DEVELOPMENTS IN WARSHIP DESIGN AND ENGINEERING

BY

C.V. Betts, MA, FEng, FRINA, RCNC
(Director General Submarines, Ministry of Defence and Head of the Royal Corps of Naval Constructors)

This is an edited version of the Sixty Eighth Thomas Lowe Gray Lecture, that was presented at an ordinary meeting of the Institution of Mechanical Engineers on 24 January 1996.

ABSTRACT

Warships, together with their weapons and major sub-systems, take ten to fifteen years to design and build and then spend twenty-five years or more in service. The Royal Navy fleet of today was designed during the Cold War for conditions rather different from those now pertaining. Designs now on the drawing board (or, more correctly, on the computer screen) and the research and development required to underpin them are aimed at requirements where the enemy threat is uncertain, warfare technology proceeds apace and the need for maximum value for money in reduced defence budgets is paramount.

Developments in weapon systems and command, control and communication systems are impressive and far reaching. However, developments in surface warship and submarine naval architecture and marine engineering are potentially as important to the long term effectiveness and affordability of the Fleet. This paper looks at the technologies being considered for future designs with emphasis on hull and marine engineering developments. These include novel hull forms such as the Trimaran and possibly the next major step in surface warship propulsion, that to the all-electric ship with electric transmission and low fuel consumption gas turbines as prime movers for electricity generation. The paper also discusses the importance of human factors in the design process, the increasing use of commercial standards to control costs of both hardware and software, and improvements in naval ship and submarine design tools for use in the crucial concept design phase.

Introduction

Aim

The aim of the article is to describe warship design and engineering developments that the Ministry of Defence (MoD) and the naval defence industry are pursuing today.

The harsh reality of competing goals of requirement, cost and time can be found across all industries but they are particularly acute in defence at the moment. For the warship designer and project manager, dealing with multi-billion pound projects on the cutting edge of technology against a reducing defence budget, the task gets ever more challenging.

This article will review these issues and, it is hoped, give an insight into not only the design and engineering of warships but also some of the many other building blocks which support this complex and fascinating branch of engineering.

The changing threat

Some 6 years have passed since the end of the Cold War. During this time we, together with our allies, have been adapting to the transformed strategic setting. The UK is committed to work towards nuclear disarmament and has reduced the size of its nuclear forces. Trident, for example, will now deploy a much smaller deterrent, matched to our current security needs.

Whilst we all welcome removal of the Soviet strategic threat that dominated our security concerns for so long not all of the consequences of the collapse of the Soviet Union have been positive. The previous low risk of global war has been replaced by a greater risk of smaller scale conflict and suffering, spawned by the instability present in many parts of the world. We can expect to see growing calls on the UK to support conflict prevention, conflict resolution, peacekeeping and humanitarian aid missions. We will therefore need the capability for a flexible response, whether working in conjunction with our NATO allies or, if necessary, alone where our national interests are at risk. The Royal Navy will play a key role in this process and its warships must be designed accordingly.

Constraints

Defence is still big business. This financial year, 1996/97, we intend to spend nearly £21.5 billion on our armed forces of which £9 billion is equipment related. In the past 5 years, the MoD has placed over 300,000 contracts worth around £33 billion with a supplier base of some 6500 companies. However, on present plans the proportion of Gross Domestic Product spent on defence will fall to 2.7 % in 1998/99 by which time defence expenditure in real terms will have fallen by some 20 % since the end of the Cold War.

It was pointed out 16 years ago[1] that the aim of the warship designer had changed from producing the best ship, to producing the most cost effective and now to producing the best that could be provided for the money available. Nothing has caused such difficulty so consistently for defence planners in all countries as the persistent tendency for new equipment to cost more, unit for unit, than that which it replaces in the same roles. This unit cost escalation has taken place over the last half century persistently at a rate of circa 10 per cent per annum in real terms for most types of equipment. In consequence the evolution of Western armed forces since the 1950s has been characterized by progressive reductions in numerical strength[2].

A further constraint on planners of the fleet of the future is that they do not start with a clean sheet of paper. The Royal Navy fleet currently in service and under construction will dominate fleet numbers for many years to come. It will probably be 30 or 40 years before the last of the current classes are withdrawn from service.

The current and planned fleet

The Royal Navy now holds sole responsibility for the nuclear deterrent which will be carried in the 4 VANGUARD class TRIDENT submarines. The other naval tasks are planned around the 3 core capabilities of: nuclear powered submarines, aircraft carrier task groups, and amphibious forces. The changing threat and reducing defence budget have had significant implications for the future of the Royal Navy, as they have for the Army and the Royal Air Force. Fleet reductions have included the:

(*a*) Reduction of the non-ballistic missile submarine fleet from 16 to 12 (7 TRAFALGAR, 5 SWIFTSURE class) nuclear powered attack submarines (SSN) by withdrawing diesel/electric UPHOLDER class submarines. Compared with SSNs these lack the sustained high speed and long endurance needed in the new security environment, to respond rapidly to the changing threat.

(*b*) Reduction of the destroyer and frigate force to 35 ships which was achieved in early 1995. The force level was revised as a result of the reduction in the scale of anti-submarine operations in the North Atlantic, due to the substantial decline in the former Soviet submarine fleet.

The fleet is reducing but there is still a sizeable equipment programme. An overview of the Royal Navy's Equipment Programme is provided in Table 1.

TABLE 1—*Royal Navy equipment programme*

Equipment	Number ordered up to 1995	Number ordered 1995 –96	Number delivered before 1995–96	Number delivered 1995–96	Balance Due	In Service Date
Submarines						
VANGUARD Class (TRIDENT)	4	—	2	—	2	1993
Batch 2 TRAFALGAR Class	ITT† Issued	—	—	—	—	2005
Submarine Equipment						
VANGUARD Submarine Self Protection Mast	4	—	2	2	—	1994
Submarine Command System	23	—	11	3	9	1994
SPEARFISH Heavyweight Torpedo	100	*	*	*	*	1994
Sonar 2054—for VANGUARD Class SSBNs	4	—	2	—	2	1994
Sonar 2076—for Trafalgar Class SSNs	4	—	—	—	4	2002–3
TRIDENT II (D5) (SLBM)	44	—	18	14	12	1994
TOMAHAWK Missiles	—	65	—	—	65	1998
SSN TOMAHAWK Control System	—	7	—	—	7	1998
Surface Ships						
Type 23 Frigate (DUKE Class)	13	3	10	—	6	1989
Landing Platform Helicopter	1	—	—	—	1	1998
Single Role Minehunter	12	—	5	—	7	1989
Ocean Survey Vessel	1	—	—	—	1	1997
Auxiliary Oiler	—	ITT† Issued	—	—	—	2000
Landing Platform Dock (Replacement)	—	2	—	—	2	2001

*—Classified
†—Contracts since placed (March 97)

Surface Ship Equipment						
Sonar 2050—for surface ships	31	3	3	27	4	1989
Sonar 2093—for SANDOWN Class	15	—	13	—	2	1992
GWS 26 MOD1 Vertical Launch SEA WOLF Missile and Ship System	13	—	1	11	1	1991
Type 996 Radar	37	—	4	25	8	1988
Type 23 Frigate Command System	17	—	—	—	17	1998
Action Data Automation Improvements	14	—	3	2	9	1994
SCOT SHF Satellite Comms Terminals	55	—	3	47	5	1989
Naval Aircraft						
EH101 MERLIN ASW Helicopter	44	—	—	—	44	1998
SEA HARRIER F/A2	18	—	2	—	16	1995
SEA HARRIER Mid-Life Update	35**	—	7	21	7	1994
AMRAMM	210	—	150	—	60	1995

**—One update cancelled due to loss of a SEA HARRIER

Emerging technologies

Combat systems

Technology continues to change at an ever increasing pace. Last year (1996) saw the 50th anniversary of the formation of the Weapon Engineering specialisation in the Royal Navy , and the exhibitions staged at HMS *Collingwood* in June 1996 gave some flavour of the enormous changes that have taken place in weapon engineering over this half century.

New weapon systems coming into service such as submarine launched TOMAHAWK cruise missiles being purchased from the USA and the Principal Anti-Air Missile System being developed with France and Italy for the Common New Generation Frigate (Project HORIZON) will add further international flavour, as well as new capabilities. The USA recently placed a contract for the development of an air-borne laser defence system against hostile missiles and, further ahead developments may include methods for non-acoustic detection of submarines, and the use of autonomous unmanned vehicles, both in the air and underwater. Perhaps the greatest impact will arise from the changing environment in which the Royal Navy will be required to operate. The shift of emphasis away from the open ocean Cold War scenario towards operations of an international nature, often in littoral waters, will place far greater emphasis on Command and Control, Computers, Communications and Intelligence (C^4I). In this new 'information' environment, vast quantities of data will need to be processed, not only from an increased range of more capable weapons and sensors, but also from shore and from other ships and aircraft via satellite datalinks. This will require intelligent filtering of the data and sophisticated data fusion techniques if the Command is to be presented with a cohesive and comprehensible picture, rather than simply being overwhelmed.

Increased information exchange can also bring new and potentially serious problems, as was reported in 1995 in the Defense News when an US Air Force officer (of all people!) hacked via the Internet into the command and control systems of US ships at sea.

FIG. 1 — HMS 'NORTHUMBERLAND'S' COMMAND AND CONTROL CONSOLES

Software is pervading all our projects, not just combat systems, more and more. Command and control systems currently at sea, like HMS *Northumberland*'s (FIG. 1), or under development incorporate a million or more lines of software code. Specification and development of such complex real time systems presents a major challenge to the designer. There have been some well publicized problems with these so-called software intensive projects, and these of course are not limited to warships or even to defence, as the Stock Exchange and London Ambulance Service will bear witness. To reduce these risks may require changes to our current procurement procedures and in the way we do business with industry. This is a theme that I shall be returning to later, but it is perhaps worth mentioning at this stage the setting up of the Software Engineering Centre formed by the Defence Evaluation and Research Agency (DERA) at Malvern with a 'rainbow' industry team working closely with the MoD to promote knowledge sharing and the use of open standards. A move towards greater use of these common commercial standards will allow us to take advantage of the major advances in computer hard and software being generated in the commercial sector. It will also bring with it new problems of reconciling the more rapid turnover in consumer goods, where a new upgraded model is often introduced every year, with a time-span of maybe 40 years or more between the first of class warship entering service and the last of class being scrapped. A capability for new technology insertion will need to be designed into future warships ab-initio, rather than dealt with on an ad-hoc basis as in the past.

Propulsion systems

Over the last 50 years propulsion machinery for surface warships has evolved from steam plant to gas turbines. As a result, warship availability has improved; the conditions and cleanliness of machinery spaces, and watch-keepers' environments, are dramatically better; it has proved possible to increase refit intervals to double those common during the steam age; and marine engineering complements have reduced significantly.

The overall aim of current propulsion plant development is to search for new technologies, machinery and equipment which offer the prospect of reduced overall costs through:

- Higher power density
- Improved fuel economy
- Improved reliability and durability
- Smaller marine engineering complements.

Other benefits sought are:

- Reduced signatures (such as noise and infra-red radiation)
- Clean emissions and discharges, together with improved safety.

Since the introduction of gas turbines the transmission chain, from prime mover to propeller, has become recognized as the area where a novel approach could yield most benefits and it has become increasingly clear that the next generation of warships should have integrated full electric propulsion powered by gas turbine prime movers of the Intercooled Regenerative (ICR) type (FIG. 2). Such an engine is under development for the US Navy in collaboration with ourselves and France.

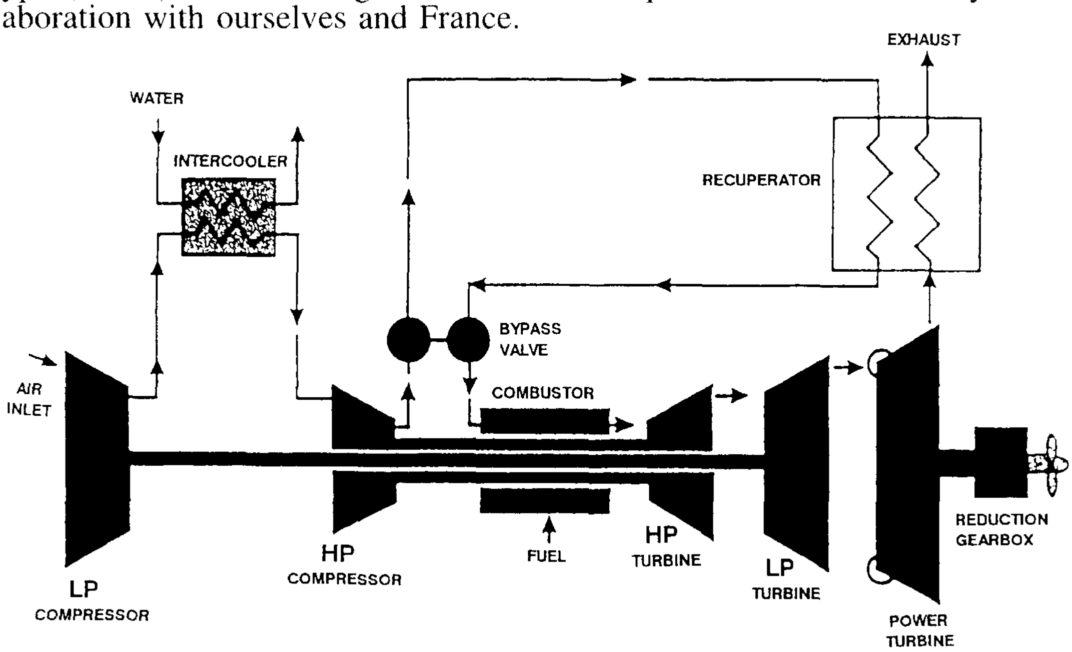

FIG. 2 — INTERCOOLED REGENERATIVE (ICR) ENGINE CYCLE

The remarkable fuel economy achieved by the Type 23 frigate, which has electric propulsion for slow speeds, has reinforced the experience of those sectors of the commercial marine industry (notably cruise liners) that have already adopted full electric propulsion. Now, the traditional disadvantages of electric propulsion—the volume and weight of the equipment—are being reduced by advances in two technologies.

Firstly, the new generation of permanent magnets can be adopted to provide power dense motors[3] that will simplify fitting to a frigate sized vessel. We are currently seeking to develop such a motor and expect to achieve a 20MW machine that will be the same volume as, and much lighter than, the 1.5MW motor fitted to the Type 23. The chart at (FIG. 3) graphically illustrates the mass and volume advantages of permanent magnet motors in comparison to synchronous motors.

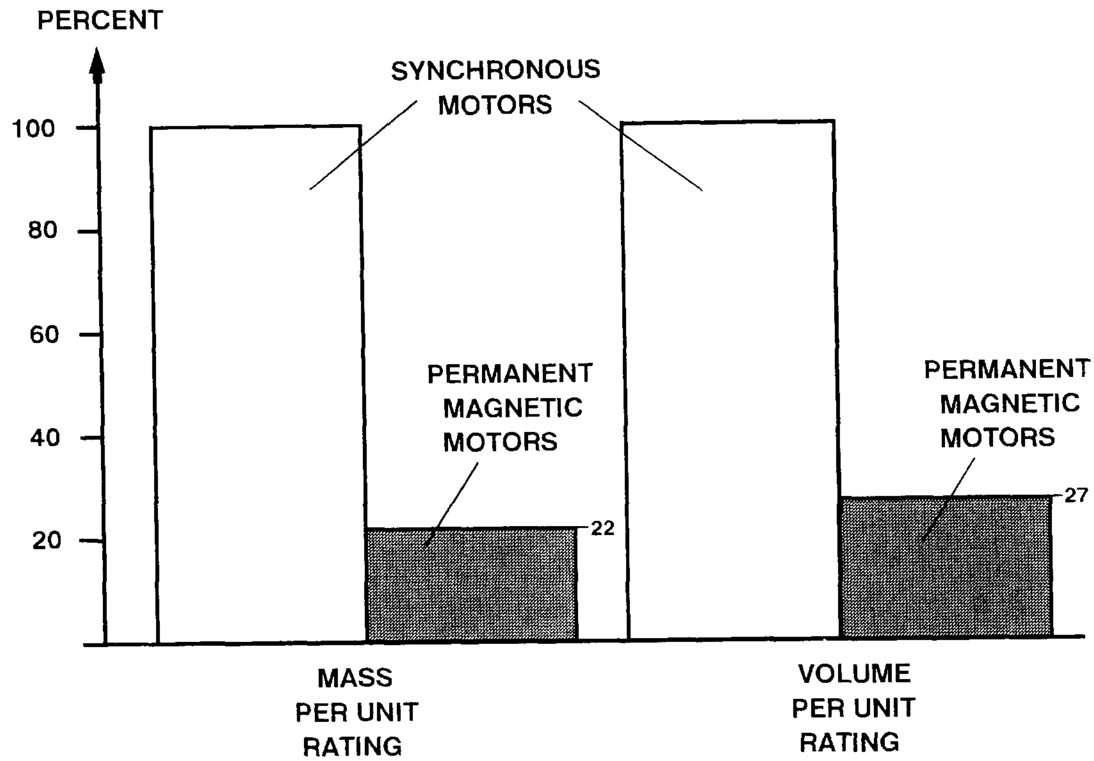

FIG. 3 — COMPARISON OF MACHINE TYPES - SYNCHRONOUS VS PERMANENT MAGNET MOTORS

Secondly, the ongoing revolution in power electronics is rapidly reducing the size of high power equipment while, with increasing device switching frequency, their distortion of the ship's electrical supplies is much reduced. We anticipate up to two orders of magnitude reduction in size and cost of the control equipment for the permanent magnet motors, compared with that at sea now.

The fuel economy demonstrated by both the Type 23 and commercial marine installations arises from their use of diesel engine prime movers for electrical generation. However, diesels will become disadvantaged by both their reduced efficiency compared with ICR gas turbines[4] as well as their requirement for large and weighty exhaust treatment systems to meet emerging exhaust emission legislation.

With the advent of full electric propulsion to warships, new freedoms are available to the naval architect:

- Motors can be fitted externally in pods or internally with very short shaft lines.
- Prime movers, with their uptakes and downtakes, can be installed where convenient to the ship layout rather than in positions determined by the shaft line.
- Significant gains in survivability can be achieved.
- Electrical power system architectures can be revised with the availability of power electronic equipments.
- Given a high reliability battery-backed electrical supply, electrical actuators can displace the need for hydraulic and air systems.

The MoD is addressing all these issues for the next generation of surface warships. All the indications are that survivability and power density can be increased and both first and running costs reduced, with the added bonus of some gains to the operational capability of the surface fleet.

Submarine propulsion and air independent propulsion

Evolutionary development of the pressurised water reactor plant installed in the VANGUARD class submarines is anticipated to meet the requirements for both the Batch 2 TRAFALGAR class submarine (the replacement for the SWIFTSURE class) and the class following known as the Future Attack Submarine. Such evolutionary development minimizes development costs and risks for each successive class whilst permitting increasing standards of nuclear safety and economy.[5]

As noted previously, all-electric propulsion is attractive for surface warships. For similar reasons it may be attractive for future nuclear submarine propulsion, where the improved efficiency would allow longer submarine lives without creating a need to refuel the reactor. If electric transmission were simultaneously adopted for both submarine and surface warships, there would be additional operational and cost benefits from common equipments and training.

Reduced production and through life costs are being sought for all elements of submarine machinery through:

- Simplification of equipment and systems
- Increased reliability
- Adoption of Commercial Off-The-Shelf (COTS) equipment where practical
- More advantageous procurement practices.

Crew numbers and costs are being reduced through the application of automation, but only where this does not reduce the ability of the crew to deal with action damage and other emergencies.

Non nuclear submarine propulsion systems, referred to as Air Independent Power (AIP) systems, have been developing rapidly. There appears to be little prospect of these systems displacing nuclear propulsion where there is a requirement for the submarine to deploy long distances at high speed. Where this requirement does not exist, however, heat engine and fuel cell based systems are both attractive enabling submerged endurance of up to several weeks, albeit at low submerged speed.

Heat engine systems already developed include the Swedish STIRLING engine, the closed cycle diesel engine and the French MESMA system using the Rankine Cycle.

The solid polymer fuel cell system, also known as the proton exchange membrane cell, is likely to form the basic fuel cell system in submarines mainly because of its power density. Because fuel is not burnt in a fuel cell to produce heat, its efficiency is not limited by the Carnot cycle and is higher than that of heat engines. In some AIP system arrangements, a fuel cell may give roughly double the submerged endurance achievable with a heat engine based system.

The hydrogen fuel required by the fuel cell can be carried as hydrogen (in a variety of ways) or produced by 'reforming' a hydrocarbon fuel. The reforming route is probably safer and may be preferred where the submerged endurance of a submarine must be maximized and the additional system complexity and cost is tolerable. Fuel cells might also, one day, become attractive for auxiliary power systems in nuclear submarines and surface ships.

Vulnerability and signature reduction

Vulnerability to enemy weapons—both above and below water—is, of course, an important consideration for the warship designer. Developments in this area cover:

- Numerical vulnerability assessment techniques
- Configuration and layout of ship systems for minimum vulnerability
- Blast resistant structures
- Fragment and bullet protection schemes suitable for shipboard use
- Study of the response of multihulls to underwater attack.

Heavy armour protection was abandoned long ago, essentially because the ship costs became unaffordable. Ballistic experiments to determine suitable lightweight armour schemes for use aboard ships are now being conducted. Protection against fragments emanating from missile warhead detonation as well as against bullets, is being developed. For a variety of reasons, armour developed for the Army's fighting vehicles is unsuitable for use aboard ship.

Research continues to provide a better understanding and prediction of ships signatures, how these are generated and their potential impact on ship vulnerability. The important signatures tackled are underwater noise, radar cross-section, infrared and magnetics.

Much has been done to reduce submarine radiated noise from machinery, fluid systems and propulsors. Propulsion machinery is now invariably raft mounted on sound and vibration isolating mounts, flexible couplings are used to reduce noise transmission in fluid systems and much work has been done on noise-reduced propellers and pump jet propulsors. Tiling fits to pressure hulls are used to provide both noise damping and to reduce sonar echo. Similar techniques can be used in surface ships for noise reduction. However, surface ships are not as noise critical and main machinery is not usually mounted. The primary problem areas of auxiliary machines and gearboxes have however, been addressed effectively in the Type 23 frigate by the extensive use of rafts and by the adoption of electric drive for noise critical operations. Radar cross-section is reduced by hull shaping, to avoid vertical surfaces, and by special coatings.

The return to littoral operations after years of concentration on open ocean scenarios has led to increased concern over the mine threat. The magnetic signature of the steel hulls of ships and submarines remains the main problem. Magnetic signatures may be controlled by fitting de-gaussing (DG) systems, essentially 3 axis coils supplied with electric current to generate fields to counter those of the hull. Such systems must be adaptive to account for ship movements in the earth's field and the consequent variation to the induced magnetism. Ideally, the DG should also adapt to changes in the hull's permanent magnetism and such closed loop DG systems are subject to research.

Novel hull forms

Contrary to the popular image of the MoD Procurement Executive (PE), as somewhat conservative when it comes to new hull forms, detailed studies have often been undertaken on alternatives to the conventional monohull. Recent studies include:

- Surface Effect Ships (SES)
- Hovercraft
- Catamarans
- Small Waterplane Area Twin Hull (SWATH) ships
- Trimarans.

More esoteric hybrids have also been considered.

Study of these forms has been driven by the search for improved performance and reduced cost. Our studies have almost invariably shown that each novel hull form has a significant advantage over a monohull in one particular aspect of performance, but may be markedly inferior in other ways. They therefore seem suitable for specialised roles rather than for multi-role front-line warships.

The US Navy TAGOS 19 class of towed sonar array ships is an example. These have a SWATH hull form to improve seakeeping, which is central to the requirement for sustained operation in high sea-states, regardless of prevailing wind and sea direction. In this they have been very successful, but they are large, slow, and awkward to handle in comparison with a monohull of similar cost. Similarly, SES have achieved high speed at reasonable power by using air cushion lift to reduce drag, at the expense of payload, range, and seakeeping capability.

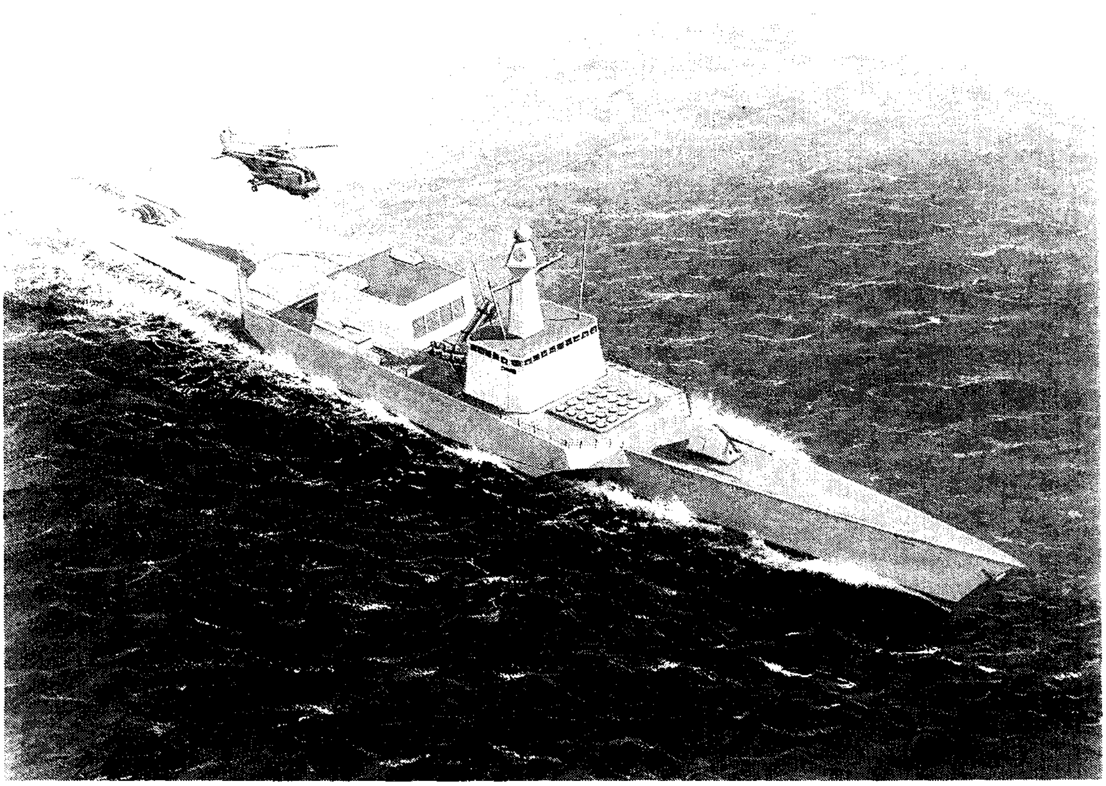

FIG. 4 — ARTIST'S IMPRESSION OF A TRIMARAN FRIGATE.

I remain an admirer of the SWATH form, which is increasingly popular commercially and could offer a number of operational benefits for a frigate. However, I must admit that the conventional monohull has continued to provide the most cost-effective compromise for warships, giving a reasonable all-round performance at an acceptable cost. A potential new rival, offering many of the benefits of a SWATH with few of the drawbacks, is the trimaran form (FIG. 4). This was first seriously proposed for warship application by Douglas PATTISON, my successor at University College London (UCL) as Professor of Naval Architecture. The trimaran form is essentially a long, slender monohull with two outriggers to provide stability. Recent work by the PE and the DERA at Haslar has suggested that this form may indeed provide a respectable all-round increase in capability, or a reduction in cost, without serious attendant disadvantages. The main benefits are reduced power, better layout, reduced vulnerability and the opportunity for increased helicopter operability.

Our investigations are continuing, and we hope to arrange the construction and trials of a large demonstrator, to prove this exciting 'new' concept. For this, we and DERA are currently seeking partners in Allied nations and industry.

Use of commercial standards

For some years it has been MoD policy to utilize British or ISO Standards, rather than Defence Standards or other specialized in-house standards such as Naval Engineering Standards (NESs), with a view to reducing costs. The potential benefits include lower intramural costs, (authorship, updating and publishing) and more to the point, savings due to the freedom of suppliers to use more widely applicable commercial standards and off the shelf equipment. This is in keeping with the Government's desire to transfer risk and responsibility to industry wherever possible. However there remains a core of military standards based on MoD experience and development for which no commercial equivalent exists. These include:

- Standards for submarine and weapon equipments.
- Survivability in the war environment, such as underwater shock or nuclear, chemical or biological attack.
- Where the philosophy of operation is different (for example controlling damage and fighting fires rather than abandoning ship).
- Where the Service requirement demands a higher standard of performance (such as ruggedness, reliability or electro-magnetic-compatibility).
- Ensuring equipment interchangeability or at least commonality of support and training across the Fleet.

An important function of our NESs is that they represent the corporate experience of the MoD's naval architecture and marine engineering professions. Many are vital for maintaining centres of expertise to advise those responsible for managing the safety and fitness for purpose of the Fleet.

MoD standards are constantly reviewed against new developments in industry, both at home and abroad, with a careful watch on UK, European Union and international legislation (which can apply directly to military systems and equipment, for example Marine Pollution Conventions and US tanker construction rules). Care is needed not to adopt a commercial standard which, though initially attractive, might lead to a heavy through-life cost burden. Constant dialogue between the MoD and our suppliers tests the need, usefulness and clarity of our standards and today only those considered essential to the particular operational requirement are mandated in our procurement specifications. The old criticism of gold-plating is certainly not applicable these days.

Developments in the warship design process

Warship design

A warship is a total military entity designed to operate autonomously for long periods. Many complex weapon systems have to be integrated with an infrastructure that provides mobility, power, personnel support and protection against both the enemy and the hostile conditions found at sea. In the case of nuclear submarines, which may be submerged for months at a time, even the atmosphere has to be manufactured and sustained. It is all this that makes the design and procurement of warships such an enormous engineering challenge. There is in fact a large open literature on surface warship design and a comprehensive picture of current UK practice, together with bibliographies, is given by ANDREWS[6] and BROWN.[7] The design of submarines is described by RYDILL and BURCHER.[8]

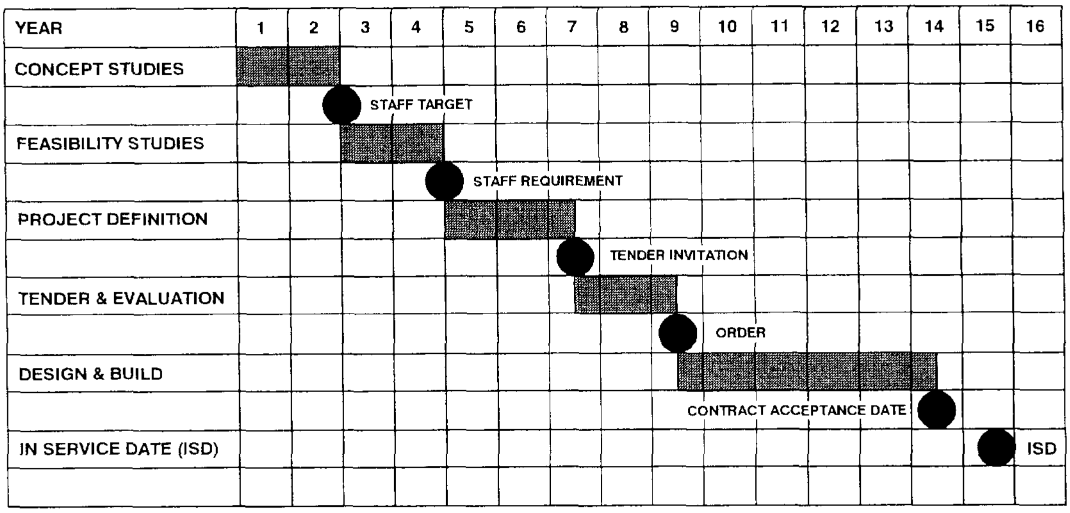

FIG. 5 — A TYPICAL WARSHIP PROCUREMENT PROGRAMME

(FIG. 5) illustrates a typical programme for a major warship based on our current procurement cycle, from the earliest study phase to the In Service Date of the First of Class. The concept study phase of design is particularly important because, although relatively little money is spent or committed, major decisions are made influencing all downstream activities and through life costs. The aim of concept studies is to support the writing of a staff target from which a technically viable and affordable warship can be developed, and to narrow down the key hull, propulsion and combat system options. It is obviously important at this stage to maintain an interactive dialogue with the customer, i.e. the Naval Staff, with the DERA who advise on emerging technology, and with industry as the eventual supplier. These aspects are more fully covered by ANDREWS.[9]

Until recently—despite lip service to the contrary—the MoD's attention has usually been focused on initial development and production costs despite the fact that in-service support costs can equal or (more usually for a warship) exceed them. Because of this we have invested significant effort in developing through life cost models so that, from the earliest concept stages, design trade-offs can be investigated and supported by investment appraisal. Integrated Logistic Support is a discipline that encourages projects to consider support issues at the early stages and a recent initiative is to include some level of support as part of the main procurement contract in order to incentivise the Prime Contractor, or to take through-life costs seriously.