INNOVATION, RISK AND THE INTEGRATED FULL ELECTRIC PROPULSION SHORE TECHNOLOGY DEMONSTRATOR

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ABSTRACT

One of the major challenges for the marine engineer is how to incorporate the benefits of Integrated Full Electric Propulsion (IFEP) in future classes of warships. This requires innovative development of electric propulsion equipment with high power density, particularly for power electronic devices and propulsion motors. This equipment must then be integrated to produce a reliable, adaptable and capable IFEP system. Finally, to be accepted as a feasible concept for warship shipbuilders, it is necessary to prove that power dense IFEP is a low risk propulsion option.

The Royal Navy is planning to meet this need by demonstrating an IFEP system at a shore facility. This facility, known as the Shore Technology Demonstrator (STD), will show that IFEP can meet the operational requirements (such as power, speed, signature, survivability) of future ships and submarines whilst achieving significant savings in total Life Cycle Costs and reducing risk. The STD will investigate factors impacting on system architecture and equipment selection, including the vessel's operating profile and role, requirement for single generator operation, fault detection and protection and system stability. These issues are discussed with particular emphasis on the ship impact of the various IFEP options and the system integration concerns that are now being addressed.

Further discussion develops the concept of an 'open' system that can be applied with minimum change across a range of warship and can incorporate future technology developments (such as fuel cell power sources) with minimum modification. Finally the preliminary results of an availability analysis are presented where the ability of an IFEP warship to meet a typical mission scenario is contrasted against conventional propulsion systems.

Background

Diesel generator based Integrated Full Electric Propulsion (IFEP) is well established in the commercial marine sector primarily because of its compact, flexible layout and lower operating/support costs compared to mechanical, direct drive alternatives. MoD studies confirmed that commercial IFEP systems reduced operating and support costs but that an IFEP propulsion system had an increased acquisition cost compared with conventional alternatives. Pay back occurred between 2 to 7 years in service, depending on the ship's operating profile. The propulsion systems specified by the Prime Contractors for the recent Landing Platform Dock Replacement (LPD(R)) and Auxiliary Oiler (AO) projects are examples of commercially derived diesel generator based IFEP and were chosen due to the LCC benefits resulting from electric propulsion.

Commercial IFEP systems generally use Diesel Generator Prime Movers with two or more generators on-line at any one time. Furthermore, in a commercial application, such as a cruise liner, the hotel service load is a significant proportion of the total load on the prime movers. At sea this total load is also relatively constant. In naval applications, such as a frigate, the maximum hotel load is only a small proportion (approximately 5%) of the maximum total load, due to the high power of the propulsion motors. However, the operating profile of the ship dictates that for long periods the propulsion power requirement is low (e.g. when loitering) and the hotel load accounts for over 50% of the total load under these circumstances. Hence a highly flexible and adaptable system is required. When this is compounded with the need for high power density, low acoustic and magnetic signature, and high survivability it becomes obvious that naval requirements differ considerably from commercial requirements. A supporting development programme was required, covering propulsion motors, fuel-efficient gas turbine alternators and electric auxiliaries, such as steering gear and stabilizers. Finally, in order to reduce acquisition and support costs it was decided to minimize the number (and types) of installed prime movers in the ship and also to implement Single Generator Operation (SGO) whenever possible to reduce total prime mover running hours.

A Marine Engineering Development Strategy (MEDS) Paper for the Royal Navy, making proposals to undertake this work, was presented in 1996 and endorsed at the highest level within the MoD. That paper gave a focused approach to reducing the Life Cycle Costs (LCC) of marine engineering systems in future ships. The strategy can be summarized as adopting advanced cycle gas turbine prime movers, IFEP and electric auxiliaries in order to reduce LCC whilst maintaining or enhancing operational capabilities and meeting all predicted environmental requirements.

The strategy is targeted on the Future Surface Combatant (FSC), Future Aircraft Carrier (CVF) and Future Attack Submarine (FASM). A potential FSC IFEP architecture is shown in (FIG.1).

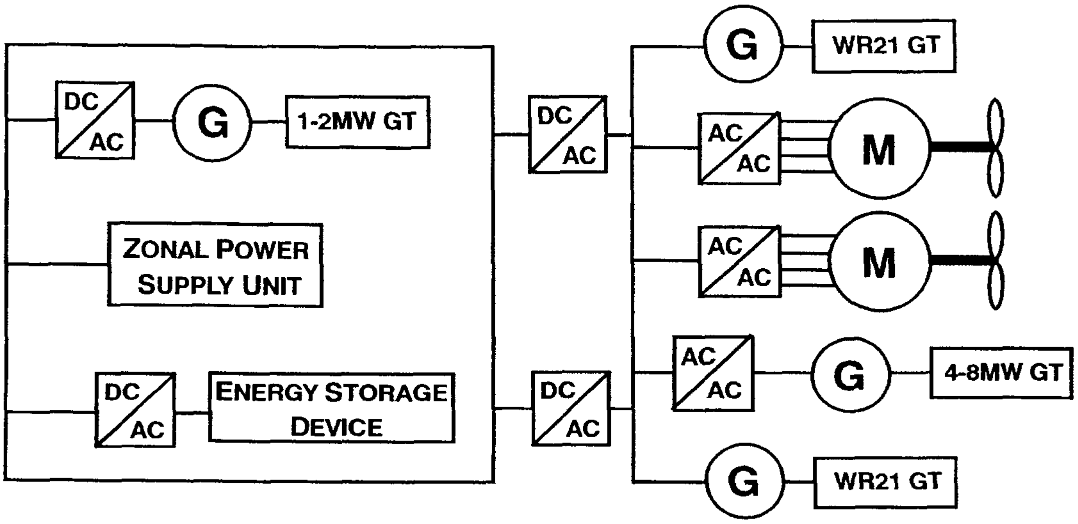

FIG.1 — POTENTIAL FUTURE SURFACE COMBATANT IFEP POWER SYSTEM

Cost Benefit Assessment

In the past, major changes to propulsion systems were often preceded by extensive shore and/or sea trials with the aim of proving that a system was suitable for naval service. This ensured that ship availability and reliability requirements were not prejudiced after introduction into service. The introduction of gas turbines (with HMS Exmouth as a trials ship in the 1960's), proving of the INVINCIBLE class Aircraft Carrier transmission system, the Type 23 Frigate propulsion test facility for diesel electric propulsion, and nuclear submarine propulsion plant testing are all relevant and notable examples of this approach. The possible consequence of not undertaking such trials is well illustrated by the Upholder submarine (SSK) experience when a major failure of the propulsion system occurred during Contractor's Sea Trials and subsequently contributed to a 2 year delay in the build programme. With current procurement strategies, in which the MoD seeks to transfer risk to the Prime Contractor, it is considered that new technology will not be easily introduced to future warships unless either:

(a) The MoD funds the de-risking of the technology to a sufficient level to enable potential Prime Contractors to propose such systems without imposing a significant risk contingency in their bid.

(b) The MoD mandates the technology and thereby retains the risks and the responsibility for the future cost of any remedial work.

(c) The Prime Contractor takes the risk without the MOD funding de-risking. In this case the Prime Contractor will seek to offset the risk by imposing a significant premium on the price of an IFEP system.

MoD investigations showed that the estimated cost of de-risking the Electric Ship Systems was significantly lower than the estimated risk premium that could be imposed by potential prime contractors. Furthermore the LCC benefits were so attractive across the potential Electric Ship applications that it was in the MoD's interest to de-risk the technology and make it available to the potential warship Prime Contractors. Without such MoD funded development experience had shown that warship Prime Contractors would propose low risk conventional systems, with attractive initial acquisition costs, but longer term built-in obsolescence and high support costs for the owners. In summary, the cost benefit analysis weighed heavily in favour of the MoD carrying out its own de-risking programme.

As a result the MoD decided to commission a Shore Technology Demonstrator (STD) for the generic Electric Ship technologies, including Advanced Cycle Gas Turbines and the IFEP architecture. In addition to de-risking the individual equipment this demonstration would also address system integration and operating issues. Furthermore it would also provide validation of models and so allow non-generic IFEP systems, such as for the FSC, to be simulated with confidence and so negate the need for subsequent demonstration of a prototype system for a particular application.

A less quantifiable, but still important benefit was that the IFEP STD would allow decision-makers in Industry and the MoD to view an innovative ship propulsion system in operation, demonstrating the attributes which otherwise could only be seen on paper.

Aim of the STD

A Technical Panel, including representatives from each of the target warship projects and the specialist technical areas, was formed to consider different methods of proving the technologies in the STD. The panel addressed the issues concerning the choice of the generic power system architecture and the extent of the demonstration that would be necessary to de-risk the technologies sufficiently. The three different methods of demonstrating a generic IFEP system considered by the Technical Panel were:

(a) *Software simulation*

This is an essential precursor to any system definition and is currently being undertaken as part of the MoD's ongoing studies. However, there are limitations on the extent to which this approach alone could be used convincingly to de-risk the technology. Of particular concern is the validation of the software, and the results for system response during transient and fault conditions. In many instances, the only means to conduct this validation is by hardware testing.

(b) *Hardware emulation*

This is the provision of hardware that reacts identically to the actual equipment. Emulation can provide a more cost-effective method of demonstrating the integrity of IFEP systems than utilizing the actual hardware, provided that the equipment parameters are sufficiently defined and validated. Further work would be needed in order to test specific military requirements, such as acoustic signatures and shock performance.

(c) *Full scale equipment*

This is the lowest risk route to achieving confidence, but it can be the most expensive unless the equipment is reused in a subsequent project. In addition, if equipment is under development, some may not be available when required by the test facility.

The Technical Panel recommendations were based on availability, costs and affordability as well as engineering analysis and judgement. Consequently, the recommended STD system will be a combination of hardware emulation and testing of full-scale equipment with the results supporting validation of software models which can then be used in the development of the ship specific designs.

IFEP Shore Technology Demonstrator

The Technical Panel determined the STD equipment fit based on the availability and risks associated with each equipment, balanced against its cost. For example, there is little point in including well proven equipment in the demonstrator as little will be achieved beyond addressing system integration issues. Conversely, inclusion of an unproven, high-risk equipment development could create so many technical problems that the demonstrator failed to achieve its objectives and the overall concept remained unproven. The resulting equipment architecture is shown at (FIG.2).

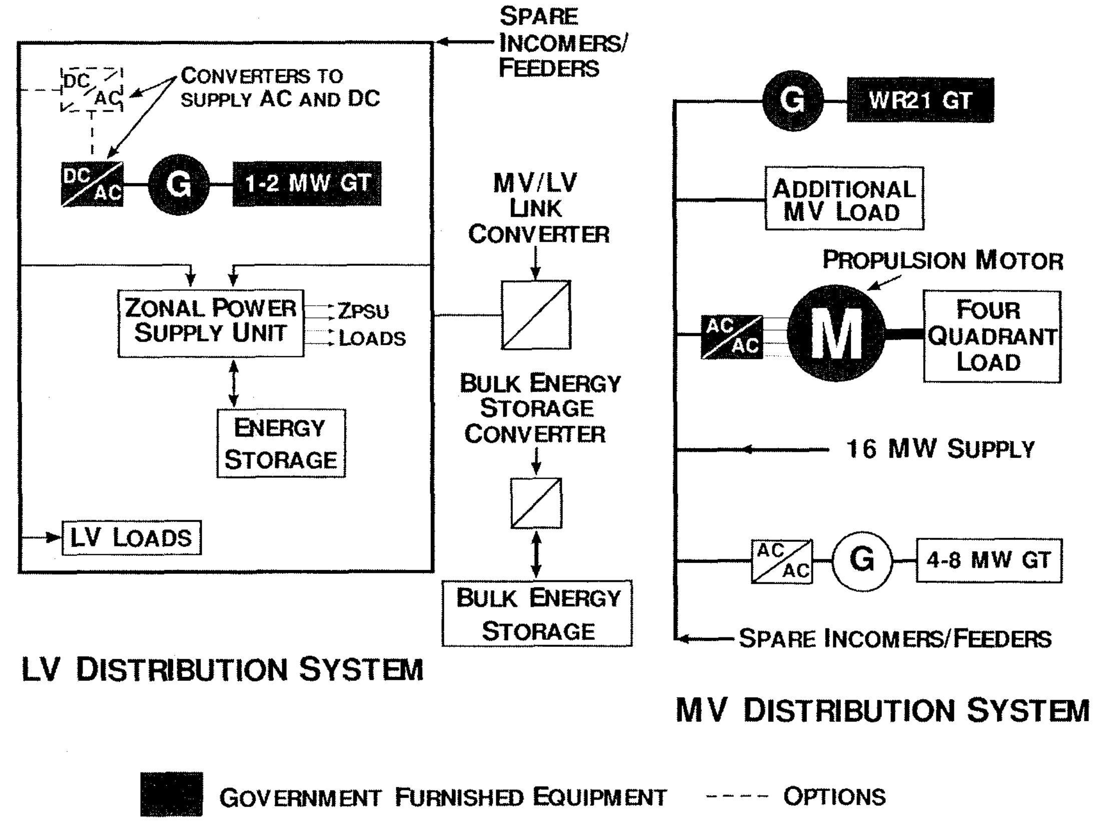

FIG.2 — PROPOSED STD SYSTEM CONFIGURATION

The STD is approximately half an FSC Propulsion System, containing all of the major elements of the IFEP system without the system and equipment redundancy required in the final warship application. It will demonstrate some of the options available for ship's service distribution and energy storage in future warship systems. In addition the Shore Demonstrator includes the loads required to enable operation in all modes.

The main features of the Medium Voltage (MV) Distribution System are:

(a) The WR21 GTA, derived from the current WR21 Advance Cycle Gas Turbine development programme.

(b) The 4-8 MW GTA, to provide cruise power for the FSC or harbour power in the CVF.

(c) The Propulsion Motor, a power dense design with a maximum output power of 20MW at 180rpm. The Propulsion Motor will require a Four-Quadrant load, to provide regenerative energy back into the system to simulate manoeuvring conditions.

(d) Additional loads for system testing and for testing the WR21 GTA prior to system integration.

The main features of the Low Voltage (LV) Distribution System are:

(a) 1-2 MW GTA, currently in the early stages of a MoD development programme.

(b) Zonal Power Supply Unit (ZPSU). The ZPSU is rated at 300kW of which 200kW are essential supplies. The ZPSU is designed to provide 440V/60Hz, 115V/60Hz, 115V/400Hz, 24V DC, and 220V DC to the particular ship zone.

(*c*) Zoned Energy Storage. The ZPSU is provided with a zoned energy storage device to allow backup to the essential supplies in case of a generator trip. This will have capacity for a minimum of 10 minutes, enough time for 2-3 Gas Turbine starts.

Connecting the Propulsion and Ship Service systems is the MV/LV Converter; this is rated at 2MW and will be capable of bi-directional power flow. The Bulk Energy Storage device is rated to provide 1MW for a minimum of 10 minutes. This can be connected to either the Ship Service or Propulsion systems.

System testing

To establish the extent of the high level tests, the Technical Panel derived a number of credible failure scenarios for the Nominal Future Surface Combatant IFEP Architecture (Figure 1) and then agreed the most severe or limiting ones. These limiting failures were then examined as system scenarios to ensure a basis for the definition of the test and the acceptance criteria.

(*a*) Short Circuit on MV system with the WR21 GTA in Single Generator operation.
(*b*) Failure of Auto-Synchronisation with a GTA being paralleled on to the System with another GTA.
(*c*) Short Circuit — Ship Service Busbar at the connection of the LV system to the MV/LV Link converter.
(*d*) Short Circuit — MV System (at Full Load).
(*e*) Crash Stop — MV System at Full System Load.
(*f*) De-Excitation of One Alternator with two Alternators in Parallel.
(*g*) WR21 GTA Trip.

The scenarios provide the interrelationships between the equipment. From the scenarios, these relationships confirmed which equipment was required to be tested at the STD.

In addition to the scenarios given above, a number of Operational, EMC, Noise and Vibration, Earth Fault, and Transient Response trials will also be undertaken.

STD TECHNOLOGIES

The requirement for the STD is to de-risk the technologies for a power-dense IFEP system for the FSC, CVF and FASM. However, these vessels may not be in service until 2012 or later, and therefore the period between the delivery of the STD system and delivery of an IFEP Propulsion system to the ship could be a technology generation away. This potentially means that the technologies for some of the equipment (particularly the power electronics) at the STD will not be the same as those installed in the First of Class. Therefore, in certain areas, the STD will de-risk the capability of the technology rather than the actual equipment.

System Integration

System integration was highlighted at an early stage as one of the main risks and therefore the STD project focuses on the associated issues. The WR21 GTA, the 1-2 MW GTA and the 20 MW Propulsion Motor are being procured under separate development contracts and will be delivered as Government Furnished Equipment (GFE) to the STD. The project management team have expended much effort in ensuring that systems and equipment requirements are fully compatible and during the design and installation phases regular integration meetings will be held between all interested parties.

AC versus DC

The debate concerning AC versus DC for the Ship Service supplies continues with technical benefits being balanced against cost and commercial developments. Although AC systems may be the system of choice today, developments may make DC systems more commercially attractive tomorrow. Therefore it was decided that the STD should demonstrate both approaches and scenarios requiring both 440V, 60Hz AC and 800V DC distribution systems were developed. This requirement will present technical challenges for the STD. An additional complication is the supply of the 1-2MW GTA, which shall be a GFE item with an 800V DC output. As a result the STD contractor will also need to provide an interface to convert the 800V DC to 440V AC.

The Ship Service system for the STD will be a ring main. The STD contractor is being given considerable latitude to propose suitable protection philosophies with functional requirements based on commercial standards and the need to reconfigure the system under operational conditions.

Power Electronics

In the last 10 years there has been a revolution in the Power Electronic technologies. New devices are capable of switching higher power levels at higher switching frequencies than ever before. In addition to the new devices, there are new converter topologies such as Matrix, Resonant and PWM. The use of the new technologies must be set against their associated risks. The requirement for the STD is being met as a functional requirement and it will be up to the STD contractor to select the appropriate technologies. To encourage the STD Tenders to introduce innovation in their bids, the MoD will award additional marks for innovative ideas.

The power electronics have no military specifications but are required to be suitable for future development to meet shock and enclosure standards. Achievable power density requirements were given to ensure that the equipment would fit into future warships without cost escalation. The MV/LV and the bulk energy storage converters have a requirement for a production power density of $0.4MW/m^3$. However, the STD has relaxed this requirement to a power density of $0.2MW/m^3$, provided that a development programme to meet the production target can be presented. The ZPSU has a production power density requirement of $0.15MW/m^3$.

Single Generator Operation (SGO)

As previously discussed an important element of the MEDS is to operate in a SGO mode to achieve significant savings in operating and maintenance costs. In this mode, there will be no running prime mover in reserve in case one of the prime movers trips off the system. SGO envisages long periods, such as cruising in open waters, when only one prime mover is in operating. It may be acceptable to lose the propulsion power under these circumstances; however, essential ship services will require some form of non-interruptible power supplies. Instead of having many localized UPS systems distributed around the ship, it is proposed that backup to these essential systems will be provided from a single energy storage device within each zone.

In addition the STD will also demonstrate a bulk energy storage device to provide power to the propulsion system in the event of the loss of the prime mover when in SGO mode. This will be of sufficient size to ensure ship safety (e.g. maintenance of steerage-way) for a short duration whilst the standby prime mover is started. It could also provide a short duration ultra-quiet mode, with all prime movers shut down, to enhance anti-submarine operations.

The energy storage devices offer other possible benefits, such as load lopping, and providing energy storage for pulsed power sources for such applications as Electromagnetic Guns, or the Electromagnetic Launch of aircraft in the CVF application.

Mandating of technologies

Rather than mandating particular technologies the MoD has discouraged the use of well-proven technologies. For example, the Bulk Energy Storage Device will not be a lead acid battery as this has been in use in submarine applications for many years. As a result the STD contractor has been encouraged to examine other technologies, such as regenerative fuel cells, or flywheels.

Future technologies

The IFEP architecture is being designed from the outset to support the concept of technology insertion and incremental acquisition. It is therefore an open architecture into which new technologies can be incorporated with the minimum of system redesign. Modern solid state power converters are the principal enabler to achieve this capability. Therefore, IFEP has the potential to reap additional LCC and operational benefits in the future with the risk limited to the single, new equipment rather than a complete, new propulsion system.

The STD provides an excellent opportunity to assess new technologies, such as fuel cells, within a representative ship system to examine such issues as transient response to step load changes. Another potential technology for future warships is podded propulsion. Podded Drives offer proven UPC and LCC savings in the commercial environment. Both IFEP and Podded Propulsion are reliant on electric drive so the results from the STD will be equally applicable. However, a military podded drive development will also need to address issues of shock, electromagnetic signature and acoustic signature. A separate programme of work is being formulated in order to examine these issues in more detail.

The STD also has the potential to examine pulsed power systems, such as those required for electro-magnetic aircraft launch system and future pulsed weapon systems, now in their early development stages. These require a high energy, short duration power source and the STD will provide an ideal opportunity to examine the implications of this requirement on an IFEP system.

System Availability and Reliability

The Life Cycle Cost benefits of IFEP are now well proven in the commercial environment and extensive work has predicted with a high degree of confidence that these benefits will be equally applicable to warships. However, the arduous operating profile of warships, combined with long periods away from base support and the introduction of the concept of SGO has meant that the latest work is now focused on assessing system availability and reliability, particularly in respect of a range of typical operational missions.

Although precise requirements are classified, many of the predicted future missions for a warship, such as the FSC, will have the following characteristics:

(a) High speed, long range transit followed by an extensive period of loitering at low speed interrupted by short periods at high speed.

(b) Lack of support, including maintenance and refuelling facilities.

Therefore, for example, a warship can be considered to have failed its mission if it does not have the fuel efficiency in a degraded mode to loiter for long periods without support after a long distance, high-speed transit (FIG.3).

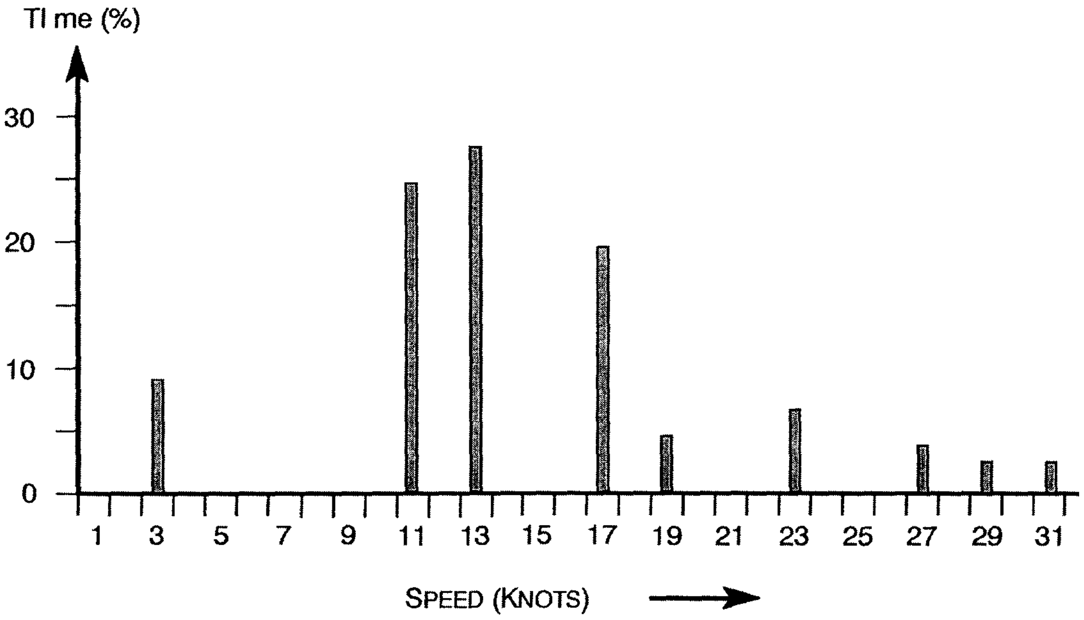

FIG.3 — REPRESENTATIVE MISSION SPEED PROFILE

The Electric Ship has a number of attributes that should enable it to perform significantly better than warships with conventional propulsion systems. These attributes include:

(a) System flexibility. Any prime mover, or combination of prime movers, can supply the power giving a wide range of fallback options in case of failure. Single points of failure are reduced.

(b) Use of advanced cycle gas turbines. A single engine failure will not result in significant degradation of the ship's speed/range capabilities.

(c) SGO and Energy Storage. Prime mover running hours can be restricted reducing the maintenance requirement and providing a good standby power capability.

These predictions have been borne out by the initial results of the availability study. Within this study a range of IFEP propulsion options are being compared with conventional mechanical and mechanical/electrical drive configurations across a range of missions which match potential operational scenarios.

Realistic reliabilities, based on in-service data, have been assigned to each equipment and from this the probability of meeting the mission requirements are assessed (FIG.4).

The initial results have supported the inherent flexibility and redundancy of the various IFEP configurations in comparison to the mechanical and electro-mechanical drives. Various IFEP configurations have an improved availability of meeting the required mission speed. With CODOG in particular there is a significant period where there is a significant drop in speed and no propulsion available at all.

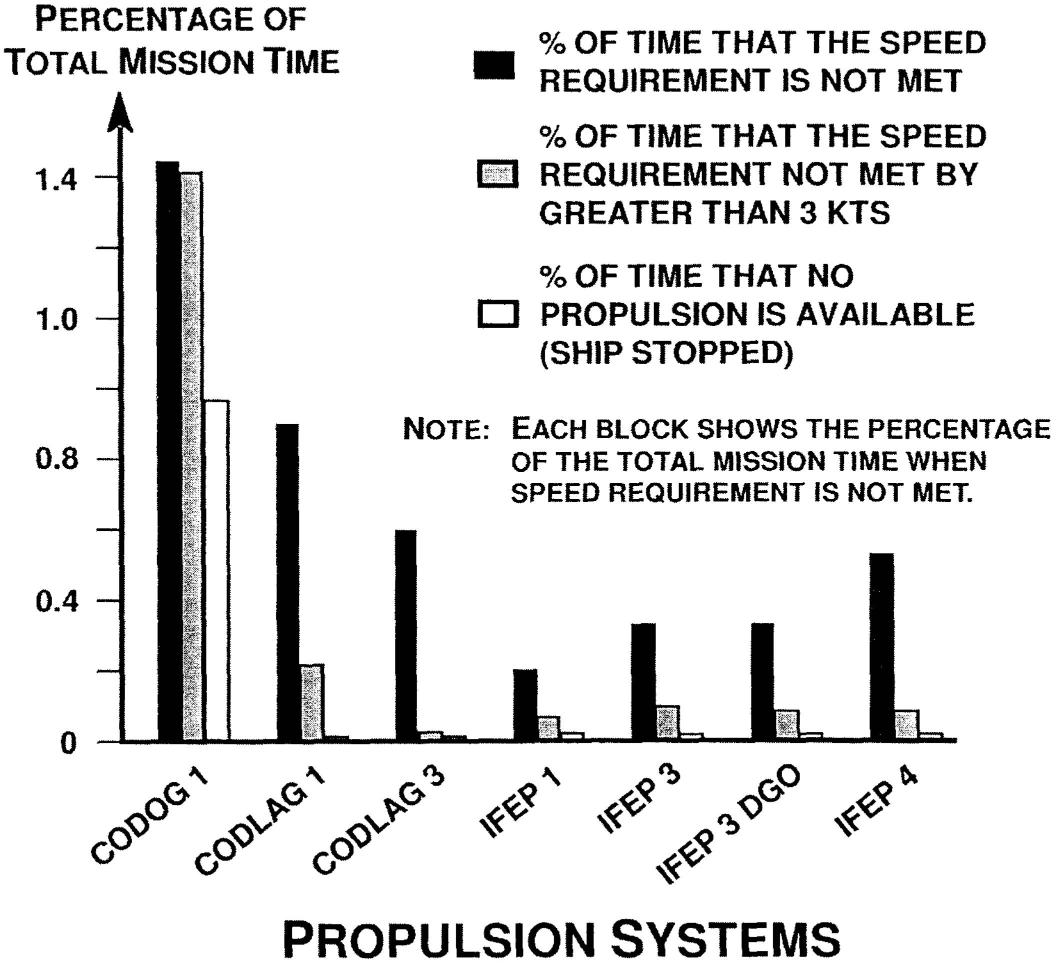

FIG. 4 — COMPARISON OF THE AVAILABILITY OF PROPULSION SYSTEM

Conclusions

The proven commercial concept of IFEP is now being applied to warship configurations. Although additional development of warship systems is required, the LCC and operational benefits are such that the cost of a STD, to quantify and reduce the risk, is fully justified. As a result, future warship Prime Contractors will be able to propose IFEP systems without imposing undue risk premiums and the Royal Navy will be able to benefit from the operational and LCC benefits. The IFEP concept will also allow future innovative developments to be incorporated without major re-design or high system risk.

Finally, a reliability analysis of IFEP systems in typical operational scenarios is now underway. Initial results show that IFEP systems have the inherent flexibility and reliability to meet the unpredictable operational requirements of future warships.

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