THE INTRODUCTION AND APPLICATION OF THE INTERCOOLED AND RECUPERATED WR21 GAS TURBINE TO MARINE SERVICES

BY

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Introduction

Over the last 30 years the marine gas turbine has come to dominate the prime mover selection for the worlds technology advanced military navies. The Royal Navy in 1967 changed its propulsion policy so that the aero derivative gas turbine became the principal propulsion prime mover for major surface warships. In the early 1970's, the United States and Royal Netherlands Navies followed suit after independent studies highlighted the benefits of the aero derivative turbines. The reason for this change was that the simple cycle gas turbine offered the naval architect and marine engineer a compact, power dense, non-reciprocating machine that had the potential for development and high reliability. The late 1990's saw the first real commercial marine market open with fast ferries and cruise liners adopting the technology.

Since the 1970's improvements in maritime turbine applications have generally moved in parallel with aero engine advancement. Although this has proved immensely beneficial to the smaller marine industry, little has been done to improve the thermal efficiency of the gas turbine cycle, as large heavy heat exchangers could not be employed in the air. The now expanding marine market and the increase in fuel costs over the last 15 years has enabled the incorporation of these heat exchangers within the ship's hull to exploit the potential for substantial fuel savings through the adoption of advanced cycles.

The WR21, (FIG.1) is the only modern engine to have completed development and is currently being introduced to service, being jointly funded by the United States Navy, the Royal Navy and the French Navy. The engine is rated at 25.2 MW (ISO) and has an outstanding pedigree derived from its two parent engines, the Rolls-Royce aero RB211 and the TRENT. Modifications have been incorporated to marinize the engine components and to effectively integrate the heat exchangers and hot-end variable geometry.

The benefits of the WR21 when compared with simple cycle engines include a radical improvement in fuel consumption, improvement in maintenance through modularization and the ability to retrofit the ultra low emission systems currently in use by Rolls-Royce. The Inter-Cooled Recuperated (ICR) propulsion system package is designed to occupy the same footprint as existing powerplant installations and to deliver high levels of reliability, maintainability and component life. The design philosophy of WR21 as an aero-derivative was to capitalise on the excellent in-service experience of the modular aero engine parent, thereby mitigating technical risk. These benefits should cause a re-examination of the dominance of the diesel in both naval and commercial marine applications

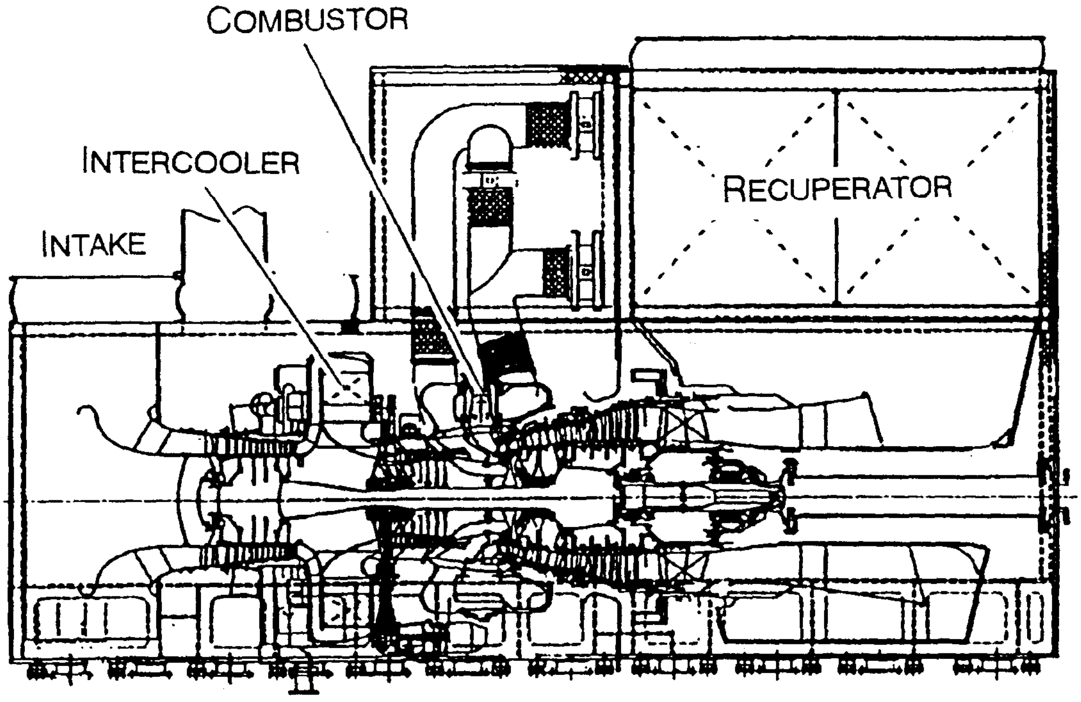


FIG.1 — WR21 CROSS SECTION

The combustion system requirements for the ICR cycle differ significantly from those of a conventional gas turbine, both in terms of the aerodynamic and thermal characteristics of the cycle and also the overall system architecture. The importance of this aspect of engine design cannot be ignored as the legislation regarding emissions progressively tightens.

THE ADVANCED CYCLE WR21

Recuperated cycles

The concept of an ICR gas turbine is not new. The first advanced cycle gas turbine, known as the RM60, went to sea in the Royal Navy's HMS Grey Goose in 1953 and continued in service for over 4 years. Although technically successful, the RM60 however, was not viable for long term production and the Royal Navy's first true all gas turbine class of ship became operational in 1958 with the simple cycle PROTEUS engine.

The WR21 achieves its significant fuel saving over existing simple-cycle engines through the use of heat exchangers to improve the part-power cycle efficiency as shown in (FIG.2). Recuperation alone improves the thermal efficiency of low pressure ratio cycles where the exhaust temperature of the gas turbine is significantly higher than that leaving the compressor. However, WR21 is a high pressure ratio cycle and just recuperation was not enough to meet the required fuel savings. Therefore an intercooler and a variable area nozzle system for the power turbine were fitted to meet the part load requirement.

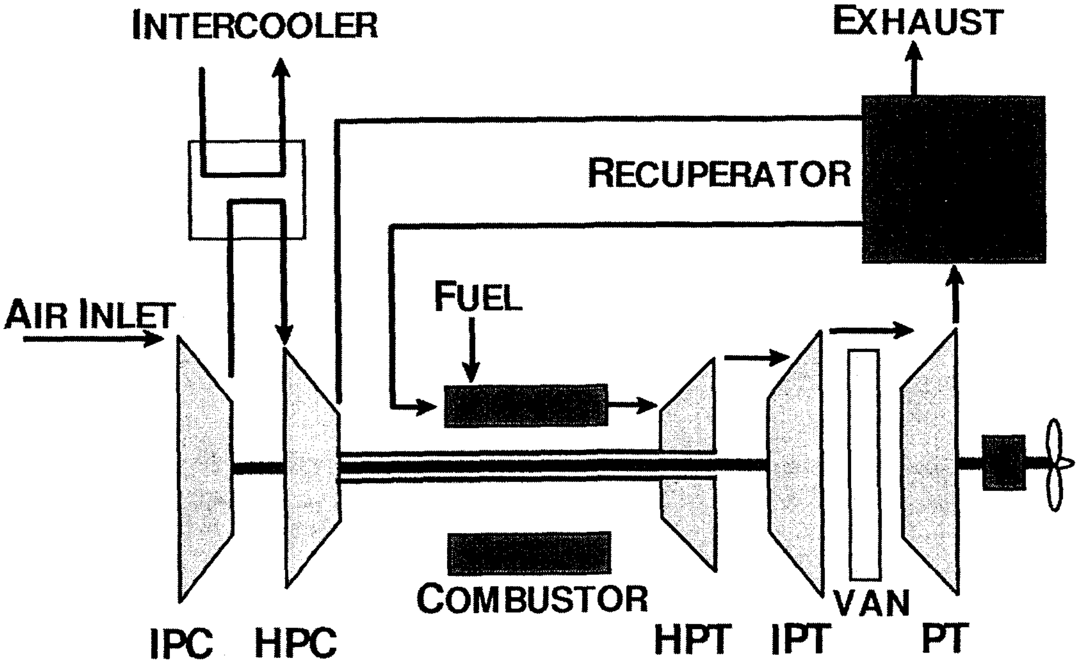


FIG.2 — PRINCIPLE OF OPERATION

WR21 Components

Compression System

Air enters the compressors via a composite radial intake, designed to maintain uniform circumferential velocity at entry to the gas generator. The Intermediate Pressure (IP) compressor, so called because it reflects the commonality with the 3 spool turbofan aero parent, has six stages of compression. Stages two to six are common with the RB211 whilst the first is modified to suit the increased flow requirements of the ICR cycle.

The intercase between the compressors transmits structural load from the engine through two support legs to the sub-base. It also houses the five intercooler segments in an outer casing and the internal gearbox within an inner casing. Both casings combine to form the airflow path between compression stages. Employing an intercooler between the compression stages on a twin spool cycle increases the specific power of the engine. The amount of work needed to drive the compressor is reduced thereby increasing the net power available. By pass valves situated on the intercooler are modulated depending on the pressure and relative humidity of the air so that condensation formation can be avoided.

Cycle thermal efficiency is approximately the same as that of a simple cycle engine as additional fuel is required to offset the drop in compressor exit temperature. However, combining an intercooler with a recuperator is attractive for higher pressure ratio engines, as it reduces the High Pressure (HP) compressor outlet temperature, increasing recuperator effectiveness and therefore overall thermal efficiency as well as leading to high specific power outputs.

The HP compressor also has six compression stages and differs from its aero origin by having a slight skew on the compressor guide vanes. Compression is split 30:70 between the IP and the HP compressor and both stages incorporate additional boroscope holes to allow greater flexibility of inspection.

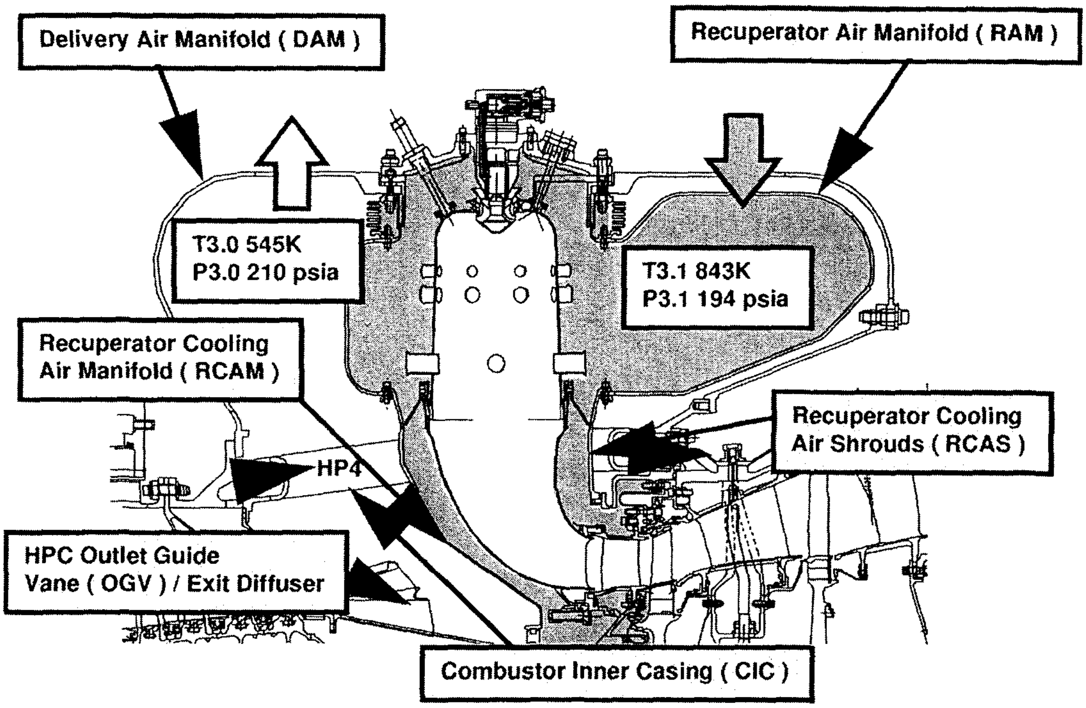


FIG.3 — COMBUSTION DESIGN

The manifold designs have undergone extensive analysis and testing to confirm:

- Structural integrity
- Aerodynamic flow distributions
- Ease of manufacture
- Maintainability.

The inner casing carries the structural load from the HP compressor outer casing to the turbine casing. This component is designed so that it provides the minimum of blockage for HP compressor exit air entering the combustion manifold and also functions to transfer HP compressor stage 4 air to the power turbine for sealing and cooling.

The Reflex Airspray Burner (RAB) method of fuel injection, developed specifically for the marine versions of the SPEY engine is utilized in the WR21 combustor. It achieves a controlled mixing of the fuel and air which allows a high burner exit Air Fuel Ratio (AFR) to be maintained with adequate flame stability. Based on previous experience, high (lean) AFR was considered an important factor in reducing visible smoke when burning diesel fuel.

In-situ removal of the combustor and burner is also a key feature of the WR21 maintainability strategy. The design permits not only ease of life monitoring but also timely repair or replacement of hardware (without engine removal) in the unlikely event of a premature failure.

Gas Generator Turbines

The HP Nozzle Guide Vanes (NGV) and rotor blade airfoils maintain commonality with the RB 211-524 parent with slight modifications to provide a smooth gas path from the radically swept discharge nozzles. The disc seals and bearing arrangements are essentially unchanged from their aero origins.

The IP NGV is skewed relative to the aero RB211-535 vane and incorporates the addition of a cast boss to facilitate the addition of a boroscope inspection hole. The blade is uncooled and manufactured from a single nimonic, common with the latest aero practice, to extend creep life.

Power Turbine

Consistent with pedigree of the gas generator, the power turbine can also attribute its origins to an aero parent, this time the TRENT. Stages two through five incorporate three dimensional orthogonal blade geometry to maximize turbine efficiency but the main difference lies in the incorporation of the Variable Area Nozzles (VAN) which control flow area. The VAN's are hydraulically actuated via a single geared ring, designed to maintain VAN to VAN throat areas within a specified tolerance.

The VAN is fully open at full power and closes at part power. This has the effect of maintaining the efficiency benefits across the whole power range by maintaining the high exhaust temperature at part powers. This allows the recuperator to be used to full effect giving the characteristic flat fuel consumption of the WR21 (FIG.4).

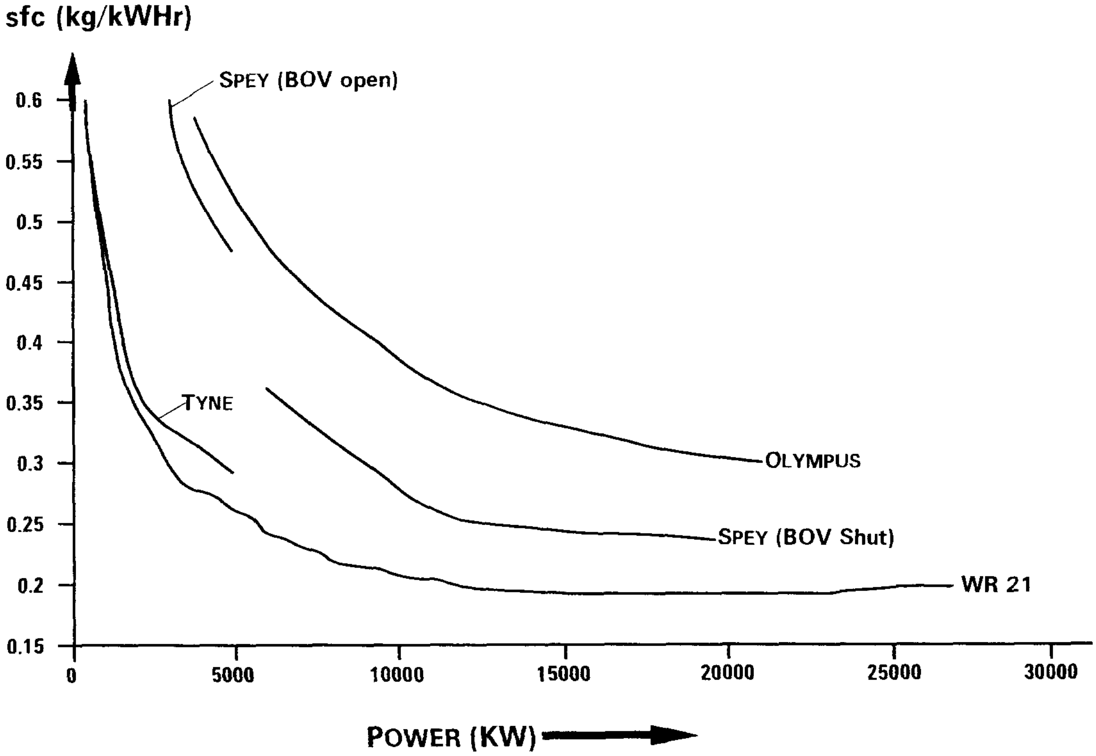


FIG.4 — ICR FUEL SAVINGS

The Recuperator

The recuperator for the WR21 has been designed to withstand higher pressure ratios than previously experienced. During engine testing, the unit has successfully undergone hundreds of hours of rigorous manoeuvres and cycles so that, ultimately, the operational unit can be installed for the life of the vessel.

A useful by-product of efficient exhaust heat recovery is low exhaust gas temperature, which is extremely valuable to a warship as it confers a reduced Infra-Red (IR) signature. Also of key importance in recuperated operation is low combustor smoke generation, since this further reduces IR signature and helps keep the recuperator operating efficiently without carbon fouling.

The Enclosure

To prevent contamination from nuclear, biological or chemical sources, the enclosure and sub-base assembly is fully sealed. The enclosure panels are structurally designed to meet blast overpressure, shock and airtightness. Insulation and acoustic damping treatment has been applied to these panels to meet thermal and noise requirements. All panels are removable with the exception of those welded to the recuperator housing. The engine can be withdrawn sideways by removing vertical supports at the front of the engine. The enclosure cooling is provided by ship's ventilation and air enters the enclosure via a connection above the recuperator ducts.

The Engine Control System

The Electronic Engine Controller (EEC), incorporating a Full Authority Digital Engine Control (FADEC) system, is responsible for controlling the system in response to commands from either the ship's monitoring and control system or from a local Man Machinery Interface (MMI). The controller includes:

- Sequencing
- Steady state and transient control
- Surveillance
- Fault detection and protection.

EMISSIONS

WR21 A cleaner engine

Marine legislation does not currently limit high levels of toxic pollutants such as CO or NO_x however the International Maritime Organisation (IMO) currently proposes legislation aimed at reducing pollution from reciprocating diesel engines. This will put limits on oxides of nitrogen and sulphur (NO_x and SO_x) from after the year 2005 although the implementation date for this legislation is currently uncertain.

Gas turbine emissions are not generally affected by this forthcoming legislation provided that they burn low sulphur fuels. The fundamental characteristic of continuous combustion in a gas turbine is that residence time at high flame temperatures. (which is the key cause of high NO_x) is capable of being controlled. This is not possible in a reciprocating diesel engine since combustion must be completed in a very short time at peak compression levels in order to give reasonable fuel consumption and prevent overheating of pistons.

The conventional combustor design utilized on WR21 will meet all near term maritime requirements in recuperated operation with the exception of coastal legislation introduced in areas such as California where land based rules for NO_x and CO are extended into harbours and estuaries. With the ICR cycle flexibility it should be possible to avoid punitive charges by switching to recuperator bypassed operation at low powers for manoeuvring in these areas. The requirement for low smoke tends to increase NO_x production since the smoke consumption zone does not rapidly quench combustion temperatures to low NO_x production levels. However, the high combustor inlet temperatures over the power range in recuperated operation ensures complete combustion with extremely low levels of CO and unburned hydrocarbons (UHC).

(FIG.5) shows pollutant levels across the power range where it can be seen that NO_x levels are high, consistent with low smoke across the power range. It is important to note that the proportion of NO_x present as NO_2 is very low and does not give rise to brown smoke. The only way to overcome high NO_x would be to introduce staged Liquid Premixed, Prevapourised (LPP) Dry Low Emissions (DLE) technology that could be retrofitted into the WR21 engine.

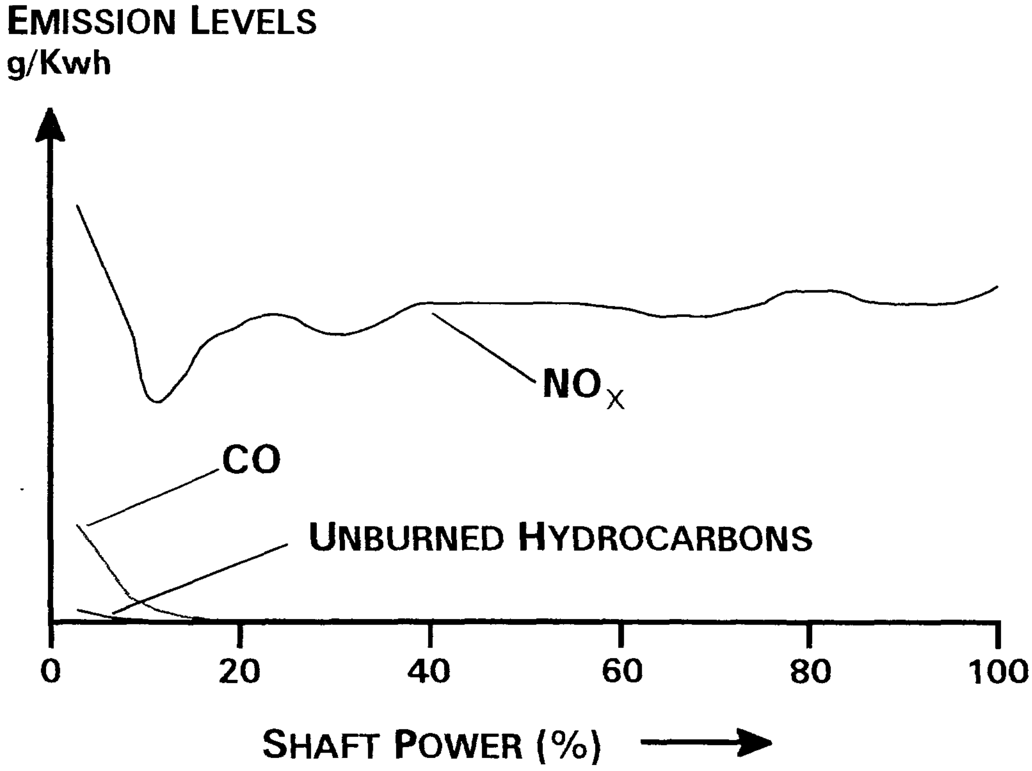


FIG.5 — WR21 EMISSION LEVELS IN RECUPERATED OPERATION.

The radial mounting of the combustor, although unique to WR21, is not unlike the Dry Low Emission (DLE) designs that feature in the latest Rolls-Royce industrial family of engines. A programme of work has been undertaken at Rolls-Royce to produce liquid DLE on distillate fuels, based upon lean pre-mixed, pre-evaporated (LPP) principles. This work has shown that a 10 fold reduction in NO_x can be achieved over conventional diffusion flame technology at high powers. Future ultra-low emission liquid fuelled combustor designs drawing upon the gas fired DLE combustor experience should be easily retrofitted if maritime emissions legislation becomes more stringent than currently proposed levels.

DLE technology does have disadvantages at lower powers when temperatures are not high enough to pre-evaporate the distillate fuel in simple cycle applications. This is obviated in complex cycles where the combustion system inlet temperature is kept higher at low powers.

Signature reduction

One of the most important aspects of operating in a military operational environment is the reduction in warship's IR signature. The need for complex stack designs to dilute the exhaust gas is removed in the ICR application, as a low exhaust temperature is a characteristic of the cycle. The inherent cleanliness of the ICR cycle also minimizes the visible exhaust emissions such as smoke and NO_2 (which gives brown smoke) as a smoke consumption zone is produced by controlled mixing of secondary port air.

The WR21 smoke characteristics are shown in (FIG.6). The target level for invisibility is around 15 SAE and this target allows for the maximum anticipated diameter of exhaust stack (and therefore the maximum visual path length through the exhaust plume). With the minimum likely stack diameter (determined by back pressure and performance loss) the target level would be closer to 20 SAE.

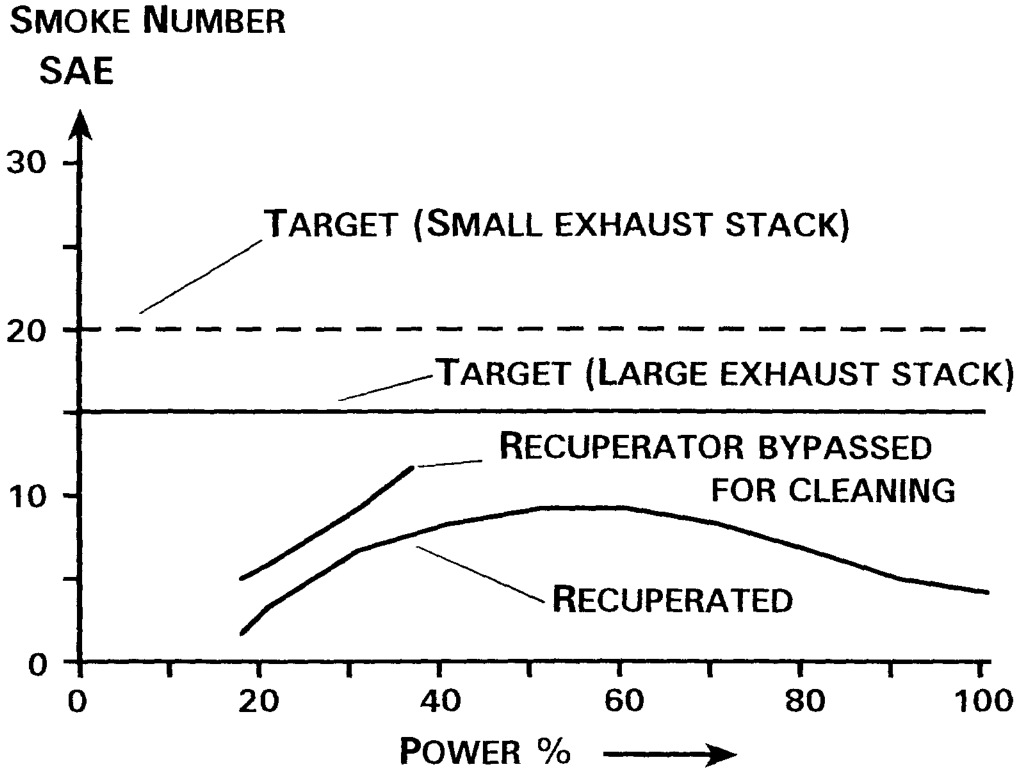


FIG.6 — SMOKE PRODUCTION

Development and Introduction to Service

To develop an engine such as the WR21 involves a considerable level of technical risk. Before the first light off of the WR21 prototype in July 1994, a risk reduction strategy was developed in conjunction with the US, Royal and French Navies. A summary of this strategy is at (FIG.7). This strategy was based on the use of analytical tools, rig and model tests and full system tests.

The analysis tools were used extensively in the design of the WR21 and covered the use of design and drafting programmes as well as the validation tools used to validate the aerodynamic, thermodynamic and mechanical behaviour of the resulting design. For such a challenging programme as the WR21, where the operation of the system can be over a wide range of ambient and cycle conditions, the use of analysis tools significantly reduced the amount of actual engine testing that was performed and made the testing conducted much more efficient. Calibration of these models against actual test also allowed the models, rather than test engines, to be used to determine performance at off design conditions.

During the WR21 design phase certain risk areas were identified where the analytical technology was not significantly advanced or the consequences of design errors would be so great that the analytical model on its own would be insufficient. To overcome this model testing was used to validate the analytical predictions. The model tests fall into 4 major categories:

(i) Aerodynamic models, usually perspex models, used to investigate flow behaviour in areas where the addition of the intercooler and recuperator have necessitated changes to the conventional gas turbine flow path.

(ii) Compressor and turbine rigs to define the performance of the major rotating components across the operating range of the engine.

(iii) Combustion rigs to address the combustor performance and feed conditions.

(iv) Simulator-stimulator tests of the electronic engine controller.

The latter allowed the investigation and proving of software algorithms before running on a real engine, greatly reducing the risk of component damage during development.

The design analysis, rig and model testing ultimately lead to a design that was carried forward into one of the 9 tests conducted under the development programme. These engines were used to conduct system testing, the purpose of which was to investigate the performance and interaction of components and ultimately confirm the engine system's suitability to enter the Introduction into Service phase. These engines were heavily instrumented to enable the gathering of data on the behaviour of system.

Over 2000 hours of rigorous development testing have now been completed. The final development test, the second of two 500-hour endurance tests, subjected the engine to its most arduous operating conditions enabling an initial production standard to be declared and approved by the US, Royal and French Navies for the project to enter the Introduction to Service Phase.

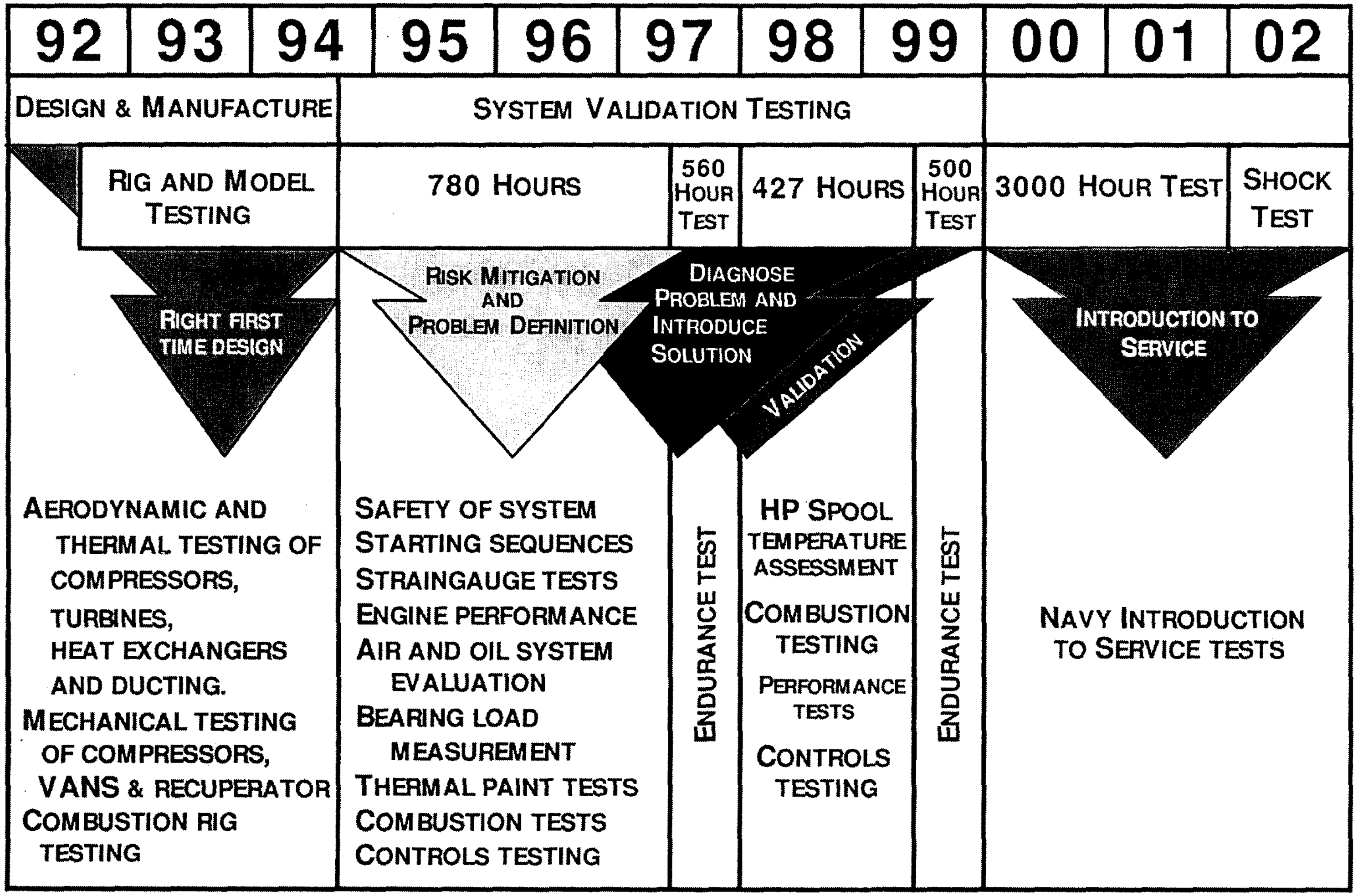
Introduction into service consists of the engine being subjected to an endurance trial and shock testing for the military. The US, Royal and French Navies all have similar requirements before an engine can be considered ready for specification or use in a ship application and each specify an endurance trial which replicates the conditions seen in service by its own operational requirements. From these three trials an endurance test has been devised which subjects the engine system to the limits. The trial consists of 3000 hours of creep, performance and cyclic profiles, similar to the extreme conditions seen in service of all three navies and the use of techniques to accelerate effects. The methods used to accelerate exposure fall in two broad categories, environment and operational.

Environment

As a ship can be operated in variety of geographical regions and subjected to various ambient temperature profiles, the endurance trial is conducted at 100°F and sea water inlet temperature 95°F. This has the effect of increasing the turbine inlet temperatures above that required on more typical ambient temperatures

Corrosion of the hot end has been found to be dependent upon the percentage concentration of sulphur in the fuel. During an engine's lifetime, the range of sulphur content fuels encountered will depend upon economic, geographical and legislative factors and the three navies perceive that the most likely worst fuel will contain 1% sulphur by weight. Thus for all the development tests and for the endurance trial this standard of fuel will be used.

For marine operation airborne salt is an obvious hazard. To stimulate the effects of compressor fouling and corrosion, the endurance trial will be conducted with various levels of salt added to the intake air.



DEVELOPMENT STRATEGY PROVIDES EARLY RISK MITIGATION OF THOSE AREAS OF HIGHEST RISK OR HIGHEST CONSEQUENCE OF FAILURE

FIG. 7 — SUMMARY OF THE WR21 DEVELOPMENT STRATEGY

Operational

It is typical that on naval vessels the engines are nominally operated at full power for around 5-8% of the time. For the endurance trial the engine will be subjected to above 90% for 44% of the time, giving a dramatic increase in the creep life usage of the power turbines rotor blades. However, the factor that normally determines engine life more than any other is the operation in the low to mid power range where the engine variable operating components (for WR21 these are the bleed valves and VANS) are exercised most frequently. To accelerate the operation of these components, the engine is subjected to a greatly increased number of cycles, where a cycle consists of a start followed by an excursion to full power and then to idle, completed by a shutdown. In a 4 hour period of endurance testing, the engine will complete 8-10 cycles compared to in service, where it may only see 2 or 3 a year. The engine system is also operated in all its failure modes, recuperator and intercooler bypassed, emergency trips etc., during the endurance trial to prove systems tolerance of events. Using these acceleration techniques mean that the 3000 hours of test reflect the type of effects seen in many more hours of operational service (for the Royal Navy, this is equivalent to 18,000 operational hours when the endurance trial profile is compared to general purpose frigate operating profile).

The final phase of the introduction into service is a conduct of a shock test. This is conducted on the same engine that has been subjected to the endurance trial to mimic possible in service conditions of a worn engine. The test consists of subjecting the engine, installed on a barge, to a series of explosive charges at a prescribed distance and direction from the barge. Success criteria are that the engine will continue to run and achieved defined levels of performance and operability after all the shocks.

In addition to the introduction to service testing, an integrated logistic support package will be conducted to determine the preferred WR21 engine system maintenance policy. WR21 aero parentage and constant close scrutiny by maintenance engineers has enabled a consistent proactive approach to maintenance concepts and design problem solving has meant that a fully modular engine system has been designed. This allows a fully flexible approach to maintenance that is now dependent upon the ship fit, not the engine. Modular removal, and replacement of engine and sub-system modules, and *in situ* repair, can be conducted inside or outside of the enclosure (FIG.8). The horizontal module change philosophies were incorporated into development engine builds to validate the suitability of the hardware and the maintenance tooling for this method of build and strip.

Removal can be via the air intake, as applicable to a DDG-51 US Navy destroyer or sideways utilizing shipping routes. The latter has been found by the Royal Navy to be more efficient, conducted in less time and will allow for module exchange.

WR21 Propulsion systems

In 1991 the development contract for the Intercooled Recuperated Engine (WR21) was awarded to a consortium of Northrop Grumman Marine Services, Rolls-Royce Marine Power and Allied Signal. The objective of this programme was to produce an engine that would fit in a US Navy destroyer (DDG51 class) propulsion system footprint with an annual fuel saving of 30%. The DDG51 propulsion system is the classic Combined Gas turbine And Gas turbine (COGAG) which uses a combining gearbox to provide power to the shaft line. This propulsion system or variants using an 'Or' instead of the 'And' gearbox is utilized by many of the modern navies and much of the WR-21 development work has been conducted to meet this variable speed direct drive requirement.

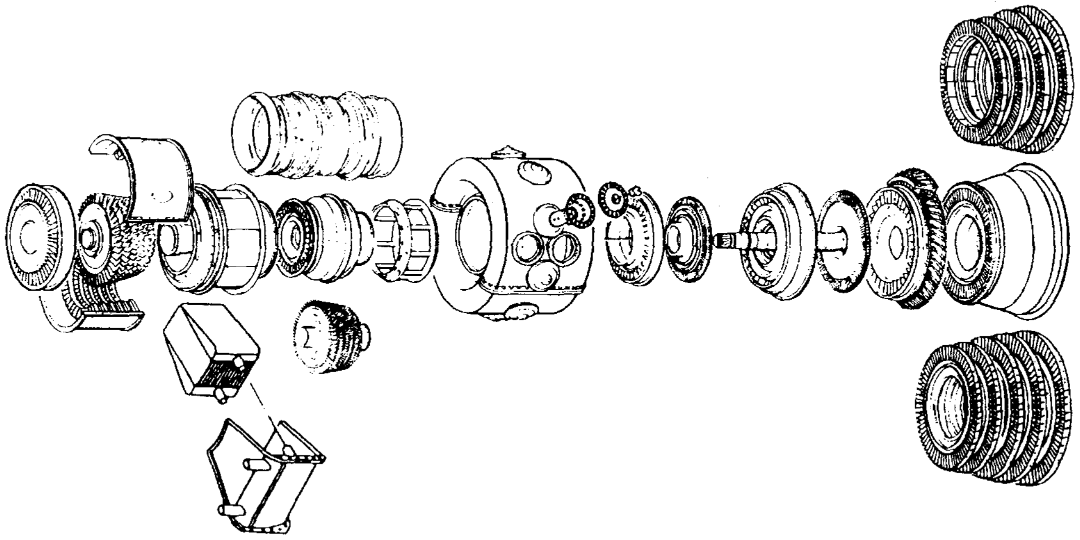


FIG.8. — MODULARITY CONFIGURATION OF THE ICR

As world order has changed so the operational and economic requirements for warship design has changed. The Royal Navy, like many others, are striving to reduce expenditure and have stated that warships are to be designed to be cheaper to procure and run, whilst maintaining their operational effectiveness. This pressure impacts on all factors in ship design, however as it is increasingly difficult to reduce the cost of weapon systems, so savings must be found from manpower, hull, propulsion power and electrical generation.

With the realization that these savings lie in the running costs of the fleet and with the current in service aero parent are being phased out, the navies have recognised that there is now another need for a step change in propulsion power generation. For the military market it has been recognised that the cost and risk implications of adopting new technology would be too high for any potential ship builder and would offer minimum return. The Royal Navy also saw that there was a potential for stagnation in the marine field as prime contractors select well proven but old technology. In 1996 the Royal Navy approved a new policy for marine engineering. The Marine Engineering Development Strategy (MEDS) prime objective is to adopt emerging technology that will give lower through life costs and comply with future legislation without detriment to the operational capability of the warship. The two technologies recommended in this policy are the adoption of the all electric ship concept (an integrated full electric propulsion and electrification of auxiliaries) and advanced cycle gas turbines.

In parallel, the commercial fleets have also been striving to find a propulsion and transmission system that reduces their total cost of ownership. In answer, full electric propulsion, utilizing diesels, has been adopted by cruise liners, shuttle tankers and ice breakers since the late 1980s.

From conception it has been recognized that the WR21 would have to meet this change in propulsion requirements and the concept of operating at a constant power turbine speed of 3,600 revolutions per minute has been successfully demonstrated during development testing. In addition it has been recognized that one of the key philosophies of electric propulsion is that the engine and generator should form a well-defined module that can be offered as a standard package for any ship. Initial designs of such a package have begun (FIG.9) and the validating integration trails, with the alternator and its associated automatic voltage regulator, are planned to be conducted in 2001 to support the Royal Navy's Electric Shore Test Demonstrator in early 2002.

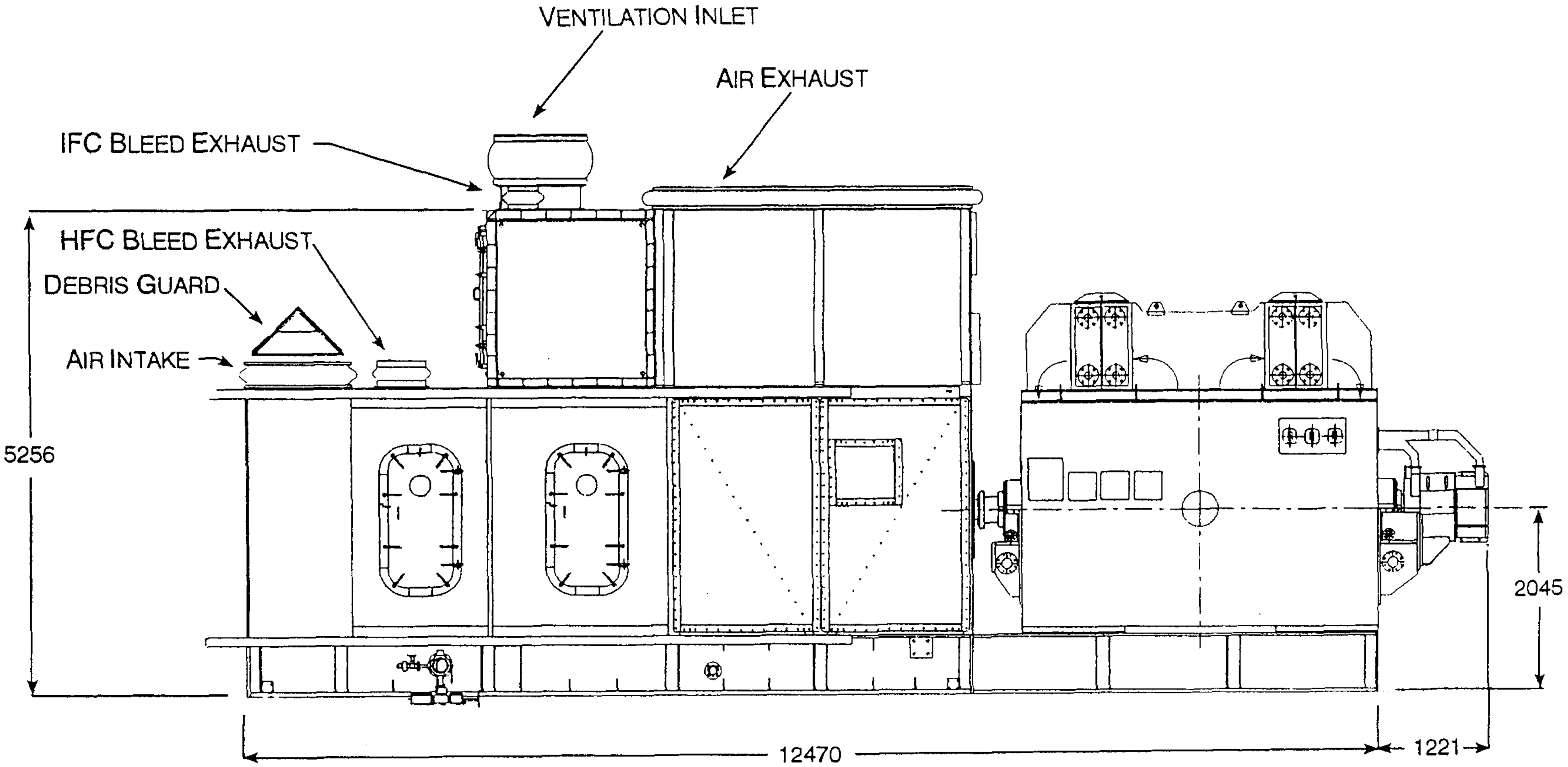


FIG.9. — WR21 ALTERNATOR SET GENERAL ARRANGEMENT

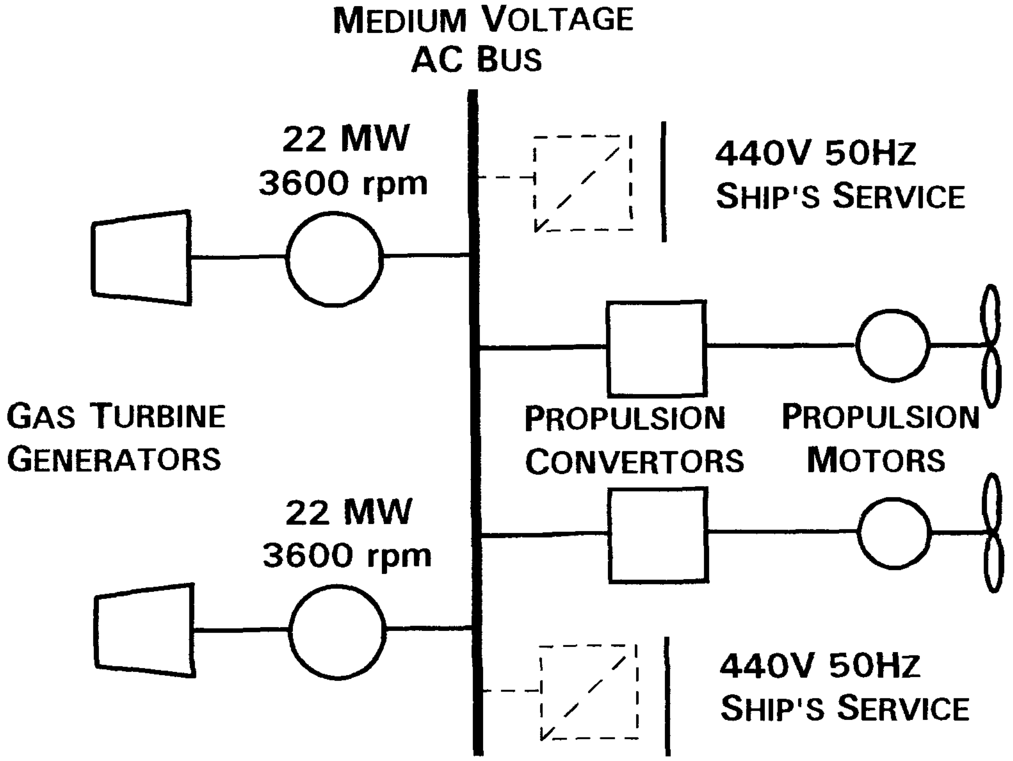


FIG.10 — A TYPICAL INTEGRATED FULL ELECTRIC POWER SYSTEM

An advantage in the utilization of WR21 in an integrated full electric propulsion system (FIG.10), is in its ability to be efficient throughout its power range as a single engine providing both propulsion and ship service load. When operating in navigable water, classification societies are insisting on the use of at least two prime movers to ensure continuity of supply. This results in each engine running typically at 50% rated output, which for a simple cycle turbine results in a substantial increase in fuel consumption, as can been seen from (FIG.11). In

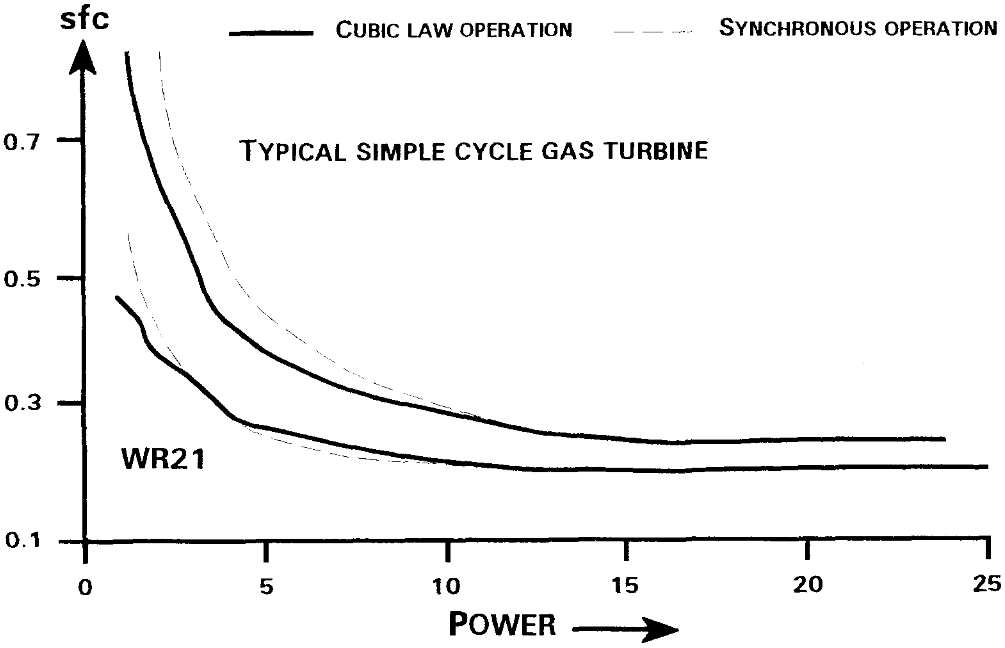


FIG.11 — COMPARISON BETWEEN SYNCHRONOUS AND CUBE LAW FUEL CONSUMPTION FOR ADVANCED AND SIMPLE CYCLE GAS TURBINE

comparison with diesels, although they offer good specific fuel consumption over a wider range than gas turbines, they attract problems with exhaust fouling and increased pollution as a consequence of low power operation.

There are a number of design issues that require careful consideration on introducing WR21 to a finite power system. The main issues are quality of supply and system transient stability.

Quality of Power Supply

The high impedance nature of marine power systems makes the system susceptible to voltage harmonic distortion. This distortion is caused by power electronic equipment drawing non-sinusoidal currents from the supply. This harmonic distortion increases as higher proportions of the generated power are converted by power electronics. The adoption of large converters for propulsion motor drives will increase the potential levels of distortion and the control of these harmonic currents will require careful management in the design phase.

System Transient Stability

The key to keeping any high power gas turbine in synchronism with a finite power system is the alternator design. It should be designed to operate at a load angle below 90E and with sufficient margin to absorb normal transients. However, the WR21 offers an improved transient response over a comparable multi-spool, simple cycle gas turbines. Transient response time is dependent upon the power turbine entry temperature and change of airflow. WR21 with its larger internal engine volume is able to respond faster to increases in load because the recuperator acts as an energy storage. Conversely the use of blow off valves throughout the cold end enables this energy to be dissipated on load shedding. WR21 has also been designed to operate near the point of flame weak extinction and therefore has addressed the problem of poor flame stability that limits simple cycle gas turbine operation in the constant speed mode.

To enable the WR21 alternator design to be incorporated into future ship designs the MoD is about to embark on a confirmatory programme. This will integrate the WR21 with a commercially off the shelf alternator/automatic voltage regulator and validate the performance prior to installation in the All Electric Ship Shore Test Demonstrator, due to take place in early 2002.

The adoption of the WR21 alternator as the prime mover in a propulsion system will allow the naval architect freedom to develop for warships the weapon position and payloads and for commercial applications the more important revenue earning items. Machinery room layout is simplified as a cruise engine or the more complex waste heat boilers and associated turbines are removed. This has the additional effect of reducing the maintenance burden and therefore manpower.

For cruise liners (troop carriers), tankers and container vessels, the WR21 allows adoption of the All Down Aft Machinery allowing generator set and the largest power consumer, the podded drive, to be adjacent. This lowers the service corridor and increases revenue space, passenger space for cabins, entertainment or recreation areas and reduces the shipping route size.

WR21 allows the warship designer to be innovative designing the ship to carry larger weapon loads, or allow the operator to transit further or faster or stay on station for longer for the same size vessel. The adoption of the WR21 alternator allows the engines to be dispersed to reduce vulnerability and for an aircraft carrier allows the engines to be placed in the island superstructure, removing the need for uptake and downtake penetration in the hangar space, therefore allowing more aircraft to be borne.

Conclusions

The WR-21 is an advanced cycle gas turbine system based on the Aero RB211 and TRENT engines. It has completed a detailed development programme and is about to commence the Introduction to Service phase that includes an endurance trial, which exposes the engine system to the most arduous of operating conditions.

Its adoption provides the ship and operator architect with:

1. Reduced emissions and ability to comply with any future emission legislation.
2. Low at sea maintenance and supports a reduced manpower requirement
3. High reliability and availability.
4. High fuel efficiency at part loads as well as full loads.
5. Minimum through life costs.
6. High power density.
7. Reduced noise and infra-red signature.
8. Minimum overall propulsion system volume and therefore maximizes space for weapons or revenue generating items.
9. A prime mover for a high powered gas turbine alternator for an integrated full electric propulsion plant.

The use of the WR21 GTA offers the system designer, reduced harmonic distortion and an inherent ability to retain synchronism under transient conditions.

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