SHORE TESTING OF GAS TURBINE SHIP PROPULSION MACHINERY

BY

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This article was originally prepared at the invitation of the United States authorities as a paper and was presented at the American Society of Mechnical Engineers' twentieth Annual International Gas Turbine Conference at Houston, Texas, in March 1975.

Introduction

The general acceptance of the gas turbine as a preferred means of propelling warships is a very recent phenomenon. The gas turbine offers the warship designer possible improvements in through-life costs, a sizeable reduction in engine-room personnel (the dominant and compelling argument) and an increase in ship availability and performance. For these reasons, it has swiftly gained in popularity, so much so that there is scarcely any warship of size being built today which is not to be propelled partly or wholly by gas turbines.

Because it is so newly into service, the widespread and varied applications of the gas turbine bring in their wake a number of problems, some of them inherent in the gas turbine itself, others in ancillary equipment or machinery, and others, perhaps more prevalent, belonging to the interfaces. The nature of some of these difficulties is often not fully appreciated until the ship is built and on trials, and it is at that time that design rectification proves to be particularly expensive, both in money terms and in ship and class availability.

Some of the problems are amenable to prediction and perhaps analysis by modelling and simulation. Useful as these techniques may be, however, they are limited in scope, and it is for this reason that recourse is made to the shore testing of ships' machinery and why is can prove to be so valuable. Although a shore test facility, comprising all or part of a ship set of propulsion machinery, cannot completely reproduce all ship conditions, most of the irritating and expensive design faults can be eradicated by the use of such a facility, and the majority of interface problems can be eliminated.

This article aims to show that the high cost of shore testing of ship's gas turbine propulsion machinery is well justified where new principles of installation are involved. In the majority of such cases, shore testing is essential if the much higher costs of rectification and redesign of ship plant are to be avoided at least in the first of class.

Background and Scope

Ships are costly items and they grow more so. This is especially true of warships where, in search of improvements in capability and performance, increasingly expensive weapon systems are put into each new class and, for this and other reasons, ships grow ever more complex. As costs soar, it is attractive to try to offset part of the capital costs by eliminating some of the initial expenses of introducing a new class of ship. In the early days of the design of a class, therefore, when a shore test facility is proposed and costed, it is tempting to argue that elaborate trials of this nature are unnecessary. For gas turbine ships, this argument can be supported by the statement that, in developing the marine gas turbine propulsion engine from its aero forebear, many expensive hours of development and endurance running have already been employed and there is no need for more. The false economy of this view has been demonstrated on many occasions and, not least, in the gas turbine world.

This is not to say, of course, that each new class should of necessity have a shore test of its propulsion machinery. The need for one should be established in a logical manner by assessing the risk involved in each equipment and system. The total risk should be balanced against the value of the proposed shore test facility in eliminating or reducing those risks. In this way the cost effectiveness of the shore trials can be estimated.

When a shore test is decided on, the question of the site arises. Generally this can be:

At the machinery contractor's works.

At the shipyard.

At a suitable establishment either controlled by PE or regularly employed by PE for the purpose.

There are arguments for each course and indeed each has been chosen in recent years for major projects. Most of the arguments are obvious but the advantage of siting at an establishment where testing is the main activity and staff need only detailed plant acquaintance before being fully effective should not be underrated. The accumulated expertise and facilities of an establishment like BSRA (Pametrada) in its day or of Navsec Philadelphia today are formidable assets.

The Royal Navy has a shore test facility for the propulsion machinery of its A/S cruiser now building. That shore test facility, which is the product of the sort of risk assessment already mentioned, is used in this article as an example to show the need for and the value of such a facility in these circumstances.

The cruiser machinery is described briefly. This is followed by the argument for the shore testing and the objectives of the trials. The Shore Test Facility is also described and the current positions of the trials given. Before the conclusions, the achievements to date are discussed.

The Ship

The A/S Cruiser (CAH) is a ship of about 19,000 tonnes. She is therefore something akin to the R.N. light fleet aircraft carrier or commando carrier (LPH). Her function is the area command of a fleet and the capability to carry helicopters and VSTOL aircraft.

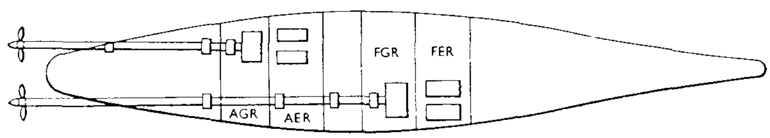

FIG. 1—THE CAH PROPULSION SYSTEM

She is fitted with two shafts, each driven by two Rolls-Royce Olympus TM3B gas turbines through a reversing gearbox and each having a fixed-pitch propeller. The Olympus gas turbines are already at sea in the Type 21 frigates and Type 42 destroyers where, together with the Rolls-Royce Tyne RM1A engine, they are part of a COGOG system. The power turbines of the Olympus engines are connected to the gearbox via torque tubes and flexible couplings of the diaphragm type. The layout of machinery is shown diagrammatically in FIG. 1 where it can be seen that the thrust blocks are separate from the main gearing and that the starboard propeller shaft is considerably longer than the port one. This is due to the separation of the pairs of gas turbines for a number of reasons, one of which is the problem of the arrangement of the air intake and the exhaust ducting over the engine rooms. An indication of the complexity is given in FIGS. 2(a) and 2(b) where the arrangement of ducting is shown for the port pair of gas turbines.

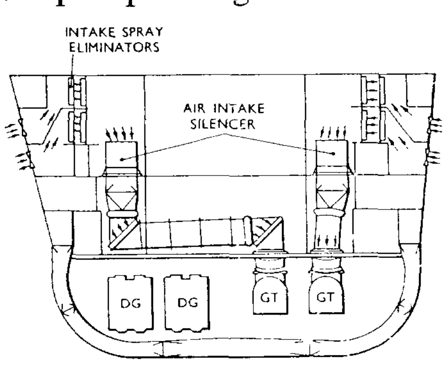

FIG. 2(a)—ARRANGEMENT OF THE CAH INTAKE DUCTING

The gas turbines are thus part of a COGAG system where low power is provided by one Olympus per shaft. At high powers, this is supplemented by cutting in the other gas turbines to give two engines running in parallel on each shaft. Each pair of turbines is solidly mounted together on the same structure, shock and noise attenuation being provided by a separate set of special mountings provided below that structure.

The triple-reduction gearbox employs a system of clutches and couplings. For

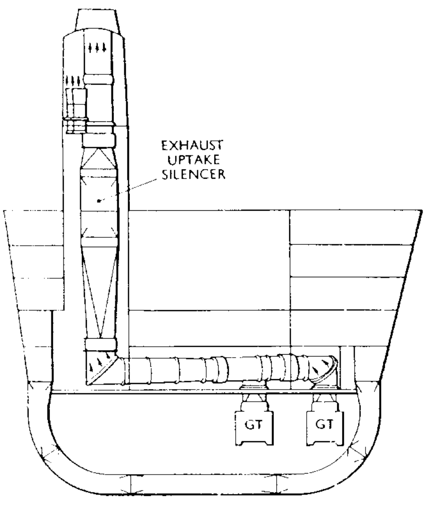

FIG. 2(b)—ARRANGEMENT OF THE CAH EXHAUST DUCTING

normal ahead running, the gas turbine (or turbines) is clutched in to drive through a standard type of SSS clutch. For manoeuvring purposes, the SSS clutch is disengaged and the drive is taken ahead or astern via fluid couplings which are emptied or filled as required.

The main propulsion controls basically are electronic and enable the plant to be controlled locally in the engine rooms, or from the Ship Control Centre, or from the bridge. The machinery compartments are normally unmanned.

The Risk

It should be borne in mind, when assessing the risks involved in the cruiser propulsion plant, that it represents the highest power per shaft hitherto employed in any R.N. ship. The cruiser will be the highest-powered gas turbine ship in the world. The gearbox, weighing some 170 tonnes, is the largest reversing gearbox ever designed for use at sea. The engine-room complement is less than half that of a LPH and the degree of auto and remote control is accordingly high.

The main risk areas therefore were felt to be:

(*a*) *The Gearbox*: None of the techniques or components used in the gearbox is new and in fact the gearbox is simpler than some in use today. However, the combined use of clutches and fluid couplings at such high powers is outside our experience. It is emphasized that the sizing and slip characteristics of the fluid couplings are of vital importance and also that the interaction of automatic clutches, fluid couplings, the propeller law and transient torques under manoeuvring conditions is an extremely complex problem and difficult to analyse. For example with a high coupling stiffness, it is possible to envisage a situation where, during a crash astern manoeuvre, one power turbine is actually being driven in reverse. Consequently, although the operation of each of the components could be tested as part of normal production routine, it was felt that trials were needed under conditions much more closely approaching those at sea, particularly in the manoeuvring mode. It is not practical to reproduce entirely all those conditions which can obtain when manoeuvring, e.g. rapid variations in shaft torque and speed imposed by the ship and propeller moving through the water. However, much valuable experience, knowledge and confidence can be gained during shore testing by artificially programming brakes and engines.

(*b*) *Uptakes and Downtakes*: Experience in frigates has shown that these must be arranged with the greatest care in order to avoid damaging vortex formations and excessive pressure drops. The problems could be severe in the cruiser where the ducting is long and tortuous (see FIG. 2), where gas speeds can exceed 60 m/s and where temperatures are high and bends sharp. Other factors affecting the design include adequate allowances for expansion of ducting, absorption of thrust at bends, high-temperature erosion and corrosion, fatigue failure due to vibration or thermal cycling, and attenuation of heat and noise. Model tests at $\frac{1}{8}$ and $\frac{1}{5}$ scale could cover only a few of the problem areas although they proved very useful in estimating pressure losses, velocity distributions and flow stability. Clearly, without shore testing, the correction of defective design in this area would be particularly difficult in the first ship. It would be not only highly expensive but also very dangerous to ship programmes.

(*c*) *Machinery Controls*: These are electronic, and the design is based on a propulsion system dynamic behaviour computer simulation. Much of the argument relating to the gearbox is relevant here. The individual components of the propulsion system could, in most cases, be well proven individually. In assembly, however, interactions in the system can present interface problems which may not be apparent during individual component testing. Problems set by transient torques and speeds are difficult to solve by simulation. Transient conditions in turn can have an effect on response times which are all important to the safety of the ship. It is essential therefore to explore the system and the control responses. Added to this is the fact that there is no experience in the R.N. of the parallel running of large gas turbines. Computer simulation cannot give the same confidence as full-scale tests. It was felt that parallel running might demand elaborate control techniques, e.g. variable-datum governing of the power turbine and closed-loop control.

Thus it was decided that there existed sufficient unknowns in the CAH design to justify the cost of a shore test facility (STF). Although many of the above risks were common, the Type 21 frigates and Type 42 destroyers were constructed without the benefit of a STF. This, however, was due less to a lack of appreciation of those risks than to the building programme for these ships which precluded the building of such a facility in time for the results of its lessons to be incorporated in the first ships.

The Objectives

The following broad objectives for the shore test facility were decided:

(*a*) To prove the functioning of each individual component; in particular, the gearbox, the inlet and exhaust ducting, and the control system up to full-power conditions.

(*b*) To prove the functioning of the propulsion system as a whole.

(*c*) To carry out full-scale investigation into the problem areas highlighted by design and computer simulation studies.

(*d*) To prove the reliability of the system and its components and to eliminate teething troubles by endurance running.

(*e*) To provide information on maintenance requirements.

A sixth objective, incidental to the prime purpose of the STF, was to provide a training facility. Because of the simulation facilities now available and the growing experience in the R.N. of gas turbine installations in other classes of ship, this requirement has now ceased.

The Shore Test Facility

This has been built at the Industrial and Marine Division of Rolls-Royce (1971) Ltd. at Ansty near Coventry. It started running in mid 1973. The installation copies the main propulsion plant of the after machinery space of the cruiser. This includes an exact replica of the intakes and uptakes for both engines from the ship's side to the funnel (see FIGS. 3(a) and 3(b)) The propulsion controls are fully represented in that the local control position for the engines and gearbox has been installed and, in addition, the ship system of

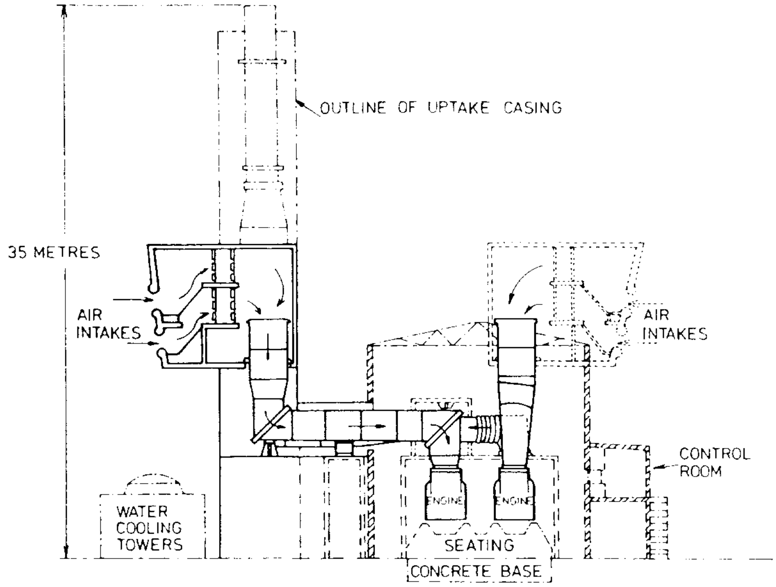

FIG. 3(a)—ELEVATION OF THE SHORE TEST FACILITY

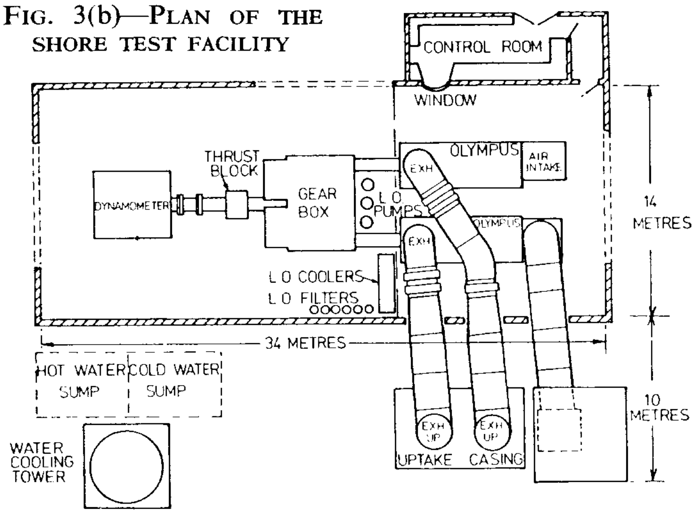

FIG. 3(b)—PLAN OF THE SHORE TEST FACILITY

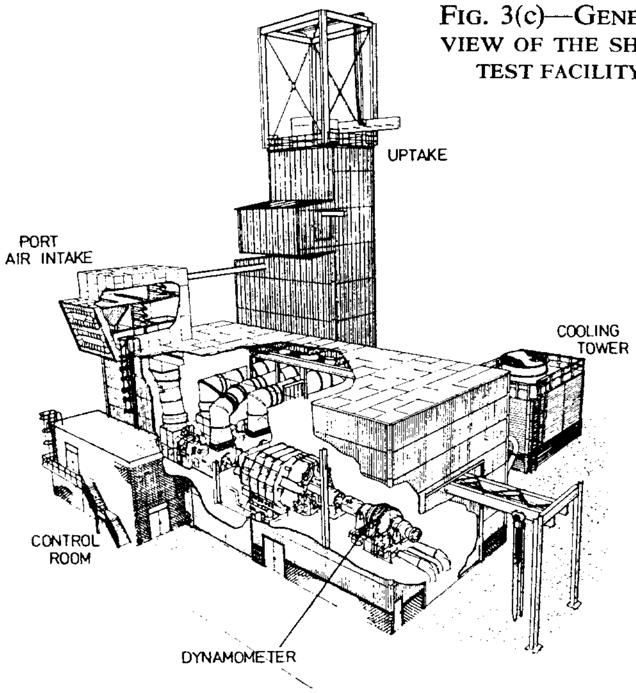

FIG. 3(c)—GENERAL VIEW OF THE SHORE TEST FACILITY

remote control from the ship control centre (SCC) and from the bridge has been situated in a separate room.

FIG. 3(c), a sketch of the test house, shows the general arrangement as viewed from the port side of the ship. Those items of interest peculiar to the STF and differing from the ship are the positioning together of the SCC controls and bridge controls in a room shown on the left directly below the port air intake; the cooling tower shown on the right; and the dynamometer brake in the test house itself. FIG. 4 shows in section the transmission line from the power turbine to the dynamometer, illustrating the turbine drive via torque tube to the gearing and giving some impression of the gearing arrangement.

The dynamometer is a critically important item of equipment. It is required, in this case, to be reversible and capable of operating on demand to a number of power/speed relationships similar to the propeller law. It is vital to the shore trials and needs to be treated with special care and shielded from undue demands and abuse. The duties of the dynamometer must be well thought out beforehand and generous safety margins built in.

The dynamometer brake employed in the STF is limited in performance because it can only provide a passive load. There is a need, however, to simulate the feedback of transient torque loadings which can occur due to ship movement through the water, for example the ahead propeller torque, derived from the ship's way, which is imposed on the transmission system during a crash stop manoeuvre from a high ahead speed. This torque, combined with the inertia torque of the machinery, tends to maintain the ahead rotation of that machinery. After the shaft reverses and while the ship is still moving ahead, the effect of continuing propeller feedback is felt as an additional resistance to the acceleration of the shaft in the astern direction. A typical curve of

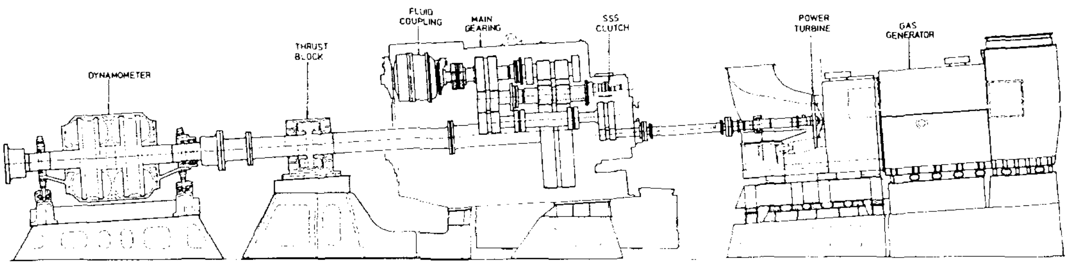

FIG. 4—LINE OF SHAFTING AT THE SHORE TEST FACILITY

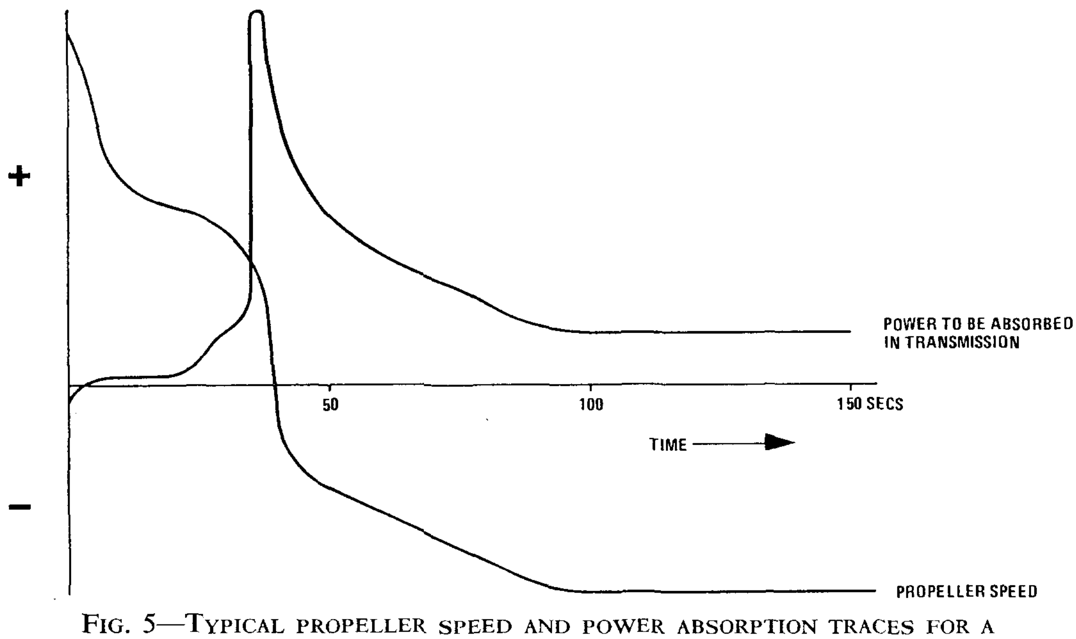

FIG. 5—TYPICAL PROPELLER SPEED AND POWER ABSORPTION TRACES FOR A MANOEUVRE FROM HIGH SPEED TO ASTERN

propeller speed plotted against time and related to the power absorption curve for a high-speed ahead-to-astern manoeuvre is shown in FIG. 5. The reproduction of this feedback during shore trials is essential if the transmission is to be shown to be capable of withstanding and dealing with it. The R.N. has had problems in the past through an inability to appreciate the extent of such transient torques. In the case of the cruiser arrangement, the fact that two engines drive into the same gearbox enables the necessary feedback to be achieved during shore trials by injecting ahead torque into the system; this is done by using one Olympus driving through its ahead fluid coupling while using the other Olympus to provide the manoeuvring power.

The dynamometer and power injection machinery can thus be controlled to follow the propeller power/speed characteristics so that the following ship manoeuvres can be simulated:

(*a*) Acceleration runs in manoeuvring drive and direct drive on one engine per shaft and two engines per shaft.

(*b*) Steady-state running at specified shaft speeds on one engine per shaft and two engines per shaft.

(*c*) One engine per shaft crash stop manoeuvres.

As described above, crash stop manoeuvres can only be accomplished with one engine driving since the other engine is required for power injection. However, computer simulation indicates that the most arduous conditions occur during the one engine per shaft crash stop from 35 per cent. full power ahead. This, therefore, is allowed for in the proposed trials.

Organization

The trials are conducted by a Joint Trials Group (JTG) to the requirements of the Ship Department of the Ministry of Defence. The JTG comprises members of Rolls-Royce (1971) Ltd. (Chairman), Ministry of Defence, Vickers Shipbuilding Co. Ltd. (who are building CAH 01), Y-ARD (consultants), David Brown Gear Industries Ltd. and (over the relevant period) HSD(E) Ltd. The manning and operation of the STF is the responsibility of Rolls-Royce (1971) Ltd.

There is much to be said, from a customer satisfaction point of view, for this type of testing to be carried out directly by the Navy. However, the JTG has proved a success and there are at least two important benefits to be gained from this type of contracted management. Firstly, the principal sub-contractors are immediately and intimately concerned in any issue, major or minor, success or disaster. They feel involved at all times and the flow of information is stimulated to a remarkable degree. Interface problems are more readily solved. The second major benefit derives from the very early and responsible involvement of the main machinery contractors and to a lesser extent the shipbuilder. Both are given the opportunity of studying decidedly in advance of normal requirements the design, procurement, operation and many other aspects of the ship installation and subsequent trials.

Progress and Achievement

The operation of the STF to date (i.e. at the time of writing) has been directed at proving equipments and systems. As yet, no endurance trials have been started and the power injection trial is still outstanding. The latter trial which is of prime importance should be largely completed during early 1975. The endurance testing will follow and will be organized on a $10\frac{1}{2}$-hour cyclic basis to a pattern similar to that shown in FIG. 6. The shape of the profile has been determined by the need to test vigorously the complete propulsion system and its various components. It differs from that used for proving the basic engine and for the much more prolonged endurance running that is carried out at Rolls-Royce (Ansty) and at the National Gas Turbine Establishment.

The STF has now accumulated over 1100 hours running out of a planned minimum 1500 hours. In that time, enough problems have been met and solved to justify well the cost of the installation and also to promote confidence that the few problems that may remain to be revealed at sea will be of a minor order. A brief description of the nature of some of the difficulties encountered follows:

(*a*) *Fluid Couplings*: As already stated, the slip characteristics of these

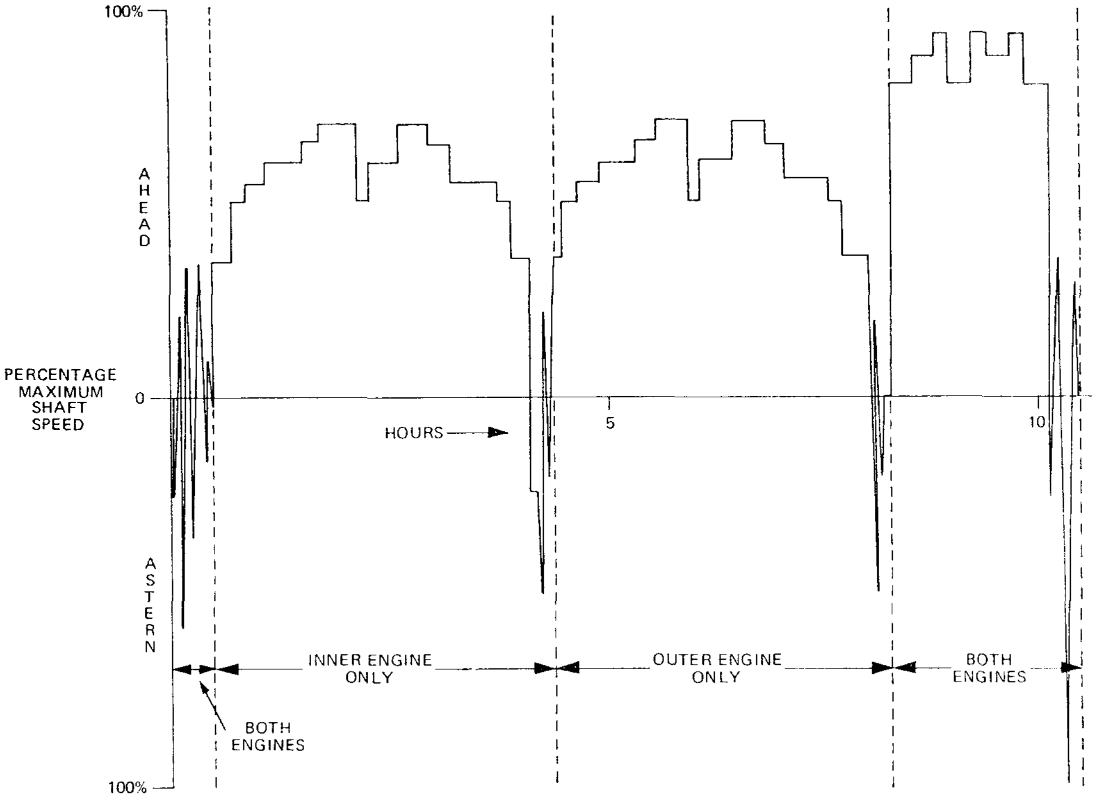

FIG. 6—OPERATING PROFILE FOR STF ENDURANCE TRIALS

couplings are of paramount importance as their effect on propulsion system performance when manoeuvring is vital to the whole concept. There was concern, therefore, when trials showed that the actual behaviour of the couplings differed significantly from that predicted by model simulation. Further trials, however, have established that the system behaviour due to this discrepancy is less of a problem than had been expected, and the effects can be largely eliminated by adjustments to the control system. Some further trials will be done during the power injection phase to confirm that the behaviour under very high slip (200 per cent.) does not raise any further problems.

(*b*) *High-speed Transmission*: It was realized that the long torque tube employed on the high-speed drive from the power turbine into the gearbox might give rise to problems from transverse vibration forces; high vibration velocities experienced early in the trials resulted in bearing damage to the high-speed line in one case. The difficulty has been overcome by very careful assembly but, as a precaution, large diameter tubes with a higher natural frequency are being fitted. In-place balancing of the torque tube and flexible couplings might be advisable in the ship fit.

(*c*) *Gearbox Bearings*: Minor alterations to the bearings used on the high-speed line have been needed to reduce the running temperatures and thus provide a better margin of safety (this requirement also arose in the frigates and had to be incorporated at a very late stage). Another more serious problem of hot bearings arose during one particular mode of operation; this was when the line of slope of the journal altered to an unacceptable degree due to the combination of shaft bending under tooth loads and thermal effects. A partial remedy has been incorporated to allow trials to continue, and a more radical and complete improvement is being built into the ship gearboxes and will be proved at Ansty.

(*d*) *Thrust Block*: Here an oil-seal clearance problem (arising from the plant configuration as a whole and not the thrust block design as such) was identified and overcome.

(*e*) *Disc Brakes*: These are pneumatically operated, and some early troubles with valves and the standard of air filtration have now been cured.

(*f*) *Gearbox Controls*: The hydraulic controls have been shown to have a number of deficiencies. It has been necessary to improve the performance and response rates by some re-design of control valves, by a change of oil type, and by an increase in the operating pressure of the oil. In the process, considerable simplification has been achieved.

(*g*) *Machinery Controls* (*Electronic*): Some deficiencies have been found in control loops and protective functions. The majority of the more severe tests on the controls are still to come, especially during power injection.

(*h*) *Uptakes and Downtakes*: Few problems have occurred so far, although fatigue failures would not be expected yet unless the aerodynamic or thermal design was particularly unsuccessful. However, it has been established that the uptake bellows which joins the exhaust volute to the deckhead produces, under running conditions, a much greater reactive force than was anticipated. The combination of expansion due to high temperatures and the stiffness of the bellows has caused unacceptably high forces to be transmitted to the turbine casing and mountings. A number of remedies are being examined. In order to prepare a fallback position should none of them succeed, a trial has been carried out running with a gap in the uptakes. The natural draught makes this a feasible—although not an attractive—operation. As expected, intake noise within the ship has proved to be rather high and some attenuation measures will be needed.

(*j*) *Mountings*: Currently, the installation is solidly mounted but a full programme of noise measurement has been completed and a change to rubber mountings is programmed.

(*k*) *Lubricating Oil Supply*: Both electrically-driven and air-driven stand-by lubricating oil pumps are fitted in the cruiser, and they are programmed to cut in automatically in emergency. Some of the trials at the STF are aimed at determining the response rates of the stand-by arrangements. These trials have indicated a need to improve the reaction time of the air supply system to the air-driven pump and also a requirement to refine the control systems in selecting the stand-by pump.

(*l*) *Gas Turbines*: Excess lubricating oil consumption has been traced to losses from a gas generator bearing occurring after shut down. This is due to the tall chimney effect of the very long uptake which creates a natural draught capable of motoring the gas generator for a very long time after fuel shut off. The high consumption has been cured by a modification to the scavenge pump. A certain amount of work has been done at the STF, for convenience, in further delineating the limits of compressor aerodynamic stability under typical installation conditions and to show that these limits will not be approached in practice.

(*m*) *Instrumentation*: This has performed very satisfactorily. Some deficiencies, however, have been noted where incipient defects have not been detected as early as they might have been due to poor siting of sensors. These sitings are being improved.

(*n*) *Maintenance Requirements*: An experienced naval team has been working for many months to identify the maintenance tasks, establish methods and the necessary support, and to indicate those areas where design for upkeep is poor. The investigation which covers both equipment, systems and installation has proved to be highly successful. At the time of writing, 80 per cent. of the investigation is complete and, so far, over 350 instances of poor design for upkeep have been brought to notice (a considerable reflection on design standards). 80 per cent. of the proposed improvements have been adopted.

The foregoing represents a great deal of rectification work. Had the majority of it been left until the machinery had started to run in the first cruiser, the costs of rectification would undoubtedly have been high and many of the curative measures would, at best, have been palliatives; nor does the above list represent the sum total of improvement that may arise from the STF. The full series of trials has yet to be completed and some highly important ones are still to come.

Limitations

Of course there are limitations to the amount and relevance of the information obtained from any shore test facility: it cannot be totally representative of the shipboard installation, the shortfall being most noticeable in the dynamic sense. Approximations of most of the characteristics of a ship can be made but, in some cases, the degree of accuracy of the approximation is apparent only after the ship itself is at sea. Such difficulties in simulation arise because the ship is a moving object within an element that imposes its own forces on the vessel. The STF is fixed and can impose none of those external forces on the installation within it.

For example, only an approximate estimate can be made of the inertia of the ship and its relation to skin friction and wave-making resistance. Consequently, the transient torques and thrusts transmitted via the propulsion system during manoeuvring (which are a function of these inertias and of the propeller characteristics) cannot be known with accuracy at the shore testing stage.

It is essential that a substantial effort be devoted to prediction of external effects if the STF is to be employed to full effect.

Again, the inertia of the propulsion system itself is not accurately represented in the STF because this is not a complete replica of the ship system. It lacks, for example, a propeller and most of the propeller shaft and bearings. However, suitable programming of power injection and dynamometer load allows many dynamic situations to be simulated.

For similar reasons and because, in shore tests under reversing conditions, the thrust-block loading is negligible, stiction torque of the propulsion system in the ship is bound to be greater than that in the STF. Again, simulated torque can be fed in, hopefully of at least the right order.

Ships change shape when afloat, when in a sea-way, and as they age. Because of this, changes in alignment occur which are difficult to predict, and the consequential loading patterns on mountings and bearings may not be represented in shore testing. It would be prohibitively expensive even to try to simulate those loadings imposed in practice due to the vessel slamming, pitching and rolling, although predicted static mean or extreme values can be and are applied.

Where controllable-pitch propellers form part of the ship installation, the problem of fully testing the CPP system in conjunction with the remainder of the plant ashore would be very complicated. Shore testing of this complexity has not yet been attempted by the Royal Navy. It would need very careful analysis to determine the most effective and economic way of achieving a good result.

The constraint placed on the timing of the STF within the shipbuilding programme, however, is a factor which can very seriously limit the value of the results. The STF must be planned, built, commissioned and run sufficiently and early enough for its lessons to be learnt, analysed and implemented in the first ship with minimum disruption to the building programme and subsequent trials. At the other end of the scale, it would be ridiculous to embark on the STF project before the details of the ship installation were sufficiently well developed and firm enough to ensure that the shore facility would be properly representative or that considerable time was not going to be lost in keeping the STF in date. It is also generally to be expected that a STF will use a large proportion of actual ship's or class spare equipment, and this often dictates the earliest start-up date.

Finance

The cost-benefit analysis of shore testing is a long disputed subject, particularly in the value to be placed on improved confidence when significant deficiencies are not in fact found.

In this case:

Total cost of shore test = approximately 90 ship-days or 1000 days of basic cost of delay in construction (i.e. excluding costs of rework or changes, and loss of use of the completed ship).

The gearbox bearing problem mentioned above has been relatively simple to rectify in the ship boxes at this stage: if it had not been discovered before contractor's sea trials (as would otherwise have been the case), the delay and cost would have been enormous and would certainly have far outweighed the total cost of the shore test. Furthermore, the process of investigation and trial of remedies would itself have been much more difficult and expensive. This incident alone, therefore, has justified the cost in the case of the CAH.

In a Class of frigates, the potential saving per ship would, of course, be generally much less but there would be a number of ships affected by any major troubles in the first of class and this could be avoided by shore test.

Conclusions

There is real benefit to be gained from the shore testing of ships propulsion machinery. The newer the technology and the greater the innovation, the greater the benefit is likely to prove. Where the gas turbine is concerned, much has yet to be learned of it in its ship propulsion role. Its potential is still being developed. Much of that potential lies with the engineering skill in applying the gas turbine to its purpose and it is in this application that new ideas and fresh concepts are being adopted and designed into ship systems. These, in turn, introduce many new factors all of which must be taken into account in determining the effectiveness of the gas turbine as part of a complex system and the performance of the propulsion plant as a whole.

With steam machinery, steady development from class to class of ship generated sufficient confidence in that process to allow the shore testing of complete propulsion systems to become the exception rather than the rule. The R.N. is not yet at that stage with gas turbine propulsion and there are sufficient unknowns in the systems employed to make it imperative that each proposed installation is carefully examined (bearing in mind the limitations of shore testing, and its timing) to determine whether full-scale shore testing should be provided before first of class.

Most aircraft are propelled by gas turbines and this seems to require the production of a number of complete and costly prototype aircraft for trial before the first production aircraft is allowed into service. Perhaps it is only traditional thinking which prevents the same being done with ships. In comparison, the shore testing of the propulsion machinery is remarkably cheap.

Acknowledgements

Much of the material in this paper is drawn from R.N. sources and the text is published with the knowledge and permission of the Ministry of Defence. The opinions expressed, however, are the authors' own, and are not attributable to the Ministry. The author gratefully acknowledges the assistance given him by his colleagues within the Ministry and members of Messrs Rolls-Royce (1971) Ltd.