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HMS 'INVINCIBLE': PROPULSION MACHINERY FROM CONCEPT TO FULFILMENT

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HMS 'Invincible': Propulsion Machinery from Concept to Fulfilment

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SYNOPSIS

HMS Invincible *is the first of the Royal Navy's three aircraft carrier/anti-submarine warfare command ships. It is the largest warship designed and built for the Royal Navy since the Second World War and is the highest powered all gas-turbine ship in the world today. HMS* Invincible *is fitted with two shafts, each driven by two Rolls-Royce Olympus TM3B gas turbines through a David Brown reversing gearbox to a fixed-pitch propeller. The evolution of the overall ship design has been described.*[1] *The purpose of this paper is to describe the design and development of the main propulsion machinery from the sketch design in 1967 to the completion of the first-of-class machinery evaluation trials in June 1981. It will also describe problems during installation, shore and ship trials; and conclude with a discussion of plant performance to date.*

INTRODUCTION

In the late 1960s the decision was taken that the fleet of the future would require ASW command ships to:

(i) Provide command facilities to control a large distributed force of ships, aircraft and submarines.
(ii) Provide a viable force of large ASW helicopters.
(iii) Contribute to the air defence of the fleet.

Ship design studies concluded that a ship of 19 500 t, with a through flight deck and hangar and with an island structure on the starboard side, would fulfil the above tasks. In 1973 the design reached the stage which enabled HMS *Invincible* to be ordered from Vickers Shipbuilders Limited, Barrow. The ship completed contractor's sea trials in mid-1979, was accepted into service in March 1980 and became operational in 1981 on completion of successful machinery evaluation trials.

THE DESIGN

Background

In 1967 the engineering section of the Forward Design Group in Ship Department, MOD(PE), in conjunction with Y-ARD Limited, examined many propulsion machinery options. This included feasibility studies of various arrangements of steam, gas turbines and diesel engine machinery.

Based on these studies, Ship Department decided in 1969 to adopt an all gas-turbine installation, using two Olympus TM3B gas turbines on each of two shafts. The major reasons for this decision were:

(i) To maintain a standard propulsion policy for all new construction of surface ships. The decision had been taken previously that all future frigates and destroyers would have gas turbine propulsion.
(ii) To provide a sizeable reduction in engine room complement.
(iii) To achieve the high availability demanded.
(iv) To minimize through-life costs.
(v) To increase power/weight ratio.

Palmer's paper[2] details the arguments supporting gas turbine propulsion.

After the selection of gas turbine propulsion, which is inherently unidirectional, the more difficult problem was confronted—provision of a means of reversing. The choice at that time lay between controllable-pitch (CP) propeller and reversing gearboxes. The latter, with fixed-pitch propellers, won the day for the following reasons:

(i) A CP propeller had not been developed to transmit the power required.
(ii) CP propellers cavitate more than fixed-pitch propellers and are therefore more noisy and less efficient.
(iii) Failure of the CPP system may require the ship to be docked.

By late 1969, therefore, the basic components of the main propulsion plant had been agreed, namely two shafts, each driven by two TM3B Olympus engines through a reversing gearbox to a fixed-pitch propeller.

Detailed design process

After deciding on the major components of the plant, the next stage in the design process was to detail. In 1970 Y-ARD, in conjunction with Ship Department, carried out a deep feasibility study to consider the various design areas in more detail. This resulted in a definition of the overall machinery space dimensions and establishment of a design basis for selected critical areas, enabling machinery specifications and guidance drawings to be produced.

To assist in this study Y-ARD produced a 1/20th scale model of the four main machinery spaces. As well as the major pieces of equipment such as main engines, gearboxes, diesel generators, boilers, etc., this model included pumps, major pipes, electric cabling, motor starters, machinery removal hoists and removal beams.

The model proved to be extremely useful at this design stage and enabled various arrangements of machinery to be evaluated with minimum effort.

During this period it was decided that the detailed design development would be undertaken by Vickers Shipbuilders Limited, Barrow. In early 1971 Vickers Shipbuilding Group (VSG) staff became involved in the project, assisting Ship Department/Y-ARD in the preparation of the guidance drawings and machinery specifications which were completed in early 1972.

Mr N. McKenna BSc(Hons), RCNC was a student apprentice at HM Dockyard, Portsmouth, from 1961 to 1966. From 1966 to 1969 he attended Portsmouth Polytechnic where he was awarded BSc(Hons) in Mechanical Engineering. Mr McKenna then held various posts in Royal Dockyards refitting warships and in DG Ships, including a spell in the Steam Turbine Design Section. He joined the DG Ships *Invincible* Class Project Group in 1979 as Head of the Marine Engineering Design Section.

Mr D. Rogers CEng, BSc, MIMechE was a student apprentice with Bristol Aircraft Company from 1956 to 1962. Following this, he worked on the design of flying control systems for Concorde. Mr Rogers joined Vickers Shipbuilding Engineering Limited in 1965 and worked in various departments. He has held his present position of Manager, Marine Design Office, for the last three years.

Design to production

The success of modelling used on the Type 42 destroyers[3] in the preparation of production and installation drawings dictated that similar techniques would be used for the CVS. (CVS is a NATO designation for this Class of ship.) One-tenth scale models were prepared for main machinery spaces and the two outside diesel generator spaces.

The construction of these models was started by Y-ARD and details were completed by VSG. All machinery and pipework down to 1-in bore were installed in the models.

As the models were developing, MOD regularly inspected them with particular emphasis on machinery arrangement, system configuration, accessibility for operation, repair and equipment removal routes. All machinery space installation drawings were prepared from direct measurement at the model. Detailed procedures were also prepared from the model for the removal of equipment. Pipe isometrics were prepared from the model by computer-aided techniques and used in the manufacture of pipework ahead of the ship-build programme.

The above was undoubtedly a major contribution to the high efficiency achieved in the fitting out of these compartments; the most efficient utilization of the space available; and the very neat, tidy, spacious feeling one immediately experiences on entering any of the machinery spaces in HMS *Invincible*.

The models, when nearing completion, were moved to the dock side and were used extensively by the production departments during the installation stage.

Final configuration

The final configuration of the main machinery spaces is shown in Figs 1 and 2. The machinery is arranged in two independent machinery units divided by a space for damage control reasons and to avoid excessive congestion of ducting for the gas turbines which would result if the four engines were arranged alongside.

Both shaft sets were positioned to move the centre of gravity of the machinery by two feet to port of the ship's centreline, to help counteract the bridge island on the starboard side. The auxiliaries were also positioned as much to port as possible. This meant a different horizontal rake to the shafting in addition to the different vertical rake caused by the different lengths of the port and starboard shafting.

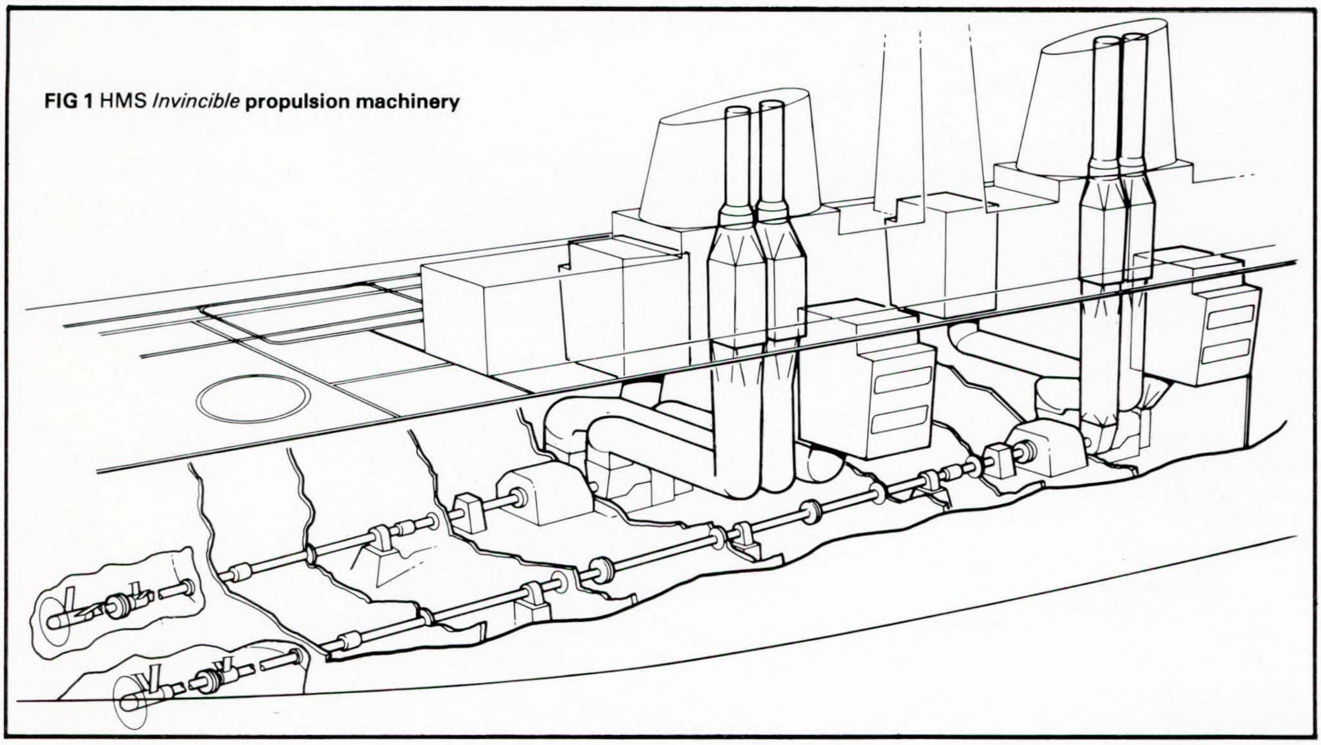
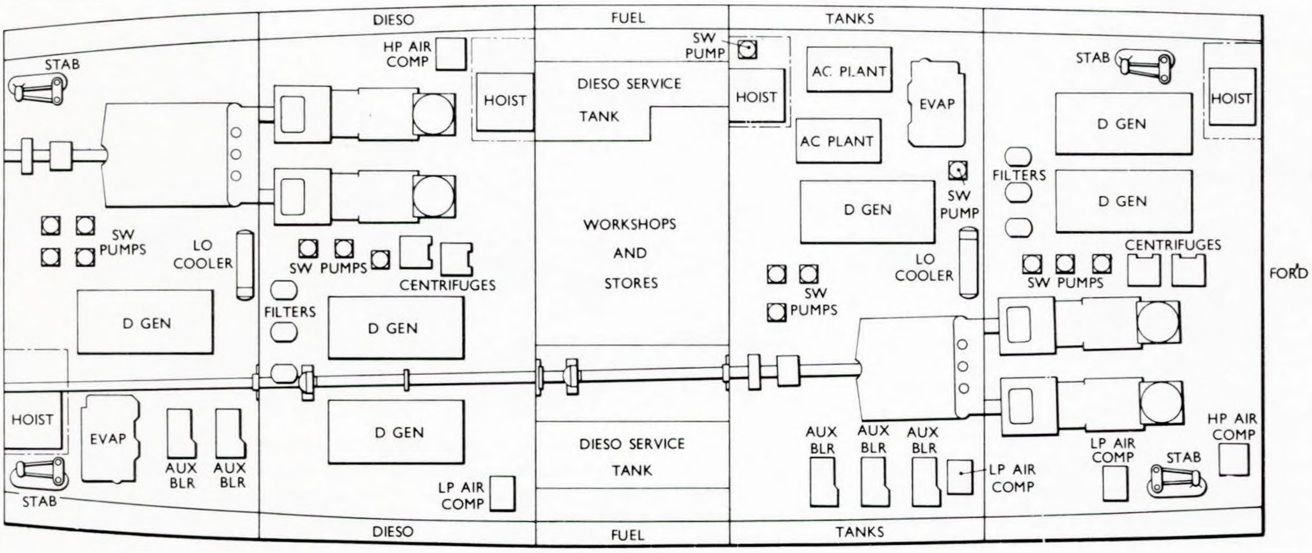


FIG 1 HMS *Invincible* **propulsion machinery**

FIG 2 Sketch plan of the main machinery spaces



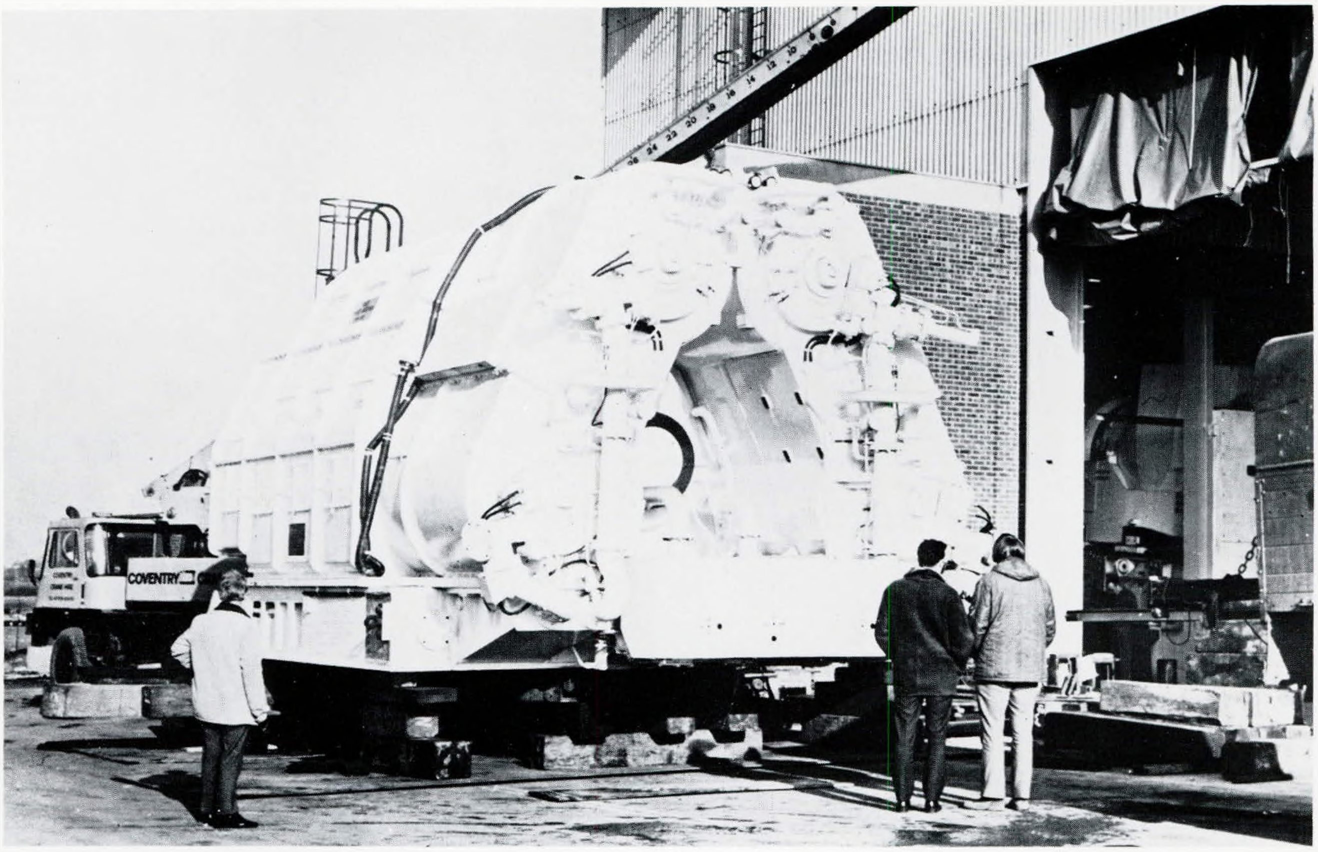
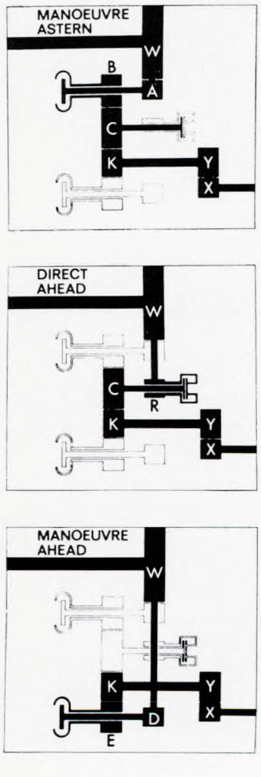
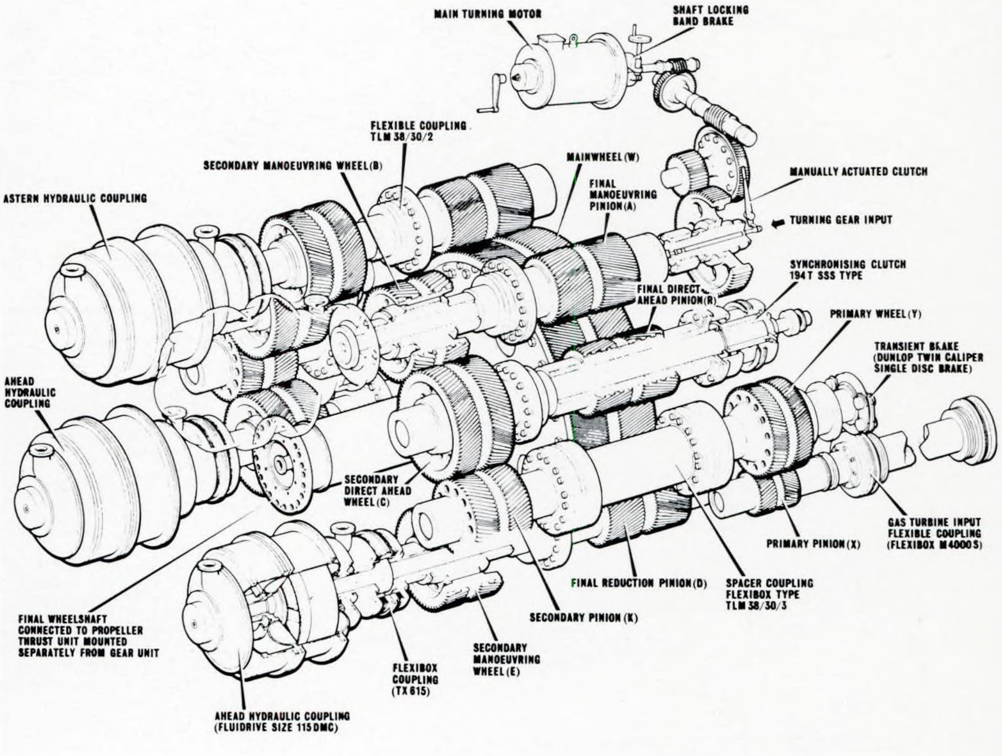


FIG 3 HMS *Invincible's* **reversing gearbox ▲**



▼ FIG 4 Pictorial arrangement of CAH gears



Engines

Two Olympus TM3B gas turbines are fitted to each shaft in the COGAG (combined gas and gas) configuration. Cruising is achieved with one engine driving, while the second engine is available in parallel for full power. These marine gas turbines are also fitted in the Type 21, 22 and 42 ships, although on these their usage pattern is totally different as they are used only when high powers are required (cruising power is achieved with Tyne gas turbines). The performance and operating success of these gas turbines are now well known and require no further comment.

The power turbines are rotating in opposite senses on each shaft set, to avoid the additional complication of a further high-speed intermediate gear train to correct rotation. The engines are also 'handed' to ensure that the controls can be operated at a central position between the pair of gas turbines on each shaft set.

To meet the underwater noise requirements, the turbines on each shaft set are mounted on a raft which is supported on soft rubber mounts. An arrangement of hard rubber pads, activated if required by pneumatics, was also fitted, as there was some concern that the raft might vibrate in resonance with gas in the exhaust ducting; and to reduce transient misalignment when operating in heavy seas. Subsequent experience has shown that neither of these appeared in operation.

As for all gas turbines, the required fuel standards are very high; namely absence of water and contaminants, particularly sodium and potassium. The fuel system is very similar to that fitted on previous RN gas turbine ships, but with improved filter/water separators.

Gearboxes

After consideration of alternative designs by GEC and Vickers,[4] the reversing gearboxes selected for the cruiser were designed and manufactured by David Brown of Huddersfield. None of the techniques or components used in the gearbox design are new. What is different, however, is the power transmitted. This box is not only the most powerful reversing gearbox ever to go to sea but also the most powerful of any type hitherto employed in any RN ship. Figure 3 gives some idea of its size.

It provides two independent gear trains, one each side of a large main wheel, to transmit the power from two Olympus engines into a common shaft. Speed reduction is achieved in three stages of single tandem, double helical, articulated gears. Triple reduction, uncommon in RN ships, was chosen partly to provide intermediate speed to suit the fluid coupling; to ease manufacture; and because additional length was more acceptable than additional width for the CVS. Figures 4 and 5 show the arrangement of gearwheels, pinions, clutches and bearings.

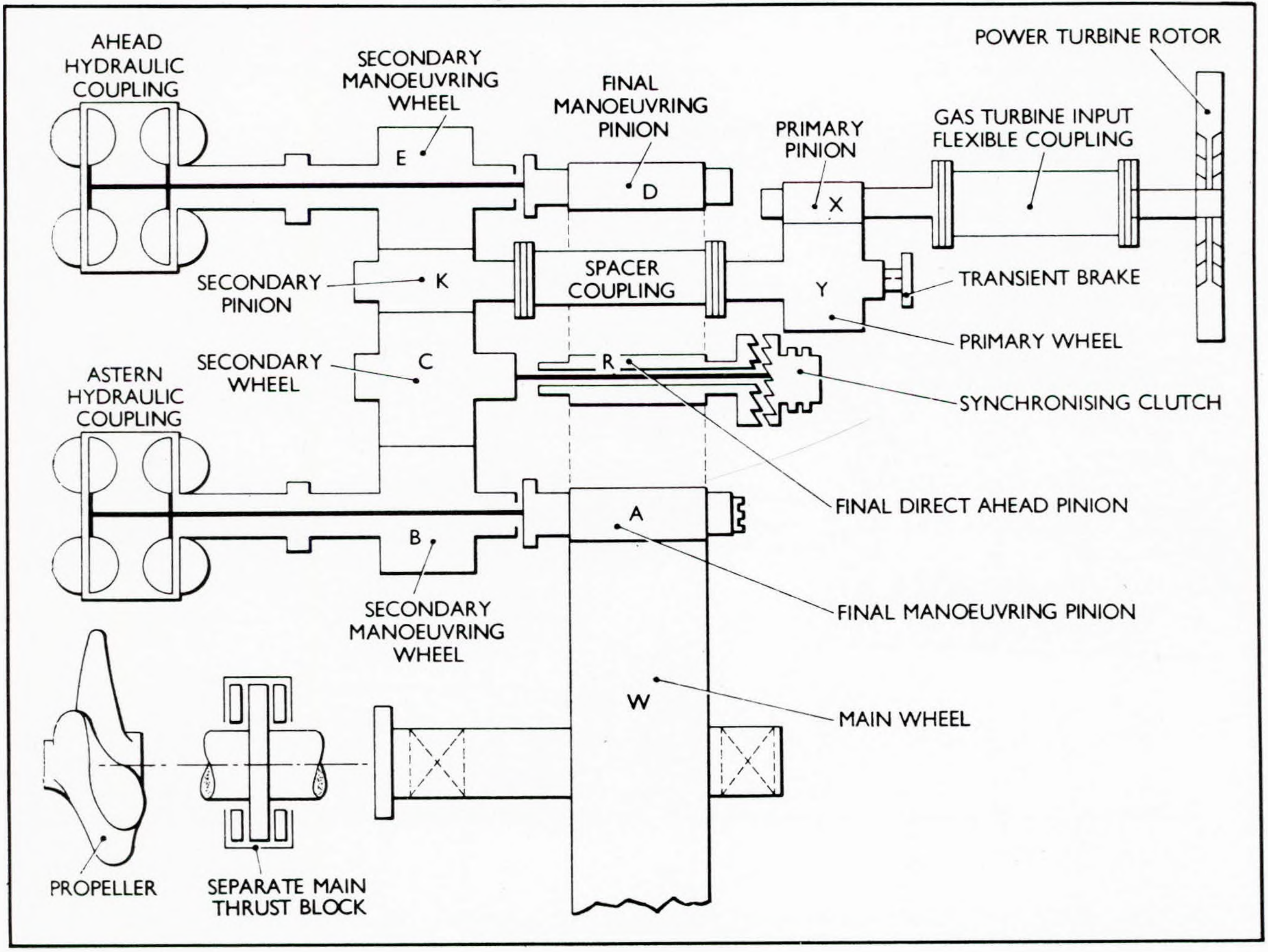
Ahead and astern manoeuvring drive is achieved through hydraulic couplings, high 'ahead' powers being achieved through SSS clutches, i.e. avoiding power losses at high power due to slip in the fluid couplings. The transition from coupling ahead to direct drive (SSS clutch) ahead and vice versa is made automatically and allows the ship to be accelerated and decelerated smoothly throughout its full power range. Figure 6 shows a section through a fluid coupling. To enable the required power to be transmitted at the revolutions specified, the coupling was split to limit centrifugal stresses and to reduce size.

Investigations showed that the gearbox need not be resiliently mounted to meet the NSR (naval staff requirement) noise requirements. It was therefore mounted on a three-point rigid support system. The after end is rigidly supported on the same seat as the thrust block. The two forward seats, one at each side, are designed to be flexible enough to bend under stress in a seaway, imparting acceptable stress levels to both the gearbox and the ship's structure to which they are welded. Figure 7 shows an elevation of the mounting arrangement. Extensive calculations were made to prove that the gearbox movements would be acceptable for shaft alignment and, as a precaution, space was made to fit a main shaft flexible coupling if required.

Lubrication system

The main forced lubrication system is shown in Fig. 8. The oil drain tank is integral with the gearbox and three pumps are mounted on the forwarded extension of the tank. Oil is supplied for the power turbine bearings, gearbox bearings and gears, and thrust bearing; and for filling and cooling the fluid couplings. In coupling drive approximately 1600 gal/min is required; in direct drive, only half this

FIG 5 Diagrammatic arrangement of CAH gears



quantity, since only a small bleed of oil for coupling cooling is required when in direct drive.

An air-driven emergency pump is also fitted. This automatically operates if electrical power is lost and supplies adequate lubricating oil whilst the gears and turbines come to rest.

The shafting system

The arrangement of the two shafts is shown in Fig. 1, the starboard shaft with three self-aligning plummer blocks and the port shaft with one. The thrust block—unlike in other RN ships—is a separate unit from the gearbox. The lubricating oil drain tank had to be positioned directly under the gearbox, with the result that adequate supporting structure could not be provided for the thrust block within the gearcase. There is no journal bearing in the thrust block, because of its close proximity to the gearbox and influence on main gearwheel alignment. The shaft is flexible enough to accept the bending moment (from thrust due to eccentricity) without serious alignment problems.

Controls

With each shaft set having two gas turbines (operating singly or in parallel), four fluid couplings, two clutches, two transient brakes and a shaft brake, plus the requirement for normally unmanned machinery spaces, the control problem is significant.

The control positions and the operations which can be performed from each control position are shown in Fig. 9. The lower levels of control will always be capable of overriding the next highest level.

When controlled from the bridge or ship control centre, the system incorporates a number of interlocks and dynamic restrictions which ensure safe operation of the propulsion machinery. When the system is controlled locally most of these interlocks/restrictions are lost, only the coupling/direct and ahead and astern interlocks being retained. Under manual control all interlocks/restrictions are lost. In the latter two conditions, the machinery operators must ensure the components of the propulsion machinery are not run outside their design limits.

Built-in test equipment

The built-in test equipment (BITE) fitted in the machinery control console will monitor the functioning of the propulsion machinery's remote control system 'off line', i.e. with a lower level of control in operation. It will identify a fault down to module or mini-module level.

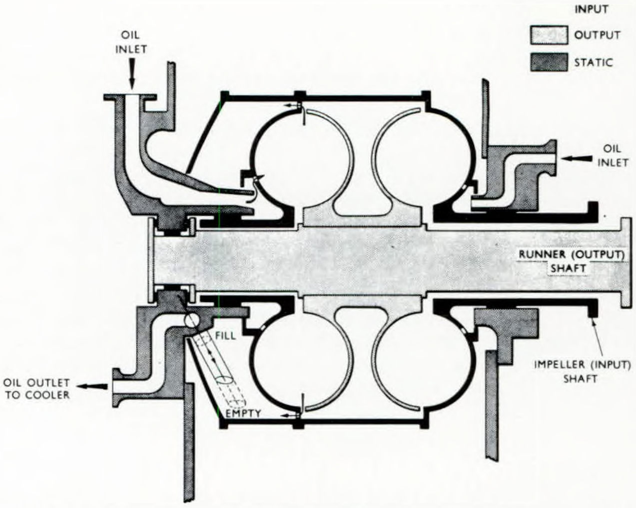


FIG 6 Double circuit, scoop-controlled, fluid couplings fitted in CAH

Pre-start integrity checks

The pre-start integrity checks facility enables the remote control system to operate the machinery actuators so as to simulate normal operating conditions, without the propulsion machinery running.

MCC mimic displays

On the machinery control console (MCC), the displays are arranged on mimic panels to assist operation (Fig. 10). Propulsion machinery controls and displays are arranged for each shaft, showing the gas turbine and gearbox states. Other mimic displays on the console are for monitoring the fuel and lube oil systems and for general auxiliary

FIG 7 Special VOD instrumentation

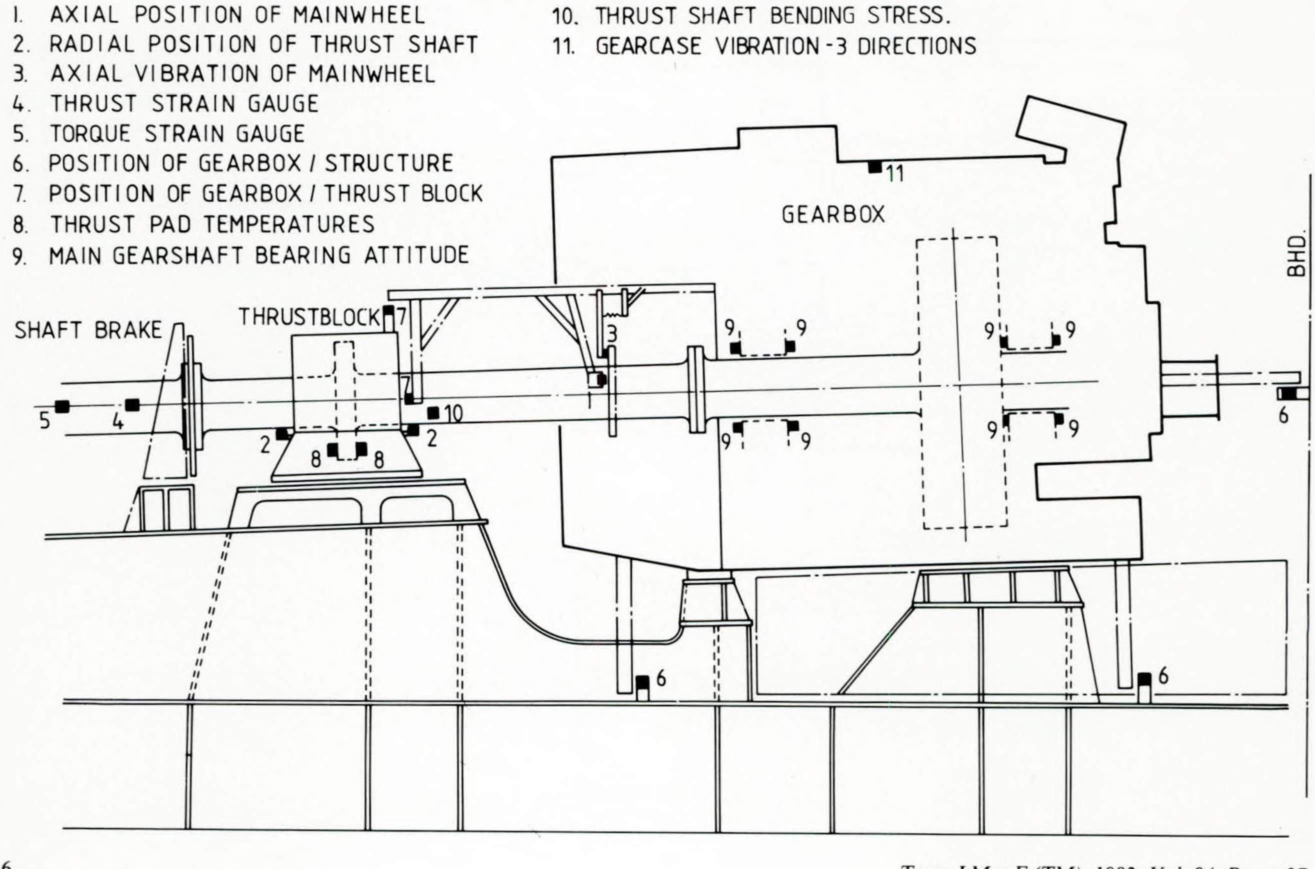
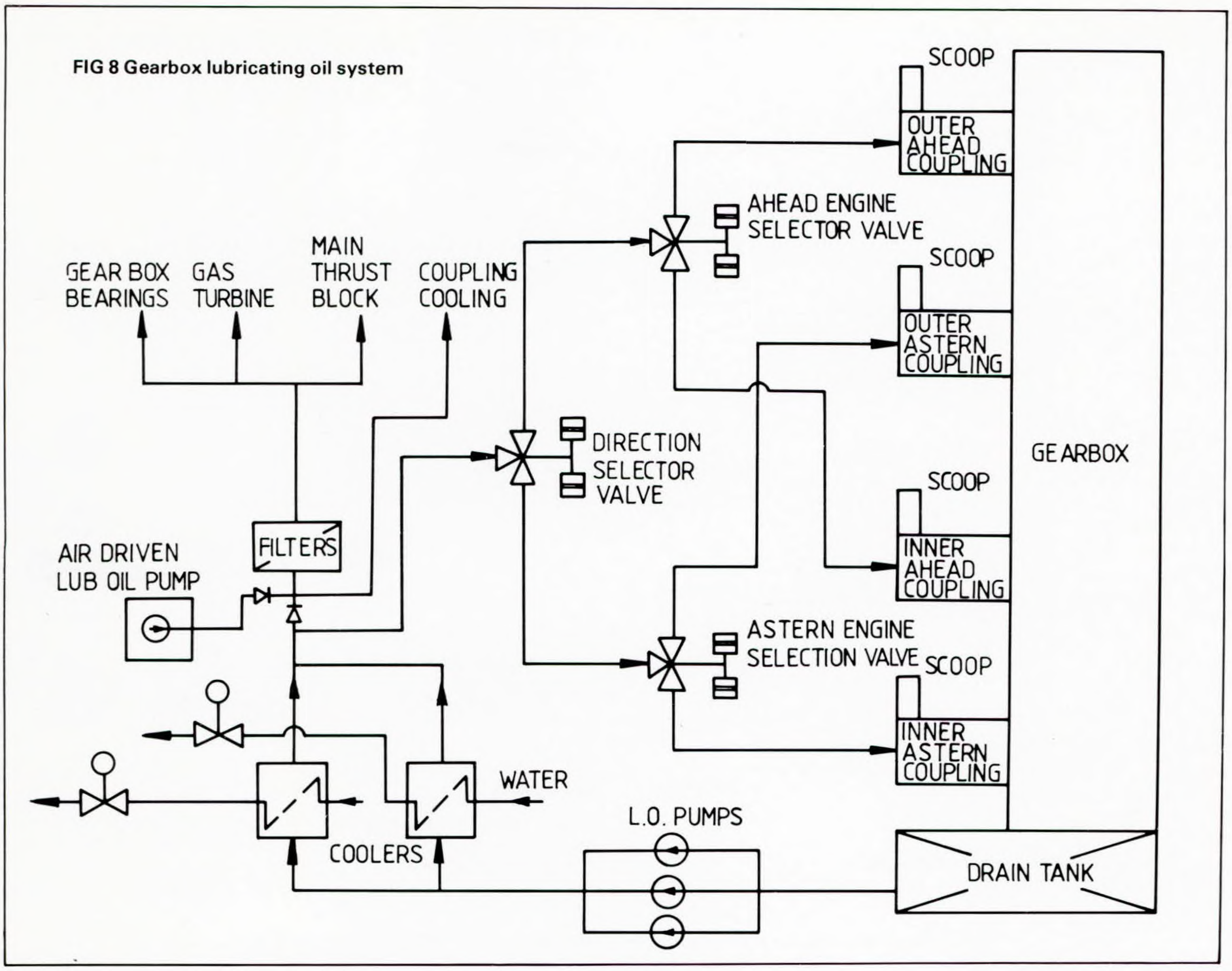


FIG 8 Gearbox lubricating oil system



machinery such as sea water systems, boilers, steam and air conditioning plants, etc.

Surveillance system

The surveillance system associated with the propulsion machinery system and certain auxiliary machinery systems comprises:

(i) Alarms for monitoring critical machinery functions and indication if limits are exceeded.

(ii) A dynamic data recording (DDR) system provides continuous monitoring and storage of selected parameters of the propulsion machinery. It comprises a 12-channel ultraviolet recorder and a multiplexed channel memo-loop tape recorder: 115 channels can be processed, 91 will be selected to be put into temporary storage on the memo-loop recorder and any 12 of the 115 can be selected for display on the UV recorder. This is of great assistance when checking the dynamic response of the control system during the ship's life. A typical DDR trace taken during a crash stop manoeuvre in HMS *Invincible* is shown in Fig. 11.

(iii) The warning and logging system comprises two Decca ISIS (integrated ship's instrumentation system) Type 300, providing a maximum of 480 channels for automatic logging (and warning) of chosen parameters of the propulsion and auxiliary machinery.

Ducting (air intake and gas exhaust)

Experiences in frigates and destroyers have shown that ducting must be arranged with the greatest care to avoid damaging vortex formations and excessive pressure drops. On the CVS it was obvious that these problems would be severe because of the long tortuous runs required. Figure 12 shows the final arrangement of the intake ducting for the CVS port shaft. The configuration was dictated by two major structural requirements:

(i) The need for a through deck and hangar resulted in the exhaust funnel having to be positioned on the starboard side of the ship on the island and hence cross-over ducts from three of the engines became essential, the starboard outer turbine having the only straight uptake. The ducting takes up a lot of space and dictated the width of the hangar.

(ii) Hull structural requirements made it impracticable to place the intakes for both Olympus TM3B gas turbines on one side of the ship within the watertight bulkheads of the gas turbine compartment. The outboard engine is supplied from the ship side on which the engine is positioned and the inboard engine requires ducting to cross the compartment to take its supply from the opposite side of the ship (see Fig. 12).

Other factors which affected the design included allowances for expansion; absorption of thrust at bends; high-temperature corrosion and erosion; fatigue failure due to vibration or internal cycling, and attenuation of heat and noise.

Air is taken from the ship's side, as shown in Fig. 12, and is led initially through a salt spray eliminator. This consists of three stages: a chevron type spray eliminator, a fibrous pad type salt coalescer and, finally, a repeat of the first stage to collect breakaway droplets from the second stage. The air speed through this system is limited to 7.6 m/s which necessitates a very large ship-side opening. The air then passes through a square-sectioned silencer fitted with flat plate splitters.

From this point on, the air is contained within a circular duct 2.13 m in diameter. The right-angled bends are 'cascaded' in order to smooth the flow.

The exhaust ducting for the port engine, shown in Fig. 13, is also 2.13 m in diameter and made of stainless steel in the hope that it will last the life of the ship. The right-angled bends are again cascaded. The exhaust silencer is 2.74 m square.

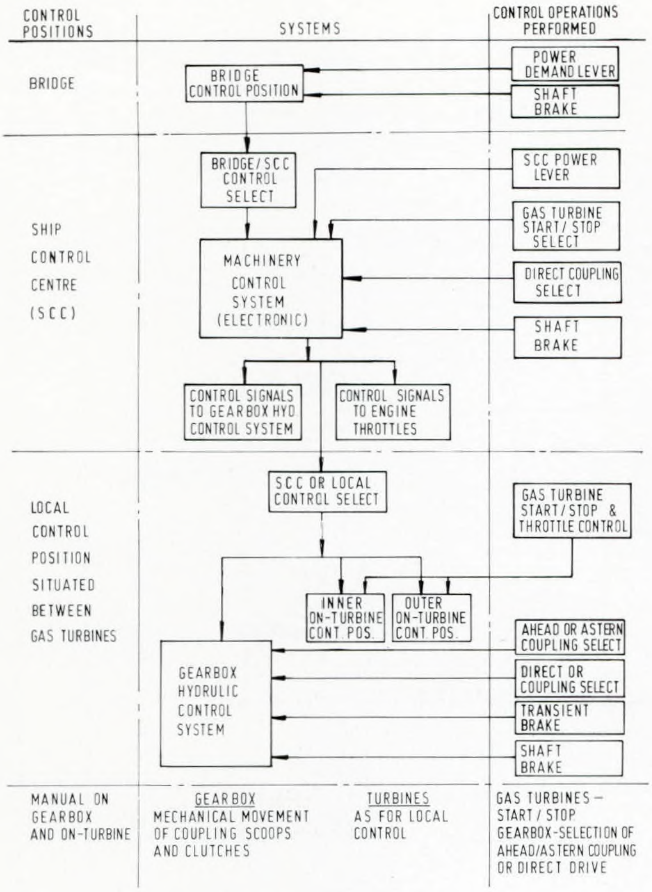


FIG 9 Controls

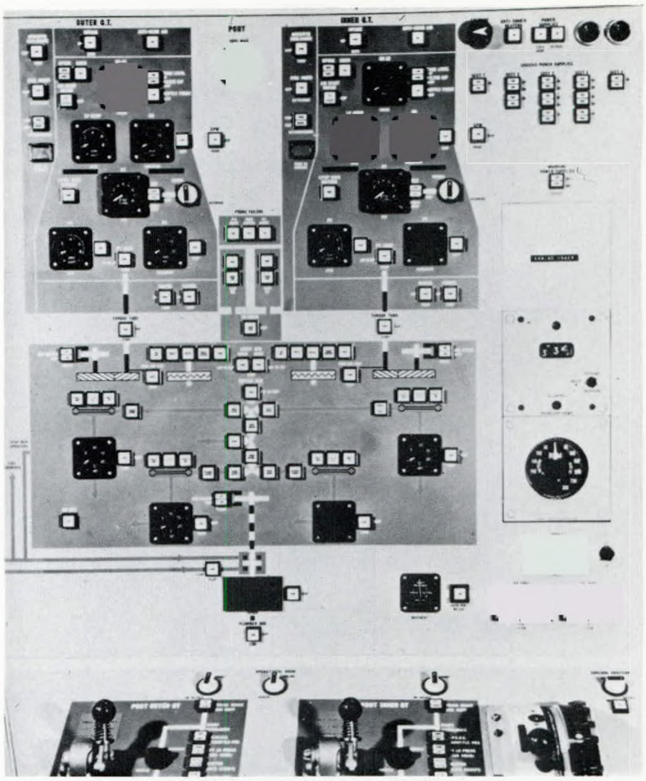
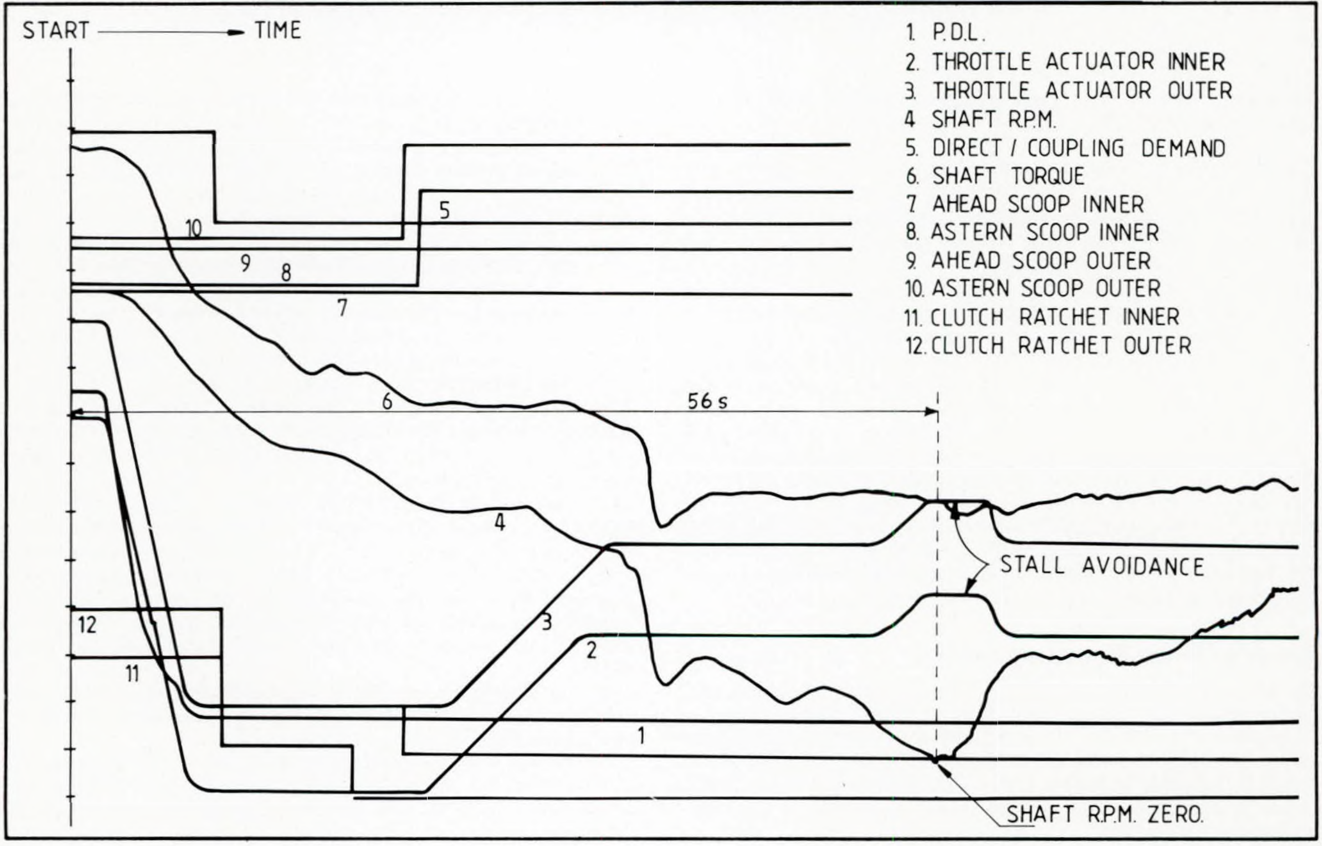


FIG 10 MMC mimic displays

Reliability

A new class of warship with a unique propulsion plant will undoubtedly have numerous teething problems. The nature of some of these is often not fully appreciated until the ship is built and on trials, when design modifications can be extremely expensive, both in

FIG 11 Ship performance DDR trace—port shaft: 95% ahead to 95% astern crash stop



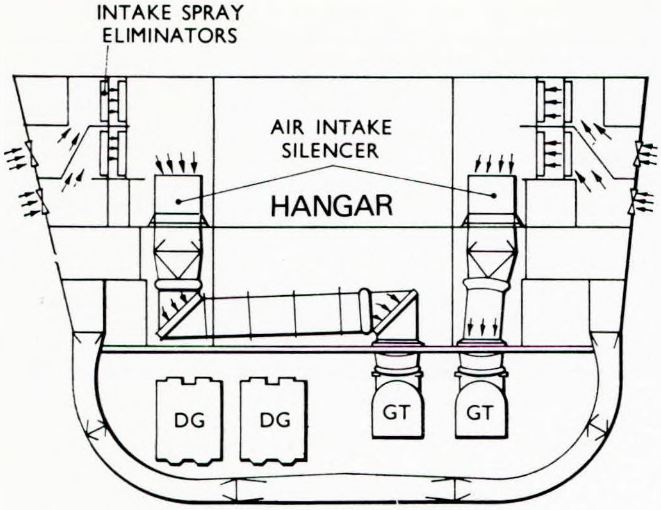


FIG 12 Arrangement of air intakes

money and in loss of ship (and class) availability. Modelling, simulation and reliability studies will undoubtedly predict some of the problems but they are limited in scope.

In 1970, when the main components of the main propulsion package had been selected, it was decided that there were sufficient unknowns in the CVS design to justify the cost of a shore test facility (STF). This was built at the Industrial and Marine Division of Rolls-Royce Limited at Ansty (1971) and started running in 1973. The STF is discussed later in the paper but it is mentioned here because of the significant part it played in the efforts to achieve the NSR reliability, availability and maintainability characteristics for the CVS propulsion plant.

Reliability studies

Reliability studies were carried out by Y-ARD and VSB on critical systems, e.g. main lube oil, fuel transfer and supply, gas turbine uptakes and downtakes, sea water systems, etc., using failure modes, effects and criticality analysis to highlight any desirable modifications to the redundancy and types of components, and to system layout. These studies resulted in, for example, a number of changes to system layouts, number and position of valves and deletion of one fuel transfer pump from the original design.

Reliability assurance studies were also carried out on the gearbox and associated hydraulic control system by David Brown Gear Industries/Vospers. No significant changes to gearbox design resulted but some of the hydraulic control system's valves were identified as extremely vulnerable. This resulted in further cyclic testing of these and, ultimately, to design changes.

Maintenance

The ship has been designed to facilitate maximum use of 'Upkeep by Exchange' with particular attention to the provision of designated routes and lifting arrangements to allow easy removal of equipment. Each machinery compartment has a removal trunk, incorporating a lift, which can take diesel generators, gas turbine change units, exhaust annulus bellows, etc., from transporting rails within compartments to the side of the hangar. A spare gas generator is stored in a canister in each gas turbine compartment, in case an exchange is required at sea.

INSTALLATION DIFFICULTIES

Shipping the machinery

Shafting, gearboxes, diesel alternator modules and other large items were slid through two large holes in the ship's side before launch, in order to avoid vertical access holes through the decks. This also avoided waiting until the ship was launched and positioned under a crane capable of lifting the gearbox.

The gearboxes were stripped down to their minimum weight of 153 t by removing lube oil pumps and oil sump, then jacked up from the building berth on lift platforms and slid sideways on temporary runways.

Prior to the main units the shafting was shipped and secured on temporary supports, clear of the line-of-shaft sight. This required considerable planning and specially manufactured supports.

Boring of 'A' brackets and sterntubes could not commence until the shipping openings were closed by welding because of the risk of hull distortion.

Alignment of shafts and gears

Because of the flexible shafting arrangement with long spans and very few journal bearings, alignment of each shaft length by conventional 'gap and sag' was impossible. The 'A' brackets, sterntubes, plummer block, thrust block and gearing seats were positioned with the aid of a stretched wire datum. Boring was then completed, using references from an optical sight line between the main 'A' bracket and thrust block seat.

After boring, the 'best' sight-line was obtained through 'spiders' fitted to the finished bores and the forward datum on the thrust block seat adjusted accordingly. The plummer bearings were then positioned and chocked to this sight-line with the aid of 'spiders' fitted to the bearings.

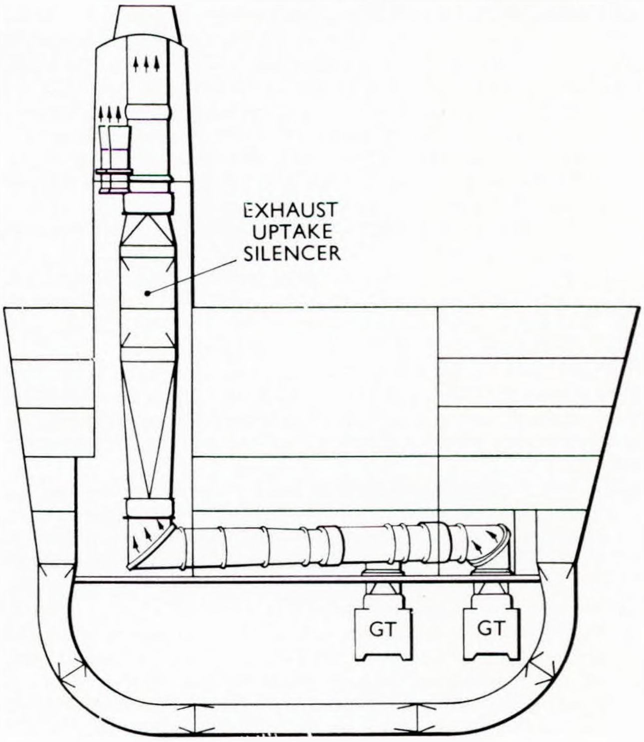
The shafts were then installed and all couplings made except that of the thrust shaft to gearbox. After launch, the forward lengths of shafting were 'straightened' using temporary supports; and a reference sight-line established above the shafting.

The gearboxes were aligned by 'gap and sag' to give the correct load distribution of the mainwheel bearings and the final coupling of the shaft was made. All temporary supports were removed and the shaft allowed to adopt its natural catenary before the thrust block was finally aligned to suit the slope of the thrust collar when released. The absence of journal bearings within the thrust block ensures there is no shaft restraint close to the gearbox.

The use of hydraulically stretched 'Morgrip' coupling bolts, keyless SKF loose couplings and pilgrim nuts for the propellers greatly assisted installation. Problems were experienced in achieving exact fits of the coupling bolts; therefore the original concept of interchangeability was relaxed and each bolt and hole were matched.

Satisfactory optical 'sweep' readings of the gearcase proved very difficult to achieve and it was eventually demonstrated that the gearcase was stiffer than the seating. It was later established that the

FIG 13 Arrangement of exhaust uptakes



datum readings had been taken with the gearbox in a different state of assembly than on the ship. This anomaly was corrected for later ships.

Another problem which caused delay was ensuring the correct axial position of the main gearwheel to give acceptable deflections, during operation, of the membrane flexible couplings that connected the fluid couplings to the final drive pinions. Eventually a new datum had to be established within the gearcase.

Alignment of gas turbines

Two turbines are mounted on each raft which is supported by anti-vibration rubber mounts. The drive to the gearbox is via light-alloy torque tubes of 2.2 m length, articulated at each end by laminated membrane flexible couplings. Although this arrangement can tolerate significant misalignment, prolonged running can cause deterioration of the coupling membranes. Therefore, during alignment, great care was taken to allow for creep of the rubber mounts, gas loads exerted at uptake and downtake, and thermal growth of raft, gearbox and torque tubes.

The alignment of turbines to gearbox was initially undertaken by optical methods. A final check by mandrel and clock gauges was not too successful because of clearance within the primary pinion bearings and the great axial distance between couplings. Checking alignment by micrometer records of flexible couplings gaps and distances of the turbine raft from the solid seating was developed to enable the turbine/gearbox alignment to be checked throughout its life.

Demineralized water-to-water lubricated bearings

Experience from another vessel in Barrow docks had shown that sea-water lubrication of 'A' bracket and stern-tube bearings, coupled with a long period between launch and the first shaft turns, could result in the formation of a very hard scale on the bronze liners fitted to the shaft. When the shafts were eventually turned under power, rapid weardown of the phenolic resin pads occurred. The scale produced was found to contain very hard deposits not expected in normal sea-water scale.

To combat the above on HMS *Invincible,* temporary shaft seals were fitted to each bearing before launch and a positive head of demineralized water maintained within the bearings during outfitting. Subsequently, the seals were removed by divers; weardown readings taken after sea trials proved this precaution successful.

TESTING

Shore test facility—Ansty

A complete set of the CVS propulsion machinery, including two gas turbines, a gearbox, thrust block, control system, ducting and lubricating oil system plus a dynamometer, was installed at the Rolls-Royce site at Ansty. The major objectives for this facility were:

1. To prove the viability of the propulsion machinery as a whole.
2. To prove the performance of the individual components: turbines, gearing, uptakes and downtakes, controls, thrust block, interlocks and dynamic restrictions, intrumentation and surveillance equipments.
3. To validate the Y-ARD propulsion plant computer simulation during manoeuvres.
4. By endurance running to investigate the reliability of the components and systems and to improve them as necessary.
5. To carry out noise and vibration surveys of the equipments.
6. To identify and analyse maintenance tasks.

The tests were carried out over a period of three years from their commencement in 1973 and enabled most of the problems found on the components destined for HMS *Invincible* to be corrected prior to installation. The major problems found and subsequently corrected were:

(a) Due to a combination of tooth loading and thermal effects the main gear wheel shaft journals slope in the bearings altered to an unacceptable degree, causing hot bearings. The main gearwheel shaft and bearings were removed and modifications carried out at the manufacturers' works. Subsequent trials at Ansty proved the modifications to be successful.

(b) High downtake noise was reduced by the additional sound insulation. The supports for the uptake ducting and silencers and the vanes within the cascade bends suffered from a spate of cracking and were redesigned to cater for the high coefficient of expansion and low thermal conductance of stainless steel.

(c) The hydraulic control system of the gearbox used the main lubricating oil as operating medium. For various reasons this was found to give unsatisfactory performance and was changed to an independent hydraulic system using the oil OM33. The operating pressure was also significantly increased and high-pressure pumps had to be fitted. Numerous other changes were made to this system.

(d) The electronic control logic for clutch engagement, throttle application, turbine acceleration rates and operation of transient brake was extensively modified.

(e) High temperatures in the bearings necessitated the redesign of high-speed line bearings and coupling location bearings, which also helped to establish the operating limits for the final drive flexible couplings.

(f) Vibration problems with the torque tubes were overcome by improving manufacturing tolerances, careful assembly and pre-installation testing. As an additional precaution, larger diameter torque tubes are now fitted with a higher natural frequency.

(g) The thrust block oil seals had to be modified to take increased radial movement.

Other minor faults, found and corrected, are too numerous to mention here. The extensive manoeuvring trials were carried out using the novel principle of simulating the ship's inertia by power injection.[5] The dynamometer was limited to 80% of full ship's power but the full-power condition was simulated by asymetrically loading the turbines and running at maximum speed.

The CVS shore trials facility is described more thoroughly elsewhere.[6]

Equipment type testing

Since the mid-1960s it has been Director General, Ship's policy that ship-fitted equipment should, where possible, be selected from a standard range of proven performance, reliability and maintenance routines. The standard range of equipment available during the early design stages of the CVS were based on frigate and destroyer requirements and, in many cases, were not large enough for a ship of the CVS size. Some 18 items of equipment were selected from the standard range but some 38 items of new equipment were required, e.g. lube oil pumps/diesels/air compressors, etc.

The performance, reliability and maintainability information available on this equipment was sparse and therefore an extensive type testing programme was initiated for these new equipments. This comprised an extensive performance testing routine with endurance running closely based on the running profiles that the equipment will meet at sea.

On completion of the trials, the equipment was stripped for examination and at this time the opportunity taken to: prepare strip and refit procedures; define any special tools required; and check maintenance 'envelopes'.

Much of this equipment was then shock tested, some of it ultimately refurbished for use on the ship and some utilized in training establishments. No major problems were experienced during the performance testing but one-fifth of the components failed under shock testing.

Many design improvements were incorporated into the equipment subsequently manufactured for the ship as a result of the above exercises. This probably avoided problems during ship testing and has led to an increase in availability since ship acceptance.

Special tests on thrust block

This is a prototype design unit which could not be tested properly at the STF Ansty, although it was used in PI (power injection) and axial shuttling trials. Also, during the early design stages, there had been reservations about the design of the thrust block seating which could be incorporated into a ship of relatively light scantlings.

Extensive computer studies during the design stages resulted in a major modification to the ship's thrust block seating but there was still an element of doubt about how this block would behave under full-power thrust, and transients during manoeuvres, coupled with the effects of a seaway on alignment.

Thermocouples were fitted to the thrust pads for sea trials and, whilst this was in progress, holes were drilled in the thrust block casing to take clock gauge spindles in order to measure the misalignment between collar and block casing in an axial direction.

When the block was reassembled, and shaft installation completed, a static test was carried out on the ship's port shaft, simulating propeller thrust by the 'ahead' hydraulic thrust-meter cylinders pressing against the shaft which was secured. The deflections relative to the gearbox of the thrust block and seating were measured by clock gauges and the previously mentioned gauges showed the misalignment within the thrust block.

The results of this test were extrapolated to full-power conditions and suggested running misalignment values would occur within the thrust block of the order of 0.75 mm (0.030 in) across the collar.

On a special test facility at Newcastle, the thrust block (ex-STF Ansty) was subjected to considerable misalignment under thrust supplied by one set of thrustmeter cylinders, with the shaft being rotated at ship's maximum revolutions by an electrical motor. The trial was designed to test the normal thrust pads as fitted to the ship; or, alternatively, the Kingsbury-type levelling pads fitted behind the metering ring on one side of the thrust collar. Thermocouples were fitted to each pad.

The results were interesting in that they proved that the block, as fitted to the ship, could tolerate more misalignment than previously thought and the levelling pads improved matters further. As a result of these tests, confidence was restored in the ship's thrust blocks, with the levelling pads available as a back-up.

Setting to work

The gearboxes were finally aligned and secured in October 1977 and the gas turbines and their rafts aligned and secured by the end of 1977. Thereafter, the pipe systems were rapidly progressed to completion.

During setting to work, each installation was checked, flushed and pressure tested before the final operational test was started. Testing of systems continued throughout 1978 until preliminary shaft turns under power were made at the end of the year.

Flushing of the main lubricating oil system presented problems due to its size: it supplies the gearbox, turbines, fluid couplings and thrust block. After several weeks of flushing the required standard of cleanliness was achieved; but it was later agreed that obtaining such a high standard on the coupling oil system was time-consuming and unnecessary.

A preliminary basin trial was completed in mid-January 1979 and this ensured that the machinery was ready for the official basin trial in mid-February 1979.

A problem which came to light during these trials was that, due to a three-bladed 'hack' propeller being fitted, a torsional resonance occurred which could not have occurred with the proper propellers. This produced loud noises from the gearcase on the shaft nearest the dockwall. Subsequent investigations proved that the proximity of the propeller to the dock bottom and wall resulted in excessive torsional fluctuations and this caused tooth separation between the main gearwheel and pinions. The trials were completed with a barred speed range.

Basin trials

The official basin trial, commenced in mid-February 1979, demonstrated to the MOD(N) Machinery Trials Unit that the machinery installation was ready for sea trials. The vibration problem with the hack propeller was again encountered. However, the smaller 'hack' propellers enabled much higher revolutions than those possible with the ship's fitted propeller to be achieved, so that the change-overs from manoeuvring drive to direct drive could be made. By running one propeller ahead and the other astern, the bollard pull was minimized but great care was taken to ensure that both shafts were stopped or slowed simultaneously.

Contractors' sea trials

The trials began on 26 March 1979 and were conducted in the following phases.

1. Run to drydock at Greenock using 'hack' propeller. The ship's propellers were then fitted and the hull cleaned and the trials resumed on 20 April 1979.
2. Preliminary trials at steady speeds proved machinery up to full power, with some basic manoeuvres and final tuning of the lubricating oil system. This was successfully completed in one week.
3. The next step was optimizing turbine performance and ensuring that the desired shaft speed was maintained and turbines balanced by adjusting the fuel schedules of the control system.
4. Trials of reversing gearboxes included manoeuvring on single and two turbines and change-overs from fluid coupling to direct drive.
5. Finally, ship performance trials such as measured miles, turning circles, consumption trials and the remainder of miscellaneous trials.

The programmed list of 60 trials was successfully completed on 24 May 1979 and the successful acceptance/delivery voyage to Portsmouth took place in March 1980.

Problems encountered

Two major problems caused disruption, but no extension, of the total trial programme. Failure of the final drive's pinion bearing in the port gearing caused a three-day delay whilst a replacement bearing was fitted. After a short running-in period, the bearing failed again. No obvious solution was apparent but, after careful gauging of the bearing and shaft diameters, it was concluded that the oil clearance was insufficient, though within the designed tolerance.

A replacement bearing, with the bore enlarged by 0.076 mm (0.003 in), was fitted at the anchorage on the Clyde. The trials were resumed and no further problems occurred with this bearing.

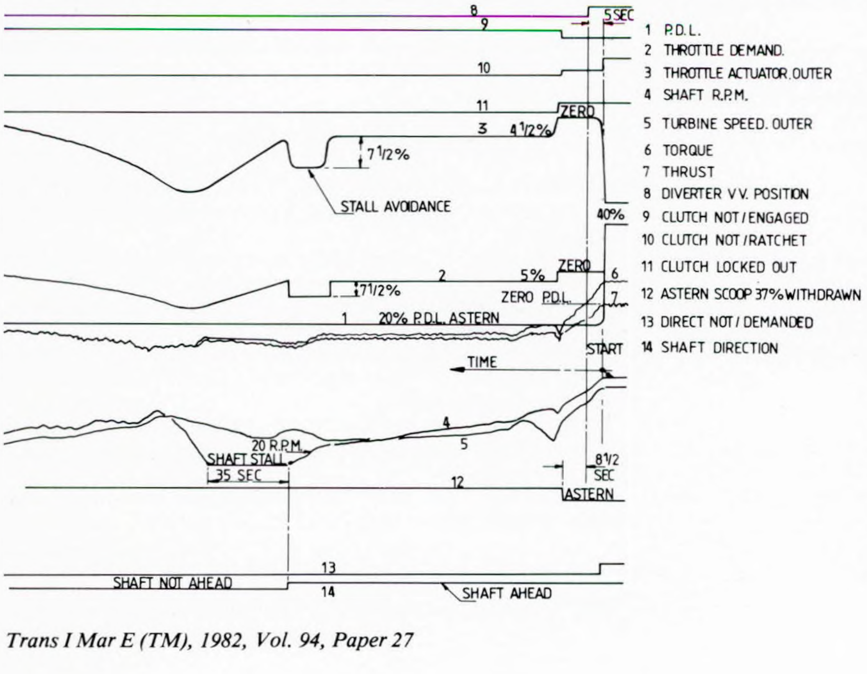
During severe manoeuvres heavy axial vibrations were experienced, particularly when going from astern to ahead and during high-speed 'U' turns. This confirmed some of the fears expressed earlier about stiffness of the thrust block seating. With the resonance changers running, the axial vibrations were reduced by 50%; ensuring that no design limitations were exceeded at any time.

Other problems, which were solved during or after trials, are as follows. A rubbing noise from the starboard gearbox was found to be due to the forward shaft shaft seal having insufficient axial clearance to cater for the increased movement of main gearshaft due to thrust-block deflection. Port and starboard seals were removed for the rest of the trials, and re-designed, and proved satisfactory during the delivery voyage.

High temperatures were experienced in the turbine torque tube covers at full power. The cause is thought to be windage. The temperature was reduced by installing permanent ventilation trunks which cool the outside of the covers and indirectly remove the heat. This modification has proved successful.

High temperature on a primary pinion bearing was rectified by changing the bearing. Further high temperatures experienced on the delivery voyage were temporarily reduced by increasing the oil supply pressure. Subsequent investigation discovered that the bearing shell was

FIG 14 CST performance trace starboard shaft: 40% ahead to 20% astern outer turbines



incorrectly assembled, reducing the oil supply to the bearing. No further problems have been experienced.

Shaft stall occurred during low-power manoeuvres as predicted at the STF Ansty. The important parameters during a shaft stall of 35 s are shown by Fig. 14. The stall avoidance system at this time injected an additional 7.5% of fuel when the shaft slowed below 20 rev/min. As soon as the system sensed the shaft starting to rotate in the opposite direction, the additional fuel was cancelled. If, as in this case, insufficient engine power was available to maintain this shaft rotation against the movement of the ship through the water and the shaft friction, then the shaft again stalls. This condition was maintained until engine power increased to 'break' the shaft away.

Following contractors' sea trials, the stall avoidance system was modified to increase the additional fuel from 7.5% to 9% and to apply this from the time the shaft dropped to 20 rev/min in the original direction until it reached 20 rev/min in the opposite direction. To date there have been no further reports of shaft stall. Figure 11, taken recently on HMS *Invincible,* although not during a low-powered manoeuvre, shows the modified system in operation.

During high-speed turns, at or near full power with either one or two engines per shaft drive, the inner shaft slowed, resulting in the maximum permissible shaft torque being exceeded. This was further aggravated when the integrator was selected. The integrator is a feedback system fitted in the propulsion control system and acts like a governor. It senses shaft speed and increases or decreases the fuel supply to the driving gas turbines to maintain shaft speed at the demanded setting. The solution was to limit the use of the integrator at high powers and to impose rudder limitations at high power.

Post-CST examination

A selection of bearings, all gearteeth and the complete port inner final drive train, including SSS clutch, were examined and found to be in good condition except for a small fluid coupling location bearing and slight pitting on a secondary gearwheel. Coupling bolts on the final pinion drive flexible couplings had to be replaced with closer fitted bolts.

'IN-SERVICE' EXPERIENCE

Operating experience

Since acceptance, HMS *Invincible* has undergone a 12 month period of evaluating trials which have required prolonged high-power running and many periods of quite severe manoeuvring. The propulsion machinery has met all the demands made on it in this period with all four engines, both gearboxes and shafting system available when required. Full power has always been achieved when required. There have of course been problems but unfortunately (from this paper's point of view) none of any significance or real interest.

In this period there were 916 attempted starts of gas turbines, of which 914 were successful; the two failed starts were corrected in two hours by ship staff.

The NSR targets for speed and endurance have been comfortably achieved, with sufficient leeway to suggest that they should be attainable throughout the life of the ship. The four-engined COGAG concept has proved very successful, combining flexibility with inherent redundancy and ideally matching the demands placed on it by the CVS.

Complement

The degree of automation incorporated in the main propulsion plant has enabled the engineering complement to be pruned in comparison with a steam ship of similar size, power and task, e.g. the ME department on HMS *Invincible* is 50% of that on HMS *Hermes.* This makes a significant contribution to minimizing through-life cost.

Fuel consumption

Fuel economy was not one of the claims made for gas turbine propulsion when it was selected for the CVS in 1969. The large increase in oil prices over the past 10 years has ensured that fuel consumption has assumed greater importance.

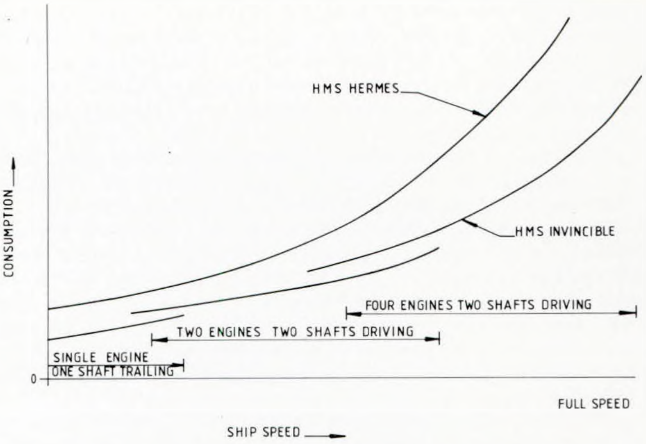


FIG 15 Total fuel consumption: *Invincible* **vs** *Hermes*

Figure 15 compares the fuel consumptions of HMS *Invincible* and HMS *Hermes.* It is accepted this is not a direct comparison, HMS *Invincible* being 30% lighter than the two-shafted steam ship HMS *Hermes;* and HMS *Hermes* burns heavy oil whilst HMS *Invincible* burns distillate. Allowing for these differences , Fig. 15 does show that HMS *Invincible* compares very favourably with HMS *Hermes* and, more particularly, highlights the economy to be gained from single-engine, single-shaft configuration and single engine per shaft running at lower powers.

CONCLUSIONS

Although it is still early days, the first year's experience from HMS *Invincible* is extremely encouraging and suggests that the CVS propulsion machinery will be a successs.

The performance to date reflects the high standard of design, manufacture, installation and testing achieved by all concerned with the development and operation of the propulsion machinery. However, the greatest contribution to the high operational reliability achieved to date must surely stem from the extensive trials carried out at the STF at Ansty. Although not analysed in detail, this facility must have already paid for itself.

ACKNOWLEDGEMENTS

Whilst this paper is published with the permission of the Ministry of Defence, the views and opinions expressed are those of the authors and do not necessarily represent those of the Ministry of Defence.

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Discussion

R. M. DUGGAN MA, CEng, FIMarE: When I first glanced at this paper it was a quarter to midnight one night. I had two reactions—one of shock and the second intense curiosity. Needless to say, I then read the paper properly from cover to cover.

My state of shock occurred because I had experienced many of the things the authors described—but my experience was, in some cases, 25 or more years ago. The *Auris II*, with gas turbine/geared hydraulic propulsion, was in fact scrapped almost exactly 20 years ago, but then I realized that work on HMS *Invincible* began only 5 years after she was scrapped, and we are talking about a slightly different HP bracket! However, the ships are virtually the same displacement.

Now although my curiosity is all-consuming, I will try and avoid reminiscence and history. There are, however, many common factors and I, of course, will not be able to entirely avoid asking a few questions which I appreciate the authors may or may not be allowed to answer.

Design philosophy

Clearly this is a design by committee, with the involvement of many firms and organizations. It must have been a real jungle to look through.

Whilst I fully appreciate items (i) to (iv) of 'Background' (page 2), it seems strange to me that much of item (v) (i.e. increase in power/weight ratio) has been thrown away in 350 tons of gearbox and associated equipment and many tons of lubricating oil. Think of the extra fuel that might be carried. The argument that a controllable-pitch propeller (CPP) had not been developed to transmit the power required can also be applied to the gearbox. However, the other points about CPPs are all too true.

No mention has been made as to why other propulsion systems were either not considered or were thrown out. Other propulsion systems include:

(a) *Synchronous electric*
- The system is well proven.
- Standard 30 MW sets. Many hundreds of the alternators were produced in the 1940–1950s and sea experience has been well proven in ships such as SS *Canberra*.
- The Royal Navy has good electrical background and experience.
- The gas turbines could be 'upstairs', with short ducts. The need for the location of main propulsion units deep down within the armoured belt of old *Capital* ships has surely disappeared with the one hit/write off philosophy.
- Power turbine reduced in size by higher rev/min.
- Both power turbines can rotate in the same direction, simplifying depot spares.

A reduction of 1% to 2% on duct losses would be quite something on 120 000 BHP. Incidentally, the main propulsion motor of *Auris I* was donated by my company for noise tests for the Admiralty after the original diesel/gas turbo electric units were replaced by the single-geared gas turbine machinery. The tests lasted for some 18 months, about 1956.

(b) *Epicyclic gearing*
- High ratios are possible.
- Since 1960 the Merchant Service has had many ship-years of excellent experience of up to 35 000 SHP per shaft. There are also British facilities and design.
- Very light and compact. (In fact I thought Vickers had a rather special robust design of their own, used in mining operations.)

(c) *Diesel generators*

It seems strange to me that there are at least six diesel generators (galloping hardware!). Surely there must be gas turbogenerators available in the right power range? Did the designers have cold feet at this point; was it an economic decision or tradition?

Having cast the die for a gearbox, I think Fig. 4 can be summed up as a real bag of worms. A really magnificent achievement by David Brown, who I am convinced will design a gearbox for anything if asked and if paid.

My first reaction is of all the power being lost. References such as that on page 96 to coupling cooling, and on page 11 to ventilation trunks to cool covers, are very reminiscent. On the *Auris II* installation, the gas 'turbineers' from Rugby used to chaff the shipyard (who also manufactured the gearbox) about the 'hot end'—which was the gearbox. That gearbox was modified at one stage to have finned aluminium covers over the primary line.

I cannot believe that this gearbox will not have seal problems; i.e. that seals will either become bearings or permit oil to leak where it should not. Coupling windage losses when empty can easily be 70 HP per ½ unit but, with an oil mist present, the figure becomes quite dramatic.

The hazard of gearbox explosions must have received a lot of attention in this design and I will simply say we had one in *Auris II* on basin trials; and would be interested in anything that can be said relative to this design.

Controls

Very briefly, and without going into details, I am intrigued to know if oil to ahead coupling is lost when manoeuvring (e.g. selector valve jams) and, as you have no compressor on power turbine (that is to say you have a free power turbine):

(a) What prevents almost instantaneous overspeed of power turbine even if fuel is shut off instantaneously to gas generator?
(b) Can you relight at any speed?
(c) From dead slow ahead can you go to full ahead (or astern) manoeuvring speed without exceeding $T_{\max}$ on Olympus or is the speed of shaft acceleration restricted? Is the navigation department told what to do?

Figure 11 is most interesting. It is a pity that only one time figure is included (I take it to be 56 seconds). Would it be possible to see the same figure (same scale) in the written discussion, for my item (c) above.

Ducting

Whilst I have every sympathy with the designers, I am puzzled by one factor. If the wind is blowing, say, on the starboard bow under cruising conditions, do you select the engines taking air from the port side and vice versa?

If not, then surely the spray eliminators must be dealing with an enormous problem. I wonder if the possibility of using the engine rooms as plenum chambers was considered. We tried this with some success; better still if you don't have diesels down there and put the engineers in soundproof boxes! Diesel engines give off much oil mist which is deleterious to gas turbine compressors but there is also scope for reducing duct losses or complications. Unfortunately these solutions increase the noise level in the machinery spaces but there is now no need to have engineers in those spaces. The splitting of the ship's side intakes is presumably to permit the spray eliminator not in use to be 'serviced'?

Reliability studies

This paragraph interested me as, in merchant ship practice, reliability studies rarely take place. How a 'design by Committee' ever managed to propose 'inputs' to such a study is intriguing, but it is a significant milestone that an attempt was made. In my experience it is very hard to get any technical person to put his head on the block and give realistic figures, and if he does the statisticians either don't like it or won't believe it.

Testing

There seems a remarkable similarity to *Auris* problems—our 'shore tests' were in the wet basin at Messrs Cammell Laird & Co.

The answer to practically all our test problems—control, manoeuvring, safety and simplification—were solved by one modification, blow-off valves. The purpose and operation of these valves has been described elsewhere (*Trans IMarE*, Vol. 74, No. 4, pp. 98–99) but they enabled up to one-third of the gas turbine mass flow to be discharged to atmosphere as compressed air from the HP compressor discharge. The quantity could be instantly adjusted to any of four stages and enabled the entire plant to be manoeuvred rapidly and safely. They also enabled the propeller shaft to be stopped from full ahead in 12 seconds.

It is difficult to apply the idea of blow-off valves to this layout as the temperature would be excessive. They certainly impressed the German Federal Navy at the time, for the entire main engine was manoeuvred by one of their officers after only a few minutes' instruction. The ship was under orders of the Elbe pilot at the time.

Now is the time to design quickly the next generation for the 1990s with the experience of the last 15 years: a relatively cheap long-life, totally-gas turbine installation utilizing the RB211 with LNG as fuel and uprated $T_{\max}$, electric or epicyclic propulsion, simple ducting and even the possibility of using the 'cold' for superconductors. I suspect the steaming range could be dramatically improved, compared to the machinery described in this paper.

In conclusion, I wish to impress on the authors that although I have retired, and am out of touch with modern practice, I have been fascinated by their paper, my nostalgia has been tickled and I most sincerely thank them for making it available to us. I am well aware of the effort it takes to produce a paper such as this and it is particularly pleasing to see a joint author from a shipyard. We rarely see their faces here but when we do we all have much to learn. I thank them both for a most interesting and informative paper.

CDR P. W. W. RIDLEY (Procurement Executive, Ministry of Defence): As the first Marine Engineering Officer of HMS *Invincible*, both whilst she was being built and during her first year in commission, I should like to congratulate the authors on their concise and lucid description of a massive, complex and highly successful venture.

The false origin on Fig. 15 is misleading. One engine on one shaft gives over 50% full speed and is a very common mode of operation. Its extensive use, particularly on passage, allows considerable fuel economies and increases the viability of the four equal-sized engine COGAG fit.

The authors explain the need to avoid exceeding torque limits at high powers, particularly during high-speed turns, and suggest that this was achieved by imposing rudder limits at high power. In practice this would have meant imposing a complicated table of instructions on the Command, with rudder angles limited in a number of ways depending on speed, the number of engines connected and whether or not the integrator and resonance changers were in use. Operationally it has been found more practicable to devolve responsibility for avoiding excessive torque to the Marine Engineer Officer of the Watch in the Ship Control Centre. The throttle watchkeeper has a digital readout of torque in front of him, is well aware of the conditions under which high torques might occur and, as limits are approached during a high-speed turn, can fine off on the relevant throttle until the moment has passed. The reduction in speed is momentary and indiscernible, and the Officer of the Watch on the bridge is left to navigate the ship free of distraction.

There is little doubt that the propulsion machinery in HMS *Invincible* has been a great success, popular with operators and engineers alike. It ran virtually free of trouble during the exacting period of sea trials whilst I was on board and is reported to have continued to do so in the full year of busy naval operations that has followed.

DR R. H. KING (YARD Limited): The authors are to be complimented on their paper, which gives an excellent overview of the conception and development of the propulsion machinery of HMS *Invincible*. Service experience has shown this to be a highly successful venture.

Over the last decade, most navies have adopted gas turbine propulsion machinery for warships. However, when the decision was made in respect of HMS *Invincible*, the concept was controversial, especially with regard to ships of light cruiser size and above. The choice of gas turbine propulsion for *Invincible* was therefore novel at the time—and still is novel for a ship of this size and capability.

It is also worth mentioning that the gas turbine selection (the Rolls-Royce Olympus TM3B) was still undergoing development ashore as a naval equipment, without any sea experience at the time. This situation is illustrated by Fig. D1. Early in 1967, when wide-ranging preliminary design studies were being initiated on the machinery for HMS *Invincible*:

- The *County* Class destroyers were at sea (with COSAG plant employing G6 gas turbines);
- Design work had started for the Type 82 destroyer HMS *Bristol* (which would use the Rolls-Royce TM1 gas turbine in COSAG plant);
- Conversion work was commencing on HMS *Exmouth* which resulted in the first Rolls-Royce Olympus TM1 going to sea in late 1968.

The decision, in 1969, to adopt four Rolls-Royce Olympus TM3B engines as the main propulsion fit for HMS *Invincible* was therefore taken at a time when even the earlier version of the engine, the TM1, had only had very limited sea experience (in HMS *Exmouth*).

Indeed, it was not until late 1973, when the first of the Type 21 frigates entered service, that the first Rolls-Royce Olympus TM3B gas turbine went to sea with the Royal Navy. This coincided with the commissioning of the Shore Test Facility for the machinery of HMS *Invincible*, about 5 years before the ship went to sea. This decision on the part of the Naval Staff in 1969 was therefore a courageous one and one which, happily, experience to date has fully justified.

The authors mention, in their paper, the role which simulation played during the design development phase of the machinery for HMS *Invincible*. This was in two parts:

1. Dynamic analysis of the full ship and machinery performance, which examined a number of ship manoeuvring performance aspects, but in particular highlighted the extent to which manoeuvring performance was critically dependent upon the characteristics of the fluid couplings within the gearbox.
2. The adaptation of this information to enable the performance of these couplings to be fully evaluated during the shore trials at Ansty.

The normal configuration of one shaft set of machinery comprises: control, from either bridge or SCC; two gas turbines, each driving through either ahead or astern fluid couplings, or a direct-drive clutch; and a main shaft line with fixed-pitch propeller.

At any instant, the entire system is trying to match the load torque imposed by the propeller and the hydrodynamic forces acting on it; and the driving torque generated by the engines through the transmission system.

In the Shore Test Facility the load has to be imposed by a dynamometer, which is just not capable of reproducing the transient forces generated by the propeller in the ship's wake. What was done therefore in the shore trials was to control one engine normally and to control the other engine dynamically by computer to augment the load available from the dynamometer, so that the driving engine, and associated couplings, were subjected to fully realistic ship loadings.

These trials were of immense practical value in confirming the coupling design; the oil flows, and peak temperatures; and the expected ship manoeuvring performance; fully three years in advance of the ship going to sea.

Finally, there are two questions which the authors would perhaps like to comment on. First: for ships of destroyer size and below, it had been traditional to employ water-displaced fuel systems as means of improving ship stability. This was not done in the case of HMS *Invincible*. Have there been any problems of fuel contamination by bacteriological growth encountered in HMS *Invincible* and to what extent have the dedicated fuel tanks contributed to this experience?

Second: it is recommended that gas turbine air intake systems face aft or inboard to afford maximum protection from heavy seas. This was not possible in the case of HMS *Invincible* but was a cause for much concern at the early design stage. It would be very interesting to learn how the outboard-facing intake filtration system has performed in heavy weather.

CDR R. N. LANGMAN (Staff of Commander-in-Chief Fleet): The area I wish to question is the justification for the provision of the Shore Test Facilities.

When the introduction of a new type of propulsion machinery is being considered, the need for advanced shore testing is always closely argued and I feel that it would be of considerable assistance to any future decision if two aspects of the CVS shore test facility could be quantified and verified.

First, the financial equation. The actual capital and running costs of the STF are known and available within DG Ships; but has any attempt been made to establish the other side of the financial equation by estimating the theoretical costs of correcting, in the actual ship, the design deficiencies which were shown up and corrected during the testing phase? Not an easy task, I admit, but if it is not attempted while the scent is still warm the question 'Well, was it worth it?' will never be answered.

Second, a number of computer simulations were used in the shore testing. On the propulsion machinery this was particularly evident in the power injection trials and, for auxiliary machinery, tests 'comprised an extensive performance testing routine with endurance running closely based on the running profiles that the equipment will meet at sea'.

It is not unusual to find that, once a new ship design comes into service, the methods and modes of operation develop in ways unforeseen by the designers. In the case of *Invincible*, has any action been taken to compare the computer simulations with the actual operating profiles and to establish the reasons for any differences as

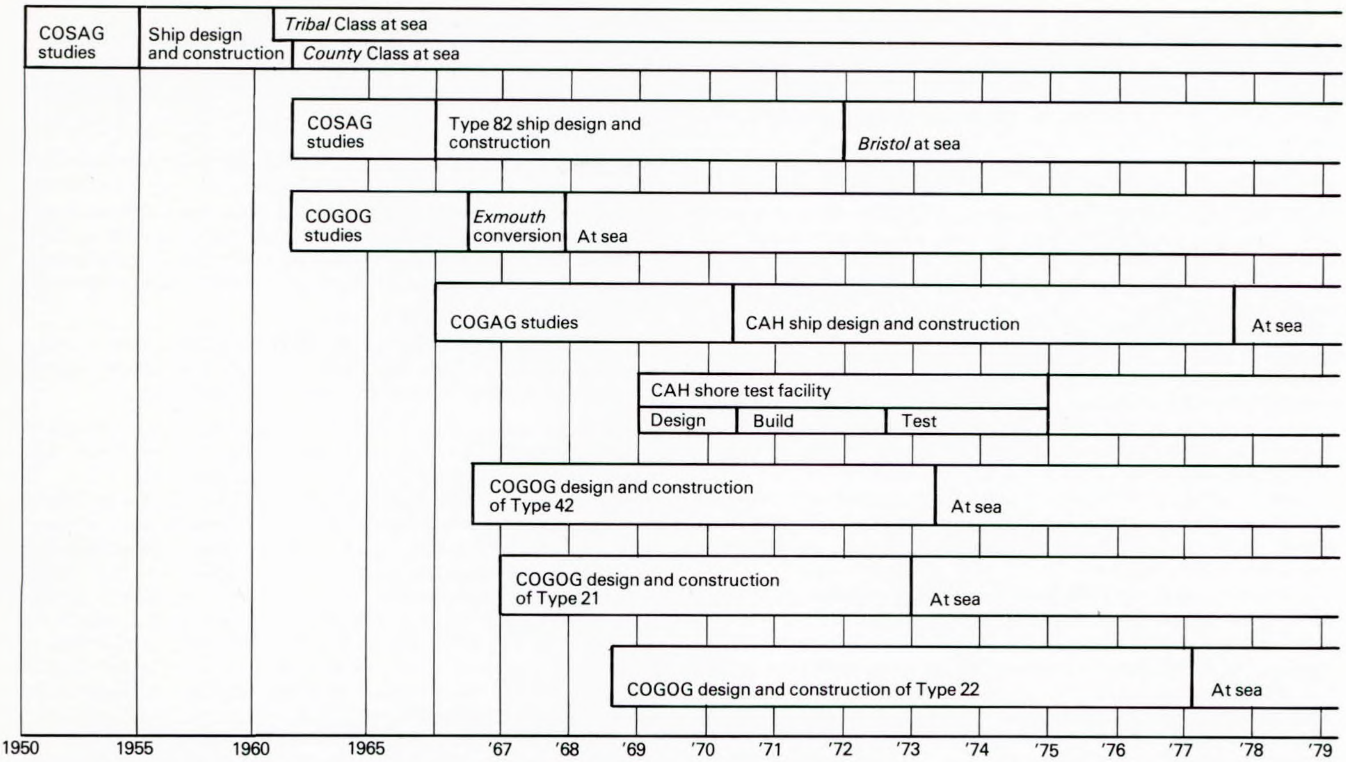


FIG D1 RN development of gas turbine propulsion

an aid to establishing closer correlations, should similar shore testing be used in future?

A. J. CLEMENTS (SSS Gears Limited): The Institute of Marine Engineers is to congratulated for selecting highly interesting and practical papers, and this paper has proved to be of a high standard with much interesting information to benefit industry.

The reasons given for the adoption of a fixed-pitch propeller (FPP) in association with a reversing gearbox are most interesting. It is often stated that an FPP is about 4% more efficient than a controllable-pitch propeller (CPP) when going ahead, and up to 30% more efficient when going astern. Could the authors give further information regarding the efficiency gain by selecting an FPP? It is appreciated that the efficiency gain is offset to some extent by the greater losses of a more complicated gearbox but the gearbox losses can be reduced by having less gears and bearings than used in HMS *Invincible*.

The Royal Navy has proved to be very advanced in its developments. With regard to the use of large naval reversing gearboxes, they are possibly in the forefront of the world. This experience began in about 1960 with the *County* and *Tribal* Classes of vessels which have separate, selectively filled, ahead and astern hydraulic couplings. These ships were followed by Type 82, having a reverse gear for use with gas turbines in the 15 000–20 000 HP range.

HMS *Invincible* is the first reverse gear for COGAG machinery in the 50 000 HP class, which gear also happens to be the first having a new arrangement whereby the direct-drive SSS clutch is mounted in a shaft system having a different gear ratio to the ahead hydraulic coupling drive. This arrangement results in a simpler method of interchanging the drive between the ahead hydraulic coupling and the direct-drive SSS clutch, but the penalty is an increase in the weight of the gearbox.

Whenever HMS *Invincible*'s reversing system is discussed, engineers usually comment on the high weight of the gearbox, which was, of course, designed many years ago. Modern designs are now available enabling the weight to be reduced substantially.

Franco Tosi Industriale S.p.A. Legnano, Italy, have designed a reversible converter-coupling (RCC) which provides selectively ahead and astern drive from a single unit in a high-power transmission. The RCC is similar to a normal hydraulic coupling having two rotors; an impeller connected to the input shaft and a runner connected to the output shaft. However, the unit is surrounded by a stationary casing and, around the periphery of the casing, 26 cylinders are mounted, each of which has its own stator vane. When oil pressure is applied to the cylinders, the stator vanes shift into the hydraulic circuit in the peripheral axial space between the impeller and runner. This has the effect of reversing the oil flow being ejected from the impeller, so the runner rotates in the opposite direction. The unit therefore acts as a hydraulic coupling when going ahead with the stator vanes retracted, and a torque converter to go astern, by simply inserting the stator vanes into the circuit.

The RRC has increased losses compared with a normal hydraulic coupling, but it is only used for manoeuvring. When manoeuvring is completed an SSS clutch, mounted in a parallel power path, is engaged to give direct drive and the RCC is then emptied. Therefore, there is high efficiency during the long periods of ahead propulsion.

All previous high-power reverse gears have suffered from the defect that there are separate power path systems, each clutchable for ahead and astern propulsion. Switching between these power path systems must usually take place when the vessel is being manoeuvred in confined waters. One of the fears is that either one power path will not declutch and the other will not connect during such critical manoeuvring. One of the advantages of the CPP is that a simple gearbox is used without the need to declutch and reclutch different power path systems to go ahead and astern.

With the introduction of the RCC, a reversing system is available with ahead and astern power being transmitted through the same drive system. Therefore, it could be described as a 'CP propeller mounted inboard'.

The Italian Navy is at present building the helicopter carrier *Giuseppe Garibaldi* with COGAG machinery incorporating triple-reduction reversing gearboxes and FPPs. Each of the 20 000 HP gas turbines will have an RCC for manoeuvring between ahead and astern drives and an SSS clutch for the direct drive.

Mainly because of the simplified shaft systems within the gearbox, the weight is considerably reduced and, in this case, the gearbox weighs a little over 70 tons, instead of about 150 tons.

In specifying reversing gearboxes, it is normal for the shipowner to give the requirement for crash astern. Such a crash astern manoeuvre is very important but is carried out very few times during the life of the ship. The vast majority of manoeuvring operations between ahead and astern is at low power and the particular requirement in this case is to apply thrust to the ship in the appropriate direction, very quickly and reliably.

This important requirement, i.e. quick application of thrust, is not usually stated when specifying reversing systems. However, a very important advantage of the RCC is the ability to apply thrust very quickly. This is because the unit remains full of oil, and ahead and astern manoeuvres are carried out merely by inserting or withdrawing the stator vanes.

R. J. WRIGHT on behalf of C. J. CHARLES (GEC Marine and Industrial Gears Limited): My colleague Mr Charles regrets not being able to be here today and would like to bring your attention to the way in which the *Invincible* gearbox fits into the overall picture of the development of reversing gearboxes for RN ships over the last 25 years.

The *County* Class destroyers, in which steam and gas turbines are combined into a reversing gearbox, were the first high-power installations using hydraulic couplings and weighed rather less than 2 tons per 1000 HP transmitted. As we have seen, the *Invincible* gearbox weighs in excess of 3.5 tons per 1000 HP. For the purpose of comparison, the *Invincible* arrangement is shown in Fig. D2.

Other solutions were considered at the time but were rejected on the grounds of indigestible novelty. For example, the solution shown in Fig. D3, employing surface-hardened gears, used hydraulic couplings with a very simple control mechanism—a single on–off valve controlling cooling oil flow.

The current solution to the same statement of requirements, which incidentally is now being seriously addressed by both the US and Italian Navies, lies in the use of the Franco Tosi reversing hydraulic coupling. As many of you will know, GEC in association with Vosper Thornycroft, were it not for the vicissitudes of Her Majesty's Government, would at this moment be testing the gearboxes for the Royal New Zealand Navy *Taranaki* conversion to gas turbine propulsion; abruptly cancelled last October, we have now been denied what would certainly have been the world's first sea-going application of the Franco Tosi coupling.

When this device is applied to the *Invincible* situation, the solution is as shown in Fig. D4. At 60 tons, we have now achieved a power to weight ratio of less than 1.5 tons per 1000 HP.

Mr Charles would like to make one further comment relating to reliability and maintainability (R & M). Could the authors of the paper comment on whether the use of conventional components in a complex and novel application is more or less likely to have an impressive R & M rating than the adoption of a relatively novel solution, but of an inherently simple concept, to which meticulous attention would naturally be directed? Reading the paper, I have the impression that novelty and resulting simplicity may well produce a higher score.

D. J. ANDREWS (RCNC Office, Dept of Mechanical Engineering, University College London): The authors are to be congratulated on a detailed exposition of the *Invincible* Class main machinery plant and the paper is an excellent complement to the overall description in Ref. 1. I think it is worth drawing the meeting's attention to the comment by Captain Mike Livesay, the ship's first Commanding Officer, at RINA last April:

> 'The propulsion I think is a joy, from my point of view . . . my marine engineer says, and I agree with him, it is the only way to drive a large warship with four equal building blocks . . . .'

This paper on propulsion machinery clearly shows, for one of the major systems in the ship, the amount of detailed effort and consideration put into the design, production and testing.

I was intrigued by Noel McKenna's description of structural reasons for separate cross-ducting. From the naval architect's point of view, there were also several other good configurational reasons why this arrangement was finally decided upon. The other comment by the authors on the constructor's impact on the machinery system concerned the shaft support. The ship structure, which is one of the reasons for the ship being so light, is highly efficient in strength but, in comparison with previous carrier structures, is more flexible and so some design effort was necessary to ensure sufficient stiffness in the machinery support was provided.

I should like to comment upon two particular points. First, the upkeep by exchange, which the authors mention on page 9, gives the ship its excellent availability but inevitably has a very significant impact on the overall configuration, as our paper (Ref. 1) showed. Second, regarding Fig. 15 in the paper, Noel McKenna mentioned that the comparison with *Hermes* could not be exact. *Invincible*, in displacement terms, is some 50% less than *Hermes* and this is obviously relevant to propulsion; however if one considers total volume as a measure of the capability provided by the design, then the comparison is all but exact. This makes the benefits of the propulsion plant even more dramatic.

FIG D2 Gearbox arrangement on 'Invincible'
Single tandem gears, triple reduction, hydraulic couplings, independent clutch, weight: 150 tons.

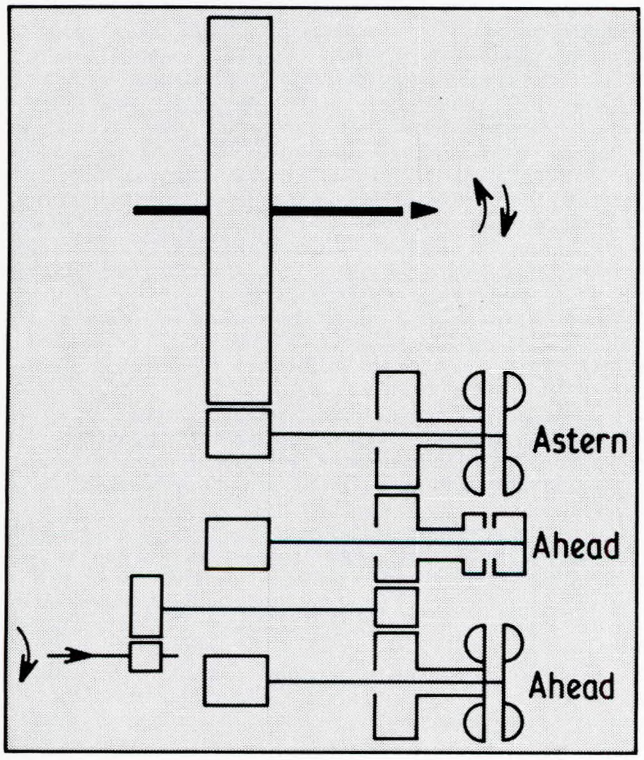
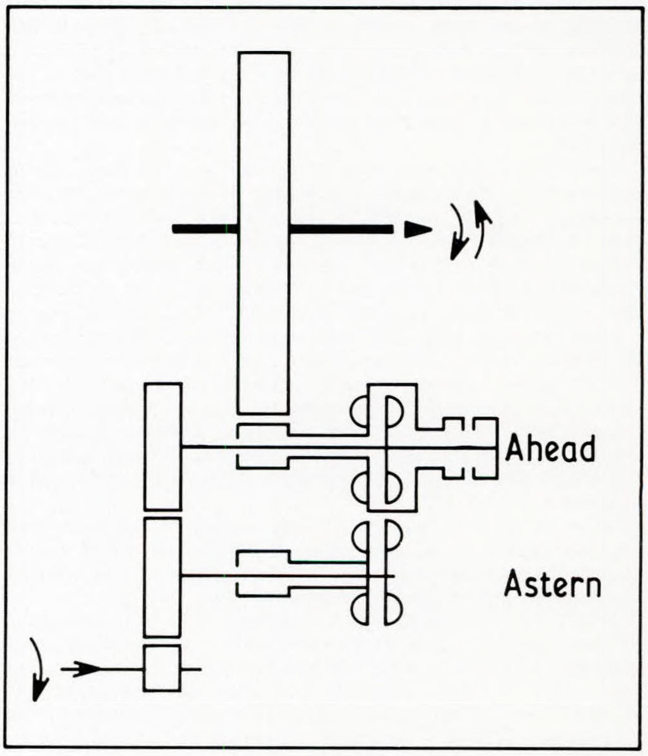


FIG D3 Alternative gear arrangement
Single tandem gears, double reduction, hydraulic couplings, weight: 90 tons.



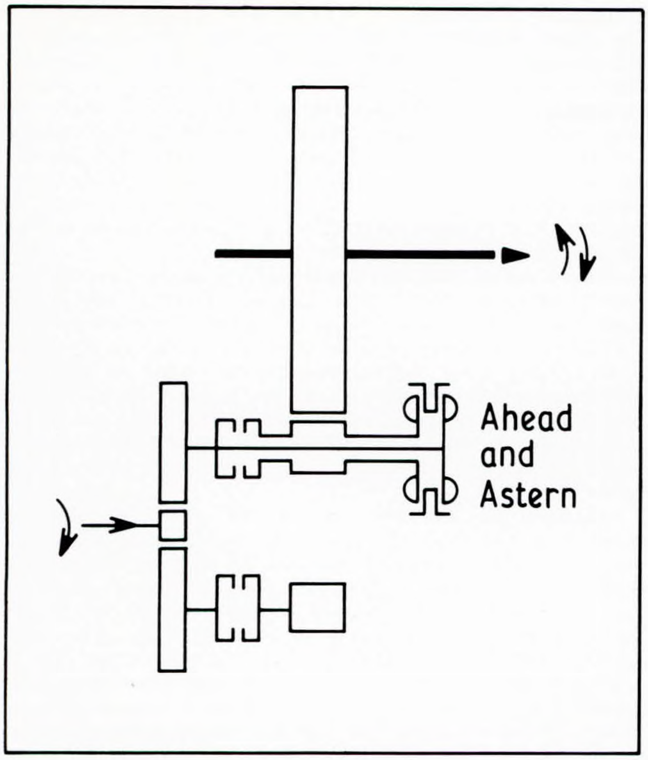


FIG D4 Application of Franco Tosi coupling to Invincible's situation
Locked gear trains, Franco Tosi reversing coupling, weight: 60 tons.

CDR M. B. F. RANKEN (Aquamarine International (Fisheries and Ocean Development) Limited): This is an important paper about an interesting installation, but it also gives further evidence of the appalling time scales and cost escalations to which we are condemned by the current incredible procurement procedures for defence equipment and HM Ships. As stated in the Synopsis, this paper needs to be read in conjuction with Ref. 1, which gives more details of the ship herself and of some of the thinking behind her evolution.

The Royal Navy has led the world in the application of gas turbines to warship propulsion and it is interesting that steam turbine propulsion, abandoned for surface ships, is now standard in the nuclear-powered Fleet and ICBM submarines, the first practical 'true' submarines, if we discount the mainly experimental Walter HTP boats which preceded them.*

Apart from the Napier 'Deltic' and the ASR1 range of diesel engines, the Navy has contributed little to diesel development since the war and current requirements for economical propulsion engines in smaller ships are unlikely to be met by any current British design, though it is to be hoped that the engines chosen will nevertheless be built in this country, especially to ensure that we have security of supply. Maybe this is a suitable subject for a future paper to this Institute, especially as the operational requirement for long endurance cannot be met by any marine gas turbine presently in service on account of relatively much higher fuel consumptions.

The *Invincible* Class ships are described nowadays as 'small' carriers but, at 19 500 tons displacement, they are the same size as (and wider and much longer than) the battleship *Dreadnought* of 1906, and 85% of the pre-war *Illustrious* Class Fleet carriers and of *Hermes* as built. At around 112 000 SHP, she presumably has substantial reserves of power to achieve her 'declared' speed of 28 knots; *Illustrious*, with about the same on four shafts, made 31 knots.

Perhaps it is a measure of the simplicity of the gas turbine that virtually no description of it is included; it would greatly enhance the paper's comprehensiveness if some technical details and illustrations were included, as well as powers, engine and shaft speeds, ahead and astern, and any unusual performance details.

I have already questioned the layout of these vessels in the discussion of Ref. 1. The present paper reinforces my impression that enormous and unnecessary handicaps and technical difficulties were built in to the ship from the earliest stages of the selected design. The choice of a basically conventional in-line reduction gear transmission system and staggered layout for damage control purposes immediately introduced all the problems of accommodating the intake plenums ducting and filters, exhausts and machinery removal trunks/routes, as well as of shaft alignment. Mr Duggan pointed to alternatives and much more flexible (and potentially equally efficient) transmission systems, well within the range of experience of the 1960s, and also obviating the need to design and construct 'not only the most powerful reversing gearbox ever to go to sea, but also the most powerful of any type hitherto employed in any RN ship'.

No doubt other design problems would have been introduced, e.g. with the propulsion motors (and reduction gearboxes?) if turbo-electric had been chosen, but it should have been possible to avoid the situation where the propulsion system in the ship seriously penalized the ship's principal operational purpose of carrying the maximum number of anti-submarine helicopters and aircraft, commensurate with her tonnage.

In the event, at least most of the heavy weights are in the right place, low down in the ship, but one wonders whether some of this might have been put to better use in direct support of the ship's operational purposes and performance.

It is all very well for Mr Andrews to point out the high internal volume (90 000 m^3; Ref. 1) built into the hull design, when such a lot of it seems to have been lost to the ship's primary operational functions.

It was probably right to reject controllable-pitch propellers (CPPs) and select reverse gears and hydraulic couplings for the high powers involved (i.e. 56 000 SHP per shaft), but it is important to counter the impression given in the discussion that CPPs are either excessively complicated or often unreliable. Very many medium-powered and small ships obtain excellent service and great manoeuvrability and flexibility from their CPPs, and seldom have breakdowns. Over-speed and over-power protection are easily built in, as is virtually equal power ahead and astern. There is some loss of efficiency at other than optimum design speed and power (and pitch), probably worse in the smaller units, but surely fixed-pitch propellers (FPPs) are only more efficient over a small range of speeds around the designed optimum, which is probably less significant the larger the size; few warships are able to operate close to this optimum for long periods, and should this be selected for the ship's maximum speed (which it seldom uses) or for some cruising speed related to one of her principal operational modes? In that case, which one should be chosen, and can the Captain be sure that he will be able to use this speed in company with other ships of several nations, as is likely in NATO operations?

Propeller noise is of course important in a warship, and it may be that a CPP tends to be noisier than an FPP under most likely operating conditions.

An immense amount of trouble on board is introduced when water-displacement fuel systems are used to preserve transverse stability, as has apparently been necessary in all the gas turbine frigates and destroyers; dare one suggest that a little more beam and a more imaginative hull form would have eliminated a major life-long problem and, incidentally, improved seakeeping and accessibility to and around machinery and equipment in those ships? The weight distribution in *Invincible* and her much greater size luckily obviate the need for water-displacement fuel systems.

However, a related operational problem is the availability of the specialized and very clean fuel needed by gas turbine ships, wherever they are operating, especially as their speeds are much higher than those of the logistic support ships which nowadays have to accompany them. There are few overseas ports today where supplies could be laid down in peacetime for use in war.

The comparison of fuel consumption in Fig. 15 with HMS *Hermes* is distinctly suspect. *Hermes* (modified *Centaur* Class, ex-*Elephant*) has two conventional pre-war cruiser sets of Parsons geared turbines and Admiralty three-drum boilers developing a total of 76 000 SHP; all excellent of their period. But gas turbines need to be compared with diesel engines and the aim must be to achieve comparable economies, which are understood to be possible with the Rolls-Royce RB211 and some other modern gas turbines.

The main engine lubrication and cooling systems are vital to the safety, reliability and life of the turbines and gearboxes, as well as to their economy. So are the remote-control and monitoring system, instrumentation and presumably data-logging, since engine performance at least can be seriously affected by salt build-up on

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* Vice-Admiral Sir T. Horlick, 'Submarine propulsion in the Royal Navy'. 54th Thomas Lowe Gray Lecture, *Proc.IMechE* Vol. 196 No. 7, 1982.

compressor and turbine blades; through-life monitoring and record-keeping must assist in maintaining best performance, detecting deterioration before it leads to breakdowns, and ensuring maximum availability. These systems and items are also vital to the safe optimum operation of all the machinery in unmanned machinery spaces, and to maintaining services under damage conditions.

Most auxiliary machinery units and systems are just as vital to the operation of any ship as the main engines. Although 'some 18 items of equipment were selected from the standard range' it was disquieting that 'some 38 items of new equipment were required'; it is also disquieting that 'one-fifth of the components failed under shock testing'. Taking into account that work on shock-proofing and noise and anti-shock mountings started early in the war (about the time HMS *Belfast*'s back was broken by a magnetic mine) and has had a major research effort ever since, it is surprising that failures were so high. One wonders whether noise-reduction in particular is today being overemphasized, in view of the much improved listening devices (and electronic processing circuitry) available in modern submarines.

It would be interesting to have some details and the sizes of the new items of equipment which had to be designed, and of the kinds of reasons which made standard units unsuitable. In the case of the electric generators, one wonders why diesels were preferred for all of them rather than gas turbines, of which so many are nowadays in use in the offshore industry and elsewhere under very adverse conditions. It would also be interesting to know whether shaft-driven generators were considered in the design and, if so, why they were discarded, observing that all but one or two of the auxiliaries are presumably electrically-driven. Alternatively, was consideration given to driving any of the main engine and gearbox auxiliaries directly from the engines, gearbox or shafting?

There is probably plenty of material for another paper on the auxiliary machinery and systems, including such items as the main electrical power generation and distribution system, steering gear, air-conditioning, auxiliary boilers and distilling plant; the latter presumably need to achieve a minimum daily output of 200 tonnes/day to meet just the current fresh water requirements for 1000 men, and one wonders what type is fitted and whether any waste heat is available to eliminate or reduce their dependence on live steam.

It would be helpful if the 'sizeable reduction in ER complement' could be explained; what is the size of the Engineering Department, the numbers in each branch, and the balance of officers, senior technical and other ratings, and junior ratings? It has been stated† that 'the most highly trained guys have the least to do'. This is obviously a most undesirable state of affairs, as boredom breeds several kinds of trouble, whereas automation should release men for more interesting work, not just reduce their number; perhaps this may resolve itself as the ship gets older. The same article states that 'berths for 106 officers and 206 non-commissioned officers' (presumably Chief and Petty Officers) 'will be lost' when the ship is sold to the Australian Navy; presumably there are junior ratings in addition. How many of all of these are engine room (mechanical) staff?

The Shore Test Facility (STF) at Ansty is a welcome addition to the design, development and construction armoury which follows aircraft practice, as do the Dounreay submarine prototype reactor plant (DSMP) and the submarine installation test establishment (SMITE) at Barrow.* These latter facilities in various forms have continuously supported the nuclear submarine programme, from near the beginning of the *Dreadnought* to the latest *Trafalgar* Class Fleet submarine (number 20 so far) and soon the *Trident* submarines. But Ansty has apparently been built only for the *Invincible* Class of three ships, which is a major cost when there is little likelihood of more being built. It is to be hoped that it can be used for ongoing marine gas turbine propulsion installations in new surface ships, when new designs begin to be built, as they must be, despite the current disastrous and unrealistic cut-back in numbers of surface ships. There is no doubt that design and construction weaknesses and faulty workmanship exposed and eliminated at this stage is money well spent, and must contribute substantially to reduce through-life costs.

What is particularly disquieting is the incredible time scale over which these ships have been in gestation. The original proposal for small, 'cheap' carriers was contained in a Naval Staff paper prepared in 1962, but suppressed by the then First Sea Lord, who was actively pursuing the large CVA 01 Class, later cancelled in 1966. The Sketch Staff Requirement (SSR) for the present ships emerged in 1967, but was already following the same disastrously expensive pattern as had resulted in the loss of the CVA 01 Class; and it was also bedevilled by the sensitive political issue that the Royal Navy was supposed to be abandoning fixed-wing aircraft. At that time the Fleet Air Arm was also hostile to the 'Harrier' VTOL aircraft, in spite of its obvious advantages for ship-borne operation, even if the first generation did not meet everyone's aspirations for supersonic aircraft with a greater endurance and weapons load. Subsequent events took their leisurely course, and the Through-Deck Cruiser became a Helicopter Carrier, and then eventually an ASW or 'light' aircraft carrier. It is almost incredible that 14 years were allowed to elapse from SSR to final operational acceptance into the fleet.

The final cost of £220 million is probably more than it would have cost for each of the CVA 01 Class (originally quoted at £60m each in 1966) and *Illustrious* and *Ark Royal* will be more; Mr Geoffrey Pattie, the Parliamentary Under Secretary of State for Procurement, quoted today's figure earlier this month as £350m—a far cry from the Admiralty's 'cheap' carrier paper of twenty years ago. Now *Invincible* is to go to Australia for £175m, at substantial loss to us and still far too expensive for them, and the Royal Navy's operational capability is effectively reduced by 50% once the two sister ships replace her in service.

Meticulous care has been taken in the design, development, manufacture and testing of the propulsion machinery, as on the hull, and the communications outfit (at a cost of £40m per ship) and no doubt on every other major and minor system and unit throughout the ship, because there was nowhere else to try out new ideas. Similar care has gone into ensuring reliability, availability and safety, and provision for ease of through-life repair and maintenance. But, in contrast to the ongoing nuclear submarine programme, no sense of urgency has been shown to bring these vessels into service and gain practical operational experience with them, one of the most essential elements in achieving worthwhile progress. Nor is there any sign that anyone involved with developing and constructing these ships (or any others conceived since 1964, probably even since the War, and not excluding the nuclear Fleet Submarines, now costing around £230m each) had any concern for the escalating cost implications, both of the individual elements and alterations continually being incorporated in them right up to delivery, and of the ever-lengthening time scale which resulted. Jackie Fisher's oft-quoted maxim to 'Build few and build fast, the next one better than the last' holds just as good today as it did at the beginning of the century: to get new ships into service quickly, to get practical experience with them on which to base the next design, and to save money which can go to the next design or to more units of the class.

This insensitivity to cost escalation far beyond the rate of general inflation is probably the chief cause of the increasingly rapid rate of emasculation of the Royal Navy, unique in its field, and still essential to the survival of this country and now also of Western Europe, but increasingly impotent even with its NATO allies to meet the demands which would be made upon it to preserve and protect our vital sea trade, on which all else depends.

The Navy can have what it needs, and eventually sufficient, within the money available, but not so long as the Naval Staff and the Defence bureaucracy continues to produce totally unrealistic designs we cannot afford singly, let alone in the considerable or large numbers needed to fulfil any of the tasks which will surely have to be performed. Excessive beliefs in technological fixes, whatever the cost, and total political blindness to the economic climate, are much greater threats to our Armed Forces than the periodical budgetary opportunism and idealogical abberations of our political parties; and no longer has each service its own political head to fight its corner.

The *Invincible* Class is just the latest and worst result of political ineptitude and bureaucratic arrogance, and maybe incompetence too. There is no future for these ships, and this must be cause for concern and for great anxiety about the future.

E. R. MAY (Technical Director, Stone Vickers Limited): The authors' remark that controllable-pitch propellers (CPPs) are more noisy than fixed-pitch propellers (FPPs), within the limits of loading used by the Ministry, I believe to be mistaken. Indeed, I understand that the authors' colleagues would not now support it?

It is quite true that CPPs are usually less efficient than FPPs, but commercial experience of calculating efficiencies is that the loss in propellers of the *Invincible* size is only of the order of 2%. The subject is of course of substantial interest, and it is unfortunate that the number of direct comparisons available between CPP and FPP models of propellers designed for exactly the same duty is less than might be desired.

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† P. Pohling-Brown, 'The engineers of HMS *Invincible*'. *Engineering Today* 15 February 1982.

T. W. BUNYAN FEng, FIMarE: After many trials and tribulations we now have a most noteworthy achievement. Bearing in mind the complexity of the machinery, the 'rough stuff' was not excessive. To break new ground you must always stick your neck out—something I have done all my life, which explains the feeling of comradeship I have for the authors.

The paper is a most interesting diary of events. It is not at all surprising that shafting alignment has accounted for most of the problems, as the complexity of 12 meshed gears, clutches, brakes, etc., was necessary to achieve a most remarkable operational flexibility.

The suppression of high-frequency noise emission from the gas turbines is a tricky problem, as silencing must be achieved without significant reduction in the gas flow. The aerial shot of the ship, taken from some height, which was shown on TV recently, indicated that 100% sound deadening was far from practical. It could be that the noise directed upward would be more acceptable from the military standpoint than noise directed laterally.

Referring to the section on 'Testing', page 10, I find paragraph (a) somewhat confusing. It states that the slope of the bull gear journals altered with loading and thermal effects, making it necessary to return the bull gear shaft and bearings to David Brown for correction. Figure 7 suggests that the bull gear may be solid with its shaft, or has stub shafts bolted to stiffened diaphragm plates—either arrangement is common practice. The alteration in the slope of the bull gear journals in the bearings suggests inadequate rigidity. In similar cases to that mentioned in the paper, the stiffness of the gear case has been involved. Would the authors please explain what was in fact the problem and how it was solved?

The hairy set-up for the basin trials—running one propeller ahead and the other astern—always amazes me. For 20 years, to my knowledge, a certain German shipyard has used no-thrust fabricated paddle wheels instead of the ship's propellers to provide a full-power basin trial for their single- and twin-screw ships, including very high-powered container ships. The arrangement must offer considerable economic advantage—and convenience—without significant technical 'hang-ups', except for the thrust block. It surprises me that this method has not been more widely adopted.

It would be most interesting to know of the degree of agreement between the dynamic impedence as derived from the finite element computer analysis made of the thrust block seating, and that actually measured.

I am most grateful to the Royal Navy for incorporating 'Pilgrim' products such as the Morgrip self-straining bolts and the Pilgrim hydraulic propeller nuts. These are big business with the US Navy who are, I am informed, also investigating the Pilgrim keyless propeller for its unique dampening of high-frequency noise, i.e. gearing tooth contact and hobber error frequencies transmitted through shafting and propeller blades. The layer of a special epoxy compound used in this propeller, for securing the sleeve in the boss, apparently does the trick.

D. G. NICHOLAS (Manager, Naval Department, Industrial and Marine Steam Turbine Division, GEC Turbine Generators Limited): In the light of present financial stringencies it is difficult to comprehend the basis from which this machinery arrangement was conceived. For the sake of retaining standard aero-derivative gas turbines it was necessary to involve the use of the complex, large and extremely heavy reversing gearbox design which has to transmit higher powers than anything previously experienced.

It therefore came as little surprise to learn that the test programme extended over a period of 3 years within an installation which itself took an additional 2 years to construct and all for a class of three ships! This sounds very expensive and it is to be hoped that these development costs were taken into account when comparing this propulsion arrangement with the alternatives which are available and seem to have been used by other major navies. The US Navy for instance has in recent years used nuclear steam propulsion for surface ships of about 10 000 tons and over, whilst the USSR has also used steam propulsion, oil-fired for the *Kiev* and *Moskva* Classes and an intriguing combination of oil and nuclear for the formidable *Kirov*.

Had oil-fired steam propulsion been chosen, it would have incurred no disadvantage compared to gas turbines in the way of manning levels or maintenance. Modern steam systems have been operating for over a decade in merchant ships with unmanned engine rooms with single-lever control from the bridge. Typically, only two machinery watchkeepers are required and the authors' comparison of manning levels with those of *Hermes* has no relevance today. Maintenance requirements have been found to be very low indeed on these merchant ships as a result of various system and component developments; for instance, by the adoption of motor-driven pumps which has eliminated the snakepit of small-bore pipework and valves which exists in historic RN steam ships; and by the elimination of the troublesome refractory bricks from the combustion chamber of the boiler which now uses water-cooled membrane walls.

Fuel consumption would be competitive with the first-generation gas turbines used on *Invincible* and it was rather absurd to make the comparison with the almost prehistoric machinery used in *Hermes*.

Space requirements could well have been less and a further aspect in favour of steam would be its proven survivability in battle. This compares with the untried capability of gas turbines to survive shock or blast or even quite minor damage to ductwork and thin-alloy engine casings.

Despite these criticisms, the authors are to be congratulated in their presentation of a record of success—even if it was by development rather than by initial design.

R. F. CROOK (Chief Electrical Designer, Vosper Thornycroft (UK) Limited): Would it not have been a better 'bet' to have gone to electric propulsion which would have resulted in less cost; more integrity; low noise; economic cruising; greater degree of flexibility in the use of propulsors, and considerably shorter build time of the ship?

The minor disadvantages of electric propulsion would be increases in machinery weight and in the area required in machinery spaces (this should not be too much of a problem as the *Invincible* spaces appear to be generous). Possibly there would be a loss of continuous top speed, but do you need a speed above 25/26 knots in a carrier using V/STOL with 'ski-jump' and helicopters?

The savings that could have resulted from going for GT/electric propulsion are as follows:

(a) There would be no need for an expensive and protracted shore test facility as carried out at Rolls-Royce, Ansty.

(b) No complex and expensive lube oil system would have been required for each reversing reduction box.

(c) There would be no main reversed/reduction box, but this cost could be offset by electric generators and electric propulsion motors. However, the number of diesel generator sets could be reduced because any one of the GT sets could supply the ship's system in an emergency—albeit this would be a 'steam hammer to crack a nut' situation.

(d) The overall control system would have been simplified.

(e) The GT generator sets could be sited with a higher degree of flexibility and would be easier to shock mount.

(f) There would be one shaft alignment problem—from the electric motor to shaft.

The integrity of an electric system is high and would allow the use of a large bow thruster for both manoeuvring and docking; and even a secondary 'get you home' system in the event of action damage to rudders or main propellers.

Large electric propulsion systems have proved to have a high degree of reliability and are simple in concept and operation: for example, to quote but two, the famous US carriers of World War II, *Lexington* and *Saratoga*, and the flagship of P & O, *Canberra*.

Finally, I apologize if I appear to be hypercritical of the design as I know a great deal of ingenuity, thought and hard work went into achieving the end result, but I am only challenging the basic design philosophy.

With 'tongue in cheek' I remind the authors of the case where the USS *Lexington* relieved the power shortage at Tacoma—and made a profit. During the summer and fall of 1929 a drought had depleted the main hydro-electric power reservoir of Tacoma and approaching freezing weather would have greatly reduced the output at the Nisqually streamflow plant of the city. The prospects for continued operation of industries, and an adequate supply of power to the homes, were none too bright.

Thus, the Navy Department ordered *Lexington* to supply power to the city at a flat rate of ¼ cent/kWh for a connected load of 20 000 kW, plus 1 cent/kWh for power actually received. During the ship's stay, from 17 December 1929 to 16 January 1930, the cost was $78 509.60 (01.85 cents/kWh). The cost to the ship for fuel and incidental expenses was $18 627.69; leaving for ship's repairs a surplus (disregarding crew salaries, depreciation and loss of ship from active service) of $59 881.91.

If *Invincible* had been turbo-electric it could well have supplied power during last winter's power failures, made a profit and perhaps then would not have to be sold to Australia.

F. SUTCLIFFE CEng, MIMarE, MIMechE: Do the authors consider that the bearing problems experienced on *Invincible* trials are an acceptable fact of life when the prototype machinery had been extensively shore tested?

In this day of computers, are there areas of bearing design which are unknown or is it misalignment which is causing problems?

Perhaps there is a need for an updated paper on 'Marine bearings' and their tolerance to misalignment.

C. A. ROWNTREE (Vickers Shipbuilding Group Limited): I should first like to congratulate the authors on a very interesting paper with which I have few arguments. However, as I was involved in the hardware end of the propulsion machinery for some 8 years, both STF and CAH 01 as it then was, I feel there are some points which require amplification.

Gearboxes

The fluid coupling was a twin-circuit, single-scoop type and considerable development was carried out by the coupling and gearbox manufacturer to ensure that the circuit farthest from the scoop was efficiently evacuated on scoop insertion. In Fig. 6, the coupling drain oil is shown as returning to the cooler; this, of course, is via the gearbox drain tank.

I understand that the gearbox and thrust block seats and substructure have been modified in 02 and 03 and that the vibration problems during high-power crash stop manoeuvres are now considerably alleviated.

LO System

The air-driven LO pump, affectionately known as the ADLOP, would also cut in on low oil pressure. I would add that a considerable amount of work was carried out on the initiation of this pump to give a satisfactory cut-in characteristic with respect to transient LO pressure.

An interesting characteristic manifested itself on shore trials at low temperatures, with two LO pumps performing less effectively than one.

Controls

The lack of interlocks at the local control position was emphasized on shore trials when the ahead couplings were run, in error, to within 1% of full speed for a short period. It should be noted that no defects occurred, which gave us a high degree of confidence in this particular component.

With regard to surveillance systems, both at Ansty and for CAH 01 trials, a gearbox mimic was fitted to give instant identification of bearing alarms to the MCR watchkeeper without going to the side of the control console and then remembering what the legend on the alarm window meant. I would be interested to know if the ship's staff feel its retention would have been beneficial.

Figure 9 should include the transient brake in the SCC operations (they were only used to assist in disengaging the SSS clutches under certain conditions) and the manual control operations should include transient and shaft brakes.

Ducting

The filtration system was designed to remove spray and aerosol salt down to very low levels and was, I believe, eminently successful. Certainly, with a fire hose directed at the outside of the first stage with engines at power, there was no evidence of water penetration.

Three types of cascade bends were used at various positions at the STF. Following extensive uptake thermal cycling trials, when cracking occurred on two, the ship's fit was decided. In view of the extensive modifications following STF phase I trials, which appeared successful in phase II (see p. 10: 'STF—Ansty', paragraph (b)), the in-service defect record would be interesting.

One problem which arose during ship commissioning concerned the accurate and repeatable operation of the intake bypass doors; these were not fitted at Ansty which was, in my view, unfortunate. I think we got it more or less right at Barrow after much effort but, again, comments on in-service performance would be of interest.

Reliability studies

The gearbox hydraulics, once operating correctly, proved eminently reliable and the defects were minor and of the 'count them on one hand' order. This, on three gearbox systems over some 4 years of use, speaks for itself. One major design change was on the direction and engine selector valves (Fig. 8). It was found that the seals were drawn into the valve during opening and then cut off on closing. Whilst this did not worry the fluid couplings, it was undesirable and in the end the seals were deleted. Leakage when closed was slight and merely augmented the coupling cooling supply.

Maintenance

Some alarm occurred when it was realized that the spare gas generator was stored with its main axis athwartships. It had been designed for normal fore and aft G loads along this axis, which are lower than athwartships. A modified canister mounting system solved this one.

I understand that maintainability at sea has, in fact, exceeded expectations; confirmation of this would be welcome.

Alignment of shafts and gears

Gearbox sweep and mainwheel axial position problems were first encountered at STF, as was the power turbine to gearbox torque tube alignment. It was perhaps unfortunate that they manifested themselves at the ship stage as well.

The mandrel and clock gauge method was adequate at STF but, due to bolt pitch circle concentricity problems in the torque tube, a large amount of time was spent clocking at up to 14 positions to establish the errors. At the ship stage, only one out of four gave any major problems and this was cured by opposing off-centre pitch circles. This brought the power turbine vibration well within limits.

STF Ansty

(a) I think 'hot' is a slight understatement. However, a cure was devised, namely a stiffer main shaft, compliance at the inner end of each bearing and a degree of slope boring. It was felt that we had slight overkill, as any two would probably have cured it, but it has proved successful. In fact, compliant bearings only was the first-stage modification and there were no subsequent failures during phase II trials at the STF.

(b) The use of gearbox LO was deleted prior to installation at Ansty, due to viscosity problems at ambient temperatures in a basically static system. We started with the same low pressure and a low-viscosity oil. This oil was later changed due to incompatibility with the main LO. It was only for the ship that the high-pressure OM 33 system was used, based on STF results.

The major changes in this system were due to drain line back-pressure, which inhibited valve operation. This was eventually overcome by changes to spring rates and valve actuator piston sizes. As I mentioned earlier, the system, once modified, performed extremely well.

(c) Details here are long and involved. Suffice it to say that some of the logic originally did not work; some did but was simplified and, following the bread board modifications in phase I, STF, these were fully engineered and proved in phase II trials. I must admit we felt it would be very difficult to fool or break the machinery in service—this was certainly the case at STF and on CSTs.

There were additional changes of which the most significant, from the operator's point of view, was probably the addition of automatic LO temperature control.

In addition, we had problems with transient brake face seals which were found late during gearbox strip and were resolved at the ship stage. Engine uptake bellows were a difficult area and, after extensive trials in another facility at Ansty, a soft type was fitted instead of corrugated stainless steel.

Clutch disengagement and shaft stall trials were also carried out at Ansty, and a considerable amount of work was done on the dynamometer operating equations to give accurate control in the power injection mode (see Ref. 5).

Thrust block

This was also used on STF to simulate shaft friction by nipping the collar between both sets of pads. It would be interesting to know how this unit has performed since delivery, since there were doubts expressed as to its tolerance to the bending and subsequent misalignment of pads and collar that might occur in service.

Setting to work

Flushing of the fluid coupling system is indeed unnecessary and perhaps this point should have been made more forcefully earlier—*mea culpa*. However, an interesting exercise was carried out to compare the standard measure of cleanliness, using a 100-mesh full-flow gauze, with millipore sampling techniques. Sampling points were chosen where turbulent flow was expected and the two systems were run in parallel. From results on the two ship's systems—and backed up by, admittedly incomplete, STF results—it would appear that a satisfactory clean gauze is only obtainable when the millipore standard is Charn 200–400, specified only for very sophisticated hydraulic control systems. The ship's general hydraulics, for instance, were flushed to Charn 15 000 or Conpar 9.

The reason is considered to be that millipore takes a small, slow sample from the edge of a large, high-speed, LO flow, of up to 8 in diameter. Particulate matter will, in the main, be carried past the sampling point, hence the full-flow 100-mesh gauze is still preferred. Millipore is fine where smaller flows and diameters occur, as in hydraulic systems where it is extensively and successfully used. An interesting line of investigation might be carried out into the point at which millipore becomes unrepresentative unless pitot tubes placed in the flow path are used.

Apart from problems already mentioned, there was only one other at the ship stage that we had to fight, and that was fuel tank level indication. At high bunkering rates, an air pressure was created in the top of the tank due to the high degree of internal subdivision. This gave a false reading on the air-operated level gauges. Again due to the subdivision, fitting a simple one-point DP system was not necessarily the answer. As it was not fully resolved in CAH 01, though it was understood and could be catered for, I would ask if any modifications were carried out for 02 and what the in-service experience has been?

Basin trials

The fact that we could achieve higher rev/min, though less load, in the dock with hack propellers did indeed enable us to carry out all manoeuvring operations covered in Fig. 9 prior to going to sea, with obvious benefits. It should be noted that single-shaft running to limited powers in coupling drive was also possible.

CSTs

Item 3 was much simplified by a dockside test devised by Rolls-Royce, which allowed the engine to run with full-power fuel pressure at low powers. This meant that much of the setting-up normally done at sea could be done alongside.

One of the many interesting trials carried out was a repeat of an STF trial to monitor the main gearwheel attitude in its bearings following the modification, theory and test results being vindicated.

It would be interesting to know how close the whole YARD simulation was to the ship (or vice versa?) at the end of the day.

Problems encountered

With respect to the final drive pinion bearing failure, it is interesting to note that, for all the computer analysis, 'a thou per inch and one for the chief' still appears to hold good.

The primary pinion bearing problems were due entirely to incorrect assembly, the design problems which resulted in overheating on shore trials having been cured by a small increase in clearance and a groove in the top half to increase the cooling oil flow.

A further problem was that, while running for lengthy periods astern, the SW pumps became aerated and suction was lost; this involved the trials team in much effort and speedy work to keep enough pumps adequately vented to maintain the required supply of cooling water. It would be interesting to know how the ship's staff have managed under these circumstances, which were somewhat unusual, I suppose, in that one does not often go full astern for 15 minutes plus.

At the risk of going on too long, I must say again how much I enjoyed this paper and the opportunity it afforded to meet old friends from both shore and ship trials; a little older and, in some cases, a little rounder, but still the friends I knew before. I wish that more had been able to attend.

DR J. F. SHANNON PhD, BSc, CEng, FIMechE, MIES: The design of the gearing is straightforward but it gives only one pinion for the final direct ahead drive. A development on this would include a straightforward clutch, forward of the ahead hydraulic coupling, connecting pinions E and D through the quill shaft, thus giving the two pinions D and R driven in locked train for the direct ahead drive.

This would reduce the size of the gearbox considerably. An example of this is given in my book *Marine Gearing* (Institute of Marine Engineers), Figs 12.5a and 12.5b ('Marine manoeuvring gear twin gas turbine input').

The size of gearbox may not be so important in a ship of this Class, so this may be the reason for the simpler system—as shown in Fig. 5, 'Diagrammatic arrangement of CAH gears'—with the single final direct ahead pinion.

Authors' Reply

To reply in full to the many varied and interesting issues raised by the contributors could justify numerous papers in their own right. For this and, of course, security reasons, we apologize to the contributors if some answers are not as detailed or complete as they may wish.

Many of the contributors have questioned the basis on which the *Invincible* machinery package was conceived. It is, however, interesting to note that each contributor then proceeded to offer their ideas of better arrangements, which included steam, electric and diesel propulsion options, locked train or epicyclic gearboxes, reversible fluid couplings, etc. Many claims were made in support of the alternative options but we do not consider this the correct forum to discuss these claims.

However, we should like to reiterate that many machinery options were investigated in great detail and feasibility studies were carried out prior to MOD making the final decision in 1969. These included various arrangements of steam, gas turbines, diesel and electrical propulsion. No doubt the final decision was not taken lightly and the arrangement selected was considered by MOD to be the best combination of components available at the time, or likely to be available in the not-too-distant future, which would meet the many aspects of the Naval Staff Requirements for the overall ship.

Possibly with the many advances in technology in the past 15 years the decision, if taken now, might be different from the original. The proof of the pudding must be in the eating and the bold decisions taken in 1969 have been fully justified by the performance of *Invincible* to date.

In answer to Mr Duggans's comments, although it is accepted that the gearbox is very large and heavy, there is little doubt that the present arrangement produces a larger power/weight ratio than any of the other realistic options available at the time would have done. It is possible with the advances in technology that a smaller reversing gearbox could be produced today. In saying this, it has still not been proved that a smaller gearbox could be manufactured to transmit the power, provide the performance and achieve the high availability of the present design. The performance of the *Guiseppe Garibaldi* gearboxes will be awaited with much interest by many and, hopefully, will be the subject of a future Institute Paper.

An epicyclic gearbox was one of the options considered in 1969. Unfortunately, we are not in possession of the detailed analysis of the gearbox options considered but it is understood that one of the major problems was in developing the brake required to give the epicyclic gearbox its reversing capability.

With reference to the number of diesel generators, the remark 'galloping hardware' is totally unjustified. To provide the high integrity of electric supplies required by a warship, it is better to provide numerous generators dispersed around the ship. Gas turbine generators were considered; but a suitable British unit was not available.

It is interesting to hear of other people's experiences with coupling cooling but, on *Invincible*, the main concern was not the power loss (the STF showed the maximum total gearing loss to be of the order of 4% whilst for a similar reduction gear without couplings 3% would be expected), but the temperature in the region of the 2.2 in long torque tube and its effect on the membrane couplings. The provision of aluminium finned covers on the primary line on *Auris* would seem a very sensible modification and would certainly have improved matters on *Invincible*.

The initial seal design at the STF did cause problems as it was not capable of handling the gearbox-to-shaft relative movement. A redesigned seal was fitted and has proved totally satisfactory to date.

Loss of oil to ahead coupling is most unlikely, as the oil supply system is a high-integrity system with alternative electrical supplies instantaneously available to the lube oil pumps. When manoeuvring, and when couplings are being selected and filled, the gas generators reduce to idling. Until the control system registers that the selector valve has moved and the coupling has filled to a limiting figure, the engines will not receive a signal to reaccelerate to the required speed.

The rate of opening of the throttle on the engines is dictated by the control system and is set to avoid $T_{\max}$ being exceeded, among other things.

We would have liked to provide further information but detailed performance parameters are classified.

Experience to date suggests that the spray eliminators have worked extremely successfully under some very trying conditions and an examination of a replaced gas generator after 4000 hours of running has not suggested otherwise. We are not aware that there is any restriction on which engine is run, in connection with sea conditions or wind direction.

The remarks made on reliability studies are agreed but it is better to try, and have partial success, than not to try at all.

In an ideal world it would be the time to take the experience from *Invincible* and design the next generation of ships for the 1990s; but, until a requirement is forthcoming, no action will be taken.

We thank Mr Duggan for his comments which show that, although retired, he is in touch with today's marine engineering problems.

It must be very gratifying for the courageous decision-makers of the late 1960s to hear these comments from Cdr Ridley, the first ME Officer.

It is agreed that Fig. 15 is misleading. The speed axis starts from -12 knots.

The procedure described by Cdr Ridley to avoid excessive torque during turns is sensible from an operational point of view but preparation of the rudder limits on trials was to let bridge and ER staff know of the effect of turns if the throttles are untouched.

We thank Dr King for giving the state of development in the years when the design was finalized and illustrating how little experience of gas turbine propulsion was available at that time.

Regarding dynamic simulation of manoeuvres on the STF, this enabled changes to be made to the control system well in advance of ship completion. Contractor's sea trials (CSTs) did prove that actual ship performance can never be 100% simulated on shore trials.

There have been some reports of minor fuel contamination by bacteriological growth but it has not been a problem and is much less than that experienced with sea-water displaced fuel systems.

The reply to Mr Duggan's question on air intake filtration covers Dr King's question on this subject.

In reply to Cdr Langman, we are not aware that any attempt has been made to quantify the costs of correcting the deficiencies found at the Shore Test Facility. It would be extremely difficult to do, particularly in qualifying cost in relation to delays in completion of a warship or carrying out repairs against, say, a merchant vessel where each day out of service represents loss of earnings.

To have found some of the faults during *Invincible*'s CSTs, rather than 6 years earlier on the Shore Test Facility, would also have affected the other two ships in the Class, one of which had been launched and the other was on the building slip.

If the main wheel bearing problem had not been found on the STF, the cost of correcting this on all six gearboxes could have almost paid for the STF on its own.

It is accepted that actual operating profiles will differ in detail from those used by the designer. As the demands on a warship can vary considerably, the designer must try and extract (from simulation, prototype testing, etc.) the expected performance of the plant at sea over as many operating sequences as he can foresee within the restrictions placed on him, e.g. the limited scope of computer simulations, limitations in the trial installations, i.e. lack of propellers and ship effects, time available and finance available.

There is no question that the main propulsion plant was put through almost every conceivable operating sequence likely to be seen by the ship at sea and within the limitations mentioned above. The results helped to validate the computer simulations which were then used to predict the plant performance at sea throughout its full operating range. Comparisons of this simulation and the results achieved by *Invincible* have been made and there was reasonable correlation.

We cannot believe Mr Clements' statement that fixed-pitch propellers are 30% more efficient than controllable-pitch propellers when going astern because this must depend a lot on the blade profile and astern pitch. Cdr May's contribution claims a loss of 2% in the ahead direction, which is nearer the MOD's thoughts than 4%. With the gearing losses given in reply to Mr Duggan, the gains for the fixed-pitch propeller are just about balanced by the difference in the gearing losses with the *Invincible* box when compared with a gearbox without reversing couplings.

If the Franco Tosi reversible converter–coupling had been available in 1969 there is no doubt that it would have been very actively considered for use on *Invincible*.

Reference to the Italian Navy helicopter carrier *Guiseppe Garibaldi*, and the quicker application of reverse thrust acheived by the Franco Tosi coupling, provokes one question—will the ship stop any quicker? It would be interesting to compare the performance of the two ships.

The three alternative proposals described by Mr Wright are very welcome for anyone contemplating future designs. Perhaps it is unfortunate that we are not in possession of all the facts and figures relating to alternative design proposals considered during the conceptual design stage.

Referring to the most attractive proposal, Solution 3, we assume that SSS clutches are fitted in each line to transmit direct drive when not manoeuvring.

One of the reasons for triple reduction on *Invincible* is to limit gear-tooth contact stresses to acceptable values, so it is surprising that a double reduction with locked train would overcome the problem with such a big reduction in weight. Note also that the lube oil tank, pumps and contents are included in *Invincible* gearbox weight.

Regarding the comment on R & M ratings, we can only give a valued judgement. The use of conventional, well-tried components will give a higher R & M rating in comparison to untried novel components. However, this will, in part, be balanced by the lower R & M rating given to the conventional box which will have more moving parts.

It was most heartening to hear again, this time from Mr Andrews, the very complimentary remarks made by Captain Livesay about the plant.

The point raised on the stiffness of the machinery supports is well made. The importance of the provision of adequate support in the area of forward plummer bearing, thrust block and gearbox cannot be overstressed, because very small relative movements can have catastrophic effects.

The reference to upkeep by exchange presumably refers to the machinery removal routes which are unequalled in any other RN ship.

In reply to Cdr Ranken, steam turbine propulsion is standard for nuclear-powered submarines simply because there is no true alternative. This in obviously not the case for surface ships.

The value of 112 000 SHP is incorrect—the true figure is somewhat less.

Detailed description of the gas turbine was consciously omitted from the paper as there is already a great deal of published information available on the Olympus TM3B. The performance details requested were not included as some of the information is classified.

In addition to the general comments made earlier in the reply about alternative machinery options, we would add that the effects of the machinery on the overall ship design is one of the inputs in the machinery selection process. The effect of the ducting on the hangar size must obviously have been acceptable to the ship designer.

The MOD's early experience with controllable-pitch propellers is somewhat different from that indicated by Cdr Ranken, although design changes have now overcome the initial problems.

It was the original intention to include auxiliaries in the paper but this was not possible due to limitations on length. We prefer not to enlarge the scope of the discussion by introducing details on the auxiliaries. There is no doubt that the auxiliaries would provide an excellent subject for a later paper. Suffice it to say that we agree completely with Cdr Ranken on the importance of auxiliary equipment to the operation of the ship. It is for this reason that any new range of equipments undergoes extensive type testing and this includes shock testing. Type testing is designed to find any weakness in the equipments so they can be put right on the units for ship. There are bound to be failures and many of those that occurred during shock testing were relatively minor. All the shock-tested units were subsequently repaired and are now used in various applications. There were no catastrophic failures.

Being a much larger ship than any recent ship design, the demands placed on the auxiliaries are totally different to any recent MOD experience. This is the major reason for the selection of non-standard units, e.g. the evaporators, boilers, diesel generators, stabilizers, steering gear, air conditioning units, hydraulic pumps, aircraft lifts, main pumps, e.g. lubricating oil, sea water pumps, avcat pumps, etc.

The question on shaft-driven generators was raised by Cdr Ranken and was replied to in Ref. 1. We have no further useful comment to make.

Almost all the engine auxiliaries are driven directly from the engine. The major gearbox auxiliary is the main lubricating oil pumps and as these are often required when the gearbox is not rotating, e.g. when warming through prior to running, removing residual heat from the gearbox components on shutting down and, of course, flushing, it would be inadvisable to drive them from gearbox or shafting.

Cdr Ranken's remarks on the Shore Test Facility are not disputed. It may help to note that the engines, gearbox, ducting and thrust block have all been used on the sister ships. The dynamometer has been sold for use in another application and many of the other components and test equipment have been snapped up by various research bodies. The test house is again being used by Rolls-Royce.

The remainder of Cdr Ranken's prose raises wider issues which we are unable to comment on as we are not privy to much of the information that Cdr Ranken appears to have available.

Having discussed the question of noise comparison of fixed- and controllable-pitch propellers with our colleagues, the views expressed by Cdr May are fully supported. This has only recently been accepted by all parties. Apologies to Cdr May.

We are pleased to be considered by Mr Bunyan as 'comrades' and agree that the paper can be considered as a diary of events, as we were just completing our apprenticeships when MOD(N) were 'sticking their necks out'.

It is correct to say that noise directed upwards is more acceptable than noise directed laterally. Considerable attention was given to this subject, for ship habitability reasons, by providing intake and uptake absorption silencers and lagging of the ducting. This was very successful and at all powers, including full power, normal conversation on the flight deck is perfectly feasible—weather and aircraft permitting!

The problem with the bull gears is one of misalignment and compliance, the gear shaft being a one-piece hollow shaft with diaphragm plates bolted to flanges. The question of rigidity is relevant but tests conducted at Ansty suggested that there is some thermal distortion of the gear case, as there must be in such a large structure. The detailed solution to the problem is Messrs David Brown's copyright; but, if a paper is prepared on 'Marine bearings', as suggested by Mr Sutcliffe, this would be a classic example to include.

Regarding the basin trials, one has only to be in the control room to see the complete control of the machinery; and running one shaft ahead and one astern proved perfectly safe.

The 'hack' propellers were a necessity, to move the ship from Barrow to drydock at Greenock, but it was an added bonus that they could be smaller than the ship's propellers and allow the greater range of trials to be completed.

Reference to finite element analysis of thrust block seating compared to actual results is very topical and suggests that 8 years ago the results of a finite element analysis were not very accurate. We have more faith in this type of analysis today.

Use of Morgrip bolts and Pilgrim nuts does assist installation but lessons were learnt the hard way: that their fitting requires closer tolerances and higher technology. The Morgrip bolts can easily be over-pressurized, with potentially lethal results, and fitting the propellers by Pilgrim nut is very dependent on a very consistent standard of cleanliness for the shaft and propeller.

In reply to Mr Nicholas, we do not wish to add further to our opening comments on the claims and counter-claims made for alternative propulsion options for *Invincible*.

There is no question that the Shore Test Facility costs were considered when making the original decision. As stated previously, we have no doubt that the STF has paid for itself. Mr Nicholas seems to assume that if a steam plant, either nuclear or oil fired, had been selected, no STF would have been necessary. We suggest this is an incorrect assumption when one remembers the Boiler Test Facility at Haslar, the Submarine Prototype Reactor Plant at Dounreay and the Submarine Installation Test Establishment at Barrow.

When comparing manning levels one must not only consider the requirement for watchkeepers but also the requirement for maintenance/repair. RN and merchant ships differ greatly in the latter requirement due to operational profiles and support availability. We believe that a steam ship is likely to require more operators than the *Invincible* gas turbine installation.

The word 'absurd' is somewhat strong when discussing Fig. 15. The text clearly states that a direct comparison cannot be made for the various reasons quoted and claims no more than '*Invincible* compares favourably with *Hermes*'. *Hermes* was used to give some dimension to the vertical axis, as the actual figures are classified.

Finally, the point regarding shock superiority of steam turbines is very suspect, as the light aero-derived gas turbines benefit from being able to be resiliently mounted as on *Invincible*.

The remarks made previously on the alternative propulsion options also apply in response to Mr Crook's comments. The question raised about ship speed is outwith the scope of this paper but it should not be forgotten that the ski jump was not available until well after the ship started building. The bow thrusters allowed by Mr Crook's alternative propulsion option would be a very welcome luxury.

It was interesting to hear about USS *Lexington*'s secondary role. With 'tongue in cheek', possibly the MOD should involve the CEGB in future warship design to ensure compatibility with the grid.

Coming from one of Mr Rogers' colleagues, Mr Sutcliffe's question is raised because, after his close involvement with the whole project, it is his view that either engineers have forgotten how to design bearings, or correctly designed bearings are expected to take up excessive misalignment of the journal or thrust collar.

The major failure at Ansty was solved by increasing the stiffness of the gearshaft and introducing 'compliance' into the bearing. The thrust block, however, performed well under a misaligned condition because the flexible shafting has enough 'compliance' to absorb most of this but the tests at Michells proved that their tilting pads can absorb a large proportion in the oil film, even though heavily loaded.

We agree that an updated paper on 'Marine bearings' would be useful, with particular accent on what misalignment the bearing will stand, based on full-sized tests and not merely theory.

It is pleasing to see that another colleague of Mr Rogers, Mr Rowntree, has put pen to paper to explain some of his experiences with testing and commissioning at the STF and during contractor's sea trials.

The intention of the gearbox mimic would have been very beneficial but the ship's staff have managed very satisfactorily without it. It is to be remembered that, until the limit settings were finally set, a number of different bearing warnings were coming up at the same time and required the mimic to identify which bearings were the cause of the alarms. Now that the settings have been finally set, if the alarm comes up it is usually associated with only one bearing.

The intake bypass doors have not been called upon in service so they have caused no problems. The need for automatic bypass doors is being actively reconsidered by DG Ships.

Although, to date, an engine change has not been carried out at sea, the ship's staff have been more than pleased with the 'maintainability'.

The question on fuel tank level indication during RAS would seem to have been overcome on *Illustrious* by improvements to the limber holes in the tanks.

The problem associated with aeration in SW pumps has been fully overcome by improved venting arrangements in the sea inlets.

Dr Shannon's proposal to resite a straightforward clutch, forward of the ahead coupling, connecting pinions E and D through the quill shaft, thus giving the two pinions D and R driven in locked train for the direct ahead drive is very interesting. It is assumed a friction clutch is what is meant by the term 'straightforward' and the specialist DG Ships Gearing Section have little confidence in friction clutches at this time.

We would question whether this arrangement would retain bumpless change of drive mode; and if it would make a noticeable change in gearbox size.

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