FUEL SAVING

IS WASTE HEAT THE ANSWER?

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Introduction

During the design of a new warship, it is important to examine many features of the ship's performance and costs. Most aspects of ship design are interactive and so a false picture can be obtained if a single design aspect is examined in isolation. However, before a ship design can be progressed very far, information on particular features must be made available at a time when much of the design will be unknown or poorly defined. The required information must therefore be produced, if not in total isolation from other design aspects, at least well removed from them.

It is in this environment that the merits of fuel saving using the heat in the exhaust gas from the propulsion gas turbines to generate steam which is expanded in a steam turbine and forms a combined gas and steam propulsion system (COGAS*) were approached. The precise proportion of a ship's through-life cost that is due to fuel costs depends on many design and operational features, but for a frigate at sea today a figure in the range 10-15% would not be uncommon[1]. COGAS is potentially much more efficient than the propulsion installation types that predominate at sea with the R.N. now.

Designers and manufacturers of propulsion plant are fully aware of the importance of propulsion system efficiency to their customers, and this is evidenced by the progressive improvements in specific fuel consumption—this being the inverse of efficiency—which engine manufacturers have been achieving by design refinement. In the highly competitive diesel engine market, this performance characteristic has received enormous attention, and has resulted not only in the power unit itself being made more fuel-efficient, but has also placed emphasis on various heat recovery schemes which produce improvements in overall system efficiency.

This approach, when applied to waste heat recovery from the exhaust gas of propulsion gas turbines, has given rise to a combined cycle of gas and steam. In a naval context, perhaps the best known installation of this type is the U.S. Navy RACER system (RAnkine Cycle Energy Recovery) considered for the DDG51 Class of ships [2, 3, 4].

The comparison of propulsion installation designs in terms of their fuel efficiency, however, must be undertaken on a carefully defined basis if valid conclusions are to be reached. If the same operating profile for the ship is used as a common basis for comparing the annual fuel consumption of each different machinery installation (which is the integration over the year of

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*This definition of COGAS should not be confused with the use of the term to denote an installation of gas and steam turbines independent except for the combination of their output shaft power, as in the GMDs and H.M.S. *Bristol*.

specific fuel consumption, power level, and time spent at each power level), then it is obvious that a change in any of these parameters may result in a change in the annual figure.

Thus a system design change which alters the power level available when a particular configuration of engines is driving, may well alter the cumulative time spent annually in that drive mode, and hence have an effect on annual fuel consumption. This change will be superimposed on that resulting directly from any improvement in specific fuel consumption of the engines themselves.

Similarly, operational procedures and practices must also be considered and can affect the total annual fuel consumption achievable with modified machinery configurations. For example, it can be assumed that for a fairly high proportion of the time spent at low powers and speeds (well within the power level available from a single engine in a multi-engine two propeller shaft ship), a ship will operate with power to both shafts and with two engines connected even though it may be more fuel efficient to operate on one engine with the other shaft trailing.

When importance is placed on savings offered by cruise operation on a single shaft while trailing the other, elimination or reduction of trailing losses (up to 20% in power) by effecting a power cross-connection from the driving engine can be seen to be worthwhile. This can be done mechanically using a cross-connect gearbox, or in a waste heat, combined cycle installation it may be possible to use the steam generated in the exhaust of the driving gas turbine to drive a steam turbine arranged on the other shaft. Numerous other schemes for achieving this objective have also been devised.

While these and other practical operational considerations may seem merely to confuse the comparison required between the fuel efficiency of one installation and that of another, unless they are allowed for on a rational basis improvements in efficiency which appear possible in theory may prove to be unrealizable in practice or be masked by some other indirect effect. Often the value of the savings can be significantly reduced when taken over the annual operation of the ship.

These are important considerations when placing contending machinery configurations in an order of merit and when assessing the allocation of resources to machinery development programmes which have the saving of fuel as their principal aim.

This was the background to some recent work undertaken within the Directorate of Marine Engineering at Bath to examine the potential of various propulsion machinery systems. There is a continual need to examine all types of propulsion machinery to ensure that developments in the various fields which could alter the balance of advantage of one type over another do not go unnoticed. Change from one type of propulsion system to another carries with it various penalties to the infrastructure, e.g. the need for new stocks of spares, new training courses, etc., and so only when the potential gain of a new propulsion type is great is a change likely. This particular examination of propulsion systems was to assess the implications of a COGAS fit in various arrangements both in terms of the advantages which they might offer if tailored to a particular future class of ship or foreseeable operational requirement, and also in terms of their relative merit when compared with other installation designs.

The all gas turbine (COGOG) fit of Tyne RM1C and Olympus TM3B, the basis of the Royal Navy frigate and destroyer machinery programme over many years, was adopted as a reference for comparison with possible future all gas turbine (COGAG) fits employing the SM1A.

These in turn provided a basis against which the potential benefits of introducing diesel engines (in CODOG and CODAG arrangements) could be assessed; all diesel fits (CODAD) were also examined to establish just how far diesel economy could be taken.

Having established the improvements in economy arising from the use of conventional, commercially available propulsion equipments, the merits of developing waste heat recovery systems (COGAS) similar in principle to the U.S.N. RACER scheme, but based upon the SM1A gas turbine, were assessed.

Combined Diesel and Gas Turbine Machinery

The lightweight high-speed diesel engine has been widely accepted in overseas warship propulsion machinery designs, principally on account of the fuel economy which can be achieved in cruise operation. There is an extensive literature dealing with the many facets of the design of diesel installations for warship applications, including the increasingly important aspect of noise and vibration suppression[5, 6]; it is proposed to concentrate upon the effect which diesel machinery has on economy of operation, although of course it is accepted that other design or operational requirements may well dominate in the particular circumstances of a ship design.

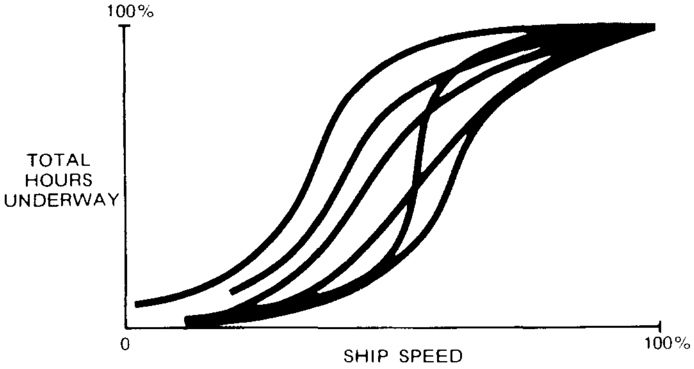


FIG. 1—WARSHIP OPERATING PROFILES
Reproduced from reference 7

Warship operating profiles are many and varied (see FIG. 1) but whenever a warship has a substantial peacetime cruise role, perhaps amounting to 80% of the total ship hours at sea using cruise power or below, then the introduction of dedicated, fuel efficient cruise diesel(s) to a gas turbine fit can have a dramatic effect in reduction of boost engine utilization and hence on fuel usage and stowage.

An all diesel engine fit (CODAD) presents even greater scope for fuel economy, although comparable high ship speeds may only be attainable by using the more complex highly turbo-charged engine designs which may introduce penalties in overhaul life, maintenance load, and fuel consumption.

Comparison of COGAG machinery, comprising two large gas turbines, with a CODOG fit in which a single cruise diesel had been added, showed that during peacetime cruise operations, annual running hours of each gas turbine fell from over 2000 hours to just over 100 hours, diesel engine operating hours accounting for the difference. As combat-readiness of the ship increases, however, with greater periods of time being spent at higher speeds, the running hours of the gas turbines increased dramatically to account for about two-thirds of total time underway.

Until recently, the power of available diesel engines has been low relative to that of naval gas turbines; thus an additive arrangement (CODAG) yielded

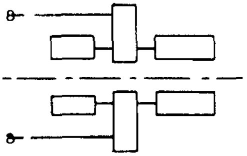
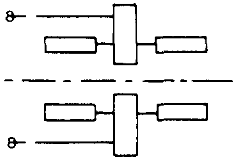
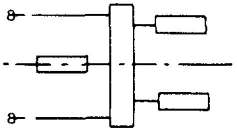
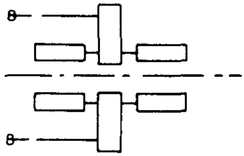
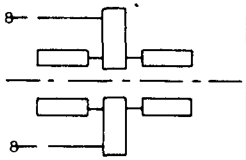
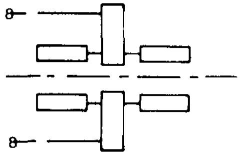
Machinery Configuration	COGOG	COGAG	COGAG	CODOG	CODAG	CODAD
Propulsion Machinery	2 Tyne RMIC 2 Olympus TM3B	4 Spey SM1A	3 Spey SM1A	2 Diesels 2 RB211	2 Diesels 2 Spey SM1A (2 speed gearing)	4 Diesels
Machinery Arrangement						
Operating Modes	1 RM1C (trailing shaft) or 2 RM1C or 2 TM3B	1 SM1A (trailing shaft) or 2 SM1A or 4 SM1A	1 SM1A or 2 SM1A or 3 SM1A	2 Diesels or 2 RB211	2 Diesels or 2 RB211 or 2 Diesels + 2 RB211	2 Diesels or 4 Diesels
Fuel Usage on Operating Profile Including Auxiliaries	Basis	-9%	-14%	-21%	-30%	-30%
Maximum Ship Speed knots	Basis	+1½	-½	Same	-½	+1
Machinery Weight tonne	Basis	+50	-30	+90	+60	+70
Fuel Stowage tonne	Basis	-10	-60	-160	-150	-110
Total tonne	Basis	+40	-90	-70	-90	-40

FIG. 2—THE DIESEL ALTERNATIVE TO ALL GAS TURBINE MACHINERY

little increase in the top speed of the ship, thereby providing little incentive for the development of CODAG machinery for ships of frigate size.

With the advent of diesel engines of higher power output, (now available up to almost 7.5 MW) suitable for naval applications, the CODAG arrangement becomes much more worthwhile; it can be expected to become a serious alternative to the hitherto more common CODOG arrangement.

FIG. 2 illustrates the order of savings in annual fuel usage likely to be achievable with various diesel schemes when compared first with the traditional all gas turbine fit of Tyne and Olympus, and then with the possible future combinations of 3 × SM1A gas turbines (COGAG, with combining gearbox) and 4 × SM1A gas turbines, COGAG.

Compared with the most economic of the all gas turbine schemes (3 × SM1A, COGAG), the combined diesel schemes offer further potential savings in fuel usage in the range 8% (CODOG) to 18% (CODAG and CODAD).

The main reason why the CODAG and CODAD machinery fits show similar fuel usage rates is the need in the CODAD fit to use highly turbo-charged engines (to give the power required) which have a higher fuel consumption than the single turbo-charged engines in the CODAG fit.

While some development of suitable gearing and transmission should be anticipated if any of these combined diesel schemes were to be adopted as basis for a warship machinery installation, the development risk would be low. A wide range of well-proven diesel engines exists commercially from which a suitable match with ship requirements can be achieved.

Combined Gas Turbine and Steam Machinery

It is against this background that the introduction of combined cycle plant, based on the generation of steam for propulsion from the gas turbine exhaust gases, must be assessed. Not only will the fuel savings with COGAS plant be compared with other options available but the status of plant design (especially heat exchanger design) must be considered, and a view formed of the scale of the development work necessary to provide robust marine equipment.

Simple cycle gas turbine installation designs typically found in frigates and destroyers have in common the rejection, via the exhaust gas flow, of a substantial proportion of the total energy being generated at any time. The precise proportion varies with power, but is approximately 60% at the full power rating of the SM1A gas turbine of 12.75 MW(no loss). This is high grade energy, with exhaust gas temperatures in the range 300° to 400°C plus, again depending upon the particular gas turbine and the operating power level. It is worth considering the possibility of recovering some of this energy by generating steam and then combining gas turbine and steam turbine power outputs, whether to increase total power (and hence slightly increase ship speed) for a given gas turbine power, or to permit the required gas turbine power level to be reduced for a given ship speed.

The specific fuel consumption (s.f.c.) curves of a typical simple cycle gas turbine and typical diesel are shown in FIG. 3. As can be seen, the diesel curve is reasonably flat over the usable power range while the simple cycle gas turbine has a rapidly rising s.f.c. as power demand drops. This poor part load efficiency of a simple cycle gas turbine makes running the gas turbine at part load undesirable for fuel efficiency reasons. The COGAS plant has a much flatter s.f.c. curve than that of a simple cycle gas turbine.

Such waste heat recovery schemes have been considered for naval application on a number of previous occasions but were always found to be of limited attraction because of the increased complexity of installation and operation which they introduced; while some penalties of these types must be expected, the value today of fuel savings may alter the relative priority attached to the factors involved.

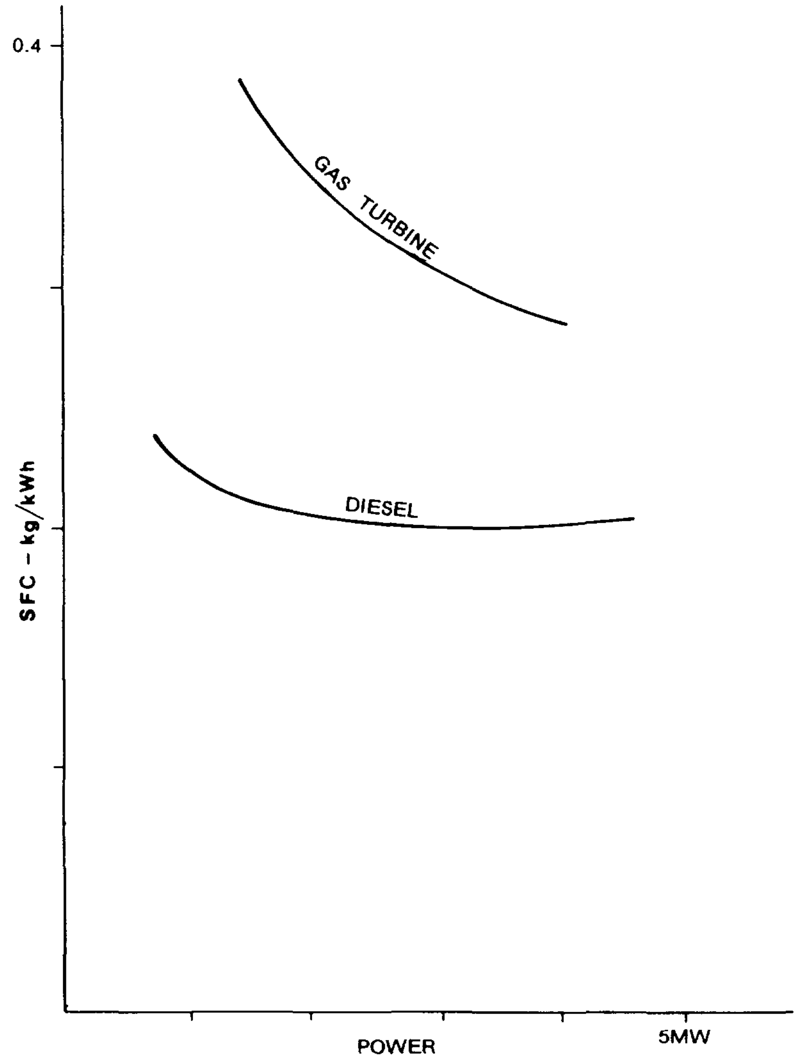


FIG. 3—TYPICAL SPECIFIC FUEL CONSUMPTION

As mentioned above, the United States Navy has been particularly active in evaluating possible design options offering the prospect of enhanced fuel efficiency with turbine installations, and a large literature now exists dealing with subject generically[4] and specifically with respect to the RACER system.[2, 3].

In the land-based commercial field there are many examples of combined cycle COGAS plant being used successfully, on some occasions mainly to improve the efficiency of the power generation system and on other occasions mainly because there is a separate requirement for process steam. Such co-generation plant, based upon aero-derivative or heavy industrial gas turbines, is in common use and typical examples of such systems are the plant at John Player and Son in Nottingham incorporating Ruston gas turbines, and the plant in Marathon Brae A offshore platform incorporating Rolls-Royce gas turbines.

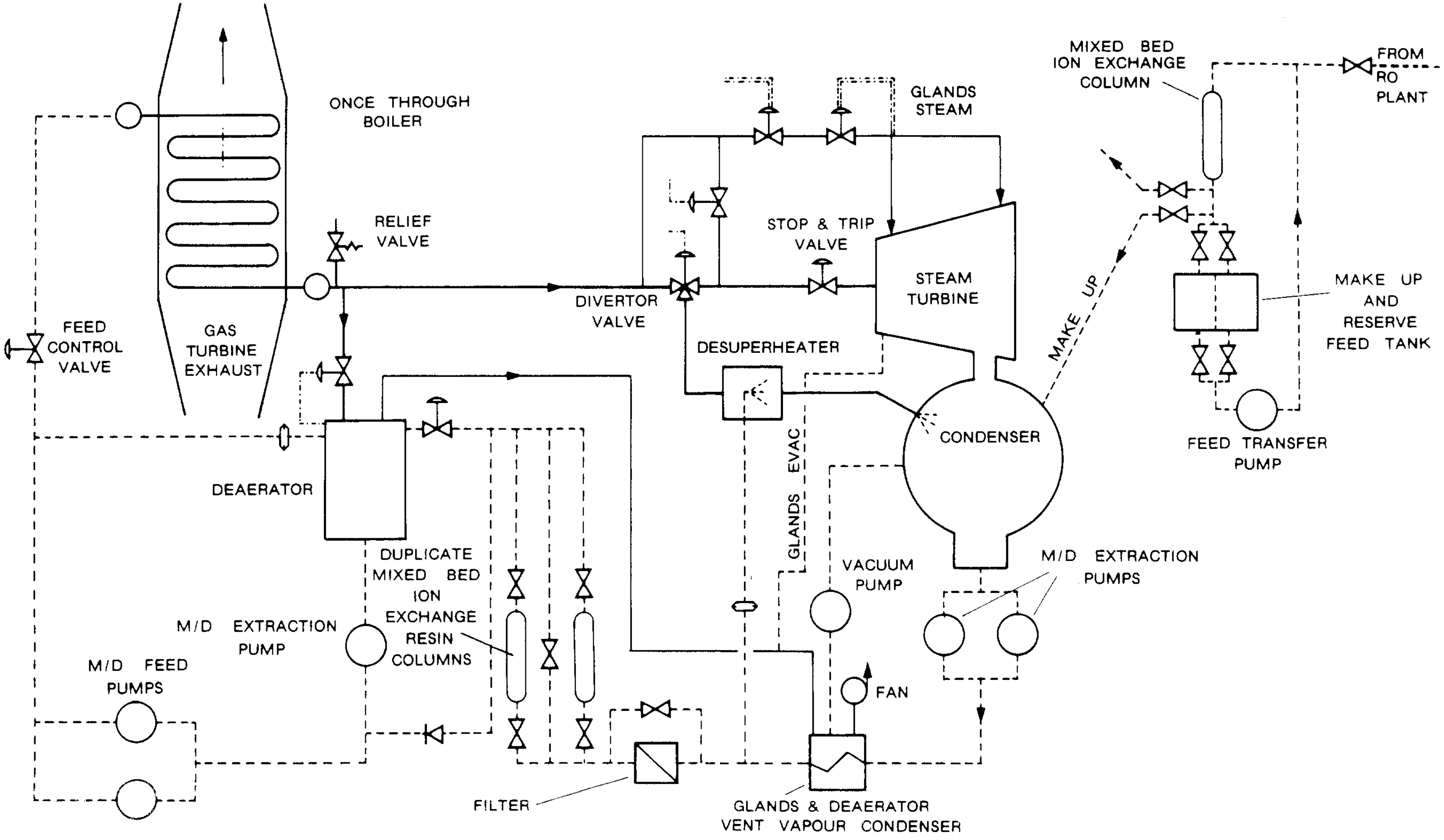


FIG. 4—COGAS PROPULSION PLANT STEAM AND FEED SYSTEM

In the commercial marine field, the use of gas turbines for propulsion power has all but ceased due to the relatively high running costs of gas turbine powered ships when compared with their diesel-powered alternatives. An interesting account[8] has been published of a COGAS marine plant in a 25 knot Ro-Ro vessel, the *Kapitan Smirnov* of the Soviet merchant fleet; the twin propulsion gas turbines are stated to be of the aero-derivative type, each generating over 14 MW, with waste-heat recovery from each exhaust generating a further 4 MW of steam power used partly for propulsion and partly to generate electricity.

In general the overall objectives to be attained in the development of a combined cycle system for warship propulsion are well summarized[2] as:

- In achieving fuel savings, the system must not affect safety or ship mission capability.
- It must be simple to operate, have high reliability and availability, and not impair the gas turbine's characteristics of fast start-up and fast response to load changes.

In the recent work based upon the SM1A gas turbine, a datum waste heat recovery plant was defined with valuable assistance from Rolls-Royce and NEI and from a number of potential manufacturers of heat exchange equipment. These companies gave preliminary indications of design and operating limits, performance and cost. Using this information, the COGAS plant was examined in a range of nominated ship installations, taking account of such aspects as:

(*a*) Machinery arrangement.
(*b*) Fuel consumption.
(*c*) Ship speed and endurance.
(*d*) Initial and through-life costs.
(*e*) Philosophy of combined plant controls system.
(*f*) Reliability and availability.
(*g*) Maintenance and manning.
(*h*) Development status and requirements.

The systems design work was subject to the following general constraints:

(*a*) The Rolls-Royce SM1A gas turbine at a rating of 12.75 MW (no loss) to be used.
(*b*) Once-through type steam generators only to be considered.
(*c*) U.K. sources of manufacturers to be considered where possible.
(*d*) An earliest in-service date of 1995 to be observed.

As a base case, a twin shaft installation having either two SM1A gas turbines per shaft set, or three SM1A gas turbines with a combining gearbox, seemed appropriate.

The outline diagrammatic of the steam and feed system finally evolved with the assistance of a number of the U.K. equipment suppliers is shown in FIG. 4.

At the start-up, the gas turbine exhaust gas would flow through the empty boiler. On selection of the steam plant, feed water would be introduced to the boiler and directed to the condenser until a steam condition acceptable to the steam turbine had been achieved. At this stage the steam plant would be in the stand-by condition and when selected by the operator the steam would be diverted to the turbine. The boiler would be left to run dry if the steam system were shut down for any reason while the gas turbine was in use.

Although the boiler would be designed to operate in this manner, it would be prudent to consider a normal mode of operation where the boiler is always circulated with feed water to avoid continual temperature cycling. This would be quite consistent with an operating philosophy of maximum utilization of the waste heat recovery system.

The design requirements for a system of this type, and the proposed method of operation were the subject of considerable discussion with potential equipment suppliers in the course of the design study.

Adoption of modern steam system practices would help to eradicate the maintenance and manning problems which were frequently met in steam systems in the past. Four aspects of the design of such a system were recognized as being in need for careful assessment and development if a combined cycle installation of this type were to become a serious option for naval use:

(*a*) Feed water quality.
(*b*) Materials.
(*c*) System losses.
(*d*) Controls.

In a once-through boiler system it is essential to maintain a very high standard of feed water purity to avoid deposition of impurities on the tube surface.

The corrosion of the conventional material, i.e. carbon steel, is notoriously high with even small quantities of aggressive impurities present in the water. It would therefore be necessary to have a condensate ion exchange plant which would effectively remove aggressive impurities and condition the water to inhibit corrosion. However, if different materials were used these problems might be reduced considerably. Possible alternatives are Monel 825 boiler tubes, stainless steel high pressure pipework, plastic low pressure (condensate) pipework, and titanium condenser tubes.

A desirable feature of a once-through boiler system to maintain high feed quality is low feed and steam losses. Vapour losses of about 2 kg/h are considered a realistic target for future plants. It is also necessary to ensure a leak-tight system such as one with all welded construction, seal welding, and a well engineered glands evacuation system, and with mechanical sealing of the turbine rotor.

It is important that the control requirements of the combined cycle plant be kept as simple as possible, with the minimum of operator involvement.

The normal operating configurations envisaged are:

- Cruising: gas turbine and steam driving on one or two shafts.
- Manoeuvring: gas turbine only driving with the steam system shut down or warmed up on stand-by.

There is no particular need for the steam turbine to remain in operation during manoeuvring. For normal accelerations the gas turbine would provide sufficient response and the steam system, being driven largely by gas turbine outlet condition, would inevitably lag behind the gas turbine.

There should be no requirement for additional watchkeepers over those for a gas turbine only system. There should therefore be:

(*a*) Provision for automatic start up and shut down of the steam system from the machinery control centre.
(*b*) Full remote monitoring of the state of the steam raising plant.
(*c*) No local operating controls for the steam system other than those required for maintenance purposes and for emergency shutdown.

Nevertheless, the transient performance of a once-through steam generator during power changes or following equipment failures requires more detailed consideration in order to avoid control instabilities and to establish the type of system protection features required and their response characteristics.

Performance Assessment of Selected Systems

Very approximately, the steam system and steam turbine design evolved for the application yielded an additional 25% power above the power level hitherto available from a single SM1A gas turbine; i.e. at full power, on a 12.75 MW no loss rating for a single SM1A, the power available increased to just under 15 MW.

In a practical multi-SM1A installation, involving perhaps two SM1A gas turbines per shaft set of machinery or a total of three SM1A gas turbines driving into a cross-connected transmission system having two output propeller shafts, it was considered unlikely that each of the gas turbine exhaust gas flows would be utilized to generate steam. Instead it is much more likely (on grounds of cost and complexity) that steam generation would be limited to one gas turbine per shaft set only or, in the case of the three gas turbine fit, to one of the three gas turbines.

FIG. 5 summarizes the comparisons made between the performance of all gas turbine installations and variants of the design of combined cycle plant involving the SM1A gas turbine.

The following major points emerge:—

(*a*) It would be possible to achieve an improvement in fuel usage over the existing Tyne/Olympus machinery of up to 21% depending upon the machinery fits selected.

(*b*) It will be seen however that this is not solely as a result of incorporating a COGAS system. When compared with the best 'all gas' system (i.e. 3 SM1A COGAG), the improvement in fuel usage achieved by adding the waste heat system is just 8%.

(*c*) The increase in ship speed when adding a waste heat system in the machinery arrangements examined is generally less than 1 knot.

(*d*) When comparing constant power systems (i.e. the power available from the steam system being used to reduce the gas turbine power demand), the additional fuel savings are small—less than 1%.

(*e*) FIG. 5 also indicates the reduction in fuel stowage needed to meet a particular endurance. Conversely, of course, the existing stowage arrangements could be retained with a subsequent increase in the range of the ship.

It is emphasized that the comparisons of fuel savings made in FIG. 5 were carried out by relating the fuel consumption characteristics of each machinery configuration to the ship operating profile (i.e. at all ship operating speeds over a given mission time). The improvement in fuel consumption between a single SM1A operated continuously at full power when fitted with a waste heat recovery plant, and an SM1A gas turbine alone, would be 19%.

Brady[9] quotes a corresponding full power fuel saving of approaching 25% for the U.S.N. RACER system (based upon the GE LM2500 gas turbine) when compared with an all LM2500 gas turbine fit. The annual fuel saving achievable with the RACER system will be influenced by actual ship operating profiles, and by the operational procedures exercised by the Command, etc.

In the case of both the R.N. and the U.S.N. it is clearly this projected annual fuel saving which will be more important in determining the support to be given to the system development programme.

Although the datum waste heat recovery plant described above would require about 2 to 3 years of development, it would not be a fully optimized

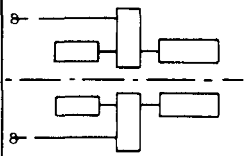
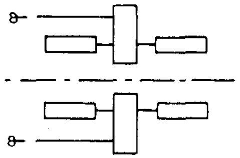
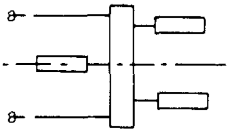
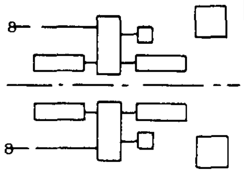
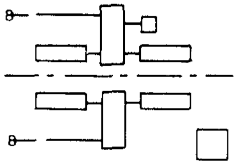
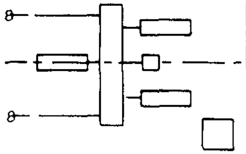
Machinery Configuration	COGOG	COGAG	COGAG	COGAS	COGAS	COGAS
Propulsion Machinery	2 Tyne RM1C 2 Olympus TM3B	4 Spey SM1A	3 Spey SM1A	4 Spey SM1A (2 with Waste Heat) 2 Steam Turbine	4 Spey SM1A (1 with Waste Heat) 1 Steam Turbine	3 Spey SM1A (1 with Waste Heat) 1 Steam Turbine
Machinery Arrangement						
Operating Modes	1 RM1C(trailing shaft) or 2 RM1C or 2 TM3B	1 SM1A (trailing shaft) or 2 SM1A or 4 SM1A	1 SM1A or 2 SM1A or 3 SM1A	1 SM1A + 1 ST (trailing shaft) or 2 SM1A + 2 ST or 4 SM1A + 2 ST	1 SM1A on STBD. Shaft + 1 ST on PORT Shaft or 2 SM1A + 1 ST or 4 SM1A + 1 ST	1 SM1A + 1 ST or 2 SM1A + 1 ST or 3 SM1A + 1 ST
Fuel Usage on Operating Profile Including Auxiliaries	Basis	-9%	-14%	-19%	-21%	-21%
Maximum Ship Speed knots	Basis	+ 1½	-½	+ 2	+ 1¾	Same
Machinery Weight tonne	Basis	+ 50	-30	+ 220	+ 140	+ 60
Fuel Stowage tonne	Basis	-10	-60	-70	-120	-120
Total tonne	Basis	+ 40	-90	+ 150	+ 20	-60

FIG. 5—THE WASTE HEAT GAIN WITH GAS TURBINE MACHINERY

design in either performance or physical size. If such optimization were undertaken it is expected that the resulting design would be much more compact and with a performance close to the U.S.N. RACER system, the initial consideration of which began some 10 years ago. However, the cost of optimization would be high and, with the foreseeable improvement in further fuel savings likely to be limited (possibly 3% or 4%), careful justification of such development work would be required.

Conclusions

Saving in fuel consumption can be a high priority in a ship design but in most warship designs it is just one of many factors that demand the designer's attention.

A COGAS plant based on a particular simple cycle gas turbine will be more efficient than the simple cycle gas turbine by itself. However when COGAS is part of a propulsion system optimized to a particular set of ship requirements, the gain in fuel saving compared with other propulsion systems (each also optimized for the ship requirements) using prime movers currently available, may be modest.

Greater gains in COGAS efficiency could be achieved by increasing the development and maybe the risk factor, but COGAS is only attractive if the overall implications (advantages and disadvantages) can on balance override the penalties of change.

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