DR JULIA KING CBE FREng
DIRECTOR OF ENGINEERING & TECHNOLOGY – MARINE, ROLLS-ROYCE PLC
DR IAN RITCHEY
HEAD OF RESEARCH & TECHNOLOGY – MARINE, ROLLS-ROYCE PLC

Marine *propulsion* The transport technology for the 21st century?

Marine transport has generally been seen as having a lower environmental impact than other forms of transport. The increasing demand for economical yet rapid movement of both passengers and freight has brought renewed momentum to the development of marine propulsion systems. New technologies are aiding the production of propulsion systems that are capable of driving vessels at higher speeds; that are more efficient; that provide better manoeuvrability; and are quieter, with less vibration. Here, the latest developments in marine propulsion are brought into focus.

Introduction

The start of the twenty-first century has brought a resurgence of interest in marine propulsion. Major navies world-wide are assessing and updating their fleets. The Internet offers international shopping to every household, fuelling demand for fast and economical freight transport. Travel is a stressful element of many people's jobs, so the cruise increasingly offers a pampered and relaxing way to visit many destinations from a single hotel room. Prior to the attack on the World Trade Centre on 11 September 2001, market predictions indicated healthy growth in world shipbuilding, supporting this positive view of opportunities in marine transport (see Figure 1). The tragic events in the United States gave us cause to reflect, both personally and professionally. Whilst it is still early to judge the long-term effects on marine markets, the initial impact on cruise bookings has now been reversed and there appears to be no reason why the long-term fundamentals will be changed.

Changing customer requirements

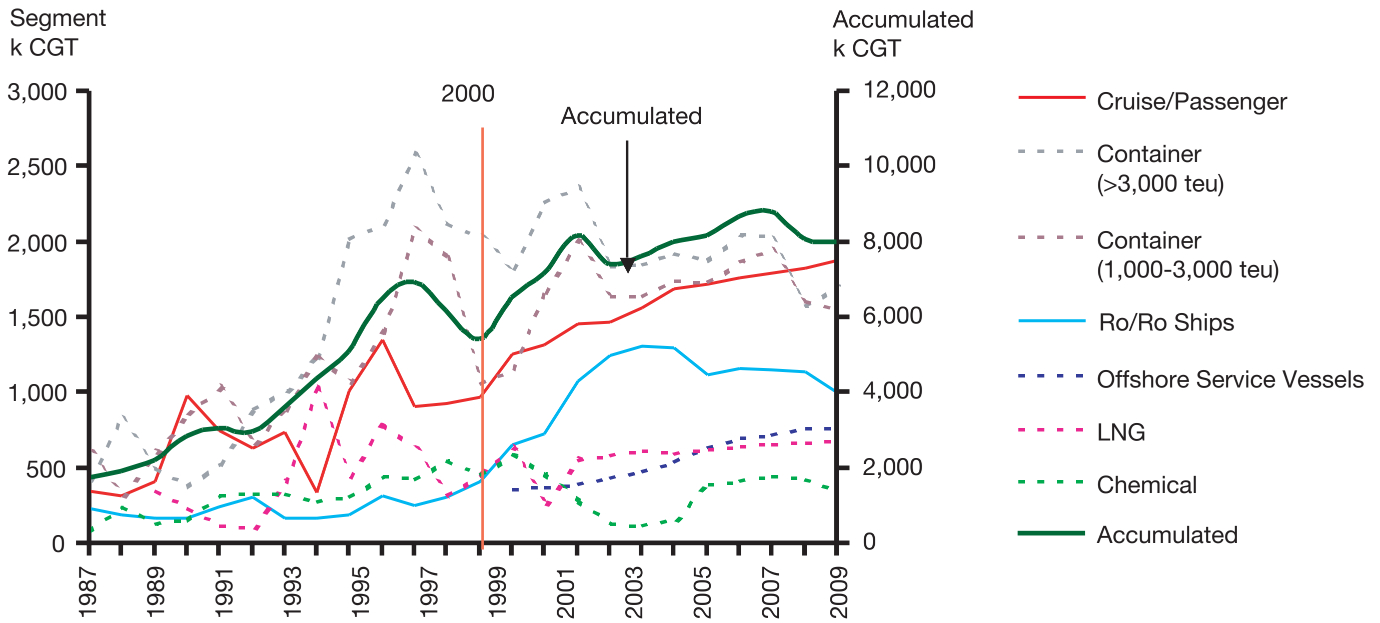
Markets as apparently diverse as deepwater offshore production, cruise ships, fast cargo and advanced naval vessels share many common requirements:

- safe, reliable and cost effective operation and maintenance
- high levels of ride comfort and stability, for the care of passengers, crew, cargo and complex equipment
- increasing demand for speed, for ships to arrive on time whatever the weather
- outstanding manoeuvrability to allow vessels to keep station above a well-head or berth at a busy port.

These challenging requirements, along with the overall need to reduce emissions and energy usage, are driving developments in technology. The role of the marine propulsion supplier is changing, from the supply of individual items of equipment to the delivery of sophisticated, integrated systems with guaranteed performance and through-life support.

Speed and power

The continuing internationalisation of trade and production, combined with increasing congestion on land and in the air, is generating interest in novel concepts for fast cargo and passenger vessels. In the naval arena, a requirement for rapid force deployment capability, while avoiding the need to station troops close to sensitive areas, is providing further stimulus and funding for fast vessel developments.



Source: Drewry Shipping Consultants Ltd August 24, 2000

Figure 1: Shipbuilding market trends

The first challenge for the propulsion system, in terms of increasing the speed of a ship, comes from the cube law relationship between speed and power for a conventional propeller driven system. Put simply, the problem is that doubling the speed requires an eight-fold increase in power.

Around 95% of ships are powered by diesel engines, where the relatively low power-to-weight ratio is associated with intermittent combustion, with each cylinder contributing in turn to the power generation process. Marine gas turbines, derived from aeroengines, provide prime movers with between four and ten times the power-to-weight of a marine diesel through a combination of a continuous combustion process and design to minimise weight (see Figure 2). Figure 3 shows a comparison of the Marine Trent engine and the Trent 800 aeroengine, where some 80% parts commonality is retained between the marine and aeroengine variants. Additional benefits of the modern aeroengine parentage include the excellent reliability, good turndown capability for harbour manoeuvring and excellent emissions performance as a result of significant and continuing aeroengine technology investment.

Rolls-Royce and marine engines

That marine transport has long been an area of interest is evident in the original Memorandum of Association of Rolls-Royce Ltd, dated 1906:

> ‘The objects for which the Company is established are: (i) To manufacture, sell or let or hire or in any manner dispose of or turn to account, motor vehicles for use on land, water or in the air, and any parts or accessories to the same’.

With the acquisition of Vickers in 1999 Rolls-Royce has become a world-leading marine equipment and systems supplier, with a product range spanning prime movers, propulsors, steering and stabilisation systems, deck machinery, propulsion and electrical systems and controls, right through to whole ship design in specialist sectors.

The second propulsion challenge is cavitation, which limits the maximum speed of propeller-driven ships to between 30 and 35 knots. As propellers are driven faster, cavitation starts to develop in low pressure areas on the blades, until at high speed the low pressure faces of the propellers are covered in tiny bubbles. These proceed to coalesce and collapse, creating rapid surface damage to the propeller, pressure pulses that are experienced as noise and ship vibration, and a marked reduction in propeller efficiency.

To avoid such problems, fast vessels are propelled by waterjets – huge pumps which suck in water below the vessel and pump it out at the stern (see Figure 4). The construction and flow through a waterjet are illustrated in Figure 5. Because the impeller of the waterjet is enclosed, in contrast to exposed propeller blades, higher pressures are achieved and the impeller and stator designs are optimised to suppress cavitation. The shaft speeds of waterjets are typically double those of propellers at similar power levels. Rolls-Royce is now applying the CFD codes developed for the analysis of complex multi-row aeroengine compressors to the design of advanced waterjet pumps. The use of such codes

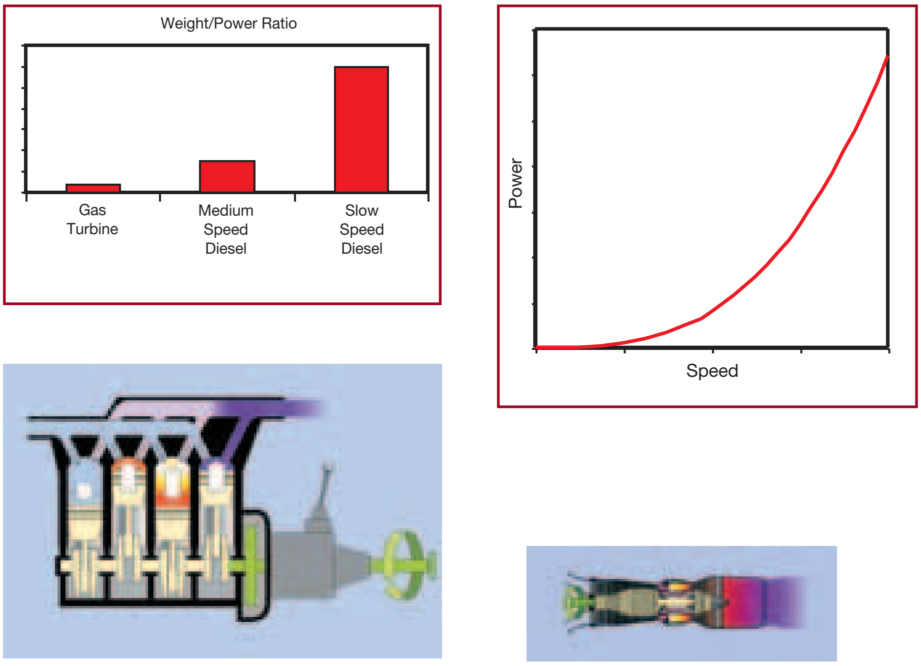


Figure 2: Power-to-weight ratio: the diagrams of the reciprocating engine and the gas turbine are at approximately the same power level

offers significant reduction in both the cost and lead time for the development of new designs, with the potential to look at a wide range of variants before progressing to model testing. Waterjet propelled vessels operate with maximum speeds of 35 to 70 knots, depending on the hull design and nature of the operation.

Several projects to develop fast sea transport services are currently in progress around the world. Rolls-Royce has been selected to supply both the gas turbines and the waterjets for the transatlantic project known as FastShip (see Figure 6). FastShip features an innovative semi-planing hull which will be powered by five 50 MW Marine Trent gas turbines, each driving a 3 metre diameter Kamewa waterjet. The service is designed to operate between specially developed port facilities at Philadelphia and Cherbourg, crossing the Atlantic in 3.5 days, so that 7-day door-to-door delivery can be achieved. At a cost of around 25% of that of air freight, and with delivery times typically four times faster than conventional sea freight, FastShip will offer a new type of service for long distance transport of high value goods.

The technical challenges in such developments are considerable. FastShip has to be able to maintain a speed of 36 knots in 7.5 metre significant waves. The impact of air ingestion into the waterjets is a key factor in the mechanical design of both the jets and the gas turbines – in 7.5 metre waves air ingestion in the outer waterjets is likely to occur, and, in more extreme sea conditions, emergence of all five waterjet inlets is a possibility. In order to ensure that the loads experienced in such events are understood, special measuring equipment, including a 6-component dynamometer attached to the impeller hub, has been developed to enable dynamic recording of all forces and moments acting on an impeller during

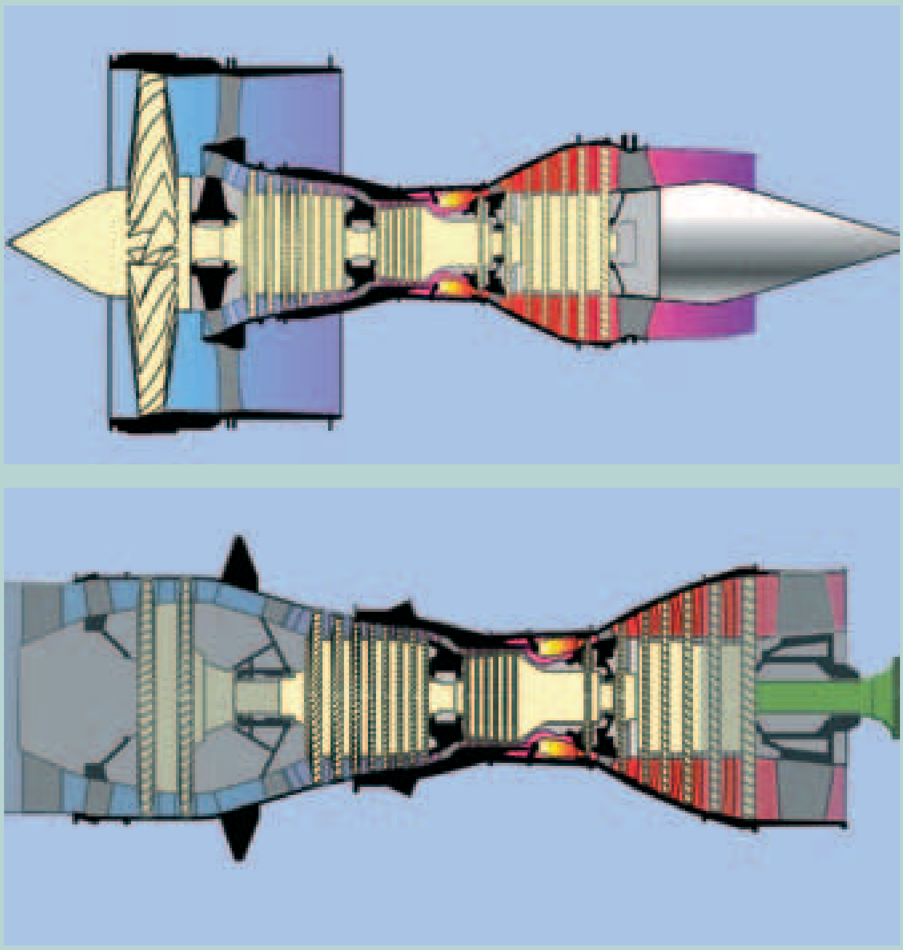


Figure 3: The Marine Trent and the Trent 800 (top) aeroengine

Figure 4: Waterjets in operation at the stern of a fast ferry

normal operation and air ingestion. This provides the information required to verify the waterjet design and meet classification society requirements relating to loads on the shaft and surrounding structure. The gas turbine needs to be able to respond to the sudden drop in power demand: as the load torque drops the engine must be designed to be able to reduce power sufficiently rapidly to avoid an overspeed trip. Dynamic simulation of the entire propulsion train is used to verify the functionality of the control system during air ingestion and emergence events.

Better use of space

One of the greatest contributors to increasing the useable space in a ship, most notably a warship or a cruise liner where the premium on space is greatest, is the concept of the Electric Ship. Integrated Full Electric Propulsion, IFEP, lies at the heart of the Electric Ship. IFEP also offers valuable running cost advantages, combined, in some cases, with purchase cost savings. In an IFEP system, the ship's propulsors are driven by electric motors alone, and the power for the electric motors is drawn from a unified electrical power system that also provides all of the ship's electrical services. The power and propulsion systems are therefore integrated, because there is only one electrical power system where more conventionally there might have been two.

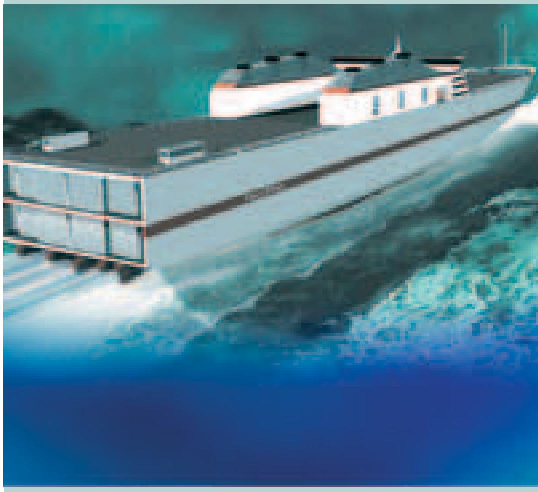


Figure 6: (Above) Two artist's impressions of the FastShip

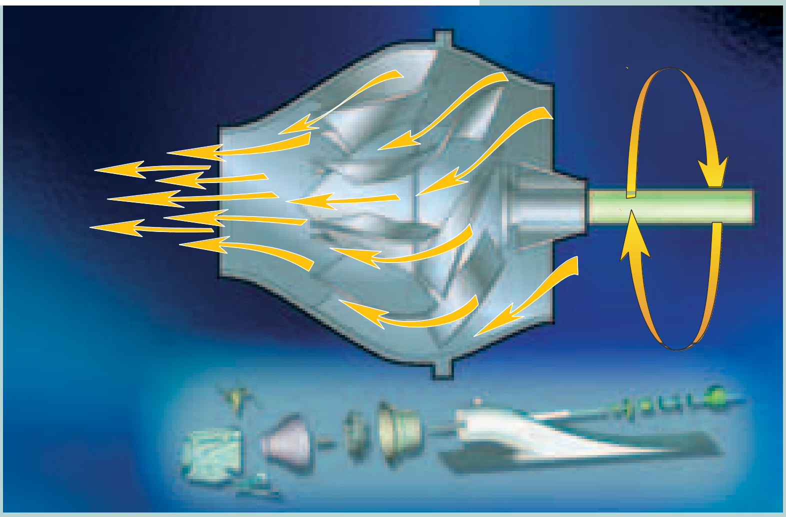


Figure 5: Construction and water flow through a waterjet

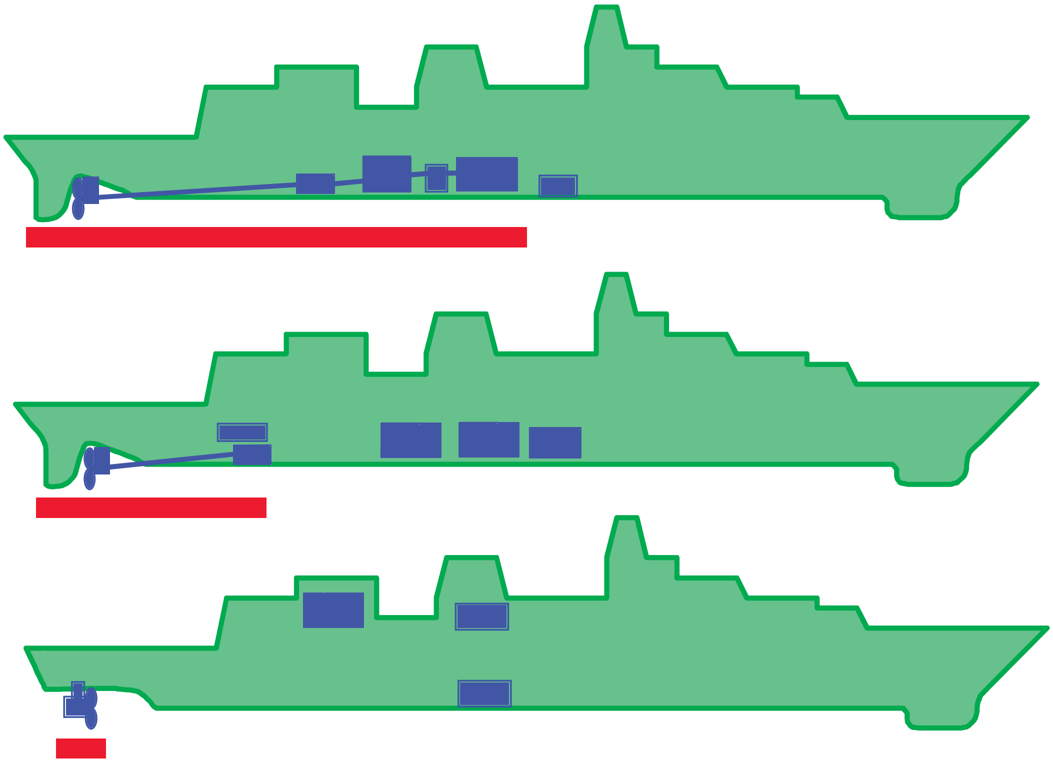


Figure 7: Layout of mechanical and electrical propulsion systems

A major benefit of IFEP is the layout flexibility offered through removal of the 'tyranny of the shaft line'. Since the prime movers are no longer directly coupled to the propulsors, there is considerable freedom in their location, permitting more effective use of the available space, as illustrated in Figure 7. In a warship this opportunity to distribute the power and propulsion system around the ship offers added benefits in terms of preservation of functionality and reconfigurability in the event of battle damage.

One of the key technologies enabling the realisation of the benefits of IFEP, particularly in naval vessels, is the compact electric motor. Over the past ten years there have been significant improvements in the torque density of electric motors, moving from conventional motors to advanced induction motors and permanent-magnet propulsion motors (see Figure 8). The transverse flux motor, currently being developed by Rolls-Royce, is a permanent magnet motor with a novel topology in which the magnetic and electrical circuits do not compete for space, so allowing the development of particularly high torque densities (see Figure 9). Figure 10 indicates the importance of developments in motor technology to the application of IFEP to smaller ships. The future has more to offer in this area. Over the next ten years we may well see the development of superconducting motors, offering a further step in the evolution of compact motors and further extending their application.

The greatest flexibility in ship layout is achieved if the motor is actually moved outside the vessel, into a pod

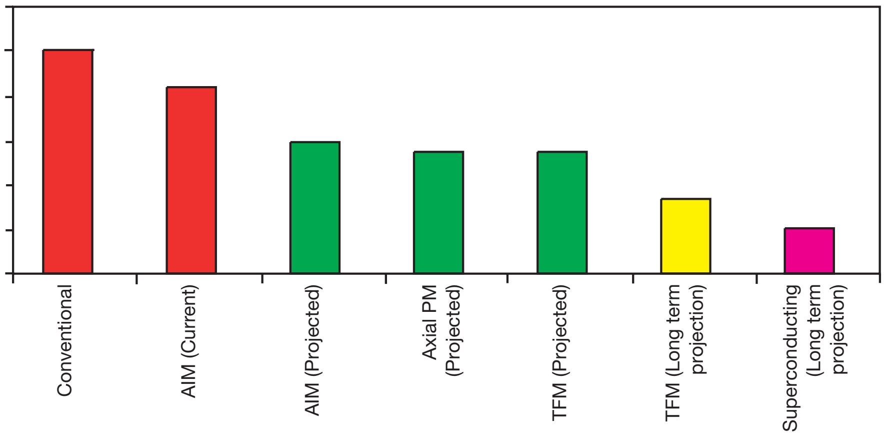


Figure 8: Comparative size of different propulsion motor technologies
AIM – advanced induction motor
PM – permanent magnet
TFM – transverse flux motor

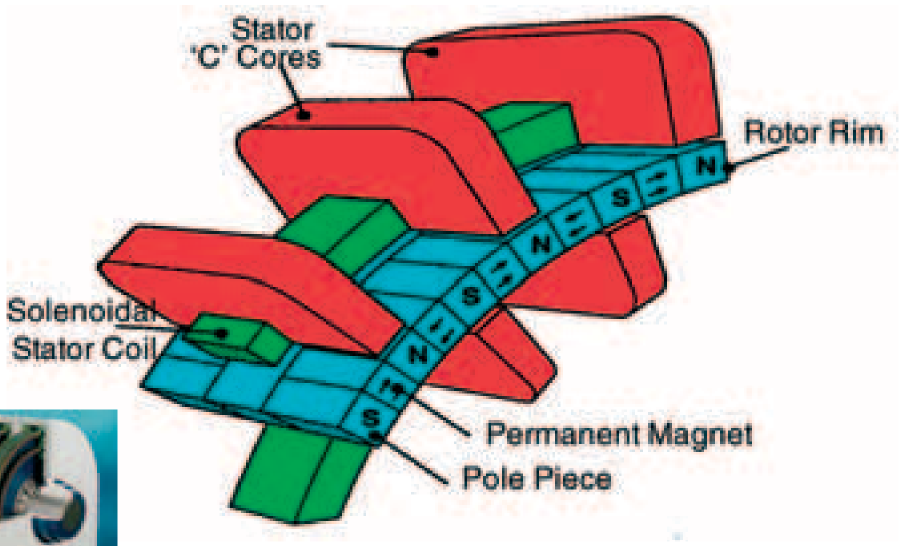


Figure 9: Layout of the transverse flux motor

below the ship, directly driving a propeller. Such podded propulsors have already been taken up by the cruise industry, including in the new Queen Mary 2 Cunard liner, where they offer increased space, reduced noise through complete elimination of the shaft penetrating the hull and outstanding manoeuvrability, as they can be rotated through 360° and act as both rudder and propulsor. An example of such an arrangement, the Mermaid™ pod, is shown in Figure 11.

Reduced fuel consumption

In addition to layout flexibility, IFEP offers fuel savings because the ability to run any part of the propulsion or power system from any prime mover, combined with the base load of the ship's service power demand, can be used to ensure that the load on the prime movers never falls to inefficient levels. Vessels such as warships and cruise liners, with relatively high service loads and operational profiles that frequently leave the propulsion system operating at fractional loads, offer an ideal platform for the IFEP system to generate fuel savings.

Improvements in prime movers, however, are key to reducing the fuel consumption of any propulsion system, mechanical or electrical. In both cases the goal is to offer a combination of high power density and low fuel consumption. The next generation of marine prime movers is exemplified by the WR-21, illustrated in Figure 12, the most advanced marine gas turbine currently available. It incorporates both intercooler and recuperator heat exchangers, the combined effect of which is to allow

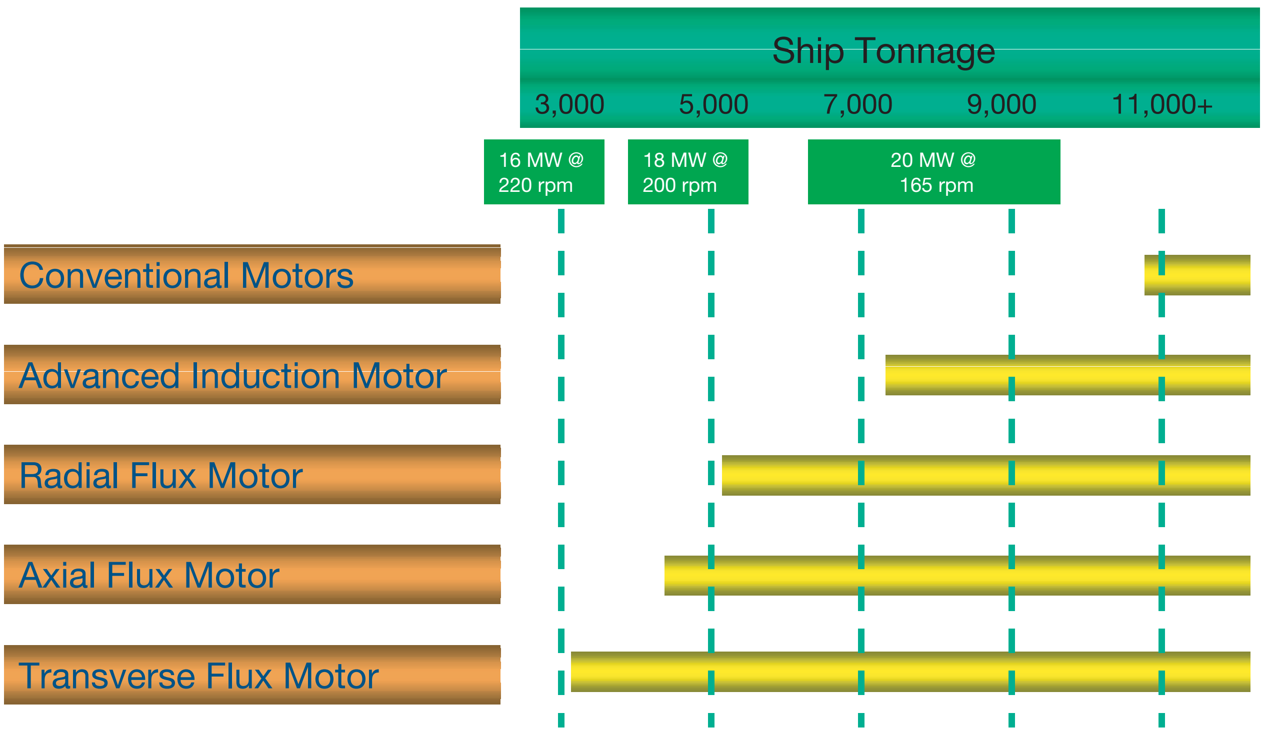
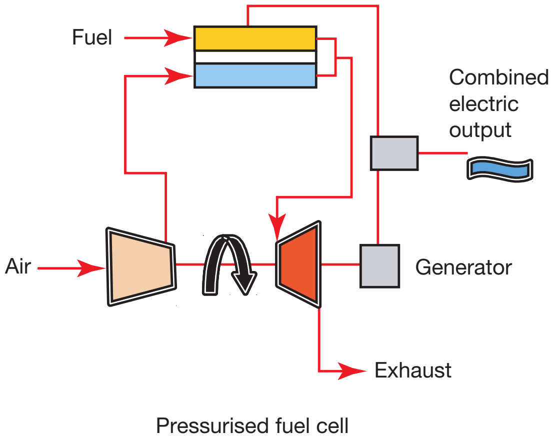


Figure 10: Motor technologies required for application of IFEP in different ship sizes

Figure 11: Mermaid pods on the Millennium cruise ship



- Fuel cells transform chemical energy directly into electricity, using hydrogen as a fuel
- Reformer technology required to convert methane or diesel to hydrogen
- A fuel cell consists of an ion-conducting electrolyte between two porous electrodes through which air and fuel flow
- Thermal efficiency of 40–50% stand-alone and 60–70% pressurised by a gas turbine
- Ultra-low NO_x emissions
- Initial small-scale applications 0.2–1 MW – expected to grow to over 20MW

Figure 13: Solid oxide fuel cell schematic

'waste' heat to be recovered from the gas turbine exhaust, providing significant fuel savings across the entire power range.

Although the WR-21 was originally developed for naval applications and will go into service in the Navy's new Type 45 destroyer, there are some strong similarities between the requirements of warships and cruise liners. Consequently, there is considerable interest in the use of complex cycles in cruise applications, illustrated by the selection of a combined gas turbine and steam turbine electric drive system (COGES) for Celebrity Cruises' Millennium class ships. In this instance a steam bottoming cycle rather than intercooling and recuperation has been chosen as an alternative solution to reduce fuel consumption through recovery of exhaust heat.

Manoeuvrability and stationkeeping

Manoeuvrability is a basic safety requirement for all vessels, as well as being an intrinsic element of the operational capability in some applications. These requirements are met through a combination of compact, powerful and efficient thrusters and the control systems that manage them. Podded propulsors provide a high level of manoeuvrability (for example the Millennium class has a tactical diameter of less than two ships lengths from an initial speed of 24 knots). There are equally innovative designs for mechanical drive applications, such as steerable mechanical thrusters.

In demanding offshore applications, such as floating production platforms, vessels must maintain station within a few metres. This is validated at the design stage using simulations of the performance of the ship and its power and propulsion systems in a range of wind, current and sea states. Naval vessels have similar requirements so that they can be replenished at sea.

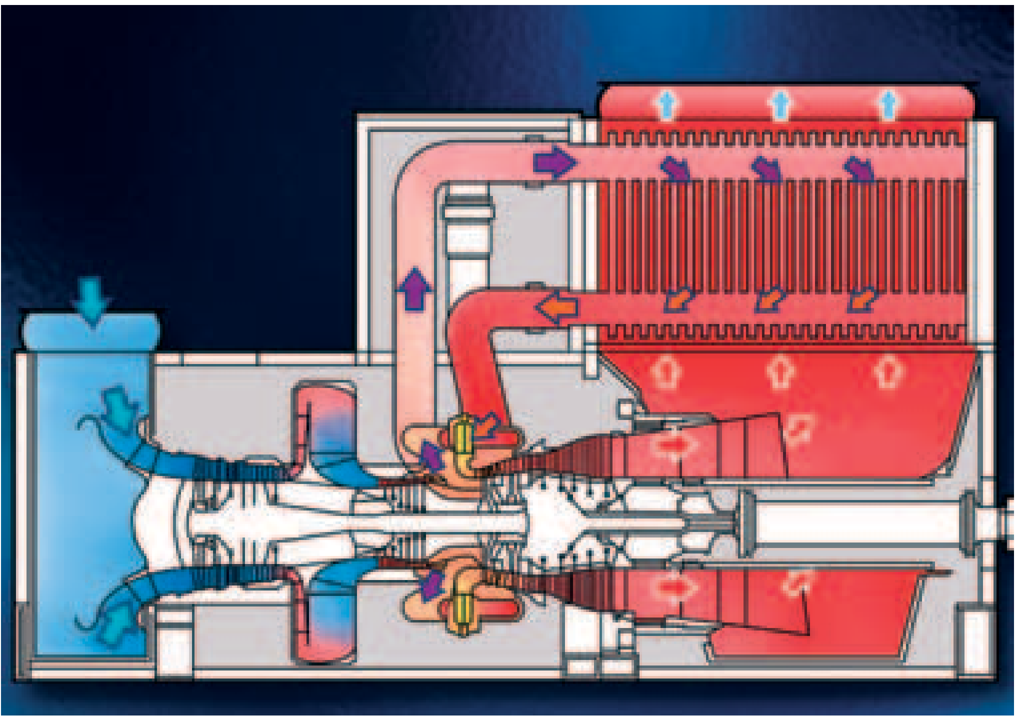


Figure 12: WR-21 gas turbine airflow diagram

Noise and vibration

Much hydrodynamic research, both computational and experimental, is focused on noise reduction. Key areas include tip vortex cavitation, hull propulsor interaction and hull pressure pulses, and blade-guidevane interaction in waterjets. Alongside these efforts to reduce propulsor noise at source, gas turbines offer an in-built reduction of prime-mover noise, since they emit high frequency noise that is readily damped to ensure passenger comfort even in close vicinity to the engine room.

Rolls-Royce is leading a major European Union (EU) funded project to develop validated design tools for system simulation, vibration isolation and fluid-borne noise modelling. The major technical areas to be addressed include:

- reduction of propulsor noise at source
- isolation of propulsion machinery noise
- control of intake and exhaust noise.

The challenge is to develop vessels that can exceed new comfort class requirements being developed by classification societies for cruise ships and fast ferries, while meeting the conflicting requirements for low costs and high power-to-weight ratios, particularly with fast ferries.

New waterjet impeller designs that minimise blade order and harmonic pressure fluctuations, to reduce important low frequency (<100 Hz) hull vibrations, are being developed, and reduction of noise transmission from the water jet tunnel through double skin isolation is being investigated. Propulsion machinery vibration isolation has been extensively developed in naval programmes and full-scale noise transmission trials on naval vessels have developed an in-depth understanding of propulsion system vibration isolation requirements. This has enabled finite-element models of complete propulsion system installations to be used to analyse noise transmission paths and develop effective mounting and isolation systems.

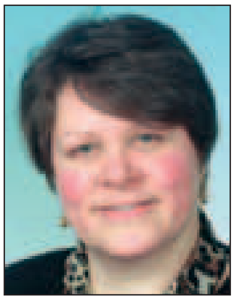
Environmental impact

Marine transportation is generally perceived to have a lower environmental impact than most other forms of transportation. However, increasing attention is being paid to the emissions from marine diesel engines (in Japan, for example, it is estimated that 17% of domestic nitrogen oxide is due to coastal shipping), particularly with regard to nitrogen oxide, sulfur oxide, soot and visible smoke, whether driven by legislation or less tangible but equally valid issues of public perception. This is an area where gas turbines have an inherent advantage, emitting no soot or visible smoke in the exhaust and significantly lower levels of nitrogen oxide and sulphur oxide than diesels. Marine gas turbines benefit significantly from investments being made in combustion research for land-based and airborne applications. Despite the difference in fuels the drive towards lower emissions is common, and the basic understanding of combustion processes, as well as the dry low emissions combustor designs that result, have broad application.

Carbon dioxide emissions from gas turbines, and hence their contribution to global warming, are generally higher than diesels. However, more efficient advanced cycle gas turbines such as the WR-21 significantly reduce the levels of carbon dioxide produced towards the levels emitted by the diesel engine. In the long term, Rolls-Royce is developing fuel cell systems, such as the solid-oxide system illustrated schematically in Figure 13 for land-based applications. Such systems could ultimately be applied in marine systems, particularly in electric ship applications, subject to the development of reforming technology to enable them to operate on typical marine fuels. With thermal efficiencies of up to 60–70% (potentially achieved in hybrid fuel-cell gas turbine systems) and almost no reduction in efficiency at part-load, this would yield a 40–50% reduction in fuel consumption, and carbon dioxide emissions below those of the most efficient diesel engines.

Concluding remarks

As our world becomes increasingly crowded, integrated transport systems exploiting a broader range of modes will become essential to reduce pressure on roads and airports. This will bring increasing opportunities for new developments in the marine sector. New technology in areas such as clean combustion technology, computational design and analysis methods, power electronics, advanced electrical machines, fuel cells and magnetic and superconducting materials will find application in marine vessels of the future. However, if the UK is to maintain and develop its position to exploit these developments, we need to find ways to improve the perception of the marine industry amongst our schoolchildren and young engineers, convincing them that it offers exciting and challenging career opportunities. ■



Julia King spent 16 years as an academic researcher and university lecturer working in the field of fracture of structural materials, before joining Rolls-Royce Aerospace Group as Head of Materials. She has continued to work for Rolls-Royce in various roles, and from 2000, for its Marine Business as Director of Engineering & Technology – Marine. In July 1999 Julia was awarded the CBE for services to materials engineering. In September 2002, Julia will start a new role at the Institute of Physics as its Chief Executive.

Ian Ritchey is Head of Research and Technology in Rolls-Royce's Marine Business. He has been in this role for two years, preceded by two years as a Professor at Newcastle University and six years in various roles with Rolls-Royce before that.