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This report provides a review of the history of marine gas turbines (MGTs) as propulsors for the Royal Navy, and some of the technological extensions that now appear to be expecially promising. Beginning with the Gatric engine in 1943, successive engines are described which, in 1967, provided the confidence necessary for the UK to opt for total MGT propulsion in future naval surface craft. The developments from 1967 onward are briefly summarized, and the current state-of-the-technology is described. Special attention is given to gas generators and their associated ducting systems for

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25 FEBRUARY 1977

UNITED STATES OF AMERICA

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THE MARINE GAS TURBINE--THE UK PROVIDES A CASE STUDY IN TECHNOLOGICAL DEVELOPMENT

BACKGROUND AND SUMMARY

In 1967 the Navy Department of the United Kingdom made what has come to be referred to as the "bold" decision--to go for 100% gas turbine propulsion for all future surface warships. The wisdom and foresight of this decision has since been proven many times over as nation after nation has adopted the gas turbine for their own Navies as well as for export to the Navies of the less-developed but well-endowed countries.

The far-reaching extent of the decision is characterized by the apparent extrapolation of gas turbine application from the supersonic rarefied regime of the advanced jet aircraft to the dense, undulating and salt-laden milieu of the surface ship. Equally impressive was the apparent decisiveness of an act whose impact was of a scope that usually seems sufficient to keep bureaucrats and politicians haggling across several decades and administrations. Thus the UK experience in marine gas turbines (MGTs) holds a certain political as well as technological intrigue, and it was for both of these reasons that I set out to examine the birth, growth, and current status of the technology in the UK.

In some ways my education in these matters has led to disappointment since the decisiveness image is a bit dimmed by the realization that the UK got into the MGT business as early as 1941. The 1967 decision therefore was based on a considerable backlog of experience so that it might better be described as "inevitable" rather than bold. Nevertheless, it has been interesting to uncover the sequence of events, the rationales and the lessons, that led the UK to the 1967 decision and to its position (now somewhat tenuous) of leadership in the MGT field. Today the Royal Navy operates all-gas-turbine destroyers with 50,000 shp and a 4-MW electrical load requiring an engine room staff of 2 officers and 40 rates. In the previous generation of similar steamships it took more than 50 men to keep track of an engineering plant delivering 30,000 shp and 2.5 MW. Engine rooms are no longer characterized by mazes of lagged pipes, hundreds of valves (many of them bearing oily-rag bandages), oppressive heat and noise, oily decks and bilges, and grimy "snipes" making up the infantry in the war of man against machine. High technology has finally reached the engine room, making the crewman a technician and putting the deck officer in almost immediate control of his propellors. Operational and maintenance improvements are equally significant. The advent of the MGT, largely due to the impetus provided by the Royal Navy and the UK gas turbine industry, has led to significant changes in naval operations, ship upkeep, and shipboard life.

This report is an attempt to provide a connection between the current status of the MGT and its origins. Within the limitations of my exposure, I have tried to point out the events, conditions, and players in MGT history and to identify some of the present pacing problems and areas worthy of future research. Much of the material found herein derives from papers presented and conversations held at several European symposia. In addition, I am particularly grateful to the many knowledgeable and gracious individuals who provided invaluable personal insights. These include CDR T. Jefferis, RN (Gas Turbine Section, Director General Ships, MOD (PE) Foxhill, Bath), Mr. B.H. Slatter and Mr. W.J.R. Thomas (Industrial and Marine Division, Rolls-Royce (1971) Ltd., Ansty, Coventry), and Mr. J. Bowes (Y-ARD Ltd., Glasgow). Finally, it should be noted that the Royal Navy has kept a careful record of their experiences with the MGT, and the references listed here are ideal for those who wish to investigate further.

THE MARINE GAS TURBINE SYSTEM

The MGT System, consisting of inlet, exhaust, power system, power train, propellor, and controls, does not vary dramatically in thermal efficiency from that of an equivalent steam turbine system. Of the energy available in a given amount of fuel, no matter which way you cut it, about 20% ends up at the propellor shaft. In the closed steam system, most of the waste heat (about 60% of the input energy) is rejected to the condenser cooling water while about 20% goes up the stack. In the open MGT system, and this is a major difference, about 75% of the input energy, which is almost all of the waste heat, goes up the exhaust uptakes and out the stacks. The heat sink for the MGT is the atmosphere rather than the sea. The exhaust gases from an MGT may reach temperatures as high as 500°C and velocities up to 200 ft/sec. In addition, a back pressure increase of one inch of water can lead to a loss of about 100 hp from the engine. From a ship design point of view, therefore, a major impact of the change to MGTs is the need for massive gas handling systems (the air flow is typically about three times that required for boiler-feed in a steam system), both inlet and exhaust. For large engines, like the Rolls-Royce Olympus, cross-sectional areas on the order of 6 m^2 are required for inlet and exhaust trunks, which must be thermally and acoustically-lagged. The efflux of hot gases can pose serious problems for above-deck equipment, air inlets, and noise and IR radiation levels. Inlets must be designed to control salt water ingestion. The gas turbine is an inherently high-speed unidirectional machine and therefore requires a goodly amount of speed reduction and reversal machinery in the power train: typical turbine and prop speeds are 5000 rpm and 150 rpm respectively. When these problems are considered together, there is some reason to wonder if the realities of applications to ship systems do not nullify the virtues stemming from the basic compactness of gas turbine engines. Why, in other words, go to the trouble?

One of the first answers to this question, besides the significant benefits of the absence of a condenser, lies in flexibility. The naval mission imposes an operating schedule on gas turbines that is drastically different from that of the aircraft installation. In most conventional naval vessels (excluding high-speed patrol craft) the vast majority of the time has been spent at between 15% and 30% of total installed power, whereas jet aircraft typically operate at 90% power or greater for up to 95% of the time. Since the specific fuel consumption (SFC) of most gas turbines (those operating on a simple thermal cycle) is at its lowest at high power, it is necessary to provide cruise power from MGTs specifically designed for that role. By proper combination of large and small gas turbines aboard ship it is possible to obtain near-optimum performance over a large range of operating conditions. Thus the Rolls-Royce Tyne engine, which is used for cruise power aboard Royal Navy Type 21 frigates and Type 42 destroyers, operates for lengthy periods at or near full load where it delivers about 2 shp for each lb/hr of fuel consumed: the specific fuel consumption (SFC) is 0.5 lb/shp-hr. Even when separate auxiliary loads increase this figure to about 1.0 lb/shp-hr, it is still about 20% better than a comparable steam plant at cruising speeds [1]. Gas turbine plants are generally about 15% lighter than steam turbine plants of the same rating, but, in spite of the removal of the condenser, the center of gravity of the ship need not be significantly affected. MGT plants can be started in a matter of minutes rather than hours, and power changes are easily and rapidly accomplished. Engine rooms are no longer places to avoid, and about 20 fewer crewmen are required to man them in a frigate-class ship. The duties of these men approach those of the long-envied electronics technicians as white-coated diagnosticians rather than lowly grease monkeys--there is a wider scope for intellectual satisfaction, and morale, and hence performance and recruiting are improved.

In steam turbines there is a need to control boiler feed-air and water, fuel, steam, and condenser cooling water, in addition to several other parameters. In the MGT system the number of controlled parameters is significantly reduced, and these have relatively fast responses and are amenable to electronic control.

MGTs can be maintained by means of an equipment exchange process, and this is enhanced by the possibility of maintaining rigid standardization between engine installations--a program most vigorously pursued by the Royal Navy. Though individual costs vary, the total through-life cost of MGT plants (including procurement, upkeep, fuel, and crew) would be about the same as that of the steam plant if it were not for an estimated [1] saving of 40% over a 20-year lifetime due to crew reduction aboard the MGT ship. In addition, there is an expected cost benefit from the administrative efficiency accompanying planned and standardized maintenance procedures.

Finally, there are the priceless and unpriceable advantages in naval operations. These stem from such MGT capabilities as immediate cold starting (including such intangibles as improved crew morale because of reduced engine room watches at anchor), bridge control of ship thrust, flexibility of engine selection (ships with combined gas and steam systems often make short trips without even lighting-off the steam plant), rapid engine replacement (reduced time in inoperable status), weight and space reductions, low noise level (especially in the engine room, but intakes and uptakes can also be effectively silenced), and low vulnerability to shock (MGTs are by no means insensitive to shock and vibration, but there are fewer components to worry about and they can be effectively isolated from the hull).

In spite of the difficulties involved, the shift to MGT power appears to have been worth the effort. It is sometimes difficult to separate needs from accomplishments in reading the UK literature, since those who report MGT progress [2, for example] often start out with a list of requirements that look suspiciously like a list of MGT capabilities. Nevertheless, the Royal Navy and the UK industry have shown that the MGT can equal or exceed steam systems in cost and performance, and that the less tangible benefits of such systems are therefore realizable.

A BRIEF HISTORY

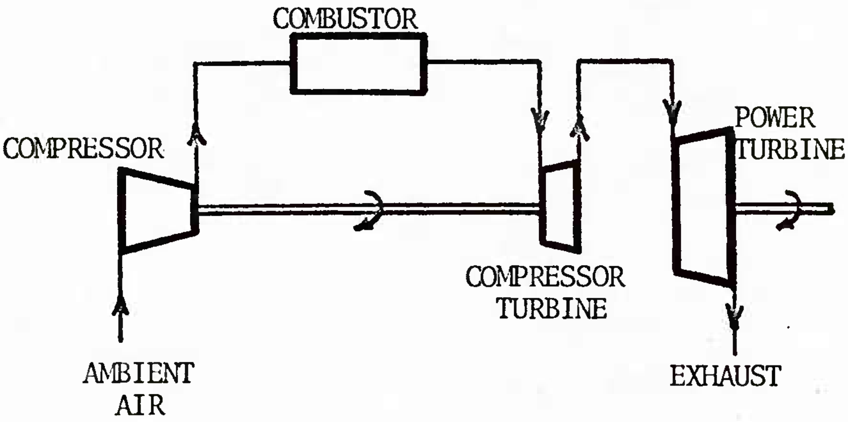
Although the impact of the events at Pearl Harbor in 1941 are not seen by many to have had their happier side, there is some reason to believe that the technology employed by the US Navy was significantly improved by the subsequent crisis. With a major portion of the US fleet destroyed or immobilized there was an urgent and overbearing need for new ships and, if possible, advanced technology. The propulsion technology was available from the US industries providing turbomachinery for steam and hydroelectric powerplants, and it led to a new generation of steam propulsion systems for the US Navy.

In the UK at this time, there was no such opportunity to regenerate their naval technology, for they were immersed in a full-time program of making-do with what was at hand. Thus at the close of the war the UK was essentially equipped with a Navy that was based upon the technology of the 30's, and this probably was a major cause for their interest in new marine technologies as opposed to the relative complacence in the US where the average naval ship age was on the order of a few years.

Anyway, that's one way of looking at it, for those who seek the reasons behind the great shuffle forward that began in the mid-40s in the UK, and not in the US. In 1942, only a year after the initiatives of Sir Frank Whittle had led to the first British aircraft jet engine, the Engineer-in-Chief's Department of the British Admiralty (now the Procurement Executive of the Ministry of Defence) was receiving unsolicited proposals from Metropolitan Vickers for the construction of a gas turbine for use aboard small patrol craft.

The Gatric Engine

In 1943 a contract was awarded to Metropolitan Vickers that led, in 1947, to the installation of the Gatric gas turbine engine as a boost propulsion system in an experimental version of the M.G.B. 2009--the first vessel to be propelled at sea by a gas turbine. (This historic event followed by 50 years the demonstration of the first steam turbine plant aboard the *Turbinia* on the occasion of Queen Victoria's Diamond Jubilee in 1897. This transition from reciprocating steam systems may well be surpassed in importance by the "next act" which was to follow in British marine technology.) The Gatric was based upon the rugged F2 aircraft engine (a heavy industrial design) whose simple thermal cycle was modified by adding a power turbine in lieu of a jet exhaust for power extraction; and modifying the fuel system to run on diesel oil. The simple thermal cycle is illustrated below:



The Gatric was rated for 2500 hp and replaced the center of three gasoline-powered engines, all with separate power trains and propellor shafts. The engine was designed for only 300-hrs operating life, its overall pressure ratio was 3.5, the compressor turbine entry temperature (TET) at maximum power was 750°C, and it had a specific weight of 2.8 lb/shp.

Over four years of operating experience the Gatric was remarkably trouble-free even though well over 600 hours of engine-time was accumulated. As so often seems to happen in the history of a technology, this initial success, though followed by many less-happy experiences, established the feasibility of a concept--sea-going gas turbines. Had the Gatric failed, there was an adequate supply of skeptics and critics who might well have been able to block the further development of the MGT for a significant length of time.

Not everything was smooth sailing for the Gatric in M.G.B. 2009, but those problems that did arise were "easily" solved and were therefore classified as "teething" troubles and were not debitable against the MGT concept.

Above-deck noise was found to be a significant problem and one that was highly installation-dependent. In M.G.B. 2009 the main noise difficulty was with disturbances originating in the compressor and radiating back through the air intakes. The noise reduction methods employed in the M.G.B. 2009, which consisted largely of the installation of a variety of flow splitters constructed of sound-absorvent material and installed in the ducting, are largely those used in the UK today.

It was in the Gatric installation that main bearing failure first manifested itself as an anathema for the MGT. The long periods of high speed and high temperature under seagoing conditions were found to put considerable strains upon the existing thrust-carrying capabilities of ball and roller bearings, and this area of engine design continued to be of prime concern through the development of the MGT technology. There is something of an historical paradox in this, since the M.G.B. 2009 belonged to the class of gunboats that were used to run German blockades in order to deliver much-needed Swedish ball-bearings during the war.

Initially, there was considerable compressor fouling due to contaminants in the inlet air. A long-surviving precedent was again established by the utilization of intermittent freshwater injection for engine cleaning. On the M.G.B. 2009, 10 gal of distilled water were injected at the rate of 2 gpm at intervals dictated by decreases in compressor efficiency (every 3-12 hrs). Water washing, in addition to a slight modification to blade material, was also instrumental in solving a problem of intercrystalline corrosion in the compressor section of Gatric.

Additional MGT problems identified and solved in this pioneering effort included the cooling and ventilation of engine enclosures and the use of various qualities of fuels. In the latter instance, several new design concepts were evaluated for heating and pumping systems and for fuel injection and combustion devices. These tests were carried out ashore at the Admiralty Engineering Laboratory (AEL) and were the first in a long series of shore-based programs in very direct support of fleet installations--a characteristic of the UK MGT program.

The G2 Engine

Gatric provided the proof of MGT feasibility, at least for use in small patrol craft, and the UK wasted little time in pressing on. In 1948 a contract was awarded to Metropolitan Vickers for MGTs to provide boost propulsion to the Bold class of fast patrol boats. The engine was the G2, and two each were eventually installed aboard *Bold Pioneer* and *Bold Pathfinder* on either side of a centerline marine diesel engine. The G2 was designed for 4500 shp although early versions were limited to 3800 shp because of matching problems between the gas generator and the power turbine. The engine was designed for a lifetime of 1000 hrs (reflecting the confidence being accumulated with Gatric), had an even lower specific weight of 2.3 lb/shp, an overall pressure ratio of 4.0, and a full-power TET of 800°C.

The first sea trials of the G2 began in late 1951, and it soon became clear that this installation was to lack many of the virtues (some of them serendipitous) of the Gatric/M.G.B. 2009 system. There was an immediate redesign necessary because of a mismatch between lube-oil pumps and gearbox scavenging pumps--a supply and demand discrepancy resulted in gearbox flooding.

Many of the difficulties with the G2 were related to vibration, both hull-borne and internal. Early-on, a compressor blade failure occurred when, at about 5500 rpm, severe vibration was excited by resonance between the last compressor blade row and the two rows of rigid outlet support struts. The problem was solved by removing the forward row of struts. Another compressor blade failure occurred, this one in the forward row, with considerable subsequent damage; foreign-object damage had apparently set up a weakened condition. A third blade failure occurred due to "rotating stall" in which a local compressor stall is propagated in "patches" that rotate with the compressor but at slower speeds. The blade excitations that can derive from these sources are therefore spread over a wide spectrum of resonant frequencies--in this case at engine speeds between 3000 and 4800 rpm. The solution in the case of the G2 was simply to avoid continuous running within the critical speed ranges.

Problems related to hull vibrations were manifested by repeated main bearing failures. The axial loads transmitted by these vibrations were beyond the carrying capacity of the power turbine ball bearings and led to cage failures. The vibration situation, which was apparently resolved through redesign of the lube system and by operational constraints, precluded the determination of the basic feasibility of ball and roller for use with MGTs. A valuable lesson was learned, however, in that this hull-borne vibration problem was found only in *Bold Pathfinder*. The absence of the problem in *Bold Pioneer*, which had a different hull design, pointed up the dependence of MGT performance upon the total ship design and the need for refinements in the analysis of and design for the cause and propagation of ship vibrations.

The G2 experience was not as successful as that of the Gatric, and it is interesting to speculate upon the events that would have ensued had the two engines been introduced in reverse order. Even so, most of the difficulties with the G2 were not inherent to the MGT application and those that were, specifically the hull-borne vibration, were identifiable and amenable to engineering solution. Further, as pointed out in [2], "The fact that an aircraft engine compressor has been cleared for flight duty [the Beryl MkI aircraft engine had begat the G2],..., is no guarantee that blade vibration troubles will not be experienced when operating at low speeds, as may be necessary in naval applications."

The Gatric and the G2 were both based upon simple thermal cycles and were envisioned as boost propulsors in installations that provided other more-conventional engines for low SFC at cruising speeds. The achievement of main propulsion by gas turbine was also under consideration in the UK, and this interest took the form of more complex systems in which heat exchange (to reduce waste heat) and intercooling (for higher pressure ratios) were employed in an effort to reduce the dependency of SFC upon load. In 1946, between Gatric and G2, contracts were awarded to the English Electric Company and Rolls-Royce for the development of some then quite elegant systems, the E.L. 60A and the R.M. 60, respectively.

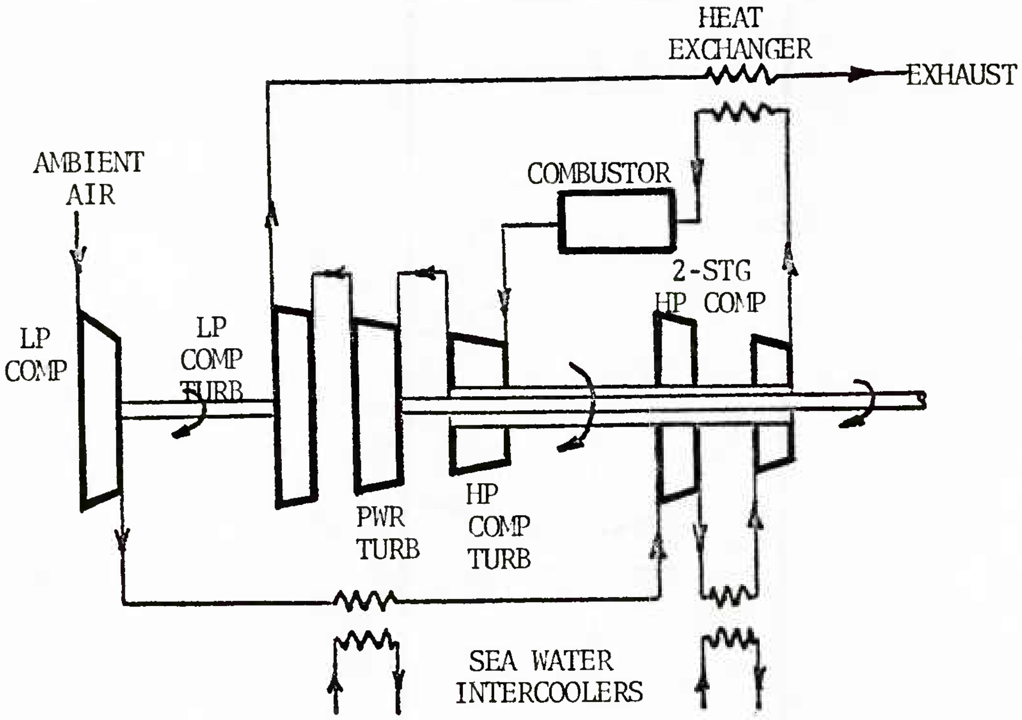
The E.L. 60A Engine

This engine was intended to replace one of the two steam turbo-electric systems aboard the lend-lease vessel H.M.S. *Hotham*. The installation severely limited design flexibility, and it cannot be said that the E.L. 60A was a "new-generation" engine, although the idea of putting this basically heavy-weight industrial gas turbine aboard ship was certainly new. The E.L. 60A system consisted of a single compressor feeding through a heat exchanger into a combustion chamber from which the hot high-pressure gases were split between two turbines, one for driving the compressor and the other on a separate shaft for driving the 6500-hp synchronous alternator. Exhaust from both turbines was used to preheat the air entering the combustor.

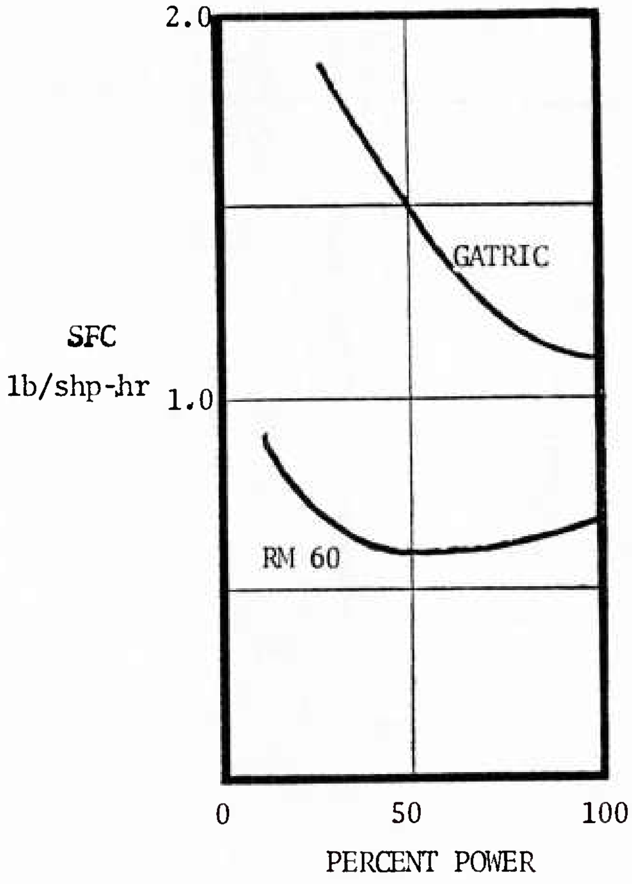
The industrial nature of the design was exemplified by the specific weight of the engine, a whopping 27.2 lb/shp, and the planned lifetime of 10,000 hours. The overall pressure ratio was 4.0 and the TET was 704°C. Due to production delays (the first shore-based tests of the complete system did not come until 1951) and the concurrent development of the lighter and more versatile R.M. 60, the E.L. 60A never went aboard ship. Nevertheless, several advances in technology were stimulated by the development of this engine: improved heat-exchanger and combustor designs, an intricate but effective compressor bleed-air system for the cooling of turbine rotors and blade roots, experience with automatic control of the two-shaft parallel flow system, and a general appreciation for the persevering and forgiving nature of heavyweight gas turbine machinery. Even though the E.L. 60A was obsolete before it was ready to go to sea, it demonstrated the practicality of yet another arrangement for gas turbines at sea, and, as is true for the R.M. 60, the concept may yet find application in merchant vessels where ruggedness and long service life are worth the price of a high specific weight.

The R.M. 60 Engine

This engine possessed a complexity that must have been fascinating if not frightening to behold when design work commenced late in 1947. The thermal cycle is sketched below.



The straight compound cycle involved three compressors with intercooling between each of them, a concentric shaft design for the power and hp-turbines, and heat exchange. Reheat between turbine stages was also considered but was rejected for a variety of reasons, not the least of which must have been that in the matter of complexity "enough was enough." The R.M. 60, as was the E.L. 60A, was designed to be a prime mover, in this case for the fast patrol boat *Grey Goose*. The designed engine lifetime was 1000 hrs, and a specific weight of 5.3 lb/hp was achieved in spite of the multi-component design including the intercooling that allowed an overall pressure ratio of 18.5. At the first trial of the all-up system ashore, in June, 1951, 5300 shp of the 5400 shp rating was achieved. The installation of two R.M. 60s in H.M.S. *Grey Goose*, which previously had the lightest (4000 shp) steam powerplant yet produced, provided a considerable increase in power within less space and with a decrease in specific machinery weight by more than half. That a considerable improvement in SFC was obtained, which was the primary justification for the added complexity, is illustrated in the figure below. [2].



Bearing troubles were again found in the shore-based testing of the R.M. 60. These were overcome by increasing the thrust-carrying capacity of the ball and roller bearings, redesigning the bearing cages and lubrication system, and finally by imposing operating limits to avoid compressor surging. The intercooling system in R.M. 60A led to water-impingement difficulties in the first stage of the centrifugal hp compressor. Though these were at least temporarily alleviated by a change from aluminum to stainless steel for the impeller, it was learned that water separators might be required in future intercooled systems. Further heat exchanger insights were obtained, among them the need to maintain good combustion and/or provide for periodic cleaning in order to control the buildup of carbon deposits on the high temperature side. The *Grey Goose* installation featured a controllable pitch propeller (CPP), and this also provided many lessons to the engineering team. In particular, it was found that mid-range propeller pitch control provided only a small improvement in overall performance. Thus in the *Grey Goose* the CPP was used only to provide reversing capabilities. Other important experiences in this program were related to noise and the dependency of engine performance upon ambient conditions, the latter of which would be found to be critical in the near future.

At-sea experience with the R.M. 60 in the *Grey Goose* (some 1500 hours) was somewhat mixed, with many of the infrequent breakdowns related to the complexity of the system. The issue was rapidly becoming moot, however, since the main thrust of Royal Navy gas turbine thinking was keyed to the simplicity of the basic gas turbine, and the R.M. 60 design did much to neutralize this inherent characteristic. The project was abandoned in 1955 in favor of simple cycle engines. At about this time, CDR G.F.A. Trewby [2] uttered some truly prophetic words in predicting the future of the MGT. He said that in his opinion, "...gas turbines will be introduced in increasing numbers for the propulsion of high speed coastal craft. In major warships the first applications will be as 'boost' units for use at high powers with steam turbines or possibly Diesel machinery for cruising. At a later stage gas turbines may become the sole means of propulsion in some warships." This is exactly what happened, except in the UK and elsewhere it was not a matter of "some" warships, but all warships.

It might be useful to interject here a remark concerning the gas turbine rumbles that were being heard in the US Navy. In 1950, for instance, an article appeared [3] in which a COSAG (Combined Steam and Gas) system was being proposed. Two MGTs would be connected through clutches to the same gear train as that driven by a 9000-shp steam plant. Clutching-in the MGTs would provide a power boost up to a total of 30,000 shp. The UK was already taking the first tentative steps and, with the exception of long experience at sea, there was every indication that MGTs were there to stay, in one form or another, in naval vessels. The next step in the developing technology was the beginning of the G6 MGT program. This was to be the last of the MGT systems that was not a marinized version of existing aircraft engines, and it was to be looked on by many sailors as not only a boost engine, but a "get-you-home motor." The G6 was the test bed on which most Royal Navy engineers got their initial experience with, and eventually their conversion to gas turbines.

The G6 Engine

In 1953 the Royal Navy scorebook for MGTs read something like "E.L. 60A--a sturdy beast but not for the Navy, R.M. 60--a technological dream but a mechanic's nightmare, G2--some rotten luck but basically sound, Gatric--absolutely smashing." All these engines said "go" for gas turbines but some more than others. Gatric, in particular, had created a definite fondness for simple cycle engines, and this is where the emphasis turned and remained. The G6 engine, manufactured by Associated Electric Industries (formerly Metropolitan Vickers) was in fact an offspring of Gatric although of a heavyweight industrial design.

The G6 was destined for COSAG service in Tribal class general purpose frigates and the County class destroyers. COSOG (Combined Steam or Gas) operation could also be obtained in which hydraulic couplings were used to isolate the G6 engines for running on gas turbines alone. The 8600-hp engine (7500 hp at the shaft) operated with an overall pressure ratio of 5.68 (almost twice that obtained about 10 years earlier with the Gatric), a TET of 793°C, a specific weight of 4.8 lb/hp, and an expected lifetime of over 2000 hours. The first ship to put to sea with a G6 engine was H.M.S. *Ashanti* which, in 1961, was the first large operational naval craft to utilize an MGT for main propulsion. Her launching, of course, followed extensive shore-based testing, and as *Ashanti's* sea trials neared an end it appeared that nothing had been left to prove at sea. This happy situation come to an abrupt end when something hit the fan in the Caribbean.

As mentioned previously in connection with the R.M. 60, considerable learning had been achieved in evaluating the detrimental effects of high ambient temperatures upon gas turbine performance. In appreciation of this fact, and since shore-based simulation was not feasible, the *Ashanti* sea trials included a 12-hour run at full power on both steam and gas turbines in tropical air, and what hit the fan was the hot and humid atmosphere of the Caribbean. The failure originated in the rim of the first stage turbine disc. A brief fire ensued when severe vibrations led to breakage of fuel and lube oil lines. Remarkably, the debris emanating from the failed rim was either chewed up and ejected in the turbine exhaust or was lodged in downstream passages of the G6.

A detailed investigation followed the *Ashanti* incident, and this was supported by extensive and highly imaginative testing of the G6 system at the Naval Marine Wing (NMW) of the National Gas Turbine Establishment. A number of contributory factors were suggested, but the main cause of the failure (to make a long story short) was determined to be an imbalance in the cooling flows to the early turbine stages. A series of cooling system modifications led to a temperature reduction at the point of failure of from 640°C, to 450°C and this was accomplished without loss of engine power, although not without great difficulty.

The *Ashanti* incident was a major event in the test history of the G6, but several other issues received special attention including compressor vibrations, combustion chamber life, and starter-motor performance. The G6 also reaffirmed the advantages in ruggedness accruing from the industrial design philosophy.

Though the MGT technology had been advancing steadily in the UK from the mid-forties to the early sixties, the aircraft gas turbine business had experienced a definite boom, and it now became clear that exploitation of this burgeoning technology held clear benefits for the MGT program. It was the dawning of the age of "marinized" or "aero-derivative" engines, and the scene was being set for the bold decision of 1967.

The G6 had worked well-up-to-specifications and was in many ways the darling of the marine engineer in the Royal Navy. From the point of view of fleet acceptance it is difficult to refrain from quoting at length from CDR N.K. Bowers [5]. His feelings can be summarized, however, by his statement regarding the role of the G6 in winning the hearts of the sailors away from steam power: "From the point of view of ships staff there is no question which is the more attractive form of prime mover." The question now (in 1963) was becoming one, not of steam versus gas, but of industrial versus aircraft design philosophy. Again a successful example was at hand when one was needed, and when its absence might have drastically altered subsequent events. This example was the Proteus.

The Proteus Engine

The Proteus was built by Bristol Siddeley Engines Inc. which, through a sequence of events with which I am only vaguely familiar, was purchased by Messrs. Rolls-Royce which late became Rolls-Royce (1971) Ltd. These were relatively small engines intended to deliver 4250 shp each, in sets of three, aboard the Brave class of fast patrol boats. That this was an aircraft engine is evidenced by some of its statistics: overall pressure ratio 7.32, TET 852°C, specific weight 0.83 lb/hp, SFC at full power 0.57 lb/hp-hr, and a life expectancy of over 1500 hours. Shore trials had commenced in 1955 and H.M.S. *Brave Swordsman* had begun sea trials in 1958. A unique aspect of the Proteus was that, because of its turboprop origins, its power output shaft was at the front of the engine. Thus the eliminator of a power output shaft immersed in the turbine exhaust allowed a rather neat and unencumbered machinery layout in the Brave boats [4]. By 1963 the Proteus had proved the ability of aero-derivative engines to withstand the life at sea (this included, in the Brave boats, speeds in excess of 50 kts): running at sea level temperatures and pressures, with salt and moisture-laden surroundings, enduring water-generated and hull-borne shocks and vibrations, requiring massive air handling systems, power transmission, and reversal.

The advantages of industrial engines were largely characterized by ruggedness stemming from a lavish expenditure of weight and space: beefy blades were less sensitive to shock, vibration, and corrosion; there was room to design especially for the marine environment; and massive intake and exhaust ducting were already features of "land lubber" gas turbines. Aircraft engines, on the other hand, were in widespread use and had experienced extensive development and refinement at aircraft industry expense.

Both these factors led to low first costs. In addition, the aircraft engine was light, compact, and easily removed for maintenance and/or replacement (a virtue much longed-for during the repairs aboard the *Ashanti*), and its lifetime had increased to over 4000 hr in the air. On balance the aero-derivative engine looked good in 1963, if it would last a reasonable time at sea. This was shown to be the case by the Proteus: it established a threshold value of reliability and perseverence at sea that was sufficient to sway sentiment in favor of the aero-derivative MGT. (In 1969 the Proteus was still at work aboard H.M.S. *Brave Borderer* and the ships of several foreign Navies.) The G6 was the last of the industrial "Big Daddies" in MGTs, and having decided to "go aero," the Royal Navy could now shop in a well-stocked jet-engine supermarket. In 1963 they chose the Olympus, the jet engine of the Vulcan bomber, for their next generation of MGT's.

The Olympus Engine.

The marinized Olympus 201 (Bristol Siddeley Engines, Inc.) represented a quantum jump in power rating of MGTs: 22,300 shp at maximum rating. The essential marinization actions were only two in number: bearing and combustion chamber modifications to extend the life at sea to beyond 3000 hrs; and a cantilevered mounting for shock resistance, accessibility, and ease of gas generator removal. Overall pressure ratios of 9.7 were attained, with TETs of 852°C and SFCs on the order of 0.5 lb/shp-hr. Specific weights were on the order of 3 lb/shp.

The Proteus engine, having led to the development of the Olympus, now continued to provide useful data. Extensive shore tests (mainly to evaluate life expectancy with humid salt-laden intake air) were conducted, using Proteus as the protoype; and in 1965 H.M.S. *Exmouth* was converted to accept the (then) Rolls-Royce Olympus as the main propulsion unit and the Proteus for cruising in a COGOG configuration. It was the first major naval vessel to put to sea with all gas-turbine propulsion.

The 1967 Decision

Considering the individual and cumulative boldness of the myriad of decisions that had led the Royal Navy to its very qualified position to judge the MGT in 1967, it seems that their subsequent commitment to these systems for future surface vessels was less bold than inevitable. (Thus the image of a courageous and lucky Admiral pounding his fist to the green velvet is a fanciful one.) Nevertheless, the decision is to be highly respected in the light of future developments and especially because of the depth of experience that the Royal Navy was able to bring to bear in the considerations. Notwithstanding Gatric, G2, E.M. 60A and

R.M. 60, it is estimated that at the time of the 1967 decision the Royal Navy had the following installed gas turbine power and accumulated hours (including shore trials):

Engine	Installed Horsepower	Accumulated Hours
G-6	250,000	50,000
Olumpus	21,000	3,000
Proteus	32,000	35,000

Though not mentioned here, there had also been major progress in the use of gas turbines for auxiliary shipboard systems.

Besides this depth of technical experience, most of it favorable and all of it useful, there were other factors that must have influenced the selection of MGT's in 1967. On the public and political scene, defense was not an issue that found widespread popularity. In addition to the tightening of defense procurement budgets, there was the more-subtle effect of difficulty in recruiting. With no popular call to arms it had become increasingly difficult to attract volunteers to serve in the environments of boiler rooms and engine rooms of steamships. The MGT would, in the estimate of the Royal Navy, enhance recruitment potential. And, of course, there was the more direct benefit that the MGT required considerably less manpower per horsepower (men per horse).

On the industrial and economic side, the steam turbine industry was not the flourishing concern that it had once been, since gas turbines had been on the rise ashore as well as elsewhere. There was considerable doubt that steam turbine manufacturers could even be found who would be willing to tool-up for the relatively small orders that the Royal Navy was expecting to place. Definitely not so with the aircraft gas turbine industry. These companies, which had already footed the bills for extensive development costs, were very much in a position to expand their product line to include seagoing systems.

Thus the decision makers were comparing systems, of which one had been found to be lighter, smaller, sufficiently reliable, more easily maintained and controlled, faster in starting, stopping, and changing power, cleaner and less complex, and manageable by a smaller crew. Citing most of these factors, CDR N.K. Bowers, RN, said, in 1966 [5]: "Without risk of contradiction, the future can clearly be seen to involve an increase in the marine gas turbine field." When social, political, and economic factors are also considered, it is a small wonder that the nod went to the MGT.

The US had had less experience with MGTs in 1967, and consequently there was less enthusiasm for, and confidence in, these systems. In any case, the US Navy was not then in a generation change of ships and propulsors. This position was soon reached in the US, however, and we are fortunate indeed to have had the experience of the Royal Navy to serve as an example. The surge in MGT activity in the US, coupled with the recent history in the UK, has led to a shift, many would say a reversal, in the balance of MGT technology between the two countries.

Recent History

At the time of the 1967 decision there were fourteen major warships commissioned in the Royal Navy in which COSAG propulsion systems were used. These consisted of the seven Tribal Class General Purpose Frigates, each with a single G6 engine (which has also come to be referred-to as the Metrovick engine), and an equal number of Guided Missile Destroyers of the County Class in which four G6s were used in conjunction with two steam turbine systems for a total of about 60,000 shp. One more County Class ship was under construction (the *Norfolk*, to be commissioned in 1970) and the light cruiser H.M.S. *Bristol*, whose keel was laid in 1967, was to be commissioned in 1973 with two marine Olympus TM1A engines combining with steam to deliver about 60,000 shp. The all-gas-turbine H.M.S. *Exmouth*, whose conversion was completed in 1966, was the prototype providing the best kind of feasibility demonstration: operation at sea.

Today, all of the ships mentioned above, with the exception of H.M.S. *Hampshire**, are still operational [7]. In addition, and as a result of the 1967 decision, a number of new major warships have been added to the Royal Navy Line. These are all COGOG (Combined Gas or Gas) ships and use the marine Olympus/Tyne family of MGTs. In 1969 the keel was laid for the frigate H.M.S. *Amazon* (Type 21) in which two main engines deliver 56,000 bhp and two cruising engines provide 8,500 bhp. *Amazon* was commissioned in 1974 and there are now five ships of this class with three under construction. Almost immediately following the *Amazon* the destroyer *Sheffield* (Type 42) was born, with a similar propulsion system, and there are now three of this class commissioned with one under construction and two more on order. The keel for the ASW Cruiser H.M.S. *Invincible* was laid in 1973 with a hoped-for commissioning date of 1979. One more

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**Hampshire* was the second of the County Class destroyers. Commissioned in 1963, she was "deleted prematurely" as the result of a recent defense review--"at least seven years before she might have been expected on the disposal list" [7].

of this class has been ordered (at twice the cost), and it will utilize a COGOG arrangement in which 112,000 shp is available from four marine Olympus engines. The most recent warship keel was laid in 1975 for H.M.S. *Broadsword*, the first of the Weapon Class (Type 22) destroyer. One other of this class is presently on order, with a propulsion system similar to that of *Amazon*.

Most of the UK industrial expertise in MGTS now resides with the Industrial and Marine Division of Rolls-Royce (1971) Ltd. Rolls-Royce (1971) now boasts about 200 marinized engines--100 Olympuses, 50 Tynes, and 50 Proteuses--in service with fleets of several nations. Many of these installations are in module form that give the MGT the appearance of a versatile, if huge, black box. The systems are coming close to the plug-in module concept popularized by the electronics industry.

No detailed description of the technological events leading to the development of these ships will be given here. It is worth mentioning, however, that the installation of MGTs aboard ship has continued to receive an enormous amount of shore-based backup testing. This has taken place at government installations (the NMW), and at industrial facilities [Rolls-Royce (1971) Ltd.], and has consisted of virtually total simulation. Full-scale complete plants have been erected ashore and, although the plants do not pitch, roll, or heave; intake, gas generator, uptake and power train are all carefully duplicated. There are even facilities for the simulation of seawater ingestion into the intake separation system. This shore-based duplication appears to have been cost-effective, even in the light of the relatively small number (compared with aircraft power plants) of MGT systems actually finding their way to sea. Great benefits have been realized in design evaluation and in analysis ashore to extents far greater than are possible at sea. The shore-based simulators are also fertile sources of R&D insight, notably in seawater separation, vibration, controls, and noise. Finally, there are the great virtues accruing to the training of personnel in the operation and maintenance of MGT systems. There is no question that the "do it ashore first" philosophy of the Royal Navy has greatly enhanced the rapid acceptance and good performance of MGTs in the fleet.

Unfortunately, many of the economic and political constraints leading to the 1967 decision have, if anything, intensified. In the Foreword to *Jane's Fighting Ships, 1976-77* [7], Captain John E. Moore, RN, writes: "Great Britain's policy has been stated clearly in both the last Defence Review and in the more recent White Paper on Defence: an intention to withdraw the ships of the Royal Navy to an inner area, the Eastern Atlantic." The pattern of new construction is, he says, "...dictated by the amount of money allocated rather than the needs of the country's defence..." Constraints such as these have limited the growth of MGT technology in the UK, and there are many who would accept that the leadership in MGT technology has shifted away from the UK. In the US, for example, as of September 1975, keels had been laid for 17 of a planned 30 ASW destroyers of the *Spruance* class. These ships, of which five were commissioned as of July 1976, are powered by four General Electric LM-2500 gas turbines, each rated at 27,500 shp. The LM-2500, which is a derivative of the TF39 engine powering the C-5 and the DC-10 aircraft, is a sophisticated and relatively complex system; its several advanced features lead many to consider it to be a new generation of MGT. Though the lead may have changed hands, as it did in the early '40s in steam technology, it is appropriate in concluding this brief history to again point out the dominant role that the UK has played in taking the gas turbine to sea.

THE STATE OF MGT TECHNOLOGY

In this section a few brief remarks are made concerning some of the main issues extant in MGT technology. Emphasis is again on the UK situation, and much of the information herein is condensed from the Proceedings of the 1976 Symposium On Gas Turbines--Status and Prospects [8], and the 1975 Conference on Gas Turbine Inlet and Exhaust Systems for Ships [9]: both of these are highly recommended reading. The main MGT components considered here are the gas generator and inlet and exhaust systems. Power trains, propellers, and controls are beyond the scope of this report.

Gas Generators

Because the marinized aircraft engine has become the accepted product for use aboard the naval ship, the developments in aircraft gas turbine technology are essentially the ones that will impact the MGT. Of course, such things as high by-pass ratios and the duty cycles do not carry over between the two applications. Nevertheless, the main goals of improved performance and reliability, both at minimum cost, are common to the two technologies and many improvements in naval MGT technology will continue to originate with the aircraft industry. (This is not necessarily true, incidentally, in the case of merchant ship applications where the goals of aircraft and ship operations are less in conformity.)

For a given rate of fuel supplied, the amount of power that a gas turbine makes available for useful work (in this case to drive the power turbine) is directly influenced by the pressure increase provided by the compressor and by the turbine entry temperature--they should both be as high as possible, all other things being equal (which they never are). These two quantities have always been of fundamental concern to gas turbine designers, and a measure of the intensity of development along these lines is obtained by comparing the Gatric engine with the TF39: from 3.5 to 17 in compressor pressure ratio (CPR) and from about 750°C to 1260°C in TET. The corresponding improvement in SFC has been from about 1.2 lb/shp-hr to 0.4 lb/shp-hr, respectively.

The achievement of higher CPRs and TETs is strongly coupled, of course, to the maintenance of high efficiencies in compressor and turbine machinery. As might be expected, an increase in CPR is often accompanied by a decrease in compressor effiiency. The multi-stage core compressors now operate at stage pressure ratios in the range 1.2 to 1.4, and their efficiencies are, correspondingly, from about 90% to 86%. In axial compressors, little appears left to be done in improving the basic core-section performance. (There is much to be attained in the fans, however, because of their very high tip-to-hub ratios.) There is, on the other hand, the important area of computer-aided design, which can allow the calculation of complex and sophisticated blade and stage geometries and thereby lead to optimized designs with less reliance on cut-and-try testing methods. In addition, the advent of cooled turbines in which compressor bleed air is the cooling medium has led to problems of a new nature in the design of compressors.

Probably the most important sub-technology of the gas turbine is that of high temperature. This is especially true in the MGT operating enivronment where ambient conditions are relatively warm and even the unheated air may reach 500°C after compression. In the quest for higher TETs, the main directions taken have been towards materials and cooling techniques.

According to F.W. Armstrong (NGTE, Pyestock) [8], improvements in materials allowed an increase in TET at the rate of about 10°C/year up to 1960. These efforts had centered around the conventional nickel alloys and have reached the present state in which unidirectional solidification and single crystal casting are expected to take these alloys to a working limit of about 250°C from their melting point of about 1330°C. Some useful results have been obtained with the casting of submicroscopic inert particles within more-conventional matrix metals. These materials possess good strength characteristics close to the melting point of the matrix metal, but their effectiveness is less at the lower temperatures. Other initiatives have been taken in directionally-solidified eutectic materials and other alloy systems using chromium, tungsten, niobium, tantalum and molybdenum. Although these alloys possess sufficient strength at temperatures up to about 1300°C, they must be protected against high temperature oxidizing atmospheres. Great strength and chemical inertness at high temperatures (approaching 1500°C) are obtained from the ceramics, but their brittle nature still argues against their use for major engine components. In this context, it is thought that brittle materials and coatings may find application in closed-cycle gas turbine systems where close control of the quality of the working fluid allows a measure of protection against impact from suspended solids. Closed-cycle gas turbines are under consideration for use in conjunction with gas-cooled high-temperature reactors (see S.C. Kuo and R.T. Schneider, ONRL Report R-3-77).

Though there are many gains yet to be made in the exploitation of new materials and their combinations, the trade-offs between high-temperature creep and fatigue strength, handling and machining properties, and corrosion resistance present continuing dilemmas for the materials engineer. For near term increases in TET, therefore, much attention has been given to blade cooling techniques.

Cooling techniques have evolved from simple convection systems to the elaborate forced-air systems such as those that make the turbine nozzle guide vanes of the RB211-22 (used in the L-1011 Tristar) look like slabs of Swiss cheese. An example provided by R.M. Denning and T. Jordan [8] again illustrates the existence of design trade-offs. If, as is often the case, blade cooling air is derived from the compressor delivery air, an increase of engine pressure ratio can result in a significant increase in cooling air temperature. A decrease in TET would then be required in order to maintain a given blade metal temperature. With a low cooling effectiveness, an increase in pressure ratio may actually lead to a decrease in overall performance.

Turbine blade cooling offers an area in which considerable engineering research is needed. Techniques such as film and transpiration cooling, though holding much promise, have yet to be completely understood in the gas turbine application. In addition, the effects of these cooling flows upon core flow, both through the turbine and the compressor, are yet to be predicted accurately. Another promising scheme is the cooling of compressor bleed air before using it as a coolant; such a process will add weight and complexity and may therefore be most feasible for MGTs and industrial systems. The same can be said for the two-phase systems such as heat pipes. Though MGTs draw heavily on aircraft gas turbine technology, there are several areas, such as turbine blade cooling, in which the MGT allows more flexibility than the highly weight- and volume-sensitive aircraft engine.

The introduction of blade cooling resulted in a jump of about 100°C in allowable TET. Transpiration cooling methods are expected to lead to values of cooling effectiveness (ratio of difference between hot gas and blade temperatures to that between hot gas and cooling gas--when $E = 1$, blade temperature equals cooling gas temperature) of up to $E = 0.8$ for a cooling air flow of 5% that of the mainstream flow [8]. Much of these achievements will depend upon realistic simulation of the gas turbine environment, such as that obtained in the experimental rig at the High Temperature Demonstrator Unit operated by Rolls-Royce (1971) Ltd. [10].

Advances in technology are also expected from research directed at materials utilization for areas less critical than the turbine. Improvements in weight and fatigue life are attainable through the use of titanium alloys in, for instance, rotor discs. Composite materials are expected to find useful application in engine containers. The good strength/density characteristics of these materials offer advantages in aircraft systems, as the relative weight of nacelles increases with decreasing system weight.

In this context, the MGT counterpart of an aircraft nacelle is the enormous air intake required aboard ship, and composite materials should prove beneficial both here and in the exhaust system.

Combustion technology is also a fruitful field for gas-turbine-related research. Though combustors and injection systems have matched the pace of refinement in gas turbines, much new incentive has been provided by increased emphasis in pollution standards and, in particular, the high cost of fuel. MGTs must operate on good quality distillate fuels and, although these are available for most naval vessels, they are relatively expensive. Fluidized beds hold promise in the use of heavy liquid and solid fuels. These devices provide control of combustion at a temperature below that at which ash products are produced and, in addition, they allow for removal of sulphur products. There is the usual trade-off, of course, and in this case temperatures in excess of about 850°C are not expected to be obtainable--a restriction that would render moot a good many of the advances in high temperature technology. Again, however, it is quite possible that MGT systems, relative to aircraft systems, would be more tolerant of the resulting low efficiencies.

To summarize this section, it can be said that the further development of the aircraft gas turbine is likely to lead to advances in the technologies associated with high temperatures, combustion, and manufacturing materials and processes. These will carry over into the MGT field. As the MGT becomes more of a standard and less of a novelty, however, it can be expected that the associated technology will become less dependent upon advances in the aircraft gas turbine. The relative design freedom in space and weight aboard ship may allow the introduction of refinements that are not feasible in aircraft. Possibilities include more-elaborate turbine blade cooling systems (including compressor bleed-air coolers that might also be used as intercoolers), extensive use of composite materials, and heat exchangers. The last-mentioned change would constitute a major step back from the 1963 "marriage" to aircraft technology, but would also greatly reduce turbomachinery complexity by avoiding the need for high pressure ratios. Finally, the multiple benefits accruing from fluidized-bed reactors may lead to their serious consideration for use in seagoing systems. Though reduced TETs would alone cause serious decreases in efficiency, much of this might be regained by means of heat recovery such as heat exchange--and the move away from extreme temperatures would cause noticeable relief among MGT designers.

There is another area that is peculiar to the MGT system and, if left unattended, could cancel any gains obtained through improvements in the gas generator. This is the system of gas handling, intake and exhaust, aboard ship.

MGT Intake and Exhaust Systems

The rule-of-thumb used by MGT system designers to estimate the effect of intake and exhaust (I&E) systems on overall performance is that a 1% increase in pressure drop in the intake will result in a 2.2% loss of power and a 1.2% increase in SFC; the figures for the exhaust system are 1.1% degradations for both power and SFC with a 1% increase in pressure loss. In the Olympus TM3B the I&E system must provide flow rates on the order of 110 kg/sec with the result that, if the maximum recommended mean air intake velocity of 15 m/sec is applied, these ducts must have a mean cross-sectional area of about 6 m^2. In providing delivery of gases to and from the MGT, the I&E system must also provide for filtration, silencing, and proper distribution of the flow at compressor inlet and funnel exhaust outlet. The massive ducts must turn and twist to provide vertical passage from topside to engine spaces; the simplest installation requires at least two 90-degree bends since the gas generators are horizontally mounted in all current designs. In addition, there are requirements for expansions, contractions and transitions in cross-sectional shapes. All of these requirements must be met with the utmost attention to optimal design, for the I&E systems, as well as influencing performance, use up prime ship space and can contribute significantly to weight high in the ship. The technology of I&E systems appears to be relatively underdeveloped because of an initial lack of awareness of its importance and the constant emphasis upon the gas generator and machinery elements of the MGT system.

The main aerodynamic objective of I&E duct design is to provide a uniform undistorted flow, throughout the system, with a minimum loss of flow energy. In many cases compromises are called-for since such things as settling chambers and flow-straighteners are sources of pressure loss. The importance of flow uniformity was demonstrated to the Royal Navy in a dramatic way aboard H.M.S. *Exmouth*. During sea trials of this first all gas-turbine ship, a compressor failure resulted because of inadequacies in the intake system. This early design incorporated a simple box-like plenum chamber from which air was drawn by the compressor. There was no apparent attention to aerodynamics in the design of this box, and protruding edges were located in such a way as to provide generation surfaces for vortices which subsequently detached and became intensified by the acceleration of the flow as it approached the compressor entry region. The result was severe distortion of the inlet flow that eventually led to blade failure. In hindsight, the design of the *Exmouth* intake seems to have been incredibly crude, since wind-tunnel technology had demonstrated, well before 1965, that turning vanes are essential in the ducting of flows around corners. This simple expedient solved the problem in *Exmouth*, and turning vanes are now used extensively in I&E systems.

The nature of the aerodynamic problems within I&E systems is essentially one of a slightly compressible turbulent boundary layer with a high level of freestream turbulence, several regions of acceleration and deceleration, many potential separation points, and a variety of three-dimensional regions such as corners and bends. Not surprisingly, a large amount of the research in these systems is experimental. At Rolls-Royce (1971) Ltd., for example, there are several special flow facilities that provide 1/8- to 1/5-scale testing at Reynolds numbers up to 1.2×10^6 (average full-scale Reynolds numbers for intakes and exhausts are on the order of 6×10^6 and 1.75×10^6, respectively [9]). In spite of intensive past efforts there is much yet to be done in developing uniformly distributed flows with acceptable pressure losses. Typical flow distortions at the volute exit (after turning the power-turbine exhaust flow 90° and transitioning from circular to rectangular geometry) give ratios of local-to-mean velocities that range from 0.6 to 2.0. When this flow is decelerated through a diffuser, the distortions are amplified and the ratios can range from 0.4 to 2.5--and this is the chaotic flow that enters the exhaust silencer section.

Another important area for research in fluid mechanics is that of the exhaust funnel exit. Here it is important to condition the flow in such a way that the hot stack gases do not impinge upon topside equipment or otherwise foul the above-decks region. The basic problem is to propel the stack gases beyond the local ship flow field and into the atmospheric outer regions. Again, this problem is treated largely by experimental means, and analytical techniques are relatively under-developed. In the US, eductor systems are under consideration in order to cool the stack gases and tailor the exhaust plume.

From the point of view of structures, the MGT I&E system again offers several challenges. Materials are, of course, of primary interest. In the Royal Navy, intake ducting is normally of aluminum construction. Both stainless steel and aluminum-sprayed mild steel are used for exhaust ducting. In the exhaust system, account must be taken of oxidation and corrosion conditions as well as the high excursions in temperature which lead to requirement for compensation for thermal expansion (in a typical installation, the exhaust ducting may change as much as 120 mm in length during normal ship operations). Shock and blast are also factors to be included in the I&E design specifications. And, of course, light weight is essential to minimize elevations in ship center of gravity.

The UK engineering community has been eminently successful in providing adequate filtration of MGT inlet air (and, sometimes, green water). Extensive tests at the NMW have resulted in a separation system that has met every operational test. The performance criteria for the separators currently in use are to eliminate droplets above 2 μm in diameter and to maintain NaCl concentrations below 0.01 ppm. The system consists of a compact three-stage arrangement in which heavy spray and green water are initially eliminated by inertial turning vanes. The resulting mixture (with droplet sizes of 13 μm or less) impinges upon the second stage, or coalescer, which consists of a fiber mat construction. Under high humidification conditions water droplets are reformed in the coalescer and re-entrained in the downstream flow, thereby necessitating a third-stage inertial separation. At the nominal duct entrance velocity of 8 m/sec, and standard inlet air quality [9], the total pressure drop through the system is about 9 mbar. Probably the most important question yet to be answered, with respect to this system, is that of performance in Arctic regions. At-sea tests have been conducted, but "unfortunately" conditions of severe cold coupled with high seas have not yet been encountered. It might be added here that the cold-weather performance of I&E systems in general is still a partially unresolved issue.

Silencing is another issue that has yet to be resolved. The Royal Navy MGT ships all incorporate silencing apparatus in their intake and exhaust ducting. These include acoustic lagging of duct walls as well as the insertion of acoustically-absorbent flow-splitters in the inlet and exhaust flows. These splitters are a source of many problems. For one thing, they are major obstructions to engine removal. They occupy about 50% of the available flow area and thereby require enlargements, and cause local flow distortions and accelerations, and increased pressure drops. In the hot, high-speed flows found in exhaust ducting, the structural integrity of flow-splitters is always a problem. Since to be acoustically-effective the splitter filler material must be exposed to the noise media, the packaging and retention of these fibrous elements is a challenging task. A number of compromises are required between such things as acoustic effectiveness, top weight, flow blockage, pressure drop, reliability and, of course, cost. Effective silencing is relatively easily obtained in intake ducting, but the high temperatures and low frequencies present in the exhaust lead to great difficulties. Many potential improvements are needed in MGT I&E silencing systems, not the least of which is the establishment of comprehensive criteria as to how much noise is too much. Detailed shipboard sound maps, at varying operating conditions, are required to assess the importance of MGT-generated noise properly.

Upkeep and Maintenance

In general, the MGT has fulfilled its promise to greatly improve propulsion plant upkeep and maintenance. M.H. Piper has recently documented the Royal Navy's experience with Olympus and Tyne [8] and, though at-sea trials are still too limited to permit a final judgment, it is his opinion that extensive shore trials have effectively pre-empted serious future problems. Piper cites a few component difficulties (limited combustion chamber life and pitting and cracking of compressor blades), but these and most other problems appear to be related to the commencement of construction prior to the completion of development. Logistics and documentation problems have inevitably arisen due to the introduction of a new fleet system. The Royal Navy has adhered to the philosophy of elapsed time overhaul but is planning to go to "on condition" removal and overhaul procedures pending the accumulation of service experience sufficient to allow confidence in inspection and detection methods. In this connection, the MGT has led the Royal Navy deep into the field of Engine Health Monitoring (EHM). The "upkeep by exchange" system, in which entire gas-generator systems are replaced, *in toto*, by removal through I&E ducts, has thus-far proven to be highly successful (although, perhaps fortunately, experience is here, too, lacking). The Royal Navy uses Gas Turbine Change Units (GTCUs) and plans to be able to meet their 48-hour exchange goal with relative ease. In June 1975, an Olympus GTCU was installed in H.M.S. *Sheffield* in 50 hours.

CLOSURE

This report has briefly described the history of the MGT in the UK, and has attempted to point out a few of the more pressing issues that remain to be resolved. Much has been mentioned only in passing, and several areas have not been covered. These include the extensive developments in gas turbines for marine auxiliary equipment and offshore installations, the most interesting question of MGTs for merchant vessels, and the consideration of advanced combined systems such as those using diesel and MGT propulsion. In the section on the state of MGT technology, only a few areas have been mentioned, and these only in the most general terms. It is hoped, however, that some readers will be stimulated to look further into these and other important areas--the references will provide useful points of departure.

In summary, it has been shown that through a careful and systematic approach the UK has led the world into the use of gas turbines aboard ship. This approach has been characterized by intensive large-scale shore-based testing--a feature that contributed heavily to initial successes and continues to be a mark of the UK MGT technology. Recent political and economic trends have led to developments in other countries that have placed the UK lead in jeopardy, but this in no way detracts from the magnitude of the achievements that culminated in the 1967 decision.

In research, there is much to be gained from analyzing the present state of MGT technology. Even this brief study has pointed out several meaningful areas for study: high temperature and lightweight materials, advanced combustion systems, several engineering problems associated with intake and exhaust systems, and thermal system analysis including the feasibility of MGT extensions that are independent of the aircraft gas turbine technology.

Finally, the reader is reminded of the need to continually assess the changing requirements of marine propulsion. Many of the 1967 groundrules have changed, most noticeably the cost of fuel. These changes do not nullify the significant advantages of MGT propulsion, in my opinion, but they can cause rearrangement of priorities. For instance, a low-temperature system, featuring advanced heat recovery, fluidized-bed combustion, and widespread use of composite materials, particularly in ducting, may now appear to be feasible for MGT application where 10 years ago this would not have been considered.

In any case, we can expect a continued rise and fall in the popularity of ship propulsion schemes. As Palmer [1] has pointed out, the sail was the thing until the early 1820's when its decline was matched by the emergence of the reciprocating steam systems. The crossover point in utilization of these two systems occurred around 1870. Reciprocating and turbine steam systems crossed in about 1915, and the MGT has now superseded the steam turbine in naval surface vessels. Nuclear systems are the next potential leaders on the horizon, but it is clear that the many and diverse difficulties with these systems, and the advances latent in the MGT approach, will give the MGT a significant reign.

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