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BOILER AND TURBINE TESTING*

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Introduction

Before describing some of the testing of boilers, turbines and associated machinery, that has been carried out under Admiralty auspices, it is as well to be clear as to the objectives of testing, and about the limitations both of ashore and of afloat testing of marine engines. The lessons of history will be very briefly reviewed and the shore testing facilities available to the Admiralty to-day will be examined, since it is in the main from shore trials that data of real importance are obtained.

In discussing some of the trials that have been carried out, the general line of advance of naval steam engineering can be followed, and it will be seen that thought is directed as much to the practical problems of operation and maintenance of machinery as to the more theoretical problems of economy of fuel and space.

It must be made quite clear from the outset that security regulations prohibit publication of figures relating to the performance of post-war warships. However, this should not detract seriously from the value of this paper since naval machinery design is a compromise, mainly between efficiency, robust performance, weight and space; figures for steam or fuel consumption taken by themselves are apt to be misleading.

It should be appreciated clearly that the Engineer-in-Chief's Department of the Admiralty is not in itself a testing agency, but one which sponsors work to be undertaken elsewhere. It follows therefore that the information contained in this paper is derived in the main from trials reports written by various testing agencies to whom acknowledgement is due, in particular to the Admiralty Fuel Experimental Station, Haslar, and to Pametrada, whose excellent reports have been of the greatest assistance.

Acknowledgement is also due to those members of the Engineer-in-Chief's Department who have been associated in collecting the information contained in this paper.

Objectives and Limitations of Testing

Broadly speaking, testing of machinery will fall into one of four categories—research-testing, prototype-testing, proof-testing, or component-testing.

Research-testing is required to prove that an idea is practicable or to determine design factors that may be employed with confidence. Frequently such tests are carried through to destruction.

Under prototype-testing is included any new design which shows marked departure from previous practice, or in which the factors of ignorance (sometimes called factors of safety) have been substantially reduced.

Proof-testing is really confirmation of correct manufacture and is a demonstration that repeats of an existing design achieve the standard of performance. It is also appropriate for new designs which depart but little from their predecessors.

Component-testing may follow any of the above general lines, or a combination of them. It is frequently a matter of development, often aimed at improved maintenance, and it is therefore perhaps nearest to the heart of the sea-going engineer.

It would clearly save time and money if trials of propulsion machinery could be carried out afloat without delaying the completion and handing-over of the vessel. All proof-testing is normally done afloat and can readily be performed with sufficient accuracy to prove to the customer that he is getting what he specified, and at the same time provide the operator with a yard-stick against which to check performance on service. Trials afloat are however limited in the accuracy to which performance can be measured; wind and weather, draught, and state of bottom all affect the relationships between ship's speed, propeller r.p.m. and s.h.p.; measurements of liquid quantities are generally dependent on tank readings which are less accurate than the weighing arrangements practicable ashore; it is usually impracticable to separate the main engine condensate from that of the auxiliaries; and it is not usually possible to check the accuracy of the various gauges and instruments against a standard at reasonable intervals. It follows, therefore, that it is usually not possible to obtain test results afloat of sufficient accuracy to enable the designer to confirm his data. Of all the specialists in mechanical engineering design, the designer of land generating stations is the most fortunate, for his product is constantly operating under laboratory conditions with detailed evidence immediately available should performance not accord with design. The marine engineer has no such check, either when the machinery first goes to sea or during its subsequent life; the evidence the designer wants is seldom available. It is because of the difficulty of obtaining accurate data from trials afloat that most of the information contained in this paper is derived from trials ashore.

If a new design develops detail weaknesses on trials, and this is to be expected if other than limited advances are

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attempted, it is very much easier to modify the design and try again in the case of shore trials than if trials are afloat, and the cost of keeping a whole ship and her crew idle will be avoided. Shore trials, however, also have their limitations. No brake has a true propulsive characteristic; rotational speed and torque must be adjusted to an assumed propeller law for each trials setting; an astern trial usually requires special provision; and manoeuvring trials are generally restricted. Flexibility of hull and its effect upon alignment problems are absent. The effects of salt-laden air, of tropical and of arctic conditions can seldom be simulated. It is, however, in the operating and maintenance aspects of the plant that shore trials are most lacking. There is no proof the equal of user experience to show whether machinery has fulfilled requirements.

Historical

It is as well to look very briefly at the lessons of history. Sir Charles Parsons, to whose genius all engineers owe so much, was very clear about the need for testing and the way it should be done. *Turbinia's* trials constitute a remarkable record of what can be done in the way of afloat trials.

Between the two wars Naval machinery represented successive logical steps forward from previous designs, sea trials were largely proof-tests and these proved a satisfactory method of recording limited advances. The re-engining of an old ship brings the aggregate of such advances clearly into the lime light; in re-engining the Queen Elizabeth Class the machinery space was reduced by one-third, the machinery weight was halved and the endurance at 10 knots was trebled. Especially in the case of boilers were these advances the reward of testing. Small scale tests at Babcock and Wilcox's works at Renfrew resulted in superheaters being sited in a bank just behind the fire-row tubes instead of near the outer tube rows. Successive shore trials of naval boilers, each carried to considerable overloads, enabled the forcing rates of boilers to be progressively advanced, and the resultant troubles, whether of circulation, feeding, or of carry-over were dealt with at each step.

The classic lesson, not to be repeated, was H.M.S. *Acheron.* Completed in 1931, she had experimental turbine machinery employing steam at 500 lb. per sq. in. and 750 deg. F., her contemporaries using 300 lb. per sq. in. 625 deg. F. steam. She was, in fact, a marked departure from previous practice. Had the machinery been prototype-tested, preferably ashore, the troubles associated with the first use of high-pressure and temperature would have been appreciated and cured, and it would have been possible to have built the economies of fuel and space resulting from advanced steam conditions into this country's warships at a much earlier date. Unfortunately, experience had not then pointed the need and the ship was used as an operational unit as soon as she passed into service; although her whole engine-room department struggled heriocally with entirely new maintenance problems, she became a lame duck and was therefore unpopular.

Testing Facilities

The principal resources available to the Admiralty for testing machinery ashore are listed below. In addition to these facilities, Admiralty contractors undertake component-testing of their own equipment, while most of the gas turbine manufacturers are building test cells capable of testing the complete machinery.

Admiralty Fuel Experimental Station, Haslar (A.F.E.S.)

The A.F.E.S. was set up in 1902 primarily to study the burning of furnace fuel oil; practically all the oil-burning equipment used by the Royal Navy up to the present time has been developed by this station.

From time to time Haslar has been called upon to handle a wide variety of problems; the "flaming sea" method of beach protection, and the development of the liquid pre-cooler for CO_2 refrigerators are but two examples. Nevertheless, the main function has always been boiler development.

The station is now equipped with two boilers for general services and for long term burner and refractory experiments; a high rating test boiler with elaborate instrumentation; an external combustion chamber for flame study and another totally enclosed for operation under superatmospheric pressure. The latter provides for a more accurate determination of CO_2 and unburnt gases than can be obtained where the combustion chamber pressure is below the external pressure. Rigs are installed for atomizer testing, both routine and experimental. The station has well-equipped laboratories for refractories and for oil analysis and testing, and also a test shop for miscellaneous experiments on boiler fittings, accessories and instruments.

It has not been practicable to erect naval boilers for trial at Haslar prior to installation on board. These trials are carried out at the main machinery contractors; special facilities exist now at Messrs. John Brown and at Messrs. Yarrow, and the A.F.E.S. is made responsible for the conduct of trials and for instrumentation. In addition, boilers associated with prototype machinery installations selected for testing at Pametrada are thoroughly tested concurrently with the turbines.

Parsons and Marine Engineering Turbine Research and Development Association (Pametrada)

The activities of this association are fully described in a paper entitled "A Marine Turbine Research and Testing Station," T. W. F. Brown, D.Sc. (Transactions of N.E. Coast Institution of Engineers and Shipbuilders, Vol. 64) and cover both steam and gas turbines.

Briefly, Pametrada was set up in 1944 by the shipbuilding industry with Government support. It has two main objectives—research and development to ensure that the design of turbines for the marine engineering industry is kept in the forefront of world competition, and the full-scale testing of turbine installations. This paper is concerned with the second of these activities.

A Heenan and Froude dynamometer, capable of absorbing 60,000 s.h.p. at 160 to 360 r.p.m. is sited towards the centre of the main test bay; while Daring Class machinery was being tested at the south end of the bay, a gas turbine plant belonging to the association was being erected at the north end. The circulating water system can provide 25,000 g.p.m. for condenser cooling of plant under test. Space is available for the erection of a complete marine installation, boilers, turbines, condenser, and all auxiliaries. In addition to a supply of saturated steam at 250 lb. per sq. in., the station has its own boiler which can supply 28,000 lb. steam per hour at 1,200 lb. per sq. in., 950 deg. F., with a second stage superheater capable of raising the steam temperature to 1,150 deg. F. A further dynamometer of the dynamatic absorption type, capable of absorbing 4,000 s.h.p. at 3,000 to 9,000 r.p.m. is also available, and there is ample space and the necessary resources to undertake component-testing concurrently with prototype-testing of the largest marine installations.

One of the greatest assets which Pametrada possesses is its instrument laboratory, which is superlative in the production of electronic test equipment and which rejoices in being set a really difficult problem. A fine team of technicians, with this laboratory behind it, is rapidly making a name for itself in diagnosis.

Admiralty-Vickers Gearing Research Association (A.V.G.R.A.)

This is an Admiralty-sponsored research organization which uses the facilities of the two manufacturers of the largest gear-cutting machines—Messrs. Craven Bros. and Messrs. David Brown (Huddersfield)—together with Messrs. Vickers-Armstrongs, Barrow, and which is supported by specialist committees drawn from the leading technical men in the field of gearing throughout the country.

Avgra's work is almost entirely in the field of research-testing. Their first job was to improve the accuracy of gear-cutting machinery, then to utilize that accuracy in the production of high load-carrying capacity gears, and finally, in association with Pametrada, to determine appropriate design factors. The first call was for more accurate measuring instruments, and here the National Physical Laboratory played a large part. The testing of gear-cutting machines is carried out both at the maker's and at the customer's works and the load-testing of gearing is undertaken either at Barrow or at Pametrada.

Distilling Experimental Station—Portland (D.E.S.)

This station, which is just being completed, is designed for prototype-testing new designs of distilling plant, for component-testing of existing evaporators, and for the investigation of feed water treatment and de-scaling processes.

D.E.S. has its own boiler and electric generating plant and has space for three separate new designs under trial in addition to the "hack" plant which is typical of the equipment in naval use at the end of World War II, and which will be used for component, development and process-testing.

The merit of Portland as a site is that the sea water there is free from effluent and of similar composition to that normally encountered at sea—a condition difficult to find elsewhere in Britain other than at very isolated spots.

Naval Wing of the National Gas Turbine Establishment (N.G.T.E.)

Arrangements have been made with the Ministry of Supply for the Naval Wing to have full access to all the facilities of the N.G.T.E. These include compressors for supplying air up to four atmospheres pressure for full-scale testing of combustion equipment, and a power supply up to 6,000 s.h.p. and 18,000 r.p.m. for testing compressors; a single-stage turbine rotor driven by air is provided as a rig test for turbine blading and there are extensive laboratories for metallurgical, chemical and mechanical work.

In addition, a test cell is being constructed for the Naval Wing in which gas turbines of medium power suitable for marine propulsion, for electric generators, or other auxiliary purposes afloat, can be subjected to long-term testing under the direct control of naval engineer officers who will be assisted by the wide experience in gas turbine work which is available in the Establishment as a whole. Large marine propulsion units would normally be tested at Pametrada.

If the potential advantages of the gas turbine for marine use are to be achieved in practice, a research-testing establishment of this sort is clearly essential, since ability to operate satisfactorily under conditions similar to those which will be met in service must be developed concurrently with the advance to higher efficiency and lower weight and space requirements.

Admiralty Engineering Laboratory (A.E.L.)

The A.E.L. deals essentially with internal combustion engines, and as such it might be considered to be beyond the scope of this paper; but just as one can draw lessons from history, so also should one take note of lessons in other fields of engineering.

Set up in 1917, the A.E.L. is concerned with three of the four categories of testing. Since its inception, all the Admiralty engines fitted in British submarines have been conceived at the Admiralty and designed by a combined team of A.E.L. and Chatham Dockyard. Single cylinder units have been erected and tested at A.E.L., followed by full-scale engines which are built and tested at Chatham under A.E.L. supervision. A.E.L. experience was also utilized in preparing the guidance drawings to which Messrs. Vickers-Armstrongs have designed submarine engines for naval use. The laboratory has three test bays with brakes capable of absorbing up to 2,500 b.h.p. If, following experience in service, these engines appear prone to specific defects such as bearing trouble, piston ring groove wear, etc., the original development engine is used for component-testing to develop a remedy for the trouble experienced afloat.

Proof-testing is, of course, undertaken first in the shops, and then afloat as each new engine is installed in a ship, and this is the responsibility of the shipbuilder and the Admiralty overseer. Prototype-testing of commercial designs is, however, delegated to A.E.L.; type tests are undertaken, either at A.E.L. or at firms' works under A.E.L. oversight. The standard type test comprises three parts—(i) loop testing to confirm the engine maker's test figures and to determine the Admiralty test rating; (ii) a series of tests selected by the Admiralty according to the application; (iii) if engine is suitable and shows promise of adoption for service use, a further test of extended endurance to determine its useful life between major overhauls. The test may be carried out on a generator rating, i.e., constant speed varying load, or a propulsion rating at varying speed, the loading following a "cube" law. Length of endurance run is usually of the order of 2,000 hours.

It is, of course, very much simpler and cheaper to carry out prototype-testing of a self-contained power unit of usually less than 2,000 b.h.p. than to undertake a test of this nature with steam machinery of ten times the output, but the evidence of I.C.E. experience is clearly that prototype-testing is essential if efficient machinery with reasonable factors of safety is to give reliable operating service.

Boiler Testing

"Daring" Boiler Trials

"Daring" steam conditions are 650 lb. per sq. in., 850 deg. F., the superheat temperature being controlled by means of a two-furnace boiler. Boilers of Messrs. Foster Wheeler and of Messrs. Babcock and Wilcox design are fitted in different ships of this Class. The Babcock and Wilcox design is very similar to a boiler of which full data is available to the Admiralty; one of these boilers was provided for use at Pametrada in connexion with the turbine trials. A Foster Wheeler boiler was therefore selected for the full range of boiler trials to be carried out at the Admiralty boiler test house at Messrs. John Brown, Clydebank. This boiler was designed for use in a closed stokehold; it is fitted with an economizer, but not with an air preheater.

The boiler under test provided steam for fans, fuel oil pumps and other auxiliaries. Main steam from the superheater passed through meter recorders and then through a water spray desuperheater to the condenser. Since the boiler was completed before its own steam auxiliaries were ready, six forced draught fans, spare from Weapon Class destroyers, were arranged in two groups of three in series discharging into a closed boiler room. The exhaust steam from the auxiliaries was also desuperheated before passing to the condenser. Arrangements were made for feed heating to the same degree as would be expected in the ship. Feed water and oil fuel rates were determined by graduated tanks and meters.

The objectives of the trials were to prove that the boiler was capable of achieving its designed performance, to show what, if any, design modifications were required before it was fully suitable for Naval use, and to obtain as much data and information as possible on the various aspects of boiler design and operation for the use of the Admiralty and of the designer.

Tests began in January, 1948, and, after certain teething troubles, the boiler was steamed up to 6/5 full power to check circulation and to establish that the boiler could develop full power safely. This trial indicated that the boiler would be safe at 7/5 full power, but readings taken of gas temperatures below the economizer showed a large degree of stratification with temperatures of 1,150 deg. F. occurring against the side casing, apparently due to gas by-passing the superheater below the lowest tubes. With such temperatures there was a danger that any temporary cessation in feed might lead to damage of the economizer, and it was decided to fit a gas baffle between the main water drum and the superheater tube nest. As a result of this modification, the maximum gas temperature below the economizer at full power was reduced to 1,000 deg. F., the mean temperature being of the order of 860 deg. F.

At this stage, attention was turned to combustion. The boiler was originally fitted with the Admiralty 1943-type registers, an open-front type of register designed for closed stokeholds in conjunction with 1,400 lb. per hr. fuel oil sprayer caps. With this arrangement the flame volume was greater than that of the combustion chamber, so that burning continued into the tube banks, and there was impingement of fuel droplets upon the heating surfaces and the refractories necessitating considerable excess air in order to obtain a clear funnel.

It was, therefore, decided to try the 1946-type register which had been designed for use with 1,600 lb. per hr. sprayer caps; in this design the air is led behind the boiler front and has a better flow into the register. These effected a considerable improvement, but there was still some impingement of the spray upon the heating surfaces, necessitating excess air to avoid smoke. Funnel gas analysis showed 12 per cent CO_2, corresponding to an air:fuel ratio of 18·3 : 1. The A.F.E.S. was therefore instructed to develop a larger sprayer to work with this register with a view to fitting a smaller number of registers and increasing the distance between register centres and heating surface.

Circulation trials were now commenced. R. L. J. Hayden's paper—The Testing of Boilers (Trans.I.Mar.E. 1950 vol. 62, p. 85)—describes the pitot tubes used for measuring velocity of flow in the downcomers and the depression gauge which records the actual difference in pressure between the steam drum and the water drum, and, in fact, measures the motive head available for the promotion of circulation. This depression gauge is the result of experimental work at A.F.E.S. With Admiralty 3-drum boilers working at 400 lb. per sq. in. experience showed that satisfactory circulation was ensured with a depression gauge reading at maximum rating equal to one half of the vertical distance between the water level and the bottom of the fire row tubes. Using the depression gauge and downcomer pitot tube records and making assumptions which can be checked in the subsequent calculations, it is possible to determine mathematically the circulation conditions obtaining in a boiler. The heat transfer formulae employed by Grimison (Trans. A.S.M.E. Oct. 1937) are normally used in these calculations. For a boiler of the type under test twin-furnace, single uptake, 650 lb. per sq. in., boiler with external downcomers—the Admiralty will accept at the maximum boiler rating and a specified angle of heel a minimum circulation ratio of 5, associated with an entry velocity of water to the fire-row tubes (the row with the highest rate of heat transfer) not less than 1 ft. per sec., and a ratio by volume of water to steam leaving this row not less than 5 per cent.

In the present series of trials pitot tubes were fitted in all the downcomers, the boiler was steamed at 7/5th power, and the minimum circulation rate recorded was 6·27. Only the size of the auxiliary machinery available and the capacity of the oil fuel-burning equipment prevented trials being carried to an even higher rating. This circulation ratio of 6·27 provides an adequate margin for any angle of heel likely to be encountered on service, so that, from the circulation aspect alone, the boiler has a 40 per cent margin over its full power rating.

After the 7/5 trial to investigate circulation, the boiler was examined externally and internally and found in good condition. In examining the brick work, special attention was paid to the register quarls which had been supplied in proprietary brands by six manufacturers, and from this some were chosen for future use in this type of boiler.

The boiler having been proved as regards steaming capacity, and safety under steady conditions, the next stage comprised reliability, flexibility, and handling tests over the whole range of output, and at all rates of increasing and decreasing power likely to be encountered on service, including emergency conditions.

The boiler behaved admirably in nearly all respects except that the register arrangement proved clumsy to operate, the top register being 7 ft. 6 in. above the floor plates. This was occasioned by the geometry of the "Daring" Class boiler room and the fact that, at the time of design, the 1,400 lb. per hr. sprayer cap was the largest that had been developed. However, following on the earlier trials of this series, A.F.E.S. had developed a 2,100 lb. per hr. sprayer for use with the 1946 register, and a more convenient grouping of registers was therefore practicable.

The other feature that was not entirely satisfactory was boiler casing lagging. The use of economizers usually results in fitting fewer rows of generating tubes in the tube bank and therefore in higher gas temperatures over a considerable area of boiler casing; this, coupled with increasing congestion in the boiler room has led to complaints from sea of hot pockets and high firing-space temperatures. With so much thought and effort being devoted to weight-saving, it seemed desirable not to adopt an overall increase in lagging scantlings, but rather to await shore trials experience. From a habitability stand-point, conditions in the boiler room are worst at low powers, when the general air velocities in the stokehold are low and heat radiated from hot surfaces is not carried away. Trials were therefore carried out at 1/10 and 3/10 power and it was apparent that working conditions would be unpleasant in tropical climates. The average metal temperature of the boiler casings was 200 deg. F. at 3/10 power which resulted in temperatures being recorded on the floor plates some 30 deg. F. above the outside air temperature. It may be of interest to note that the boiler casing lagging comprised 1 inch thickness of Messrs. Newalls "Newtempheit" high temperature insulating block, and that the associated gas temperature inside the boiler casing during this trial was 700 deg. F.

On a weight basis the most economical method of improving habitability was to build a light metal air casing external to the boiler, arranged so as to lead the air supply to the registers. This was estimated to impose an additional resistance on the discharge side of the forced draught fans of 0·6 inch w.g., and the stokehold air pressure of 15·6 inch w.g. was already considered high enough. Again the register design was referred to A.F.E.S. to see whether by some re-design the draught loss across the register could be reduced. This was achieved by increasing the area for flow of primary air at the entrance to the register.

While new boiler fronts were being fitted to accommodate the revised register arrangement with the larger sprayers, opportunity was taken to remove some thirty superheater tubes. Although on the initial trial the superheater performance conformed with expectations, the fitting of baffles below the superheater tubes had increased the gas flow through the superheater and this raised the superheat temperature. Removal of these superheater tubes restored the balance of the design and subsequent trial proved that the additional steam pressure drop through the superheater was acceptable.

Trials were then resumed. The re-designed registers effected the necessary saving in draught loss, and the effect of the increased distance of the registers from the heating surfaces, resulting from fitting larger sprayer caps, eliminated all flame impingement. As a result a clear funnel was obtained with a CO_2 value of 13 per cent, corresponding to an air:fuel ratio of 17 : 1.

With the elimination of burning in the tube bank the mean gas temperature at full power below the economizer was further reduced from 860 deg. F. to 790 deg. F. The "habitability casing" built around the boiler resulted in satisfactory floor plate temperatures at 3/10 full power, the surface temperature of this casing being 130 deg. F.

A series of trials was now conducted up to 6/5 power which constitutes the performance record of the boiler.

During these trials, calorimeter readings had shown figures of 2 and 3 per cent wetness at high output and it was decided that a further series of trials was required to investigate and rectify this trouble. Some difficulty had been experienced with the throttling calorimeters, due largely to the awkwardness of the main steam pipe leads and to the cooling air flow caused by the habitability casing; some time was also occupied in trying different designs of sampling nozzles, but it was not found practicable to obtain an accuracy greater than $\pm \frac{1}{4}$ per cent. Several schemes for internal drying were tested, and, in addition, an external helix dryer of the Superheater Company's design was fitted in the saturated pipe between the steam drum and the superheater.

The different designs of internal gear produced results varying from 1 to 5 per cent wetness at full power. It was observed that, with a good design of internal steam separator, the additional use of an internal dry pipe reduced the wetness from about 1 per cent to about 0·8-0·9 per cent.

In the trials arranged particularly to test the helix dryer, varying degrees of wetness were produced artificially by raising the water level and by overdosing the water with boiler compound to give figures of 0·5 to 5 per cent at two or three powers. The trials showed the helix dryer capable of removing, on average, $\frac{4}{5}$ of the moisture, irrespective of the wetness before the dryer.

As a result of these trials, it became clear that the main cause of wetness was the use of an internal feed pipe which sprayed water into the steam space. By feeding below the water level a maximum wetness figure of 0·5 per cent at full power was obtained with a relatively simple arrangement of internal gear and without having recourse to an external dryer. The immediate effect of drowning the feed was to cause hunting of the water level, but the addition of a steam flow component to the feed water regulator steadied up the rate of feed and the water level hunting ceased.

Having settled the dryness problem, this prototype boiler test was concluded by a final series of performance trials to check previous results.

Throughout these trials various incidental tests were made on safety valves, brick and casing temperatures, some of which were necessarily of long duration.

Apart from the collection of data on performance, valuable to the designer as a check on his technique and methods, and valuable to the Admiralty for present use and also in the identification of possible troubles in service, these trials gave timely indication of the necessity to modify superheaters, combustion equipment—both from the efficiency and handling aspects—and the internal drying gear.

Trials at A.F.E.S., Haslar

Oil-burning equipment. The above notes on Daring boiler trials give some indication of the work done at A.F.E.S. on the development of oil-burning registers. 13 per cent CO_2 is considered the standard to be achieved for combustion efficiency with 15 per cent the aim, though this latter figure represents only 10 per cent excess air.

In these tests, CO_2 readings are taken with an infra-red, an electrical conductivity, and two chemical type recorders drawing samples from single and multiple nozzles above the economizer.

With a draught loss of $6\frac{1}{2}$ inch across the register, 2,000 lb. per hr. sprayers have been burned to give a compact flame 8 to 9 feet in length. In a normal design of furnace this will give a heat release rate of the order of a quarter of a million B.Th.U. per cu. ft. combustion volume per hour. To improve upon this, a higher draught loss across the register will be necessary, which brings many problems in its train; for a register draught loss of 15 inch w.g. would mean a total drop across the boiler of around 50 inch w.g.

Tests which have been carried out with many different burner caps, with fuel oil pressures varying from 100 to 1,500 lb. per sq. in., show that combustion is best when the droplet sauter mean diameter is between 80 and 110 microns. For a given output, the higher the viscosity the larger the droplets, while increase of fuel oil pressure decreases the droplet size. Because of the need for sufficiently small droplets at minimum output, it was found necessary in one Naval design to use an oil pressure for full output of 600 lb. per sq. in.; at that pressure a viscosity between 40 and 75 seconds Redwood I gave the best results.

Extensive tests are being made of wide-range burners, and various commercial types are being tested from absolute and comparative aspects. The objective is to develop a fully reliable burner with a maximum output between 3 and 5 thousand pounds of oil per hour, and having a 20:1 turn down, as compared with 1·4 : 1 for the type used in Daring trials. It appears very desirable that the spray angle shall be as nearly as possible 90 $\pm$ 5 deg. over the full range.

Constant attention is given to the installation and user aspects in that the simplest possible arrangement of plant, piping and control is the objective, and also that the burner shall require the minimum attention for cleaning or adjustment. The types of burner under test are the centre spill, outside spill and air or steam-assisted atomizers.

To give more scope and facility for burner and register tests, the present test boiler, which is an 80,000 lb. steam per hour, 400 lb. per sq. in. per 700 deg. F. high rating boiler, is being superseded by a specially designed combustion test boiler with a rear wall which can be adjusted to give a furnace length from 7 ft. 6 in. down to 3 feet, and fitted for any degree of air preheat and for very high air pressures.

Modern boiler designs tend to use more furnace cooling surface; good combustion at low boiler outputs is therefore more difficult to achieve. The combustion test boiler will have an all-cooled furnace.

Refractories. Another field of activity of the A.F.E.S. is the testing of refractories. Here the effort has been directed to the production of material specifications which will ensure the greatest resistance to spalling and slagging of firebricks, avoid the use of materials not available in this country, and provide a serviceable and light design of furnace lining as a whole. During the course of this study, it has become apparent that firebrick temperatures are not as high as had been generally supposed, even with quite high furnace heat release rates. Typical figures for a furnace having three refractory and three tube walls, at a heat release rate of $0{\cdot}2 \times 10^6$ B.Th.U. per cu. ft. per hr. show a furnace temperature of 2,600 deg. F. and a firebrick hot face temperature of 2,200 deg. F.; with the higher heat release rates produced during experimental trials, furnace and hot face temperatures of 2,850 deg. F. and 2,400 deg. F. respectively have been recorded. The brick temperatures quoted are those of the hottest bricks in the furnace; those adjacent to tube walls would be about 100 deg. F. cooler. The direct effect of excess air has been shown to reduce furnace and firebrick temperatures by about 70 deg. F. for every 10 per cent excess air.

Firebricks are refractories, not insulants. The temperature drop across the whole thickness of a $4\frac{1}{2}$ inch brick is of the order of 300 deg. F., leaving a drop of some 2,000 deg. F. to be absorbed by the insulating bricks and the slabs of insulating material which are arranged behind the firebricks. If the thickness of the firebrick is reduced to $2\frac{1}{2}$ inch the additional temperature drop of 130 deg. F. is accommodated almost entirely by the insulants, and the resulting decrease in hot face temperature of the firebrick is less than 10 deg. F. The testing of insulants has not yet quite reached the stage where results can be reported.

In these trials, brick temperature measurements were taken both by the temperature gradient method and by direct surface measurement using platinum : platinum-rhodium thermocouples, while furnace temperatures were measured with aspirating thermocouples.

The minimum limit of alumina specified for firebricks for Naval use has been progressively raised in order to give a higher refractoriness, but, quite recently, study at A.F.E.S. has led to the conclusion that an increase in alumina over the range 38 to 43 per cent nearly always leads to a lower sea salt slagging resistance. This, together with the knowledge that firebrick temperatures are lower than was supposed, has led to the pyrometric cone equivalent being fixed at No. 33 (3,145 deg. F.) which can be met with a 43 per cent alumina content. The alumina limit is therefore omitted from the latest refractory specification, and clauses covering porosity and contained fluxes have been tightened up.

Spalling and slagging call for some opposing qualities; spalling resistance generally increases with coarse grain and porosity, while slagging resistance is lowered. Trials are therefore in hand at the station to test coatings resistant to the slagging mechanism on a firebrick highly resistant to spalling.

Fuel Contamination. Of great significance, both in the testing of combustion equipment and in the testing of refractories, is the question of fuel oil quality, and, in particular, contamination of oil by salt water in the form of an emulsion. This contamination arises chiefly in ships in which empty fuel oil tanks have to be ballasted with sea water in order to preserve a suitable margin of stability. In such ships emulsions containing 15-20 per cent of sea water have been encountered; 76 per cent sea water in emulsion is the maximum physically obtainable, and in one exceptional case an emulsion containing 50 per cent sea water was recorded in one of H.M. ships. With emulsions containing 15 per cent or more of sea water, the fuel oil sprayers commence spluttering and the presence of water is apparent, but emulsions containing 11-13 per cent have been burnt without any evidence of contaminated fuel at the sprayer.

The problems of contaminated fuel are not peculiar to ships in which fuel tanks are ballasted. The problem will arise in old hulls with leaky bottoms, dependant upon the type and quality of fuel oil carried. It must be remembered that a 1 per cent sea water in fuel oil emulsion will throw into the furnaces 700 lb. of fluxing agent per 1,000 tons of fuel oil burnt.

The results of burning these emulsions are the slagging of furnace brickwork and the formation of bonded deposits in the superheaters. Diagnosis of these troubles together with a solution of the problem of how to break these emulsions has been the result of trials at A.F.E.S., and this work has already been reported in a paper, "Sea Water Contamination of Boiler Oil Fuel and its Effects" (Gray and Kilner. Trans.I.Mar.E. 1948, vol. 60, p. 43).

Turbine Testing

"*Daring*" *Turbine Trials*

Until the testing facilities of Pametrada came into operation, the testing of marine propulsion turbines had necessarily to be carried out afloat. It was not possible accurately to separate the turbine water rate from the total water rate, or to instrument adequately for other than steady steaming runs. The Admiralty normally specified for cruisers and above a series of 6-hour consumption trials at perhaps eight or more different powers, with two 12-hour trials at particularly important points, and an 8-hour full-power trial; for smaller ships the consumption trials were reduced to 4 hours' duration and the full-power trial to 6 hours. The data from these trials would be all that could be made available to the designer for his future guidance.

The "Daring" trials at Pametrada constitute the first occasion on which the designer can compare design data with recorded evidence of performance.

There are three designs of turbine fitted in the Daring Class destroyers, all of which are being tested at Pametrada. At the time of writing, full results and reports of the first series only are available, so that unless otherwise stated, remarks apply to the reaction design of H.P. and L.P. turbine. In this design, known as Daring I, the H.P. turbine comprises a Curtis wheel followed by reaction stages, with a by-pass from the wheel chamber to one of the lower stages, while the L.P. turbine is a double-flow reaction turbine with an astern Curtis wheel at each end. Double helical double reduction locked train gearing is employed. Daring II is identical except that the H.P. turbine is of all impulse design. In Daring III, both the H.P. and L.P. are impulse designs, the latter being a double flow turbine with an astern Curtis wheel at each end. All three variations were designed to have very similar steam consumptions over the whole working range.

Daring I turbines and gearing, together with the associated auxiliaries and the boiler, were erected at Pametrada by the Wallsend Slipway and Engineering Company, Ltd. Special care was taken to reproduce important features of the ultimate ship arrangement, such as the relative positions of the extraction pump and the condenser, and the boiler room air intake and uptake arrangements.

The trials comprised, in addition to preliminary proving tests, consumption trials of six hours duration at 1/5, 2/5, 3/5 power, full power, and overload, with 1-hour check readings at intermediate powers, a series of manoeuvring trials, and a series of astern trials. A brief report of this trial has been published by Dr. T. W. F. Brown (The Testing of Motive Power Machinery—Papers of the Greenock Philosophical Society, January, 1951), but some repetition is desirable here for completeness of record. The trials were very fully instrumented, no less than 525 separate quantities being measured during some of the runs, and an accuracy of $\pm \frac{1}{4}$ per cent was achieved with reproducible results on repeat trials. So consistent were the results that the duration of the consumption trial could be reduced without loss of accuracy. At the design points the designer's figures for water rate were achieved to within less than 1 per cent and even at lower powers where turbine clearances play such a significant part, the greatest departure from expectation was only 4 per cent.

In all, the machinery was run for 407 hours, including 23 hours astern trials. This occupied thirty-four weeks, which included considerable periods for examination of machinery, including three halts each of four weeks duration, some modifications, and the eradication of teething troubles; moreover, this was the first occasion on which this extensive testing equipment had been used.

In addition to the main trials, some important associated researches were carried out at the same time, and since security forbids the publication of the main performance data, it is proposed to deal with some of these other tests.

Astern trials. The object of these trials was to determine the behaviour of the turbines during prolonged astern running. Trouble has been experienced in the past on account of distortion and overheating, necessitating in some cases restrictions of astern power and running periods.

The two chief problems requiring investigation were the rate of increase of temperature in the H.P. turbine and the ahead blading of the L.P. turbine, due to "windage" losses, and the distortion of the L.P. turbine casing due to the presence in the casing of high temperature exhaust steam discharged from the astern turbines.

It was not found possible to measure turbine blade temperatures, but it was considered that these temperatures would approximate very closely to the steam temperature, provided conditions were not altering too rapidly.

The first trial was carried out with steam at 650 deg. F. which is the temperature that will normally be employed at

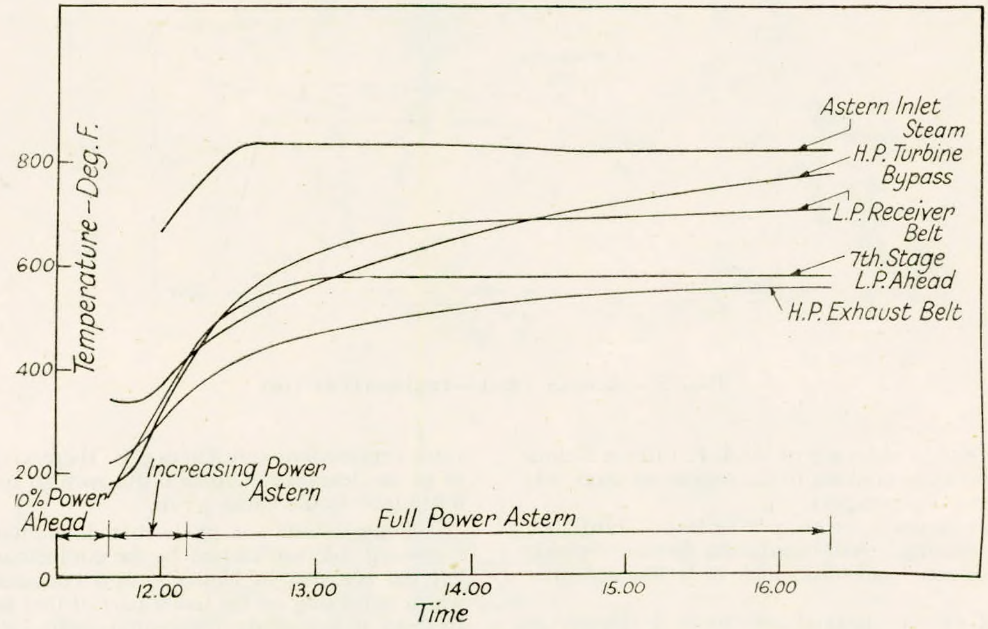

FIG. 1.—ASTERN TRIAL WITH 825 DEG. F. STEAM. VARIATION TIME—TEMPERATURE IN TURBINES

sea when manoeuvring. The machinery was first run at 10 per cent power ahead to get the engines properly warmed through, and was then worked up to full astern power in half an hour. After 3 hours' running, temperatures in the ahead turbines had, in the main, become steady. The highest temperature in the L.P. turbine was 550 deg. F. at the receiver belt, and in the H.P. turbine 565 deg. F. at the by-pass belt.

A second trial was then carried out with steam at 825 deg. F., as there can be no certainty that, when on service, the engine room staff will always reduce the steam temperature when manoeuvring. Again the engines were warmed through at 10 per cent power ahead, and then reversed, half an hour being allowed to work up to full astern power.

The results, which are illustrated in Fig. 1, showed that there was a rapid increase in temperature in the L.P. turbine during the first ¾-hour, approximate figures being:—

L.P. ahead (7th stage) from 160 deg. F. to 550 deg. F.

L.P. receiver belt from 160 deg. F. to 580 deg. F.

The L.P. casing temperature rose to a range of 400 deg. F. to 500 deg. F. under these conditions. After 2½ hours' running, the L.P. turbine temperature became steady, when the maximum reached was 710 deg. F. in the receiver belt. The H.P. turbine temperatures were, however, still increasing after 4½ hours of astern running when 770 deg. F. had been reached in the by-pass belt.

Maximum acceptable blade temperatures had been fixed at 800 deg. F. for the L.P. and 900 deg. F. for the H.P. and it can be assumed that these temperatures will never be reached even under the most arduous astern running conditions.

It is worth noting here that in Daring II trials, with an all-impulse H.P. turbine, the H.P. wheel chamber reached the permitted maximum temperature of 900 deg. F. after three hours at full astern power with steam at 825 deg. F. With this design of turbine it is therefore imperative to reduce the steam temperature at the boilers during prolonged astern running.

Reverting to Daring I trials, hog gauges were fitted to the L.P. turbine casing to measure the deflexion during prolonged astern running. Fig. 2 gives the readings of these gauges. During the first ¾-hour the hog at both sides of the casing increased rapidly to a value of about 0·030 inch. This rapid increase period corresponds to the temperature increase mentioned above. After reaching a maximum of 0·035 inch hog in about one hour, it fell off very slowly until after four hours astern running it had reached a value of 0·028 inch. The increase in hog experienced after stopping and again going ahead will be referred to later.

Fig. 3 shows the temperatures at the L.P. receiver belt, at the turbine casing and at the rotor bore in approximately corresponding positions. Over the period of the first ¾ hour the receiver belt temperature, and therefore presumably the blade temperature, rose rapidly, but the rotor and casing temperatures lagged far behind. This must evidently cause a reduction in the radial clearances. The designed minimum radial clearance was 0·050 inch, and, as can be seen from Fig. 2, the casing hog will absorb 0·035 inch. The remaining margin was clearly too small for safety and it was decided to increase the minimum radial clearance to 0·070 inch. The estimated effect upon steam consumption of this modification was less than 1 per cent.

An attempt was made to correlate mathematically the hog experienced and the measured temperatures in the turbine casing. It was estimated that a temperature gradient in a vertical plane of 29 deg. F. per foot would be required to produce a hog of 0·030 inch but, while a gradient of this order could be found during the early stages of the astern run, the gradient became very much less as the trial proceeded, although the hog was but little reduced. The possibility

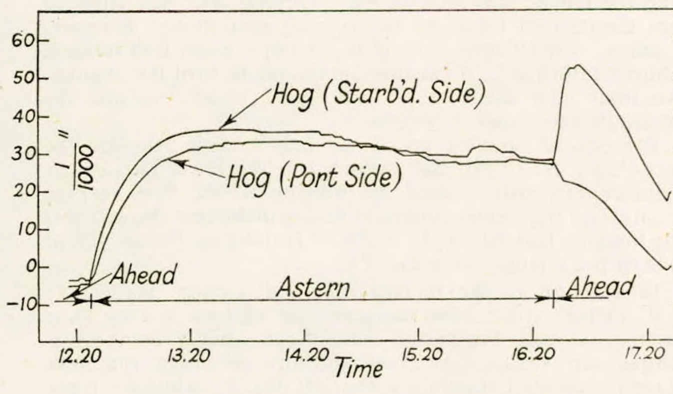

FIG. 2.—L.P. TURBINE DISTORTION

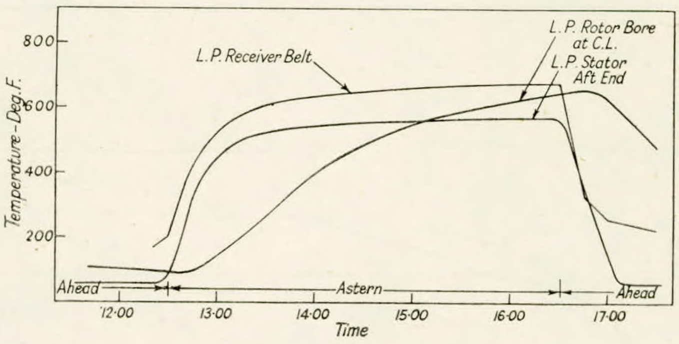

FIG. 3.—ASTERN TRIAL—TEMPERATURE/TIME

that the hog was due to jamming of the L.P. turbine sliding foot, or to a temperature gradient in the condenser shell, was disproved by practical experiment.

The H.P. turbine casing never exceeded a hog of 0·010 inch during the astern running. Axial clearances decreased slowly through the astern run from 0·035 inch to 0·020 inch after 4½ hours.

The method of measuring axial clearances is interesting. Three methods were tried; an electronic capacitance instrument which suffered from condensation of water vapour; a telescope measuring the axial clearances between fixed and moving blades in one of the later expansions, in which trouble occurred due to fouling of the observation window; and a third instrument which comprised a gauge acting against the face of the after gland thrower ring. This gauge took the form of a box with one open side so arranged that the gland thrower face completed the sixth side, but with a clearance, which of course varied depending on the relative movement of rotor and casing. The box was supplied with compressed air through an orifice, on the upstream side of which the pressure was maintained constant. The pressure in the box itself was led to a manometer which was calibrated in terms of axial clearance. After the technique had been mastered this gauge was found capable of accurate and consistent calibration. It worked very well under all conditions and enabled an extremely useful record to be made of relative rotor and casing expansion.

An unusual misadventure. The astern trials were at the time chiefly remarkable for troubles that arose when subsequently going ahead. After the astern run with 650 deg. F. steam, the turbines were run at about 10 per cent power ahead for some 25 minutes while the soot-blowers were used, and no difficulties were encountered. The high temperature astern run was also followed by a period at 10 per cent ahead, but after some 20 minutes the turbine started vibrating and the engine was shut down. Turning gear was engaged but the current taken by the turning gear motor, normally 7 amps., was 10 amps., rising to 30 amps. every half minute. Shortly afterwards, it became impossible to turn the engines. An hour later the engines were found to be free and the turning motor current normal.

Subsequent opening up of the L.P. turbine revealed the fact that a blade rub had occurred in the lower half of the cylinder, evidently caused by hogging of the L.P. turbine casing, and the measurements of casing distortion showed that the hogging had taken place almost entirely on the starboard side of the casing. (See Fig. 2.)

In addition to the turbine casing distortion, records of L.P. turbine rotor bore temperatures showed a very slow decline, whereas the casing was cooled rapidly by the low temperature steam. At about the time when the rub took place the casing temperature was 300 deg. F., while the rotor bore temperature was 600 deg. F. (See Fig. 3.) If the mean rotor temperature were 450 deg. F., there would be a reduction of blade clearance of some 0·014 inch so that a hog of only 0·036 inch would cause a rub.

The suggestion was made that differential cooling of the starboard side was caused by the cool exhaust steam, which left the last row of blades with a considerable amount of whirl, impinging on the lower part of that side of the casing. In order to reduce the differential cooling effect, a system of light metal shields was fitted to the lower half of the casing and to the stiffening grid in the lower half of the casing. In a subsequent trial it was found that the hog of the outer casing when the engine was going ahead was considerably reduced and it was possible to carry out a trial of 4 hours full astern followed by 1 hour at 10 per cent full power head without recurrence of the rubbing. Fig. 2 actually refers to this trial.

The metal shields had somewhat reduced the asymmetrical hog, but they were by no means the complete answer. Later trials revealed that the real cause of the trouble was the air ejector re-circulating water.

The re-circulating water pipe, which connected the main condensate line downstream of the air ejector to the condenser, was led to the forward side of the condenser shell almost in line with the starboard side of the L.P. turbine casing, and the water was sprayed into the condenser over an arc extending from about 60 deg. above to 60 deg. below the horizontal. The water therefore sprayed on to the lower part of the starboard side of the turbine casing. When going from full astern to 10 per cent full power ahead, the re-circulating valve was always opened, to maintain a sufficient flow of condensate through the air ejector, and the effect of the water spraying on the casing was to cause differential cooling in the starboard side of the casing. A minor modification to the re-circulating water pipe effected a complete cure of the trouble.

Manoeuvring trials. The object of these trials was to determine the ability of the engines to stand up to the most severe handling that might conceivably be encountered on service. Only with the full instrumentation that was available was it possible to determine whether an operation was risky and yet be able to stop before serious damage was inflicted. Before commencing these trials the H.P. turbine axial clearance was increased from 0·030 inch to 0·045 inch cold.

For the first trial it was decided to start with cold turbines, allow half an hour for warming through and raising vacuum, and then work up to full power in 20 minutes. Gland steam was put on and vacuum raised to 20 inch Hg. - time taken 15 minutes; the engines were then turned by bursts of steam at ¾-minute intervals for 5 minutes; full vacuum was then raised in a further 10 minutes and the engines started, 20 per cent, 40 per cent and 60 per cent power being achieved in 1, 4½ and 9½ minutes respectively, and full power in 20 minutes.

The axial clearances in the H.P. turbine decreased rapidly in the first 10 minutes of running from 0·045 inch to 0·017 inch, after which they increased gradually to 0·030 inch at which point they became steady.

Negligible distortion occurred in the L.P. turbine casing, but a hog amounting to 0·010 inch to 0·015 inch was recorded in the H.P. turbine casing. These results were roughly in agreement with those obtained for steady running and it appears that no serious distortion is induced by the transient conditions.

No unusual temperature increases were recorded apart from the rapid rise during the period of power increase, which reached a maximum after approximately 15 minutes of steady running. It is perhaps worth noting that during the period of warming through prior to the trial, turning the engine by bursts of steam made no appreciable difference to the h.p. turbine casing temperatures and could have been omitted.

Condensation is most severe during the first few minutes from starting, when almost all stages are operating with saturated steam and casing temperatures are considerably below the steam temperature. It is difficult to assess the importance of this factor, and probably the only reliable guide is that the trial was completed without damage to the machinery.

The above trial showed that the H.P. axial clearance was the only factor which might be critical during violent increases in power, so it was decided to try an even more rapid rate of increase to see if this factor became limiting. In the next trial the engines were increased from 10 per cent to 100 per cent power in 10 minutes.

The results of this trial were comparable to the previous one. The casing temperature curves became almost flat within 15 minutes of reaching full power. The decrease in axial clearance indicated very clearly the effect of differential expansion between the rotor and the casing when power is increased rapidly. This is illustrated in Fig. 4. It appears, therefore, that the principal limitation on the rate of increase in power, so far as the turbines are concerned, is that imposed by the reduction of the H.P. turbine axial clearances.

The next trial simulated conditions when, owing to sudden deterioration in weather, it becomes necessary to get under way in the shortest possible time. No attempt was made to warm the engines. Gland steam was put on and vacuum raised. When vacuum had reached 25 inch Hg. (8 minutes from putting on gland steam) the engine was started and the power increased to 10 per cent in 12 minutes. Full vacuum was attained approximately 8 minutes after starting the engine.

The results were similar to those obtained from previous warming through trials. There was no serious distortion of either H.P. or L.P. turbine casing and no reduction in H.P. axial clearance. It was noticeable that putting on gland steam had an appreciable effect in raising the temperature at the ends of the H.P. turbine casing and the top half of the L.P. turbine casing.

Finally, the effects of a sudden call to stop the ship at sea were investigated. After a period of steady steaming at 20 per cent power, the ahead throttle was shut off rapidly and the astern throttle opened to give 10 per cent astern power, this being the maximum power that can be absorbed by the brake when running reversed. This trial was repeated from 60 per cent and again from 100 per cent ahead power.

The most noticeable effect was that these reversals show no sudden change of temperature in H.P. turbine casing. In the 100 per cent trial the maximum H.P. casing temperature dropped approximately 120 deg. F., and in the other two trials it remained sensibly constant. H.P. turbine hog tended to decrease slightly after the reversals. There was a sudden slight decrease in H.P. turbine axial clearance after reversals which was probably due to the thrust collar centring itself between thrust pads when the thrust came off the blading.

On the other hand, the L.P. turbine casing temperature increased rapidly after the reversal due to the presence of high temperature exhaust from the astern turbines. Temperature curves flattened out after about 15 minutes of astern running, by which time the L.P. turbine casing hog had increased by about 0·005 inch to 0·010 inch.

It was clear from these trials that the speed at which the reversal was effected was not, in itself, important and that any effects which did occur were caused by the normal astern running conditions.

Investigations were also made of various methods of warming through the turbines, and of conditions obtaining when the engines are stopped but available at immediate notice. In all these tests there was no evidence of untoward

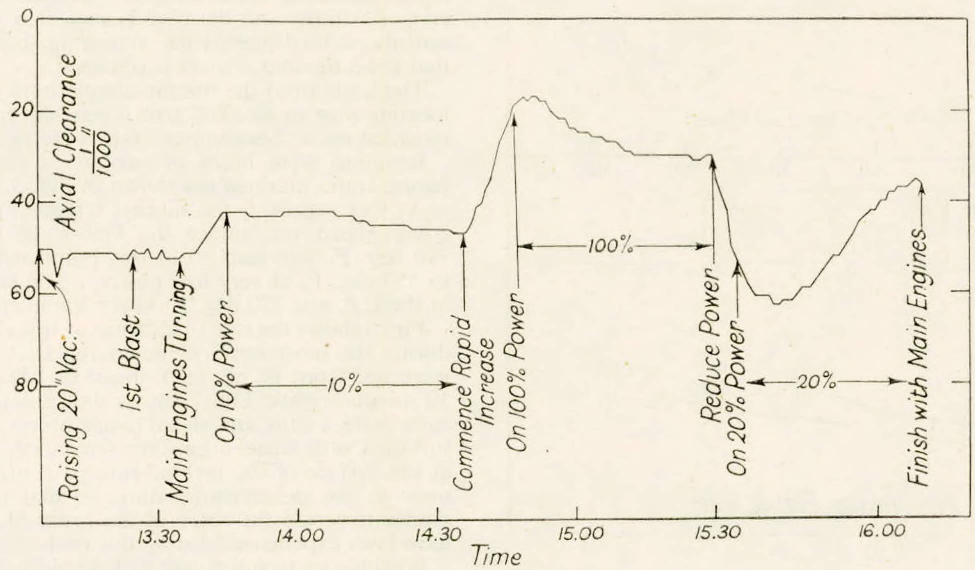

FIG. 4.—H.P. TURBINE BLADE AXIAL CLEARANCE DURING MANOEUVRING

distortion or expansion and the machinery had thus been proven as being adequately robust for all conditions of service.

From the record of relative movement of the H.P. turbine rotor and casing taken over the whole series of manoeuvring trials it was decided to maintain the coarse axial clearance of 0·045 inch for normal service, although 0·040 inch would just provide a safety margin even at the most rapid rate of increase of power.

It is known from the results of the consumption trials that an increase of axial clearance from 0·030 inch to 0·045 inch raises the steam rate by 2 per cent at full power. This has given rise to the suggestion that it might be worth considering the fitting of a form of pulling-up gear, such as is used in land turbines of this type, to allow a smaller axial clearance to be used under steady conditions than when manoeuvring. From the operational point of view, large increases in power can normally only be made over a period of several minutes, owing to the limitation of boiler output, and therefore during an increase of power sufficient time should be available for increasing the clearances by means of the adjusting gear. On the other hand a rapid decrease in load, which might be carried out in a matter of seconds, would involve no danger as such changes cause the clearances to open up. Before such a device could be accepted for naval service it would need to be both simple and also proof against mis-handling by semi-trained watchkeepers.

Turbine rotor bore temperatures. Reference is made above to rotor bore temperatures. The apparatus used to record these temperatures consisted of five thermo-couples located axially in the rotor bore. At each thermo-couple position a split

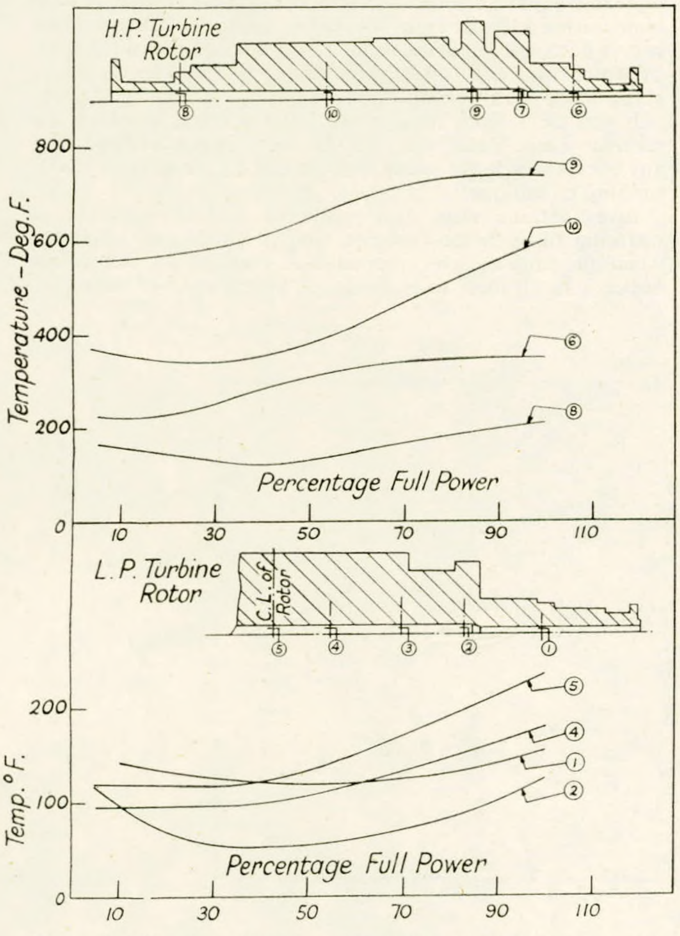

FIG. 5.—STEADY ROTOR BORE TEMPERATURES AT VARIOUS POWERS

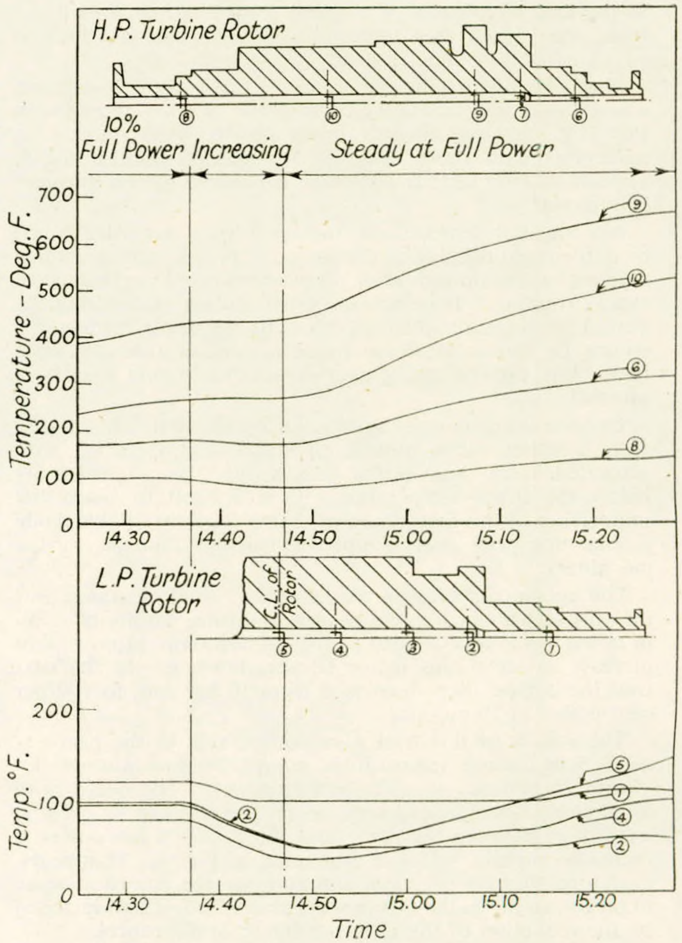

FIG. 6.—ROTOR BORE TEMPERATURES DURING MANOEUVRING

copper cylinder with three tongues was attached to the locating pipe and the thermo-couple was brazed into the centre of one of these tongues. The clearance between the copper cylinder and the bore is such that when rotating, the centrifugal load presses the tongue against the rotor wall so that good thermal contact is obtained.

The leads from the thermo-couple were then led down the locating pipe to an axial type 6-way slip ring and the results recorded on a "Speedomax" type automatic recorder.

Readings were taken at various powers and the steady temperatures attained are shown in Fig. 5.

As was expected, the highest temperature recorded when going ahead was under the first stage Curtis wheel and 740 deg. F. was reached at this point at full power, falling to 550 deg. F. at very low power. The highest temperature in the L.P. was 270 deg. F. under the inlet belt.

Fig. 6 shows the rate of increase of rotor bore temperatures during the most rapid manoeuvring trial, when power was increased from 10 per cent ahead to 100 per cent ahead in 10 minutes, while Fig. 7 shows the simultaneous records of rotor bore, casing and steam temperatures in way of the H.P. turbine Curtis wheel during the same trial. The temperature at the surface of the turbine rotor will presumably approximate to the steam temperature, so that radial temperature gradients across the rotor of the order of 260 deg. F. must have been experienced during this trial.

Working up to full power with a cold turbine may produce even steeper radial temperature gradients in the H.P. rotor. Fig. 8 shows rotor bore temperatures taken in the "0-100 per

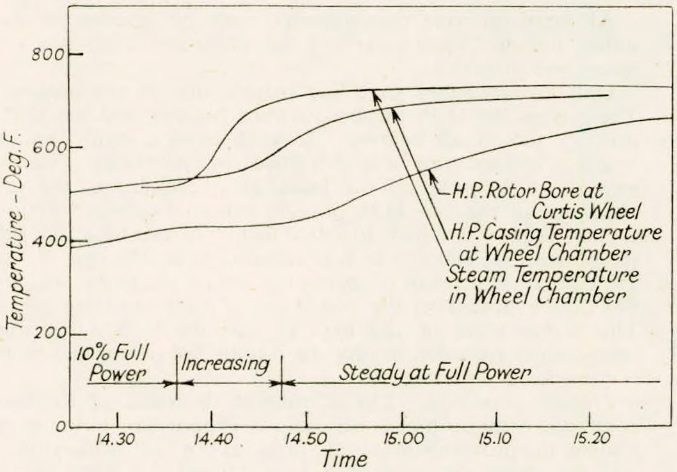

FIG. 7.—H.P. TURBINE TEMPERATURES DURING MANOEUVRING

cent ahead in 20 minutes" trial with Daring II machinery. Generally the rotor bore temperature records in Daring II gave very similar records to those of Daring I, the temperatures differing only by a few degrees, though in the case of the increasing power trial the response of the rotor bore temperatures was naturally quicker owing to the lesser thickness of metal. The initial temperatures were from 70-100 deg. F. and had increased to about 150 deg. F. when the engines were started. Since the wheelcase temperature at the lower power is about 500-550 deg. F. increasing to 750 deg. F. at full power, it appears that a temperature difference of some 400 deg. F. may exist between the outside and the inside of the rotor under these circumstances.

Generally speaking, the rotor bore temperatures attained after a reasonable period of running are very close to the steam temperature at that position and under these circumstances little in the way of temperature stress is to be expected. Conditions at the glands and journals may be somewhat complex but, as the rotational stresses here are small, it is unlikely that any undue stressing will arise in a rotor under steady conditions. The conditions on first admitting steam are, however, much more complex and work has been carried out on the rate of heating of a section of a rotor similar to that on which the first series of rotor bore temperatures were taken. From the temperatures observed during the initial warming, it has been possible to compute the stresses due to the temperature differentials. This investigation has not yet been completed, but it would appear that considerable stresses may be caused by temperature alone, particularly at the reduced diameter between the Curtis wheel and the dummy, and at the bore. It may well be proved on further investigation that the rate of working up a cold turbine may be limited from this consideration, though the gashed impulse type of turbine is better off in this sense than the solid rotor reaction turbine.

Operating Troubles.

It is generally considered inappropriate to say much about troubles experienced with a new design, but a new design which has no troubles at all is usually one in which the advances on previous practice are very limited; the diagnosis and cure of troubles are matters of essential interest to engineers. In order to maintain proper perspective, let it be understood clearly that there were very few mechanical troubles throughout these extensive, and, in some instances, punishing trials.

Some teething troubles were experienced with feed pump and extraction pump systems and boiler equipment, but these were eliminated before the trials proper had proceeded very far. The main defects on trials which entailed considerable investigation were:—

(i) A few cases of overheated bearings.
(ii) L.P. turbine distortion (discussed above).
(iii) Wear on flexible couplings between turbines and pinions.

Bearing temperatures. It is difficult to measure true bearing temperatures, and the various compromises adopted include the measurement of the bearing shell temperature and outlet oil temperature. In the case of the Daring bearings the thermometers are placed in a separate outlet

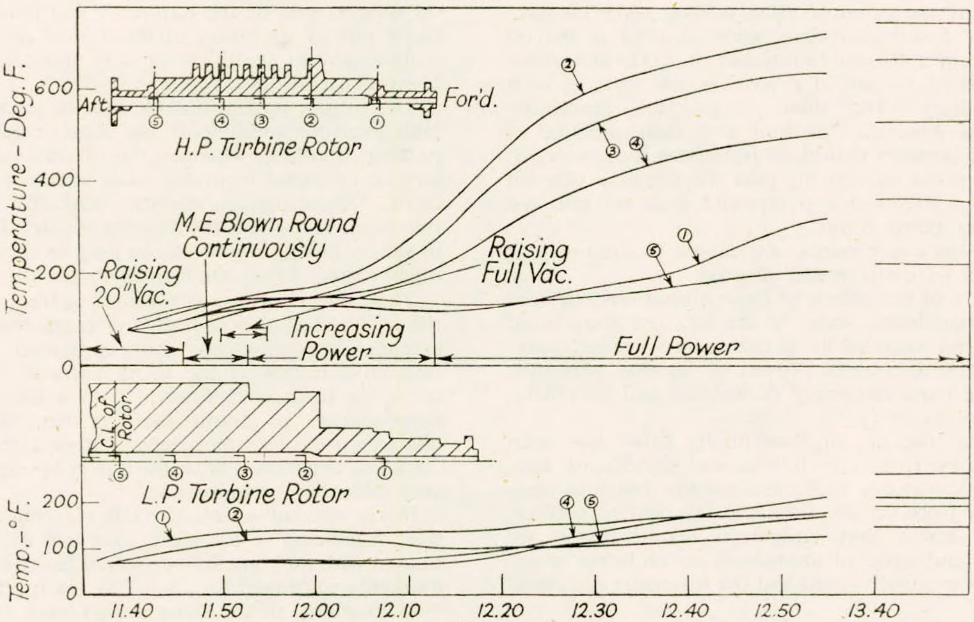

FIG. 8.—DARING II—ROTOR BORE TEMPERATURES WHEN FORCING COLD TURBINES

path from the main oil discharge. This construction was not successful in the case of most of the bearings as first fitted since at one or more conditions of running the oil pressure at the bleed point was insufficient to cause the oil to be pumped up to the thermometer.

In order to get up to the thermometer, the bleed point must clearly be at a zone of high pressure in the journal; even at positions no more than 50 deg. away from the load line there may be insufficient pressure for an oil jet to reach the thermometer. Pressure zones were analysed under different conditions of load and plotted on polar diagrams; these diagrams showed clearly the cause of the trouble. Fig. 9

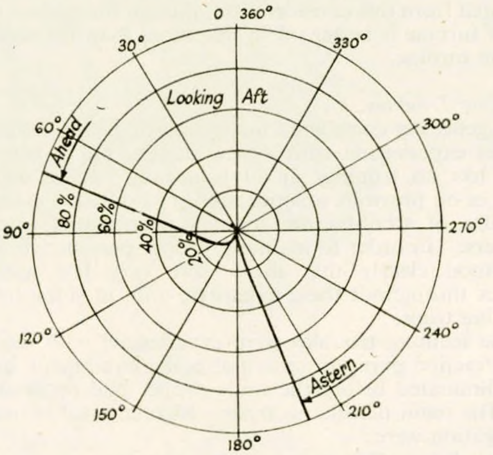

FIG. 9.—VARIATION OF LOAD LINE WITH PERCENTAGE LOAD

shows a typical polar diagram from this investigation. A circumferential groove was needed to collect oil, close enough to the boundary of the bearing so as not to affect the oil distribution over the journal, yet not so close as to cause excessive side leakage. An oil groove $\frac{1}{32}$ inch deep effected but little improvement. Considerations of oil conditions in the groove suggested that the drag of the shaft upon the oil in the groove was sufficient to prevent equal pressure obtaining all round the circumference; to overcome this drag effect conditions of turbulent flow were required in the oil groove. To obtain a Reynolds number of 2,000 at turbine speeds below 100 r.p.m. an oil groove $\frac{3}{8}$ inch wide $\times \frac{1}{4}$ inch deep was necessary. The final design was practically identical with an American method and their practice of putting a dam in between two bleed holes was incorporated; if there is no dam the oil moving past the pressure take-off hole might act as an injector pump and suck oil into the groove rather than pump it out.

As a result of the experiments, alterations to the bearings of the whole class were afterwards effected.

Since evaluation of the effects of these alterations required running of the machinery, some of the bearings were fitted with special thermo-couples as a precaution against overheating; these thermo-couples proved to be very sensitive, but, owing to the requirements of robustness and simplicity, were not fitted permanently.

Experience with the bearings as finally fitted has been entirely satisfactory from the lubrication standpoint and, although the temperatures indicated on the bearings may differ appreciably from the conditions at the bearing surface, experience has shown that dangerous temperatures are readily indicated and allow of immediate action being taken.

The bearings as originally fitted had the following diametral clearances:—

Primary pinion bearings (6-inch diameter) ..	0·007 inch
H.P. turbine bearings (6-inch diameter) ..	0·010 inch
All other bearings (up to 17½-inch diameter)	0·015 inch

All bearings were manufactured with oil recesses at the joints, but no "wash away" of the white metal into the oil recess was provided.

Only two bearings gave any trouble due to overheating. These were the H.P. turbine forward bearing and the H.P. primary pinion aft bearing. In both cases a reduction in bearing temperature was obtained by providing "wash-aways" at the sides of the bearings. In addition, the oil clearance in the two H.P. primary pinion bearings was increased from 0·007 inch to 0·010 inch. In this case, the oil temperature at full power was reduced from 197 deg. F. to 190 deg. F. as a result of increasing the oil clearance, and to 183 deg. F. following the "wash-away" at the bearing sides. This temperature of 183 deg. F. was the highest bearing temperature recorded during the 6-hour full-power run, and is considered satisfactory.

Flexible coudlings. The scoring of the faces of toothed couplings is by no means uncommon experience; so far as is known, the problems involved are as yet not fully understood, and the proper design remedy is still awaited. The Daring trials were no exception and the teeth of the flexible couplings did show signs of distress.

These couplings, which are of heat-treated 3½ per cent nickel steel, are designed to allow axial sliding, the teeth of the male ends of the dumb-bell coupling being enlarged in diameter at the centre to give a fine clearance at the root of the female coupling, thus keeping the two parts concentric. Oil is fed to the coupling by an oil thrower which directs oil axially to the roots of the male teeth, but it is doubtful whether an oil film would be formed between the teeth and it is probable that most of the oil passes through the clearance between the tips and the roots of the mating teeth.

When the shafts are out of alignment the teeth in the plane of mis-alignment can easily adjust themselves, but the teeth at 90 deg. will be under an unequal distribution of load with concentrations at one end or the other of the teeth. Thus each tooth will experience the change of a concentration of stress along its length and back again per revolution of the turbine.

Two different types of pitting were noted on each tooth, each definitely confined to one half of the driving or driven face.

The pitting on the inside half of the teeth (remote from the oil supply) was of the nature of fret corrosion with brown-black pits of the order of 0·001 inch deep. Fret corrosion is indicative of small movements under load in the presence of small quantities of oil.

The pitting on the outside half of each tooth indicated a high pressure welding of the mating surfaces followed by parting of contact between the mating surfaces and a transference of metal from the male to the female component's teeth. These regions do not show any discolouration and this seems to indicate the absence of oil. The pits are irregular in shape, being, in general, as long as they are broad, as one might expect if they are formed by parting of welded surfaces.

These couplings were examined at frequent intervals during the trials; the areas of both fret corrosion and of torn metal extended progressively, but remained peculiar to their respective halves of the tooth surfaces. Twice during the trials the teeth were dressed with a file and eventually the deterioration of tooth surfaces became stabilized. This phenomenon of surface deterioration arresting itself is fairly common experience with flexible coupling troubles, but it is very difficult to comprehend.

In the second series of trials (Daring II), new couplings were fitted and in each case one end of the dumb-bell was treated with molybdenum di-sulphide. The treated ends gave markedly improved results. For Daring III, a further set of new couplings of the same design were fitted and were also treated with molybdenum di-sulphide; the results were not so good as with Daring II, but appeared to be acceptable after some running, though signs of distress clearly remain.

The defects, whether fret corrosion or tearing of metal subsequent to welding, are clearly due to axial movements of the coupling parts. It was therefore surprising to find in a front-to-front test of single helical gearing, where the pinions are located axially by thrust blocks, that fret corrosion and axial tears had both taken place. These couplings were also of 3½ per cent nickel steel, heat-treated, and were also treated with molybdenum di-sulphide.

Material with considerably higher ultimate tensile stress has been specified for the flexible couplings of some machinery now under construction. Trials will also be made with a nitrided steel and with a coupling having barrelled teeth designed to avoid end loading, but it is not felt that either hard material or a minor change in tooth profile will prove to be a complete cure for the troubles experienced in this type of coupling.

Gas Turbine Testing

The Admiralty has a number of gas turbines for marine propulsion under development. Each of these is, in the first place, being tested at the maker's works against a brake with full instrumentation; these test facilities are of the same order of completeness as those available at Pametrada, and in each case the work must be classified as research-testing. Subsequently it is intended that the machinery shall be installed in suitable craft, and, although the units may not in fact become prototypes for repeat orders for Naval use, the trials will be analogous to prototype-testing. None of these developments has yet reached the stage at which they can be reported upon.

With one exception, these propulsion units represent ambitious advances even in the very new science of gas turbine engineering. A rather more orthodox advance is the B.T.H. gas turbine produced for the Anglo-Saxon Petroleum Company for installation in the Diesel-electric tanker *Auris*, some particulars of which have recently been released to the Press (Shipbuilding and Shipping Record, 22nd February, 1951). The shore trials carried out at Rugby on this installation constituted true prototype-testing.

The Admiralty was responsible for the first gas turbine driven vessel in the world when a gas turbine with the code name of Gatric was fitted into a motor gun boat and commenced trials in 1947, just fifty years after the trials of *Turbinia*.

Gatric is a marine version of an aircraft jet engine developed by Metropolitan-Vickers, with a free power turbine fitted in place of the jet pipe; the engine develops 2,500 s.h.p. and drives the centre propeller of a 3-shaft installation through a clutch and gearbox. Two 1,350 h.p. Packard petrol engines are coupled to the wing shafts for low speed and astern running.

This machinery was installed in M.G.B. 2009, now renumbered M.G.B. P.5559, after only the minimum of preliminary shore-testing, since it was merely an experiment "to see if it worked." Two additional engines had been ordered to enable shore tests to be carried out concurrently with the trials at sea. The success of the latter was in part due to the fact that engines were available ashore for development testing.

The main objectives of installing Gatric in M.G.B. P.5559 were to gain experience of installing, operating and maintaining a gas turbine at sea, and to determine the effect of a salt-laden atmosphere on the compressor blading. M.G.B. P.5559 was in effect a floating test bed (possibly the first the Engineer-in-Chief has ever had at his disposal) and considerations of speed, or of the most efficient installation for the job, did not enter into the problem. It was, in fact, somewhat of an *ad hoc* arrangement but as such produced most valuable results and has pointed the way for future development.

The outstanding success of the preliminary trials did in fact hamper progress, as for the first month or so a lot of this floating test bed's time was taken up in giving sea demonstrations to numerous visitors, from pressmen's girl friends to Admirals, all intrigued with the novelty of the idea. During the demonstration period, Metropolitan-Vickers' engineers handled the engine, at the same time answering a continual flow of questions, the best of which was perhaps "Where do you keep the gas?"

The trials were surprisingly trouble-free, apart from seizure of the disconnecting clutch, and much valuable operating experience was obtained. The trials also provided important data on noise characteristics, and the effectiveness of various silencing and heat insulation methods.

Very early in the sea trials, a noise survey was undertaken in the boat to obtain data which could be used as a basis for the design of silencing equipment.

It was found that the greatest noise level in the engine-room (117 dB) originated from the gas turbine gearbox. On deck, just aft of the bridge, the level was also 117 dB, the major source being traced to the compressor air intake; on the bridge itself noise from the funnel predominated, the total level being 102 dB.

The most serious component of noise was considered to be the high frequency note emanating from the axial compressor and transmitted through the air intake trunking and settling chamber, and experiments were carried out to reduce this. Two methods of silencing were tried; firstly, the settling chamber was lined with "Fibreglass" and "splitters" of the same material were fitted in the intake; and, secondly, a reflector-absorber unit designed and manufactured by Messrs. Vokes was fitted in the settling chamber.

The "Fibreglass" method gave a reduction in the compressor blade note of 39 dB, while the Vokes unit gave one of 12 dB. Various combinations of these two methods have also been tested.

Reduction of the intake noise has also made possible a more accurate evaluation of the exhaust noise, and it has been found that the compressor blade note is present here also. Silencing equipment, including a "torpedo-type" splitter, has been fitted in the funnel, but no results are to hand at present.

Owing to the close proximity of the two petrol-driven Packard engines great care was necessary in the design of Gatric's heat insulation, and it was finally decided to enclose the entire engine in a ventilated casing. Gatric itself was lagged with 2-inch asbestos mattresses, and a light metal casing was then fitted over this lagging, but not in contact with it. Air supplied by a small fan was blown between the casing and lagging, and exhausted up the funnel. The fan was later removed and air drawn through the casing by an engine exhaust operated ejector fitted in the funnel.

One of the principal objectives of the trials was to investigate the effect of a salt atmosphere on the performance of gas turbine compressors especially of the axial flow type.

The compressor blades were manufactured from aluminium alloy R.R.56 and anodized by the chromic acid process. Examination after the first 50 hours' running revealed that the blades had been attacked by inter-crystalline corrosion. The corrosion occurred locally, the average depth being 0·005-0·010 inch. As a result, the material was changed to R.R.57 which is more resistant to this type of attack. No further corrosion troubles have been experienced, though it is considered that corrosion would still occur in the absence of water washing.

After 120 hours' running, the efficiency of Gatric began to fall rapidly. The compression ratio had fallen to 94 per cent and output to 86 per cent of their design values. Examination showed a light snow-flake salt deposit on the compressor blades. To overcome this fouling problem, Metropolitan-Vickers designed and fitted a water-spray ring in the compressor inlet. A ten-gallon injection of distilled water increased the compression ratio and output to 98·5 per cent and 97 per cent of design, and a second injection of 10 gallons restored them to their design values.

It was found that injection rates lower than 100 gallons per hour were not very effective, and continuous injection was therefore ruled out. The best results were achieved by injecting 10 gallons in 5 minutes after every 10 hours' running time. The use of liquids other than water has not been tried.

All this information will prove to be of great value, and most of it, especially the effects of a salt atmosphere, could only be obtained from sea trials. It should be noted, however, that the maximum running time that could be achieved even in good weather was only about 24 hours per week, and it did, in fact, require some 5 months to complete the first 50 hours, of which 13½ hours were taken up in demonstration runs. These figures emphasize the difficulties of obtaining long runs at sea, and show why it was necessary to carry out simultaneous shore trials.

Two Gatric engines were available for shore tests, one installed at Metropolitan-Vickers' Works (this has since been presented to the National Science Museum) and the other at the Admiralty Engineering Laboratory; both these were used for development testing and the proving of new components.

At Metropolitan-Vickers an investigation was made into the effects of using high sulphur Diesel fuel. The sulphur content of this was 2·78 per cent by weight. The sprayer shields, which were made of inconel, were badly eaten away but the rest of the engine remained unaffected. This was followed by preliminary tests on the combustion of Naval boiler fuels. The boiler fuel used had a viscosity of 492 seconds Redwood I at 100 deg. F., a sulphur content of 2·04 per cent and an ash content of 0·02 per cent. The major element of the ash was sodium. The preliminary trials on heavy fuel combustion at Metropolitan-Vickers which included a successful 50-hour run, were continued on the third engine at the Admiralty Engineering Laboratory, and over 200 hours' running on two different types of boiler fuel have been completed there. After 130 hours' running, the deposits formed on the turbine nozzles were not sufficient to cause any noticeable drop in performance and consisted mainly of sodium sulphate. During subsequent inspection, it was found that the greater part of these deposits could be washed off with cold water.

A second series of trials on a high vanadium boiler fuel has been carried out, but results are not yet to hand.

The operational difficulties of heating and pumping the fuel have also been investigated.

All this work, involving frequent stripping and cleaning of the engine, modification of fuel heaters, etc., would have been very difficult to carry out at sea, and progress would have been much slower. As a result, however, of extensive trials ashore, it was possible to instal a well-tried heavy fuel system in M.G.B. P.5559 and to operate it with reasonable confidence.

Testing of Gears

No summary of Admiralty trials in the marine propulsion field would be complete without reference to the testing of gears. There is little that can be added on this subject to the information provided in a paper by Commander (E) J. H. Joughin—"Naval Gearing—War Experience and Present Development" (Institution of Mechanical Engineers, 15th December, 1950) but in view of the wider scope of this International Meeting, it may be as well to give a short summary.

The object of the Admiralty development programme is to obtain gearing of the minimum weight compatible with reliability. In general it covers two main fields.

(*a*) Machine accuracy. The requirements for machine accuracy have been stepped up. The British Standard Specification 1498/1948 and the draft British Standard Specification for "Turbine Gears" provides the basis for the machine and gear accuracy now required. Instead of undulations of the order of 2/1,000 inch, undulations are now required not to exceed 2/10,000 inch.

(*b*) Improved materials.
- (i) Production of gears of the hardest materials that can be machined by hobbing machines. It is anticipated that materials of 60-65 tons per sq. in. U.T.S. can be used for large secondary wheels and 70-75 tons per sq. in. U.T.S. for pinions and primary wheels.
- (ii) Case hardened and ground gears.

Designs have been accepted for gears in which advantage has been taken of the expected gains from these developments. These can be summarized as follows:—

(i) Hobbed and shaved existing materials.
Primary wheels and pinions 40-45 tons per sq. in. U.T.S. 3½ per cent Ni.
Secondary wheels 34-38 tons per sq. in. forged steel.
Loading primary 876 lb. per inch of face.
Loading secondary 1,356 lb. per inch of face.

(ii) Hobbed and shaved hardest material.
Primary wheels and pinions 70-75 tons per sq. in. U.T.S. E.N.26.
Secondary wheels 60-65 tons per sq. in. U.T.S. E.N.30.
Loading primary 1,270 lb. per inch of face.
Loading secondary 2,955 lb. per inch of face.

(iii) Hardened and ground (Design 1).
Primary wheels and pinions E.N.36 (approximately) case hardened.
Secondary wheels 85 tons per sq. in. U.T.S. E.N.30 (approximately) air hardened.
Loading primary 1,808 lb. per inch of face.
Loading secondary 2,582 lb. per inch of face.

(iv) Hardened and ground (Design 2).
Primary wheels, pinions and secondary wheels E.N. 36 (approximately) case hardened.
Loading primary 2,710 lb. per inch of face.
Loading secondary 5,110 lb. per inch of face.

The design basis has been fixed by consideration of the large amount of data available on tests of gear materials. In the main these have been confined to small gears. It is essential, therefore, to do some full-scale testing in order to determine the limiting conditions.

In warships a relatively small time is spent steaming at high powers. This permits higher gear loads to be carried than in merchant ships. To run warships for an extended period at full power to test the life of gearing is impracticable. Moreover, it is possible to run the gears to destruction when testing ashore.

Testing ashore can be done either against a brake which is expensive since motive power equal to the full power of the machinery is required for the trials, or two sets of handed gears can be run against each other with torque locked into the circuit by some loading device, in which case the only driving power required is that needed to overcome frictional losses. For single reduction gearing the two gearcases are arranged back-to-back, the main wheel shafts being coupled to each other and drives to the pinion shafts led out at the after end of the gearcase and connected to the torque applier. With double reduction gearing, it is not usually practicable to lead the primary drive through the after end of the gearcase, such gears are therefore coupled front-to-front for 2-cylinder lay-outs; in this case no connexion is made between the main wheel shafts, but torque is applied through one pair of pinions and opposed by the other pair. Front-to-front testing has the disadvantage that the loads on the main wheel are applied in opposite directions by the H.P. and by the L.P. drives, which tends to confuse the issue so far as testing of the main wheel teeth are concerned; it is also not possible to vary the proportions of torque carried by the H.P. and L.P. pinions individually.

The following gears are being tested to destruction in order to determine their ultimate load-carrying capacity:—

(i) Standard materials.
Pinions 40-45 tons per sq. in. U.T.S. $3\frac{1}{2}$ per cent Ni.
Wheel 34-38 tons per sq. in. U.T.S. forged steel.
Loading 798 lb. per inch of face.

(ii) Case hardened ground primary gears.
Pinions and wheels E.N.36 case hardened.
Load 3,860 lb. per inch of face.

(iii) Case hardened and ground secondary gears.
Pinions and wheels E.N.36 case hardened.
Load 7,620 lb. per inch of face.

(iv) Induction hardened gears. Secondary gears.
Pinion and wheels E.N.24 induction hardened.
Load 7,620 lb. per inch of face.

Design details of these gears are given in Table 2 of Commander Joughin's paper.

The tests on the first set of gears of standard materials has been concluded. The results were briefly:—

Design load 798 lb. per inch of face.

Pitting commenced 200 per cent load after 229 hours running at loads of 100 per cent and above.

Gear failed by tooth fracture 300 per cent load after a further 172 hours at loads of 200 per cent and above.

A further test with the same gear design and materials, but with pinion corrected for the calculated bending and torsional deflexion at 200 per cent load, has enabled the gears to take a load of 325 per cent without pitting, though a few random pits occurred at 340 per cent load. The tests are being continued.

It was found during these tests that the total torque to run the two gear sets at 4,100 r.p.m. on full load was 200 lb. ft. of which 170 lb. ft. was attributed to bearing losses and 30 lb. ft. to gear tooth friction losses.

Testing of Auxiliary Machinery

All auxiliary machinery for naval service is tested at the maker's works before acceptance. The first off of any order is type-tested and the resultant performance curves accepted as typical for the whole order, though, in the case of a large order, repeat type-tests are required as the order proceeds. The bulk of the order is proof-tested only, a few check readings being taken to prove that the individual machine conforms to type-test. Any considerable innovation in design is developed and tested by the manufacturer in the first case, and, because Naval requirements are so different from commercial needs, the principal features of design performance of a new auxiliary are discussed with the Admiralty at an early stage.

An interesting example of development-testing of auxiliary machinery is the small high-speed turbine for auxiliary drive at present under test at W. H. Allen, Sons and Co., Ltd., of Bedford.

It has been the practice for a considerable time in Naval engineering to use non-condensing steam auxiliaries for the greater part of the propulsion auxiliaries, the exhaust steam being utilized for feed heating. This leads to small, light auxiliary machinery which is one of the prime requirements for Naval work and is in general economical, since these machines act as a single stage tapping for bleed feed heating. It is, however, essential for economy that the latent heat in the auxiliary exhaust shall be utilized either for feed heating or for distilling. Surplus exhaust dumped in the condenser makes the small turbo-auxiliary an expensive item in the whole installation, and it is then better replaced by electric drive to obtain the best economy. As propulsion machinery advances to lower water rates, so must the steam auxiliaries improve in efficiency if excess exhaust steam is to be avoided, and this trend is accentuated by the rising power demanded of the auxiliaries to meet the needs of higher steam pressures and higher draught losses across the boiler installation.

The design of this type of turbine was therefore re-examined. It was clear that a turbine containing a number of Rateau stages was the most efficient but its weight and space was considerably increased, while the 3-row Curtis wheel had too low an efficiency. It was decided, therefore, to carry out trials on the simple 2-row Curtis wheel designed up to the maximum speed possible without recourse to very special materials.

A 3 per cent chrome molybdenum steel was selected for the rotor and it was decided to machine the blades integral with the rim; a pitch circle diameter of about 9 inch was chosen as being the smallest convenient size. The steel selected had a 0·2 per cent proof stress of 32 tons per sq. in. and U.T.S. of 43 tons per sq. in. at 650 deg. F. and was considered to be safe up to 29,000 r.p.m., giving a blade speed of 1,150 ft. per sec. and a velocity ratio of 0·30 under the steam conditions 540 lb. per sq. in. 825 deg. F. exhausting to 10 lb. per sq. in. gauge.

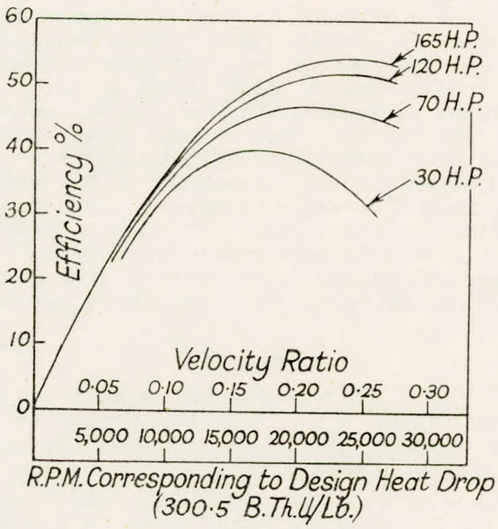

FIG. 10.—HIGH SPEED AUXILIARY TURBINE. OVERALL EFFICIENCY—VELOCITY RATIO

Trials were carried out at varying powers and speeds and the overall efficiencies obtained are plotted in Fig. 10. With the four nozzles in use a maximum of 165 h.p. was obtained. Since the nozzle arc was only 100 deg., the maximum power that could be obtained from a turbine of this size would be nearly 500 b.h.p. on a turbine weight of about 12 cwt. including gearing, but this would result in the sizes of steam and exhaust pipes and the necessary valves becoming excessive, and it is probable that a limit of about 250 b.h.p. is desirable.

The maximum blading efficiency achieved with this set was 62 per cent, the limiting factors proving to be partial admission and the small blade heights associated with this design. Further trials are being carried out with modified blade-paths and stainless steel rotors with which slightly greater blade speeds and efficiencies will be possible.

Conclusion

As machinery design advances, the margins in design become less. Higher temperatures, higher speeds of rotation and higher stresses are employed and the effects of these factors become more difficult to predict. The need for rigorous testing to ensure reliability therefore becomes progressively greater.

Further, it is only by accurate trial results that the performance gains from high efficiency machinery can be demonstrated reliably and only thus that the steps towards even higher efficiency, necessary to give increased endurance to the warship and lower fuel costs to the merchant vessel, can be consolidated.

The cost of testing on the scale that has been described in this paper is very considerable. Trials of the nature of the Daring trials at Pametrada will cost of the order of £100,000, including erection and dismantling and all modifications undertaken in the course of the tests. As has already been stated, a considerable number of research schemes were included in these trials. Had the programme been restricted to recording performance, confirming design data, and proving the design for operating conditions, the cost would have been considerably less, but even so would have been of the order of two to three times the cost of two weeks' sea trials of a comparable ship.

These expenses must be looked at from two aspects. Confirmation of design data is essential if further marked advances in economy or performance are to be achieved, and the shipbuilding industry of this country depends for its existence upon continual advances in design in order to maintain its predominant place. Secondly, reliability of performance year in, year out, fully justifies expenditure during building—owners of all classes of ship, whether mercantile or naval, demand economy of performance and 100 per cent reliability. Only advanced designs which have been thoroughly tested can satisfy both demands.

In addition to financial expenditure, all this testing has incurred much effort both at headquarters and at the various establishments and firms concerned. There is, however, no doubt at all that the improvements in performance which have been achieved, and the elimination of weak points that had been effected, fully justify all the labours and exertions involved.

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This paper was read on Wednesday, 27th June 1951 at the Central Hall, Westminster, London, S.W.1. at a meeting o, the International Conference of Naval Architects and Marine Engineers, which was organized by the Institution of Naval Architects, Institute of Marine Engineers, Institution of Engineers and Shipbuilders in Scotland, and North-East Coast Institution of Engineers and Shipbuilders.

DISCUSSION

Mr. J. H. King (M.I.Mar.E.) said that the paper was particularly interesting to those from overseas, in that it gave a picture of the facilities and methods of boiler and turbine testing in the United Kingdom.

He quite agreed with the authors' statements on "Objectives and Limitations of Testing". Personally, he was specially pleased to note that the authors used the term "factors of ignorance". He hoped that more people would look a the so-called factor of safety in that light, because as more and more was learned about materials, designs and so forth, the factor of ignorance diminished. It was sometimes difficult, however, to obtain approval of lower so-called factors of safety, so that if one could consider this as really a factor of ignorance, then as ignorance diminished so should the factor. For example, they were accustomed to calculate the hoop stresses in the design of a drum. They now added to that the calculations on out of roundness. Certainly this latter information removed some of the ignorance and should, he believed, lower the factor of ignorance.

On the historical section of the paper, he felt that the introduction of welding was a development of outstanding importance, in that it made possible the development of boilers of higher pressures. The United States Navy furnished the incentive to the development of welding by private industry, and in fact in 1930 had given final approval to a specification and method of welding boiler drums. The first such drums had been subsequently installed in the U.S. cruisers *Minneapolis*, *New Orleans*, and *Astoria*. Since that time all boiler drums in the U.S. Navy, and in the U.S. Merchant Marine, had been welded.

On the historical side again, he thought that the great progress and advance in the development of alloys suitable for higher steam temperatures was of great importance.

At this point he also mentioned that most of the development work in America had been done by private industry. The Navy furnished the incentive by setting forth general requirements, but the actual development of new and advanced designs, and the construction thereof, was done by industry, subject to final approval by the Navy Department.

With regard to the description of the various testing facilities, he thought that it might be of interest to call attention to a paper*, by Captain Kranzfelder, U.S.N., entitled "The Naval Boiler and Turbine Laboratory." This paper gave quite a complete description of the U.S. Navy Laboratory at Philadelphia.

Under the caption "Boiler Testing," the authors mentioned the tests of the Babcock and Wilcox design, which, the authors stated, "is very similar to a boiler of which full data is available to the Admiralty." He (Mr. King) presumed that this referred to tests conducted at the U.S. Naval Boiler and Turbine Laboratory. It might be of interest to note that those tests had been conducted in the early part of the last war, and that boilers of this type, operating at similar pressures and temperatures, had been installed in a large number of U.S. Navy combatant ships and had thoroughly proved their reliability and high efficiency, with resulting long-cruising radius, under war conditions.

Furthermore, a double air-casing had been installed on this test boiler, a feature now used in all ships in the U.S. Navy. This of course eliminated the many problems of closed stokehole, while offering many military advantages. A great deal of thought had been given to air-casing design, and casings were now available in which the air leakage was not more than 3 per cent after service.

In regard to the wetness of steam on the test described in the paper, it might be of interest to note that the U.S. Navy specified a maximum moisture content of one-quarter of one per cent, and they had no difficulty at all in obtaining and bettering this requirement.

The authors' comments on oil burning equipment and refractories paralleled largely the U.S. experience. However, in the U.S. they did have available oil burning equipment, including wide-range burners, that gave very satisfactory combustion results. There had also been considerable development with regard to refractories, and quite satisfactory refractories and insulating material were available.

They did not have too much difficulty with fuel contami-

* Kranzfelder, Capt. E., U.S.N. Trans. S.N.A.M.E., Vol. 55, p. 341.

nation from water. Their principal difficulty at the present time had to do with the constituents of the oil, such as vanadium, sodium, sulphur, and other minerals contained therein. This had been quite a serious problem, and while it had not as yet been satisfactorily eliminated, considerable progress had been made. Also, there appeared to be great promise in the experimental work now being undertaken with certain additives to the fuel before burning.

Finally, he wished most heartily to endorse the conclusions of the authors. Considerable sums of money were expended in the U.S. in the testing of boilers, turbines and other equipment before installation in the ship. The cost, particularly under today's conditions, was heavy, but nevertheless it was felt to be a most valuable investment and well worth the cost.

Dr. S. L. Smith (M.I.Mar.E.) said that the paper was very impressive, revealing as it did the many-sided activities of the Engineer-in-Chief's Department in connection with boiler and turbine testing. He was sure that no one reading the paper could fail to realize that the Admiralty were determined that the machinery installed in His Majesty's ships was to be the very best that modern science and engineering could provide.

Of special interest was that section of the paper dealing with the astern and manœuvring trials of the Daring class machinery. So far as he was aware, this was the first time that such data had been published, and all would agree that it should prove invaluable to designers. It should also convince the most sceptical of the great value of full-scale testing ashore of prototype machinery. This was the only way to get accurate information.

He was interested in the part of the paper dealing with refractories, since this was a problem which existed in a fairly acute form in many merchant ships, and in consequence the British Shipbuilding Research Association were at the moment engaged in a fact-finding investigation involving the examination of boiler brick work in a large number of merchant ships. From this investigation it should be possible to define the problem more exactly as it affected the Merchant Marine, with the ultimate object of improving brick work life.

The Admiralty appeared to have devoted their main effort to tightening up their specification for firebricks, and so far as Naval boilers were concerned, this might well be justified. So far as the Merchant Marine was concerned, however, it seemed that the questions of boiler operation (or maloperation) and brick work design were equally, if not more, important than the actual material used.

He noted with interest that the Admiralty had recently come to the conclusion that no advantage was to be gained by increasing the alumina content of firebricks beyond 43 per cent, since he believed that at one time they had been considering the use of bricks having an alumina content of about 60 per cent. It was particularly fortunate that they had come to this conclusion, since the material required for bricks having an alumina content greater than approximately 43 per cent had to be imported. The clays in this country were mostly suitable only for the manufacture of refractories containing 30 to 37 per cent alumina, whilst only a small proportion could be used for alumina firebricks containing 41 to 45 per cent alumina.

Incidentally, it had long been appreciated that specifications of alumina content meant little as regards refractoriness, so that he was not surprised to see that this had been omitted from the latest Admiralty specifications and replaced by the more logical pyrometric cone equivalent, together with more rigid specifications covering porosity and contained fluxes.

He was glad that the authors had drawn attention to the fortunate position of those specialists in mechanical engineering design dealing with land generating stations, where machinery was constantly operating under laboratory conditions and thus continuously accumulating accurate data. It must also be borne in mind that the main aim of land practice had been to improve thermal efficiency, whereas Naval practice, although requiring good performance at full power, had to provide for good endurance figures at cruising speeds. Too often marine practice was accused of lagging behind land practice, but it must never be forgotten that marine conditions called for absolute reliability and in the case of single power units there was no standby set to switch in. Major failure in the propulsion unit might entail not only the total loss of the machinery, but of the ship as well, with its valuable cargo and many lives. While all marine engineers were aware of those facts, he did not feel that they could be emphasized too much or stated too often.

Dr. T. W. F. Brown (M.I.Mar.E.) thanked the authors for their kind references to the work done by Pametrada. It was clear that in addition to research and development, a most important function was performed in providing designs of marine turbine machinery for member firms. Such designs embodied the experience gained in trials such as those described in the paper.

The statement about the Instrument Section was especially appreciated as departments of this type were sometimes regarded as an expensive luxury. However, compared with the cost of full-scale testing, which included the erection and dismantling of half of a complete engine room and boiler room installation, and the burning of considerable quantities of fuel, the additional expense of instrumentation, and of the special investigations which were thus enabled to be carried out concurrently with the routine testing, was remarkably small.

It might be of interest to state that three high-powered turbine sets had now been run on test and had aggregated more than 1,000 hours, including eighty-four hours of astern running. Running time of this order would have enabled a ship fitted with such machinery to have more than completed a circuit of the globe, and to have run astern from the Tyne to Gibraltar. It was in the light of such figures that the trials should be viewed.

The accuracy obtained in the measurements of brake load and water consumption was in the region of $\pm\frac{1}{4}$ per cent. Scarcely any variation occurred in sequential readings, and repeat trials gave results of the same order of accuracy. In

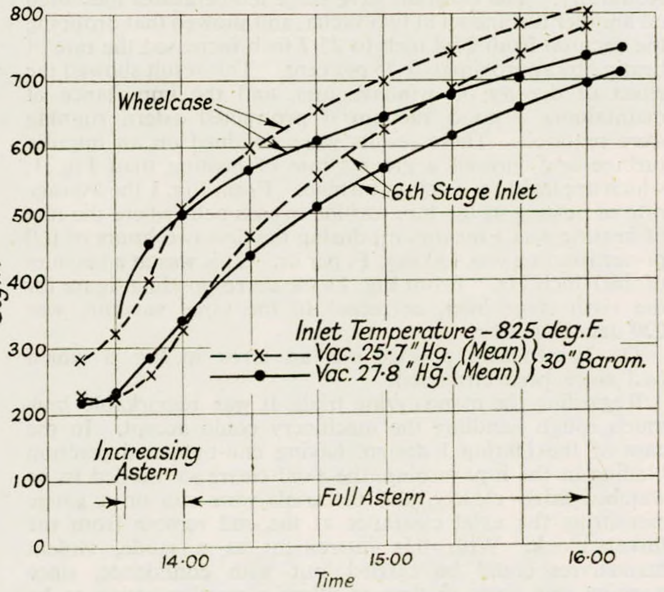

FIG. 11. EFFECT OF VACUUM ON INCREASE IN H.P. TURBINE STEAM TEMPERATURES DURING ASTERN TRIALS

ship trials, measurements of power and water consumption would not have been made with an accuracy better than about ±2 per cent, that is, the errors would have been eight times as coarse.

Experience during the trials showed that the buildings and equipment provided by Pametrada were adequate—weights were readily handled, and services such as cooling water, power absorption, etc., were satisfactory.

The running time of 407 hours quoted in the paper for the first series of trials was bettered in later trials, the figure for the third set being 197 hours, which included some repeat trials.

Referring to some specific points in the paper, some further confirmation of the statements made on page 183 regarding boiler furnace temperatures was provided by the following results, obtained from a different boiler. At a heat release rate of $0{\cdot}30 \times 10^6$ B.Th.U. per cu. ft. per hr., a gas temperature of 2,850 deg. F. and a brick face temperature of 2,200 deg. F., were measured.

On the question of heating up of ahead blading during astern running, some information supplementary to Fig. 1 was given in Fig. 11, which was reproduced by permission of the

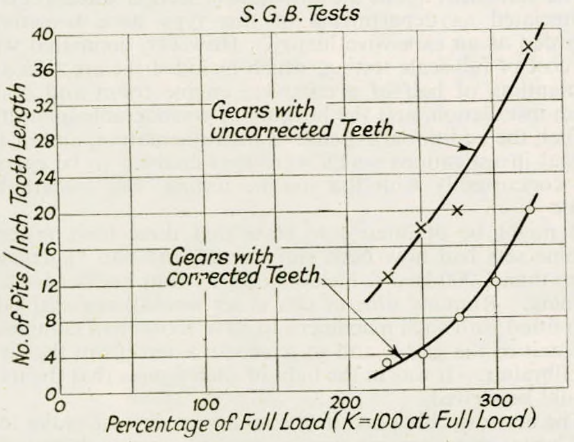

FIG. 12. COMPARISON OF PITTING IN GEARS WITH CORRECTED AND UNCORRECTED TEETH

Admiralty. The diagram gave stage temperatures measured on another turbine set at two vacua, and showed that dropping the vacuum from 27·8 inch to 25·7 inch increased the rate of heating by approximately 25 per cent. This result showed the effect of density on windage loss, and the importance of maintaining a good vacuum if protracted astern running were required. These results were obtained on an impulse turbine and showed a greater rate of heating than Fig. 1, which applied to a reaction turbine. From Fig. 1 the average rate of heating at the h.p. turbine bypass belt (where the rate of heating was a maximum) during the first two hours of full power running was 130 deg. F. per hr. This was at a vacuum of 26·1 inch Hg. From Fig. 11 the corresponding figure for the sixth stage inlet, corrected to the same vacuum, was 220 deg. F. per hr.

Dr. Brown also pointed out an error in Fig. 3 which had since been corrected.

Regarding the manœuvring trials, it was remarkable how much rough handling the machinery could accept. In the case of the Daring I design, having end-tightened reaction blading in the h.p. turbine, the axial clearance needed to be watched fairly closely, and the trials were run on a gauge measuring the axial clearance at the end remote from the thrust block. With this instrument as a guide, violent manœuvres could be carried out with confidence, since warning was given in time to allow corrective action to be taken if required.

The bearing troubles described on page 190 were, significantly, confined to the high-speed line, and a contributing factor was probably the relatively light loading. The load on the primary pinion bearings was, in fact, theoretically zero (apart from the weight of the pinion) since the pinion acts between two primary wheels in a locked-train gear. In later trials oil criticals were also met with in h.p. turbine bearings, owing to the light loading. An increase in loading from 66 to 100 lb. per sq. in. of projected area had been found to improve the performance of these high-speed bearings, and it was believed that further considerable increases in specific loading would have beneficial effects.

A second point in this connexion was that for experimental purposes the best measure of bearing temperature was that taken at the bearing shell on the load line. With the usual oil groove and thermometer pocket, the temperature measured was the mean temperature of the oil spilling out of the ends of the bearing, which was in general much lower than the temperature in the region where the minimum film thickness occurred. It might happen that an increase in load actually decreased the temperature of the spilled oil, while increasing the maximum temperature in the bearing.

In the case of the back-to-back gear tests described on page 194, the method of testing now allowed all gear losses to be separated and the coefficient of friction at tooth contact to be determined. The coefficient of friction for a hobbed gear was found to be 0·047, while for a hardened and ground gear it was 0·03. The relative load-carrying capacities of the gears with corrected and uncorrected teeth, referred to on page 195, was illustrated in Fig. 12. The ordinate was the number of pits per inch, which was taken as a very approximate guide to the extent of the pitting. It was seen that in this case correcting the teeth gave an increase in load of about 70 per cent of full load.

Mr. L. Baker, D.S.C. (M.I.Mar.E.) said that at a time like the present, when stability of steam conditions was likely to be forced upon them, it was very pertinent to review the facilities available for other improvements.

The research facilities which were described in the paper were paid for by the taxpayers and by the shipowners, and it might be asked what benefit did the taxpayers and the shipowners get. The taxpayers were clearly assured of the most efficient Navy that could be produced, and he spoke with feeling when he said that this had not been so before the last war. The shipowners benefited because the knowledge that was gained was circulated, either through the people working on the various projects, or by the presentation of data in technical papers, such as the present paper. Both of these were most valuable contributions.

The need for lighter and more compact machinery was just as pressing in the Merchant Navy as in the Royal Navy. An illustration might help them to appreciate that point. In comparing steam and Diesel machinery, the Diesel engine saved about 25 per cent of the fuel, but it weighed about 30 per cent more and occupied about 15 per cent more engine room length. At 7,500 s.h.p. those three factors were approximately in balance when considering the ship as a means of carrying a cargo economically.

The Admiralty had aided the shipowner by releasing for civilian manufacture designs of equipment originally produced for Service needs. Radar was one such instance. Probably so far as marine engineers were concerned, the release of the Admiralty design of oil fuel burning equipment was the most important. As one of the very well satisfied users, he could say that by equipping ships with this type of equipment his company were saving no less than £25,000 per annum in fuel.

The history of wear on flexible couplings was of interest as there were two cases in his company's fleet in which wear was occurring; both were conventional design. One American design was known to be out of alignment, whilst the British one was associated with a secondary pinion that was causing wear of the main wheel due to lack of tip relief. They could not at present be certain that these diagnoses were correct, but time would tell.

Finally, he wished to summarize his remarks by saying that mutual co-operation between the Royal and Merchant Navies was of major importance in peace and war. Each Service had much to teach the other and much to learn. Yet he had been pleasantly surprised by the fundamental similarity between the problems of the two arms of the sea.

Mr. M. L. Ireland said that in the paper the remarks on ship trials were inclined to be discouraging, and Dr. Brown in his comments had accorded to them an accuracy range (with which he was certainly in agreement) of ± 2 per cent as the best that could be expected from ship trial measurements of any quantities involving shaft horse power, because one was faced with an accuracy limitation, at the best of ± 1 per cent, with the best available torsionmeters. Nevertheless, he wished to add his voice in support of the desirability of running such modest trials and obtaining what information was possible from them.

The use of fuel oil meters rather than weight tanks, if the meters were calibrated before and after trials, gave accurate results for the fuel measured within about one-fourth per cent. He thought that the same could be said for condensate meters, and of course it was desirable to run some limited trials with the bleeder points closed to compare the condensate flow against what one could calculate from the measured inlet nozzle area.

With regard to the astern heating tests mentioned in the paper, which were extremely interesting and paralleled some work in the United States, he noted that the astern runs had all been from a rather low ahead power—he believed 10 per cent was the figure quoted. It had been the impression in the United States, and this had been confirmed by certain tests, that the whole level of the temperatures would be influenced by the ahead condition within the turbines. If one started from 100 per cent of ahead power with resulting higher temperature levels throughout the high-pressure turbine particularly, and then suddenly reversed and ran one of these steady astern trials, the whole level of temperatures was going to be higher than from a low ahead power. Incidentally, this result was confirmed by analysis, and it should be mentioned that it was now possible to apply analytical procedures to the prediction of astern heating performance.

With regard to the bearing difficulties that were reported in the paper, a polar diagram for the load location was shown in Fig. 9. He would be interested to know whether measurements had been made of the running position of the journals, because in the United States there had recently been cases in which this had been done and there had been obtained some rather surprising results for high speed lightly loaded journals. It had been found that they had a tendency to climb right up to the top level of the brass, that is, with the journal centre well above the centre of the bearing.

CORRESPONDENCE

Mr. S. Archer, M.Sc. (M.I.Mar.E.) thought that the authors had given us, within the limits set by security considerations, a valuable account of British Naval engineering research and development in recent years, and had conclusively demonstrated the weight and importance of Admiralty contributions, either directly or by sponsorship, to current marine engineering progress. The main trouble about a paper of this calibre was that it gave one an appetite for more and the writer would therefore like to raise one or two questions relating to gearing.

Having been associated with the work of the Committee responsible for B.S.S. 1498 for gear hobbing machines, the writer wished to ask whether the minimum standards of accuracy laid down therein were being generally achieved today, particularly as regards Grade A quality both for new machines and for reconditioned old machines. The writer's own impression was that there was still a good deal of leeway to make up, particularly in the reconditioning of old machines.

Secondly, in view of present shortages of alloying elements such as nickel, had the Admiralty any experience of alternative alloys, in particular of a 3 per cent chrome-molybdenum steel which had been suggested for merchant marine pinions?

The importance of maintaining efficient operation of turbine toothed couplings could with advantage be emphasized and some recent merchant experiences with claw type couplings might be of interest. After only two years service the primary A.A. pinions (nominally lightly loaded) of three sister vessels showed a wear of 10—12/1,000 inch and, in one ship of three, failure of a number of rows of blading occurred in the l.p. turbine. On examination of the claw couplings a total wear of about 40/1,000 inch was found and the oil grooves in the teeth of the inner member had imprinted themselves on those of the outer member as protuberances, thus effectively locking the coupling against relative axial motion. Under such conditions it was not difficult to

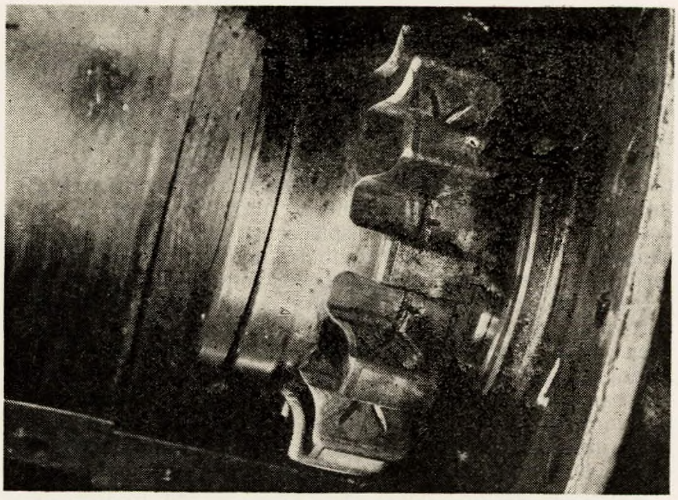

Fig. 13.

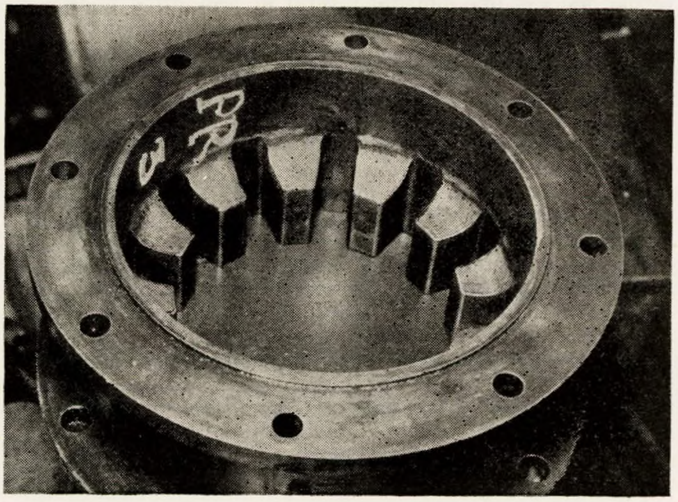

Fig. 14.

visualize the underlying cause of the troubles experienced. Fig. 13 showed the condition of the teeth in the male component, the wear ridge at the left hand end of the top teeth being clearly visible. Fig. 14 showed the corresponding teeth of the female component with the imprint of the oil grooves at the left.

Was adequate care taken by manufacturers in lining up turbine rotors and pinions, to allow for the considerable influence of thermal expansion of turbine casings in the vertical plane relative to the displacement of the pinion in its running position, under the combined influence of the torque reaction between the meshing elements and the oil clearances?

Since also one of the necessary conditions for frettage corrosion was free access of oxygen, had sufficient thought been given to the possibility of slowing up oxygen attack by arranging for oil-bath operation with a dam or equivalent internal tube for the outlet oil? It should be possible to overcome the sludging difficulty by arranging a suitable trap in the form of a belt of larger diameter on the oil-inlet side of the coupling teeth.

American wartime naval experience seemed to indicate that increased hardness and bearing area for the teeth offered the best solution. Could the authors confirm this from their own experience?

Mr. G. A. Plummer (M.I.Mar.E.) considered that a number of papers which had been presented to the Institute in the course of the past five or six years by Naval engineers, had been extremely impressive to the lay engineer and encouraging to the industrialist, showing as they had done the considerable engineering development that had taken place in connexion with main propulsion machinery and boilers for British Naval vessels over the past ten years.

The paper under discussion was no exception and clearly indicated that the necessity for thorough proving of main propulsion and auxiliary machinery before it could be accepted for service conditions was appreciated, whilst at the same time giving full scope and encouragement to research and development.

He had followed with interest the means employed for ascertaining circulation rates but would suggest, however, that this only gave an overall figure and did not indicate what was, after all, the true criterion of satisfactory circulation—the cooling rate or velocity of fluid flow necessary to prevent any tube from becoming overheated.

He was not surprised to learn of the "hunting" that occurred when the feed water was fed below the water level. The application of a steam flow component to feed water regulators was undoubtedly helpful in preventing hunting. This might be still further improved by incorporating a feed flow component though such methods were, in his opinion, only palliatives which did not deal with the actual cause; also he would like the authors to reflect on the effect of circulation inside the boiler circuits of suddenly admitting to the boilers large quantities of water varying greatly in density (on account of its low temperature) from the contents of the boiler. Feed water must be raised to a temperature and density as nearly equal to the boiler water as possible in order to avoid disturbance to boiler circulation.

In this connexion he was pleased to see that the Admiralty now included economizers in more recent designs; as far back as 1941 he had advocated this and included it in the La Mont boiler design for the steam gunboats.

He was also pleased to observe the improvement in oil fuel combustion which had been made since 1941, when combustion rates as low as 14 lb. of oil fuel per cu. ft. of combustion space per hour could not be maintained; the improvement in this respect alone over the last ten years had been an outstanding achievement.

There was one point, however, which did not appear to have received the attention it deserved. He was surprised to see from page 193 that a figure of 0·5 per cent wetness in steam was apparently acceptable. This meant a total dissolved solid content of five parts per million in the steam with a boiler water concentration of 1,000 parts per million. He would ask the authors to compare this with figures shown in the writer's paper,* where the wetness in the steam was shown to be below 0·07 per cent on high pressure forced circulation boilers.

Finally, he would like to suggest that further consideration be given to the possibilities of forced circulation for Naval purposes, not for the sake of forced circulation but for the advantages resulting, i.e. dryer cleaner steam, automatic re-circulation of economizers, increased safety, and less weight and space.

* Plummer, G. A. 1946, "The Development of the La Mont Boiler in Great Britain," Proc.I.Mech.E. Vol. 155, p. 333.

Mr. A. W. Davis (M.I.Mar.E.) wrote that the authors had presented in valuable perspective a picture of the extensive developments being made today in the realm of marine propulsion in the face of the growing adverse effects of the law of diminishing returns. Reference to turbine testing adjacent to the reference on gear testing emphasized to the reader one vital difference attending these two branches of research which tended to lead to vitally differing degrees of reliability in the conclusions reached. The initial conditions of the turbines to be tested and their condition after test could be readily defined in as adequate a manner as the human brain could register. On the other hand, in the case of gearing it was impossible properly to define the condition of tooth marking and in the limit too much often depended by way of description on the thickness of paint used in checking the meshing of the gears. Undulation records suffered from the defect that the instrument could be set to give a great variety of results on anything but a very well finished tooth, that was, except when the record of error was not measurable. This problem of definition was not likely ever to be overcome entirely satisfactorily but it was suggested that the time was overdue when an authority such as the British Standards Institution might establish a code which would define in the most concise and least ambiguous terms the condition of tooth marking for any given set of gears.

Mr. G. M. Sellar (M.I.Mar.E.) referred to the section dealing with windage effects, in which the significance of rotor temperatures would be clearer if the vacuum carried during the various astern trials could be stated, since windage losses and high ahead blade temperatures would vary with steam density.

Fig. 7, showing temperature gradient between rim and centre of the Curtis wheel, suggested why impulse wheels of shrunk-on construction were occasionally found at surveys on merchant ships to have moved position.

A brief description of the loading device used for torqueing up the gears in the back to back and similar tests would be of interest; also the method of measuring the torque when running. That gears of standard materials could be made to withstand overloads of the 300 per cent order was a remarkable achievement. Was it to be understood that standard bearings had comparable reserve capacity?

During recent years survey authorities and others had been concerned with explosions of lubricating oil vapour in crankcases of steam and Diesel engines, resulting from overheating of some part of the running gear. When considering preventative measures and safety devices it had been wondered whether a turbine gearcase presented any explosion hazard in similar circumstances. Could the authors state whether any explosion effects had been noted during the final stages of testing gears to destruction when conditions in the gearcase could be expected to simulate those which had given rise to crankcase explosions.

Mr. L. Baker, D.S.C. (M.I.Mar.E.) wrote that in addition to his remarks in the verbal discussion he wished to emphasize that weight reduction consistent with reliability was of as great importance to the mercantile fleet as to the Royal Navy. In addition, fuel economy was of the utmost importance. It was unfortunately true that marine conditions precluded accurate measurement of quantities at sea and one was therefore driven back on expedients. The facilities now available would in the course of time enable this deficiency to be minimized but as they were still limited to unit testing, sea trials would still be of value.

The dissemination of the information gained from shore tests was most important, as the demand for improvements in design could only come if the user were aware of the possibilities. In the case of the Admiralty this was well covered because the user was also the authority responsible for the trials; the position of the shipowner was less satisfactory as in general he was only able to obtain access to information through some other body who could and frequently did arbitrarily withhold data until its value was lost. The facilities for the dissemination of knowledge existed, but in contrast with America there was a marked reluctance to publish data in this country. Before the war the dearth of data might have justified such reticence but that should no longer be true with the enormous financial contributions now being made to research and development.

With regard to the details of practical trials given in the paper, there was much food for thought. Turbines were apparently not distressed by any reasonable treatment they received and it would have been interesting to have tested the turbines astern under even more realistic conditions. It was common practice to adjust the ahead and astern manœuvring valves simultaneously in order to obtain constant boiler output when going from, say, half ahead to half astern. This practice did not appear to produce any harmful result up to 850 deg. F. in merchant ships and up to 700 deg. F. in the Royal Navy; if safe, it had much to recommend it.

The problem of flexible couplings was of course very real. They were not usually considered as being flexible.when under load, yet agreement had not been reached as to the condition under which the turbine and gearing should be in true alignment. Owing to temperature changes there could hardly be more than one such condition.

AUTHORS' REPLY

Captain (E) L. A. B. Peile said that Mr. King was perfectly correct in assuming that the data available to the Admiralty on the Daring Class Babcock and Wilcox boiler had been provided from tests at the U.S. Naval Boiler and Turbine Laboratory; that information of this nature should be provided to us was a great tribute to the co-operation between the United States and this country. Mr. King's comments on the leakage in air casing had been particularly relevant. It was known from bitter experience that one of the biggest reasons for the falling off of performance in old ships was the leakage that the air casings developed on prolonged service. Mr. King had wondered what was the difficulty in regard to measuring steam wetness. The difficulty had been that in a boiler room that simulated the service boiler room it had not been possible to arrange sufficient straight length of steam piping to obtain accurate results from the throttling calorimeters.

Dr. Livingston Smith was quite right in his remarks about the alumina content of the fire bricks. The bricks must be made from indigenous clays, and it was this fact which had made the problem so difficult.

The authors were in full agreement with Dr. Smith's remarks on the importance of brickwork design. The features of firebrick design now being used by the Admiralty were: a small hot face area, 9 in. × 2½ in.; flexible keying; unpierced casings; a brick shape which allows pressure moulding; the use of insulating bricks and slab between firebricks and casing.

Regarding high alumina bricks, trials were still in hand to determine the value of 60 per cent alumina bricks for special purposes such as burner quarls, but this of course required the use of imported clays. Cost and weight, as well as the supply difficulty, opposed the general use of high alumina bricks.

He rather thought from Mr. Baker's remarks that perhaps the Admiralty did not claim as high a royalty as they might for the manufacture of oil fuel burning equipment to A.F.E.S. designs !

With regard to Mr. Baker's remarks on testing the turbines astern and the practice afloat of opening the astern manœvring valve as the ahead was being shut, some trials very recently carried out by the Admiralty at sea in a destroyer showed that when going from ahead to astern a transient torque was produced as the inertia of the turbines was absorbed; torque would also be applied to the gearing if both ahead and astern throttles were open together, and this practice might involve some danger to the gearing if the ahead revolutions were destroyed very rapidly.

Dr. Brown had spoken of the cost of instrumentation. He thought that Dr. Brown had perhaps rather understated the cost involved; it was heavy, but it was worth while, because without that instrumentation one could not get anywhere.

The figure quoted by Dr. Brown for the temperature gap between boiler furnace and firebrick, which was appreciably greater than would be calculated, raised a further case of divergence between calculated and measured brick temperatures. For a typical Naval boiler, the temperature drop across a 4½-in. firebrick would be calculated as about 300 deg. F. to 600 deg. F. Measured temperatures in different boilers and for varying heat release rates showed temperature drops about twice the calculated. It was difficult fully to reconcile this divergence, but practical support for the measured temperature drop across a firebrick could be drawn from the experience that brick bolt heads generally survived as long as the plastic refractory plug; if calculated temperatures were correct, the bolt heads would be burnt in a few hours.

Dr. Brown raised an important point by drawing attention to the effect of vacuum on the rate of heating of the ahead blading during astern running. The runs at lower vacua were carried out to simulate operation in tropical conditions.

Dr. Brown's Fig. 11 referred to Daring III trials. For administrative reasons, it was not possible to continue this run for more than two hours astern, but it was clear from this figure that, at the lower vacuum at any rate, it would be necessary to reduce the initial steam temperature during prolonged astern operation. In comparing the rate of heating of the Daring I and Daring III designs, it must be pointed out that the Daring III design employed higher turbine revolutions and blade speeds with a view to reducing the weight and bulk of the turbines; the higher blade speeds would naturally give rise to an increased rate of heating during astern running.

Dr. Brown's remarks on the possibility of the relatively light loading being a contributory factor for some of the high speed bearings reaching high temperature were interesting. Apart from any question of instability, it seemed likely that the reduced area of more highly loaded bearings would lead to lesser losses and for the same quantity of oil supplied to the bearing, lower temperatures. But as Dr. Brown pointed out, this might be associated with higher maximum temperatures in the bearing shells.

Dr. Brown's Fig. 12 gave a clear indication of the improvement in the load-carrying capacity of gears that might be brought about by "correction of pinion helices," and in other tests the improvement was considerably greater than the 70 per cent of full power load quoted by him; however, there were possible pitfalls in assuming that such improvement was always possible, and a further comprehensive programme would be necessary before the benefits could be confidently assessed.

With regard to Mr. Ireland's remarks on the astern running, they had been limited by the facilities available. The brake at Pametrada was unable to absorb more than 10 per cent of full-power torque when running in reverse direction, and that was why they had started only at 10 per cent of the ahead power. The occasions when one wanted to run astern for a long time were unusual occasions, and he did not think they were likely to have to do very long astern runs direct from full power ahead. He agreed that ship trials were valuable, but he thought they were valuable more from the point of view of the operator than from that of the designer. They gave the operator a yardstick with which to work, but he did not think that in Naval installations, which were extremely congested, it would be possible to rely on being able to get sufficient instrumentation to check back on the real design data which the designer was after.

Mr. Archer would be glad to learn that Grade A of the B.S. Specification to which he contributed was now being achieved on new machines although not always without difficulty. The reconditioning of an old machine to give this new standard of accuracy was a major undertaking; it had been achieved in some instances, but the condition and the design of any particular machine must be carefully considered before embarking upon such a project.

With regard to the question of shortages of alloying material, the Admiralty was having to extend its testing programme to find suitable substitute steels and the results of the investigations would be made known as they became available.

It was too early to say whether an increase of hardness of flexible coupling teeth when taken in conjunction with barrelling and the use of harder material for the overlapping component than for the other would cure the flexible coupling troubles referred to by Mr. Archer and Mr. Baker, and further trials were being carried out to ascertain this.

Mr. Plummer had drawn attention to the importance of velocity rather than circulation rate as the criterion for tube safety. While agreeing with this point, the authors thought that since, broadly speaking, velocity increased along the tube, the water/steam volume ratio at exit was a more practical criterion.

With reference to Mr. Plummer's remarks on steam wetness, so much difficulty had been encountered in obtaining accurate readings with the throttling calorimeter in the confined spaces of Naval boiler rooms, that consideration was being given to quoting instead a figure for the maximum carryover of solids with the steam. The figure in mind was two parts per million. The wetness figure in the paper referred to by Mr. Plummer was presumably converted from a dionic reading; the authors felt that the accuracy of such conversions was open to doubt.

In conclusion, he said that the authors were grateful for the nice things which had been said about the paper, but it was not the paper that mattered—it was the work that had been done. The real praise was due to Dr. Brown and his staff at Pametrada, to Commander Ricks, his predecessors and the staff at Haslar, and to all the firms and establishments which had undertaken research contracts for the Admiralty.

INSTITUTE ACTIVITIES

Sydney Local Section

A meeting of the Sydney Local Section was held at Science House, Gloucester Street, Sydney, on Friday, 31st August 1951, at 8 p.m. Sixty-three members and guests were present and Mr. W. G. C. Butcher was in the Chair.

A lecture, well illustrated by lantern slides, entitled "Chemists and Marine Lubrication", was given by Mr. M. D. Athey, in which he gave much information regarding the modern lubricants used in marine engineering. A very full discussion followed, to which Messrs. Lees, Buls, Piggott, Mason, Arundel, Capt.(E) Bull and Com'r(E) Purves contributed.

A vote of thanks to Mr. Athey was proposed by Mr. B. P. Fielden, seconded by Mr. H. W. Lees and carried by acclamation.

The Annual Dinner of the Section will be held on Thursday, 15th November 1951 at the Carlton Hotel, Sydney.

Membership Elections

Elected 3rd September 1951

MEMBERS

Thomas Bailey
Charles William Bennett
John Hamilton Brown
Herbert Douglas Cavell
William Glencross Christie
Norman Davies
Arthur Alfred Charles Gentry, Lt. Com'r(E), R.N.
Warwick Henry Gregory
Horace Reginald Guest
Stanley Charles Hession
William Irvine
Leo Patrick Kavanagh
Ronald Lund
Douglas Frank Nicholson
William Walker Templeton
Cyril Wallis
Michael Vincent Watt
Albert Edward Wilson

ASSOCIATE MEMBERS

Fred Hutchinson Bland, Lieut.(E), R.N.Z.N.
Herbert Godward
Ronald Joseph Parkinson
Charles Beresford Robinson
Francis William Terry
Eric Usher

ASSOCIATES

George Edward Acklam
George Baird
Ivan Barnicoat
Derek James Edwin Brooker
Thomas Chapman
Cecil Arthur Creber, E.R.A., R.N.
John Noneley Davies
John Dixon
Noel Joseph D'Sylva
Olwyn Anthony D'Sylva, Sub. Lieut.(E), I.N.
Raymond Patrick Duell
Mohamed Fatihy Elmostehy, Lieut.(E), R.E.N.
Charles William Dotchin Fergusson
Walter William Garrett
Brelsford Robert Gluyas
Victor William Howard
Bruce Hutchinson
John Francis James
Mahmoud Abdel Latif Ahmed Kataya, Lieut.(E), R.E.N.
William James McGregor
Robert McIntosh
Joseph Mambill
Abraham Mathew
Roland George Robert Midford
Richard Ulick Noel Murray
Thomas Edward Nailon
Michael Gray Radcliffe Petty
Ian Douglas Shaw
Samuel Thomson

STUDENTS

George Henry Bentley
Harry Flottiland de Vos
Geoffrey Christopher Levett
Mahmud Dawood Mistry
Brian Charles Tooke

TRANSFER FROM ASSOCIATE TO MEMBER

Albert George Bancroft
Austin Sydney William Bonner
Peter Frederick Herbert Brebner
William Weir Love
George Ronald Swan
Samuel Nuttall Walker

TRANSFER FROM ASSOCIATE MEMBER TO MEMBER

Percy Arnold Manville

TRANSFER FROM ASSOCIATE TO ASSOCIATE MEMBER

Theodore Berry
Donald Dyer
Petrus Jacobus van der Walt

TRANSFER FROM GRADUATE TO ASSOCIATE MEMBER

James Mathew
Douglas Cowie Smith

TRANSFER FROM STUDENT TO ASSOCIATE

Begamudre Ananda
Charles Martin Devlin

TRANSFER FROM STUDENT TO GRADUATE

Wallace James Ayers

OBITUARY

HEDLEY SCOTT (Member 7508) was born in 1882 and served an engineering apprenticeship, followed by a period on design work in the drawing office, with the North Eastern Marine Engineering Co., Ltd., from 1896-1903. He spent some years at sea with Messrs. Harris and Dixon, rising to the rank of chief engineer in their service. He obtained a Second Class Certificate in 1905, a First Class Certificate in 1906, and an Extra First Class Certificate in 1908. In 1914 he was appointed by the Board of Trade as a marine engineer surveyor at the Glasgow office. In September 1926 he was transferred to the Mark Lane office in London, and later, in

July 1932, to the consultative branch in the Chief Examiner of Engineers' Department at headquarters. In December of the same year he became assistant to the Chief Examiner of Engineers, and was engaged in this capacity until his retirement due to ill health in February 1942. Mr. Scott was elected a Member of the Institute in 1934 and served on the Council for two three-year periods, 1935-38 and 1940-43; he was obliged to give up active work for the Institute at this time as a result of the ill health which cut short his service with the Board of Trade, but his enthusiastic concern for the Institute's advancement, which had been his main interest for many years, never failed. He died on 2nd August 1951.

FRANCIS OLIVER BECKETT (Member 2744) was born in 1868 at Folkestone and, after a childhood spent in India and the Isle of Man, he was apprenticed first with Siemens of Woolwich and later at the Royal Arsenal there. He went to sea, serving for twelve years in various ships, including the first ship of the then Royal Rumanian Merchant Navy which he took out to Rumania from London in 1894. He obtained a First Class Board of Trade Certificate. In 1898 Mr. Beckett was appointed an engineer surveyor to the Vulcan Boiler Insurance Co., Ltd., at Lincoln, but returned to sea for a further three years in 1908; in 1911 he was reappointed engineer surveyor to the same company with a district in East London, where he remained until he retired on pension through ill health in 1933. He died on the 18th April 1951 at the age of eighty-two. Mr. Beckett had been a Member of the Institute since 1913 and, until the last war, had attended regularly at the reading of papers, frequently contributing to the discussions. He was also a Member of the Institution of Mechanical Engineers and of the Newcomen Society. He is survived by his widow and two younger sons, his eldest son, also a marine engineer and a Member of the Institute, having died at sea in 1916 when his ship was torpedoed.

ROBERT DAVISON (Member 4863) was born in South Shields in 1896. He served an engineering apprenticeship with John Readhead and Sons, Ltd., at their shipyard in South Shields and attended evening classes at the Marine School there. His first seagoing appointment was as 4th engineer of the *Savan* in 1918. In 1920 he joined the British Tanker Co., Ltd., as 3rd engineer of the s.s. *British Ensign*; he was promoted to 2nd engineer in 1923 and to chief engineer in 1927. In 1944 he obtained a Motor Endorsement to his First Class M.o.T. Steam Certificate. In 1950 Mr. Davison was appointed Senior Post Chief Engineer of the British Tanker Company; his last ship was the m.v. *British Loyalty,* which he took over from the shipbuilders in 1949 and in which he served continuously, apart from four months' shore leave, until July 1951; he died on 2nd August 1951. Mr. Davison was elected a Member of the Institute in 1923.

ENGINEER REAR-ADMIRAL JESSE HOPE HARRISON, R.N. (Member 5859) died suddenly at his home on 10th August 1951. Some time ago he was obliged to undergo hospital treatment, but made a good recovery and his sudden passing came as a shock to his family and to all who knew him. He was a native of Earlstown, near Liverpool, and became a graduate of Liverpool University. Following a period of service with Cammell, Laird and Co., Ltd., of Birkenhead, his distinguished career in the Royal Navy began in 1896, when he joined on special entry, as assistant engineer. He first served in the cruiser *Talbot* in the West Indies and in the Spanish-American War of 1898. From 1902-1904 he served in the battleship *Bulwark,* the Mediterranean Flagship, and later, in 1908-1909, in the battleship *Illustrious*. Then followed service in two destroyers, the *Kale* (1910-1912) and the *Beaver* (1912-1916). He then went to the United States and returned to the Admiralty from 1917 to 1920. A spell on the training ship *Thunderer* from 1921 to 1923 was followed by service in the *Marlborough* (1923-1925) when he was promoted captain. He returned to the Admiralty until he retired in 1930 with the rank of Rear-Admiral. He was the only engineer officer of his year who obtained flag rank. He was in all the North Sea Naval engagements except the Battle of Jutland, which he missed through being in hospital at the time. Admiral Harrison's public service for Upper Norwood, of which he became a resident in 1917, will long be remembered. He was chairman of the Housing Committee during a particularly trying time and rendered fine service on the Electricity Committee. He was one of the Council's representative Trustees of the Crystal Palace. During the last war he played a big part in the Civil Defence Committee. As a result of ill health, he resigned from the Council in March 1950.