THE REQUIREMENTS FOR A MODERN MARINE GAS TURBINE
AND
THE DEVELOPMENT OF THE WR21

BY

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This is an edited version of the paper that was first presented at the ASME Turbo 99 conference held at Indianapolis in June 1999.

Introduction

Marine gas turbines have been tested for the Royal Navy at the Defence Evaluation and Research Agency (DERA) sea level test facility at Pyestock since 1952 when the Admiralty Test House (ATH) was first commissioned (FIG.1). The aim of this facility has always been to thoroughly test and evaluate marine gas turbines using the concentrated gas turbine expertise that has built up over forty years of operation. Since the early days, the ATH test facility has seen a considerable number of different gas turbines, from AEI's GATRIC/G4/G6, Bristol Siddeley PROTEUS/OLYMPUS, to Rolls-Royce RM60/TYNE/SPEY engines, all of which have been developed by the manufacturer for use in warships of the RN.

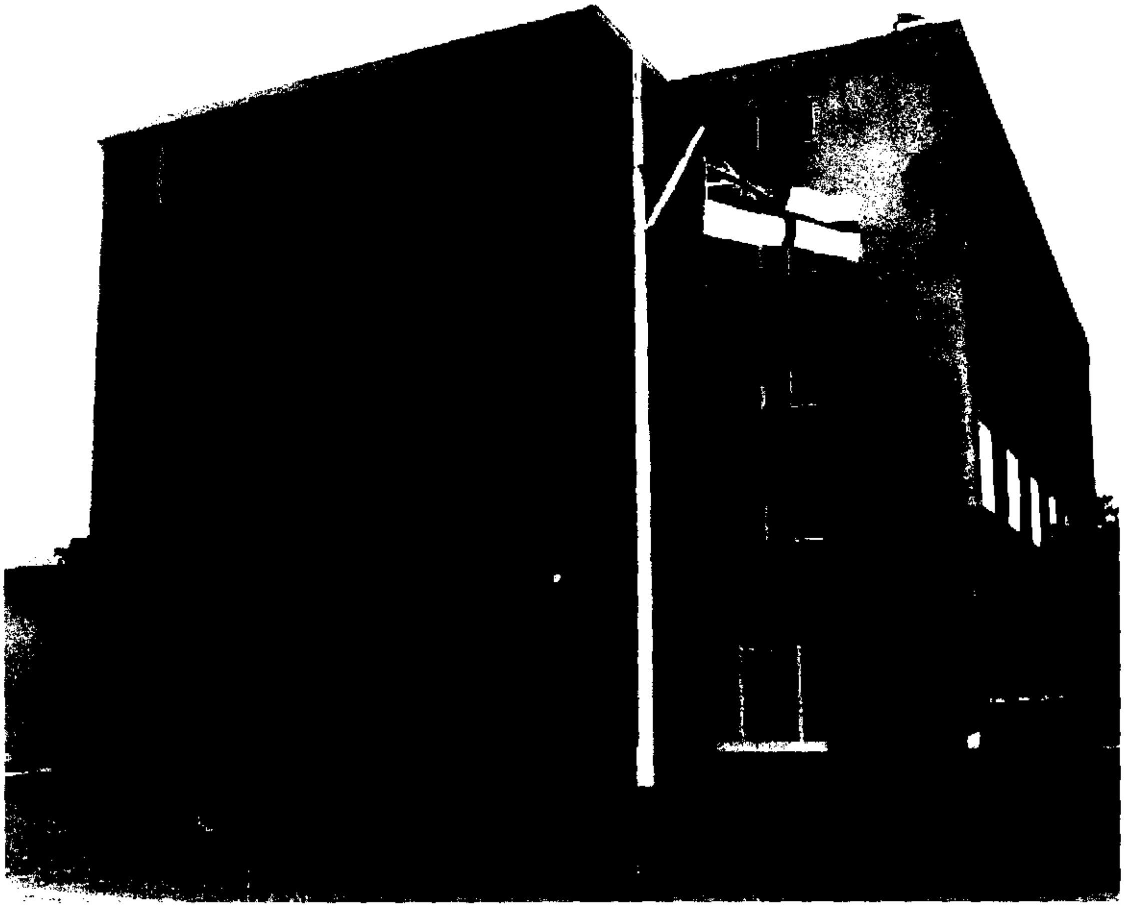

FIG.1 - THE ADMIRALTY TEST HOUSE, DERA PYESTOCK

Co-located with other specialist sections of DERA's Engine Test Department (ETD), the ATH facility provides a uniquely independent service which has shown itself to be impartial, flexible and most importantly these days, cost-effective. DERA Pyestock has concentrated on providing the customer, be it the Ministry of Defence (MoD) or a commercial organization, with an honest assessment of the test engine in terms of safety, specification compliance and suitability of purpose

Within the Armed Forces, the testing of 'suitability of purpose' has been the subject of much discussion. These discussions have rapidly grown over the last decade with the continued MoD drive for improvements in reliability and cost effectiveness, especially since the end of the 'cold war' and the governmental push to obtain 'more for less' with 'leaner, meaner' forces.

As part of this process, the marine gas turbine world was tasked back in 1985 to develop an engine that would satisfy this 'more for less' culture. The US Navy (USN), to be quickly joined by the RN, placed a Conceptual Design Study (CDS) with industry for an engine that would save some 30% on the annual fuel budget. Two initial studies were conducted when the CDS was first issued, using an Intercooled Recuperative (ICR) Rolls-Royce (RR) SPEY and an ICR General Electric (GE) F404 engine. When the USN power requirement increased in the early 1990s, the Westinghouse (now Northrop Grumman Marine Systems Inc. (NGMS)) lead consortium of Rolls-Royce Marine Power, AiResearch (now Allied Signal (AES)) and CAE, offered the RB211/TRENT 800 aero derivative 21MW @ 100°F propulsion engine as a practical solution and the WR21 ICR marine gas turbine appeared on the world stage (FIG.2).

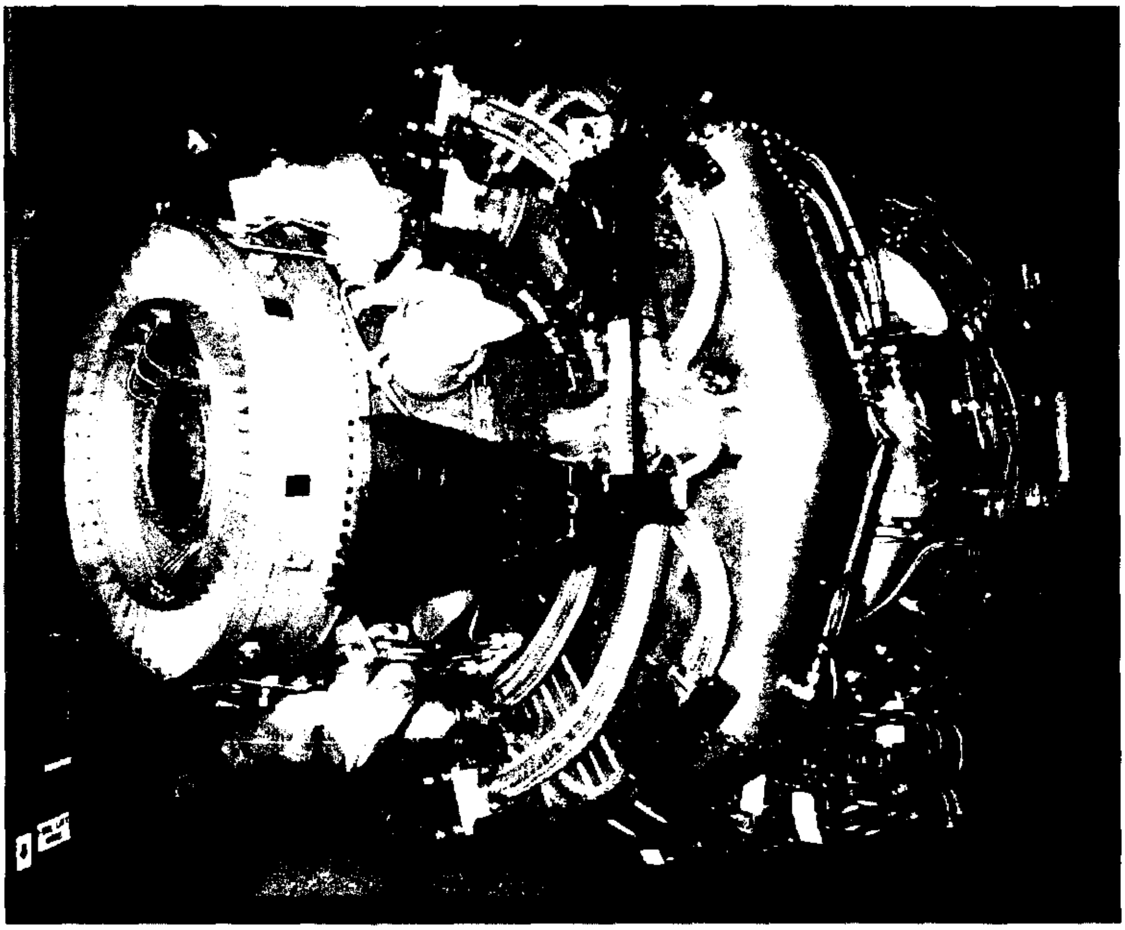

FIG.2 - THE WR21 ICR

This article intends to discuss the basic requirements looked for in a modern military marine gas turbine and the rationale for shore-based testing as seen for our experience with WR21 ICR.

Engine Requirements

If the propulsion engine design requirement was to simply provide a given amount of power for a stated size of vessel, the modern naval architect would be faced with a much simpler problem. In days gone-by this simplistic approach was acceptable because of the low level of technology used in both warships and weapons. These simplistic days are over and, if we are truthful, have been for quite sometime. The modern naval architect must now look upon the all the systems fitted into a warship from the wider aspect of how they affect the overall operational capability (fighting effectiveness) of the vessel. Should any one system prevent, degrade or adversely affect this over-all effectiveness then that warship has a major defect that could lead to its loss in time of conflict. To this end, it is suggested that the warship's propulsion plant and associated power supply systems should now be treated as yet another weapon system having a direct impact on fighting effectiveness; second best should not be allowed.

The modern day propulsion plant now has to fulfil a considerable number of design factors, which even just a few years ago, may have been given only slight attention. Some of them are listed below and are discussed later:

- Economy.
- Environment.
- Cost of Ownership - Life Cycle Costs (LCC) and day-to-day.

- Robustness of operation.
- Availability, Reliability and Maintainability (ARM).
- Noise.
- Infra-red signature.

It has already been stated that the main, initial reason for developing the WR21 ICR was to produce an engine that saved 30% on the annual fuel budget. This was based on the current usage by the USN and their LM2500 fleet of engines. Fuel costs, especially for gas turbines, are one of the main expenditures for a propulsion plant and large savings in these day-to-day operating costs are extremely popular and well understood in both the civilian and military communities. Whereas the commercial world would use the fuel savings to lower operating costs and hence increase profit margins, the advantages to the military are more involved.

Warships are limited in space and the naval architect has always fought against the many conflicting design parameters; weapons, armour, propulsion power (speed), personnel, and endurance. Therefore any machine which can offers 'more for less', as the WR21 ICR does, will fulfil one of the naval architect's greatest wishes. In this case, an engine using less fuel for a given power will enable the architect to give more endurance for a given fuel load or give more space to other systems for a given endurance. To show the extent of the fuel economy that is being demanded from the WR21, (FIG.3) shows the very flat the Specific Fuel Consumption (SFC) curve from the WR21 as compared with other marine gas turbines in service with the RN.

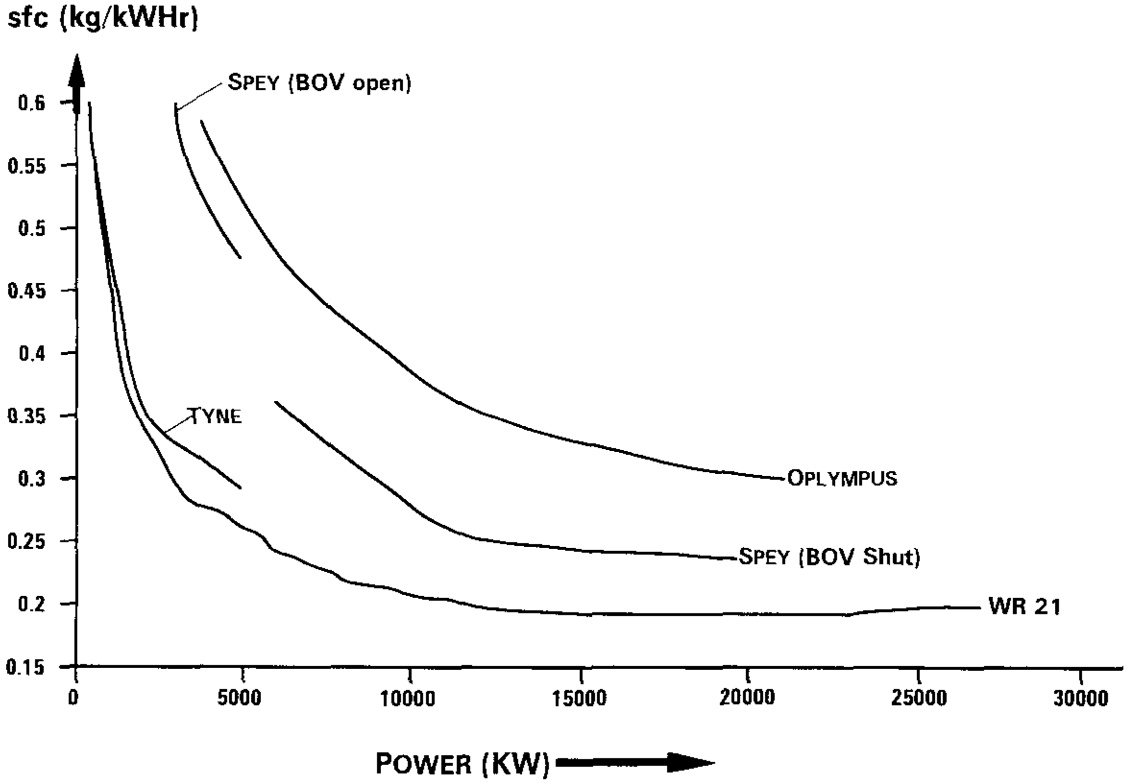

FIG.3 - SFC CURVE FOR MARINE GAS TURBINES

Many lessons can be drawn from the past and, not wishing to dwell unnecessarily, one that was quickly realised in the last World War was that a warship's endurance greatly influenced strategic and tactical plans. This is especially true today, when the number of available warship hulls and associated support vessels (tankers etc.) are considerably smaller and shows every likelihood of decreasing further. The extended endurance of the RN Diesel-Electric and Gas Turbine driven Type 23 frigate, over double that of previous classes, has already been used to great effect in the modern RN, especially in single ship operations.

Another aspect, which has grown steadily over the past few years, is the ever-increasing external restrictions being placed on the operation of all ships by environmental pollution control legalisation. The International Maritime Organisation (IMO), and in many cases individual countries, are continually pushing for tighter and tighter regulations on pollution control throughout the world. Controls on solid and liquid waste have been in operation for some time and are now common in most ports. The next move is to restrict the types and amounts of waste gases produced from the ship's propulsion plant, particularly NO_x and SO_2. In order that warships can operate without restriction in times of peace and limited operations, propulsion plants coming into service must not only meet the current regulations but also have room for growth in order to meet the future regulations that may arise in a ship's life time. The WR21 is designed to produce no visible smoke through the normal operating range, idle to maximum power. The estimated emissions through this power range are shown in (FIG.4). for NO_x, CO and Unburned Hydrocarbons (UHC). The WR21 ICR has to date shown every ability to meet this growing requirement.

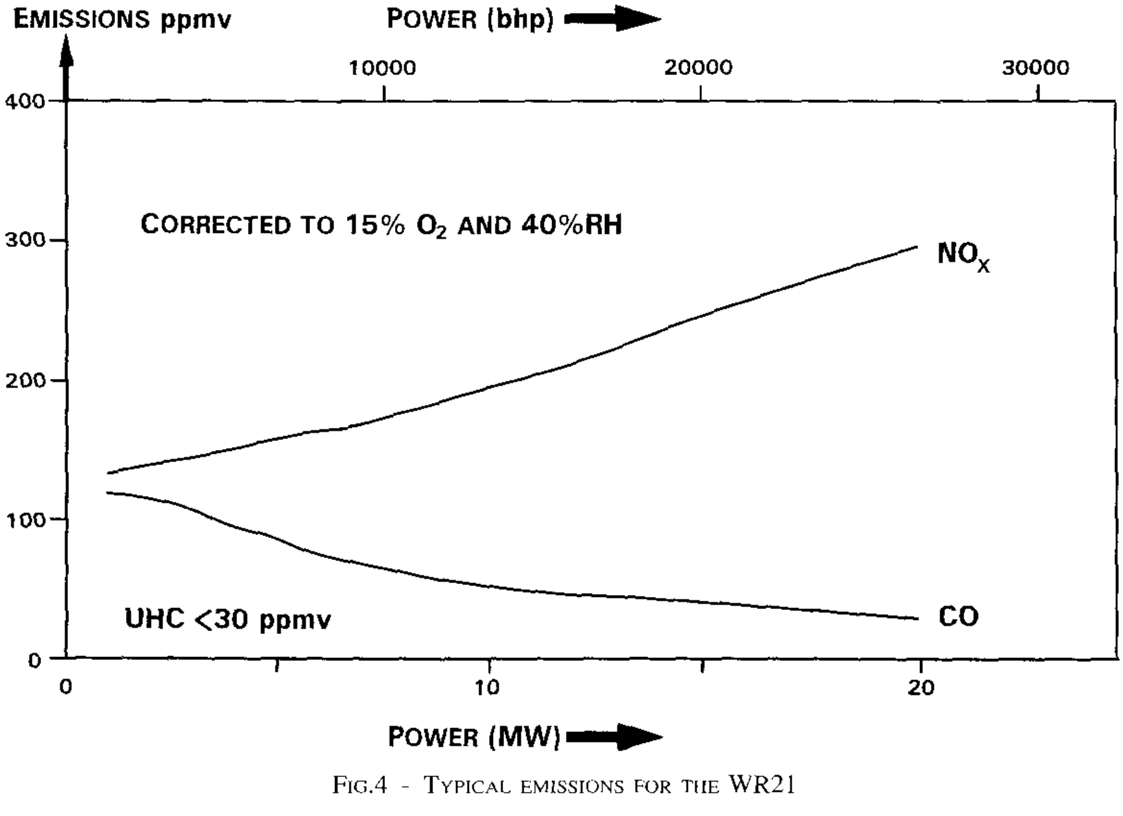

FIG.4 - TYPICAL EMISSIONS FOR THE WR21

The cost of ownership or Life Cycle Costs (LCC) is another factor that has become increasingly important over the last decade with the push for greater savings in Defence budgets. This has also coincided with the introduction of Integrated Logistic Support (ILS). Costs can be divided broadly into two main areas

1. Overall life cycle costs driven in many ways by the maintenance profile of the engine.
2. Day-to-day costs driven by fuel and consumables.

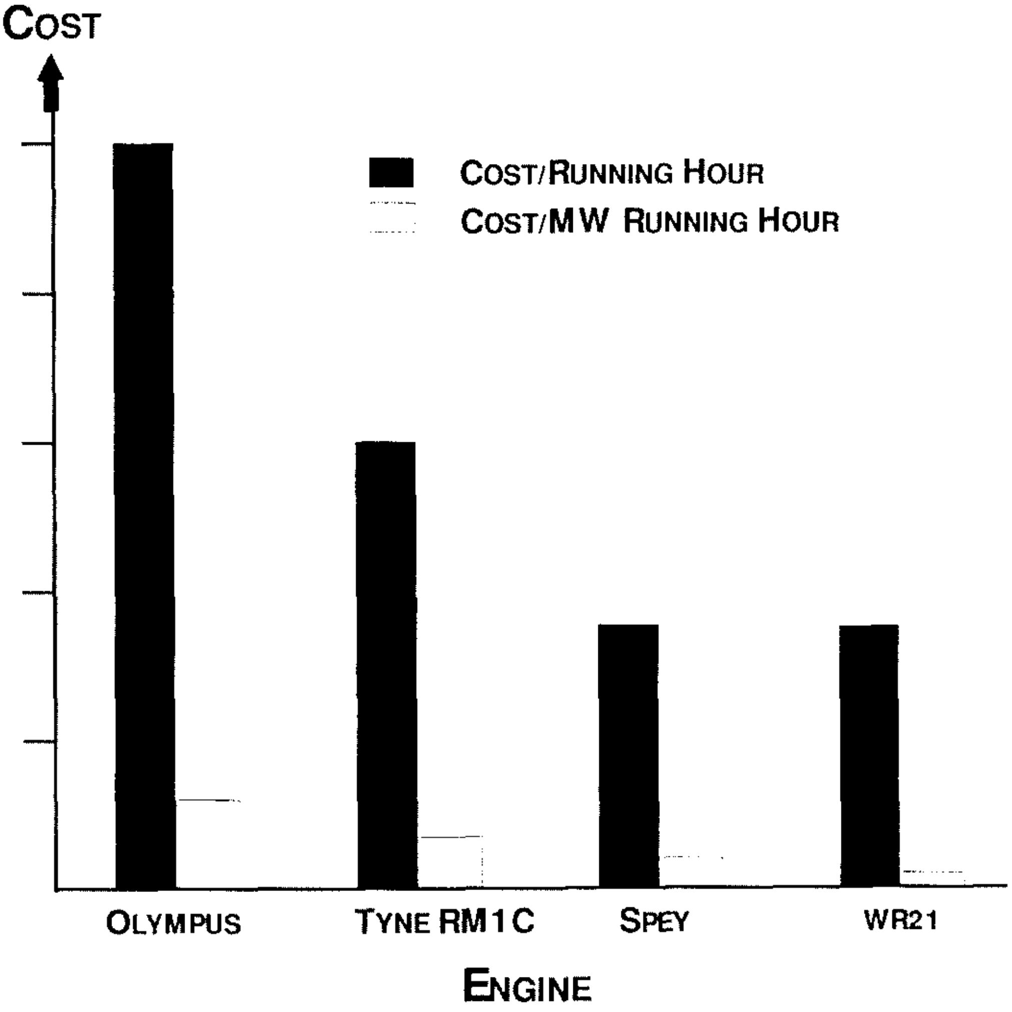

FIG.5 - ENGINE RUNNING COST COMPARISON FOR MARINE GAS TURBINES IN THE RN

The former is closely connected to the maintainability of the engine and will be discussed later, whilst the latter has already been discussed, being the main initial reason for the WR21 ICR's development. (FIG.5) shows the RN's experience with the cost of marine gas turbines since the early 1970s'. Although the costs per running hour have reached a plateau, the cost per MW still shows a decreasing trend that the RN is keen to maximize.

There are many different gas turbines presently driving the world's warships. The most common, with the NATO fleets, being the General Electric LM2500 and the RR OLYMPUS/TYNE/SPEY families. The design of these engines varies in many ways, but one aspect that has to be met is that of operational robustness. This need is demonstrated in a number of different ways:

Firstly

The engine must be flexible enough to cope with a variety of different vessels and operational profiles, for instance the LM2500 is fitted in the 8000 ton (CG-47) TICONDEROGA class cruiser and also the 2500 ton FFG frigates.

> *Secondly*
>
> The engine may also be faced with being fitted in similar vessels but performing completely different operational profiles. For instance the RR SPEY fitted into the RN's Type 22 ASW frigates as the main propulsion engine and also in the RN Type 23 ASW frigates as a boost engine where it is rarely used.

Robustness of operation should also be reflected in the engine onboard operation allowing the engineers and the operators as much freedom from restrictions as possible. An illustration of this is the ability of the engine to be operated as required irrespective of prior operations. The engine should have the ability to be stopped from full power and re-started at any time thereafter, there should be no time restrictions or cool down periods. This removal of complex operating routines greatly assists the operators cope with the unexpected events likely to occur in times of tension and conflict. Robustness of operation is also demonstrated by the engine's ability to survive various failure modes including wartime damage. The ability of the engine to work, even if at reduced power, with items inoperative or damaged greatly improves the overall confidence in the engine and allows the engineer to maintain power to the Command for as long as possible. Anyone who has doubts of these benefits should try and visit the RN's Operational Sea Training organization in Plymouth, England and witness a NATO vessel undergoing some of the most realistic operational sea training in the world. It is in this area that having serving naval officers involved with the development testing of an engine has shown the greatest benefit. The idea of robustness and lack of restrictions also produces the important side effects of improving the engine's overall availability.

Availability is a very simple idea but one which needs careful thought if it is going to be used as a qualitative measure of an equipment's worth. In very general terms, the equipment's availability is a measure of how often the operator can count on the equipment being ready to operate at a defined level and is closely connected to the equipment's reliability and maintainability. For some simple machines this is easily defined, but when this idea is developed for systems and hence whole warships the matter becomes vastly more complex. Whereas reliability is an important, intrinsic part of the equipment, obtaining higher levels of availability can be tackled on a much wider front. It is not intend to discuss the mathematics in this article, just give a few general examples of how the design of systems and procedures can improve availability and how these have been approached in the development of the WR21 ICR (FIG.6).

Until very recently, the RN use to clean it's gas turbines every 24-hours. This involves shutting down the engine, allowing it to cool and then crank water washing. Throughout this process the engine is 'Unavailable to the Command' and thus the ship has a reduced propulsion capability of approximately 25% for most warships. In peace-time this is generally not a problem, however in times of tension removing power from the Command can produce considerable problems and ultimately could place the vessel in danger or prevent it from fulfilling a given task. Close liaison is required between the engineers and the warfare operators to ensure that the requirements of both are met. To improve the availability of new propulsion engines, investigations are currently in hand with the WR21 ICR to extend the period between cleaning to beyond 48 hours. In addition, the development of a cleaning process which can be used whilst the engine is still running and hence still available to the Command, is also under active investigation. Although these measures do not sound earth shattering, they will greatly help, as there is a growing trend to reduce the number of prime movers in all future warships.

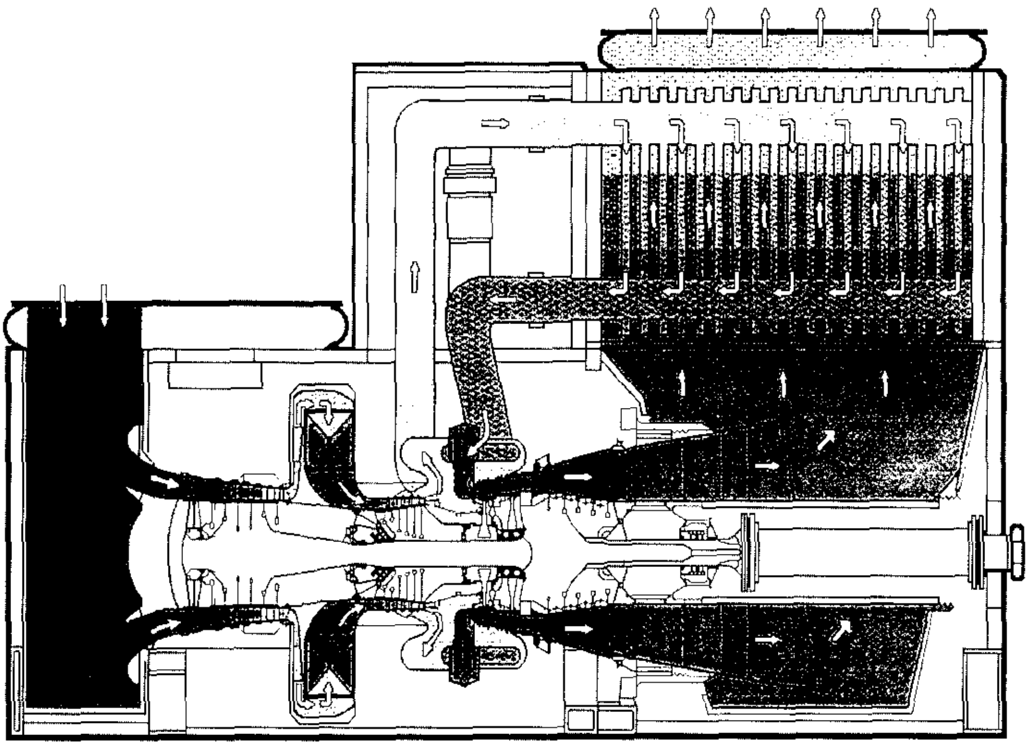

FIG.6 - THE WR21 ICR

Yet another aspect which greatly affects equipment availability is maintenance. This subject has come a long way over the last forty years and Reliability Centred Maintenance, Condition Based Maintenance, Vibration Analysis and many other maintenance tools are now well known and used throughout both the military and commercial worlds. It is a well proven fact that an equipment which has had maintainability considered at the design stage will be easier and more cost effective than one which has had maintainability 'thrown at it' later in life. A great deal of effort and thought has been given to maintenance, not only to reducing the actual amount required and it's frequency but also to ensuring that when maintenance is required, that it is easy to execute with the reduced manning and skill levels to be found in future warships. Experience from previous marine gas turbines is detailed in the table 1, and it is expected that the WR21 will continue this trend further.

TABLE 1—*Engine Release Life versus Achieved Life*

Engine	Original OEM Release Life	Current OEM Release Life	Achieved Life
OLYMPUS	3,5000 hrs/10 years	5,000 hrs/10 years	7,500 hrs/18 years
TYNE	3,000 hrs	5,000 hrs	7,000+ hrs
SPEY SM1A	3,000 hrs	3,000 hrs	6,000 hrs
SPEY SM1C	9,000 hrs	9,000 hrs	Lead engine at: 1,500 hrs

To give an example from the WR21 ICR, the engine can be visually inspected completely using dedicated endoscope ports and other 'easy to access' apertures. In addition, the engine is of a module design, similar to the RR SPEY SM1C, which allows a more rapid turn round of the engine from deep maintenance. This can also be used to provide a more flexible approach to

Foreign Object Damage or, for the military, other damage by allowing the ship to change just the damaged module rather than the whole engine. This concept has been demonstrated at DERA Pyestock by the removal and replacement of an IP compressor whilst the test engine remained on the test bed. Whether this approach will be taken up when the engine enters naval service will have to be investigated during Logistic Support Analysis (LSA) as part of the ILS process.

The discussion so far has tackled the more obvious elements of the engine and it's operation. To develop the growing idea that a propulsion system needs to be investigated from the wider aspect of how it effects the overall fighting effectiveness of a warship, we need to look at the propulsion system's by-products. Two, which come readily to mind, are noise and emissions.

Noise

This is a warship's greatest danger. Whether this noise is in the electromagnetic or audio spectrum does not really matter, any noise put into the ether or the water can be used to detect the vessel and hence target a weapon. The modern day marine engineer needs to be aware of these dangers so that his knowledge and that of the warfare operators can be used to obtain the most effective design. To illustrate this need for co-operation, it is now routine practice in the RN's ASW frigates for the Marine and Sonar senior ratings to monitor for machinery noise. A good relationship and a team approach is now essential if the ship is to remain quiet, maintaining sonar performance and reducing counter-detection ranges.

Resiliently mounted equipment is now the norm in all warships and extra protection against excessive noise can be provided by double mounting noisy equipment or equipment that must kept running during very quiet operational periods. This extra protection does not come cheaply and so an intrinsically quiet machine is always the first option in countering noise. A case in point is the noise difference between gas turbines and medium or slow speed diesels. Large diesels are difficult to mount effectively to the modern, very high noise standards that are required by surface warships towing anti-submarine sonar arrays. Hence with a mixed propulsion plant, CODOG, CODAG, etc., this difference in noise levels can lead to a propulsion engine being used outside it's normal or expected operational profile, leading to inefficiencies and degradation if used for protracted periods.

The WR21 ICR is, as are gas turbines in general, intrinsically quiet from the structural noise aspect. The advantage of WR21 ICR for the naval architect is that the flat SFC curve now provides the designer an opportunity to get away from using mixed propulsion plants to provide the economy required by modern navies, cutting capital costs and propulsion plant complexity. The WR21 ICR quieter airborne noise aspect also gives it a greater advantage over other gas turbines that should not be overlooked. The selection of a propulsion plant these days needs careful attention and must now take into account far more aspects if incompatibilities are to be minimized.

Emissions

Propulsion plant emissions are an ever-increasing problem for the naval architect and fall into two basic areas, the type and amount of emission gases and the heat output. The type and amount of emission gases has already been discussed under the comments on environmental legalisation, but the amount of heat that is put into the atmosphere is proving to be a major concern for new warships. The infra-red (IR) signature of a vessel has become increasingly more important as new generation weapons can and will use the heat plume generated from the ship's main propulsion plant to guide the weapon to the target.

Huge efforts have been made in recent years to reduce the quantity of heat that exits from a vessel. Gas turbines produce very hot exhaust plumes (approximately 500°C) and diesel engine somewhat less (230-300°C) producing an IR signature in the Middle IR(MIR- 3-6μm) and Far IR (FIR- 6-15μm) bands in particular. These bands are considered the most important because they have the most favourable propagation conditions in the maritime environment. IR signature reduction measures generally include cooling the gas plume by introducing ambient air into the plume before it leaves the funnel. With regard to the WR21 ICR, since the engine is fitted with a heat exchanger (recuperator) in the exhaust gas flow prior to reaching the funnel, the temperature of the gas flow at the funnel exit is considerably less than a simple cycle gas turbine. This reduces the requirement for cooling, making the task easier and less expensive. In addition, the reduced plume temperature will allow any IR decoy fitted to the vessel to work more effectively. This has the 'knock-on' effect of making the task for the decoy designer sufficiently less involved.

The list of design factors can be extended even further, but those discussed so far are believed to be the major ones and will give the reader a sound idea of the growing complexity now facing the propulsion engine manufacturer and naval architect. With the introduction of ILS, most projects these days now have to demonstrate these aspects before the equipment can be selected and this has in turn seen a large growth in shore based testing which will now be discussed.

Shore testing and risk reduction

The introduction of military equipment into service has always been, and will continue to be, a high-risk activity. This high level of risk has in the past been used to delay the introduction of new equipment into service, which in the longer term, has had a detrimental effect on the long term capabilities of the service. In order to improve this state of affairs the testing of all equipment has seen a considerable change, especially since the end of the last World War, and a more scientific approach to testing is now showing its benefits at sea.

The size and capabilities of the fleet have changed considerably in the last hundred years, although the opinions of many operators on testing have not. This opinion, that all new equipment must be tested at sea, gives the shore-based demonstrator an unenviable task of having to prove that shore-based testing is realistic. However, this opinion has to change as the reduced number of operational platforms available for testing is placing an impossible strain on most navies such that they are increasingly unable to provide a test platform. The building of a vessel just to prove a concept, for example the new Trimaran Demonstrator being built by Vosper Thronycroft for DERA to demonstrate this revolutionary new vessel, is very rare indeed, although the USN does use the USS *Yorktown* (CG-48) as a floating test bed for new technologies. The *Yorktown* has recently completed a 5 month deployment as part of the Smart Ship initiatives testing programme, but with all the project programmes currently in progress, a single ship cannot meet the demand for testing time and space. Thus, there has been a natural tendency to move more and more testing ashore.

This pressure has also been intensified by the greatly increased level of technology now found in all new equipment and, in many cases, the environmental and military affects of equipment failure. The submarine world has been regularly testing ashore since the introduction of nuclear propulsion; in the surface world this has become increasingly more so since the introduction of diesels and gas turbines and is planned to continue with the proposed introduction of the all-electric warship in the next century.

The ATH at DERA Pyestock had mainly been involved with the endurance style of testing in which an already developed engine was then subjected to a proving algorithm as a means of gaining knowledge of in-service performance without the risk of compromising an operational platform. The move from purely endurance testing into the world of development testing has been the most recent development at DERA Pyestock and required an extensive upgrading of the ATH facility. One of the main physical differences between endurance and development testing is in the amount of data that has to be collected from the test engine. It is in this area that the DERA Pyestock facility has changed the most. In the past data collection consisted of gathering a few hundred parameters at steady state and even less under transient conditions. This has dramatically changed, with a ten-fold increase being required at the start of development testing of the WR21 ICR (FIG.7).

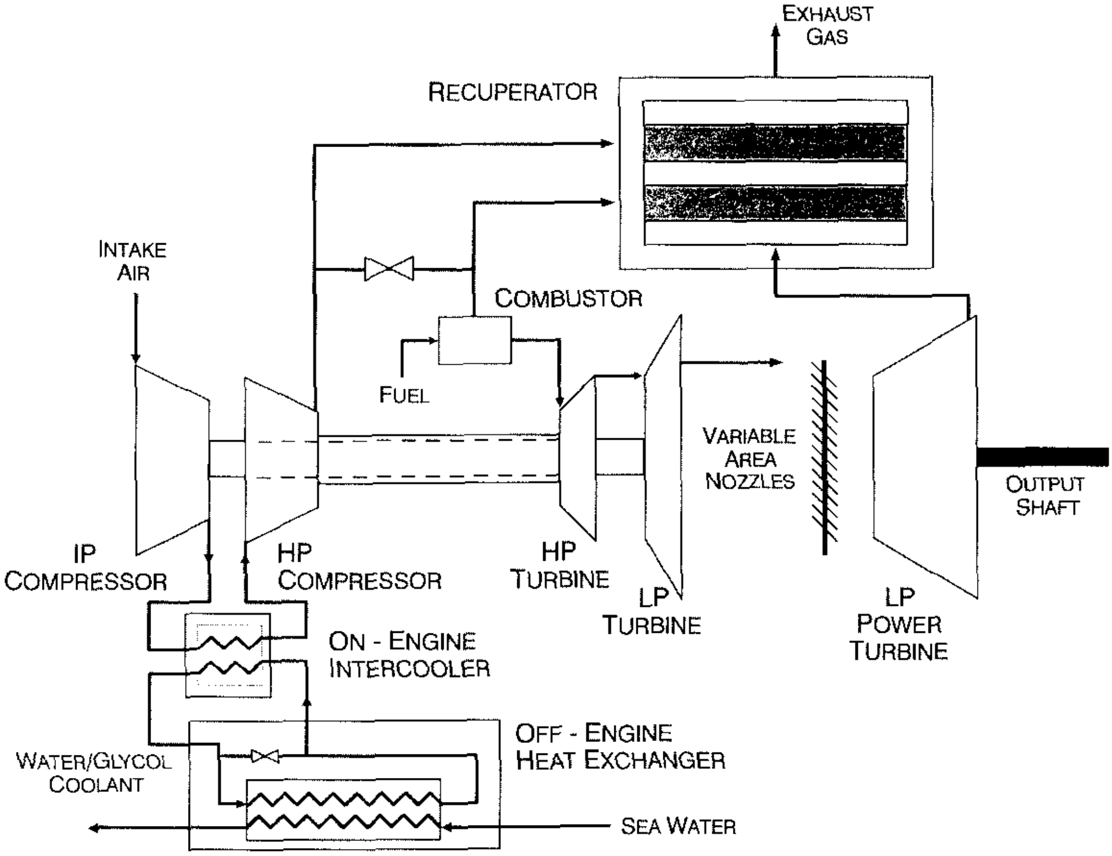

FIG.7 - THE WR21 CYCLE

The present Data Acquisition System (DAS) now collects approximately 3500 channels of real time data, at a base rate of 500 Hz. Some 250 of these channels can be allocated to the transient data logger, again at rates up to 500 Hz. Through experience, it has been found that a normal rate of 10 Hz collects sufficient data for most development purposes, although with a particular high-speed transient test, a faster rate (e.g. 100-200 Hz) maybe used. The scan rate can be changed at a moment's notice, which allows an excellent level of flexibility for the trial operator.

These changes were initiated by the requirement to assist with the development of the WR21 ICR within the required time scales to meet the proposed new platforms currently being planned. As a by-product, this has allowed the

US and British navies to be involved from the earliest stages, something which, in the UK, is unusual for propulsion engines.

Development testing covers a much wider scope than endurance testing and obviously starts at the earliest stages of the design process. In the case of the WR21 ICR engine, there was a considerable level of technical risk but it was believed that careful project management could reduce a good deal of that. Thus, well before the first light off of the WR21 ICR prototype in July 1994, a full risk reduction strategy was developed in conjunction with the USN and RN and carried out by the NGMS consortium.

There were over 30 'test rigs' which included several large Perspex models for flow visualisation, 2D and 3D computer flow simulations and rig testing of individual components, for example combustion chambers. This combination of simulation and rig testing has allowed the various components, particularly in the gas path, to be optimized prior to the build of the first prototype engine. This extensive work into technical risk management was further aided by the gas generator rotating elements being taken from, with some minor changes to skew angle, materials and anti-corrosion coatings, the already proven RB211 and TRENT 800 aero engines. Even so, there would always remain a significant technical risk in an engine which was at the forefront of current standards; areas such as the recuperator, intercooler and combustion chambers were marked as particular components which would need to be carefully managed throughout the development programme.

Overall risk was also considered in the execution of test runs and it has always been a policy that test runs were carried out on an increased gradient of difficulty. Thus any test was carried out on the engine simulation model prior to the real engine being subjected to the manoeuvre. In addition, transients were gradually developed, each small step being analysed to validate the computer model with real engine data. Predictably, the model can and has varied from that experienced in real life and considerable effort has been expended into understanding why the real engine and the computer model differ. After four years of development running the level of confidence in the model is now very high and has been used to great effect in reducing the number of development tests actually required to be run. This has allowed the development running to concentrate on those areas where the NGMS consortium team has the most concerns.

The WR21 ICR engine will also be the first engine for the RN where an operator will not have a physical connection with which to manually control the engine, everything will be done through a Man Machine Interface (MMI). No longer will there be a sometimes nervous junior engineer standing next to an engine with their hand on the throttle, there will always be a piece of software between the man and the engine, with all the normal safety circuitry to prevent those unnerving rapid acceleration and decelerations. The response to commands will be the same whether in remote or local control. This marked increase in the level of electronic control of an engine has concentrated the mind, even at the earliest stages of the development programme, and the safety critical software for the Electric Engine Controller (EEC) has been given considerable thought. The EEC is now used with a very high level of confidence.

As the reader will see, development testing is now a far more complex and involved subject. Not only are the purely technical aspects tested and developed, but also the modus operandi behind the use of the engine. This increased input now requires the customer to have a far greater and earlier input into the design of equipment. In order for this approach to work, the customer must know in greater detail how they use their present equipment and the changes need to meet future requirements. They must able to provide 'intellect customer' input into the design process, something that has not always been possible in the past.

Summary

The selection and testing of marine gas turbines has come a long way since those early days nearly 50 years ago. The WR21 ICR has been under development testing since 1994 and this will complete later this year. Confidence in the WR21 ICR to fulfil the various design criterion discussed in this article is already high and formal qualification will take place in the year 2000 in the form of a 3000 hours endurance trial which will also see the engine formally rated and accepted for service. The WR21 ICR has had many problems to overcome and the partnership between the NGMS consortium and the three navies has so far met the challenge of this 'at the cutting edge of technology' engine. Work is already in hand for developing the WR21 ICR further, particularly as a GTA prime mover, which is of the utmost importance for the all electric warship. It is strongly hoped that the ATH will be heavily involved with this work in the future, using it's extensive gas turbine testing and data collection knowledge to develop future marine prime movers for both the military and commercial sectors.

Acknowledgements

The authors would wish to thank DERA Pyestock, NGMS and Rolls-Royce for help throughout the production of this article. Particular thanks are due to Mr C.J. Bruce, Mr T. Gear and Lieutenant M. Rossiter RN for their assistance.

The views expressed in this article are those of the authors and should not be construed to be those of any Government department or agency.

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