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The Rolls-Royce Spey marine gas turbine

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SYNOPSIS

The Spey power units are some of the most efficient simple cycle gas turbines in the world. The Spey has an impressive aero pedigree, both military and civil, and in its current marine form incorporates advanced aero engine technology, which has permitted significant simple cycle improvements. For the future the well proven Spey core ideally lends itself to the step change in thermal efficiency demanded by the Navy planning for the next generation of warship; in its intercooled/regenerative (ICR) form it provides significant fuel saving, particularly at part power.

INTRODUCTION

The acceptance of the gas turbine by the major world navies for the propulsion of a significant number of surface combatants is now well recorded history. This has followed a single course from the mid-1940s, pursuing an almost wholly undiluted process of the adaptation and development of the simple open cycle aero engine. (Even the Metropolitan-Vickers 'Gatric' and G6 in the Tribal and Country Class of ship had evolved from aircraft origins.) In particular the aero engine industry, in pursuing its goal of higher thermal efficiency, has placed at the disposal of the Naval Engineer power plant which has improved its fuel consumption from over 1 lb/bhp h in the 1940s to current levels of 0.37 lb/bhp h.

The principal requirements of main warship propulsion machinery can be summarised as follows:

1. reliability – rugged construction and resistance to shock, blast and action damage;
2. flexibility – fast starting, rapid manoeuvring and good cruise endurance;
3. availability – long operational service with minimum onboard maintenance and minimum down time in harbour;
4. operational requirements – low underwater and airborne noise levels, clean exhaust and low infra-red emissions.

Since the design criteria of the aero engine include high reliability with numerous transient operations, minimum size and weight and good fuel consumption, in each of the above areas the aero derivative engine can demonstrate clear advantages over other propulsion units. The high power to weight ratio yields compact self-contained power units, requiring minimal onboard maintenance, which provide flexible power control with ease of operation and low underwater noise levels.

Additionally, the aero derivative gas turbine continually benefits from the evolutionary design improvements in its parents, providing the ability to upgrade the machinery system.

BACKGROUND

Rolls-Royce led the navies of the world into gas turbine propulsion with the introduction in 1953 of the RM60 unit for HMS *Grey Goose*. This unit was very advanced for its time, being intercooled and regenerated. However, it was swiftly followed by the outstandingly successful 3.35 MW (4500 hp) Proteus gas turbine which powered the 55 kn Brave Class fast patrol boats, and convinced the Royal Navy that gas turbine propulsion offered such attractive qualities that it should also be used for major warships. The British Amazon Class Frigates (Type 21), Broadsword Class Frigates (Type 22) and Destroyers (Type 42) followed. They were powered by the now very well known Olympus and Tyne COGOG machinery (see Fig 1); other major navies have followed this lead.

After the Olympus and Tyne developments were almost complete Rolls-Royce embarked on a new major naval project', in collaboration with the Royal Navy.

The various prospective Rolls-Royce aero engine parents were identified, but the required power of the new unit first needed to be established. This demanded study of the warships built in recent years and the propulsion powers which they had used. The Royal Navy's Whitby, Rothesay and Leander family of frigates of around 2500t had a major influence. To date, 41 of these vessels have been built for the Royal Navy, whilst a further 35 have been built for or by other countries. These ships have steam machinery of about 11 MW (1500 hp) on each of two shafts, and it was felt that the increasingly severe financial restraints on world navies would ensure that there would be a considerable market for ships of about this size in future. Hence a 12.75 MW gas turbine looked attractive and the aero Spey offered a variety of options on which a marine unit could be based. In the event the TF41 aero Spey was selected because it

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promised the achievement of the required 12.75 MW power at a lower maximum cycle temperature than any of the other Rolls-Royce aero engine parents, with the very attractive scope for uprating in due course. Thus the Spey SM1A (see Fig 2) was born and the choice of power and efficiency has been vindicated by the many orders taken for the Spey SM1A even before it entered service. At the time of writing this paper (end of 1989), 112 marine Speys have been sold or ordered and six classes of warships in three different navies have the Spey committed as their power plant (see Fig 3).

SM1A SPEY

The marine Spey is a derivative of the aero Spey turbo-fan engine. The turbo-fan engine provides a compromise between the turbo-prop and turbo-jet. Only part of the airflow entering this engine passes through the combustion system and turbines, the rest is partially compressed and then by-passes the rest of the engine, mixing with the core flow in the exhaust. This arrangement provides a quieter and more efficient aircraft propulsive unit. However, this mixture of air and hot gases is virtually impossible to use in a turbine since a homogeneous gas flow is required. It is necessary, therefore, to delete the bypass air and convert the engine back to a simple turbo-jet.

The bypass air is compressed by the first three stages of the LP compressor and so deletion of the bypass is achieved by modification to this component. Since the work required to drive the compressor is now significantly reduced, the excess is available to drive a free power turbine, again specifically designed for this application. A free power turbine enables the gas generator to operate at its optimum condition for all power/speed requirements and being gas coupled it is better suited to transient operation thus allowing greater control flexibility.

The gas generator changes to the aero Spey to produce the marine engine are described in Fig 4 and the features of the complete marine propulsion unit designated the SM1A are shown in Fig 2.

Activities to convert the aero Spey to an industrial gas generator started ahead of the marine programme, with the first engine introduced to revenue earning gas pumping service towards the end of 1976.

The lessons learnt in industrial service have been embodied in the design of the marine gas generator.

The highlights of the SM1A engineering programme

Four gas generators and two* modules have been dedicated to the marine development programme; one module at Ansty 44 Test House and the other at the naval marine wing of the National Gas Turbine Establishment (NGTE) at Pyestock.

The development contract for the full propulsion module with the MOD was completed in March 1982 and the first complete production standard propulsion module was delivered to NGTE, Pyestock, in early 1983 (see Fig 5).

The follow-on contract started in April 1982 and involved cyclic endurance testing of 3000 and 2000h trials on the first complete module and on-going gas generator work, all dedicated to life extension of the product under simulated marine testing at NGTE, Pyestock.

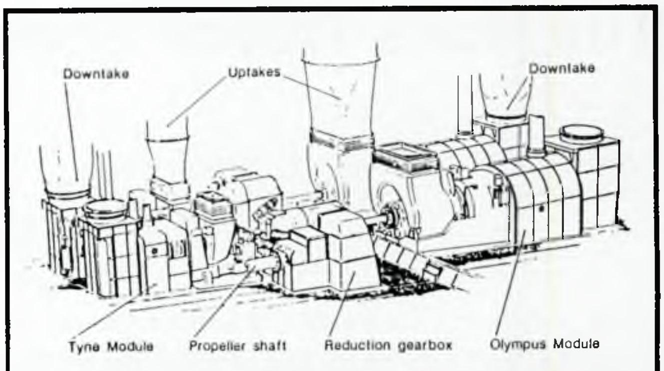

Fig 1: Typical Olympus/Tyne machinery arrangement

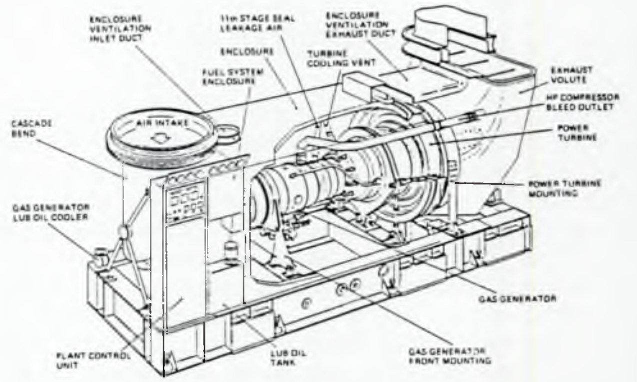

Fig 2: Spey SM1A marine propulsion module

Navy	*Ship type*	*Machinery*
UK	Type 22–07 frigate	2 Spey 2 Tyne COGOG
	Type 22–11 to -14	2 Spey 2 Tyne COGAG
	Type 23 frigate	2 Spey CODLAG
Japan	DDG guided missile destroyer	2 Spey 2 Olympus COGAG
	Improved DD destroyer	4 Spey COGAG
	Improved DE frigate	2 Spey CODOG
Netherlands	M frigate	2 Spey CODOG

Fig 3: Spey naval orders

The purpose of the modules for the shore test facility (Pyestock and Ansty 44 Test House) is to act as slave units in a plant designed to prove gearing, uptakes and downtakes and other features special to the ship configuration.

The first two production modules entered service with the Royal Navy in August 1985 installed on HMS *Brave*.

Hardware changes involved in the development

The changes were of two kinds – minor and significant.

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*For the shock barge trial this was increased by one unit, which has subsequently been installed, after refurbishment, at the Royal Navy training facility HMS *Sultan*.

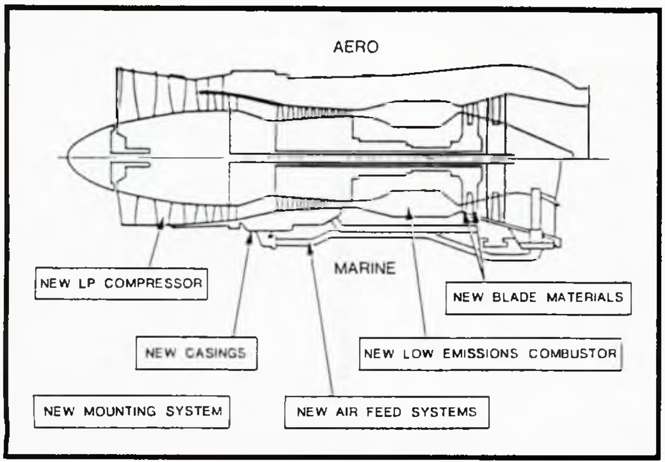

Fig 4: Marine Spey derivation

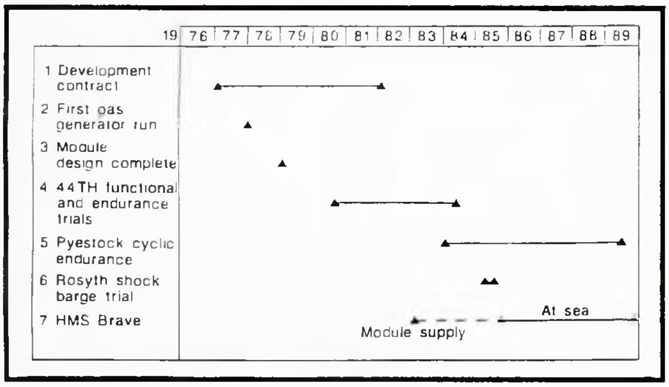

Fig 5: Highlights of the SM1A engineering programme

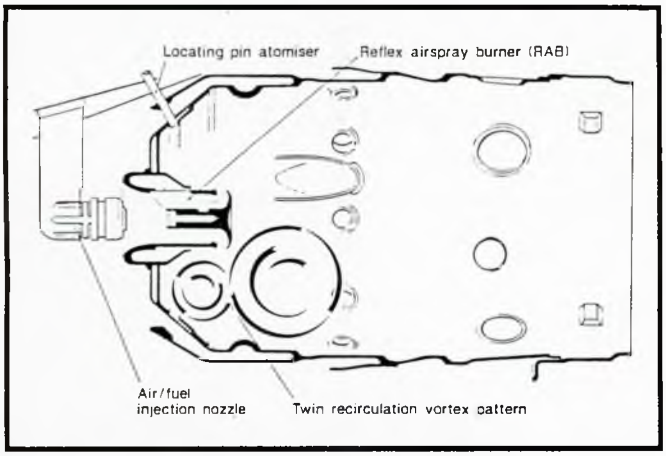

Fig 6: SM1A RAB combustion liner

Minor changes

Intermediate casing: A new casing was designed without the bypass features and was strengthened to improve its shock capability.

High speed wheelcase: Minor changes were involved in connecting this gearbox to the new intermediate casing and to reduce the number of accessory drives.

HP compressor: To cope with high shock accelerations and to provide additional air off-takes, the casing of this compressor was redesigned. The variable inlet guide vane drive system and its manifold were also revised in detail.

HP compressor diffuser: Changes were introduced to provide the manifold needed to collect seal leakage air prior to overboard discharge. An air supply is also provided to make available a source of HP compressor delivery air for ships services.

Turbine rotor blade materials: The forged blade of the TF41 aero Spey has inadequate corrosion resistance for the marine engine. Nickel-base, vacuum cast and coated is the current choice for the HP1 and HP2.

The HP rotor blades have improved cooling air entry holes and a 4-lobe root serration. This change optimises the balance between peak stresses and steady stresses. The second stage rotor blades also have a 4-lobe root serration.

Nozzle materials: The HP2, LP1 and LP2 nozzles have been changed to nickel-base, vacuum cast primarily to achieve corrosion resistance at a relatively low stress level.

Lubrication: The oil pump casing material has been changed from magnesium to aluminium alloy to improve its corrosion resistance. Individual chip detectors have been provided in each scavenge line.

An engine mounted hydraulic pump has been introduced to operate the variable HP compressor inlet guide vanes. This replaces the high pressure fuel system used on the aero engine, and has demonstrated satisfactory operation.

Significant changes

LP compressor: The LP compressor of the marine engine is a purpose designed unit which, although differing in blade angles, blade numbers and annulus profile, is mechanically similar to that of the aero TF41 Spey and the industrial MK 1900 Spey engines. The benefits of the redesign were increased part load efficiency, improved surge margin and a more equitable distribution of stage pressure ratios.

Combustor: Engine tests on a TF41 Spey fuelled by marine distillate demonstrated even with anti-smoke modifications that it did not meet the MOD requirements, nor was idling efficiency acceptable.

The duplex pressure injector was replaced with a simplex injector and radial airspray burner (RAB), the combustion liner and flare with conventional film cooling.

The RAB concept has two separate recirculation zones as follows:

1. At low power the primary recirculation zone operated at an air fuel ratio close to the stoichiometric to maximise the combustion efficiency (see Fig 6).
2. At high power the secondary recirculation zone operated close to stoichiometric conditions to minimise smoke production, and the zone immediately downstream of the secondary holes is designed to maximise smoke consumption. Engine trials have confirmed that exhaust emissions are below the 5/5.5 Bacharach typical visible level (Fig 7) and combustion efficiency over the useful power range is excellent.

SM1A POWER TURBINE DESIGN

A new marine power turbine was designed specifically to suit the Spey gas generator, for which the main requirements were:

1. long installed life;
2. high efficiency over the full operating range;

3. suitability for a range of applications;
4. low cost.

The power turbine design can be seen in Fig 8. It is a two stage machine designed to produce 12.75 MW at a nominal speed of 5220 rev/min. The design is suitable for multi-engined installations of fixed gear ratio and propeller pitch. In such installations an engine may be required to produce a given power over a range of shaft speeds depending on the number of engines in operation. The flat characteristic of the turbine ensures very little loss of efficiency in these circumstances. The design gear ratio between the power turbine and the propeller would need to be selected to ensure the most economical use of fuel over the most typical operating speed/time pattern.

Within the concept for the complete propulsion module the engine change unit consists of the gas generator only, and the power turbine remains as part of the permanently installed equipment. To achieve this requirement the power turbine has been designed for robustness to conservative design parameters, with full attention being paid to transient thermal gradients.

The two turbine disks are overhung on the mainshaft, which is supported by tilting pad journal bearings to a single central bearing casing. The main axial thrust bearing and auxiliary reverse thrust bearings are also tilting pad types. Rolling element bearings were rejected for this application since, in order to achieve the required long installed life, the axial load would need to be reduced by the use of a pressure balance system using gas generator compressor air. The performance penalty for such a system would have been about 1% on fuel consumption and was considered unacceptable.

The bearing casing is supported by the main mounting ring *via* struts through the axial portion of the exhaust diffuser, and the whole of this assembly is connected to the baseplate by two trunnions on the mounting ring and supports at the rear of the bearing casing. This rear support will assist in isolating the power turbine and the gas generator from any potential balance or vibration problems of the main output shafting. The stator system and inter-turbine duct are also located directly by the main mounting ring. However, in order to ensure maximum efficiency, the control of the radial clearance for the rotor blade tip seals has been achieved by radially locating the nozzle guide vanes at the inner diameter and matching the growth of the diaphragm and nozzles to that of the disk and blades. Maintenance of concentricity and accommodation of thermal mismatch between the outside of the nozzles and the stator casing are achieved in the normal manner by the use of dogs.

This particular type of turbine configuration was selected in conjunction with the Royal Navy after a detailed comparison with the other main options of either a straddle mounted rotor system, or a pedestal mounted rotor system with both pedestal and stator systems located by a horizontal baseplate. The advantages for the configuration chosen were:

1. Unlike the straddle mounted turbine, which requires bearing supports to pass through hot ducts both upstream and downstream of the turbine, this configuration only requires supports through the cooler downstream duct. The rear bearing support is, of course, in a cool area. Thus the oil systems for all the bearings can be routed through cool and accessible areas. Access to, and inspection of, all bearings can be achieved without removal of the gas generator. This feature was clearly of benefit to the customer.
2. Concentricity of turbine tip seals and labyrinth seals is closely controlled and does not rely on a connection through the baseplate as is the case for the pedestal arrangement. This is particularly important for a high efficiency turbine which must accept shock loads.
3. With the gas generator removed the overhung turbine arrangement provides good accessibility for inspection, and partial dismantling if required, without disturbing the bearings and the mounting arrangement.

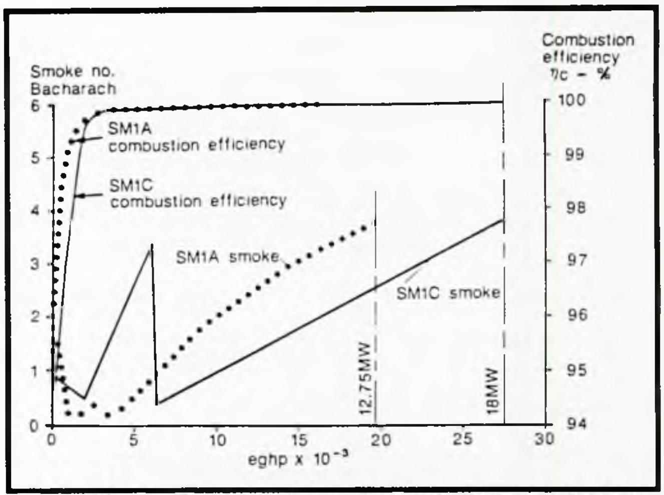

Fig 7: Marine Spey engine emissions; RAB combustor

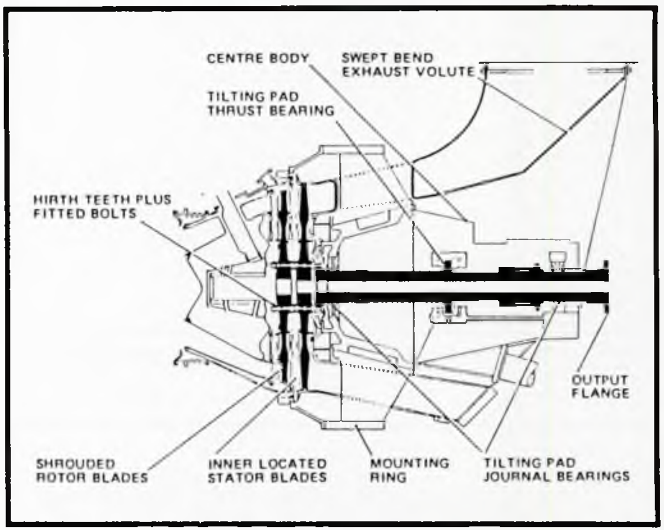

Fig 8: Marine Spey power turbine

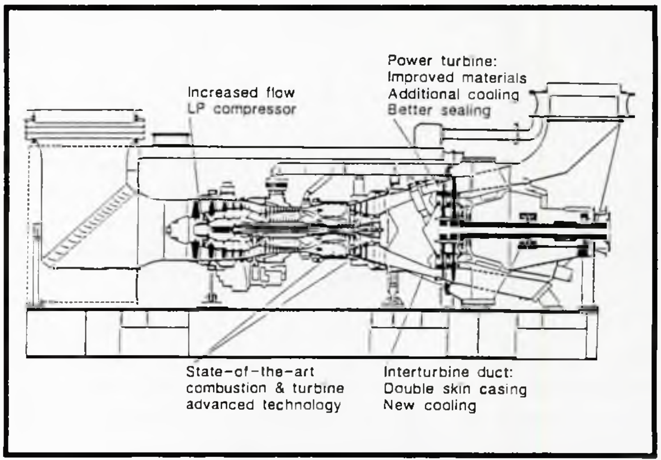

Fig 9: Spey SM1C design changes

4. As is also the case for the straddle mounted turbine, the chosen configuration does allow a reasonable degree of freedom for the use of alternative exhaust volute arrangements to suit the demands of particular installations. The preferred volute design for the MOD requirements is the swept bend shown in Fig 8.
5. The mainshaft output flange is readily accessible at the rear of the module and is not buried deep within the exhaust volute as would be the case for a straddle mounted design.
6. Although the use of a baseplate, as shown in Fig 2, is the correct arrangement for the fully integrated propulsion module concept, alternative lightweight mountings, more suited to light craft or surface effect craft, are possible by picking up the main mounting ring directly from the craft structure.

CHINA SPEY

The successful marine SM1A configuration has now evolved into an industrial unit. Five units have entered commercial operation for electrical power generation at two sites in China. The two lead units were handed over in March 1987 and have each achieved 16 000h of trouble-free operation, which further demonstrates the robustness of this design.

SM1C SPEY

Whilst encouraged by the early orders for the Spey SM1A, it has become obvious to Rolls-Royce that, despite the rising costs of shipbuilding, many navies are still building or acquiring ships significantly larger than the Leander Class, and that the power requirements for these are in excess of that available from the 12.75 MW Spey. It was therefore decided to take advantage of the stretch potential of the SM1A and an uprating programme was undertaken to increase the power output of the Spey to 18 MW by 1989. However, it was obvious that this uprating must be achieved without sacrificing the very high efficiency at 12.75 MW, which was responsible for the early success of the Spey in the market.

The guidelines for uprating the unit were:

1. the operational cycle was within the Rolls-Royce demonstrated technology;
2. that the maximum possible commonality should be maintained with the existing SM1A components;
3. that the opportunity should be taken during any redesign to introduce cost reduction features;
4. that the new unit, when achieving 18 MW, should have a life no less than that of the SM1A at its 12.75 MW rating;
5. that the opportunity should be taken to merge the design of the Tay 650 whenever possible, so that common parts could be included in the SM1C, thus taking advantage of the latest technology.

UPRATING DESIGN PRINCIPLES

The 40% increase in shaft power has been obtained by the application of improvements in technology.

In order to minimise the technical risk the engine design changes were constrained to ensure that the engine operating experience accumulated to date was built upon, and that the advanced technology incorporated was fully proven. In addition, the opportunity was taken to improve the design to ease maintainability, whilst ensuring easy interchange with 'A' rated gas generators. The considerations affecting each of the major SM1A components (Fig 9) are now discussed briefly in turn.

Low pressure compressor

A major change was made to the low pressure compressor in order to increase the air mass flow as follows:

1. the inlet diameter of the unit was increased;
2. the first three stages were lengthened, requiring new compressor blades;
3. the compressor was allowed to run at a higher speed.

The result is an increase in pressure ratio and greater air throughput.

High pressure compressor

The existing high pressure compressor design was suitable for the duty, ie an increase in air mass flow.

Combustion

Whilst the existing fuel pumps, being identical to those on the much larger Olympus engine, would be suitable for any proposed uprating, the combustors have been checked for satisfactory combustion at all powers up to the new maximum selected.

New technology has been applied to the combustion chamber system as the burner 'cans' now use a graded Transply material for the flame tube barrel and one piece flare. The revised dilution inserts change the turbine traverse to achieve the desired turbine life.

Transply is a sheet material which has internal air channels and hence a high heat transfer and thus minimises the amount of air used for cooling.

High pressure turbine

The new rotor blades, nozzles, rotor disks and honeycomb tip seals designed in conjunction with the successful Tay 650 turbine, employing identical design features which incorporate the latest aero technology, thus enable the turbine temperature to be increased by 150°C, yet still maintaining the same surface metal temperatures on the rotor blades and nozzles.

Low pressure turbine

Changes have also been made to the low pressure turbine section, with revised profiles to nozzle and rotor blades (except the LP2 rotor). Honeycomb tip seals and improved rim seals have been provided to increase the efficiency.

Power turbine

The power turbine has had minor design changes to introduce a cooled double-skin inter-turbine duct to accommodate the higher gas inlet temperature. Changes have also been made to nozzle materials and improved tip seals enhance the power turbine efficiency.

Advances

The design changes have brought about a significant improvement in performance. Power has been increased from 12.75 MW to 18 MW and fuel consumption has been reduced by more than 5%, from 0.396 to 0.372 lb/bhp h. This has been achieved for a propulsion unit of the same module/enclosure size.

These advances make it an attractive proposition to upgrade the 100 or so SM1A modules delivered or on order with SM1C units. The Royal Navy did this during November/December 1989, during a normal refit period, the two SM1A gas turbines in HMS *Brave* being replaced with SM1Cs.

HMS *Brave* is a Type 22 frigate which was commissioned in 1985. It was originally ordered with an Olympus/Tyne COGOG package but was delivered with SMIAs in place of the two Olympus turbines.

This was done in order to gain early operating experience with the Spey SMIA engines. Because of the lower powers of the Spey compared with the Olympus a reduction in ship speed was inevitable but acceptable, as minor variations in maximum speed are less significant in modern naval operations.

Later Type 22 frigates have had the machinery fit changed to the COGAG configuration, allowing Tyne and Spey SMIA power to be combined for maximum ship speed. Now that the SMICs are installed, HMS *Brave* will return to sea with a speed capability similar to that of the other Type 22 frigates with Olympus.

The Royal Navy is evaluating life cycle costs based on the SMIC turbine. It will be assessing fuel costs, maintenance and life components, based on service experience from the re-engined HMS *Brave*, which will establish the benefits to be gained. At present the cost of the SMIC propulsion unit is similar to that of the SM1A model. It is predicted that through life costs will be significantly reduced.

When a navy requires both high top speed and optimum endurance, the solution favoured has been to install two powerful boost gas turbines, such as the Olympus, and two diesel engines for cruise operation to achieve the lowest fuel consumption for cruising activities. With the considerably more efficient SMIC turbines in place of the Olympus in this CODOG configuration there is a major saving in fuel consumption, but at the expense of a reduction of a couple of knots or so in maximum speed.

The SMIC turbine has a much improved part-load efficiency so, taken overall, the gains with diesels at low speed are not great. Some navies, notably the Japanese Navy and the US Navy, prefer all gas turbine machinery. From the point of view of fuel efficiency the COGAG plant, based solely on the SMIC in two, three or four engine arrangement, offers the simplest and most flexible marine propulsion installation, and is also probably the cheapest to run when all aspects of through life costs are considered.

The highlights of the development programme are shown in Fig 10.

Highlights of the SM1C engineering programme

The Joint Venture contract with the MOD started in late 1984 and is to be completed by mid-1990. The development programme associated with this project is now complete.

It is worth noting that the uprated gas generator had its first run on the jet bed in August 1987 and also, during 1987, the 'C' standard power turbine and module were supplied for the Dutch 'M' frigate contract. Recently the Royal Navy has also become committed to this standard unit.

During 1989 an intense period of endurance and cyclic running of the shore trials module was completed at the Ansty 44 Test House. Also, during 1989, the SM1C gas generator was installed at Pyestock to demonstrate its compatibility with the SM1A power turbine.

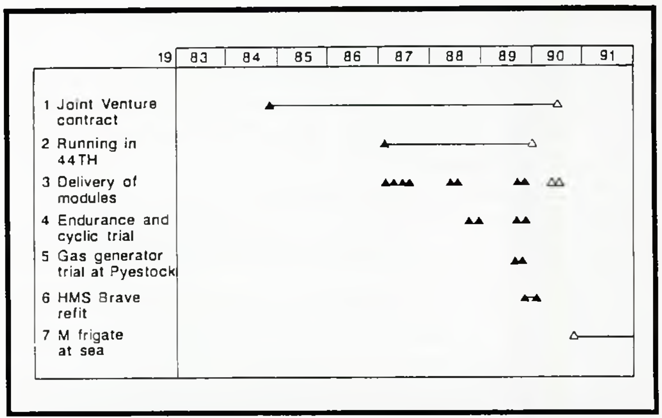

Fig 10: Highlights of the SM1C engineering programme

HMS *Brave* has been fitted with an SM1C power turbine by rotor and stator exchange and the SM1C gas generator has been replaced with production SM1C engines. HMS *Brave* is expected to be at sea during January 1990 followed in the last quarter of 1990 by the 'M' frigate ships.

INTERCOOLED REGENERATIVE SPEY

The next step, the ICR (intercooled/regenerative) Spey, will give large reductions in fuel consumption, much more power and increased flexibility.

As far back as 1953 Rolls-Royce pioneered the application of a purpose-designed marine engine with aero-type gas turbine technology, resulting in a warship propulsion unit, the RM60, which powered the Royal Navy patrol craft HMS *Grey Goose*.

A significant feature of this power plant was the use of an air intercooler between the separate low and high pressure compressors, another intercooler between the first and second stages of the high pressure compressor, and an exhaust gas heated regenerator to heat the compressed air before the combustion chamber.

This concept of the past is now being taken up again, as the result of Rolls-Royce carrying out a series of concept studies culminating in the Spey ICR propulsion plant.

Benefits

With the Spey some 25% additional power can be provided for the same combustion firing temperature by the use of the intercooler, and the regenerator allows a reduction of up to 40% in specific fuel consumption.

The intercooled/regenerative concept has not been applied to aero-type gas turbines since HMS *Grey Goose*, primarily because of the size and weight of the available heat exchangers. However, significant advantages have been made in heat exchanger design, thus allowing their incorporation into the design of gas turbine packages. The concept is the most appropriate for the next generation of warships because of the arrangement incorporated into the ICR Spey, and this, coupled with the advantages of 40 years of heat exchanger development together with the advances made in marinised aero gas turbine design, offers considerable fuel savings and increased flexibility of propulsion engine operation.

Major areas of concern for today's navies are the cost of fuel and the maximum range of vessels of frigate size and above. These parameters are of particular concern to the US Navy with

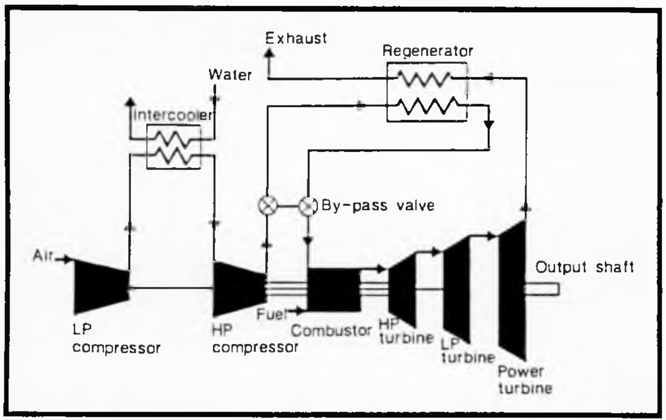

Fig 11: Intercooled/regenerated block diagram

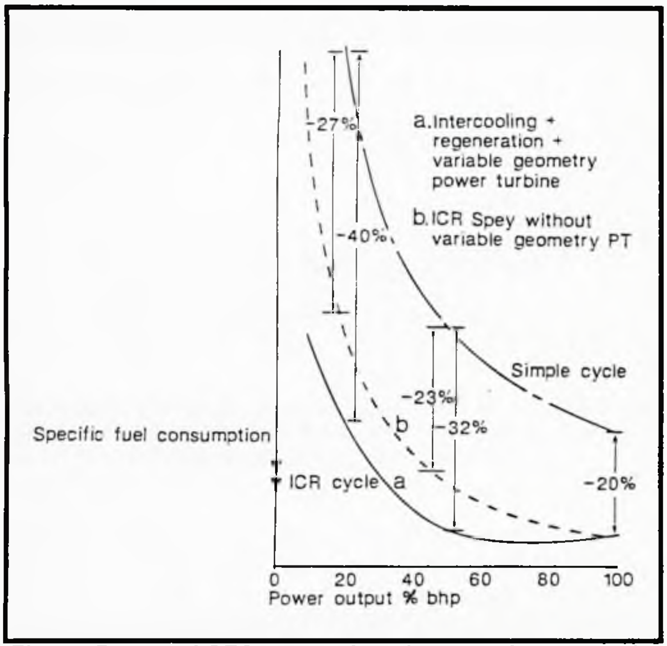

Fig 12: Part load SFC comparison between intercooled/ regenerated and simple cycle gas turbine engines

its global operations. Recent deployments in the Middle East far from home bear this out. The US Navy is, therefore, looking for less fuel-thirsty propulsion plants for its future major warships and is aiming to reduce annual consumption of propulsion fuel by as much as 30%. The ICR Spey offers this without compromising the basic simplicity and robustness of the marine gas turbine.

ROLLS-ROYCE/ALLISON COLLABORATION

To meet these demands, Rolls-Royce, in conjunction with Allison Gas Turbines, has been developing the ICR Spey marine propulsion unit. The SMIC module forms the basis for this development, which adds intercooling and regeneration to this simple cycle second generation turbine unit. The US Navy has specified the ICR propulsion engine as one of the cluster of technologies for future ships and has already awarded competitive preliminary design contracts, some of which Rolls-Royce/ Allison Gas Turbines have won and satisfactorily completed. The US Navy issued a request for proposals in October 1989 for a demonstrator and development programme. Design, production and testing schedules aim to make the initial ICR Spey propulsion modules available by the mid-1990s.

Dependent on the ship machinery configuration, ICR Spey engines can negate the need for cruise engines thus simplifying the drive train, reducing ship procurement cost and releasing engine room space for other uses and freeing more money for weapon system purchase. In the case of the US Navy's four engined destroyers, the replacement of simple cycle turbines with ICR engines can provide very significant operational cost savings.

With only one type and size of prime mover fitted, maintenance costs will be reduced, fewer ancillaries will be required and training and operation will be simplified. The alternative machinery fits (diesel engines, combined steam/gas turbine cycle plants and even nuclear power) are available and provide similar efficiency, but introduce additional working fluids and output shafts and the resulting complication in machinery, ie integration/operational differences, are expensive to run in comparison.

Intercooled regenerative cycle

It is necessary to introduce intercooling because the current marine engines, such as the SMIC, are optimised for simple cycle operation and the combustion air is at virtually the same temperature as the power turbine exhaust. Therefore the addition of an exhaust heat exchanger is not practical on its own. By simply introducing a cooler between the LP and HP compressors the HP compressor entry, and hence exit, temperature will be reduced; thus advantage can now be taken of the power turbine exhaust heat removed. A block diagram of the resulting cycle is shown in Fig 11.

The two spool layout of the SMIC enables the cooler to be easily introduced into the flow path between the LP and HP compressors. In addition, its annular combustion arrangement permits relocation of the combustors to provide space for the HP compressor air to be diffused and redirected into the generator. The most important requirement in minimising mission fuel usage is the ability to retain a high thermal efficiency at part power, since this comprises the majority of the engine operating time. Although part power efficiency is improved with an intercooled regenerated engine, the characteristic shape of the simple cycle specific fuel consumption curve still applies.

However, by introducing a variable geometry power turbine, the exhaust gas temperature at entry to the regenerator can be maintained at its full value at part power, with a consequent increase in waste heat transfer and a significant fuel saving at part power. By optimising the operating schedule of the variable nozzles it is possible to move the maximum efficiency condition downwards from maximum power to half power, thereby ensuring maximum mission fuel savings are achieved. The resulting improvements in specific fuel consumption over a fixed area power turbine are displayed in Fig 12, together with the simple cycle specific consumption for comparison.

Since the intercooled regenerative cycle is built around available turbomachinery, by maintaining the same aerodynamic conditions where possible the Spey engine retains its already proven operational reliability.

However, the introduction of intercooling and a variable area power turbine both have an impact on the matching of the gas turbine components and their resulting operating conditions. The addition of an intercooler significantly reduces the air temperature at entry to the HP compressor compared with the simple cycle engine. As a result the volumetric flow into this compressor is much reduced, requiring a reduced speed and so giving a lower pressure rise. The impact on the operating regime of both compressors must be recognised and accounted for by appropriate changes to the relevant turbine parameters, as detailed as follows:

1. Reducing engine power from this condition will cause the equilibrium running line, of the LP compressor on its characteristic, to approach the surge line more rapidly than when operating as a simple cycle engine. The compressor characteristic defines the relationship between volumetric flow and pressure rise for increasing speed, and the running line describes the locus of these points for various power settings.
2. As previously discussed, the use of a variable geometry power turbine significantly improves part power thermal efficiency. In order to maintain the design point cycle temperature, as power is reduced, the power turbine area must be progressively reduced. The consequence of reducing the power turbine area is a reduction in the LP turbine work output. This lower work input to the LP compressor causes the running line to drop. However, the net result of the introduction of the intercooler and the variable geometry power turbine is that the LP compressor running line still approaches the surge line more rapidly, as power is reduced, than when operating as a simple cycle engine. The proximity of the equilibrium running line to the surge line at low powers would adversely affect the 'handleability' of the engine if not addressed.
3. The changes to the volumetric flows introduced by the intercooler are corrected by the movement of the LP compressor running line, previously described, and so have no impact on the HP compressor running line. However, the HP compressor running line is affected by the operation of the variable geometry power turbine. Since the firing temperature is maintained, for continuity of flow, the HP compressor delivery pressure must fall more slowly. To achieve this demands that the compressor running line must remain relatively high compared with the simple cycle operation. This means that the compressor will operate closer to its surge line at part power conditions.
4. Therefore, when operating in an intercooled regenerative cycle to maintain the required satisfactory surge margins established by the SMlA/SMlC, without resorting to additional surge control bleeds, both compressor design operating points must be lowered relative to the simple cycle. Any small loss in compression efficiency that this produces at high power, is fully offset by the superior fuel efficiency at lower power levels when considered over a typical ship's operation.
5. To achieve the desired LP and HP compressor operating points demands appropriate matching changes in the gas generator turbines and power turbine. An increased capacity HP turbine is required because of the reduced HP compressor pressure ratio. The change required in the LP turbine capacity is small, since the power and speed requirement of the LP compressor for the ICR engine is similar to that required for the SM1C. The resulting higher gas generator exit pressure requires a reduced capacity power turbine. In addition, design changes are necessary to the power turbine in order to incorporate variable area nozzles.

In summary, the current Spey cycle can be readily adapted to introduce intercooling and regeneration, which would yield an increase in power output of around 25% and a significant improvement in the fuel efficiency of between 20–40% depending on the power setting. The impact on the flexibility of the engine can be addressed by attention to the component design point operating points. In addition, operation can be maintained within the simple cycle aerodynamic conditions, thus retaining the proven operational reliability.

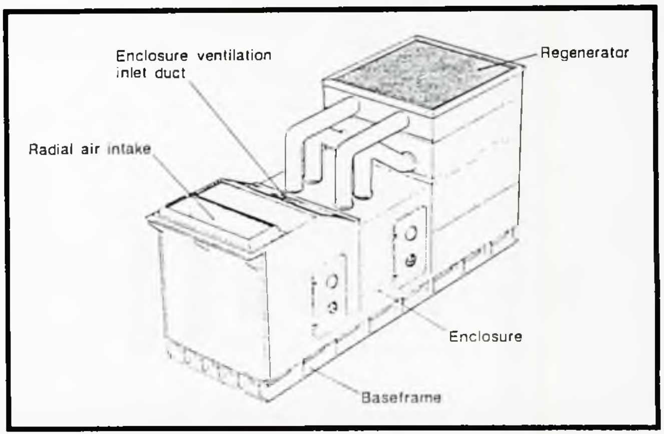

Fig 13: Intercooled/regenerated Marine Spey propulsion module

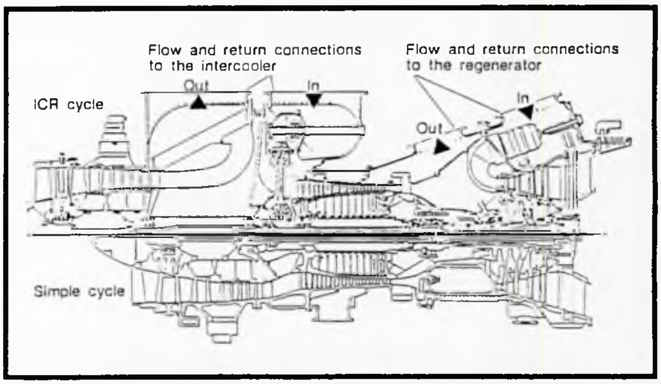

Fig 14: Comparison of Intercooled/regenerated Spey with simple cycle gas generator

Intercooled regenerative engine configuration

Continuing with the evolutionary design approach, the intercooled regenerative gas turbine module layout adapted retains as many of the SMlC module installation features and components as possible. Maintaining a footprint similar to the simple cycle module is considered an important objective, together with the use of as many simple cycle turbomachinery components as possible, since these are qualified by full scale development.

To offset the increase in length of the gas generator, described later, the cascade intake was replaced with a radial intake.

The design module layout has been achieved by the close coupling of smaller regenerators to the exhaust duct as shown in Fig 13. This integrated approach provides positive control of all of the interfaces and enables the total loadings to be taken through to the baseframe.

Gas generator changes

The gas generator changes necessary to incorporate the heat exchangers must reconcile the opposing requirements of a low working velocity in the heat exchangers and a high working velocity in the turbomachinery. Therefore each heat exchanger

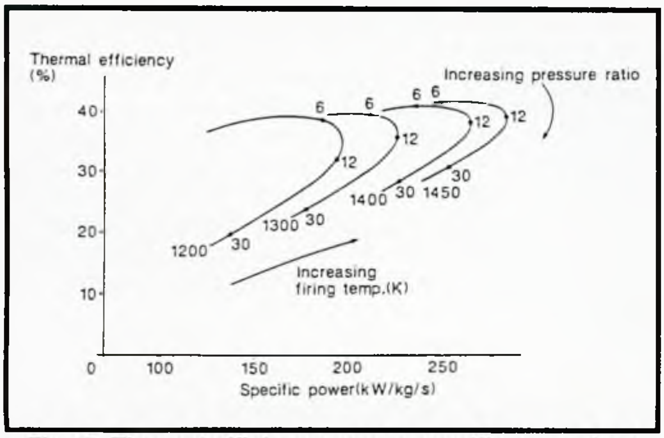

Fig 15: Thermal efficiency versus specific power for a regenerated cycle

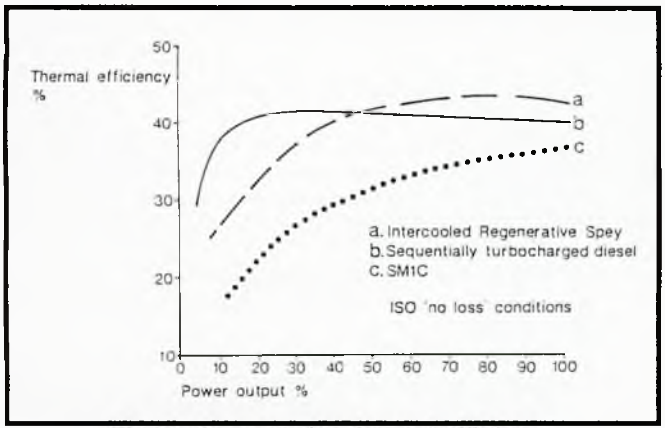

Fig 16: Comparative thermal efficiency

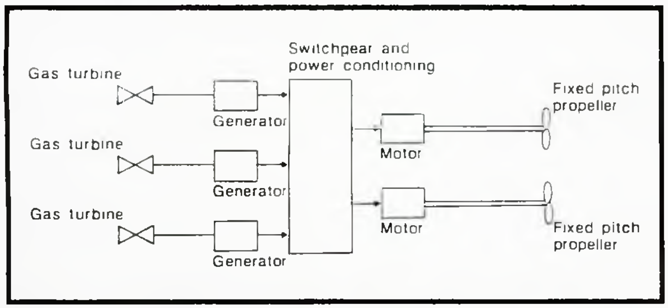

Fig 17: Electric drive schematic

is preceded by a diffuser and followed by a means for reaccelerating the flow. The efficiency of these elements has a significant impact on the overall cycle efficiency.

Since there is wide variation in the temperature of the working fluid through the engine cycle, the engine design must group the LP compressor diffuser, the HP compressor intake, the HP compressor outlet diffuser and the combustion system intake in a way which avoids excessive thermal gradients in the casing.

A main component layout which addresses this, compared with the SMIC, is shown in Fig 14.

Small gas turbine development

As highlighted earlier in this paper, the gas turbine has many advantages, over other prime movers, available for marine duties. In particular, its high power to weight ratio, which yields compact power units, makes it ideal as a main warship propulsive unit. The impact on ship fuel consumption, over a typical mission, of the characteristic shape of the gas turbine specific fuel consumption curve has been addressed by the adoption of cruise and boost engine arrangements.

In addition to main propulsion machinery warships require prime movers to produce around 2 MW of electrical power. Since the size differences of the available prime movers at this power level are not as marked, fuel efficiency becomes an important factor. These considerations have led to the selection of diesel engines in preference to gas turbines for ship services.

Equally this argument has led to the adoption of diesel engines as main propulsion cruise engines in conjunction with gas turbines for boost power. However, a very significant disadvantage of the diesel engine compared with a gas turbine is the production of low frequency noise, which permits easy detection by sonar devices. This problem has been addressed by the adoption of complex double mounting systems, but even with this treatment noise levels are still much greater than for gas turbines. Modern diesels which attempt to provide improved flexibility require complex operating cycles and hence demand greater maintenance.

Applying the technology of heat exchanging, outlined earlier, to smaller gas turbines would significantly improve their thermal efficiency whilst maintaining the proven benefits of low maintenance and compactness.

Figure 15 shows the results of a study performed to evaluate the levels of thermal efficiency possible. The component efficiencies assumed for the cycles were typical of the current levels being achieved by aero engines in the 1000–2000 hp range. As shown in Fig 15, thermal efficiencies of around 40% are achieved at modest firing temperatures. The introduction of intercooling would further improve the highest efficiency by about 2 percentage points.

To complete the picture, Fig 16 presents a comparison of engine efficiency, over the full power range, of simple and intercooled regenerative cycle Spey gas turbines and a sequentially turbocharged diesel.

It is accepted that the power brackets of these engine types may not be directly comparable, but the comparison serves to demonstrate the attractive part power characteristic of the intercooled regenerative engine.

Electric drive

A further advance in ship propulsion systems is underway. The adoption of electric drive in the Royal Navy's Type 23 frigate for cruise is one step towards the freedom that can be exercised when the 'traditional' mechanical drive limitations are removed. The US Navy has a major programme underway which is aimed at proving the concept for full electric drive in frigates and destroyers, a typical layout is shown in Fig 17.

Gas turbine prime movers would be included, which may be existing simple cycle units or, more likely, ICR units which would significantly enhance the overall operating efficiency.

Part of the US Navy funded work on the ICR concept included an analysis of operation of the units in an athwartships location, which could be a possibility with this system. Increased operational attitude changes, caused by a transverse location and vessel roll, are still far less than the parent aero engines may encounter during military operation. The problems for the gas turbine designer are thus minimal, but the ability to position the engines freely within the ship creates unique opportunities for the ship architect to maximise space utilisation and optimise weight distribution. The successful outcome of this programme could thus lead to a revolution in ship design, but a lot depends on the ability to produce the high speed generators and direct drive, the low speed motors, plus the conversion and control equipment capable of handling up to 30 000 hp, within size and weight limitations never previously achieved. The risk could be reduced if greater numbers of smaller capacity generators could be utilised, thus exploiting/extending existing technology.

CONCLUSIONS

The development of the marine gas turbine has been an evolutionary process. To date it has almost exclusively been reliant on advances in aero engine technology for its improvement. These advances have provided significant growth and increases in efficiency with the minimum level of investment. However, to provide a step change in fuel efficiency demands the introduction of exhaust waste heat recovery. It has been shown that by limited design modification the current marine SM1C gas turbine can be readily converted to an intercooled regenerated cycle. Such an engine would provide around a 25% increase in power with a fuel consumption of up to 40% less than in its simple cycle form, depending on the power setting.

In addition, application of this technology to smaller gas turbines would provide power units with thermal efficiencies close to diesel units of equivalent power. The proven benefits of the gas turbine of low maintenance, compactness and low noise, would be maintained.

The long term prospects for marine gas turbines look good. Component design progress and material technology can be applied to intrinsically more efficient gas turbine cycles to produce simple, low cost, high efficiency units with outstanding reliability. What is less clear is what sizes are required. These may vary from navy to navy but development costs, compared to the actual numbers required, are likely to demand global standardisation on fewer output ranges.

The near future may be dominated by the US Navy's plans for ICR engines and electric drive. These engines will probably be too large for a number of potential users, which may leave a partial vacuum to be filled by a mixture of diesels and current day simple cycle engines, matched to electric drive systems. Thus current simple cycle, but state-of-the art, gas turbines will continue to be employed in conventional machinery layouts whether COGAG, CODAG or CODLAG for the foreseeable future.

ACKNOWLEDGEMENTS

The author wishes to thank colleagues at Rolls-Royce plc, Industrial and Marine, for helpful suggestions and assistance in producing this paper and the illustrations.

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Discussion

Cdr R F James RN (MOD) I would start by taking issue with a minor point on p 290 of the paper where it is stated that the conversion from SM1A to SM1C in HMS *Brave* in November/December 1989 took place during a normal refit period. In practice the ship was not on refit but remained operational throughout the conversion which took place during a normal programmed maintenance period. The ship remained at operational notice for sea throughout and I wonder whether some sort of record has been set by increasing a ships available power by some 50% whilst it remained operational. Whatever, the whole exercise was an object lesson in project management. On a more serious note; the paper makes the point that considerable development effort has gone into the design of the combustion systems of both the SM1A and SM1C engines. This is obviously a critical subsystem in the design. Given the uncertainties over both availability and quality of fuels in the medium and long term future, I wonder if the author can give us some indication as to how tolerant these combustion systems are to variations in fuel specification?

J Ferrie (Rolls-Royce plc) The Marine Olympus engine has previously demonstrated the capability to burn coarser cut fuels than the current diesel specification and the combustion system in both SM1A and SM1C is a derivative of this combustion system. However, for the purpose of the SM1A and SM1C qualification testing, the fuels were limited to the current diesel specification. Throughout this testing there were no visible emissions and there was no measurable carbon generation.

Rear Adml M A Vallis (Deputy President, IMarE) I am probably the only person present who has actually been at sea in a ship propelled by an intercooled and regenerated gas turbine. I spent a day as an observer in HMS *Grey Goose* which was powered by the RM60. That engine failed because of the degradation in performance caused by ducting losses and heat exchanger fouling: there were also problems with heat exchanger leaks. Could the author say how these problems would be overcome in the ICR Spey?

The author mentioned the high reliability of the Marine Spey. Could he explain how this reliability has been obtained and what steps were taken to improve the maintainability of the engine?

J Ferrie (Rolls-Royce plc) The intercooled and regenerative Spey design, addresses the problem of duct losses through careful use of short low loss ducting, with target internal losses to be limited to 6.5% total pressure loss including the heat exchangers. Fouling of the recuperator is also fully recognised and the use of modern high temperature corrosion resistant materials allows burn off of these deposits by closing off the cool air side prior to shutdown.

Reliability and maintainability are recognised as being of paramount importance to achieve minimum cost of ownership and maximum availability and to achieve these objectives there has, over the years, been an intensive materials development programme to attain the desired lives and durability of components. Additionally, the gas generators feature modular designs to allow free interchangeability of maintenance modules that do not require any testing after assembly. The combination of these elements into the Marine Spey results in a high reliability, high availability, low maintenance cost propulsion unit.

Dr G Armstrong (Swan Hunter International Ltd) The author has provided a very interesting account of the development of the Spey engine and its future potential.

The high power/weight ratio is indeed advantageous to warship propulsion, particularly for smaller fast attack craft. Would the author provide power/weight figures for the SM1C and, if known, the intercooled regenerative engine?

Secondly, would the author be able to comment on the maintenance aspects of the engine in relation to the diesel, with reference to the shore support facility required?

Finally, I am afraid it is not very meaningful to see graphs plotted without the axes labelled adequately. Please could the vertical axis for Fig 12 be provided?

J Ferrie (Rolls-Royce plc) The power to weight ratios requested are as follows.

The SM1C has a power to weight ratio of 0.70 kW/kg and the ICR version is 0.41 kW/kg. The numbers for the intercooled regenerated engine are as yet not confirmed but on the basis of the design work completed so far, the actual engine will meet the USN specification.

The marine gas turbine is generally perceived to offer greater flexibility in maintenance planning than a diesel installation of equivalent power, in that the bulk of maintenance is shifted from ship to shore. This is achieved by a policy of upkeep by exchange under which life expired modules or engines can be removed and replaced by refurbished units in a handful of working hours. Once ashore, the outgoing module or engine can be overhauled at a location of the owner's choice.

It should be remembered that only the gas generator unit of Rolls-Royce installations is removed for module or engine exchange, as the power turbine section is designed and fitted for the life of the ship.

At the heart of any successful gas turbine support policy is a programme of condition assessment, taking only an hour or so per week, which includes optical, performance, spectrographic and statistical activities. Whilst most of these tasks are well within the capabilities of a typical warship crew, a few of the more complex activities are performed by small shore-based groups such as the Royal Navy's Fleet COGOG team. The ship and shore groups pool results to construct a continuously updated condition report, from which the remaining module and engine lives can be determined.

This predictive approach permits optimum engine usage, whilst providing the repair authority with sufficient notice to organise module or engine exchange without undue disruption to ship or shipyard.

The maintenance requirements for the modern, modular Marine Spey gas generator may be divided into six categories:

1. routine servicing and condition assessment;
2. replacement of external accessories as required;
3. specialist analysis facilities with advisory team support;
4. module exchange facilities with technical support;
5. engine change facilities with change team support;
6. module overhaul.

Activities (1) and (2) invariably fall to the ship's crew, but take only a few hours per week. Most navies use specially trained, uniformed, advisory and engine removal teams for activities (3) and (5); however these teams could equally well be made up of shipyard or contractor staff.

Activity (4), the exchange of the modules which make up the engine, is an activity roughly equivalent to the replacement of a cylinder head on a large, lightweight marine diesel engine.

As explained in my paper, the Spey gas generator is made up of a series of modules, all of which are interchangeable with those from other engines. Maintenance is effected by the removal of the life expired module and its replacement by one with life remaining. The gas generator must first be de-installed, but often no further than to the access space immediately adjacent to its enclosure, obviating the need to open the ship's removal routes.

However, the decision as to where the module exchange should be performed is usually left with the fleet operator. With a large engine population, it may be appropriate to provide the few special tools, stands, facilities and trained operatives needed local to the operating base as is common practice in aviation. However, if there are less units, and it is not cost effective to provide these facilities, it is perhaps better to return the engine to an overhaul facility for module exchange, possibly at the manufacturer's works or at a recognised contractor's premises. This is in many ways analogous to a diesel operator's policy on refurbishment of diesel engine components removed at overhaul.

Module overhaul, activity (6), is normally left to the manufacturer or an approved contractor, although there is no fundamental reason why the fleet operator should not undertake this work. Modular engine construction removes the requirement for complete engine overhaul.

In contrast, the large warship diesel is normally overhauled *in situ* as removal invariably involves the cutting of a removal route and extensive work-in-wake. (Ship structural strength limitations often limit the size of permanent removal routes with openable hatches to about the dimensions needed for auxiliary power generation diesels.) Thus, a large semi-dedicated shore support team is required and extensive ship downtime is hard to avoid.

In summary, selection of marinised aero gas turbines for warship propulsion allows a more flexible approach to maintenance, permitting the fleet operator to choose an appropriate upkeep strategy and minimise down time.

With reference to Fig 12, there is no intention to withhold useful information because the curve is really drawn to highlight the relative changes. However, if it is useful to you, it is possible to apply a scale to the plot in the following way. Project the tangency point of the lower curve on to the vertical axis, the value at this point being 0.20 kg/kW h, and the scale can then be drawn by index marks at 1 in steps up the vertical scale. Each one of these steps is equal to 0.05.

R H Barnes (Robert Barnes & Co)

1. The Metro-Vick Gatric first went to sea in 1946 in MGB 1009. It may be seen in the Marine Gallery of the Science Museum, London. The original aero engine Beryl is on the floor above. Although G6 was derived from the Armstrong Siddeley Sapphire (as G4), it can hardly be representative of the aero-derivative concept; weighing 18t. In about 1965, the options open to MOD(N) were:
   a. to uprate G6 to G9 producing about 10 000 shp;
   b. to adapt the Olympus, in marine configuration, to produce 24 000 shp (as TM1).

   Both options were costed at about £2M. However the G6, without inlet filtration, did not have high temperature sulphide blade corrosion, whereas the aero-derivative engines, from Gatric to Proteus, all did. Therefore the attached risks had to be evaluated.
2. Considerable credit should be given to the directors of the Ministry of Supply, and NGTE, for approaching the Admiralty at the end of World War II with the suggestion that the Admiralty take advantage of the aero industry's considerable and growing experience; which they did.
3. It is perhaps questionable for the author to claim that Rolls-Royce led the navies of the world into gas turbine propulsion in 1953, with the RM60 units in HMS *Grey Goose*. These were far too advanced for the materials then available. The cost of each engine was over £1M, they could not operate reliably with recuperators, and by 1956 they had been removed to Dartmouth and Manadon as static exhibits. They achieved a total of only 1500 running hours at sea.[1] The Admiralty continued development with the alternative Bristol Siddeley Proteus engines until 1965, when RR, (Derby Engine Division), reappeared with the Tyne adapted for hydrofoil propulsion in the US Navy (Gruman Dolphin). The marine Tyne RMIA followed with a separate powered turbine, as a more efficient companion for the Olympus. The prototype plant in HMS *Exmouth*, (1968–1975), was a Proteus/Olympus combination, as was the unsuccessful tender for the Canadian DDH 280 class frigate at the time (1965).
4. Turning to SM1A development, could the author state what percentage of HP air bleed is used for ship services, and are there any limiting devices to prevent excess bleed?
5. It would be interesting to hear if there have been any HP turbine blade failures, of the type experienced by the Tyne during endurance testing, either on test or in service.
6. The account of combustion development in both the SM1A and SM1C would make a subject worthy of a paper on its own, I suggest. Very sadly, one of the leaders in this field, Lt Cdr Philip Hackluytt of NGTE, died last August before he could do this. Having seen something of this work, and having worked with him previously at AMEE, Haslar, I hope that IMarE or Rolls-Royce will make every effort to produce a paper in the not too distant future. It would be a fitting tribute to him and compliment his excellent paper on boiler steam atomisation.[2] Can the author acknowledge his work please?
7. I do not believe that Bacharach numbers are a realistic measurement of smoke for a gas turbine, or for that matter a boiler. Those who worked with Hackluytt know his view was stronger. From my own experience, the prevailing atmospheric temperature and humidity, plus the amount or lack of rain and sunlight, are a major influence on smoke visibility at sea.
8. The ICR version is a fascinating and demanding concept, as the author has described extremely clearly. Mention must be made of intercooling in the 500 kW Allen generator and recuperation, tried but disregarded, in its 1000 kW predecessor. Most successful, however, was the recuperated gas turbine propulsion system in Shell's tanker *Auris*, which ran with this ICR cycle for 20 510h in service, of which 6649h were on residual fuel. It is fully described in Ref 3 below. I myself was very closely involved, between 1980 and 1984, with the recuperated Kongsberg GTAs, developed and installed on Unocal Netherlands 3 'Q'– Block oil platforms off Den Helder (described in Ref 4 below). My present view is that the heavyweight recuperator is thoroughly reliable in service, while the lightweight units, first tried in the RM60, have yet to demonstrate long term reliable service. Much work has been done, and is still being done on this point, and it would be interesting to know what Rolls-Royce's programme for the ICR Spey unit comprises, and how far they have progressed.

9. The cycle in Fig 11 shows a bypass valve across the recuperator, but the use is not explained in the paper. Presumably this is for starting in order to relieve thermal shock? If so, what type is this valve to be and have Rolls-Royce evaluated its expectations of reliability in long term service, where failure affects fuel consumption? I would think this is a vital component in the engine.
10. One of the advantages of a recuperator is the resulting very weak fuel/air mixture, compared with a simple cycle at equivalent powers. This was demonstrated in Auris and the KG2–3R, burning residual fuel; above about 36% recuperation the non rapid fouling does not occur, and long service was achieved without need for frequent burner maintenance. As the merchant marine service invariably fit heavy slow-speed diesel engines, has thought been given to using the ICR, burning heavy fuels, as a replacement?
11. I question the assumption that his ICR engine cycle, with intercooler and recuperator, bypass and variable geometry compressor and turbines, is less complicated than the present CODOG or CODAS arrangements. It may well prove difficult to achieve target reliability in a reasonable or similar timescale to the SM1A and SM1C programmes. Some hard lessons were learnt by the Royal Navy with CODAG plant. The acronym CODOG implies higher reliability with alternative prime mover, diesel or gas, ie parallel redundancy.
12. The movement of the sfc curve (Fig 12), and the introduction of a variable geometry power turbine, plus the very considerable changes in conditions at stage entry and exit of each turbine in this cycle, brings to mind an old hare raised during the 1960s of 'vapour phase' corrosion of blading. It is still true to say, I believe, that corrosion will not occur at high temperature, provided that salt concentrations in both fuel and air are kept below prescribed limits. As mentioned above (in item 4), does follow-on experience with sulphide corrosion in the SM1A or SM1C, point to potential concern about this problem occurring in the ICR cycle?
13. What are the expected losses of the intercooler, its coolant pump, and the recuperator?
14. Can the author confirm that he is talking about a recuperator rather than a regenerator in this cycle? I appreciate that the term is used loosely on both sides of the Atlantic, but the regenerator usually involves moving parts.
15. It must be a non-sequitur to say or claim that the 'operational reliability' (sic) is dependent upon the aerodynamic conditions. Setting aside the factors that govern reliability, the ICR Spey is as different an engine from its simple cycle derivative as was the Marine Tyne from the aero engine; perhaps more so. This claim is dubious, I suggest.
16. The considerable readjustment of operating conditions to prevent the necessity of blow off during a downward power transient must have exercised the minds of the designers; the paper describes great ingenuity (p292). This was a problem, also, with the recuperated KG2-3R. Being a simple cycle the problem was accepted, and an additional 3 in blow off valve fitted to retain full control. Even so the resulting noise was considerable, and wasteful, and comparable to lifting safety valves in a steam plant. With considerable additional work (variable geometry etc), the problem could have been cured, but for the recuperator's thermal inertia. Kongsberg used two versions; one in the USA, a lightweight stainless steel unit, the other in the North Sea, a heavyweight shell and tube unit. During extended works testing of the latter unit there was a clear reversal of heat flow for some 20–30s after a full load throw-off. This effect, most probably, will not be so marked in the ICR Spey, but it would add considerably to the transient thermal shock loading of a lightweight recuperator, suggested in this paper (Fig 13).
17. On the subject of small gas turbines and electric drive, the most vulnerable component of the Allen 500 was the HP turbine. This had very small blading sections at the inlet, which burnt and degraded performance more than a ship's engineering staff would wish. A reliable electronic control system would, today, greatly reduce this problem. However, the small mass flows involved, and the small cross-sectional area intakes on the upper deck, make them more susceptible to blockage by both canvas, and the occasional 'goffa', than the main engine. One unit was stopped by ingesting smoke of an alongside dockyard tug's exhaust. Operating T_{max} was some 400°C lower than those shown in Fig 15. I hope the Allen experience will not be overlooked when these smaller 2 MW turbines are considered in detail.
18. Mounting generating sets axis athwartships brings to mind a 1960s study to mount an Olympus gas generator vertically in its intake, with exhaust directed downward onto a radial, reversing, power turbine. The problem then was not the Olympus but the weight, space and cost of the power turbine. Has this configuration ever been considered for the Spey? Also, has the experience in the few floating oil production ships, such as *Petrojarl 1*, been tapped. Here the motion is totally non-traditional when the ship is moored by its central turret in a seaway, maintaining station with a dynamic positioning (DP) system. *Petrojarl's* gas turbo generators were subjected to a shore demonstration, running with the rotor axis inclined at 15 deg; the most severe condition for lubrication.
19. Like commercial airliners to which it is closely related, the marine gas turbine has made a remarkable impact on warship propulsion in the last 40 years. The author and Rolls-Royce are to be congratulated on their major contribution and, in particular, the latest engines of the Spey family. This paper is particularly welcome by those, who like myself, have participated in past programmes. However, like steam plant and the dinosaur, marine gas turbines will probably disappear in the 21st century if they fail to develop real economies alongside declining reserves of petroleum fuels. It is heartening to hear how the RM60 design has been resurrected after 37 years to guide or assist development of the ICR Spey. Perhaps, when built, these will be renamed the RM90. I think that practical problems of making a reliable recuperator work will, as in 1953, be formidable and, in closing, I wish the project every success that it deserves, including both home and overseas customers in abundance.

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4. V de Biasi, '1.4 MW recuperated plant powering N Sea platform', *Gas Turbine World Magazine*, p 85 et seq (September 1982).

J Ferrie (Rolls-Royce plc) In response to item 4, relating to SM1A development, I would like to say that currently the HP bleed available for ship's services is 5% when utilised by the Royal Navy. However, on Japanese ships this is increased to 10%. In both cases limitations are there to prevent excess bleed by use of a restrictor.

Referring to item 5 – regarding HP turbine blade failures – the only failure which has been experienced was in development on the HP turbine blade. This was due to inadequate inspection during the prototype manufacturing phase. Subsequently this has been rectified through better process control and the resultant experience, both during development testing and in service, has not revealed any additional problems, and we currently have engines which have exceeded 3000h in service.

Referring to item 6 – we acknowledge that NGTE made a significant contribution to the combustion development programme, particularly in relation to SM1A, and if RR did at some time decide to prepare such a paper, it would be inconceivable for this contribution to be omitted.

With reference to item 7 – we agree that there is no true method of measuring smoke. The only advantage of picking the Bacharach system is that it allows comparative analysis between different engines, although ultimately it is a subjective system when taking into account the variabilities of temperature, humidity and sunlight. However, we would not consider changing at this point in time since we now have a considerable database for comparison purposes which allows us to select a Bacharach level which, although it is invisible, will remain invisible under all conditions.

In answer to item 8 – you are perfectly right in identifying the recuperator as being one of the most difficult items in the ICR. The concept chosen has not been built and demonstrated by RR. It is, however, based upon a very successful industrial product made in the United States which exists in large quantities and has completed many thousands of hours of successful operation, and the only difference between the unit which we propose and that used in industrial service is the way in which it is packaged.

Referring to item 9 – the bypass valve across the recuperator shown in Fig 11 is not in fact there for starting but is to provide two facilities for the operation. Firstly, in the event of battle damage to the recuperator it allows the compressor delivery air to bypass the recuperator, which will obviously reduce the amount of power available for the engine, but does permit the system to continue to operate, albeit not at full power. Additionally, it provides a burn off capability to prevent a build up of any fouling on the exhaust gas side of the recuperator. This action has been demonstrated to be totally effective in industrial service.

In answer to item 10 – although recognising that the merchant marine service would wish to utilise residual fuels, all of this programme has been aimed, up to this point, at the military naval operations, and in all discussions that we have had with prospective customers they have always identified diesel Class A as the preferred fuel and as a consequence the present programme is limited to this type of fuel. Obviously if a commercial application did appear we would have to reconsider this position.

Referring to item 11 – the basic concept of the ICR engine has been to only use fully proven equipment which is already in service with either industrial or marine operators. If we consider the individual elements, all the elements of the basic gas generator, ie compressors, combustion, turbines and power turbine are all existing demonstrated hardware, including their variables, in some current installation. The intercooler and recuperator are again based upon demonstrated industrial hardware with sufficient time in service to show that there are no obvious limitations. It would be nonsensical to assume that combining all these together would necessarily produce the target reliabilities instantaneously, but our perception is that lives at release into service would be equal to the SM1C engine.

Since the initial installation is likely to be into a ship utilising four ICR engines, the complexity of combining the cruise engines and the boost engines is unchanged from todays installations, in which case we would not claim less complication in that respect to todays concepts.

With reference to item 12 – our experience of SM1A and the development testing on SM1C has not identified any problem of sulphide corrosion with present day materials and we would not anticipate, since the same materials are used in the ICR, that the problem would recur in that engine.

In answer to item 13 – there are obviously losses associated with the inlet and outlet ducting as well as the intercooler and recuperator. The total projected losses for all of these items is the equivalent of 6.4% at maximum pressure conditions with the intercooler coolant pump having an additional power demand of 200 hp.

Referring to item 14 – in this particular instance we are talking about a recuperator since there are no moving parts. Conventionally the terminology for regenerator is used if it is a rotating converter.

With reference to item 15 – recognising that operational reliability is one of the important factors in the selection of an engine, we have deliberately chosen the component parts of the ICR from existing marine engines, with the exception of the two heat exchangers and, although I would agree that there is a significant difference between an aero engine and its marine counterpart, by following this route we will avoid any problems of unreliability which may occur by having to include that additional step.

In answer to item 17 – the most vulnerable part of any gas turbine is always the HP turbine blade. To avoid this problem the HP blade is based upon well proven aero engine and marine engine experience. The internal cooling configuration is the most significant factor in preventing burning of this, the most highly loaded component in the engine. Although a fast response reliable electronic control system greatly reduces turbine temperature overshoot during handling, the increased reliability is more readily creditable to better materials and superior cooling configurations.

Referring to item 18 – the possibility of radial mounting of the Spey was considered. However, the consensus of opinion in warship design today is that the objective should be to eliminate the superstructure in total, which includes the uptake and the downtake, and considerable effort is being put into understanding the implication of a partially submerged intake and uptake and the impact of the wave motion on the operation of the turbine, in which case it would be impossible to mount the turbine. However, if we had pursued this particular line of thought, we know there is extensive development experience on engines for lift which operate at every conceivable angle from vertical to 45 deg and which has demonstrated that oil systems can be made to tolerate these significant and violent variations in inclination.