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MARINIZATION OF AERO GAS TURBINES

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Marinization of an aero gas turbine, in particular making it suitable for warship propulsion, involves the redesign of the jet engine to make it suitable for providing rotative power in a corrosive environment at sea level, while burning Dieso instead of kerosene. Stringent noise and shock requirements must be met. Air and exhaust gas has to be ducted to and from the engine over a considerable distance and the controls and output transmission have to be integrated in the ship's system.

The typical problems involved and development required when making an aero gas turbine suitable for warship propulsion application are described based on recent extensive development experience.

It is outside the scope of this paper to describe in detail the development work that has taken place to make the aero gas turbine a successful marine propulsion unit, but the main areas requiring investigation are highlighted. They should be borne in mind when marinizing an aero gas turbine, developing modifications in order to lengthen the time between overhaul and drawing up operation and maintenance procedures.

INTRODUCTION

The arguments for using gas turbines in warships have been reiterated recently in the Parsons lecture of Mr. S. J. Palmer[1]. It is not thought that the fuel shortage will substantially change his arguments over the next decade.

The Tyne marinization project has been chosen to highlight the design and development required (Fig. 1). The reasons for this choice are:

a) The engine was converted direct from an aero engine to a marine engine, wholly funded by the Ministry of Defence, without an intermediate conversion to an industrial engine.
b) The initial stage of development of the Tyne RM1A has been successfully completed and ships are running with the engine. 600 h of development running have been completed.
c) Further development of the Tyne RM1A is taking place.
d) An uprating project, using advanced turbine blade cooling design and advanced, cast, corrosion resistant materials, has started.

The development running that has taken place can

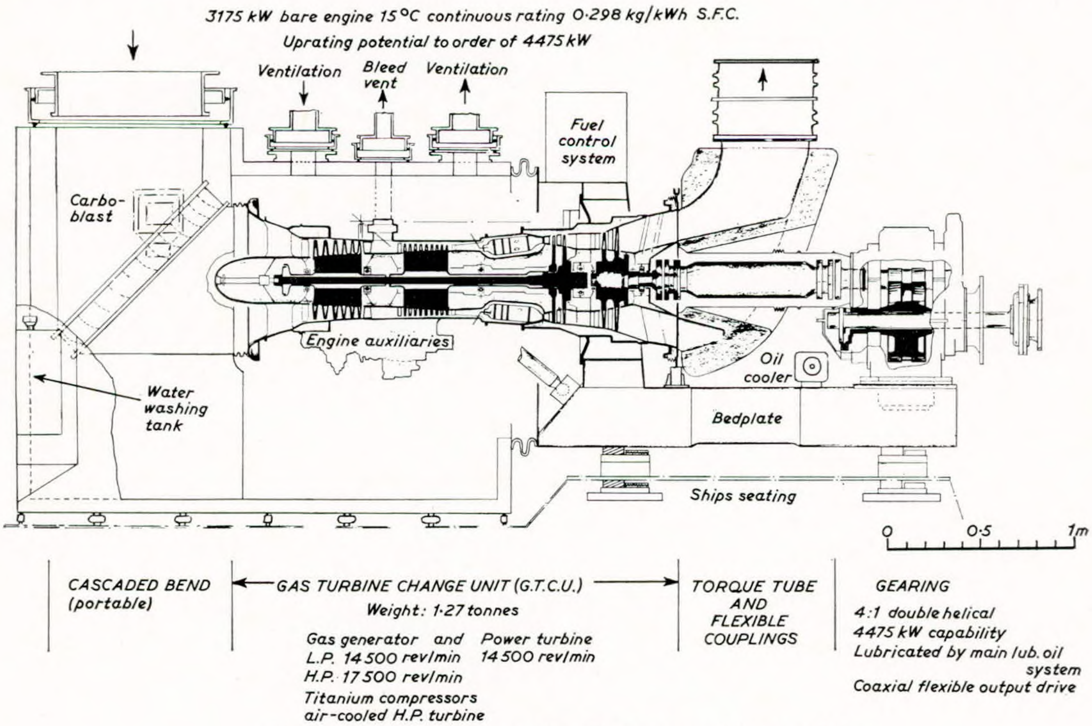


FIG. 1—*Free power turbine Tyne propulsion module*

be split into three phases, i.e. engine development at Ansty by Rolls-Royce (1971) Ltd, module development and endurance trials, simulating ship environment and installation, at Ansty and endurance trials at the Naval Marine Wing, National Gas Turbine Establishment at Pyestock. The development history has been described in (2) and (3).

The Tyne gas turbine will be used to provide cruise power for all surface warships presently planned and under construction for the British and Netherlands Navy.

CHOICE OF ENGINE

Obviously the choice of engine is first of all determined by the power required for the particular application. Unfortunately one of the basic characteristics of open cycle gas turbines is that the part load performance is poor. A characteristic curve is shown in Fig. 2. Surface ships of the 3000–4000 tonne range need in the order of 36 775 kW to achieve the required full speed of about 15 m/s. However, for about 80 per cent of the ship's life a cruising speed of about 9 m/s will not be exceeded, which coincides with the power requirement of approximately 5884 kW. According to Fig. 2 this would mean

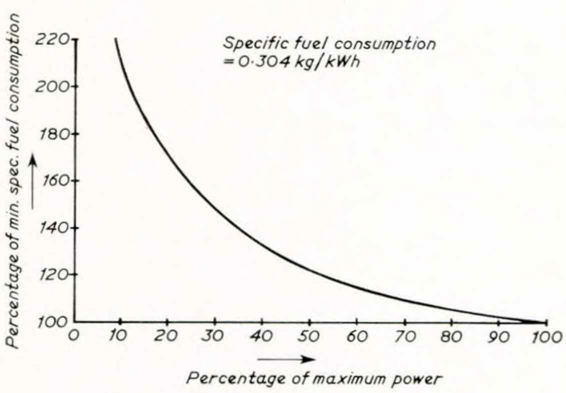


FIG. 2—*Specific fuel consumption—part load performance*

almost a doubling of the specific fuel consumption. This explains the need for a cruise gas turbine in addition to the main gas turbine. It is important that a cruise gas turbine should have a good specific fuel consumption in order to obtain an optimum range for the ship.

Non-technical reasons, such as supporting national or European industries, adequate logistical support (also in time of war), market potential and standardization of equipment play a very important role in the final choice.

Having decided on the type of engine required the following general requirements have to be fulfilled if a successful development is to be hoped for, bearing in mind that the development funds in the marine world are very small compared with the aero commitments:

a) The aero engine being considered needs to have extensive successful flight experience and needs to be still in service in order to obtain the maximum benefits in the marine application from the vast aero development funds, know-how, production capacity and rapid accumulation of running hours. The aero Tyne for example has accumulated about seven million hours.

b) The engine should not require major changes to make it suitable for marine application. While the next section will highlight the development areas of the marinization programme which should be considered when assessing the changes required, the study can be simplified by concentrating initially on only those modifications required to adapt the aero engine under consideration for industrial application, i.e. power conversion from jet energy to rotating energy at sea level. This will determine what power turbine is required and what compressor, bearing, support and casing changes are necessary. However past experience has shown that a second stage of the study, concentrating on marinization and typical warship requirements needs even more attention than previously given.

c) The engine should have considerable uprating capacity since experience shows that power requirements often rise above the original targets.

1) Since this paper concentrates on the typical marinization problems, the design changes in b) above will not be discussed in detail but some remarks are warranted on the power turbine design, since this area is crucial for the transmission in the marine application. A successful application of a reversing gas turbine does not exist and hence a reversing gearbox or a variable pitch propeller is required. In addition a low rotational speed of the propeller is required in order to obtain good propulsion efficiency. The choice between the two methods of providing astern power is determined by the power limitations of the CP propeller and relatively high underwater noise when working off design pitch on one hand and the bulk, weight, cost and mechanical complications of the reversing gearbox on the other hand. In both cases a considerable reduction of rev/min of the gas turbine output is required. A multi-stage power turbine alleviates this problem but is of course more complicated and expensive compared with a single stage turbine.

2) It is obvious that the choice is complicated bearing in mind that various other options exist and size and weight are at a high premium in warships.

3) In the case of the Tyne, which was a turbo prop in the aero application with the propeller driven by the LP compressor, the last two turbine stages were separated after removal of the propeller to form the power turbine in the marine application. This has the advantage that this part, proven in aero service, now forms a part of the gas turbine change unit. The high output speeds of up to 13 000 rev/min however made a separate 4 to 1 primary gearbox necessary. The high speed gearbox and its associated transmission presents some special problems in the marine application (see para on Transmission later). The rotational speed of the specially designed power turbine for the Olympus TM3B does not exceed 5600 rev/min.

PROBLEM AREAS OF MARINE GAS TURBINES

Corrosion

As reiterated in a recent paper for the Institute of Marine Engineers(4), corrosion is the main enemy of the marine gas turbine. Even with proper air intake filtration and careful fuel handling and treatment some sea salt will inevitably enter the gas turbine with the air and fuel. This will cause hot corrosion in the turbine area, corrosion of the compressor parts and casings and corrosion in the fuel system components. At present it is assumed that hot corrosion limits the engine life to 5000 h, depending on the operation pattern.

Hot Corrosion

a) Up to now high temperature nickel based materials are used for the forged high pressure turbine blades in marine gas turbines, i.e. *Nimonic 115* and *Nimonic 105/108*, which give adequate creep strength and reasonable corrosion resistance. Cobalt base materials are used for high pressure turbine nozzle guide vanes where less strength is required. (See Appendix 1).

b) It has been observed that the following factors influence sulphidation attack of the turbine components:

(1) Temperature (see Fig. 3). A pronounced corrosion peak occurs at about 830°C in rig tests. In engines accelerated corrosion has been observed at lower temperatures.

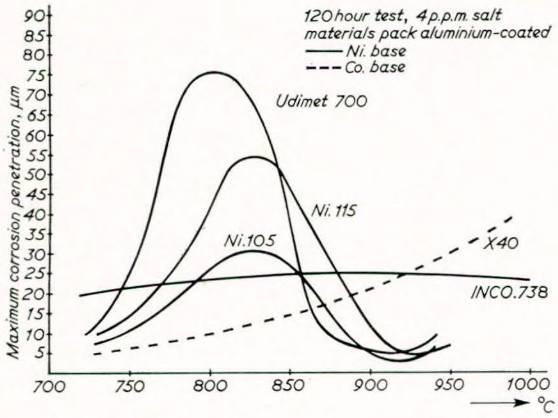


FIG. 3—*Hot corrosion—temperature effect*

(2) Gas velocity, i.e., in high velocity corrosion test rigs and engines considerably more corrosion takes place than in static or low velocity corrosion tests.
(3) The presence of sea salt accelerates the attack.
(4) Thermal cycling appears to accelerate hot corrosion attack.
(5) Time. Most notable with Nimonic 105 an incubation period seems present (Fig.4).

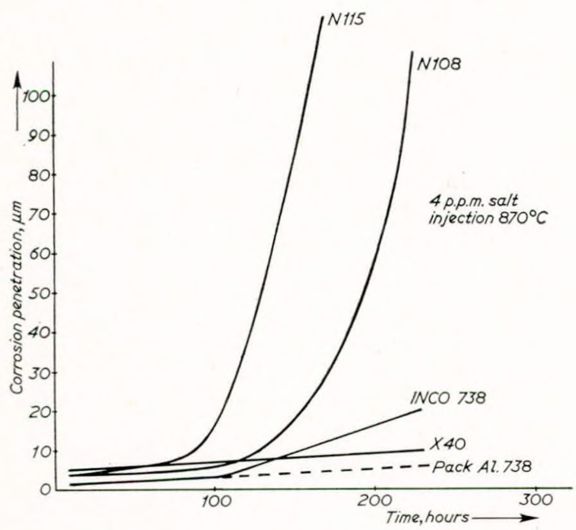


FIG. 4—*Hot corrosion—time effect*

(6) The effect of lowering the sulphur content of the fuel on the corrosion attack is minimal.
(7) A high chromium content (more than about 15 per cent) or cobalt content (more than about 21 per cent reduces the rate of attack.
(8) A high Titanium/Aluminium ratio (up to 3) and the addition of a rare earth reduces the rate of attack. The Molybdenum content should be kept below 1 per cent.
(9) The presence of carbon accelerates sulphidation attack. This list is by no means complete and obviously mechanical parameters, especially strength, operational parameters and production parameters, e.g. cast or forged, limit the freedom of choice of alloy.

c) It is necessary to construct a theoretical model fitting the observed facts before suitable countermeasures can be devised. For this purpose the Ministry of Defence has sponsored an extensive research programme in order to establish the mechanics of corrosion and to search for alloys and coatings resisting hot corrosion.

d) Mechanics of corrosion:
   (1) Sheffield University studies the formation and deposition of sodium sulphate in marine gas turbines and mass transfer and salt particle behaviour under simulated gas turbine conditions.
   (2) Imperial College studies the electro chemistry of hot corrosion.
   (3) Liverpool University studies the kinetics of hot corrosion and the effects of alloying elements on hot corrosion.
   (4) Newcastle University studies the addition of stable sulphide elements to metals in order to limit sulphidation.

The above work is supplemented by corrosion rig tests at the Admiralty Materials Laboratories and at the Derby and Bristol engine divisions of Rolls Royce, studies of protective oxide film behaviour at the Cranfield Institute of Technology and engine trials. The published results of most of this work are available[5]. Bearing in mind that by no means all experts agree on the precise process taking place during hot corrosion, the above mentioned research has clearly established the importance of chloride rather than sulphate in promoting rapid corrosion, especially if the salt particles are large.

e) The following simplified model is therefore proposed to explain the factors quoted above.
   (1) Sodium sulphate is formed in the combustion zone from the sea salt and sulphur present in fuel depositing as a molten slag on the hot metal.
   (2) The blade is protected by a layer of mainly chrome oxide. As long as a complete skin of protective chrome oxide is present only slow oxidation of the blade can take place. This may explain the incubation period in (5) above.
   (3) If the oxide layer can be penetrated nickel and chrome sulphides are formed, penetrating the base metal and depleting the metal of chromium. It appears that sodium chloride impacting on the blade, especially as large particles and at high velocity, can penetrate this oxide layer. The protective oxide layer is ruptured and the chloride evaporates or converts to sulphate. Rupture can also take place due to thermal cycling or shock.
   (4) Carbon particles can create reducing conditions locally, accelerating the attack perhaps by forming Na_2O from the sodium sulphate, which in turn combines with the stable chrome oxide to form sodium chromate. Lumps of carbon falling off the burner might possibly have an additional erosion effect.

This model is sufficient to explain most observed facts. Scientific justification is given [5, 6].

f) The model does not explain however why corrosion in service often occurs at a lower temperature than the peak of 830°C predicted in rig tests. While this might be caused by swamping of the temperature effect due to an excessive salt ingestion, e.g. in hovercrafts and fast patrol boats, it might be that aero dynamic and pressure effects in the actual engine change the temperature—corrosion relationship. Another possible explanation is that complex alkali compounds in the sea salt lower the melting point of the slag on the blade. There are indications that in engines no peak occurs but a gradual increase in attack takes place as the temperature rises, corrosion apparently being replaced by oxidation effects. Limiting the maximum blade metal temperature to 850°C for corrosion reasons, as is present practice, is therefore of doubtful value.

The other deficiency in the theoretical model is the inadequate explanation of the role of salt in fuel. There is definite engine experience indicating the harmful effects of salt in fuel[7]. This might be explained by assuming that "blobs" of salt water enter the combustion chamber due to a temporary failure of the coalescer or by the centrifuge effect and hence accumulating action of the fuelpumps. This will cause temporary high concentrations of sodium chloride (NaC1).

These anomalies are some of the reasons for embarking on a high pressure/high temperature corrosion rig project by the Ministry of Defence in order to simulate engine parameters as closely as possible, but having the advantage over the (expensive) engine trials of controlling all variables closely.

g) In the meantime the model is adequate to provide design and operational guidance and is in many instances confirmed as a workable hypothesis. A typical example is the comparison of Tyne endurance test results after 1500 hrs between trials at the Naval Marine Wing of the National Gas Turbine Establishment at Pyestock, Farnborough, Hants and Rolls Royce (1971) Ltd at Ansty. The time spent at each power band was equal in both tests, as was the installation and engine. The Ansty engine had a sea salt injection in air of 0·01 ppm NaCl for 20 per cent of the time. The Pyestock engine had a similar rate of salt in air injection for 50 per cent of the time. But in addition very finely dispersed salt water (0·3 ppm Na) was injected into the fuel for 50 per cent of the running time. In the Naval Marine Wing engine however the tighter requirement of a "cold" compressor wash at 24 hour intervals was closely adhered to while this was not the case during the initial 1500 h endurance running at Ansty. Microscopic inspection revealed that the X40 (see appendix). High Pressure Turbine nozzles and pack aluminized Nimonic 108 turbine blades were in a good condition after 500 h in the Pyestock engine but badly corroded on the pressure surface and eroded on the leading edge of the turbine blades in the Ansty engine. A further 1200 h running of the latter engine with salt injection in air, but with frequent "cold" washing revealed no significant further deterioration. It is apparent that frequent compressor washing and limiting the salt ingestion of 0·01 ppm NaCl in air prevents the accretion of NaCl in the compressor and subsequent damage to the protective chrome oxide layer of the turbine blades by impaction of large salt particles breaking off from the compressor blades. As long as ingestion of large slugs of salt water in the fuel is prevented and the sodium content in the fuel does not exceed 0·3 ppm it seems that excessive attack of the hot components due to salt in the fuel can be avoided. Both upper limits of permissible salt ingestion can be met in a marine environment with the latest three stage intake filtration equipment (an inertia separator for catching the coarse droplets, a second stage coalescing the fine droplets passing through the first stage and a third stage inertia separator to catch the coalesced droplets of the second stage) and fuel coalescers.

h) Trials are taking place to evaluate the effect of corrosion inhibition by additives in the fuel or air. In accordance with the theoretical model the aim is to combine the chloride particles with the additive to form a harmless vapour while excess additive is deposited on the blade to form a protective layer. Initial trials appear promising. If the solid additive particles injected in the air stream are smaller than 20 microns they could form a very good continuous compressor cleaning agent. The quantities required are of the order of 100 gr/h at a cost of approximately £60 per thousand hours.

i) Materials/alloys and coatings. The above described theoretical hot corrosion model can also provide guidance in the search for material and coating development providing better corrosion resistance (of course within the mechanical limitations i.e. aero dynamics and stress limitations of the turbine design). While the present forged Nimonics can be improved in corrosion resistance by applying coatings, a new family of materials i.e. cast *Inco 738* and cast *Inco 792* offer much better long term prospects (Fig. 5). *Inco 738* has a 16 per cent chrome content a higher Ti/Al ratio and lower Mo content than *Nimonic 105*, which is in line with para b) above. *Inco 792* contains only 13 per cent chrome and hence is stronger but the good corrosion resistance is still maintained due to the addition of up to 1 per cent of Hainium. (See Appendix 1). Both materials have shown in rig tests to improve the corrosion resistance of the nimonics by an order of magnitude. The Ministry of Defence has funded an investigation in these materials. The castability, especially, needs very detailed investigation and development. In addition the apparent reduction in creep strength due to the thin wall effect (cooled blades) and diffusing of Aluminide coatings is presently being studied. This problem has to be fully understood before the advanced cooled blade as presently manufactured for the uprated Tyne (Fig. 6) can be guaranteed to have a long life.

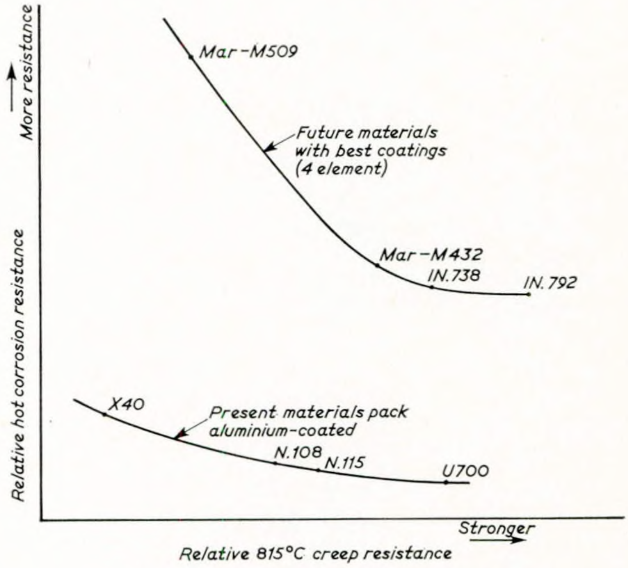


FIG. 5—*Creep/corrosion relationship*

In addition the Ministry of Defence has sponsored extensive testing and development of coatings. At present simple pack aluminizing is the only process used in the UK on marine gas turbines. These types of coatings, existing in a variety of composition, have reached the limit of their development. It is now recognized that the coating not only needs to be corrosion resistant but also erosion resistant. Furthermore it appears that in each case the inter-action between the coating and substrate needs to be studied carefully in order to achieve an optimum combination. The

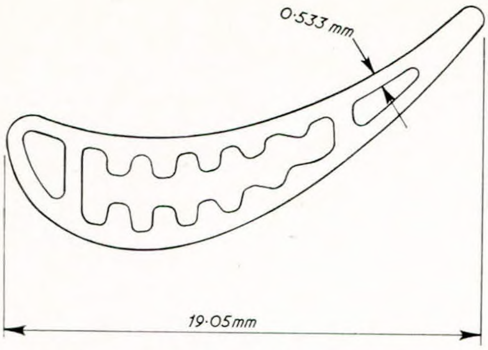


FIG. 6—*Tyne-cooled H.P. turbine blade*

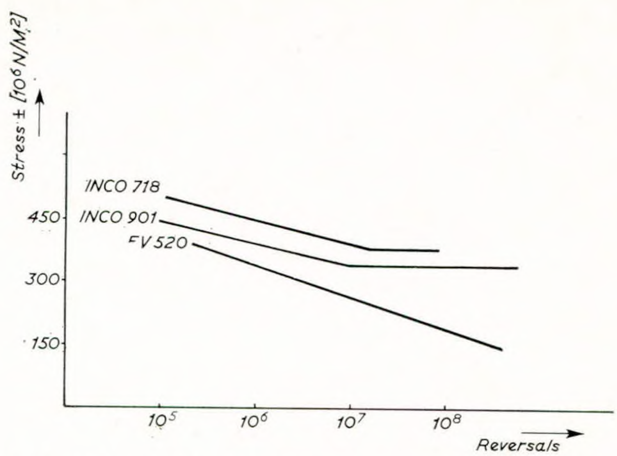


FIG. 7—*Fatigue life of compressor materials in a corrosion*

main problem with this type of coating is the diffusing heat treatment required in order to avoid cracking. The closely controlled treatment temperature should not exceed 1120°C. A drop in creep strength in the order of 40 per cent can be expected due to pack aluminizing.

New types of overlay coatings, e.g. combinations of Cobalt, Chromium, Aluminium, and Yttrium etc., seem to offer significant advantages due to their low application temperatures. However, expensive new techniques, i.e. electron beam vacuum evaporation, sputtering or ion plating are required in order to apply these coatings successfully. Nevertheless it appears that these coatings and techniques will be used more in future since they offer the prospect of applying excellent corrosion resistant coatings evenly outside and inside the hollow blades, possibly in combination with erosion resistant layers. Research in the application techniques of such coatings is being funded by the Ministry of Defence.

Compressor Corrosion

a) It was recognized in the past that magnesium and some aluminium components were not suitable for the marine environment. The initial Tyne evaluation trials at NMW-NGTE had shown that the coatings which could be applied to protect aluminium alloy blades of the compressor would not withstand erosive conditions.

b) *Titanium* (*IMI 318*) which has excellent corrosion resistance, low density and high strength at low temperatures was chosen as an alternative compressor blade material. Since there is a possibility that rubbing titanium components catch fire and titanium has a temperature limitation, the stator blades and last HP compressor rotor stages were made in stainless steel (15 per cent chrome, 6 per cent nickel, Firth Vicker 520 and 448) which was available at the time. It has since then been discovered that this material has no corrosion fatigue limit because the condensation of salt water droplets on the compressor blades can cause differential aeration which results in pitting of the steel. These pits act as notches and hence stress raisers (Fig. 7).

Nickel based materials, e.g. forged *Inco 718* (52 per cent nickel, 19 per cent chrome), and *Inco 901* are better high strength corrosion resistant alternatives in low temperature applications. *Inco 718* has been selected by the Ministry of Defence. (See Appendix 1). While the combination of *Inco 718* stators and titanium rotor blades will always give a long compressor life and hence smaller overhaul costs, the change to these materials is particularly important if high alternating stresses, say due to vibration, can occur somewhere in the running range. It is obvious that reducing cyclic stresses by changing the design can also prolong compressor life in a marine environment. It is worth noting that when considering material changes in the compressor the effects on bearing loads (function of total weight), whirling speed (function of $\sqrt{\text{total weight}}$) thermal expansion and vibrational characteristics have to be taken in account in addition to strength and stress considerations.

c) A cheaper palliative is the use of protective coatings which must be corrosion and erosion resistant. The most promising candidates are coatings of a type containing aluminium, preferably of sacrificial nature since the simpler lacquers (e.g. Rockhard) are not erosion resistant. The coatings however, e.g. PL 165 (aluminium filled polyimide), Sermetal W (aluminium filled inorganic binder) and Chromalloy A-12 (low temperature pack aluminizing) can give rise in certain applications to performance loss due to their thickness and surface roughness. While the capabilities and possible applications of these coatings have been investigated and all are being tried in the Tyne in Pyestock, it is a cautious policy to aim for a base material with optimum corrosion resistance. Coatings can, however, be successfully applied especially to casings and possibly to discs.
The injection of a water repellent fluid in the engine after shut down will reduce the condensation of water droplets and has been shown to be a successful palliative as well. WD 40 is used which is basically an organic liquid containing moisture dispersing additives and corrosion inhibitors.

Combustion

A heavier distillate, i.e. Dieso 47/20 to DEF/STAN 41/4 is used in marine gas turbines for cost and availability reasons instead of the kerosene burnt in aero gas turbines. This heavier distillate does not vapourize as well as kerosene since it is more difficult to break up. This results in more smoke, higher luminosity and hence more radiation.

Smoke

It is a prime objective in warships to have low exhaust smoke levels, not only for cosmetic reasons but especially to minimize the infra red signature which increases with an increase of carbon particles in the exhaust. A smoke level of *Bacharach 3* is aimed for (this means invisible exhaust smoke). To meet this requirement complete combustion and hence intensive mixing of air and fuel is required. This can be achieved partly by injecting the fuel droplets in a finely dispersed state, e.g. by high pressure fuel injection through fine nozzles with swirlers, air blast atomizing or the use of vaporizers. Obviously this has to be accompanied by a proper can design with its various air dilution holes. A higher primary zone air fuel ratio and a higher pressure drop will improve air penetration and mixing and hence reduce the smoke level. Especially increasing the overall pressure drop to 5 per cent and reducing the primary and secondary zone air fuel ratio to 22 has in practice shown, in the case of the Tyne, to be closely correlated to a reduction of smoke. Measurements with a *Hartridge* smoke meter might be more practicable since it can be done quicker and more objectively and give the values which are linearly related to carbon content in the smoke. (See Fig. 8 for correlation of Bacharach and Hartridge smoke units).

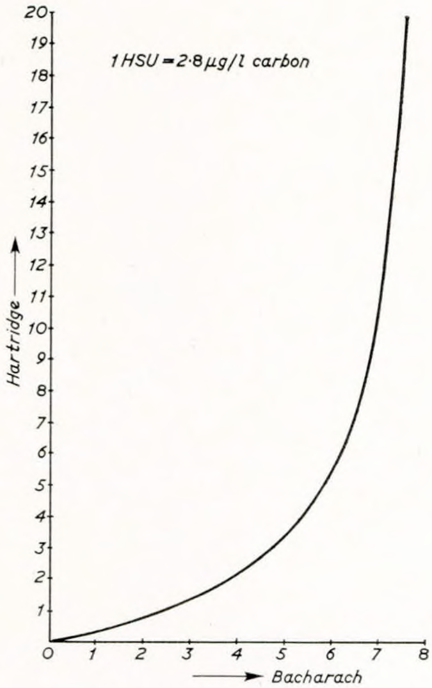


FIG. 8—*Smoke scales*

High Combustion Can Temperatures

Sophisticated cooling techniques must be employed in order to keep the metal temperature of the combustion can to an acceptable level in spite of the high radiation characteristics of the dieso flame. Nevertheless severe corrosion and burning of flares can still occur. In the Tyne this problem has been solved by introducing a multiple dish flare and changing the material from *C242* to *Stellite* (a similar material to that used in the HP turbine nozzle guide vanes, see Appendix 1). In the uprated Tyne additional film cooling is used to keep the metal temperature down. Since for efficient film cooling the cooling lip thickness to gap ratio must be low, this can be rather expensive in production (Fig. 9). Also local disturbances, e.g. due to location pins and thermal distortion can cause overheating. It is therefore to be expected that effusion cooling will be used more in the future. The casting of the complicated flares has been proved to be difficult.

Light Around

Particular attention has to be paid to the design and location of interconnectors in order to ensure good light around. A stronger starter motor can be an insurance against poor starting. The siting of the igniters has to take account of the differential fuel spray cone angle when using Dieso.

Outlet Temperature Profile

It is necessary to obtain a *temperature profile at the inlet of the HP turbine which is reasonably flat* in order to ensure a long blade creep life, bearing in mind that a 20°C higher temperature will halve the blade creep life. A radial outlet temperature distribution factor of 5 per cent is a good target (Fig. 10). The temperature peak should be at

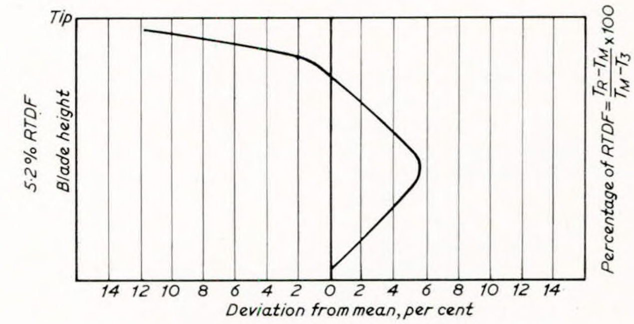


FIG. 10—*Radial temperature distribution*

about half blade height in order to obtain a maximum blade life. A flat radial temperature profile, however, causes higher combustion can wall temperatures. A suitable compromise must be achieved without impairing the combustion efficiency.

Burners

Burners can be prone to carbon build-up which is undesirable from the smoke and corrosion/erosion point of view. Development of a *fuel washed burner* is taking place in order to minimize this. In addition instability of Dieso at elevated temperatures can cause fuel break down which in turn can cause blockage of the burners or the filters in the burner arms. While obviously the time before burner blockage occurs can be prolonged by introducing more efficient filters, e.g. *Retimet filters,* a more fundamental approach is the isolation of the fuel from heat sources. The most critical place is the burner arm. A barrier, ceramic coating of this component might reduce this problem.

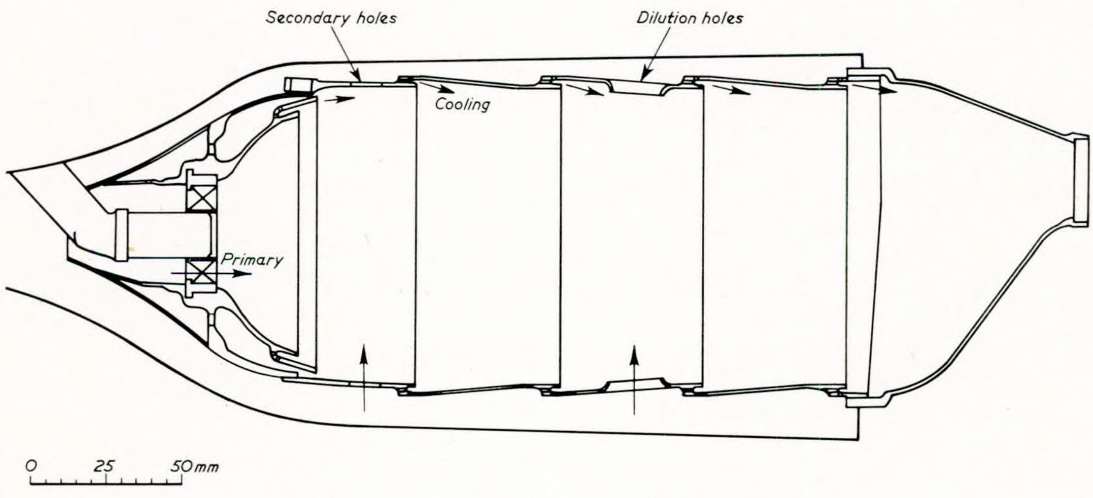


FIG. 9—*Tyne combustion can—With film cooling*

Control System

The marine gas turbine inherited from its industrial ancestor a hydraulic on-engine fuel control system, the hydraulic medium being the fuel. Basically a control loop is used with fuel quantity (throttle setting) as a demand and error signal together with various closed loops to protect the engine integrity by avoiding certain critical parameters. The fuel is injected in a controlled rate in order to avoid stall but at the same time providing maximum acceleration. This is not always an easy proposition in a ship's installation with its various air bleeds and intake and uptake disturbances. The solid state electronic ship control system is linked up to the on-engine control system in order to provide the necessary ship operating logic, e.g. pitch setting, engine changeover, installation protection etc. The ship's system as a whole is an open control loop with shaft rev/min as a demand signal, the loop being closed by the operator, when changes of the steady state are required. (Fig. 11).

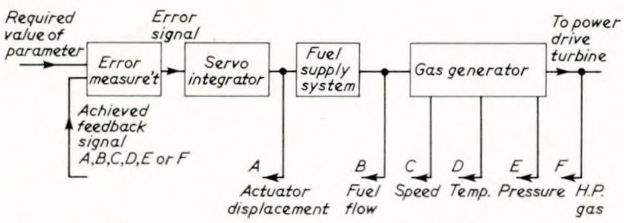


FIG. 11—*Basic gas generator control loop showing alternative feedback signals*

In [8] convincing arguments are given for using closed loop control, the engine using as main demand and feed back signal compressor delivery pressure (P3) and the ship using propeller thrust as the main controlled parameter (Fig. 12). It can be confirmed from Tyne endurance testing at Pyestock that P3 is a consistent and accurate signal, giving close correlation with power, even after considerable running time, with exhaust gas pressure (P6) as a possible alternative. Shaft power by torque measurement as a ship feed back signal in a closed ship control loop might also offer a possibility worth investigating.

Quite apart from the careful basic analysis required when deciding and designing a control system for a marine gas turbine some investigation must take place in the corrosion resistance of the fuel control system. It is assumed that in spite of the use of coalescers it will be unavoidable that occasionally salt water will enter the on-engine fuel control system. Not only has it been shown that this can reduce the life of the complicated fuel pumps drastically but it can also give rise to serious problems in the control system since the various small orifices can be blocked by salt and corrosion products. Development of components with improved corrosion resistance, the incorporation of filters and a regular maintenance routine can overcome these problems as does of course a sophisticated fuel handling system, eliminating the presence of water in the fuel control system but this is complicated, costly and in the latter case space consuming.

A better long term solution seems to be the use of a solid state electronic on-engine control possibly combined with fluidics. Not only for the reasons given in the paragraphs above but also in view of the fact that the present hydraulic system is space consuming and sensitive to shock and vibration. An electronic modular system would lend itself also more easily to modifications, fault finding and repair. Digital electronic on-engine control systems in conjunction with a mini-computer, warrant, in the opinion of the author, serious consideration for marine gas turbine applications.

Ducting

It has been established that great care should be taken in designing the ducting associated with marine gas turbines. Extensive model tests and full scale development testing have resulted in a Code of Practice for ducting design, laying down general rules, but since each new ship type requires its own ducting configuration, model testing for each new design is required.

The uptakes and downtakes for a gas turbine in a warship must meet the following general requirements:

a) Providing a smooth undisturbed flow path with minimum pressure loss, since 100 mm WG intake pressure loss results in 2 per cent power loss and 100 mm WG exhaust total pressure loss results in 1 per cent power loss. In both cases the specific fuel consumption penalty is 1 per cent. Obviously the shipbuilder wants a minimum amount of deck penetration, not necessarily directly above the gas turbines. Since the gas mass flow of the Tyne is 23 kg/sec (and the Olympus five times as much) and the exhaust gas temperature is up to 400°C, added to which the exhaust velocity distribution at the engine exit can be highly irregular, it is clear that some awkward compromises must be made. For guidance the following rules could be used.

1) Mean air velocity in the intake duct should not exceed 15 m/sec. In the exhaust duct this value can be taken three times as high.
2) In order to obtain a long life for the silencers the mean velocity within them should not be more than 1½ times the values quoted in (1).
3) The exhaust duct should be preferably circular in cross section.
4) Minimize changes in cross sectional shape.
5) Avoid changes of direction in general and in a diffusing section in particular.

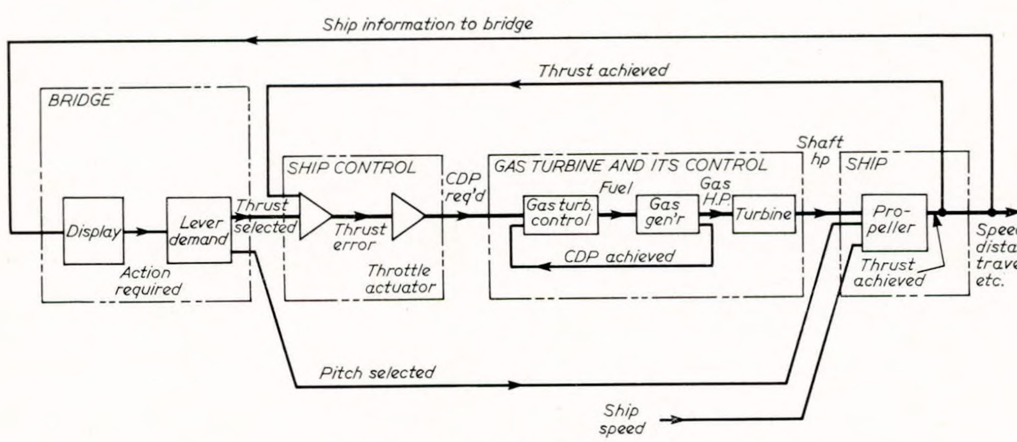


FIG. 12—*Overall ship's control system*

b) Housing the three stage air intake filtration required to keep the sea salt ingestion to a minimum as mentioned under Hot Corrosion g) above.
c) Housing the flat splitter silencers required to keep the air borne noise levels to a minimum.
d) Being blast resistant (a pressure fluctuation of about 1 bar within a couple of seconds).
e) Preventing the ingestion of foreign objects.
f) Preventing panel resonances and vibration. Especially the duct support feet can easily provide a path for a noise short but vibration attenuation in the long path of the ship's structure will not make it likely that this is a dominant source for underwater noise.
g) Providing adequate thermal expansion capability.

The high temperature and mass flow of gas turbine exhaust gases are a special concern. Not only could the hot exhaust plume melt the aerials mounted on the superstructure but it could also form a homing point for infra red guided missiles and create turbulence in the helicopter landing area. Ship wind tunnel tests are required to determine the optimum siting and direction of the uptakes.

The obvious solutions to all these problems are:
a) The minimizing of duct length, in the extreme, by siting the gas turbine on the deck level.
b) The cooling of exhaust gases.

While not immediately practical these solutions warrant consideration. Solution a) requires an electrical transmission. Solution b) could possibly be achieved by the use of waste heat boilers but much of the simplicity of the open cycle aero gas turbine propulsion plant would then be lost.

Noise and Shock

Noise reduction and shock protection are requirements of prime importance to warships. While reduction in engine room noise for habitability reasons and some resistance to shock due to violent ship movements are applicable to all marine installations, the Naval requirements are far more stringent. Meeting the ideal is virtually impossible and even meeting it partly is extremely complicated and costly. While this will not be elaborated it is obvious that one cannot isolate the gas turbine from the total ship system when designing shock and noise protection. The chain is just as strong as its weakest link and in view of the high cost of the protective measures this has to be borne in mind continuously when considering each link in the chain.

a) *Air borne noise* levels not exceeding grade E (about Nr 82), i.e. 82 dB at 1 kHz are desirable from the habitability point of view, but underwater noise is of prime concern in a warship. It is thought that airborne noise below approximately Nr 100 does not contribute significantly to this underwater noise, but even reducing the noise to this fairly high level requires considerable sound isolation. In the case of the Tyne this is accomplished by the sound proof gas generator enclosure. But since the heat radiation of the enclosed area is about 1 per cent engine power this poses considerable cooling problems.
b) *Underwater noise* is undesirable for the following reasons.

1) Submarine detection.
2) Activation of acoustic mines.
3) Attraction of homing torpedoes.

The contribution of gas turbines to the underwater noise is mainly through vibration transmitted through its support. This can be reduced by introducing noise attenuating mountings. This will, however, increase the vibration on the gas turbine itself and since the noise attenuating mounting must have a low stiffness also, alignment problems will be created and the possibility of instability, i.e. large movements due to external low frequency (less than 10 Hz) oscillatory forces (gas forces, propeller excitation) coinciding with the natural frequency of the resilient mounting system exists.

c) *Shock attenuation.* One of the most difficult problems for the engine system designer is to design a propulsion system which can withstand large shock inputs. The aim is to design a propulsion system which just comes to a grinding halt as the ship sinks (full hull lethality). The latter will happen if the ship is subjected to a shock acceleration of hundreds of "*g*". It is out of the question to redesign the lightweight aero engine to meet these shock acceleration levels. In fact the marine Tyne gas turbine was designed by the manufacturer to withstand 40*g* vertical, which was already a formidable task, bearing in mind that all the engine mounted accessories, electric components, fuel system and enclosure have to be designed to meet this target and to be tested accordingly. The small clearances between rotating and stationary components of the gas turbine and the maximum permissible stress levels are the main limitations in improving the shock resistance. Fortunately shock loading times are mostly only a few milliseconds. However, a mounting system is necessary which can not only absorb the difference between the maximum shock inputs at the engine seatings and the maximum shock resistance of the gas turbine, but also restore the engine after the violent shock movement to its originally aligned position.
d) *Mounting systems.* To meet requirements of para b) and c) two systems can be considered:

1) *Active mounting system.* Nearly complete align-

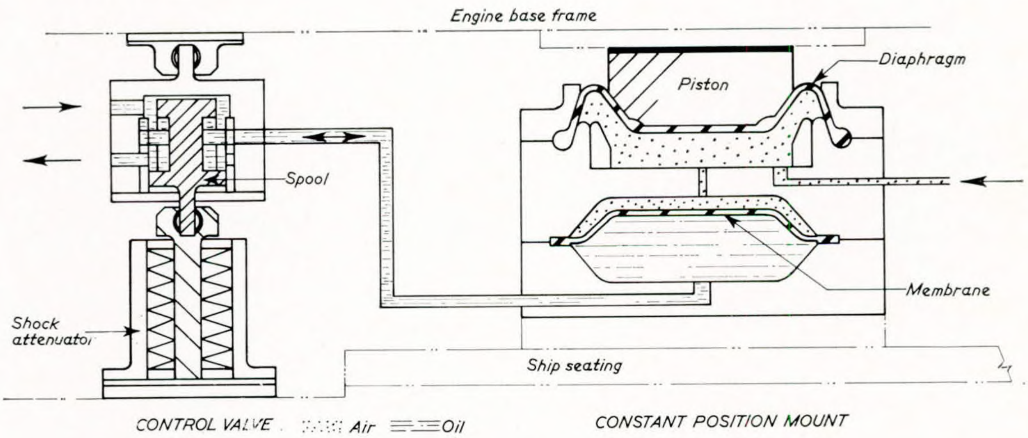
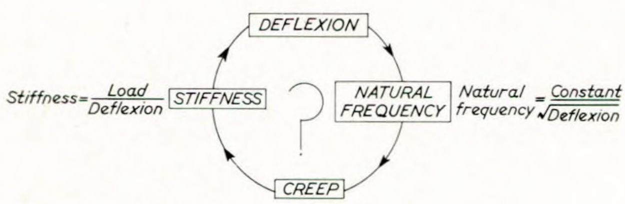


FIG. 13

ment of the gas turbine to the rigidly mounted main gearbox can be ensured in spite of the large variations in gas forces, torque forces, etc., over the power range and randomly varying gravitational forces due to ship movement, by a hydraulic system controlled by displacement measurements. An air cushion will provide the necessary noise attenuation (Fig. 13). This constant position mounting system requires in parallel shock attenuation and is complex and costly, but is predictable in its behaviour under dynamic conditions and provides excellent alignment of the high speed output shaft of the gas turbine to the gearbox. A constant force crushing device in parallel can provide the necessary shock attenuation and the full travel permitted by the transient deflexion capability of the flexible output shaft couplings can be utilized for shock energy dissipation.

2) *Passive mounting system*. The Tyne uses a rubber mounting system which is simpler and cheaper and still has good noise attenuating characteristics. To arrive at a rubber mounting design which is a satisfactory compromise between alignment, shock and noise attenuation, is however not easy. For good alignment and a stable mounting system the stiffness of the rubber should be high, but then the noise attenuation and shock absorption is low. The picture is further complicated by the fact that the natural frequency of the system should not coincide with that of any of the oscillatory forces mentioned in the section on underwater noise and the fact that secondary creep causing long term malalignment is worse with low stiffness rubber (see Fig. 14). The crucial question really is how



Variation of variables

STIFFNESS	DEFLEXION	NATURAL FREQUENCY	CREEP
High	Low	High	Good
Low	High	Low	Bad

FIG. 14—*The vicious circle*

much malalignment one can permit between the engine and gearbox, bearing in mind that the effects of seaway movement are large and not accurately predictable. The output shaft speed of the Tyne power turbine is 13 000 rev/min and it is obvious that a malalignment between the Tyne and its primary gearbox must be kept to a minimum. This is achieved by mounting the gas turbine and primary gearbox on one raft. Raft mounting of the main gearbox carries however severe space penalties and is complicated. Much depends on the predicted high speed line characteristics in making the final choice between a rubber and a Constant Position Mount System (CMPS) and predictions are not always accurate. I suggest however that with good flexible couplings with low angular stiffness and hence little cross coupling that misalignment if within the flexible coupling capabilities is not as important as suspected. Tyne malalignment trials substantiate this fact. If this is so the balance tips definitely in favour of a lower mount stiffness, mainly for shock considerations. The maximum shock movement allowed is limited by the transient malalignment capabilities of the flexible coupling, and this should be equal to the total shock movement caused by the underwater shock (see para c above). Within this deflexion capability the rubber mountings have to absorb the difference of shock energy input to the seating and the engine shock absorption capability. In other words the mounting system must not transmit a larger force to the engine than the shock acceleration capability of engine times the mass of the engine as "seen" by the mounts at the end of the permissible travel of the output flange. Rubber mounts in compression stiffen however under deflexion.

Above 10 per cent compression this happens exponentially. Bearing in mind that the rubber mounting system is already compressed due to engine loads which also takes away some of the coupling deflexion capability available, there is only a limited percentage of the mounting thickness available for shock attenuation before the rubber mount becomes virtually solid. The CPMS is in that respect in a slightly better position. With a very thick low stiffness mount there is obviously more shock attenuation capability, especially if parallel constant force crushing devices are used. But in order to keep the alignment over the running range within reason and the natural frequency high enough, this would imply very large mounts with bad mounting system stability under seaway movements. Furthermore it can be concluded that it is an advantage if the rubber mounting system "sees" a large mass (virtual mass), bearing in mind its characteristic of rapidly stiffening up. This virtual mass is smaller than the actual mass of engine and varying due to its flexibility. Increasing the actual mass by mounting the gas turbine and its gearbox on one raft, as is done with the Tyne, is obviously beneficial from the shock point of view, if the raft is stiff enough to treat gas turbine and gearbox as one mass.

Lastly it should be mentioned that the manufacture of rubber mounts needs close quality control in order to maintain a reasonable tolerance of stiffness, avoid delamination of the rubber under shock and to ensure adequate bonding of the rubber to the metal backing plate. The alignment of a rubber mounting system will always be a complicated problem since it is a 6 degree of freedom system. But low cost and simplicity are powerful incentives to continue the presently Ministry of Defence sponsored rubber mount development.

3) Possible alternative could be, especially in view of the stringent shock requirements, a simple hydraulic shock absorbing mount with a rubber pad for noise attenuation on top, or the incorporation of constant force shock attenuation capability in the CPM system.

Transmission.

An area warranting detailed system analysis when considering marinization of an aero gas turbine is the transmission system. This is obviously closely associated with the previously discussed mounting system chosen.

Since the main gearbox is generally solidly mounted, some form of flexible transmission between the gas turbine and the gearbox is required. The output shaft speeds of the gas turbine are often high as previously stated.

It is self evident that critical speeds must be avoided in the running range. The calculated critical speed should be at least 20 per cent above the maximum running speed in order to provide a safe margin. The mathematical model used for these calculations however needs careful consideration taking proper account of the stiffness of the flexible couplings and bearings. Generally speaking the critical speed is dependent on the mass, centre of gravity, (and hence the length) and stiffness of the flexible transmission shaft, the bearing stiffness and the bearing dimensions. Engine room geometry limits the freedom of choice considerably with regard to the torque tube length. If the options to raise the resonance above the running speed are listed the usual need of a compromise will be evident.

a) A stiffer transmission shaft, by increasing the diameter, will increase the hoop stresses of the high speed shaft. Strengthening to cater for this will increase the mass and reduce the critical speed.

b) Lightening the shaft, within the strength capabilities of known shaft materials, is limited in its scope due to stress limitations and the construction of the flexible coupling assemblies. Furthermore there is a real danger that a very light output shaft will give rise to a very lightly loaded power turbine bearing. If this is a plain bearing this can cause bearing instability, i.e. half speed whirl. An anti-whirl bearing, such as a lemon bore bearing, will cure this.

c) A bigger diameter bearing will give higher critical speeds but the bearing dimensions are obviously determined among other things by the load and maximum rubbing speeds and hence the maximum surface temperature permissible.

Estimates of bearing stiffness tend to be rather on the high side. It appears that a stiffness of 350 times 10^6 N/m (2×10^6 lb/in) is a fair guess at the Tyne primary gearbox bearing stiffness, which is 40 per cent lower than originally estimated.

The high rotational speeds and consequent high rubbing speeds also give rise to high bearing metal surface temperatures in plain and tilting pad bearings. This can also be the case in the thrust surfaces of gearbox location bearings if the thrust loads imposed by thermal expansion are underestimated. This can cause two interesting but undesirable results, i.e.:

a) The white metal bearings show faceting (ratcheting), a uni-directional growth of tin crystals at high temperature showing up as a rough surface.

b) The white metal shows signs of corrosion, resulting in cracks, in certain installations. The design loadings of the gear teeth assume the presence of a "high pressure" dope in the lubrication oil (OEP 69), but since this is a chlorinated wax, high local temperatures in the bearing oil film can cause a breakdown of this dope resulting in the formation of Hydrochloric acid and hence bearing corrosion attack. Some installations appear more prone to this attack than others and the presence of copper ions is suspected to act as a poisoner.

While both phenomena and their long term effects are by no means completely understood it seems prudent to avoid them with the following actions:

a) Reducing the temperature of the bearing by routeing the oil directly from the inlet to the hot bearing. Reducing the inlet temperature of the oil to the bearing by 2°C will lower the metal surface temperature by approximately 1°C in the case of the Tyne gearbox pinion. In thrust pad bearings this can be done by a directed oil feed instead of flooding the thrust bearing with oil.

b) In plain bearings the application of a circumferential oil groove in the unloaded half of the bearing will reduce the temperature by approximately 14°C in the case of the Tyne gearbox pinion bearing.

c) Increasing the thrust carrying capacity of the surface of gearbox location bearings by the incorporation of a tapered land bearing will reduce the metal surface temperature.

d) The use of AS 45 (40 per cent Sn rest A1) in bearings will increase their corrosion resistance, avoid facetting and the material has also better fatigue and load carrying capacities. A lead based bearing offers a slightly inferior alternative.

e) Possible other methods of reducing the maximum bearing temperatures could be the increase of the angle between oil entry and loading point, the increase of bearing width and increase of clearance.

CONCLUSIONS

When considering an aero gas turbine for conversion to a propulsion plant for a warship the following areas need close consideration and development apart from the more obvious mechanical changes required to convert jet energy to rotative power:

a) Material changes to improve corrosion resistance. It is the opinion of the author that there is presently enough knowledge available to make a proper choice of materials. Especially the new cast super-alloys, e.g. Inco 738 and Inco 792 with appropriate complex coatings promise enough hot corrosion resistance, if adequate air intake filtration and fuel treatment is provided and regular compressor washing will take place in service, to obviate the necessity to impose a life limitation on the engine for corrosion reasons.

b) Combustion modifications in order to enable the marine gas turbine to burn Dieso smoke free over a wide range of power, while maintaining adequate life of combustion hardware. It appears that extensive rig testing is necessary. Adequate pressure drop over the combustion can is required to ensure low smoke levels. Multi dish flares are required to keep flare temperature down and Stellite is required as flare material in order to obtain a long life combustion can. In addition can cooling has to be incorporated without deteriorating the outlet temperature distribution. Effusion cooling shows more future promise than the presently used film cooling. The problem of can distortion and burner carboning has to be overcome.

c) Control system design with special investigation into the improvement of component corrosion resistance and ability to accept considerable contamination besides the more obvious analysis of control parameters and method of control of the gas turbine within the ship system, providing optimum response but avoiding stall problems at the same time. A solid state electronic digital control possibly combined with fluidics is believed to offer real advantages for the control of a gas turbine in a warship application.

d) Ducting design requires model testing. While aero dynamic considerations are of prime importance, thermal expansion warrants detailed analysis as well. Since the blast requirements dictate that the uptakes and connecting bellows are stiff the thermal forces exerted on the gas turbine can be quite considerable. The use of blast-proof soft exhaust bellows is highly recommended.

e) Noise and shock requirements make a detailed analysis of the acoustic treatments and in particular the mounting system design necessary. Perhaps in the past not enough emphasis was placed on an overall ship system design. While in a narrow sense the proper design of the transmission system will ease the alignment requirements and hence make a simpler rubber mounting system more attractive, in a wider sense the cost and effectiveness of all noise and shock countermeasures in the ship has to be assessed and the weakest link to be improved first. For example a marginal improvement of the shock resistance of the gas turbine can be very costly and to little avail if the seating on which it is mounted collapses before the limit of the turbine shock resistance is reached.

f) Finally the transmission system needs careful design, especially if the output speed of the power turbine is high. The possibility of a lower speed multi-stage power turbine becomes more attractive in the light of the problems associated with high rotating speeds and hence high bearing temperatures.

When hearing all these changes required to make the aero gas turbine suitable for warship propulsion, one might easily wonder if it would not be more easy to design a marine gas turbine from scratch. This is certainly not the case. The main areas, problems and consequent developments described are only a minute proportion of the total investment which has gone into the initial development and subsequent well proving of these aero gas turbines. Similar developments from scratch and proving a new marine gas turbine would involve at least as great a total investment again. The conversion work described does however substantiate the author's opinion that there must be strong reasons indeed to change to a new type of gas turbine or ship for that matter. The complicated and costly logistics are further good arguments to stick to the once chosen gas turbine and spend development money on improving this one by introducing minor modifications or embarking on uprating projects in order to improve the engine capability and hence life. This will also enable the build up of extensive background data on the engine which will make health monitoring and fault diagnosis more accurate and easy.

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Appendix

Nimonic 105

A creep resisting nickel based forging alloy for service at temperature up to about 940°C, containing 15% Chromium (Cr), 20% Cobalt (Co), 1·2% Titanium (Ti), 5% Molybdenum (Mo), 4·7% Aluminium (Al), the balance being Nickel (Ni).

Nimonic 108

Similar to Nimonic 105 but with closer compositional control and/or different melting techniques applied.

Nimonic 115

A Vacuum-processed creep-resisting nickel based forging alloy for service at temperatures up to about 1010°C, containing 15% Cr, 15% Co, 4% Ti, 3·5% Mo, 5% Al, the balance being Ni.

Inco 738

A high temperature creep-resisting nickel based casting alloy, containing 16% Cr, 8·5% Co, 3·4% Ti, 1·75% Mo, 3·4% Al, 0·9% Niobium (Nb), 2·6% Tungsten (W), the balance being Ni.

Inco 792

A high temperature creep-resisting nickel base casting alloy, containing 12·5% Cr, 9% Co, 4% Ti, 2% Mo, 3·5% Al, 4% W, 4% Tantalum (Ta), 1% Hafnium (Hf), the balance being Ni.

X 40 (Stellite)

A high temperature oxidation and corrosion resistant cobalt base material containing 10% Ni, 25% Cr, 7·5% W, the balance being Co.

C 242

A heat resisting, nickel based casting alloy, containing 20·5% Cr, 10% Co, 10% Mo, the balance being Ni.

Inco 718

A vacuum processed alloy with exceptionally high tensile, yield, creep and rupture strength up to 400°C in the single aged condition, containing 52% Ni, 19% Cr,, 3% Mo, 1% Ti, 5% Nb + Ta, the balance being iron.

Inco 901.

A vacuum-processed precipitation-hardening alloy, containing 42% Ni, 12·5% Cr, 5·7% Mo, 3% Ti, the balance being iron.

Discussion

MR. W. J. R. THOMAS, F.I.Mar.E., said that on behalf of all present he congratulated the author on an excellent, interesting and most informative paper, written and delivered in impeccable English.

After several years in the Gas Turbine Section of the British Ministry of Defence in Bath, on loan service from the Royal Netherlands Navy, the author was now the Engineer Officer of a steam driven frigate. He hoped he would be forgiven if he quoted from a letter he had received from the author recently, stating: "One month on board a steam ship has convinced me again we are following the right track with gas turbines. All those leaking drains, flanges, and what have you". He said he would not read any more otherwise those listening would be too saddened at what this gas turbine enthusiast was suffering.

The paper described in considerable detail many of the fascinating problems which arose in marinizing an aircraft gas turbine. There was little in it to quarrel with. It described factually a fascinating process. The Tyne, in particular, had required a fairly major re-design of the bearing systems for the two spools, involving as it did the removal of the aircraft propeller drive. It was very much to the credit of the design team concerned (and in this he included the Navy personnel who had collaborated) that the marine version had proved so trouble-free during development running.

He then said it was worth mentioning that the Tyne primary gearbox ratio had been selected to give roughly the same output revolutions per minute at full power as had the Olympus gas turbine at the same power. Thus it was possible for the secondary gearbox maker to use a common pinion for the two gas turbines, should he so wish.

He then corrected a small error which occurred in the paper. There the author had said that "The Tyne gas turbine will be used to provide cruise power for all surface warships presently planned and under construction for the British and Netherlands Navy". In fact, this should refer to frigates and destroyers because, for instance, the Olympus would provide the cruise power for the Through Deck Cruiser now being built at the Vickers Yard at Barrow-in-Furness.

Marine gas turbines had to suffer conditions unknown in the air. A great deal of the paper therefore rightly dealt with corrosion, to which the gas turbine, with its high cycle temperatures, was particularly prone. Research and development on materials and coatings could be handsomely repaid in terms of increased engine life. Similarly, the work undertaken jointly by the Royal Navy and by the contributor's company, Rolls-Royce, in testing air intake filtration systems could yield a dividend out of all proportion to its cost. Shore testing, with salt injection into both fuel and air, had been invaluable and there had been the benefit of seagoing experience in hovercraft—a terrible environment—and also in H.M.S. *Exmouth*.

Despite what the author had said, many of the problems he had described were not new. Corrosion, noise and even smoke had been known in steamships. In fact, the contributor said he used to measure the amount of smoke he had been making when he was Senior Engineer of *Ark Royal* by the captain's face rather than *Bacharach*. Some of the problems undoubtedly were to do with fast rotating machinery, and it did not matter whether one had a steam or gas turbine; it was always difficult to maintain alignment with gearing when the turbine must be on anti-vibration mountings and needed also to withstand violent ship motions and severe underwater shocks. Few marine engineers had not suffered scuffing or even welding of turbine flexible couplings, so this was not a new problems.

He said he did not entirely agree with the author when he said that he preferred rubber to the constant position mounting system. The active constant position mounting system described in the paper, although admittedly complex and relatively costly, offered the possibility of good alignment even after underwater shock. It was known that the engine would take the shock because it had been tested in the shock barge. It was critically important ensuring that the rest of the system had the same capability.

He agreed with the author when he said that change should be avoided for change's sake. Perhaps this, too, applied to controls. He said that he, for one, preferred not to have the task of persuading the average seaman to ask for thrust or torque instead of revolutions per minute. He said that in many four shafted ships in which he had served he had found great difficulty in getting one torsion meter to read within 20 per cent of any other; he questioned whether torque or thrust would be a sensible feed-back to use.

Perhaps the greatest advantage to the naval engineers of the increasing use of gas turbines lay in the degree of standardization which could be achieved. For example, there were five separate classes of warships built, building or being designed which were using Olympus and Tyne COGOG machinery. 125 Olympus and 79 Tyne engines had been ordered for naval use. A continuing programme of product improvement could be planned logically which should have ensured a steady increase in mean achieved life and hence a reduction in hourly operating costs. The work of marinization described in the paper was not the end of the road but the beginning. There was a lot of work still to be done and he was sure that it would prove economic in the long-run.

MR. E. A. BRIDLE, M.I.Mar.E., said that his company had been closely associated with the application of marinized aircraft gas turbines to warship propulsion, both for the Royal Navy and for other navies, including that of the author.

He congratulated the author on an excellent review of British developments up to the present day with a few brief glimpses into the future, and said he would confine his remarks to three aspects of the paper.

The first of these was corrosion and creep resistance. At first glance, Fig. 5 suggested a real break-through in materials development. However, the comparison in Fig. 5 was given for 815°C, which was just about the area where the peak referred to by the author occurred (i.e. the one shown in Fig. 3). Figure 3 also suggested that the corrosion resistance of the *Nimonics* might be considerably better at somewhat higher temperatures. The author himself had suggested that the blade temperature might be unnecessarily limited to 850°C. It would be useful if the author could comment on whether or not the picture shown in Fig. 5 looked any different at, say, 850°C and 950°C.

Two of the new materials shown in Fig. 5, namely *Mar-M432* and *Mar-M509*, were not mentioned elsewhere in the paper. Could the author give more information on these two materials?

Referring to ducting, the author had made a passing reference to the effect on uptake design of what he called a highly irregular velocity profile at the engine exhaust. One might, perhaps naïvely, be surprised that this was still a problem in view of the large numbers of industrial gas turbines built over the last 30 years with the same type of exhaust configuration. On the other hand, one of the rival American designs did not seem to suffer from this problem, and the makers of the General Electric *LM 2500* claimed a relatively good exhaust velocity profile from the power turbine. This was no doubt largely due to their use of a multi-stage power turbine, with its relatively lower blade speeds and gas velocities. Could the author comment on the extent to which the poor distribution he referred to was associated firstly with the use of a power turbine with only one, or at the most two, stages, and secondly on possible constraints placed on the engine designer on the amount of space occupied by the exhaust volute for warship applications. Looking at Fig. 1, for example, the exhaust volute from the power turbine looked very cramped compared to the space allowed for the intake, even allowing for the greater sensitivity of the compressor to flow disturbances.

In the section of the paper dealing with transmission, the author referred to another advantage of a multi-stage power turbine in avoiding transmission problems associated with high rotational speeds. In particular, he referred to the problem of lightly loaded high speed bearings. An interesting paper on this subject had been given to the ASME by Rentzepis and Sternlicht. Their results showed how the threshold speed for the instability of a lightly loaded bearing could be related to the bearing clearance and eccentricity, and with an eccentricity ratio below 0·6 a simple rule of thumb emerged from their results. This suggested that the threshold speed in revolutions per minute for a typical journal bearing was very roughly equal to 500 divided by the square root of the radial clearance in inches. If one took typical bearing clearances for the type of bearing used in the British gas turbine designs, the rule suggested that trouble might be expected with speeds in the region of about 6000 revolutions per minute. A multi-stage turbine in which the speed was likely to be considerably lower than 6000 rev/min would therefore tend to be free from this trouble, and was helped, in fact, by its heavier weight, which tended to give more "respectable" loads on the bearings. The advantages in avoiding transmission and bearing problems were likely to outweigh any difficulties associated with the need to have a buried bearing at the hot end of the longer and heavier turbine. However, since the present generation of British naval gas turbines had high speed lightweight overhung turbines, one had to face the ensuing problems.

One of the problems referred to by the author was that of whirling, and he referred to the use of mathematical models in the analysis of whirling problems. One could question whether, in fact, complex mathematical models were always necessary for whirling analyses: the damping effect of the bearing oil films generally tended to suppress any tendency to whirl until the flexural movements of the shaft became large compared with the movements of the journal, so that in practice the actual whirling speed always tended to coincide with the flexural critical speed. Therefore, provided that an analysis based on rigid bearings and simple supports gave an adequate margin over the running speed, the design should be satisfactory. However, if a full analysis was thought necessary (and this was a point which the author had stressed to some extent) it was most important to take account of all the various stiffnesses and damping factors particularly those in which there was a coupling effect between vertical and horizontal movements. If one tried to aim at a "half way house" between the simple solution and the rigorous solution, one was likely to get very misleading results.

COMMANDER T. R. SHAW, F.I.Mar.E., said the paper had been inevitably written several months ago, like all papers for learned societies and professional institutions, and the only up-dating needed was to say that it was still all true. Shortly after he had written it, the author had become a real sailor again and had left the British Ministry of Defence. Since that time the Tyne engine, for the development of which the author had been largely responsible, had continued to operate very satisfactorily, both at sea and in further endurance running ashore. The *Daily Telegraph* of July 4th had carried a photograph of both *Amazon* and *Sheffield* at sea together.

He said he would like to make two comments on the paper, one supporting it and the other extending it. One of the points made on blade materials, namely the postulated mechanism of corrosion by the impaction of salt particles, had been raised a few months previously in a paper that the author had co-authored in the United States. This had been at a conference specifically on the material aspects of marine gas turbines, and subsequent discussion had shown that the author's hypothesis had been generally supported.

The scope of the present paper had included two kinds of peculiarities that a marine gas turbine possessed:

a) special design features inherent in making it operate in the marine environment;
b) certain characteristics that enabled it to interface with the rest of the ship.

There was yet a third peculiarity of aero-derived marine gas turbines which, although it was outside the intended scope of the paper, deserved mention at a meeting of marine engineers. It was the upkeep and logistic support area. In order to take full advantage of the ability to reduce downtime by changing the main engine very rapidly instead of refitting it on board, there must be, and was, a stock of spare engines in store, an organization for despatching them by air to the ship in any part of the world, and a documented drill for the engine change itself, together with the associated commissioning procedure. In this respect the Navy had become more similar to the airlines of the world, although there were still one or two differences. The Navy had, he knew, rescued holiday-makers from Cyprus in 1974, but that was not their main business.

MR. M. HARTNELL-BEAVIS, said that his company had been closely involved in the design and development of the noise, vibration and shock measures applied to the Tyne module. He thought it would be of interest if he made a few comments on the choice between the rubber and air mounting systems described in the author's excellent paper. This had probably been made more interesting by the fact that on the one hand Bill Thomas was advocating CPMS and on the other hand Rudi Lutje-Schipolt had been advocating rubber. Rubber presented many problems and these had been reviewed recently in an excellent survey in the Journal of Naval Engineering, June, 1974, by L. A. Ward. MoD (PE) had placed a contract with the contributor's company to establish a basis for the prediction of rubber mountings for the gas turbine module with consistent and satisfactory properties.

Initial tests on a number of nominally identical mountings indicated variations from the nominal mounting stiffness of 50 per cent or more. A large deviation from the nominal stiffness had been associated with a shortfall in rubber quality. A tendency to de-lamination had occurred in high stiffness samples and to excessive hysteresis in low stiffness samples. It had been established that the first requirement was proper quality control during manufacture. Test samples provided by the Natural Rubber Producers Research Association had shown that with close control a design precision of 10 per cent or better on stiffness could be realized.

The general investigation into the properties of the NRPRA test samples had provided design formulae and procedures and an understanding of the behaviour of the mountings under impactive (shock) loading.

Consistent mounting properties could be obtained only if a good bond was made between the rubber and its mating surfaces. Under controlled laboratory conditions this could be achieved using a suitable adhesive, but under factory production conditions chemical bonding was required. It was believed that the new module mountings would be satisfactory under normal operating conditions at sea, but they failed to provide adequate shock protection against severe underwater explosions due to the rapid "stiffening up" with compression. Whether these mounts would exhibit satisfactory long term creep behaviour under operating conditions could only be confirmed when they had been at sea for some time.

TABLE I—MOUNTING SYSTEM OPTIMIZATION PROBLEM INPUT DATA

1. Mounted Item Parameters:	Dimensions, weight, C.G. Movement limits (seaway and shock) Shock capability
2. Static Input Forces:	Torque and gas loads Exhaust bellows cold/hot forces and stiffness
3. Dynamic Forces:	Seaway motion limits (position of ship) Major internal vibration forces
4. Seating Shock Motion:	Design maximum shock motions (vertical, transverse) as a function of reaction loadings
5. Vibration/Radiated and Self Noise Targets:	Source levels (versus speed): seating point and transfer mobilities; levels of other essential machinery.

Optimization of a marine mounting system was a more complicated process than might appear at first sight. Table I listed some of the input data to the problem of optimization. This problem was generally simplified by considering first the seaway and shock vertical and athwartship motions, assuming these to be decoupled, and finally designing the full six degree of freedom system when the field had been narrowed down. The requirements effecting the choice were generally interdependant. For example, vibration attenuation must be considered in relation to the levels from other essential machinery. The Tyne drove through the main gearbox, itself solidly bolted to the ship seating, and the minimum mount attenuation requirement was to match the Tyne vibration transmission to that of the gearbox. Provided that due attention was paid to the provision of a high impedance seating, the required attenuation could be obtained with a relatively stiff (high natural frequency) system. This meant that the seaway relative motion could be satisfactorily reduced while still achieving adequate vibration attenuation, and this strongly influenced the choice in favour of the simple passive rubber mounting system.

The constant position mounting system as illustrated schematically in Fig. 13 of the paper was considered as an alternative mainly because of its potential in reducing relative seaway movement, absence of creep and its high damping at resonance. The system had been originally developed by the contributor's company for mounting large rafted main machinery installations, and it was relevant to note some of the system characteristics. The control valve of Fig. 13 had been made with a small overlap and became inoperative for frequencies slightly above the resonance frequency. Hence, from the point of view of vibration attenuation, the CPMS could be compared with a passive system of the same "passive" natural frequency. The natural frequency of a mass supported on an air mount depended only on the mount height and was given approximately by:

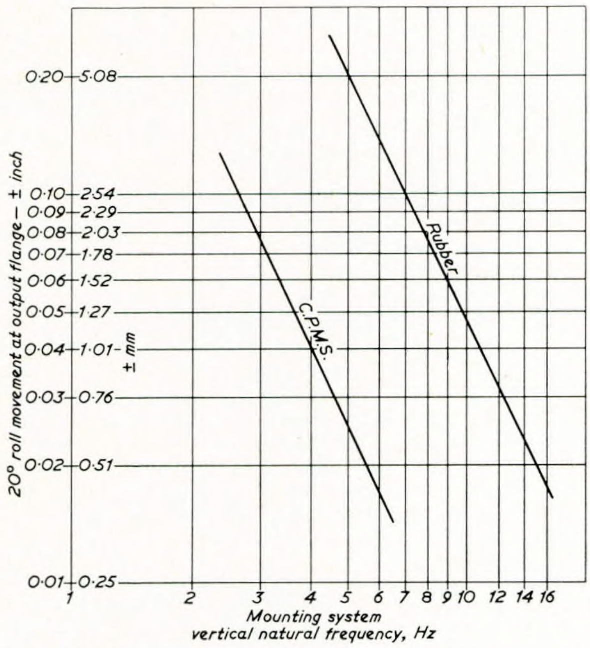

FIG. 15—*Tyne module approximate seaway movement under 20° roll*

$$f_n = \frac{3}{\sqrt{h}}$$

where h was the clearance in inches between the piston and mount base in the mount illustrated in Fig. 13. Hence the clearance was about 1 inch (25 mm) for a 3 Hz system, but only about 0·1 inch (3 mm) for a 10 Hz system. Since adequate internal shock clearance must be provided, an upper limit to the natural frequency was about 6 Hz.

There was a practical stability limit to the sensitivity of the control feedback loop provided by the control valve of Fig. 13. Taking this into account, a reduction of seaway movement by a factor of about seven could be obtained in practice, comparing the CPMS seaway response with that of a passive rubber system of the same natural frequency, as shown in Fig. 15. From this figure it could be seen that if a 16 Hz rubber system adequately attenuated vibration, the CPMS gave little or no advantage in respect of reduction of seaway movement, although shock protection could be significantly improved if constant force shock mounts were installed in parallel with the CP mounts.

The Tyne could be satisfactorily supported on four vertical rubber mounts. A disadvantage of the CPMS, which became more pronounced for a small mounted item such as the Tyne module, was that fore–aft and athwartship mounts and control valves were required to provide movement reduction in these directions.

Running experience with the Tyne on rubber mounts had shown that they exhibited adequate resonance damping. Thus most of the attractive characteristics of the CPMS, particularly its potentially high vibration attenuation and high load capacity per mount, could not be applied with advantage to the Tyne module. The first choice in this case must be the simplest possible rubber mount system, with possibly added shock refinements, and with the CPMS as a back-up system should unexpected difficulties with the rubber system materialize during long term operation at sea.

MR J. CLIFFE said he was concerned with the marine application of turbines not for ships but for offshore structures, particularly North Sea platforms. He said he would like the author's comments on extending his experience to the application of turbines in this field. A figure of 500h life would not be considered acceptable for this application. He was looking for something around 20 000h. The type of fuel used would be largely gas although there would be short periods of operation in liquid fuels, including the possibility of crude fuels. Water spray was not considered to be a problem for a platform because it was felt that the relative humidity might be more important, particularly relative humidities of around 75 per cent or below. This might cause difficulty in removing salt, even in a three stage filter. He said he would like the author's comments on this.

Also, once a sulphidation attack had started was it considered to be self-sustaining? Did it continue with the engine shut down?

MR. L. A. WARD endorsed what Mr. Hartnell-Beavis had said from their company's point of view about the hopeful adequacy of a rubber mounting system for gas turbines generally. He said his particular sphere of interest had been with the Olympus engine, although, as Mr. Hartnell-Beavis had said, the Tyne had shown adequate performance on rubber. Referring to Mr. Thomas' remark that a rubber mounting system gave inadequate restoration of alignment after shock, he said that with a rubber mounting system, the principle achievement of it after shock was to restore alignment to within a sensible tolerance.

He said he would like to very briefly go round the vicious circle (Fig. 14) to expand what had already been said. Starting at the top of the circle, deflexion at nominal load, was a principle design parameter which needed to be directly related to the amount of misalignment deflexion that the flexible coupling could withstand between the engine and the gearbox. This, in turn, determined the amount of motion that could be tolerated by the mounting system under shock. Of course, the laws of nature being what they were, the amount of deflexion resulting from shock was fairly large in comparison with that which could be accepted by the deflexion capability of the coupling. Therefore, one had a compromise to meet even on deflexion.

Deflexion, in turn, gave an indication of natural frequency which had been set, determined the performance of the system from a noise attenuation point of view and also determined its response to vibration excitation.

Mounting deflexion, temperature, established the properties of the mounting rubber, determined the amount of creep which the system would have exhibited, and hence the effect on the long term engine/gearbox alignment. The amount of creep occurring in a rubber mounting system must be kept to a low absolute value, particularly since it was highly desirable to ensure that the engine did not need to have its mounting system shimmed or replaced over a refit period. To minimize the effect of creep initial system, alignment would be set slightly high then as creep occurred the alignment would slowly pass through the optimum alignment position to a slightly low position.

Finally stiffness was also related to the other parameters discussed. The purpose of his comment was to indicate that in designing a rubber mounting system for marine gas turbines one would never arrive at a perfect solution.

MR. P. A. KNOWLES, M.I.Mar.E., said that his interest was directed towards the treatment of air and fuel.

Conclusion (a) dealing with hot corrosion resistance was that the new super-alloys were satisfactory but this was conditioned on adequate air and fuel treatment. Rolls Royce, as mentioned in the paper, had set limits of 0·01 ppm of sodium in the airstream and 0·3 ppm in the fuel. He asked the author if this was really being achieved in practice? It seemed that it was not, because the author mentioned large particles came off the air filters, and large slugs passed through the fuel coalescers. If this were so, obviously some further development was required on the treatment equipment. Assuming the set limits were being achieved, how could one measure these very low levels whilst at sea? Were there instruments available with sufficient sensitivity and robust enough for seagoing conditions?

Conclusion (c) dealt with another aspect of corrosion in the control system. The author seemed to favour, in the short term, better corrosion resistant materials because present coalescers passed water under certain conditions. But even if coalescers could be designed to give water free fuel under all conditions, problems could still arise during shut down periods when, on cooling down, dissolved water in the fuel would precipitate out and settle in pipes and components.

The author believed that a better long term solution lay in the use of solid state electronics. However, whatever the mode the final controlling component must surely be a mechanical valve which would be subject to corrosion.

Accepting the present limitations of air and fuel treatment, what was the author's opinion on the chances of the development of a corrosion resistant aero gas turbine?

Author's Reply

The author, in reply, thanked Mr. Thomas for his flattering remarks. The author favoured rubber mounting system since it was a cheap and adequate solution, taking all ship system limitations in account. If proper quality control had taken place full alignment could be restored with a rubber mounting system. It remained to be seen if a CPM could achieve the same. While Mr. Thomas' doubts regarding the accuracy of torsion meters was understandable, the author was reliably informed that in Holland nowadays, accurate torsion meters are commercially available.

The author was grateful for the amplifications on the mounting systems by Mr. Hartnell-Beavis and Mr. Ward. The author would like to re-emphasize that the ultimate choice should not solely depend on technical merits but also on economics, weighing carefully the priorities of meeting the staff targets of the complete system. Bearing this in mind, a properly designed rubber mounting system could be satisfactory for a gas turbine of Olympus size as well. A strict quality control was, however, imperative.

Mr. Bridle had asked some interesting questions about corrosion and creep at higher temperatures. Obviously, the paper was not the place to explain all the test results in detail. However, a paper given at the conference to which Commander Shaw had referred, had described all the test results the Ministry had obtained on these materials. *Inco 738* had not shown a pronounced peak in sulphidation attack in laboratory tests. There were no indications yet that it would do so in full scale engine tests. Engine trials had started with *Inco 738* to verify this, but a significant improvement of the *Nimonics* were expected. With an increase of temperature, oxidation replaced corrosion, the attack increasing with an increase in temperature, but without a "peak" of sulphidation attack unlike the *Nimonics*. At much higher temperatures the *Nimonics* would be superior, but since running at lower power and hence temperatures could not be avoided, these materials were not preferred in the long term.

The author had mentioned some materials in the figures without elaborating on them: these were materials tried as back-up materials with the Tyne RMIC development. *Mar-M509* was a cobalt material. *Mar-M432* was an alternative to *Inco 738*. Both materials were good in corrosion but showed casting difficulties.

The irregularities of the exhaust gas velocity profile could be explained by the shape of the exhaust volute and ducting lay-out. As Mr. Bridle probably knew it was one of the staff requirements to have an accessible journal bearing as an Olympus power turbine bearing, which resulted in an awkward volute shape. The Tyne did not suffer from this design compromise. Due to the cramped space in European warships the ducting lay-out could not be perfect. Perhaps USN warships had less financial and hence space limitations. This comment applied as well to the multi-stage power turbine concept, i.e. this might be technically desirable but expensive and space consuming.

The author agreed with Mr. Bridle's last point about whirling problems. It was, however, also true to say that this was not necessarily a serious problem. There were fairly simple cures described in the paper which had been tested and worked perfectly well. They did not have to be used because the problem as such did not warrant further counter measures.

He said it was difficult to express a strong opinion on the critical speed calculations. It was fact that simplified analysis often proved to provide too inaccurate predictions.

Most important in the Tyne high speed application where things initially went wrong was the bearing stiffness assumption, which was too high. The author preferred a fairly thorough analysis of the transmission system in order to provide as accurate a prediction as possible. On top of that a safety margin of 20 per cent was recommended.

The author agreed with Commander Shaw's point about upkeep and logistics. One of the major reasons for choosing gas turbines was because there was a large degree of standardization possible and by proper and well organized support there was the possibility in the future that the Navy could be able to work in a more planned manner. In fact a naval ship was supposed to work in rather arduous conditions and also in times of chaos, and if there were enough standardized spares available it was hoped and expected that the downtime would be reduced.

In reply to Mr. Cliffe's questions: for offshore structure applications the gas turbines discussed had to be downrated. A long time between overhaul was quite possible bearing the Avon gas turbine experience in mind, especially when running on gas. Since on a platform the space distribution could be better, many problems described in the paper would not apply which would improve the expected engine life substantially, especially since much more steady running would take place. The author did not share Mr. Cliffe's belief that spray would be less of a problem. Experience had shown him that fine spray was a problem existing in the application referred to by Mr. Cliffe. Adequate filtration could cope with this problem.

Sulphidation attack was not self-sustaining under shutdown conditions, but the prime concern was to avoid damage of the protective layer on the blades.

Turning to Mr. Knowles' points, the author noted that the permissible salt limits mentioned, such as 0·01 ppm sodium chloride in the air and in the fuel were limits chosen because they could be met. With correct air filtration and proper working coalescers the author believed these limits could indeed be met, if not 100 per cent of the time certainly 90 per cent of the time. It was also true to say that this was not a continuous level of contamination that was experienced. This was the peak level of contamination which should not be exceeded, and this level had been chosen in hindsight wisely. At the time it was chosen because one thought that it was an achieveable level of filtration. It was not the intention that one should measure the salt level at sea. The intention was to develop an air and fuel inlet filtration which, with a certain realistic amount of salt injection, would reduce the level to the level required. Of course further improvements were desirable and development was continuing. Nevertheless a build-up of salt on the compressor blades would still take place and hence the need for a regular engine wash.

The corrosion process could never be entirely stopped in a sea environment, but the rate could be reduced by proper design and the effects minimized. This was quite feasible in the way suggested in the paper.

A corrosion free aero gas turbine would never be built, since this would not be cost effective. Creep would still be a life limitation. Long life aero gas turbines exist already.