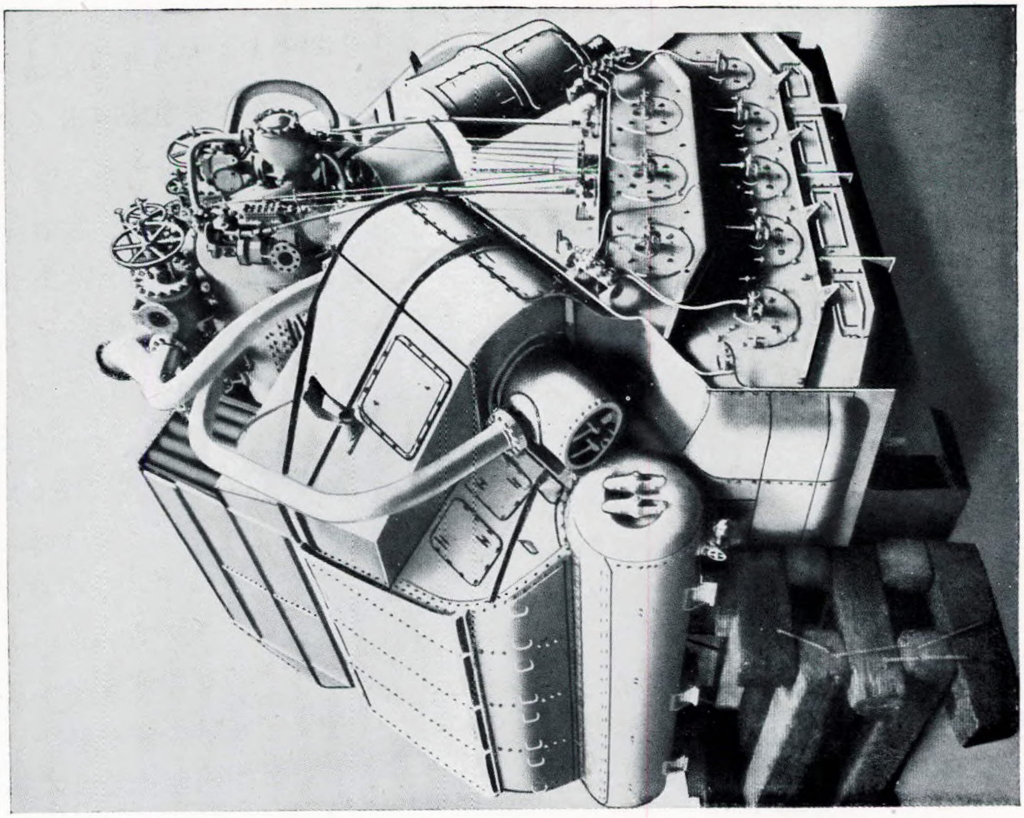


FIG. 2—*H.M.S.* Decoy *boiler*

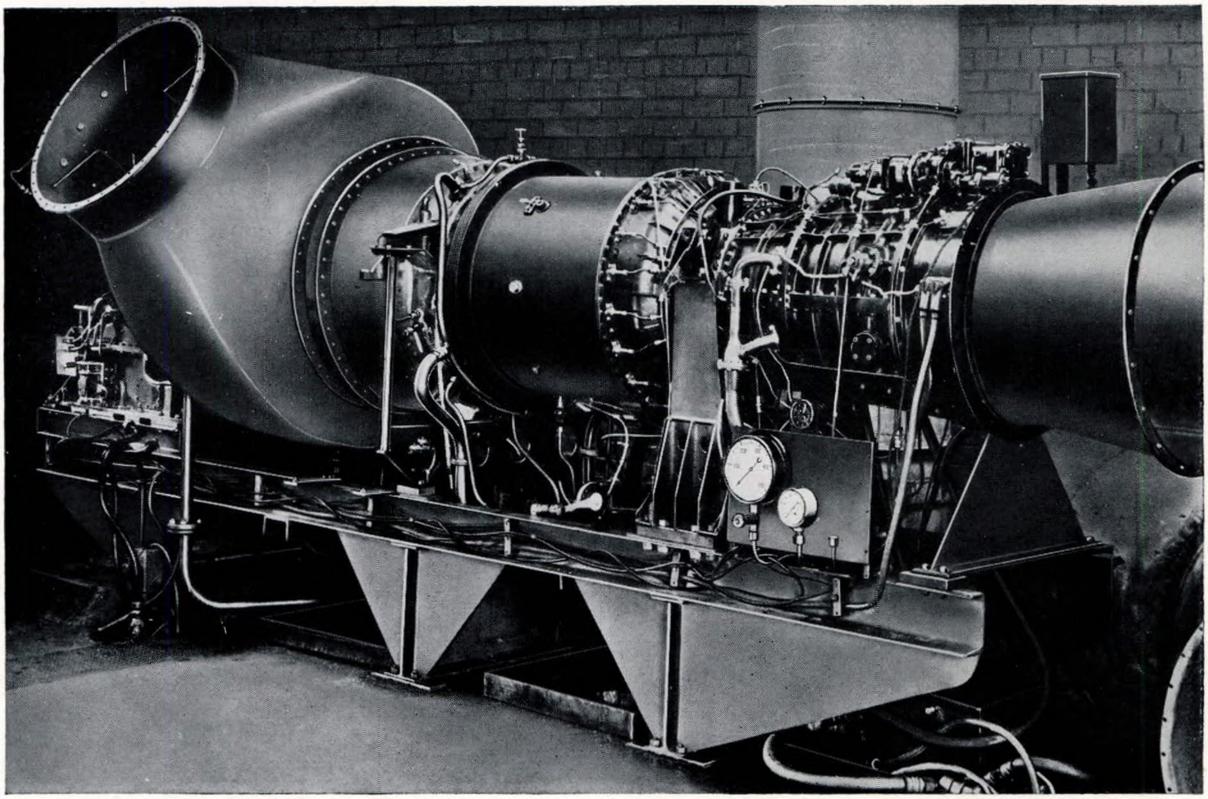


FIG. 9—*Gas turbine for M.G.B. 2009 as seen from gas turbine end*

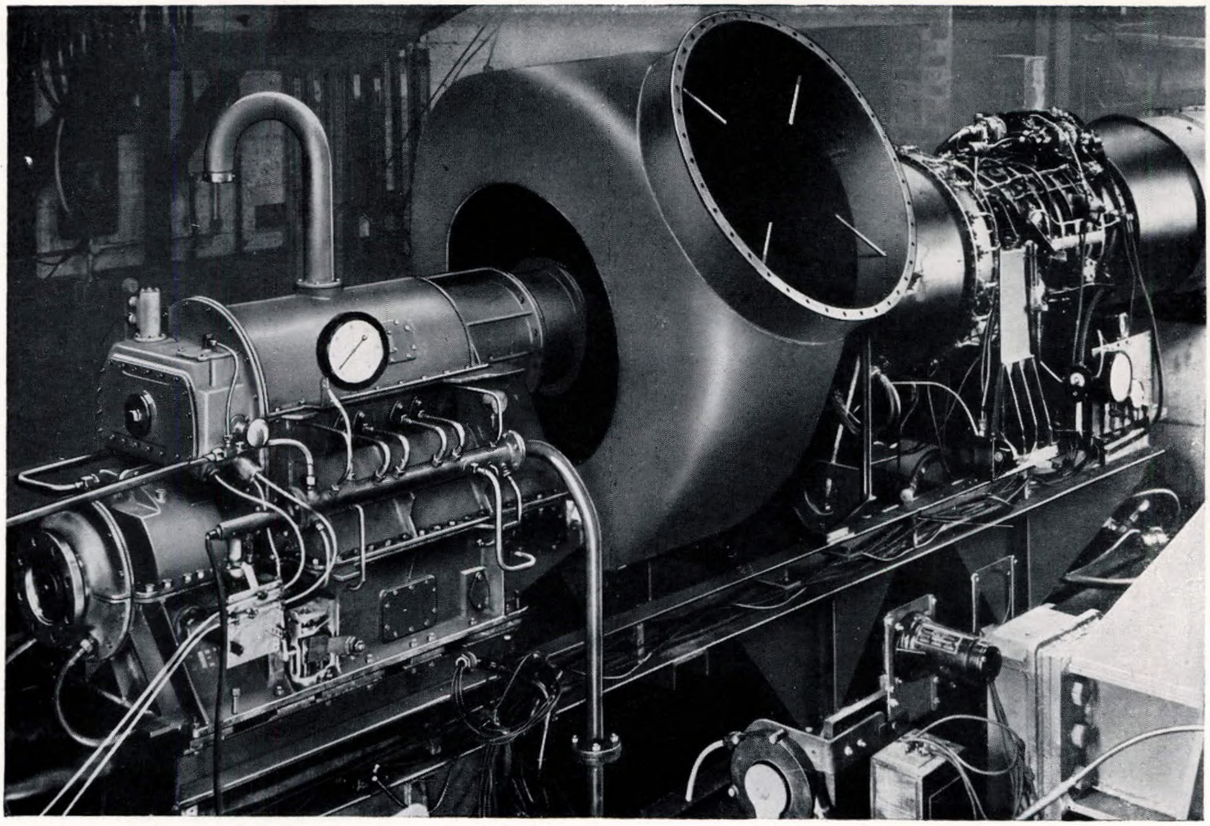


FIG. 10—*Gas turbine for M.G.B. 2009 as seen from gearing end*

(*a*) *Testing.* Progress in gear testing has been hampered by the lack of testing facilities, but useful results should now be obtainable from the test house at Pametrada where full-scale tests can be carried out. Provision is also being made for the running of all gears under torque on the lines of the American back-to-back tests.

(*b*) *Materials.* The materials used in the gears have served us well, and have not been altered over the period, though the possibilities of using harder materials have been investigated from time to time. With the recent developments in gear-grinding machines, it is possible that advances in the material field may not be far distant.

(*c*) *Gear Cases.* At the beginning of the period, gear cases consisted of two heavy iron castings with a horizontal joint near the centre line of the gear wheel shaft. Early in the nineteen-thirties the design was changed to give a deep box construction to the strength member, the top covers being of aluminium, and the sump of sheet steel; rectangular gaps in the upper part of the two ends of the box were provided for the assembly of the gear wheel and closed by cast-iron distance pieces using fitted bolt joints. War experience proved the weakness of cast-iron cases against shock, and all new gear cases have been of welded construction.

Figs. 7 and 8 show the gearing of a "Kent" class and a modern cruiser unit of the same power, and Table 5 shows the resultant saving in weight and space.

Table 5. Advances in gears and gear cases

	"Kent" class cruiser	Modern cruiser of same power
Type of gearing	Standard involute	A.A.
High-pressure gear ratio	10·1	11·6
Low-pressure gear ratio	7·0	8·2
Length of pinion between extreme ends of gear faces, inches ...	61	34½
Weight of gear wheel and pinions, tons	14·08	10·29
Weight of gear case, tons	14·98	12·94
Total weight, tons	29·06	23·23

Turbine Couplings. Flexible couplings are used to connect the pinions to the turbine spindles, and are of the claw type designed to transmit the torque, to allow for axial freedom and for any small lack of alignment resulting from the journals of turbines and pinions running in clearance bearings. Under normal conditions these couplings gave no trouble, and it was rather surprising to find, during the trials of one of the converted "Queen Elizabeth" class, that the claw faces had been seriously damaged. On investigation it was found that, at high speeds, the ends of the pinion shafts were shuttling axially in the couplings, and that the movement was most severe on the inner shafts on the outside of the turn when the ship was under helm. As an immediate corrective measure, instructions were issued to ease the outer shafts on the outside of the turn when the ship was turning at high speed, and so reduce the interaction between the propellers. This, though inconvenient, was successful in reducing the wear on the couplings. As similar, though in general milder, shuttling was found to be occurring in other ships, a full investigation was carried out in the Engineer-in-Chief's Department (Rigby 1948), which showed that every shaft had a natural frequency of axial vibration and when this coincided with propeller blade frequency a critical speed was encountered. Owing to the greater length of shafting in modern ships, the critical speed was occurring just within the running range; although the axial movement was considerably damped by the propeller itself, it might become serious if other conditions were contributory—as in the case cited, where the slip stream of the outer propeller cut across the disk of the inner when the ship was turning at high speed. The best way to cure the trouble would be to move the critical speed above the running range, but this would necessitate moving the thrust blocks farther aft in order to reduce the length of the shaft. A simpler method, adopted in the worst cases, is to fit four- or five-bladed propellers in place of the existing three-bladed propellers.

Auxiliary Machinery. At the beginning of the period under consideration, most auxiliary machinery was of the reciprocating type using saturated steam, and necessitated the provision of a saturated steam lead throughout the machinery spaces; this was an undesirable complication. Rotary auxiliaries using superheated steam gradually replaced the reciprocating types, although for reasons of economy, a few of the latter specially designed to work with superheated steam are still to be found in the boiler rooms of destroyers. The development of rotary auxiliaries would make a lecture on its own and it would be impossible here to do justice to the subject.

Motor-driven auxiliaries have been generally fitted as emergency units and for the steering-gear pumps, which are at a distance from the machinery spaces. It has always been Admiralty policy to use steam units under high-power and war conditions, and steam steering-gear pumps have now been developed. In certain instances (forced lubrication pumps, for example) automatic cut-in devices have been fitted to both motor and steam units, to ensure that, should the unit in use fail, the other would cut in immediately.

Apart from the major change from reciprocating to rotary auxiliaries, many other changes have been made, during the last twenty-five years, in order to improve efficiency and reliability and to simplify operation and maintenance. It is not within the scope of this lecture to do more than refer to a few of these changes, but anyone well acquainted with the machinery of our warships in 1922 would find himself in a strange new world if he visited the machinery spaces of a modern warship. The closed-feed system has been adopted in all our major war vessels, and there is little resemblance between the modern system and the rather crude units fitted in some destroyers built at the end of the 1914-18 war. Advances have also been made in the design of condensers: new types of automatic feed regulators have replaced the older types which were unsuitable for use with turbo-feed pumps. Much attention has been given to the air inlets, trunking, and fittings of boiler-room fans in order to reduce noise and air losses on the inlet side and to ensure a better distribution of air in the boiler rooms. Telemotor systems in connexion with the steering engines have advanced a long way from the simple units originally fitted. Corrugated steam pipes have replaced expansion glands. Improvements in materials have generally kept pace with requirements and many new instruments and devices have been adopted.

A completely new development is the equipment for launching aircraft from ships. Cordite-operated catapults were fitted to certain ships to catapult the small planes of those days, weighing about 8,000lb., at a speed of 50 knots. With the arrival of the aircraft carrier, the requirement changed; "accelerators" are required to launch a number of planes at regular and frequent intervals. The accelerators were hydro-pneumatically operated, but, with increasing staff requirements for speed and size of plane and rapidity of launching, the pumps are becoming so large that their steam consumption has an appreciable effect on the size of the boilers; consideration is therefore being given to alternative methods of launching.

There was an urgent need for facilities for full-scale testing of this and other flight deck equipment, and arrangements have now been made to set up a naval section at the Royal Aircraft Establishment, Farnborough, whose officers have always co-operated with the Admiralty on the aeronautical side of this work.

INTERNAL COMBUSTION ENGINES

Development of the internal combustion engine in this country was slow, and there is little doubt that in 1922 British practice, particularly in the compression-ignition or "Diesel" field, was behind that on the Continent. It was mainly due to this, and to the fact that such marine engines as were being manufactured were too heavy for naval service, that the Admiralty set up its own establishment for research work, in particular, for the development of engines for submarines. This establishment, called the Admiralty Engineering Laboratory (A.E.L.), was set up at South Kensington in 1917, and transferred to its present site at West Drayton in 1920.

Submarine Engines. The engines used during the 1914-18 war were of the direct-injection type and tended to have a smoky exhaust, a most undesirable feature in any submarine. Partly due to this, and partly because we knew the Germans used blast injection in their submarine engines, our post-war submarines were fitted with blast-injection engines, the design being based on a single-cylinder unit developed at the A.E.L.; the cylinders had a bore of 20 inches, and aluminium pistons were used to reduce inertia stresses. These engines gave a good deal of trouble with seized pistons and air-compressor failures, and much work was done on improving the design of the unit engine and the technique in the casting of aluminium pistons. This work produced good results but, although the reliability of the engines was improving, the Engineer-in-Chief still considered that the direct-injection engine would give better results; it was therefore arranged for A.E.L. to carry out development work on two single-cylinder units of 14½-inch and 17-inch bore. Both these developments were very successful and formed the basis of the engines fitted in the "S" and "T" class respectively.

As a result of adverse criticisms of British engines, it was decided to carry out a comparative trial in "T" class, using four different types: Sulzer, M.A.N., Vickers, and the Admiralty engine. Although the 1939-45 war started before the trial was completed, there was evidence to show that the two British designs were in every way as good as, if not better than, the two foreign engines, and all subsequent "T" class submarines were fitted with either Vickers or Admiralty engines, which gave excellent service throughout the war.

The A.E.L. also developed a lighter and faster running engine for the "T" class, the speed being 975 r.p.m. as compared with 480 r.p.m. of the standard engine. This engine was successfully tested at the A.E.L. but was not fitted in any vessel—mainly because gearing would have been necessary, and this might have been objected to on the score of noise, and would certainly have increased production time.

The Admiralty "S" class engine, fitted in nearly all the "S" class submarines, also gave excellent service throughout the war.

In the small submarines of the "U" class, we fitted Diesel-electric drive, the power being supplied by two 275-kW. generators driven by Paxman engines; this arrangement was quite satisfactory, and the engines gave very good service.

At the A.E.L., development work continued on the unit engines and their power was increased by supercharging, without any loss of reliability; this work had been completed in time to meet staff requirements for an even larger submarine than the "T" class—for operations in the Pacific. These "A" class submarines were fitted with Vickers or Admiralty engines, and although they were not completed before the end of the war, the machinery has given good service during subsequent exhaustive trials.

During the 1939-45 war, the production of submarine engines was given the highest priority, and the submarine firms, assisted by a number of Diesel manufacturers who made engines to our standard designs, did a splendid job in providing all the machinery for the large war programme.

Motor Boat Engines. In the late nineteen-thirties a big change took place in Admiralty policy on ships' boats, the medium-speed, round bottomed boat, driven by steam or medium-speed paraffin engines, being replaced by the faster hard chine boat driven by high-speed petrol engines. The steam engines in the picket boats were very reliable units, but the paraffin engines always gave trouble: they were not sturdy enough for the rough usage of a ship's boat, and the electrical installation in particular suffered from the dampness of the atmosphere.

The engines fitted in the fast boats being of the high-speed petrol type were even more prone to troubles under marine conditions, and it was evident that the difficulties would continue until we could replace petrol engines by the more robust Diesel engine. Fortunately, the Perkins 65-h.p. Diesel engine which had been developed between the wars was just coming into production, and with its arrival many troubles in the larger boats disappeared, but we had no Diesel engine suitable for the smaller boats: this development was pressed on during the 1939-45 war, and the Kadenacy 50-h.p. engine was developed and fitted in the later years of the war. In the meantime, running experience with the large, fast boats in open anchorages had not been very satisfactory, and the Admiralty decided to revert to the earlier practice of supplying medium-speed picket boats to the big ships of the fleet: these boats were fitted with Gardner 85-h.p. Diesel engines which gave excellent service.

The slow boats of the fleet were already fitted with Diesel engines and these were generally satisfactory.

With the expansion of the Navy during the 1939-45 war, there was a corresponding increase in the number of boat engines required, but the internal combustion engine industry rose splendidly to the occasion. The main production problem arose over the large demands for internal combustion engines for motor minesweepers and minesweeping equipment, coastal craft, landing craft, harbour service craft, and the many small Diesel-driven auxiliaries required afloat and ashore, not only for the Navy but also for the Army and the Air Force. Most of these requirements were met from our own industry except in connexion with coastal and landing craft.

Coastal Craft Engines. Since the coastal motor boats (C.M.B.'s) of the 1914-18 war, very little work had been done in connexion with coastal craft until about 1937, when prototype motor torpedo boats (M.T.B.'s) were built by several firms, the engines used being the Napier *Sea Lion* of 550 h.p., the *Isotta* of 1,150 h.p., and the Rolls-Royce *Merlin* of 1,100 h.p. These were all petrol engines, as no suitable Diesel engine was available, although a contract for the development of a lightweight Diesel engine had been placed in 1938. A unit engine was successfully developed, but the engine itself failed on test: under normal conditions the weak features in this design could probably have been overcome, but in the early years of the 1939-45 war there was little time for development and, as it was evident that the power would be insufficient for future requirements, the project was dropped. One of the Diesel manufacturers had been working independently on a similar development, but their engine also failed to develop the required power. We had no suitable engine for this service and were forced to obtain our requirements from America, who supplied Packard 1,250-h.p. petrol engines: these gave excellent service throughout the war, but it would be quite indefensible to rely on such help again, and the development of a suitable Diesel engine has been put in hand. As an emergency measure, we carried out a trial with Bristol *Hercules* engines of 1,600 h.p. in one boat: this was successful, but as these engines are air-cooled the need for large air-trunks added an undesirable complication to the machinery arrangement, and no further boats were so fitted as the supply of Packard engines met all requirements.

Landing Craft Engines. Even less development work had been done on landing craft between the wars than on coastal craft, although a prototype boat had been built with Gill jet-propulsion. For the earlier small landing craft of the 1939-45 war, engines were supplied from this country, but it was evident that requirements would soon grow beyond our capacity, and once again we had to get engines from America. For the larger landing craft, a Paxman 500-h.p. engine was available; later, when still higher-powered engines were required, a unit consisting of two Paxman engines coupled to one gearing through oil-operated (S.L.M.) gears was developed and tested at the A.E.L.

Other Propulsion Units. The possibility of using internal combustion engines for propulsion purposes (generally in combination with steam machinery, the internal combustion engines being only intended for cruising purposes and to be disconnected at higher powers) in other than submarines and small craft had been considered from time to time. Most of these plans came to nothing, as the internal combustion engine had not been sufficiently developed, but in 1927 an experiment was carried out in the minelayer *Adventure*, two Diesel-electric units being fitted for cruising purposes with separate steam engines for higher powers; the experiment was not successful owing to the high maintenance of the Diesel engines. The only other naval ship fitted with Diesel-engine propulsion was the submarine depot ship *Medway*, the main engines being of the heavy, slow-running type similar to those employed in merchant ships.

Various types of engines were tried at the A.E.L. in the hope of finding an engine which would be reliable enough for warships and within an acceptable weight. These were not successful, but progress in the submarine field gave us greater confidence in the Diesel engine, and in recent years commercial Diesel engines have been fitted in two "Bangor" minesweepers and in some Admiralty tugs and have given good service.

Diesel generators have been fitted in warships for many years, but experience during the 1939-45 war stressed their importance, particularly in ships damaged by enemy action, and the latest policy is to extend their use to all classes of ships and increase the proportion of the electric load carried by the Diesel units. Unfortunately, many of the Diesel engines used in the larger units are too heavy, and there is an urgent need for the development of lighter and more reliable engines for this service.

Owing to our varied experience with internal combustion engines manufactured in this country, we decided to institute a type test by means of which any engine offered for the naval service could be tested as to its suitability for the duty required. This work was carried out at the A.E.L. and its value was appreciated by the manufacturers once they realized the purpose of the test.

The large numbers and many types of internal-combustion engines fitted during the 1939-45 war raised many problems in maintenance and overhaul of engines, and on storage and distribution of spare gear, and careful consideration will need to be given to these aspects of the case when preparing the policy of internal-combustion engine development.

GAS TURBINES

In view of the advantages gained as a result of the change from reciprocating steam engines to steam turbines, it was only natural to look forward to a similar advance from the reciprocating petrol or Diesel engine to the gas turbine, and close contact was maintained with developments in all parts of the world. Progress was slow, and at one time we thought it might be necessary to pass through an intermediate stage with reciprocating compressors and gas turbines, and development of a free piston compressor unit and a gas turbine was actually started at the A.E.L. in 1940.

With the success which attended the work of Air Commodore Sir Frank Whittle on the jet engine for aircraft, it was realized that the time was ripe for the development of the marine gas turbine; the very great difficulties which were to be expected were appreciated, and, as such a development would take some years, a simple full-power unit was ordered at once in order to gain practical experience in the running of the gas turbine under marine conditions. The simplest and quickest way to achieve this object was to take an existing boat and replace one or more of the reciprocating internal-combustion engines by gas turbines, leaving the remaining reciprocating engines for low-power operation, manœuvring, etc.; by this means the gas turbines had to be designed for maximum efficiency at full-power only, and we avoided all problems of reversing, etc. (Figs. 9 and 10, Plate 2). As reported in the technical press, the experiment was carried out in M.G.B. 2009 in the summer of 1947 and was successful. This craft will continue to be run experimentally, and it is hoped will provide much useful information on the practical running of the gas turbine. In the meantime, the development of other marine units is proceeding, units in the design of which full consideration has been given to the usual naval requirements of reliability, economy at all powers, and durability on a reasonable weight and space basis. The problem of reversing has not been overlooked, and the possibilities of the variable-pitch reversible propeller are under investigation.

As with other developments, the need for full-scale testing ashore is an essential to progress. Arrangements have been made for a gas turbine to be installed at the A.E.L., but if powers increase the units will grow beyond the present capacity of the A.E.L., and the problem of finding adequate testing facilities will need urgent consideration.

WAR EXPERIENCE

In the 1939-45 war as in the 1914-18 war, the machinery of our warships did all and more than was expected of it. We had our difficulties and anxieties (Holt and Clemitson 1948, and Gray and Killner 1948), but it would be imprudent to say much about them at the present time; it may, however, be of interest to mention some of the problems we had to solve.

The periods spent at sea, particularly during the Pacific operations, and the distances steamed by the convoy escorts were so much greater than had been anticipated that we had to develop improved methods for fuelling and provisioning our ships at sea.

In the Pacific, the scene of operations was so far from the nearest dockyard that it was essential to provide facilities for the docking, repair, and maintenance of the ships of the Fleet in a more forward position. The possibility of erecting an advanced shore base was considered, but the final decision was to provide a floating base, and from this grew the "Fleet Train", an assembly of floating docks, repair ships, special maintenance ships for the various classes of ships, store ships, ammunition ships, tankers, accommodation ships, and large numbers of harbour servicing craft.

Although our ships had been designed to operate in any part of the world, and many had operated in the tropics in peace time, the long periods at sea under war conditions put a strain on personnel, and as a result of the work done by a committee of medical and technical officers, various modifications were carried out in our ships to improve conditions on board; air-conditioning was provided in certain compartments, the numbers of domestic refrigerators, ice-making machines, etc., were increased, and laundries were installed in the larger ships. Machinery spaces, although well ventilated, were very hot, and action was taken to improve lagging, and to eliminate sources of heat wherever possible, as in the turbine-gland evacuation system already mentioned.

It was equally important to improve living conditions in harbour, and two amenity ships were added to the Fleet train; the Engineer-in-Chief's department had the unique task of working with a British brewery firm to develop the first marine beer-making machinery for installation in these ships.

At the other end of the temperature scale, the ships employed on the Russian convoys were subjected to cold weather conditions more severe than anything anticipated in the design stage, and special heating arrangements had to be provided to prevent the freezing up of sea inlets, water and oil systems outside the machinery spaces, and upper deck fittings.

Shock damage was a new problem, and arose from the non-contact explosion of magnetic mines or from near misses by bombs; the damage was quite different from that resulting from contact explosions. A great deal of work was carried out to evolve a theory to explain the circumstances and to develop methods of preventing or reducing damage in future incidents. Actual experiments were carried out on an old destroyer to check our theories and to prove our curative measures. An instrument for shock-testing small equipment was installed in the electrical department of the A.E.L. and a Naval Construction Research Establishment was set up to co-ordinate the work. The damage to our machinery from shock from non-contact explosions (Bonny 1948) was far worse than anticipated from the experiments carried out by the Admiralty in the between war years, and immediate action had to be taken to develop measures for restricting damage in existing ships and to modify designs of new ships.

Aerial bombing increased the fire risks in ships to a far greater extent than had been anticipated, and much work was put into improving fire-fighting arrangements and in training personnel. Fire-fighting schools were set up at various ports for the latter purpose, and a fire hut was erected at Haslar for experimental work on fire-fighting.

During wars, requirements invariably arise for new types of ships, either to support some operational plan of our Naval staff (for example, the "X" craft which attacked the *Tirpitz* in a Norwegian fiord) or to counter some new enemy device (for example, the S.G.B. designed to hunt and destroy the German E boats). The S.G.B. provided the design departments of the Admiralty with an interesting problem. From the machinery aspect, lightness was the essential requirement, and we developed a steam unit whose total weight of machinery was 49 tons for a power of 8,000 s.h.p., about half the specific weight of normal destroyer machinery (Lay and Baker 1948).

Another interesting design was in connexion with the machinery of the Light Fleet Carriers built during the 1939-45 war. The hulls were on merchant ship lines, and a twin-screw arrangement was fitted, with the machinery in two compartments, each containing a complete unit of boilers, turbines, auxiliaries, etc.

At the height of the Battle of the Atlantic, the Naval staff stated that they required two hundred escort vessels in the shortest possible time. This requirement arose at a time when our shipbuilding and engineering firms were fully employed on the construction of naval and essential merchant ships, and it was evident that they could not undertake this additional work. It was, therefore, decided to fit the simplest kind of machinery, consisting of reciprocating engines and Scotch boilers, and simple reciprocating auxiliaries. The main engines were made by some thirty-four firms, many of whom had never built a marine engine before; boiler and auxiliary machinery were made by the recognized makers; all shafting, piping, valves, etc., were ordered and distributed by the Admiralty, who were also responsible for the distribution of the larger machinery items to the shipbuilder as and when required for installation. It was a very creditable performance by all concerned.

Probably the greatest difficulty was, on the administrative side, in connexion with the supply and distribution of spare gear. With ships being moved over the seven seas like pieces on a chess-board, it was very difficult to ensure that spare gear was always available where it was required. The position was even more difficult in connexion with the large number of small craft, particularly those fitted with American engines. By the time the war had spread to the Far East, we had established a number of spare-gear distributing centres at home and abroad for supplying the needs of the Fleets. We learnt that spare gear for steam machinery must be more interchangeable than in the past; this will lead to a greater degree of manufacture to jigs and gauges, as is already done in the case of small internal-combustion engine work.

CONCLUSION

Apart from the gas turbine, there has been no outstanding change in the types of propulsion machinery in use in warships, but I hope I have shown that there have been quite appreciable advances in all fields.

One of the major hindrances to progress has been the emphasis on weight-saving, imposed by the Washington Treaty; every design is a compromise and it is only possible to stress one feature at the expense of others; the S.G.B. design is a good example: these were built for a war purpose and a lower degree of durability was acceptable. This, and the omission of standby or emergency machinery (the acceptance, that is, of a slightly lower degree of reliability) enabled us to make a remarkable saving in weight. Ever since 1921, the ruling principle has been that saving in weight is of primary importance and greater even than efficiency. Any such limitation is greatly to be deprecated, and it is to be hoped that, in future designs, reliability, efficiency, and durability will be the primary objectives, whilst the weight and space are kept to the minimum consistent with maintaining the best overall design of the ship as a fighting unit.

Perhaps the greatest advance has been in the recognition of the fact that rapid progress is only possible if adequate facilities are available for research and development and for shore testing of new types of machinery and equipment. No one can yet say when and how nuclear power will affect the machinery of ships, but it is evident that plans for the immediate future must be made now, and without considering what may happen should nuclear power become a practical proposition for the propulsion of ships.

It is considered that the steam engine will remain the main propulsion unit for our major warships for some years to come; the Diesel engine will become general for all small craft and may even become available for smaller warships by the gearing of a number of units to one shaft. The gas turbine may well fill the gap between the above two, but it is too early yet to say whether or to what extent it will replace either the steam engine or the Diesel.

For the steam engine, it is probable that future designs will all be based on higher steam conditions, but it seems unlikely that the very high steam conditions used in shore stations can be usefully employed at sea. The whole question of optimum steam conditions for marine plant, including the provision for astern power and the best arrangements as regards steam and exhaust from auxiliary machinery, needs most careful and thorough examination.

It is probable that future developments of internal-combustion engines for the Naval service will aim for greater reliability, lightness, and a degree of standardization in order to reduce the number of types, and so simplify production, maintenance, and spare gear.

For the gas turbine, much development work lies ahead, particularly in the combustion arrangements, as, if these units are to be fitted in warships, the fuel used must be the normal furnace fuel, as used in our boilers.

Acknowledgment. In conclusion I should like to pay tribute to all the main and auxiliary machinery contractors and sub-contractors for their great production effort during the war years, and for their help and co-operation throughout the period. I should also like to acknowledge the assistance given us by the N.P.L., A.R.D. Woolwich, B.N.F.R.A., and other scientific bodies. With such technical and scientific aid, the high standard of naval machinery will, I am confident, always be maintained.

It only remains for me to express my appreciation and thanks to the Engineer-in-Chief of the Fleet and to the Officers of his department, both Naval and Civil, for the assistance given me in preparing this lecture.

APPENDIX

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Trends in the Development of Marine Reduction Gearing

A. W. DAVIS, B.Sc. (Member)

Further Discussion

MR. A. G. JONES, M.Eng., A.M.I.Mech.E. (Visitor) commented that the author's suggestion that in the near future, gear units having hardened and ground pinions running with shaved, "tough", wheels, raised a number of queries. Firstly, was it of equal importance to have both elements of a gear unit of high accuracy? He raised this point because he had observed various gear units produced by a particular English firm, in some of which only the pinion had been lapped, and in others, only the wheel had been lapped. In every case, abrasive was present in the tooth surfaces and indications were that the lapped unit tended to lap the unlapped unit; obviously this was highly undesirable. A second point raised by the suggested design was that of forming the helices of the pinions as two loose sleeves, each of which could be cut, hardened and ground, and finally fitted to the pinion shaft. The design could be made compact if the pinion was located on accurate registers and drives to the shaft through internal and external gear tooth couplings. The only objection he could see was that the use of a quill shaft became impossible if the diameter of the pinion was small. However, since the drive could be taken under the teeth, torsional deflexion could be reduced and better load carrying characteristics obtained.

The author told very little in his paper on actual gear production but he noted with interest the statements regarding the relative merits of creep and non-creep machines. It was now conceded that, if the worm assembly was made accurately, then a machine with a non-creep table might produce gears equal to those produced by creep machines. He would query this conclusion, for noise tests on identical gear units in which the rotating elements had been cut on both types of machines had proved that, providing the non-creep undulations were closely pitched (i.e., a fine pitch master wheel was used), the non-creep cut gear would be appreciably quieter than the creep cut gear. This regardless of the magnitude of the undulations, although these obviously affected the bearing area and hence the service of the gears. In the case of accurately finished gears, either lapped or shaved to give smooth undulation records such as that shown in the paper, there appeared to be no difference whatsoever in the total noise produced by gears cut on either type of machine. Thus it could definitely be stated that, especially if shaving was to be universally adopted, there was no advantage whatsoever in using a creep drive. In fact, since any creep machine might, by virtue of the creep fractions of every element of the machine, or possible beat effects between elements, produce long undulations, it appeared highly desirable to drop all such machines from production in favour of non-creep machines having fine pitch master wormwheels. The fact that the creep drive might render inaccurate gears less noisy, as suggested by the author, was, he felt, a complete condemnation of the mechanism.

MR. DAVIS wrote in reply to the points raised by Mr. Jones, that it was certainly of importance that both elements of a gear unit should be finished to an equally high degree of accuracy particularly so far as adjacent pitch, tooth profile and helical angle were concerned. Clearly the measure of the accuracy of the finished gear was that of the least accurate component. Mr. Jones rather forcibly expressed his dislike for creep drive machines thereby indicating a bias which was perhaps a little unjustified in view of the unexcelled quality of work such machines were producing.

Mr. Jones's closing remarks on this matter imputed to the author a statement which would in fact have differed quite widely from the general views expressed in the paper.

Fuel Efficiency in Coastwise Shipping and the Trawling Industry

Lecture given by G. H. BARNARD to the Swansea Local Section on 17th February 1949

INTRODUCTION

The Ministry of Fuel and Power have regarded the importance of the subject of fuel efficiency sufficiently highly to set up a Fuel Efficiency Branch which has included the formation of Fuel Efficiency Committees, established in various parts of the country, to consider the problem of increasing the efficient use of fuel in industry and in the domestic field. In addition, a staff of experienced fuel engineers have been engaged to act in an advisory capacity to study the various problems and assist consumers of fuel and power to obtain more efficient results.

The work already done has shown the need for closer investigation into all branches of fuel consumption, and attention is being directed to marine fuel usage.

Preliminary considerations point to the necessity of devising ways and means of promoting fuel and power efficiency aboard vessels plying in the United Kingdom coastwise shipping trade which used around one million tons of coal per annum. It was also thought that the trawling industry could be included in this preliminary investigation.

NATURE OF THE PROBLEM

When considering the overall performance of a ship it is necessary to differentiate as far as possible between the hull performance and the motive plant performance, in order to be able to determine those modifications on which money can be most efficiently expended.

Analogously, when considering motive plant performance it is necessary to differentiate as far as is practicable between boiler-room performance and engine-room performance. In this connexion whilst it is not unduly onerous to assess changes of boiler performance in respect of changes of rates of evaporation, it is not so simple to trace analogously change of engine performance with regard to changes of power output or of speed. This will be realized when it is recognized that true mean boiler performance can be determined fairly accurately—at least over a whole trip—from a study of the "pound per pound" evaporation figure, the CO_2 chart readings, and the readings of the stack thermograph.

On the other hand, to follow changing engine performance under conditions of changing load and, or alternatively speed would necessitate systematic and periodic indicating of the engine. These points have been considered in some detail in order that a true perspective may be gained of the limitation of the data, pertaining to the ship's overall performance, that can be acquired from practical tests of the combined motive power plant, on a trip of short duration, and at a cost and effort proportionate to the results likely to accrue.

Although considerable economy may be possible in the use of steam, heat and power in the various ship's services outside the boiler and engine rooms, adequate data are not available at the present time to admit of much guidance of a systematic nature being offered here. The subject is an important one, and one that will entail a considerable amount of detailed investigation, and it should be regarded as distinct from the boiler-room and engine-room investigations.

In this light it would seem possible to itemize the possible distinct and separate efficiency surveys aboard ship into a number of simply defined catagories. In the following proposed list it will be seen that hull performance and engine-room performance have been split into two sub-sections.

(1) Boiler-plant efficiency
(2) Main engine thermal efficiency
(3) Propelling plant mechanical efficiency
(4) Ship's steam, heat and power utilization efficiency
(5) Propeller efficiency
(6) Hull efficiency.

It is with the first four items only that some immediate action can be taken.

CONTRIBUTION BY SHIPOWNERS AND MANAGERS

There is no evidence that owners and managers are not fully aware today of the necessity for efficiency in the use of fuel and power aboard their ships, nor that they do not take reasonable steps, amidst the commercial and economic difficulties of the times, to secure it—at least under a limited programme of provision, operation and maintenance. Probably, a general enquiry to them would elicit that their business is equipped with a substantial organization for promoting and maintaining efficiency.

In many cases owners or managers avail themselves in port of the services of marine consultants, and from such bodies and also from ship repairing concerns it is to be hoped that, not only would much initial and essential information become available to the Ministry's engineers, but also that the fuel efficiency engineers might receive in due course the active collaboration of such bodies and may, in return, be able to assist the latter in many ways. Indeed, it is thought possible that much practical work could be undertaken by such bodies, with relief from many tasks, for some of which the Ministry's engineers would be ill-equipped, in respect of time and tackle, and also of experience.

At the very least, it is anticipated that owners would prove most willing to become co-operative in our attempts to effect improvements in their organization and practice pertaining to the economical operation of their ships' motive power equipment, and would welcome and be willing to implement simple suggestions for economy that did not involve undue capital expenditure or interference with the general handling or movement of their vessels.

PLANT AND MACHINERY ABOARD COASTING VESSELS

There is probably not a great variety in the basic types of plant met with aboard coasting vessels. Boilers are usually of the multi-furnace "Scotch" marine type, and propelling plant generally consists of a triple expansion, or sometimes a four cylinder triple expansion or quadruple expansion, engine, with the main pumps driven from the cross head. Auxiliary machinery and dynamo sets are also fairly standardized as regards general type and characteristics. On the other hand, auxiliary plant and appliances can vary considerably in detail, and, by reason of these variations, their economical operation, upkeep and maintenance calls for the services of engineers who have been soundly and broadly trained in steam and general engineering practice.

It is not possible at this stage to comment in more than general terms on ships' service of steam, heat, power, etc. supplies nor on the plant and layout normally adopted for effecting such services. Nevertheless, the subject is of considerable moment to ultimate fuel efficiency, and it warrants step-by-step investigation in due course. Such surveys should trace out the general character of the supply services, and should investigate the usage of supply at all principal points. Matters of prime importance are considerations such as the lay of pipe runs, venting and trapping of steam circuits and appliances, the return of condensate to the engine-room and the use of the heat it contains, tightness of steam fittings, glands and joints, isolation of steam serves infrequently used, stand-by and warming-up losses, heat insulation, etc.

FACTORS AFFECTING FUEL EFFICIENCY ABOARD COASTERS

It may be helpful at this stage to suggest that the outstanding count, relative to the largest proportion of the fuel saving that could be effected in a given vessel by attention to one single item, may be found to be that of securing the self-disciplining of the stokehold personnel. Other possible factors are:—

(1) Ship's general design characteristics—vessels may sometimes have been designed and built "down to a price".
(2) Age of vessels.
(3) Poor hull performance—this could be a predominant count.
(4) Poor propeller performance—this could be an important count, difficult of assessment.
(5) Inappropriate ratio of boiler plant rating to main engine rating.
(6) Inappropriate ratios of piston displacement—the fitting of cylinder liners would be costly and difficult.
(7) Inconvenient plant layout—some improvement in respect of individual plant items might be admissible in individual cases.
(8) Absence of superheat—where space considerations allow superheaters might be fitted in some cases where the main engine could take, or could economically be arranged to take, higher-temperature steam.

Possible factors pertaining to owners' or managers' "organization and methods" and to staffing considerations are:—

(1) Shortage ashore of supervisory staff for "organization and methods".
(2) Shortage of plant, materials and men for ships' maintenance.
(3) Shortage afloat of supervisory staff.
(4) Calibre and supervision of engineering personnel afloat.
(5) Accommodation and convenience for staffs afloat.
(6) Absence of a fleet voyaging combustion engineer.

Possible factors pertaining to character, arrangement, condition and handling of ships' engineering equipment, etc. are:—

(*a*) *Boiler-room*

(1) The psychology of firemen.
(2) Inadequate routine firing drill.
(3) Inadequate routine supervision by engineer-officers
(4) Inconvenient or inadequate plant layout.
(5) Inadequate provision of boiler-room instruments.
(6) Low average boiler feed-water temperature.
(7) Excessive boiler (cold) feed make-up.
(8) Excessive boiler blow-down.
(9) Excessive use of forced draught.
(10) Unduly low, or high, CO_2 content of flue gases.
(11) High stack temperature.
(12) Dirty smoke tubes.
(13) Cold air ingress into smoke-box or into combustion-air preheater.
(14) Defective lagging of hot surfaces.
(15) Steam and water leakages from joints and glands.
(16) Too low a rate of combustion per unit of effective grate area.
(17) Low average steam pressure.
(18) Absence of superheat.
(19) Defective boiler-room ventilation.
(20) Inadequate or defective firing and tube-cleaning tools.
(21) Inadequate spares, replacements and stores.
(22) Difficult withdrawals and disposal of furnace refuse.

(*b*) *Engine-room*

(1) Low average high-pressure steam-chest pressure.
(2) Low referred mean effective pressure.
(3) Poor vacuum.
(4) Faulty setting of valve-gear.
(5) Loss of engine-room condensate.
(6) Faulty steam traps, and misuse of trap by-passes.
(7) Steam and water leakages from glands and pipe joints.
(8) Defective lagging of hot surfaces.
(9) Inadequate provision of ordinary and special (hand) tools.
(10) Inadequate provision of engine-room instruments
(11) Inconvenient or inadequate plant layout.
(12) Inadequate spares, replacements and stores.
(13) Inadequate frequency of indicating of main engine.
(14) Inadequate logging of operation data of boiler-room and of outgoing ships' power supplies.
(15) Defective engine-room ventilation.

Coal Characteristics

It may help to consider the characteristics of the coal used when attempting to assess any steam-raising problem. Considering Welsh coals, seeing that some 325,000 tons of Welsh coal are included in the figure of one million tons supplied for coastwise shipping. The South Wales coalfield extends from Monmouthshire in the East to Carmarthenshire in the West, and as a rough guide, the volatile content of the coal decreases gradually from the highly bituminous coals of Monmouth to the anthracites of Carmarthenshire.

The coal produced is divided into:—

(a) Bituminous 17-36 per cent volatile.
(b) Semi-bituminous 13-18 percent volatile.
(c) Sub-bituminous 9-14 per cent volatile.
(d) Anthracite 4·5-9·5 per cent volatile.

The bituminous coals are sub-divided into:—

(a) Gas coals 29-36 per cent volatile.
(b) Coking coals 22-30 per cent volatile.
(c) Caking coals 17-23 per cent volatile.

The semi-bituminous coals are slightly caking and the sub-bituminous are generally free-burning.

For marine purposes it is usual to supply the bituminous or semi-bituminous varieties. These coals have a calorific value of the order of 15.500 B.Th.U.s as compared with some Yorkshire coals which run at 14,300 B.Th.U.s, Stirling (Scotland) 14,400 B.Th.U.s, Lancashire 13,700 B.Th.U.s, Derbyshire 13.500 B.Th.U.s It will be seen, therefore, that the South Wales coals are an excellent steam-raising coal.

Generally speaking, bunker coals are large coals but sometimes special bunker mixtures are shipped which comprises large and small and may have different volatile content.

The lower volatile coals give their best performance with forced draught and a coal of less than 15 per cent would need forced draught; at 18 per cent volatile upwards the use of forced draught is not a necessity.

As a broad principle Welsh steam coals burn best when left alone; in no circumstances should the fire be knocked about. A pricker can be used under the fire if necessary, and if the coal has caking or binding properties the slice should be used sparingly.

The thickness of the fire naturally varies with the draught. It should not be less than 5 inch, or more than 10 inch with forced draught. A ready guide is given by the colour of the flame: this should be as nearly white as possible. If it becomes red it is proof that the fines are too thick for the draught available.

Firebars should be spaced $\frac{5}{8}$-inch apart when new for natural draught and $\frac{3}{8}$-inch when forced draught is used. Large coal should not be broken down by a hammer—a pick is the correct tool to use and does not make an excess of small during the breakage.

One realizes that a ship may bunker in ports where Welsh coal is not available, and other coals may call for a somewhat different technique. It is hoped, however, that these few hints will be of value.

TRAWLERS

All previous remarks are equally applicable to trawlers, but they are in a somewhat special category. All the problems of coastwise shipping are met in the trawling industry, together with those of more confined space conditions, very unskilled labour, fishermen's psychology, and the ups and downs of the fish trade. There is, however, one comforting feature which a recent investigation brought to light at Milford Haven. Trawler owners are now keenly interested in fuel efficiency to such extent that one owner, after listening to an explanation of the effect of CO_2 on the coal consumption of boilers, is prepared to instal a recording CO_2 instrument on one of his vessels and thereby expect a straight line of 13 per cent CO_2 to be shown during the trip.

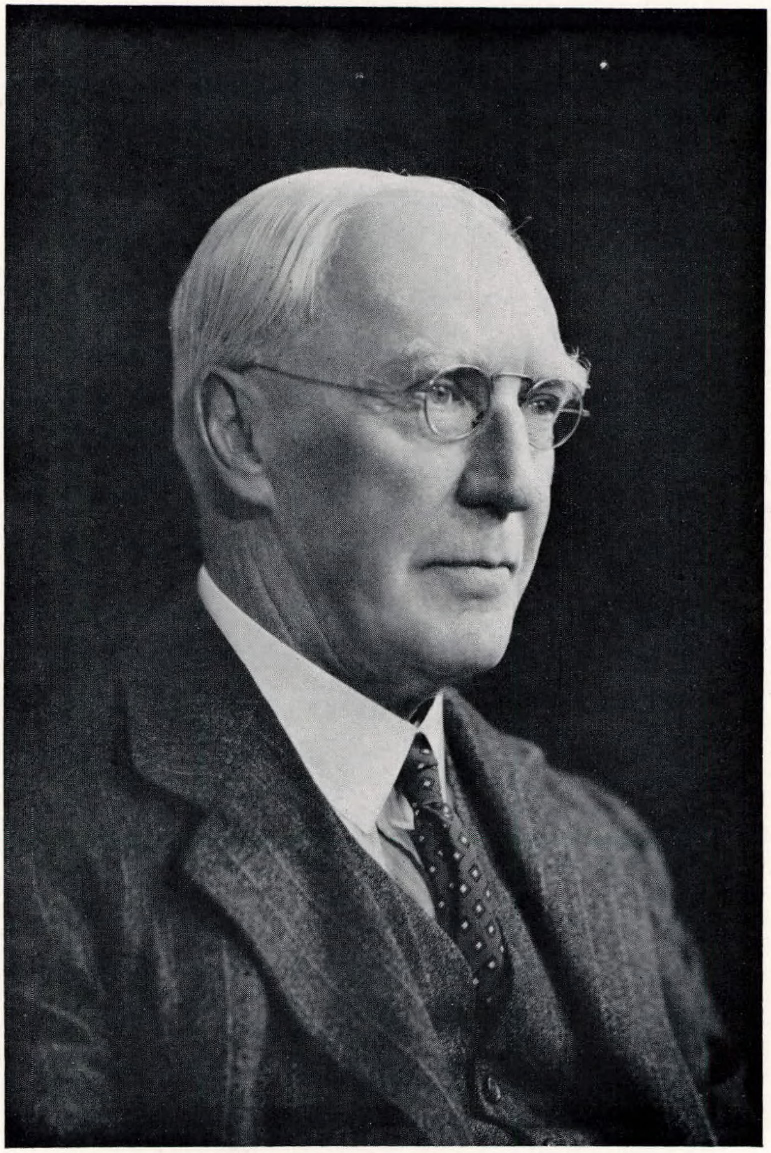
Where an oil-fired vessel is concerned a recording CO_2 instrument could definitely be included in the equipment, together with a smoke stack temperature recorder.

A very brief fuel efficiency survey of fishing fleets brought out some outstanding points that could be readily taken care of without touching upon matters of long-term policy such as the training of engineers and firemen for trawlers.

The control of the stack damper is generally in an inaccessible position; this should be convenient to the fireman and used by him. Feedwater heaters either non-existent or not used due to sheer carelessness or because it needs repair. Firebar design is neglected and firebars ordered by weight much to the delight of the foundry. Lagging is non-existent or in need of renewal. Steam leaks are always in evidence. It may not be generally realized that a hole $\frac{1}{32}$-inch diameter will waste steam equivalent to one ton per year if the boiler pressure is 100lb. per sq. in. Steam is wasted in warming up. Winches etc., and drain cocks are left open to atmosphere and, in many cases, no provision is made for coupling the exhaust from auxiliaries to the main condenser. The possible use of steam traps instead of open ends for drainage should be considered.

Unnecessarily high vacuum is used in the condenser. It should be realized that an excessive amount of cooling water will reduce the temperature of the condensate and thus reduce the feedwater temperature.

The remedy suggested is education in fuel efficiency and more frequent inspections by consulting marine engineers and some incentive offered to the crew to increase the efficient use of fuel aboard ship.



The Late RICHARD HENRY GREEN
Past-President

RICHARD HENRY GREEN

Richard Henry Green was born in London in 1865, and was educated at Uppingham. He served his apprenticeship as a shipwright with James (later Sir James) Laing and Co. at Sunderland, and made two voyages to Australia in a sailing ship before joining the family business, R. and H. Green, Ltd., at Blackwall. In due course he became a director, and when in 1910 the firm amalgamated with Silley, Weir and Co., he was the first chairman of the new firm, R. and H. Green and Silley Weir, Ltd. He remained a member of their board of directors until about two years ago. Mr. Green served on the executive committee of the Shipbuilding Employers' Federation from 1926 to 1940, and was President in 1931-2. He was President of the Institute in 1917-18. He was also chairman, for a number of years, of the River Thames Dry Dock Proprietors' and Shiprepairers' Association. He took a great interest in civic affairs. His father, Henry Green, had been the first Member of Parliament for Poplar, and he himself was the first Mayor when Poplar was incorporated as a borough in 1900. He deposited in the Poplar library a fine collection of his firm's ship models—since transferred to the National Maritime Museum at Greenwich. He was a governor of the Pangbourne Nautical College, a member of the Worshipful Company of Shipwrights, and the founder and first Master of the George Green Lodge of Freemasons.

To him the human relations factor in industry was all important. He was in close touch with the Trade Unions, and worked unceasingly for better relations with them. He was a far-sighted man with a strong sense of public responsibility, and early realized the trend towards the emergence of big units in industry and the significance of this for the community. He died at his home at Haslemere on the 2nd July 1949.