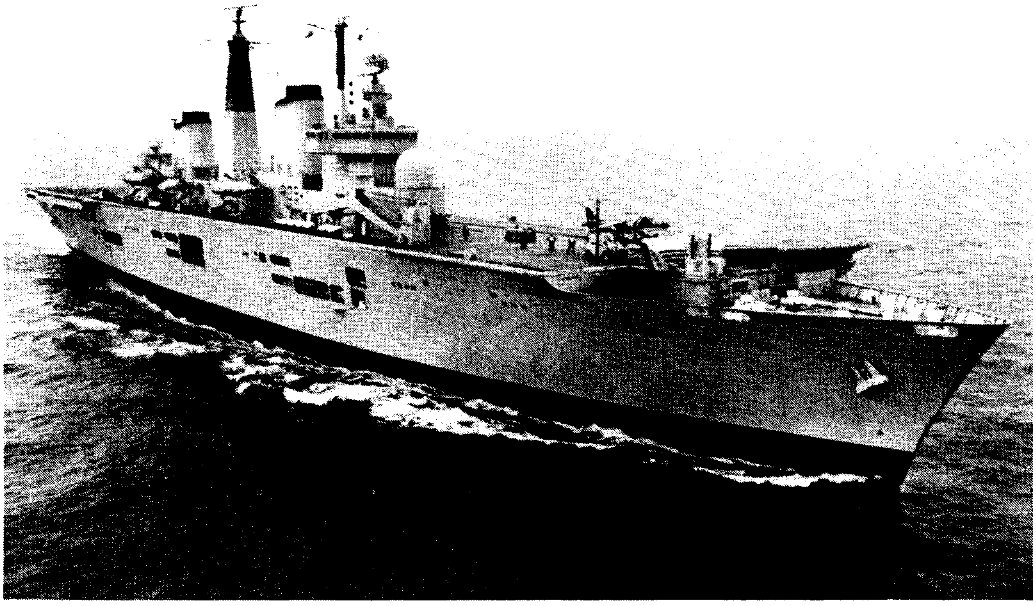

FIG. 1—H.M.S. 'INVINCIBLE'

H.M.S. 'INVINCIBLE'

THE MAIN PROPULSION SYSTEM

BY

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Introduction

Formally commissioned by Her Majesty the Queen in the summer of 1980, H.M.S. *Invincible* became fully operational in June 1981 after fifteen months' sea trials under the White Ensign.

In Reference 1 the ship was described as an anti-submarine cruiser. Five years and innumerable photographs like FIG. 1 later she has at last been officially recognized as an aircraft carrier. Hopefully the Royal Navy has at last been allowed to sink without trace the political euphemism 'through-deck cruiser'.

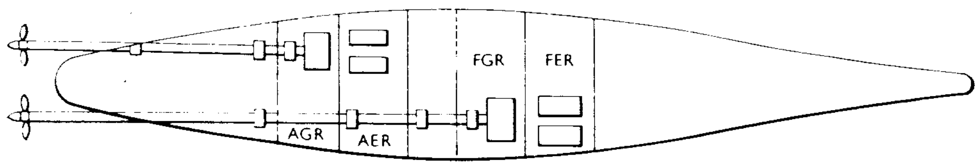

FIG. 2—MAIN PROPULSION SYSTEM

Gas Turbines

The new aircraft carrier is a ship of about 19 000 tonnes, though with her relatively light scantlings and voluminous uncluttered internal design, she looks and feels much larger. She is fitted with two shafts, each fixed-pitch propeller being driven by two Rolls-Royce Olympus TM3B gas turbines in a COGAG configuration through a reversing gearbox (FIG. 2). The Olympus power turbines are connected to the gearbox by torque tubes and flexible couplings of the membrane type.

Main downtake and exhaust ducting arrangements are shown in FIGS. 3 and 4. Inevitably systems have to be longer and more tortuous than previously experienced in the R.N. and their complexity has been aggravated by the need for all four exhausts to be concentrated into two funnels in the island on the starboard side.

Intake air is taken from both sides of the ship at 1 and 2 deck level. For each individual gas turbine it passes in succession through a chevron-type spray eliminator, a fibrous pad salt eliminator and a second spray eliminator that collects any droplets breaking away from the second stage. The air speed in this initial section has been kept down to 8 metres per second, so openings in the ship's side are large. There follows a square-sectioned silencer fitted with flat-plate splitters (maximum speed 60 metres per second) before the ducting changes to a circular shape of 1·8-metre diameter to guide the air into the compressor. Right-angled bends in the downtake are cascaded to smooth the airflow, as are those in the 1·8-metre diameter uptake. The exhaust system includes bellows in both horizontal and vertical legs and supports arranged to take up the thermal expansion and isolate noise from the ships structure. The uptake silencer is 2·3-metres square and is fitted with portable flat splitters designed for easy removal.

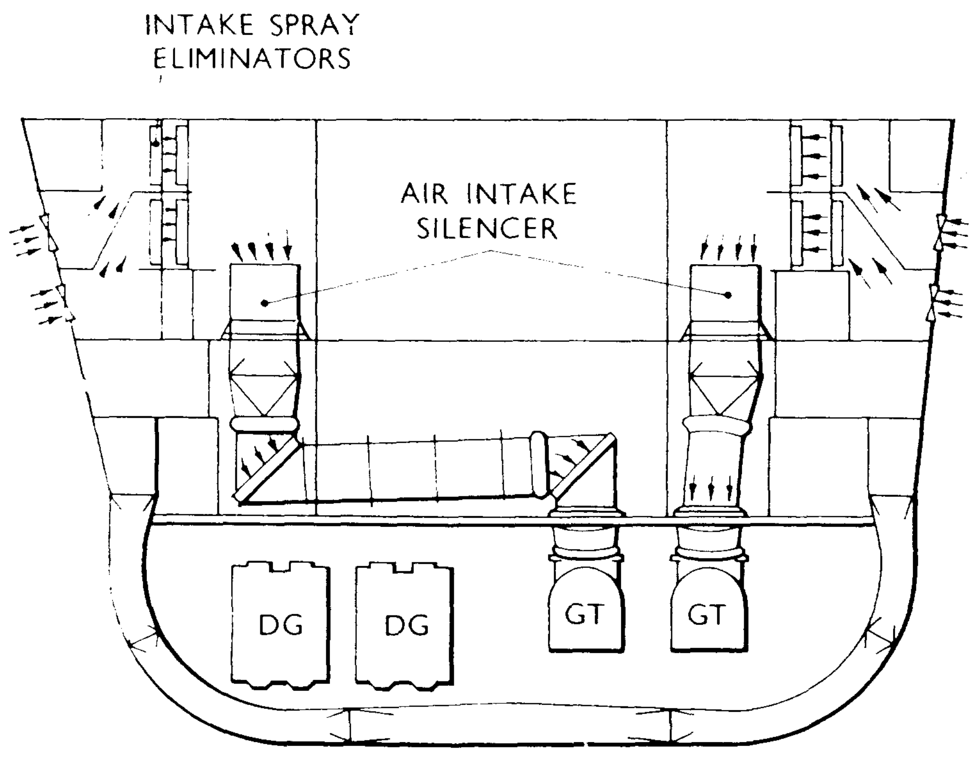

FIG. 3—GAS-TURBINE INTAKE ARRANGEMENTS

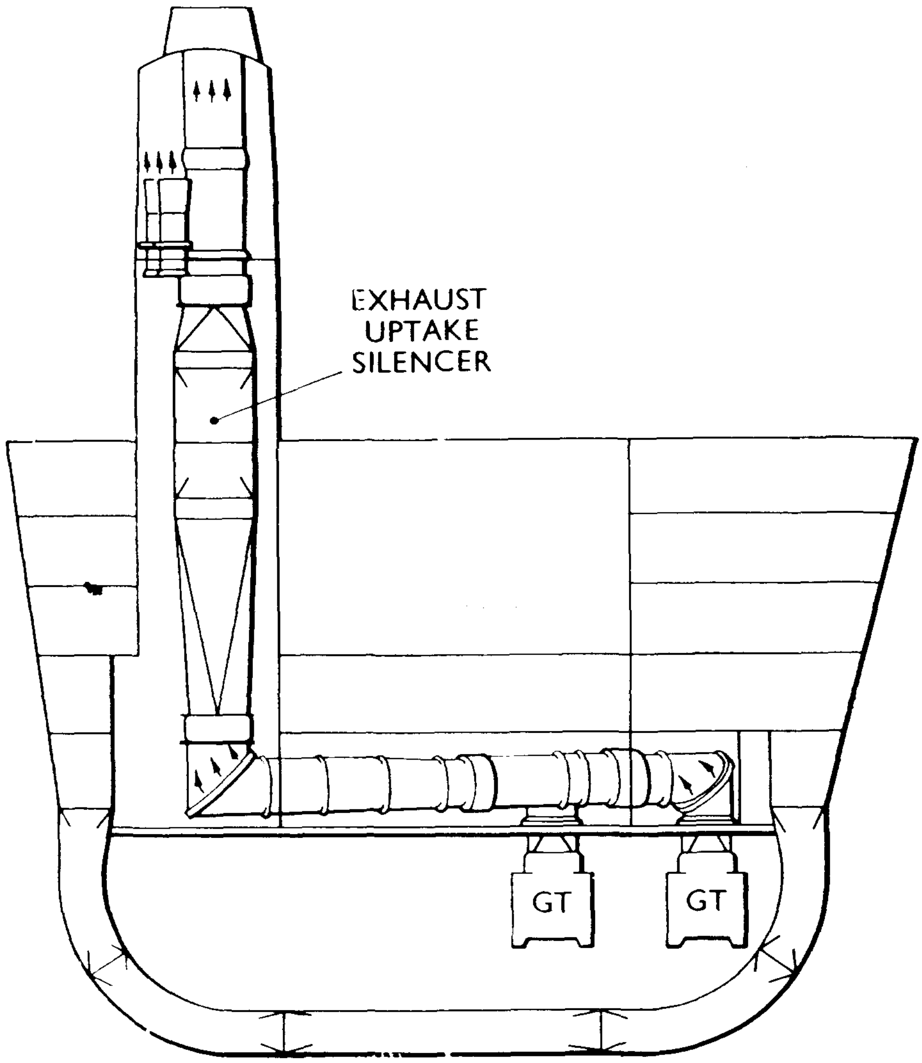

FIG. 4—GAS-TURBINE EXHAUST ARRANGEMENTS

Gearbox

The layout of the gearbox is shown in FIG. 5, which represents the train of wheels between one gas turbine and the main wheel. Both power turbines on each shaft turn inwards so that, with triple reduction, the propellers turn outwards.

Except when the ship is stopped in the water, all the wheels and pinions in FIG. 5 are rotating continuously; the type of drive is varied by choosing the means by which power is transmitted from the second to the third stage. Three drives are available, ahead 'coupling', astern 'coupling' (both known as manoeuvring drives) and ahead 'direct'.

Ahead or astern manoeuvring drive is achieved by filling the appropriate fluid coupling whilst emptying the other. Couplings are double circuit and take about 20 seconds either to fill with oil or to be emptied by scoops. The maximum power that they can transmit is limited by the heat generated by slip and for higher ahead powers direct drive has to be employed. In earlier generations of R.N. warships, such drives were engaged manually, with ships stopped in the water. In H.M.S. *Invincible* the change from coupling to direct is carried out whilst underway; the transition is smooth, with the briefest plateau in acceleration. Once 'direct' has been selected by the watch-keeper in

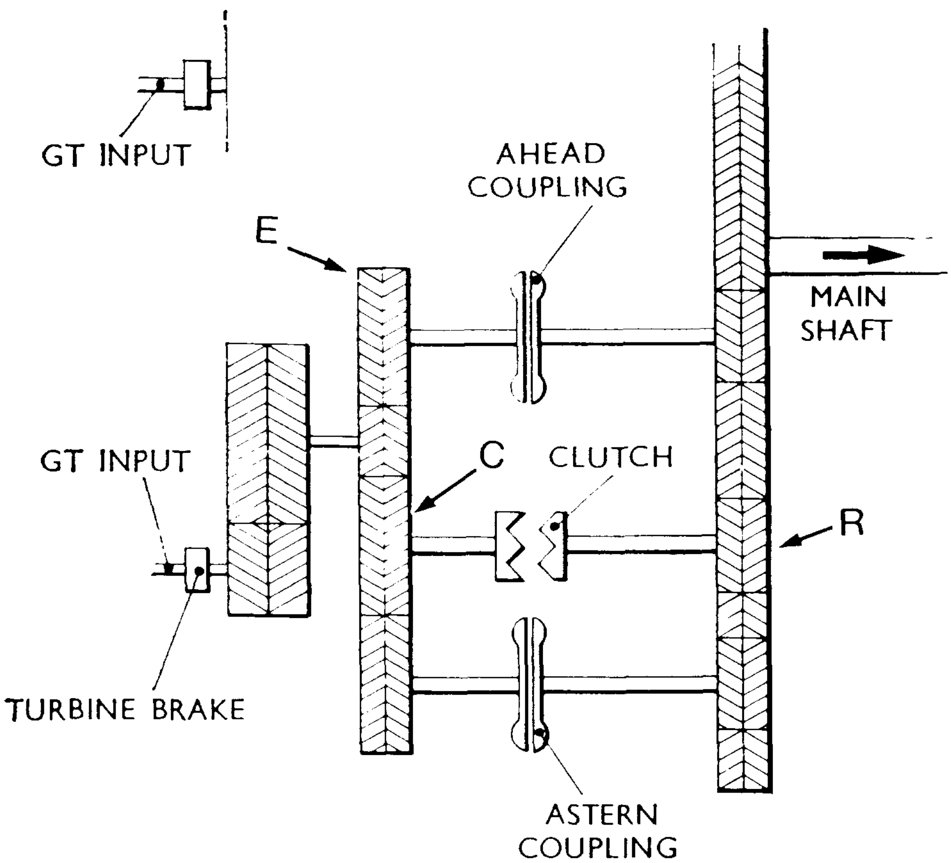

FIG. 5—GEARBOX ARRANGEMENT

the Ship Control Centre, the SSS clutch is moved to the ratcheting position, awaiting the speeds of its input and output shafts to be matched. The ahead scoop moves in to start emptying its coupling, which begins to slip. This means that the speed of the main shaft and its associated wheel and pinions (including 'R') will increase more slowly than that of the secondary train. But as it has 11·8 per cent more teeth than the secondary coupling wheel (E), the secondary ahead wheel (C), and hence the SSS clutch input shaft, is already turning more slowly. As power is increased the speed of the clutch input shaft rises towards that of its output shaft (driven by wheel R) until a happy union occurs, with the SSS clutch engaging as the ahead coupling empties. Electrical interlocks in the control system and, failing them, a mechanical baulk ring prevent the clutch trying to engage if the relative torques and speeds of its input and output shafts are incorrect.

The change from direct to ahead coupling drive merely reverses the process, a brief application of the turbine brake (known as the 'transient' brake) decelerating the high-speed line to give torque reversal if necessary during a particularyly energetic manoeuvre.

The two gearboxes are large and of conservative design with comparatively low 'K' factors. In terms of ship stability this is weight in the right place, occupying an area of the ship of little use for anything else.

Controls

Main machinery can be controlled:

(*a*) from the bridge (or 'compass platform');

(*b*) from the ship control centre (SCC) on 6 deck;

(*c*) from a local control panel sited between the two gas turbines;

(*d*) manually.

The first two rely on electrical control signals to the local control panel, from which divertor valves for filling couplings, scoops, and clutch operating cylinders are actuated hydraulically. Under all normal circumstances the ship is controlled from the SCC which is situated three decks above the main machinery deck plates in the ship's section between the two units (FIG. 2). The SCC also contains the primary electrical control console and the NBCD headquarters. Machinery compartments are unmanned, although they are visited hourly by touring watch-keepers, and all main machinery operations, starting and stopping of gas turbines, changing of drives, manoeuvring and power alterations are conducted from the SCC.

Operational Statistics for the First Year

1. Number of sea days	150
2. Distance travelled	34 000 miles
3. Proportion of seatime single shaft running (one engine)	25 per cent approximately
4. Proportion of seatime on all four engines	9 per cent approximately

Note: The percentages in lines 3 and 4 are untypical. As the whole year was given up to trials, the ship spent an abnormal proportion of its time at higher speeds. More typical peacetime figures are expected to be 35 per cent. and 4 per cent. respectively.

Overall Performance

Throughout the first year of the ship's life the main propulsion system has worked splendidly. Targets for ship's speed and endurance have been achieved comfortably and with sufficient leeway to suggest that they will remain attainable throughout the life of the ship. The Combined Gas and Gas (COGAG) concept employing four equal-sized engines matches flexibility with inherent redundancy and ideally satisfies the demands of a warship in general and a VSTOL aircraft carrier in particular. The gas turbines, the gearboxes, and their associated control systems are exceeding all expectations for performance and reliability.

Reliability of the Olympus

As can be seen from TABLE I, between them the four Olympus gas turbines were started a total of 916 times during the first year at sea. Two starts only were failures, one as the result of a failed starter motor and the other due to a defective diaphragm in the constant pressure valve in a control system. Both defects were repaired at sea by ship's staff in a matter of hours and neither affected the ship's operational programme.

Starting reliability is particularly important as the greater the confidence in the system the greater the possibilities for fuel economy. More than half full ship's speed can be obtained with one engine on one shaft (with the other trailing) and 4/5ths is available in the cruising state with one engine per shaft. FIG. 6 demonstrates the additional endurance available through operating with as few engines as possible. Naturally if a fixed passage speed has to be made good, there is little latitude in the number of engines that can be used. However, much of the time at lower speeds is spent in situations where traditionally the Commanding Officer asks for a greater number of engines than is strictly necessary, either in case one should fail or in case an unexpected demand for increased speed might not be honoured swiftly enough if an engine

TABLE I—*Engine statistics for first year's running*

Column	1	2	3	4	5	6
Gas Turbine	*Hours run (including build period)*	*Hours run in year*	*Starts*	*Average hours per start*	*Failed starts*	*Debris detector reports*
Port Inner (PIG)	1256	755	216	3·5	0	4
Port Outer (POG)	2015	1540	259	6·8	1	0
Starboard Inner (SIG)	1208	717	226	2·8	0	4
Starboard Outer (SOG)	2731	2174	215	10·1	1	3

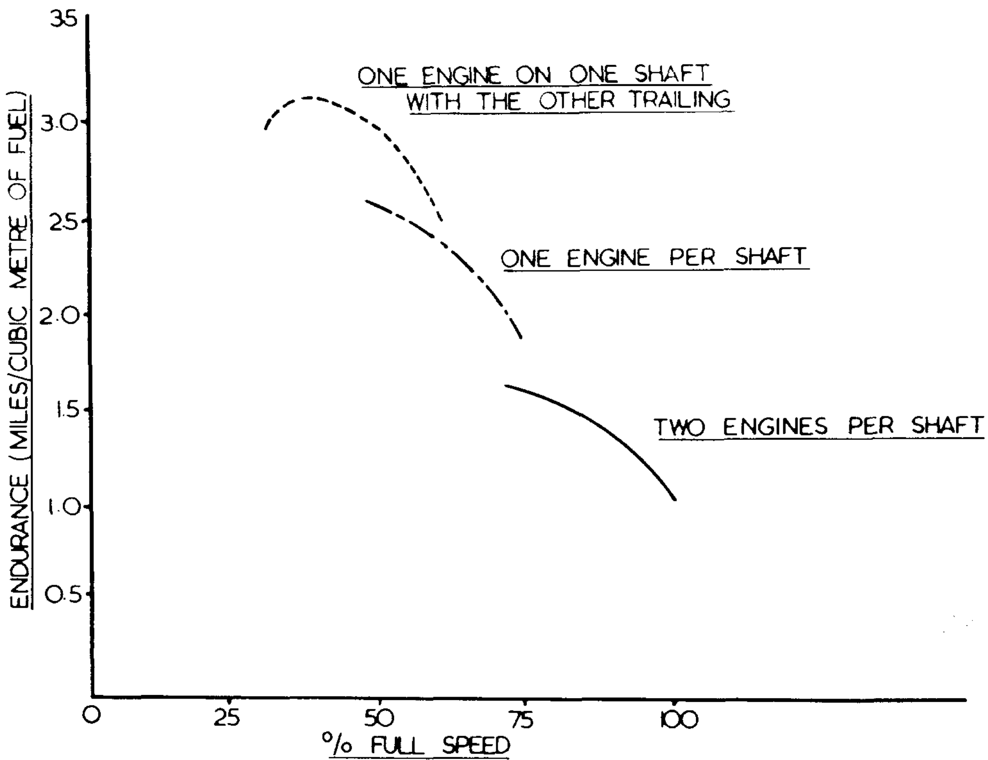

FIG. 6—SPEED-ENDURANCE CHARACTERISTIC

were reluctant to start. For example, in previous carriers, whenever aircraft were in the air or ships were manoeuvring in confined waters, the policy used to be to have all available engines connected. *Invincible* was operated in this way during her first few months in commission, all four engines being run during preparations for sea, for flying, and for entering and leaving harbour. However, since the end of summer 1980, confidence in Olympus starting has grown to such an extent that, conditions permitting, flying operations are conducted with one engine running per shaft. Similarly during preparations for sea gas turbines are run up for trial only if they have not been run in the previous 24 hours—otherwise they are started for the first time 15 minutes before proceeding and, if high speeds are not immediately required, two are shut down as soon as the ship has left the wall. Similarly when going alongside, when the risk of collision if one engine fails is considered the greatest, the second pair of Olympus are started six cables from the jetty and left running 'deselected' in case of trouble. So far they have never been needed.

There is little doubt that as experience grows these policies will be relaxed even further. Helicopters have already been operated with the ship on only one engine on one shaft, and only during fixed-wing flying is it considered that both shafts should be available so that full manoeuvrability is retained in case a Harrier ditches after taking off over the bow.

Thus ever-increasing confidence in the gas turbines has allowed considerable fuel economies, but these are not the only savings. TABLE I, Column 3 lists the number of starts on each engine. It will be seen from Column 1 that the outer gas turbines have been run far more than the inners, with the starboard outer (SOG) leading. This has been deliberately contrived to give the necessary stagger for maintenance and GTCU changes. Provided it is available, SOG is always run before any other engine, and the outer pair of gas turbines is used in preference to the inner. It will be noted that, for the very reason that it is not stopped but left on load whenever a decrease in the number of engines is possible, the starboard outer, whilst it runs the most, also enjoys the least number of starts. The average running hours per start for each engine are given in TABLE I, Column 4. Whether or not this parameter has a greater effect than expected on the number of defects will only be determined later in the life of the engines; initial inspections suggest that it does. It will be interesting to compare the history and condition of the starboard outer with, say, those of the port inner when they become due for overhaul.

Washing and Inhibiting

As in other R.N. ships, engines are washed with water rigorously every 24 hours, usually during the middle or morning watches. In order to minimize the number of starts, it is common in H.M.S. *Invincible* for a gas turbine being washed not to be replaced by the other engine in the same unit for the period of its wash, and the Navigating Officer has learnt to adjust passage speeds accordingly. This even applies when the ship is on one shaft only (the Captain is usually happy for the ship to stop on passage for the hour or so it takes to complete a wash.)

Further refinements to water-washing techniques are being considered by Director General Ships, particularly in relation to the inhibiting of engines. In addition, experiments are being conducted in the Naval Marine Wing of the National Gas Turbine Establishment at Pyestock to determine the feasibility of washing with engines still at idle. This would certainly reduce the overall number of starts, although it is suspected that the likelihood of increased turbine corrosion and damage to the protective coatings on compressor blades will restrict this procedure to use in emergency only, when engines cannot be shut down completely for tactical reasons.

Engines are inhibited with PX24:

(*a*) when at twenty-four hours notice or more;

(*b*) when shut down for a period specifically known to be longer than twelve hours, including routine or breakdown maintenance.

It seems that this combination of washing and inhibiting has resulted in unusually clean engines. Recently after their 3000-hour examination of the starboard outer, Commander-in-Chief Fleet's gas turbine inspection team reported that it looked as if it had done only half that number of hours.

Routine Maintenance

Gas turbines are inspected by ship's staff at 500-hour intervals. Combustion chamber life has recently been extended to 2500 hours on the 'Phase I' type fitted in H.M.S. *Invincible,* although the full benefit of this will not be felt until overhaul lives (presently either 3000 or 3500 hours depending upon the modification state of the engine) reach 5000 hours. Maintenance routines are often carried out overnight at sea, with a 1000-hour routine taking about 16 hours to complete. Whilst this is going on, the top speed of the ship is obviously limited but, with the high speed available on half power, it is unusual for the operational programme to be interrupted. In any case a routine would not be started if a requirement for higher speeds could be foreseen; the maintenance tail should not be allowed to wag the operational dog. Routines are conducted when convenient to the ship, with combustion chamber changes and engine replacements planned into the operational programme as the latter dictates, rather than being carried out the moment that they become due. Of course, the flexibility of COGAG helps considerably, allowing an engine to be used more and more sparingly as it approaches a maintenance milestone.

Gas Generator Changes

Two spare gas turbine change units (GTCUs) can be carried on board in pods, one in each engine room; thus gas generators can be changed when the ship is deployed. With large machinery lifts from each main machinery space opening directly onto the hangar, only one spare GTCU need be carried to serve either main propulsion unit. In peacetime, however, it will be uncommon for spare engines to be carried onboard, and replacements will be delivered from shore in the normal way. Even so, supply and removal routes are much simpler than those in frigates where internal gear in the intakes has to be removed to clear a path down to the engine. In *Invincible,* GTCUs are lowered from a shore-side crane or from a helicopter straight onto a trolley positioned on one of the main aircraft lifts, taken down to hangar level, and wheeled to the top of the appropriate machinery hoist. It is estimated that a practised ship's GTCU team will be able to change a gas generator in less than 36 hours.

Non-destructive Testing

Olympus lubricating oil systems are fitted with magnetic chip detectors (MCDs). These are checked daily for unusual increases, and routine readings are taken at weekly intervals on a debris tester. A set figure has been established for the ratio of the amount of debris to the hours run since the last reading, above which samples must be forwarded to laboratories ashore for analysis. During the first year's running it has been necessary to seek advice eleven times as shown in TABLE I, Column 6, but on no occasion have chips or debris been found to be significant. The most common source of debris has been No. 3 detector, sited after the HP compressor rear and inter-shaft bearings. The first MCD readings warranting further investigation occurred after 460 hours on the port inner.

Operational Factors

Smoke is of particular concern in a warship and even more so in an aircraft carrier when it is vital that conditions on the flight deck should remain tolerable even with the wind in the wrong direction. The smoke characteristics of the early Olympus engines have given rise to modifications to the combustion chambers and H.M.S. *Invincible* is one of the first ships with the new 'Phase I' outfit. From the user's point of view the latter is undoubtedly a success. Vaporous white smoke is still comparatively heavy at very low powers and at idle (another encouragement to use as few engines as possible), but at all other times the level of smoke is perfectly acceptable. Flying operations, which in any case are rarely conducted with the ship stopped or at low speeds, have been unaffected.

Another factor enjoying a considerable improvement is the noise on the upper deck. The silencers and the long uptakes mask main engine noise very effectively and at all powers, including full speed, normal conversation on the flight deck is perfectly feasible, weather and aircraft test runs permitting.

Impact on the Ship's Company

Enthusiasm for the main propulsion plant is widespread. Gas turbines may have been the exclusive means of propulsion in new R.N. ships for almost ten years, but they continue to have a great impact and this has been enhanced by the new COGAG configuration. Of course it is natural for marine engineering staff to be proud of its machinery; morale is high and the spacious machinery compartments are kept clean and well maintained, often wringing gasps of admiration from visitors. There is a strong sense of being 'up-to-date'—of belonging to the Space Age (however remote from the truth this may be). But there is a similar reaction from seaman officers, and the Captain in particular is delighted with the response and acceleration of his ship, the flexibility of her propulsion arrangement and the reliability of its components.

In a perfect world the Captain would like to be able to forget his engines entirely—the intrusion of a rudder or engine limitation into his thoughts during a tricky manoeuvre can be dangerously distracting. In *Invincible,* this ideal is virtually attained. Obviously power is limited by the number of engines in use, but apart from this the entire responsibility for safeguarding machinery, for avoiding torque limitations and deciding when to move into direct or manoeuvring drive, has been delegated to the Marine Engineer Officer of the Watch. Taking torque limitations as an example, in the past it was not uncommon for the Officer of the Watch on the bridge to be confronted with a series of rudder and engine limitations varying with the many available configurations of the main propulsion system. (This was particularly true of COSAG plants). In *Invincible,* the throttle watchkeeper in the SCC assumes this responsibility. If the circumstances are such that over-torquing of the gearbox primary pinions may occur, during a high-speed turn for instance, he keeps an eye on the digital read-out of torque and, if the limit is approached, he fines off on the relevant throttle until the moment has passed. The reduction in speed is usually indiscernible as the ship is more often than not in the middle of a turn, and the Officer of the Watch on the bridge is left free to concentrate on his navigation.

TABLE II—*Comparison of ME department complements*

	H.M.S. *Albion*	H.M.S. *Invincible*
Officers	9	7
Senior ratings	73	46
Junior ratings	172	65
Total	254	118
Percentage of ship's company	27	16

Complement

The effect of the choice of main machinery on the number of men required in the Marine Engineering (ME) Department is shown in TABLE II, which compares H.M.S. *Invincible*'s ME complement with that of H.M.S. *Albion,* a steam-powered light fleet carrier (now scrapped) of similar size and fighting capability. Some of this saving is the result of the absence of flight-deck machinery, particularly steam catapults and arrester gear. Nevertheless, a significant reduction has been possible elsewhere, and it has not been achieved at the expense of a corresponding increase in skilled maintenance staffs ashore. As explained above, major routines can be conducted comfortably overnight at sea with the other engine in the unit driving, and the ship runs its own team for replacing gas generators, rather than joining the frigates in relying on specialist teams in Fleet Maintenance Groups.

Breakdown Drills

If maintenance routines have been streamlined, then so have many of the other ME activities on board. Breakdown drills, for example, exercised two or three times a week have been greatly simplified. Long forgotten are the complicated evolutions safe-guarding machinery after, say, a leaking tube in a boiler or the loss of a main feed pump. Apart from a number of basic exercises associated with the loss of lubricating oil pressure, most drills concern control failures, involving practice in changing from remote to local control at the panel between the main engines or ultimately to manual control when clutches, scoops, and throttles are all worked individually by hand. At first, the last evolution was a hair-raising exercise—a wrong move on the gearbox can have drastic results, both on the machinery and on the career of the Marine Engineer Officer—but, after a few nail-biting practices in slow time, confidence and team-work have waxed and a competent watch has been established, fully capable of manoeuvring the ship in and out of harbour in manual control. For the last, each operating position is manned by a senior rating with a head set, and the whole process is co-ordinated by an officer, positioned not unlike an orchestral conductor at a vantage point in a central position in the gear room, passing directions to personnel over the machinery space communications loop.

Fire and Damage Control

Another drill regularly practised is a 'fire' in a gas-turbine module. The scenario usually opens with an exercise for the ME watch alone as they activate the BCF gas system that drenches the module. For the sake of the exercise, if not of realism, this fails to put out the 'fire', which spreads into the machinery space itself through a door carelessly left open by a watchkeeper (again an unlikely event as lights and interlocks in the SCC guard against such indiscretion). The ship's standing sea fire party are called out but are beaten back, usually leaving somebody behind 'trapped by flames' (a role eagerly sought by extrovert youngsters who enjoy acting out their panic over the main machinery broadcast and being hauled up ladders strapped in a stretcher). The high-level seawater sprays in the engine room are switched on as a team in breathing apparatus and fire-resistant fearnought suits fight to reach the unfortunate victim. Meanwhile the ship has gone to full emergency stations, the 'fire' is spreading throughout the uptakes, aircraft in the hangar are endangered, NBCD headquarters has to be evacuated, and there is a flood in the port plummer-block space. All problems, however, are magically resolved in time for dinner!

It is easy to be facetious about such evolutions but the tragic impact of fire is suffered all too often by every Navy in the world; and in *Invincible*'s first year alone four real fires occurred (rather less than average for the size of ship). None were associated with the main propulsion plant however, and there can be little doubt that a gas turbine in a module with a serviceable gas-drench firefighting system is one of the safest units available.

The extent of the remote control from the SCC ensures that there are no restrictions to machinery operation when the ship is closed down during nuclear, biological, or chemical attack and, provided the machinery block remains undamaged, full manoeuvrability is retained. Flexibility is improved further by emergency ducting that switches machinery space ventilation to recirculate through sea-water coolers, so that all areas in the machinery spaces outside the gas-turbine and diesel-generator modules remain uncontaminated. Rounds and machinery repair are thus possible with the minimum danger to personnel.

Automation

One topic that remains the subject of frequent and heated debate at all levels is the proliferation of automatic control. The ME complement, in common with all others in the ship, has been pruned to the minimum required for ship's husbandry, maintenance, damage control, and safety. Evidently the smaller the crew the greater the case for automation, but if men are to continue to go to sea at all then it is essential that they should continue to enjoy a measure of personal job satisfaction, an elusive parameter that is particularly vulnerable to the insidious spread of automation. The stage is now fast being approached when it will be found that any further growth in the amount of automation not only is no longer cost effective but also undermines morale and ultimately overall efficiency. Of course this situation is not peculiar to the Royal Naval—it confronts workers and management in nearly every field of technology—but its effect is never felt more acutely than in a warship at sea where facilities for leisure are comparatively limited. The following are two examples of what might be regarded as unnecessary over-sophistication.

Integrator

For a given lever position, this device automatically 'closes the loop' on speed by sensing main shaft revolutions and adjusting engine powers to counteract fluctuations due to variations in sea conditions and the heel of the ship. However, the throttle watchkeeper himself is always present to make speed adjustments and can do so with an alacrity which, whilst not as sensitive as that of the integrator itself, is perfectly acceptable to the Captain. In any case in peacetime it is not possible to do away with the throttle watchkeeper—it is an essential post, being the only one suitable for a young artificer or mechanician training for his Marine Engineering 'Unit' Watchkeeping Certificate. Use of the integrator removes much of his responsibility, making it more difficult for him to concentrate on his machinery and systems.

Bridge Control

In *Invincible,* remote control of the main engines from the compass platform is viewed with suspicion by seamen and engineers alike. There seems little operational advantage for the not inconsiderable financial outlay. Under normal circumstances when he is positioned by the central compass pelorus, the Officer of the Watch can just as easily pass engine orders on the broadcast system to the SCC as to the Quartermaster at the engine control console beside him. In a close manoeuvring situation when it might be an advantage for the OOW personally to drive the ship like a picket boat, he is unlikely to want to remain by the central console from which the view is very restricted; thus for bridge control to be useful at all, a second expensive control position is required on the bridge wing.

From the marine engineering point of view, bridge control is a positive disadvantage. Once again the watchkeeping post in jeopardy is that of the throttle watchkeeper (the sole billet for artificers under training) and if a rating has to be retained in this position then the point of bridge control is largely lost. If a man is not saved, the principal argument remaining in its favour is that it cuts out one step in the communication chain, giving one thing less to go wrong in an emergency. But it achieves this only at the expense of an additional complex control system which itself must be equally vulnerable. Finally, and perhaps most importantly, there is a full professional team in the SCC, headed by an officer or a chief artificer. If they are to monitor the performance of their machinery correctly, they must know precisely what is being demanded of it at all times. They need the umbilical cord attaching them to the machinery itself which personal control of the main engines provides.

Upkeep by Exchange

One of the two Olympus defects mentioned above was a pinhole in a small diaphragm on the constant pressure valve (CPV) in the high-pressure shut-off cock (HPSOC) on the fuel system. As a spare diaphragm was not held, a jury one was fitted until a proper spare could be obtained. It was quickly discovered that, to obtain this tiny item costing only a few pence, it was necessary to order not just a spare diaphragm, nor even a CPV, but an entire HPSOC. It is natural to assume that the man at sea wants life made as easy for him as possible. The truth is that all men at all levels are eager to practice their trade and may well become disenchanted if the opportunity is denied to them by a blanket upkeep-by-exchange maintenance philosophy. The omission of basic technical drawings can be a similar discouragement to self help and great care has to be taken to achieve a cost-effective balance between manpower and support without destroying job satisfaction.

For a variety of reasons a warship has to be manned, particularly in peace-time. In the extreme, it is possible to envisage a ship that has on board merely its Captain and his steward, who would also lower the lifeboat in an emergency. But how can that Captain be produced without all the intervening rungs on the ladder of experience? If lesser jobs are retained then they must be seen and felt to be useful. In H.M.S. *Invincible,* the balance struck is just about right, but it is believed that further automation will have to be approached with great care unless the way in which ships are employed and manned, and hence the whole character of the Royal Navy, is to be radically altered.

The Future

In a field in which the perfect compromise between cost, flexibility, reliability, maintainability, and fuel economy is never likely to be achieved, H.M.S. *Invincible*'s marine engineers are certain that, for a 20 000 tonnes ship at any rate, their propulsion system provides the most balanced solution. How far the advantages of such a configuration can be translated to other warships must depend on the extent to which the available building bricks match the new staff requirements.

Acknowledgements

The author acknowledges with thanks the assistance of colleagues in H.M.S. *Invincible* and the Ministry of Defence. The views expressed are those of the author and are not necessarily those of the Ministry of Defence.

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