ENDURANCE TESTING OF MARINE GAS TURBINES FOR THE ROYAL NAVY

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ABSTRACT

Royal Naval policy since 1967 has been to employ gas turbines for major surface warship propulsion. In support of this policy, all new engines have been subject to endurance testing at DTEO Pyestock.

Marinised TYNE and OLYMPUS aero engines were tested during the 1960s and 70s which confirmed their initial suitability for RN service and uprated performance. Lessons learnt in formulating the test process were applied to the SPEY SM1A engine programme in 1982. Further refinements, following comparison of sea operating experience with test bed results were applied to the 3000 hour endurance trial of the 18 MW SPEY SM1C engine, which completed in 1993.

The current testing at Pyestock is of the 21.6 MW Intercooled Recuperated (ICR) WR21 engine, presently under development for the USN in cooperation with the RN. The endurance trials being planned will require a further change in emphasis in order to address the unique operating regimes of an ICR engine.

The article describes the evolution of endurance testing techniques, highlighting the particular requirements for complex cycle engines and discusses the opportunities that arose for piggyback trials during typical endurance testing regimes.

Introduction

Endurance testing of gas turbines for military and civil applications is conducted prior to installation as a proving algorithm for new development engines, and as a method of developing knowledge about in-service engines without compromising application operations. In many cases of new development, the successful completion of endurance testing, and the performance of an engine during endurance testing will be critical aspects in the contract development of a project. In the case of in-service engines, endurance testing is used both for large scale performance enhancement experiments and also as a base for minor trials which require close technical supervision.

The conduct of endurance testing depends largely on the perceived application of the engine under test. A military marine engine will clearly require a significantly different test profile to that used for commercial marine or industrial base power generation engines.

Another aspect of endurance testing, often overlooked, is the retrospective comparison of test results with in-service experience, whereby the efficacy of the test regime can itself be judged. This not only enables more accurate testing of the same engine at a later date, but also increases expertise for the testing of future engines in similar applications.

This article aims to review the endurance testing of gas turbines used by the Royal Navy, and in considering the current development of the WR21, to discuss the particular aspects of endurance testing complex cycle engines destined for the marine market.

The aims of endurance testing

The aims of endurance testing can be many, and vary with engine type, development status, foreseeable or current applications as well as other variables such as testing authority and engine manufacturer. However, the overriding aims are to demonstrate fitness for purpose, at minimum cost with acceptable risk prior to introduction into service.

Achieving the above allows the Programme Manager to optimize the balance of development cost against in-service cost, whilst expanding the in-house knowledge base for the engine.

Testing can be designed to a known in-service operating characteristic, supplying data for use when the engine goes into a particular application, or can be a more generic characteristic, verifying engine performance and reliability against a wide range of operating conditions and powers.

Early endurance testing for the Royal Navy

Trials of the AEI G6 gas turbine were conducted in the early 1960s, at the manufacturers works, and at the National Gas Turbine Establishment (NGTE) at Pyestock. HMS *Ashanti* was also fitted with the AEI G6 to create a trials ship programme to be progressed in parallel. The object of the trials at Pyestock was stated firstly to be to run a large number of hours ahead of the engines at sea to gain advance knowledge of engine life and any defects which might arise, and secondly to investigate and correct any defects which might occur at sea. It was considered that the greatest risk to the engine lay in thermal shock due to rapid load changes and therefore the first objective would be best served by arduous cyclic running. The first 1000 hours endurance trials were run on a cycle which involved 86 major power changes per day and included a total of 200 hours above 88% power although only a small proportion of this was at full Turbine Entry Temperature (TET) due to low ambient conditions.

The trials were progressing well when HMS *Ashanti* suffered a catastrophic failure of a turbine disc, while conducting a full power trial in the Caribbean (ambient air temperature 90°F). Questions were inevitably raised as to why the ship's engine had failed prior to the engines under trial ashore, which had accumulated many more high power running hours. The failure was eventually attributed to leakage of cooling air through glands, whilst operating in tropical conditions with a salt fouled compressor. Further investigations showed that it was likely that the shore trial engines would eventually have failed in the same manner as that in HMS *Ashanti*, thus confirming the relevance of the testing but emphasising the need to either conduct shore trials in advance of sea trials or to accelerate the effects by the use of more arduous shore testing. Later trials were successfully developed to test the new cooling system and recover the power loss penalty incurred by the rectification of the cooling flow problem.

Endurance testing of the PROTEUS engine

The failure of HMS *Ashanti*'s G6 was a contributory factor in the decision in the mid '60s to adopt aero-derivative gas turbines for warship propulsion. Subsequently, trials of the Marine OLYMPUS and PROTEUS engines were conducted, in the latter case trials were conducted ashore and afloat in parallel.

As aero-derivative engines, the OLYMPUS and PROTEUS could be said to have a number of endurance hours already accumulated prior to their inception as marine propulsion units. However, it must be remembered that there is a considerable difference between the typical operating profiles of an aero-engine and a military marine propulsion engine. Warship propulsion engines operate for much of their time at low power, and are subject to much slower rates of acceleration and deceleration than aircraft engines. The lower average operating temperature also favours the marinised engine, but the relative ambient environments favour the aircraft engine, as does the requirement to burn the heavier grade diesel fuel in a warship.

The Marine PROTEUS was installed in the BRAVE class of patrol boats, as well as being trialled in parallel at Pyestock, where a good deal of effort was made to build a salt injection rig to try to model typical sea operating conditions. After a small number of hours in the shore rig, performance drastically reduced in a way that had not been mirrored in similar running at sea, except where extreme weather conditions had been experienced. The cause of the reduction in performance in the shore rig was found to be severe corrosion of turbine nozzle blading. Later environmental investigations were to show that the original estimate of salt ingestion rate was incorrect by a factor of 10, causing the rapid, and unrealistic, failure of the engine under test. This formed the principal lesson to be highlighted, namely that if the environment is not accurately modelled the validity of the test conclusions can be called into question.

Endurance testing achievements

The preceding illustrations demonstrate the difficulties facing engineers in developing valid testing regimes for marine engines. They also demonstrated the considerable benefit in conducting the tests, as they proved the ideal vehicle for development trials of the engines in terms of re-engineering as a result of emergent defects.

The lessons learnt in these early trials made a considerable contribution to the development of the marinised OLYMPUS engine.

Endurance testing of the marine OLYMPUS

Initial shore trials of the marine OLYMPUS TM1A engine totalling over 2500 hours were conducted at the Industrial and Marine Gas Turbine Division of Rolls-Royce at Ansty, near Coventry. Building on the Royal Navy's now considerable experience, the object of the trial was to run the unit under as near at sea environmental conditions as could be simulated. By keeping running hours significantly ahead of the trials ship HMS *Exmouth* it was expected that early warning of areas of concern would be achieved. The first run took place on 10 August 1966, and was followed by a number of months proving the installation. A complete Type 82 destroyer inlet and exhaust system was fitted, together with a salt injection system (to give a realistic rate of ingestion).

For endurance running a repeated 12 hour cycle was used. Each cycle incorporated 48 throttle movements, three starts, two slam accelerations and one slam deceleration/acceleration, with the longest period at any steady power being 90 minutes. This was considered a particularly arduous cycle and was intended to be about three times more severe than that which would be experienced at sea.

The engine performed well and two vibration related failures, which did occur to the power turbine and shaft were rectified by damping and alteration of bearing journal separation distances with no recurrence.

Another defect had been experienced in the aero and industrial derivative engines, namely HP turbine blade failure, this was found to be a greater problem for the marinised OLYMPUS. As suspected prior to testing, the reason for this difference was attributed to the significantly altered stress spectrum of the marine engine, operating at low powers in a marine environment, as opposed to the high power characteristic typical of aero and industrial engines. This is just the kind of problem area that endurance trials are designed to highlight, and modifications to correct the problem were embodied increasing engine life by at least a further 2000 hours running prior to *Exmouth*'s acceptance trials.

Despite these obvious successes, the endurance trial did not provide advance warning of a failure of the LP compressor in *Exmouth*, which was later found to be due to the peculiar shape of the ship's intake ducting causing a vortex generation effect at compressor inlet.

A further difference between shore and sea trial was identified when *Exmouth* reported that carboblast (a powder injected into the engine intake to clean the compressor blades) was causing blocking of the burner shrouds. This had not been a problem during shore testing and this time the explanation was the difference in running schedules; in the shore trial the cleaning cycle was followed by a period of high power running, which was not the practice at sea.

After completing 2548 hours of endurance testing, the shore trial OLYMPUS engine was subjected to a thorough strip, and although it was found to be dirty, no new areas of concern were identified and the engine was rebuilt for service at sea.

The latter development of the OLYMPUS engine (the TM3B, still in RN use) was also subjected to endurance trials at both Ansty and Pyestock.

Endurance testing of the TYNE engine

Endurance testing of a Marine TYNE (RM1C) was conducted at Pyestock in the summer of 1967. The design of the endurance cycle was subtly altered for this trial, as the TYNE was envisaged as a cruise engine in the Type 21/42 Combined Gas or Gas (COGOG) arrangement, and as such would operate at high power for a greater percentage of its installed life than would the larger OLYMPUS boost engine. The engine was run for a total of 1000 hours, which included an amount of high power running, against a profile designed to be equivalent to 4000 hours of cruise duty in a warship.

The trial took the form of 42 test cycles, each of 24 hours duration including 10 hours at maximum TET to provide the high power running equivalence described above. The now proven salt laden environment was again utilized throughout the trial.

The engine completed this trial with less than one hour unscheduled stoppage. On completion of the trial, some defects were found that were attributed to the severe operating cycle, and some found to be as a result of a change of fuel from Kerosine to Dieso. With these exceptions, the condition of the engine was found to be very good, and the engine had successfully demonstrated its suitability for naval duty. The marinisation of the engine was improved based on the testing, in particular signs of salt water erosion of LP compressor blading resulted in the adoption of titanium rotor blading.

Such was the confidence in the engines demonstrated in endurance trials, that the Type 21/42 COGOG system was adopted, and a total of 14 propulsion units were ordered before even a single set had completed its sea trials.

Endurance testing of the SPEY engine

At the time of adoption of the SPEY engine as the new generation of gas turbines for warship propulsion in the Royal Navy, aero and industrial derivative units of the engine had accumulated over 15 million engine hours, and therefore, carried a proven endurance performance into the test programme (albeit at somewhat different conditions, the importance of which was raised during testing of the Marine OLYMPUS).

Full development of the marinised SPEY SM1A was completed in 1982, and a 3000 hour endurance trial commenced at Pyestock in April 1984.

SPEY SM1A testing

An additional aim was specified for the SPEY testing, as a result of at sea operating experience of the TYNE and OLYMPUS, that of proving maintenance and defect rectification procedures and documentation.

In direct response to changes in warship operation, driven by the drive to maximise efficiency and minimise operating costs, the testing was conducted using two different propeller cube laws. The first simulating full power with both shafts driving, and the second simulating driving with one shaft trailing, the ratio of time spent on the respective cube laws was 5:1 in favour of the former. In addition, three separate endurance cycles were adopted, (FIGS. 1–3).

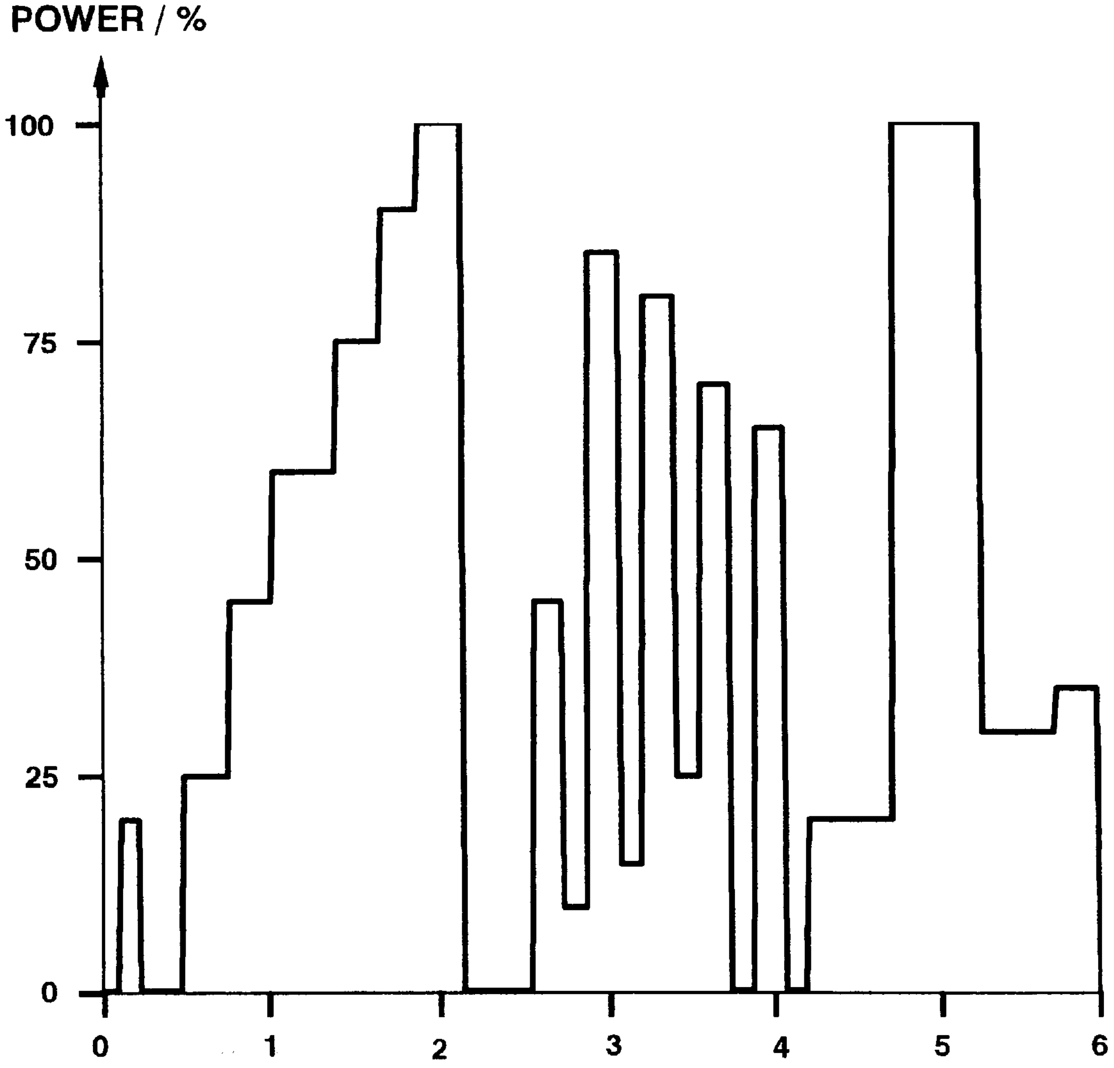

FIG. 1—SPEY SM1A FIRST ENDURANCE SCHEDULE

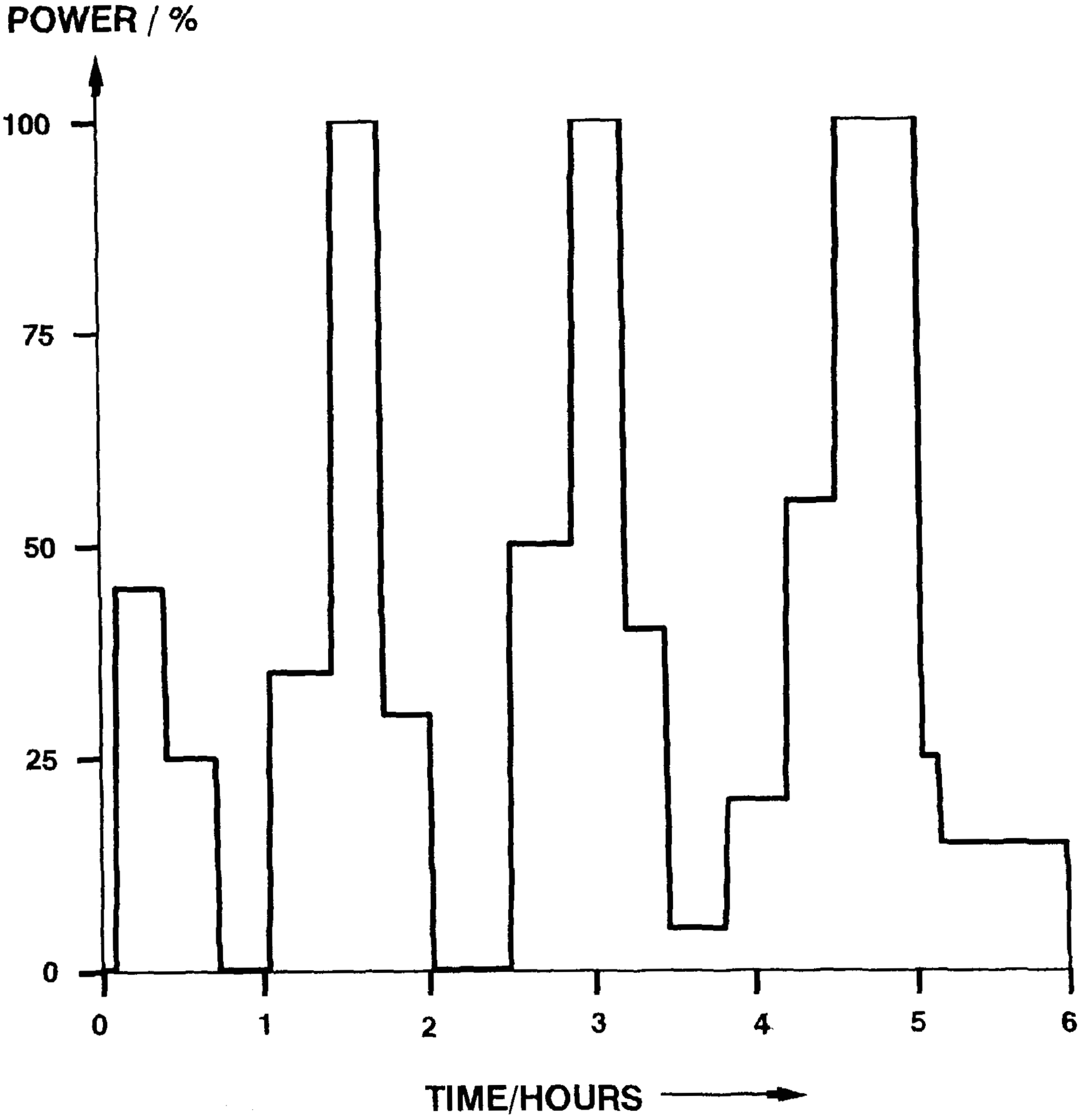

FIG. 2—SPEY SM1A SECOND ENDURANCE SCHEDULE

The ratio of time spent on the three cycles was 4.5:4.5:1. The trial was conducted with salt injection throughout, at a rate equivalent to the maximum limit stated in Naval Engineering Standards and based on intake filter performance trials.

The engine successfully completed the 3000 hour trial, identifying three areas to be addressed;

LP Shaft thrust bearing

After 300 hours running, high vibration was sensed on both LP compressor and turbine at 90% power, chip detector readings and a vibration survey indicated a significant problem. This was found to be the result of insufficient axial loading causing skidding of the bearing.

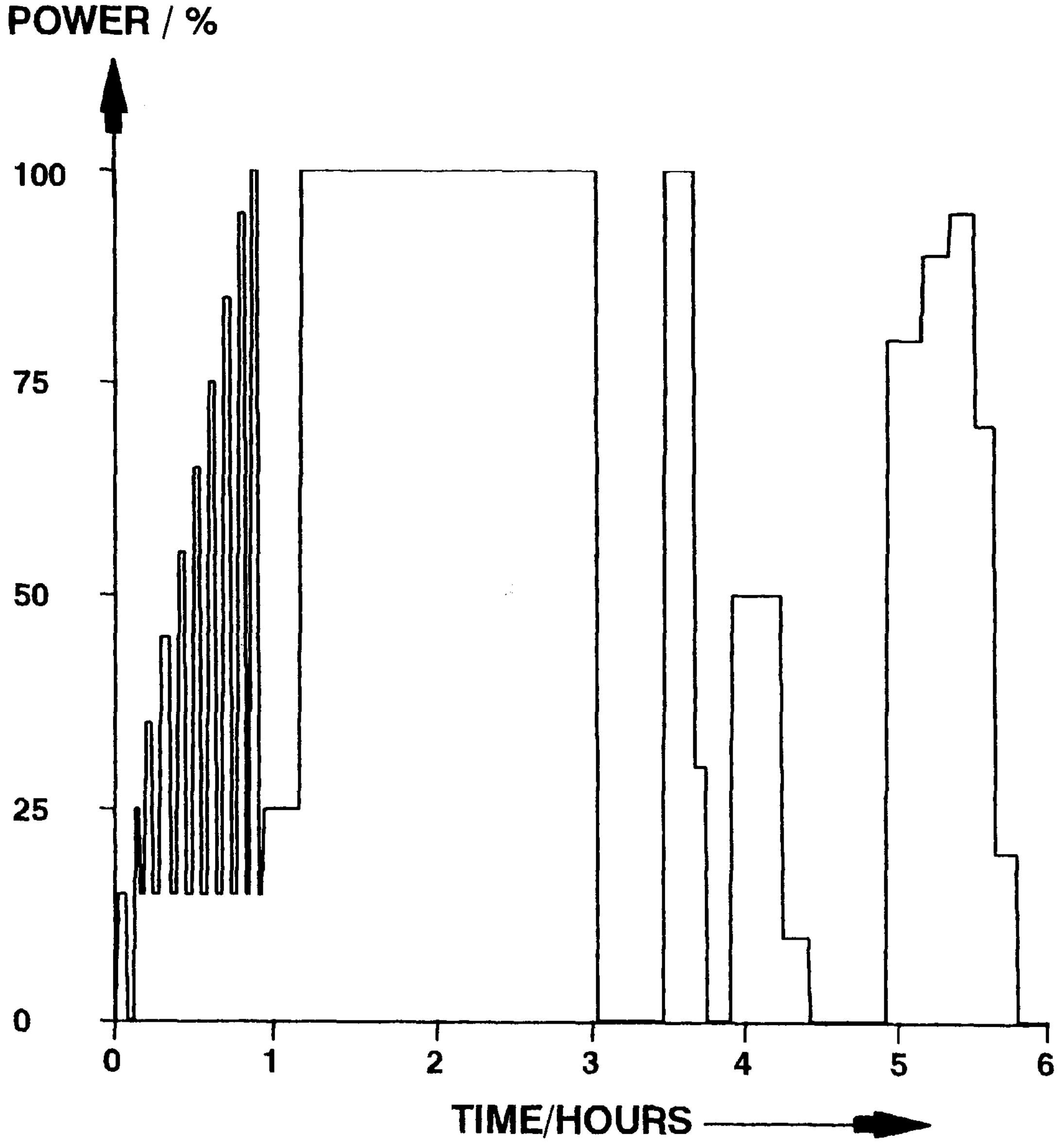

FIG. 3—SPEY SM1A THIRD ENDURANCE SCHEDULE

Combustion cans

After 1350 hours, high smoke readings were obtained and on investigation, several cans were found to be holed in the region of the V ring. The cause of this defect was a combination of thermal shock cracking, and severe corrosion induced by the sulphur in the fuel. The cans were replaced with cans having a protective internal coating, and the remainder of the trial conducted with a more realistic lower sulphur content fuel.

HP1 Turbine blading

The HP turbine had been coated with a rainbow of 19 different coatings for the trial to determine their relative effectiveness. Early in the trial, erosion and corrosion effects were observed. After 2,440 hours, the erosion/corrosion had caused the leading edge cooling channel to be penetrated in the worst case, although with close monitoring, the trial was still completed. The most significant cause of this problem was found to be carbon erosion, the carbon being formed in the combustor particularly at low powers, collecting and then being shed to impact on the turbine blading.

Performance measurements

Throughout the trial, daily performance checks were conducted, as well as regular smoke and emissions readings. In retrospect the emissions readings in particular were a good guide to the condition of the deteriorating combustion cans. There was a measured reduction in the performance of the engine between the start of the trial and the end of the 3000 hours, further investigations revealed that this deterioration was almost entirely due to reduced efficiency of the HP turbine, consistent with the erosion problems mentioned earlier.

Throughout the trial, operating and maintenance procedures and documentation were closely evaluated, with suggested improvements being adopted by the appropriate authorities.

At the end of the trial, the performance of the engine was pronounced satisfactory, although the reduced life of the combustors caused some concern. The carry over of this concern into service emphasises the fact that a proven aero pedigree must be viewed in the context of the environmental conditions under which it has been achieved. There was also some concern over the efficacy of the propeller cube laws used, as the effect of Towed Array (TA) operations had not been taken into account. The fuel used in the trial had been supplied from Naval sources, the variation in sulphur content proved awkward for analysis of blade and combustor corrosion, a recommendation was made that future trials specify the use of fuel at the maximum MoD specification for sulphur content ($<1\%$ sulphur) for endurance testing purposes. Adoption of the recommendation would remove one more variable from the analysis and accelerate any sulphur induced combustion hardware lifing problems.

SPEY SM1C development and testing

During engine development, the SM1A was run to a power significantly greater than its rating, in order to aggravate any design shortcomings, and accelerate their occurrence. As a result of this running, the engine proved itself fully capable of increased duty, and a Feasibility Improvement Study was conducted and the programme to develop the SPEY SM1C was conceived. Testing of the SM1C was conducted at Pyestock, in parallel with sea trials in HMS *Brave* a Type 22 frigate.

SM1C testing

The stated aims of SM1C endurance testing were as follows:

- To assess the achievement of SM1C uprated engine performance.
- To establish further confidence in the life capability of the SM1C propulsion module.
- To evaluate component developments.
- To investigate solutions to early in-service problems highlighted by engine experience in HMS *Brave*.
- To evaluate documentation and special tools associated with the SM1C.

To conduct minor trials on the engine and its auxiliaries.

Building on the established format the testing was split into three phases, each of 1000 hours duration. The first phase was completed between April and July 1991, and was followed by a strip inspection of the engine. The second phase commenced in November 1991, and was 80 hours short of completion when excessive combustor degradation brought a premature halt to the test. These 80 hours were completed with temporary combustors, prior to a new design being delivered for the final phase of running. The third and final phase of SM1C endurance testing began in November 1992, and concluded in March 1993.

Engine running hours were accumulated at the rate of 14 hours per day, 5 days per week, with the engine shut down overnight. The running profile, in terms of total time spent in specific power bands, remained constant throughout the trial. The engine operating pattern was centred around the profile shown at (FIG. 4), which could be programmed for a duration of 5 hours, 1 hour or 30 minutes.

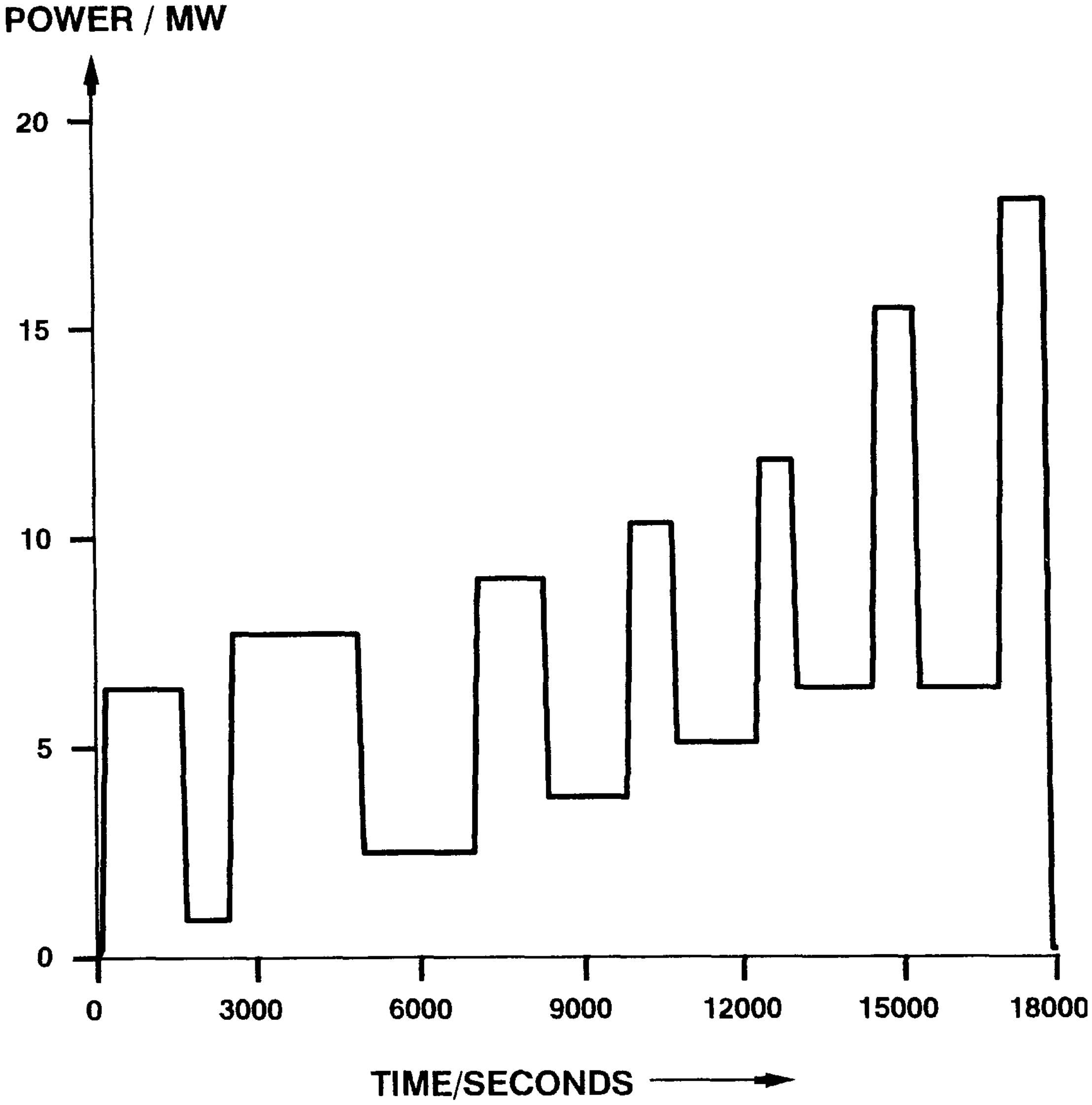

FIG. 4—SPEY SM1C ENDURANCE TESTING SCHEDULE

These schedules were combined with engine handling, transient tests, performance mapping and compressor washing requirements to develop a typical 50 hour mission profile. The majority of this running profile was developed from the mission profile of a Type 23 frigate, although at the request of Rolls-Royce, a total of 9% of cumulative running time was allocated to powers above 80% of rated power. Again the accumulated testing experience drove the SM1C test towards ensuring that the test profile was relevant to the predicted in-service usage.

The SM1A cube law debate had been reviewed and the entire SM1C trial was conducted on a single propeller cube law, the assessment having been made that the decoupling of GTCU and power turbine means that changing the cube law has little effect on the GTCU.

Salt injection was conducted throughout the trial to simulate the marine environment, at a flow rate that varied with LP compressor speed, ensuring that the rate of injection in parts of salt per million of air by mass remained constant at all powers. With the exception of the first 500 hours of Phase 1, the entire trial was conducted with high sulphur fuel (i.e. close to the MoD limit of $<1\%$ sulphur).

Phase 1

During Phase 1, there were only two significant problems to interest the endurance test engineer. Firstly, a blockage in a P3 splitter orifice plate that caused the HP7 bleed valve to stick in the open position, and also preventing movement of the VIGVs. This defect uncovered an omission in the published documentation, which did not show the orifice plate. Secondly, a lub oil spillage occurred during a crank with the module vent flaps closed, which caused the pressurisation of the lub oil tank by the air start motor exhaust. Again a solution was identified and implemented prior to the engine's installation in the warship. Endoscope inspections were conducted at regular intervals throughout Phase 1, allowing an early assessment of combustor condition.

Phase 2

Phase 2 commenced after a full strip and inspection of the engine had been completed. The most damaged combustors were replaced during the rebuild of the engine, and regular endoscope inspections were conducted once more to assist in monitoring for any further degradation. After 1,920 hours the PTET spread became consistently excessive and an endoscope inspection revealed a large amount of barrel material missing from one combustor, together with an adjacent interconnector. The decision was taken to conclude Phase 2 testing at this time and the engine was returned to RR Ansty for strip and inspection.

Other component and engine issues raised during Phase 2 included the failure of the HP7 bleed bellows and repeated low lub oil pressure warnings. The HP7 bellows became holed as a result of its embrittlement in the hot gas environment when combined with the pulsation effect experienced by the bellows with bleed valve operation. The repeated low lub oil pressure warnings was thought to be a result of air entrainment due to sprung pipework generating excess strain in pipe unions.

Phase 3

Phase 3 started by completing the remaining 80 hours of Phase 2. A high module temperature was experienced during these 80 hours, and continued throughout Phase 3, this was thought to be due to a number of gas leaks in on-engine systems.

The combustor degradation problem was monitored closely during the final phase of testing, and further evidence of the cracking and corrosion was gathered. Different standards of combustor were also assessed, firstly two combustors with Angled Effusion Cooling were fitted which gave some evidence of delaying the onset of the problems. Secondly, a trial was conducted to compare four new developments of bond coatings in the combustor. This kind of rainbow testing can be useful in reducing the time and cost associated with development of a solution to the problem. The draw back of rainbow tests can be that the trial is prevented from completing the prescribed schedules by the life of the least suitable candidate component.

The frequency of low lub oil pressure warnings was significantly reduced at the start of the final phase, but increased towards its completion. No apparent cause could be identified, and the fault appears to have been specific to the Pyestock engine.

Minor trials

Once a major engine test is scheduled, the opportunity arises to build additional smaller packages of work into the programme. This technique of piggybacking related studies on to the endurance test reduces the overhead for all concerned. A number of minor trials were conducted throughout the endurance testing of the SM1C, the following list is not an exhaustive summary but gives some idea of the scope of trials conducted:

BTM module fire fighting system

This was assessed as safe and recommended for use at sea.

An alternative GTCU Lub Oil

This was used throughout the 3,000 hours and subjected to periodic laboratory analysis. The oil was recommended for further trials at sea.

GTCU Lub oil debris analysis

Three separate debris monitoring systems were trialled at various stages of the endurance trial.

On-line Vibration Analysis

This system was tested throughout the trial and proved awkward to operate and difficult to analyse. Little confidence was developed in the results and the system was said to require further development work.

Low Cycle Fatigue.

A system to log accumulated low cycle fatigue data was developed and operated occasionally during the 3000 hours. The results found were sufficient to recommend the unit for further trials at sea, and the system is currently being used in WR21 development trials.

Assessment of the SM1C endurance trial

The 3,000 hour endurance trial of the SPEY SM1C took approximately 57 weeks to complete and while the primary objective was achieved, some further development work was deemed necessary to satisfy all of the acceptance criteria. Most significantly, shortcomings were exposed in the life capability of hot end components, particularly in the combustion system. SM1C trials continued at sea in HMS *Brave*, and the engine has since been accepted for service with SM1A and SM1C units installed in the Royal Navy's newest Type 23 frigates.

The completion of endurance testing of the SPEY SM1C marked a most significant turning point for Gas Turbine endurance testing in general and DTEO Pyestock in particular. A new challenge was to be presented in the form of a development programme for a complex cycle gas turbine—the WR21 ICR gas turbine. This was to be the first time that Rolls-Royce would use an outside agency's facility to conduct development testing.

Endurance testing of the WR21 ICR engine

Background

The WR21 gas turbine is a complex cycle engine (Intercooled and Recuperated—ICR) being developed for the US Navy by Westinghouse Electric Corporation with Rolls Royce as the principal sub-contractor. Both the Royal Navy and the French Navy have individually signed agreements with the United States Navy, known as a Memorandum of Understanding (MOU), to cooperate on the development testing of the WR21.

What is a Complex Cycle Gas Turbine?

The difference between this complex cycle gas turbine and the simple cycle machines previously discussed in this article is the inclusion of the following additional components;

The Intercooler

A heat exchanger introduced between the LP and HP compressors, cooling the air leaving the LP compressor to near ambient temperatures before entry into the HP compressor. This reduces the amount of work the HP compressor has to perform and so increases overall power output by approximately 25%.

The Recuperator

A waste heat recovery heat exchanger mounted in the exhaust uptake. The recovered energy is used to raise the temperature of the compressor delivery air prior to entry into the combustors. A given combustor outlet temperature can therefore be achieved using less fuel and an overall fuel saving at full power is achieved.

The Variable Area Nozzle (VAN)

The VAN is fitted immediately before the power turbine. As demanded power reduces, for part load operation, the temperatures in the power turbine and exhaust are maintained artificially high by closing down the effective nozzle area. The temperature difference across the recuperator, therefore, remains large and a high effectiveness is retained.

The overall result of all of these measures increases power density, and offers significant fuel savings over equivalent simple cycle engines, with a near flat specific fuel consumption (sfc) curve being maintained from full power down to 40%. Control of the engine is afforded by the Electronic Engine Controller (EEC), a full authority digital control system developed by another sub-contractor CAE of Canada. A schematic of the WR21 complex cycle is at (FIG. 5).

Complex Cycle Consequences

The principal mode of operation of the WR21 is in the full ICR mode. However, the inclusion of the intercooler and the recuperator when combined with the military requirement for redundancy result in fallback operating modes, where each or both of these heat exchangers may be Out of Action (OOA) and the core engine still produce useful power. This further complicates the already difficult task of endurance testing. (FIG. 6) illustrates the different operating lines for the WR21.

The outside of the envelope defined by these operating lines represents the extremes of temperature, speed and Air Fuel Ratio (AFR) the engine and combustion hardware may see in service. The wide variation in these parameters has meant that the testing philosophy developed through endurance testing the previously mentioned simple cycle gas turbines again needs to be re-evaluated for the WR21.

Development of the ICR testing regime

As for other gas turbines, the primary aim of endurance testing is to identify likely in-service problems early. This again requires realistic environmental conditions and an operating regime similar to that of the target warship. However, with tight budgetary constraints, engine trial timescales are also

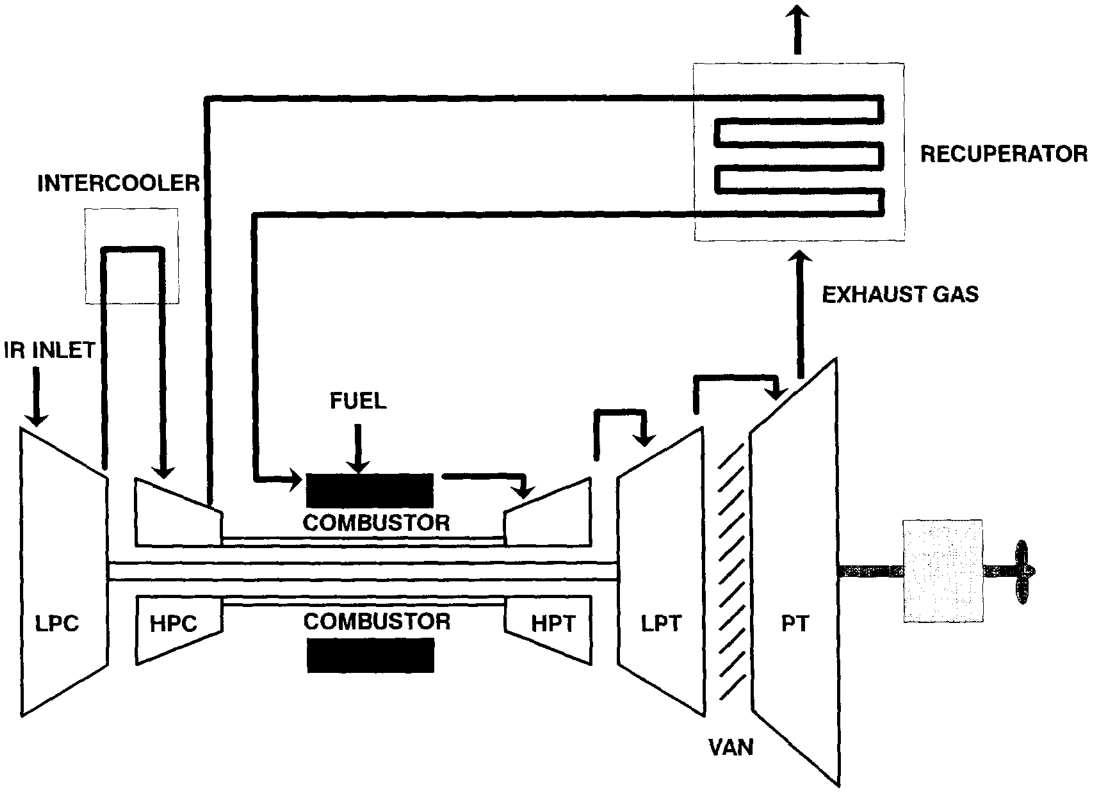

Fig. 5—The complex cycle

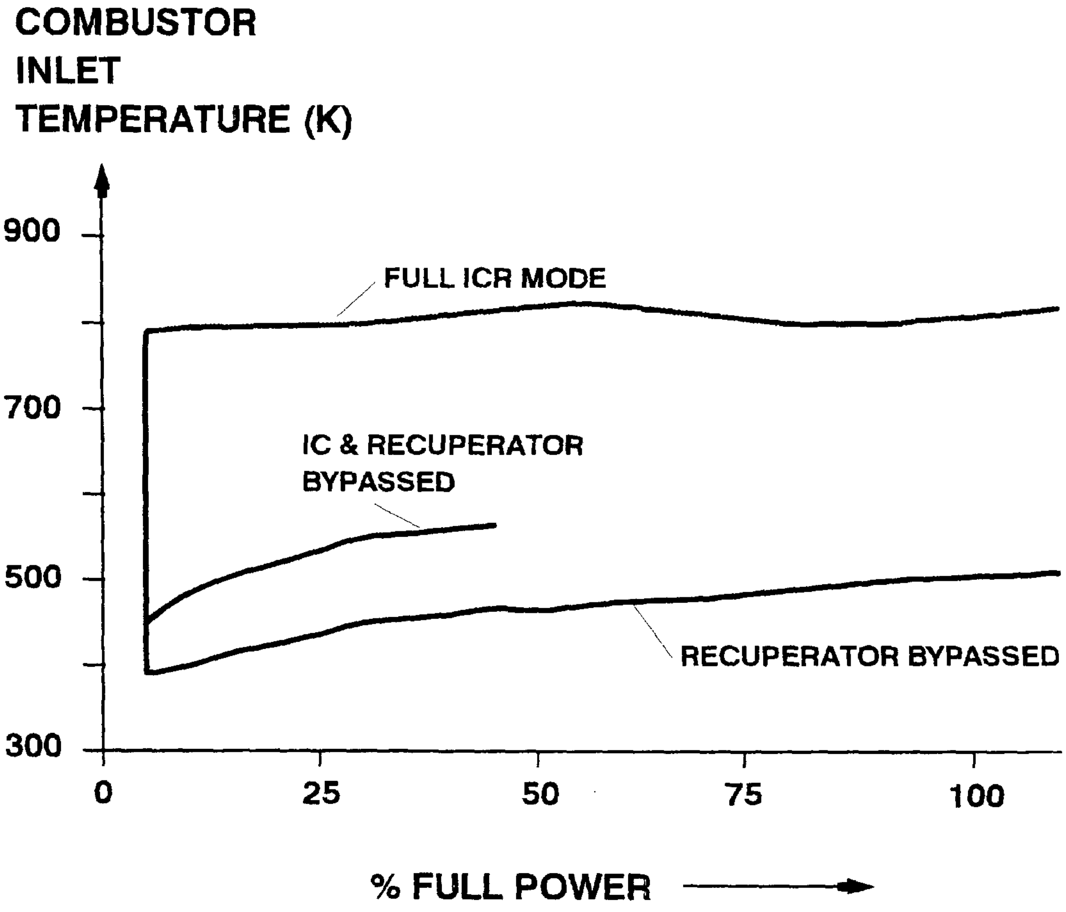

Fig. 6—WR21 ICR gas operating lines

paramount and so the testing must be defined to accelerate the onset of problems.

To test the engine predominantly at high/full powers, as with the SM1A, which could be argued to have some merit for simple cycle machines, does not necessarily impose the greatest temperatures or stresses on a complex cycle gas turbine. By maintaining cycle temperatures high with the VAN and recuperator, the combustion hardware and hot end components can be exposed to higher temperatures with lower mass flows at part loads than at full power. Yet adopting a test regime based purely on the operating profile of a given warship could also be flawed since an engine such as WR21 is targeted at several warship types/designs that will have differing requirements and/or theatres of operation.

Consideration of previous endurance test results in conjunction with engine characteristics and likely warship operating requirements enabled a test philosophy to be developed for the ICR engine.

In common with previous tests a 3,000 hour endurance trial is being defined. It will be conducted using a single set of engine build components and will again be divided into three 1000 hour periods. This enables different strategies to be applied to each phase and evaluation of the overall gas turbine to be simplified. The detail of each test phase has yet to be finalised but the current intent is for testing to be based around the following elements:

Engine Performance

Establish engine performance in the full ICR operating mode, and use this measured performance datum for comparison throughout the trial. This datum would also be used in the assessment criteria to be applied when determining compliancy with the contract specification.

Handling Trials

Conduct Handling/Accel Decel schedules based on typical warship operation—Aimed at accelerating the initiation of problem areas, in addition to proving safe operation and confirming cyclic damage rates. The selection of a representative warship operating profile will undoubtably be a compromise. Common ground tends to be derived from the basic need for all warships to be able to fulfil more general purpose tasks than just their primary specialist role. The general purpose roles tend to cover a much broader spectrum of engine operation and as such reduce the risk of unrealistic trial results.

Engine life assessment

Having demonstrated engine performance and utilised a warship operating profile to detect operating weaknesses and initiate lifing problems, the third element of operation is designed to assess such factors as corrosion resistance, combustion hardware life and operation in the fallback modes. The design intent for the WR21 and any other ICR engine is or should be to operate predominantly in the full ICR mode. Obviously this provides the greatest payback against the initial investment in an ICR. Fallback modes of intercooler and/or recuperator bypassed are to be examined in the later stages of the test, in order to reduce the risk of a reversionary mode failure preventing completion of the more important full ICR testing.

Summary

This article has illustrated that the design and conduct of endurance trials is more complex than might at first be expected. There is a need to ensure that the environmental conditions and operating profiles are matched as closely as possible to in-service conditions. This requirement must also be balanced against the need to deliver the test at a competitive price. The time-scale of procurement precludes the use of prototypes, and even with a considerable development budget, such as in the case of WR21, there is an equivalent of only two and a half engines to support the development phase prior to the introduction of a production standard engine for the 3000 hour endurance test.

DTEO Pyestock has, in its various guises, amassed a significant knowledge base in the field of engine testing. It should be noted that there is another half of the story, yet to be told, describing the evolution of the facility through both engine development and endurance testing.

This article has outlined some of the difficulties the test engineer can encounter when the engine, environment or application are not fully understood. Only by continuous close cooperation with both customer and engine manufacturer, coupled with diligent attention to detail can useful information regarding the predicted in-service operation of an engine be obtained.

Conclusions

The achievement of successful, cost effective engine endurance test programme is dependent on the following;

- Reproduction of realistic environmental conditions.
- The testing schedule needs to incorporate operation at the worst conditions likely to be seen in-service and at the conditions most frequently seen in service.
- Techniques employed to accelerate the identification of problem areas need to be carefully considered. If not, the risk of identifying and addressing a concern that will never occur in the actual warship is increased. Of much greater concern is the possibility of not detecting something which leads to a catastrophic failure at sea.
- The engine design dictates areas of operation with associated risk and as in the case of simple cycle versus complex cycle machines can necessitate radical changes to tried and tested methods.

Finally 'any views expressed are those of the authors and do not necessarily represent those of HM Government'.

Bibliography

1. Bowers, N. K., 'Gas turbines in the Royal Navy', *Journal of Naval Engineering*, Vol.16 No.2, June 1966, pp.194–242.
2. Morgan, S. J., Lamport, A. W. Smith, A. J. R., 'Gas turbines in the Royal Navy', *Journal of Naval Engineering*, Vol.19 No.1, June 1970, pp.71–112.
3. Foster, R. B. L., 'Olympus development', *Journal of Naval Engineering*, Vol.18 No.3, December 1969, pp.379–387.
4. Harris, C. J., 'The reliability of marine gas turbines', *Journal of Naval Engineering*, Vol.21 No.1, June 1973, pp.33–46.
5. Sherwin, D. J., 'Some thoughts on the reliability of gas turbines for warship propulsion', *Journal of Naval Engineering*, Vol.21 No.1, June 1973, pp.46–50.
6. Shaw, T. R., 'Gas turbines in the Royal Navy, 1970 to 1973', *Journal of Naval Engineering*, Vol.21 No.3, June 1974, pp.350-365.
7. O'Hara, D., 'Shore testing of gas turbine ship propulsion machinery', *Journal of Naval Engineering*, Vol.22 No.2, June 1975, pp188–199.
8. Pack, C. R.; Page, K. G., 'The SM1A-The Royal Navy's next propulsion gas turbine', *Journal of Naval Engineering*, Vol.24 No.2, June 1978, pp.125–136.
9. Pearson, A. D., 'Gas Turbine Life—Influence of Ship Design and Operation', *Journal of Naval Engineering*, Vol.28 No.3, December 1984, pp.504–508.
10. Harry, N. J. F. V., 'Marine Spey—A short cut to longevity', *Journal of Naval Engineering*, Vol.29 No.1, June 1985, pp.53–59.
11. Harry, N. J. F. V., 'Marine Spey—1986 update', *Journal of Naval Engineering*, Vol.30 No.1, December 1986, pp.173–183.