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GAS TURBINE GENERATOR DRIVE FOR ICEBREAKING APPLICATION

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Mr. McCullum

The gas turbine is but one more technique to be used by marine engineers and naval architects to enhance the effectiveness and utility of ships of all kinds. That process of enhancement has been aggressively pursued in the western world for about 500 years as the ships of western Europe went forth to all points of the globe. The measure of success and of impact of that process has been to bring western civilization, western thought and western learning to the door step of almost every land in this world and produce an accelerating effort in all those lands to "westernize", in fact, if not in name. Marine engineering and naval architecture have had, therefore, a collossal influence on the course of history and on the progress of western civilization.

Those in Canada, especially, know that the challenges of sea travel have not been exhausted nor have they been ignored. In his book "The Ice Was All Between", T. A. Irvine chronicled the historic voyage of *Labrador* through the North West Passage in the summer of 1954. In his introduction to that book, Commodore O. C. S. Robertson heralded the intensive attention the Canadian Arctic would command in years to come.

Now, over 15 years later, similar exploits by powerful ships of the Canadian Coast Guard have continued to add to their own distinguished record of Arctic achievements. One can also read promising reports of finds of natural gas and the active pursuit of oil and other minerals, and of Arctic navigation successes. All of such reports from the north can be seen as a re-enactment of the reports that stimulated the will of western Europeans centuries ago to set forth by ship to see for themselves and develop those lands.

To develop the lands of the Canadian Arctic, then, is a distinctive Canadian challenge, especially for those charged with responsibility for the movement of ships through the Arctic.

This paper is a first report of the design, development and testing of a gas turbine for use with electric transmission in the Canadian Coast Guard icebreaker *Norman McLeod Rogers*.

The ship employs both gas turbine and Diesel engine prime movers for the propulsion system. The relationship and ratings of all these is indicated in Fig. 1.

INTRODUCTION

The requirements to be satisfied by the gas turbine prime movers can be summarized briefly as follows:

a) rated $2{\cdot}984 \times 10^{6}$ J/s continuously at gear output shaft, at sea level and with inlet air at 15·5°C, after allowing 500 N/m^2 for inlet and 500 N/m^2 for exhaust duct losses. Simple cycle;
b) rated $3{\cdot}282 \times 10^{6}$ J/s, 2 hours overload rating, etc., at 4·5°C;
c) supplied with reduction gear and couplings to direct-current propulsion generator, all with a common underbase, to be shipped as an assembled set;
d) withstand the environmental conditions of service at sea and the high transient performance requirements of a multi-engined electric drive system icebreaker application.

THE PRODUCT

The design, development and testing that was undertaken to satisfy those requirements is described under the following headings:

i) selection of unit from standard model range;
ii) review of turbine design and changes introduced to withstand environment;
iii) design implications and changes arising from application and system considerations;

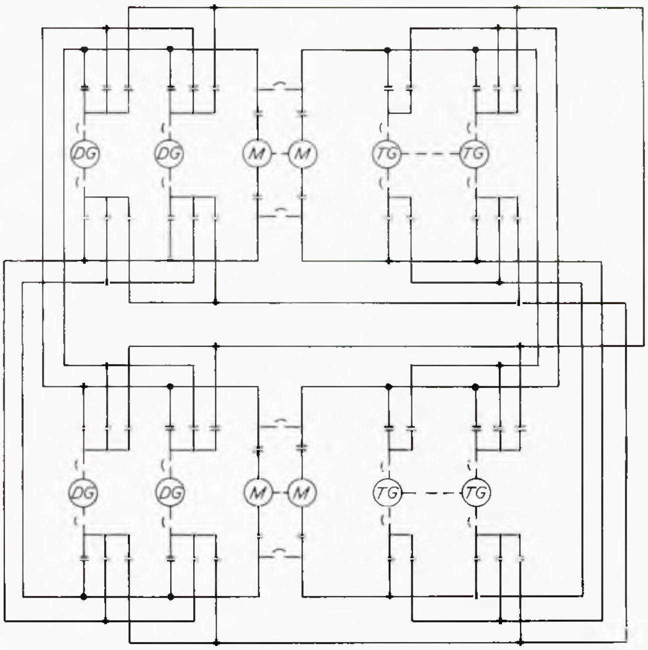

FIG. 1—*Propulsion power circuits*

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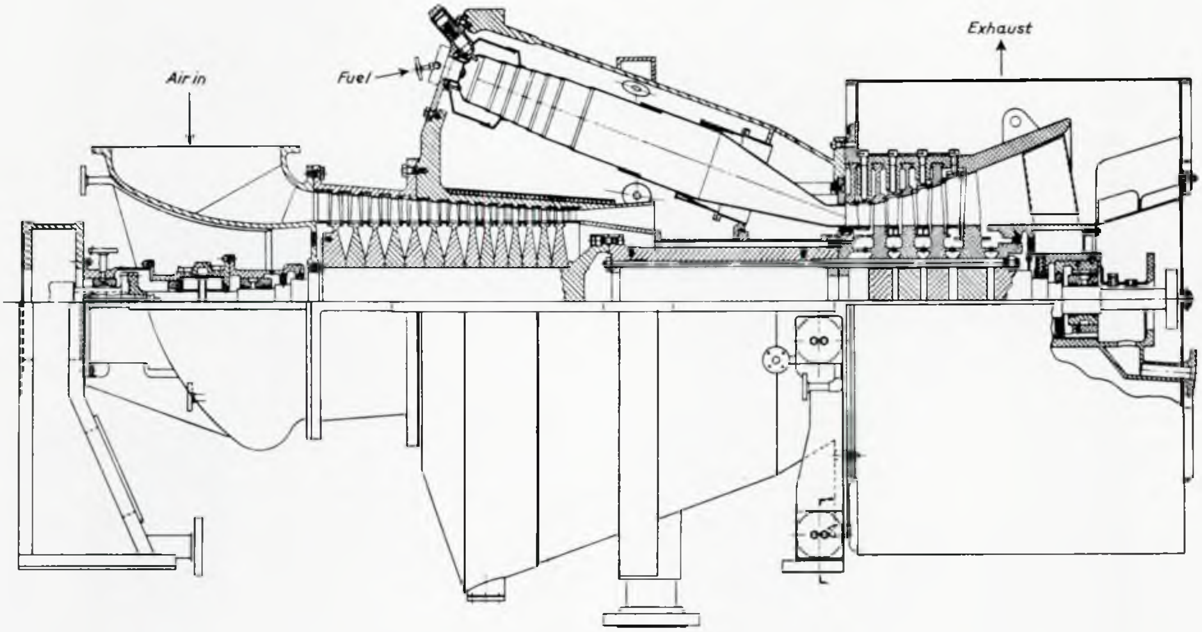


FIG. 2—*Model W-*41 *gas turbine cross section*

- iv) accommodating the gas turbine in the ship;
- v) classification implications;
- vi) shop, dock and sea trials;
- vii) observations to date.

(i) *Selection*

The standard unit selected for adaptation was a Westinghouse model W-41, simple cycle, gas turbine. This is the smallest of a range of second generation Westinghouse gas turbines which had been applied successfully in generator drive and mechanical drive duty in industry. It is a single-shaft type unit. In the service intended, the fuel savings of high efficiency regenerative cycle were not high enough to warrant other than simple cycle. This industrial style construction had the advantage of being able to contain any conceivable damage, and was likely, therefore, to be more readily acceptable by personnel.

The reasons for selecting this unit were as follows:

1) its rating was adequate;
2) its operating record in respect of frequent starting and rapid loading in industrial service was excellent;
3) its single shaft construction left the widest range of choice on how to absorb regenerated energy from the propellers;
4) its exclusive use of journal type bearings removed the hazard of the effects of steady vibration and shock on stationary bearings;
5) silencing problems would not be onerous.

The gas turbine is illustrated in Fig. 2.

Its rating as offered for industrial service (both simple and regenerative cycle) and as applied here is also given in Table I. As can be seen from these tables, the unit has been applied very conservatively with respect to power and temperature.

Thermal efficiency appears low and this is accounted for by pressure ratio and turbine inlet temperature. However, this is an area of secondary concern since it can be raised by use of the regenerative cycle shown or by incorporating growth factors in

TABLE I—MODEL W-41 GAS TURBINE RATINGS

	Industrial service simple cycle	Marine service simple cycle	Industrial service regenerative cycle
Rated operating speed—rev/min	8500*	8550*	8500*
Trip speed—rev/min	9200**	9350	9200**
Power—J/s—at sea level 27°C	$3{\cdot}267 \times 10^6$	$2{\cdot}760 \times 10^6$	$2{\cdot}775 \times 10^6$
Turbine inlet temperature—°C	787	732	787
Turbine exhaust temperature—°C	482	396	—
Maximum cold weather—power—J/s	$4{\cdot}774 \times 10^6$	$3{\cdot}367 \times 10^6$	$4{\cdot}774 \times 10^6$
Air temperature for maximum power (sea level)	—6·5°C	4·5°C	—23·5°C
Thermal efficiency, full load per cent*	20·8	19·2	28·3
Pressure ratio	5:1	5:1	5:1
No. of compressor stages	14	14	14
No. of turbine stages	4	4	4
Exhaust flow—kg/s	24·46	24·46	24·46
Fuel	Distillate oil (or natural gas)	Distillate oil	Distillate oil (or natural gas)

*Output measured at turbine coupling
**Mechanical drive service

TABLE II—MODEL W-41 GAS TURBINE MARINE SERVICE MATERIALS REVIEW

Item	Industrial service	Marine service
1. Structure items	Carbon and alloy steel forgings, castings and nodular iron minor items	Same except substitute steel for nodular iron
2. Bearing material	Standard tin base babbit	Standard tin base babbit
3. Air compressor moving blades	12 per cent chrome steel	Same plus epon-phenolic baked enamel
4. Air compressor stationary blades, diaphragms	12 per cent chrome steel	Same plus epon-phenolic baked enamel
5. Turbine moving blades		
row 1	Inconel 700	Udimet 500
row 2	Inconel X	Udimet 500
row 3	Inconel X	Inconel X
row 4	Inconel X	Inconel X
6. Turbine stationary blade diaphragms		
row 1	Udimet 500	Alloy X45
row 2	AISI 310	Alloy X45
row 3	AISI 310	AISI 310
row 4	AISI 310	AISI 310
7. Combustor baskets	Hastelloy X	Hastelloy X
8. Turbine discs	Discalloy	Discalloy
9. Compressor discs	Chrome/moly steel	Same plus bonded high temperature ceramic/aluminium coating
10. Exhaust bearing supports	AISI 422 stainless steel	Same plus bonded high temperature ceramic/aluminium coating

the unit, such as increased pressure ratio and turbine inlet temperature. The prime concern was to design to satisfy marine environment and icebreaker application. The techniques for raising power output and efficiency are well known; the requirements for surviving in a marine environment and for icebreaker application are those which are being established.

Fig. 3 shows the major dimensions and weights of the unit complete with the generator.

(ii) *Review of turbine design and changes introduced to withstand environment*

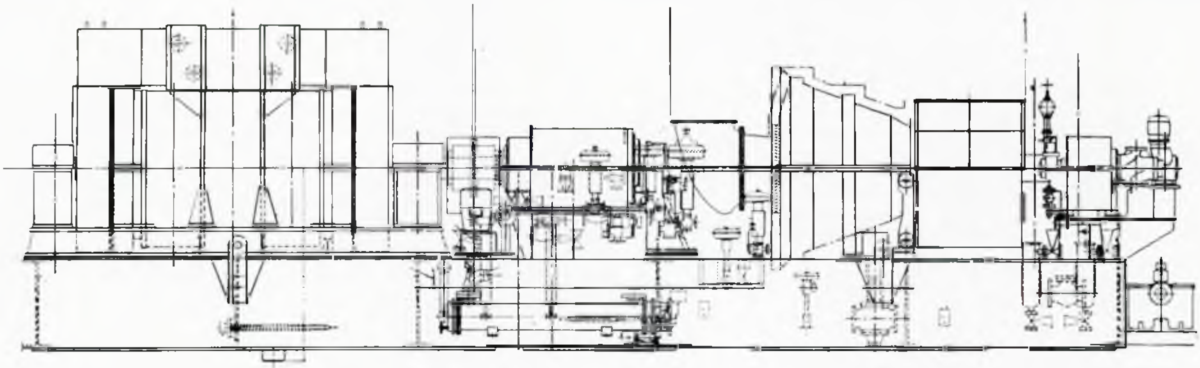
The first of these changes was implied by the earlier reference to the comparison of the industrial rating and the rating in this ship. There are two benefits to be expected from this:

a) salt in the air and/or fuel will lead to less potential corrosion effects on turbine rotating and stationary blades;

b) the amplitude of the temperature cycling expected is reduced with consequent minimized thermal stressing of the hot parts.

The second area of review was that of turbine materials. The structural elements of the gas turbine are steel forgings, castings or fabrications. Nodular iron castings for the bearing caps were replaced with steel, and this was the only substitution necessary to realize the shock and vibration resistance advantages of steel. The materials in the active elements of the turbine were reviewed in detail and are listed in the tabulation in Table II. The changes made are noted with reasons given.

Third, the sizes and arrangements of journal and thrust bearings were examined under conditions of roll, pitch, vibration and 1 g of shock. The normal working pressures of these ranged from $8\cdot53 \times 10^{5}$ N/m^2 (exhaust) to $1\cdot04 \times 10^{6}$ N/m^2 (inlet), and the bearings were concluded to be of adequate proportions for the service. The shipyard and turbine designers worked together



Overall length of complete set 12·15 m

Approximate breakdown of dimensions

Auxiliary and lubricating units length	1·1 m OR	9 per cent of total overall length
Turbine length	4·32 m OR	36 per cent of total overall length
Gear length	2·16 m OR	18 per cent of total overall length
Generator length	4·575 m OR	37 per cent of total overall length
Total overall length	12·15 m OR	100 per cent

Total weight $6\cdot89 \times 10^{4}$ kgf

Approximate breakdown of weights

Turbine longitudinal	$1\cdot01 \times 10^{4}$ kgf	14·5 per cent
Auxiliary gear	$1\cdot48 \times 10^{3}$ kgf	2·2 per cent
Main gear	$2\cdot54 \times 10^{3}$ kgf	3·4 per cent
Generator	$2\cdot78 \times 10^{4}$ kgf	40·0 per cent
Valves, piping, etc.	$6\cdot97 \times 10^{3}$ kgf	10·0 per cent
Bedplate	$1\cdot41 \times 10^{4}$ kgf	20·2 per cent
Lubricating oil	$4\cdot54 \times 10^{3}$ kgf	6·6 per cent
Cooling water	$1\cdot45 \times 10^{3}$ kgf	2·1 per cent
Total weight	$6\cdot89 \times 10^{4}$ kgf	100·0 per cent

FIG. 3—*Model W-41 gas turbine, marine service—weight and dimensions*

closely when the shipyard designed the vibration and shock isolation mounts.

Fourth, the clearance between moving and stationary blading was checked. This is limited by rotor thrust bearing location to $5{\cdot}1 \times 10^{-3}$ mm (at load) but is more than adequate to assure clearance in pitching.

Fifth, the clearance between blade tips and cylinders, rotor and stationary blade diaphragm seals was checked under conditions of rotor motion during 1 g shock, and it was concluded a clearance would be maintained.

Sixth, accessory material selection for responding to the specifications meant the use of stainless steel lube oil piping, and the absence of copper in the fuel system fittings.

Seventh, the oil reservoir was designed with the required baffling to counter pitch and roll effects, and to permit deaeration of oil.

Eighth, the vibration detection system was changed from the standard land based seismic mounted sensors to proximity type.

Ninth, armoured lead cable was substituted for the normal conduit and wire arrangement used in land service.

Tenth, the turbine air inlet is fitted with a compressor water wash nozzle to dissolve away accumulated salts. It is also equipped with a spent catalyst injection for compressor cleaning chores. However, this catalyst cleaner will probably be infrequently required, and will preferably be infrequently used in order to preserve the compressor blade coating finishes.

(iii) *Design implications and changes arising from application and system considerations*

1) The first change dealt with space considerations. One was the adoption of a double reduction, Allen Stoeckicht, epicyclic type gear between turbine and generator. This retained co-linear centrelines and a regularly shaped outline of the set. Its companion move was to dispense with a separate starting device, and the electric transmission system manufacturer arranged to operate the propulsion generator as a starting motor instead.

2) Probably the biggest single design change arose from consideration of how to deal with energy returned from the propellers in the execution of certain power manoeuvres. Fig. 4 illustrates typical conditions of energy reversals in the propulsion system during such manoeuvres.

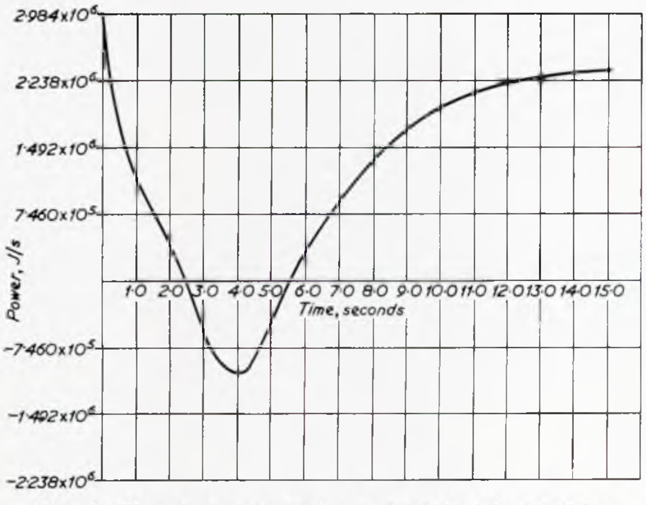


FIG. 4—*Transient energy rates, gas turbine/electric drive*

While the hull form of icebreakers tends to minimize head reach and stern reach of the ship, it is also advantageous to manoeuvres in close quarters to provide some means of dissipation of ship and propeller kinetic energy. That is, the energy that can be regenerated from the propellers (see Fig. 4) is dissipated in an acceptable way. It is usual practice with Diesel engine electric drives to allow this energy to raise the engine speed, at which time fuel injection ceases and the compressed air re-expands on the expansion stroke. Thus the energy finally transferred is consumed by inertia, the compression stroke and by friction losses, and these loads are sufficient to hold engine speed well under trip speed.

By its very nature, the gas turbine is a continuously ignited heat engine and that same practice is not directly usable. Computer calculations were made of the effect on turbine speed of various specified likely amounts of energy to be returned to the turbine. It was concluded that the turbine generator set inertia was too low to depend upon it absorbing the energy input while at minimum fuel or flame setting without exceeding trip speed.

Three methods of coping with this were studied:

a) rapidly switched electric resistance loading was studied by the electric transmission manufacturer;

b) addition of extra inertia by means of a flywheel was studied by the turbine manufacturer;

c) means of venting compressed air, after compressor discharge, and before the combustion and turbine zones, to prevent increased air flow as a result of compressor acceleration, from performing work in the turbine stages.

The first was rejected as a result of space and cooling considerations.

The second was rejected on the basis of excessive impact on dimensions and cost.

The third method was adopted on the basis of least cost and maximum effectiveness.

3) Having referred to the significance of regenerated energy, the unusual specification for the gearing should be mentioned. The gearing is rated to match the rating of the turbine but is also capable of transmitting $1{\cdot}641 \times 10^6$ J/s intermittently from the normal output to the normal input.

4) Although the output of the gas turbine driven d.c. generator is not normally paralleled electrically with that of either the other gas T.G. set or other Diesel driven generators, the combined voltage droop characteristic of the T.G. set (i.e., the result of governor droop and generator voltage droop characteristics) remained a matter of some importance to the electric transmission manufacturer. At the same time, it was important that turbine speed should not be allowed to dip excessively, during transient loading, to avoid the consequent turbine temperature rise resulting from the decreased air flow and to retain readiness to accept load at a proper rate. Accordingly, the turbines were equipped with a fast-acting isochronous electric governor. Voltage droop characteristic was then essentially under the control of the electric transmission manufacturer. Load control and underspeed monitoring prevent speed depression into the compressor surge zone.

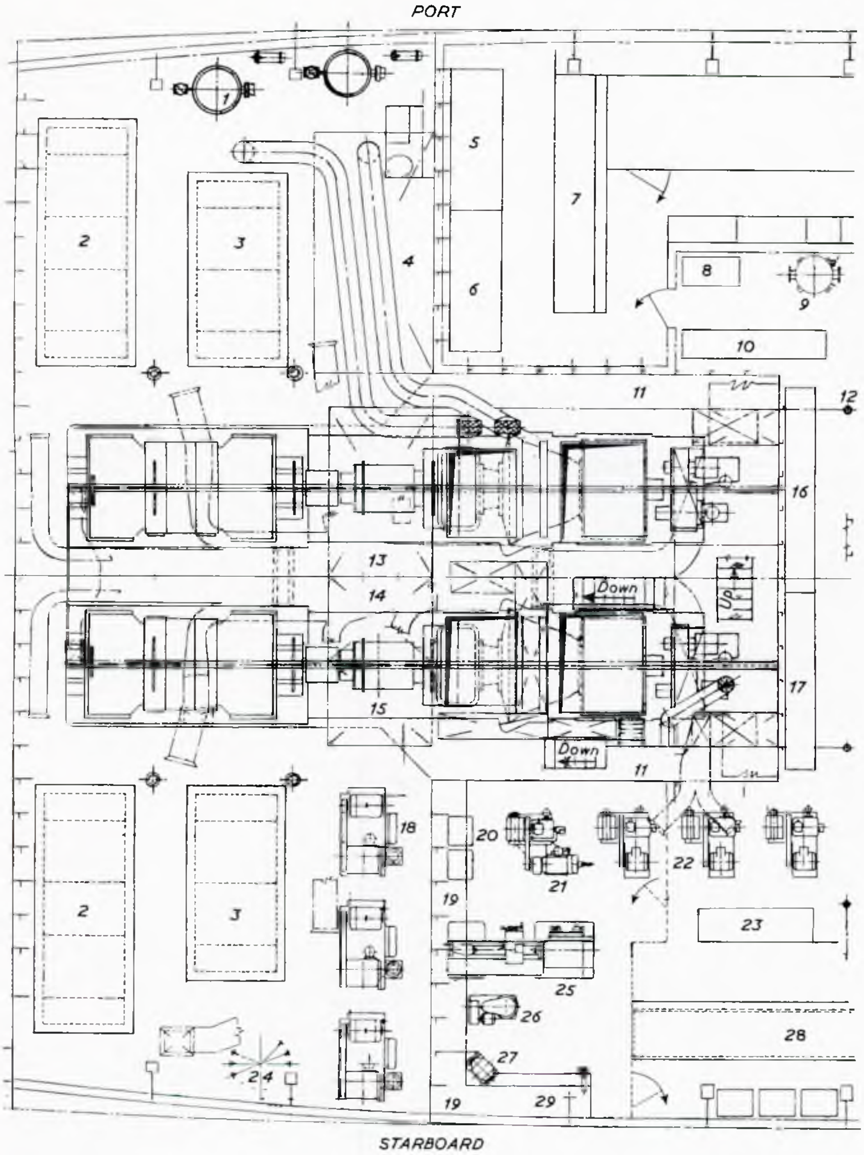
5) The turbine, the gear and the generator are flexibly connected. Each element has thrust bearings to withstand its own thrust, including inertia forces.

6) It is the practice in the industrial version of this turbine line to employ spark igniters on two of the six combustors and to connect all six combustors with cross-flame tubes joined to them in the same area as the spark plug. Compared with gaseous fuel, oil fuel is always the less easily and reliably ignited. Accordingly, these units employ spark ignition on each of the six combustors, as well as using cross-flame tubes. In addition, the spark plug itself is a heavy duty type, employing ring fire effect rather than single gap fire.

iv) *Accommodating the gas turbine in the ship*

Fig. 5 shows a cross sectional arrangement in the machinery spaces. The principal concerns of the gas turbine designer cover:

a) control of duct losses;



1) Calorifiers
2) M.E. gen't set-up cubicle
3) G.T. gen't set-up cubicle
4) Storage space
5) Gas turbine control console, port
6) Gas turbine control console, stbd.
7) Propulsion control desk
8) M.C.C. emergency section
9) L.O.F.F. filter
10) M.C.C. essential section no. 3
11) Casing bulkhead
12) L.O. filter
13) D.G. lube oil storage tank
14) G.T. lube oil storage tank
15) G.T. centrifuged lube oil tank
16) M.C.C. essential section no. 2
17) M.C.C. essential section no. 1
18) Atomizing air compressors
19) Shelves over
20) Arbor presses
21) Diesel driven air compressor
22) Motor driven air compressor
23) M.C.C. non-essential section
24) Atomizing air tank
25) Lathe
26) Drill
27) Grinder
28) Main switchboard
29) Work bench with drawers under

FIG. 5—*Machinery space arrangement*

b) removal or prevention of entry of foreign objects in the inlet air stream;
c) avoiding arrangements which may permit formation of potentially large and, therefore, harmful deposits of ice;
d) co-operation in design for heat insulation and noise attenuation.

The first of these yields easily to standard techniques, and 500 N/m^2 was allowed for each of inlet and exhaust.

The second and third are matters of careful design to avoid the use of bolts or fasteners which may work free. The shipbuilder gave these very careful attention.

At certain ambient air temperatures, approximately —3 to +1°C, and adequate humidity, frost build-up at the inlet guide vanes of the gas turbine is likely. This will usually break off and pass through the turbine, and it is of such a nature as to cause no harmful effect.

The designer is more concerned with accumulations of water or condensate in pools which may freeze during idle periods, or frozen condensate accumulations on vulnerable surfaces in the duct or plenum. These accumulations may become large enough to represent serious hazards when operation is resumed, and the passing air strips these away and carries them into the turbine. Therefore, the shipyard very carefully avoided protrusions in the duct and plenum which might attract moisture, and all low spots are equipped with drains.

The air inlet system at the upper deck provides for some centrifugal removal of liquids and dust. This duct system is illustrated in Fig. 6.

As a heat engine, the gas turbine expands and contracts as one expects. Being a single shaft type of machine, the designer has the choice of coupling the load to either the hot or the cold end of the turbine. As can be seen in Fig. 6 the cold end was selected, there being no reason not to take advantage of this choice. The hot, or exhaust, end movement of approximately 10 mm is accommodated in the exhaust duct flexible connexion.

In the arrangement employed, all of the start-up and shut-down operations are conducted at the turbine control. Once "ready for loading condition" is reached, the main control room is signalled and the output of the T.G. set is controlled from there or from the bridge. In addition to the usual annunciation devices, a scheme of rapid fault finding is used.

Silencing of the turbine was given careful attention by the shipyard, using data supplied by the turbine designer. An unsilenced model W-41 gas turbine has noise characteristics as shown in Fig. 7. The operational noise level was not the subject of precise specification. The shipyard, however, provided inlet

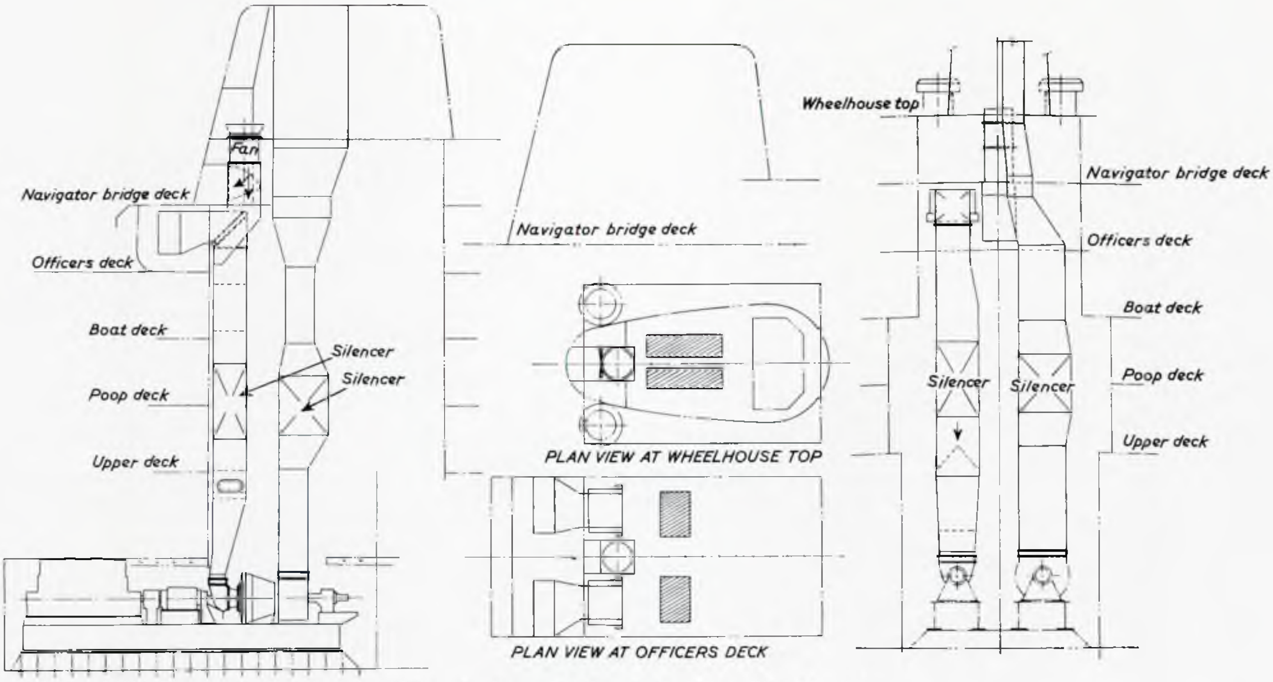


FIG. 6—*Gas turbine air intakes and exhausts*

and exhaust silencing which reduced sound levels to quite tolerable magnitudes, and evidently significantly more comfortable than the Diesel engine sound level.

Figs. 8 and 9 illustrate the start-up cycle of the gas turbine generator set.

Along with the usual gas turbine temperature recorders, the electric transmission manufacturer added recording type generator kW meters. These were a novel addition and were used to provide a record of electric load variation to compare with turbine temperature variation, and so indicate the extent of thermal cycling.

The turbine oil fuel specification was compatible with Diesel engine requirements and posed no problem. The turbine, gear and generator common lubrication system was built integral with the unit.

v) *Classification implications*

There was close co-operation with Lloyd's and the Steamship Inspection Service during the design and manufacture of these units. This phase of the work went smoothly, and no significant departures from the regular practice of material inspection, vibration analysis, etc., were required.

vi) *Shop, dock and sea trials*

The programme of shop trials followed the practice for Canadian Coast Guard equipment with the addition of a number of other informative tests. These other tests included:

—behaviour checks of the high pressure air blow-off system;
—simulated salt air intake effect on compressor performance;
—speed rise on load rejection;
—starting reliability;

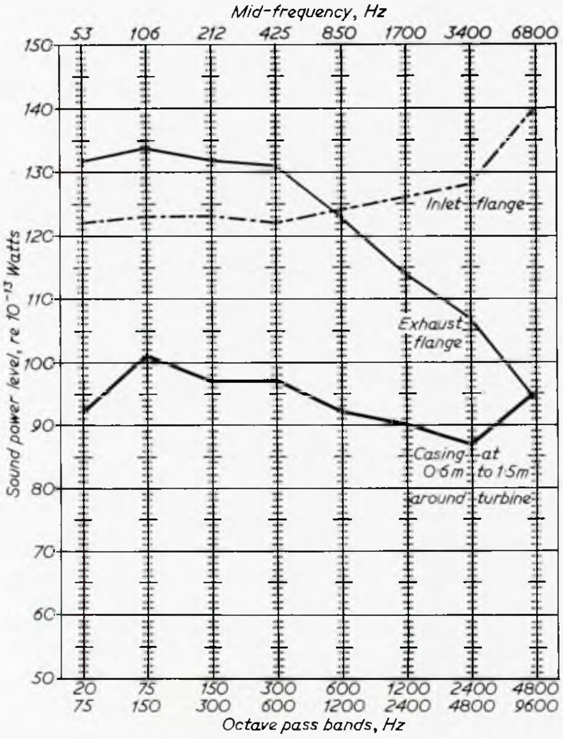
running time on shop tests ran about 100 hours per unit.

The programme of dock trials and sea trials followed the objectives of the specifications.

Manoeuvring and endurance trials at sea were carried out at full contract power conditions and the equipment performed as planned.

vii) *Observations to date*

1) An icebreaking mission power profile is not a matter of precise prediction like, say, aeroplane flights, or perhaps naval missions, and certainly unlike commercial ship missions.



W-41G gas turbine icebreaker.
Sound power level (P.W.L.).
Inlet and exhaust levels separated for one gas turbine only

FIG. 7—*Model W-41 gas turbine, sound power levels*

The ship operators are free to use the gas turbines as they are required or preferred. However, power level control has been recalibrated to less than 100 per cent as part of a stepped programme of operation and inspection to observe the effects of increasing power levels in this service, and so assist in providing empirical support for projecting results at power levels beyond contract levels in future. These levels will probably be 70, 85 and 100 per cent.

As of 28 January 1970, each unit had accumulated 370 hours total running time.

2) Full inspection technique involves lifting the turbine covers. However, it has been found that removal of the canted combustor basket (see Fig. 2) and the use of portable illumination and optical sighting from the combustor opening provides useful inspection of row 1 stationary and row 1 moving blades. It is expected that this technique will be adequate for the programme in (1) above and to signal any need for cylinder opening in future.

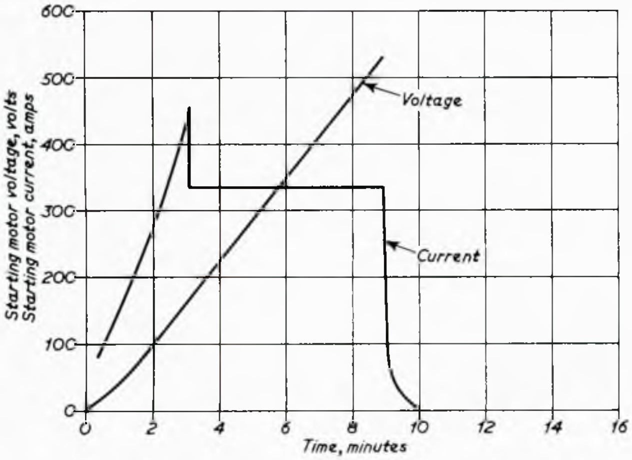


FIG. 8—*Model W*-41 *gas turbine—startup cycle*

3) The high pressure blow-off system has served well in preventing overspeed operation in manoeuvres. In addition, it has tended to stabilize turbine inlet temperature during rapid reversing, or "power on—power off—power on" type manoeuvres, and to provide flame stability. It is considered to be a technique of real value for this and future work.

4) Smoke emission was typical of second generation gas turbines. It was found to be relatively unaffected by whether the atomizing air equipment was in service or not. On the Bacharach scale, at full load it measured between 7 and 8.

Reduction of smoke emission has received a good deal of attention by the gas turbine designer in recent years. By laboratory testing and redesign, levels of up to Bacharach 5 maximum are available today on large machines. The turbine designers could achieve these same results on this model to meet such a specification requirement in future.

5) The use of the propulsion generator as a starting motor does complicate the electric transmission system. Where space and power plant arrangements permit, some form of auxiliary electric starting would be re-examined.

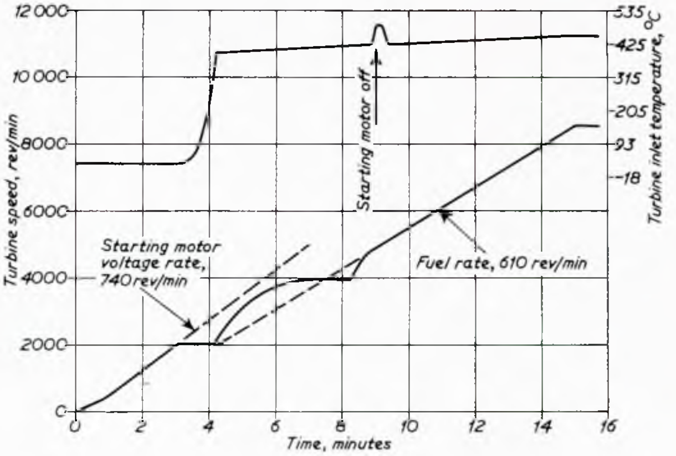


FIG. 9—*Model W*-41 *gas turbine—startup cycle*

6) The prolonged series of shop trials on the T.G. sets and their controls is seen in retrospect as having been very important in minimizing dock and sea trial period attention, to correcting minor faults and to establishing behaviour characteristics. The designers are as conscious of costs as any, but it would be their view that such combined testing should remain a feature of future specifications.

In conclusion, the total experience of participating in the propulsion plant for *Norman McLeod Rogers* has given us a strong threshold of confidence and enthusiasm to apply gas turbine power to icebreakers in the future. The lessons of this ship to date and in the future will be the major factor in guiding this work.

CONVERSION TABLE

10^3 J/s = 1 kW = 1·3410 hp
10^5 N/m^2 = 1 bar = 14·504 lbf/in^2
°C = 5/9 (°F−32)
1 mm = 0·03937 in

ACKNOWLEDGEMENTS

Only the generous assistance of the author's engineering colleagues of the Turbine and Generator Division of Westinghouse Canada Ltd., the co-operation of Canadian Vickers Shipyards Ltd., Canadian General Electric Co. Ltd., and W. H. Allen Sons and Company Ltd., and the assistance and encouragement of the Marine Operations Branch of the Department of Transport and of the Marine Systems Division of the Department of Supply and Services have made this report possible. All of this is gratefully acknowledged.

Discussion

LT. CDR. R. H. RANDLES, R.N., C.Eng., A.M.I.Mar.E. said that the Royal Navy had selected the gas turbine for the main propulsion machinery of all future warship designs. As a result of that decision, they had been carrying out a programme of work at the National Gas Turbine Establishment, and they were broadly concerned with all aspects of application of gas turbines to ship propulsion. Less broadly, he was concerned with problems connected with air intakes, and he said he would like to raise the question of the possibility of icing up in cold weather conditions. In the United Kingdom, one was blessed with what the geographers called a "temperate climate". Consequently, they had very little experience of operating marine gas turbines in extremely cold conditions. *Norman McLeod Rogers* had now had a lot of operating experience, and he asked Mr McCullum if he would care to comment on any icing effects on the intake ducting or intake structure.

MR. V. A. WEBB asked what sort of filtration and protective devices had been employed in the inlet tract in the ship. Most gas turbines were capable of being de-iced or anti-iced in their own intake, but what was the protection in the trunk of the ship? It would appear from the illustrations in the paper that some form of cascaded bend was used, but there had been no mention of this.

One thing which was not referred to in the paper had been the frequency of cleaning operations on the engine, assuming that there was some salt encrustation in both the inlet tract and in the engine itself.

Another thing which was of interest in that particular area was the degree of silencing that was employed in both the inlet system and, perhaps more particularly, in the exhaust duct. From the noise figures which were quoted in the curve in the paper (and one assumed that this was an unsilenced noise spectrum) there appeared to be quite a big problem in the 75 to 150 Hz band—quite a high sound pressure level. The diagram showed what would appear to be an inordinately short length of silencer to cope with this degree of sound.

Another interesting point, considering the conditions under which the vessel operated, would be to know what material was used, particularly in the exhaust duct, and what sort of surface treatment was employed, assuming it was not stainless steel. What was the effect of dew point on it because of the long periods of shut down of gas turbines? Also, what was the depth of ice that was tackled, and what were the sort of shock and vibration conditions experienced on the engine itself?

Mr. A. de Ville said that as Mr McCullum had stated in the introduction to the paper, one of his company's specified responsibilities had been the supply of the reduction gearboxes and couplings for installation between the gas turbines and d.c. generators. The two epicyclic gearboxes selected were double train speed reduction units of Allen design and manufacture based on the well known and proven Stoeckicht principles. The gearbox was designed to transmit the overload power of 4400 hp with a speed ratio of 8550/750 rev/min with loadings and materials to meet the requirements and survey of Lloyd's Register of Shipping.

At the tendering stage, consideration had been given to using a single train planetary gear to cover the overall ratio of 11·4 : 1, and although the complete length of the gear unit would have been reduced by about 20 in, a substantial increase in centre height, width, weight and cost when compared with the double train arrangement would have resulted.

Mr. de Ville then showed an illustration indicating the sectional arrangement of the unit. Starting at the turbine end, the coupling flange was bolted to the turbine output shaft flange, torque being transmitted to the sunwheel on the first train by a tooth type flexible coupling.

The first train was of the star type with a ratio of 3·3 : 1, i.e. the star wheel carrier was fixed to the gearcase and the sunwheel, star wheels and annulus rings with their associated couplings were the rotating elements.

The annulus system of the first train was connected to the sunwheel of the second train by a tooth type flexible coupling, the second train having a ratio of 3·45 : 1. This train was the planetary type, i.e., the annulus system was stationary and the planet carrier was the output component. The planet carrier was bolted and dowelled to the output shaft at one end and to a short stub shaft at the other, these providing the journals for the two white metal lined bearings which supported the assembly.

The star and planet wheels in both trains were supported by spindles that were accurately positioned in the carriers, the spindles being white metalled to provide a bearing surface.

The output shaft and the generator were connected through a grease packed tooth type flexible coupling.

Turbine quality lubricating oil was supplied to the gear

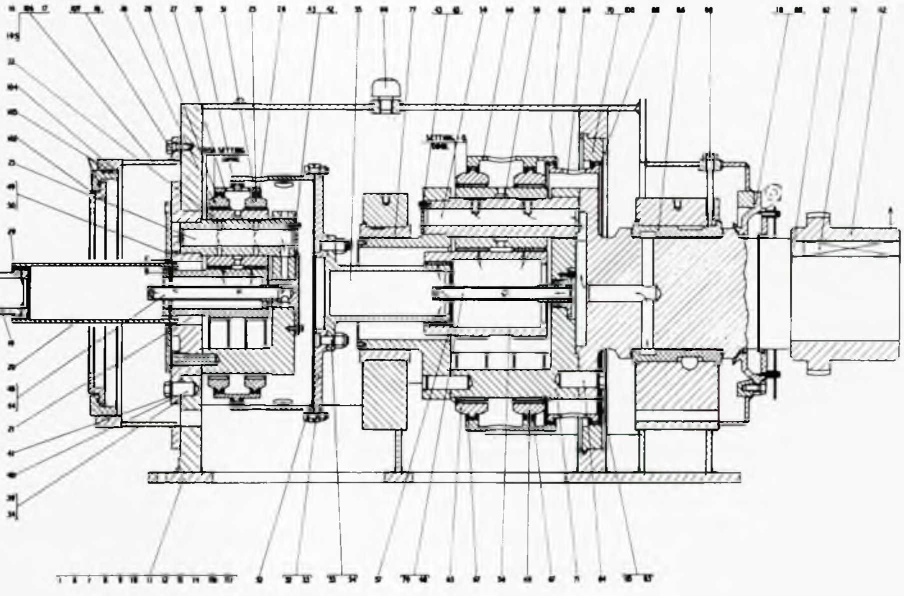


FIG. 10—*Section through epicyclic gear*

1) Gearcase
6) Fitted bolt $\frac{5}{8}$ B.S.F.
7) $\frac{5}{8}$ B.S.F. nut
8) Hex. head bolt $\frac{3}{4}$ B.S.F. × $2\frac{1}{4}$ long
9) $\frac{3}{4}$ B.S.F. nut
10) Dowel $\frac{5}{8}$ dia.
11) Dowel $\frac{3}{4}$ dia.
12) Bearing cap studs $\frac{3}{4}$ B.S.F. × $8\frac{1}{2}$ long
13) Bearing cap studs 1 B.S.F. × $9\frac{1}{4}$ long
14) Nyloc nuts 1 B.S.F.
15) Wedglok screw $\frac{3}{4}$ B.S.F. × 2 long
16) Hex. hd. bolt $\frac{1}{2}$ B.S.F. × 2 long
17) Nut $\frac{1}{2}$ B.S.F.
18) Hex. hd. bolt $\frac{5}{8}$ B.S.F. × $1\frac{1}{2}$ long
19) Sunwheel coupling flange
20) Sunwheel coupling sleeve
21) Sunwheel
22) Starwheel
23) Starwheel spindle
25) Internal gear ring R.H.
26) Internal gear ring L.H.
27) Coupling ring (internal)
28) Spring ring (17·782 dia. × 8 s.w.g.)
29) Spring ring (4·400 dia. × 12 s.w.g.)
30) Spring ring (19·800 dia. × 6 s.w.g.)
31) Coupling ring (external)
32) Special fitted bolt $\frac{1}{2}$ B.S.F.
33) Nyloc nut $\frac{1}{2}$ B.S.F.
34) Star carrier Assy.
39) Hex. hd. screws $\frac{3}{4}$ B.S.F. × $1\frac{3}{4}$ long
40) Dowel $1\frac{1}{4}$ dia.
41) Locking plate
42) Spindle cover plate
43) O.B.A. socket cap screw × $\frac{5}{8}$ long
44) Oil nozzle
48) Socket cap screw $\frac{3}{8}$ B.S.F. × 1 long
49) Oil inlet channel cover
50) Socket cap screw $\frac{3}{8}$ B.S.F. × $1\frac{1}{4}$ long
51) Socket cap screw $\frac{3}{8}$ B.S.F. × $1\frac{3}{4}$ long
52) Sunwheel coupling flange
53) Special fitted bolt $\frac{3}{4}$ B.S.F.
54) Nyloc nut $\frac{3}{4}$ B.S.F.
55) Sunwheel coupling ring
56) Sunwheel
57) Spring ring 5·50 dia. × 12 s.w.g.
58) Planet wheel
59) Planet wheel spindle
63) Standard end plate
64) Internal gear ring R.H.
65) Internal gear ring L.H.
66) Coupling ring (internal teeth)
67) Spring ring 22·517 dia × 6 s.w.g.
68) Spring ring 23·375 dia. × 6 s.w.g.
69) Coupling ring (external teeth)
70) Coupling flange
71) Planet carrier Assy.
77) Bearing (non locating)
79) Oil nozzle
82) Low speed shaft
83) Hex. hd. bolt $\frac{3}{4}$ B.S.F. × 3 long
84) Dowel $1\frac{1}{2}$ dia.
85) Locking plate
86) Bearing (10 in locating)
88) Oil and windage baffle Assy.
98) Thermometer pocket
99) Tecalemit air breather filter $\frac{3}{4}$ B.S.P.
102) Pedestal adaptor ring
103) 'Gaco' cord (0·275 dia.)
104) End casing adaptor ring
105) High speed end casing
106) Fitted bolt $\frac{1}{2}$ B.S.F. × $1\frac{7}{8}$ long
107) Dowel $\frac{5}{8}$ dia. × $1\frac{1}{2}$ long
108) Round hd. screw 2BA × $\frac{3}{8}$ long
109) Nameplate
110) Warning plate
111) Key $2\frac{1}{4}$ × $1\frac{1}{2}$ rect. taper
112) Zurn coupling F. 108
116) 6 B.A. screws ch. hd. × $\frac{1}{4}$ long
117) Cable clips

inlet at 30 lb/in^2 from a common system which also fed the turbine and generator bearings.

The gearbase construction was fabricated steel, the bearing cap material being steel as specified for the turbine.

The compactness and lightweight features of this arrangement, together with the co-axial input and output shafts, made the epicyclic gearbox ideal for this type of application in which the space available and accessibility were somewhat restricted. The co-axial arrangement of the gear had considerable advantage in simplifying the under-bed construction and reducing its width.

After full speed/no load tests at the works, followed by dismantling for component examination as required by the survey authority, the gearboxes had been shipped to Canada for extensive tests with the turbines and generators prior to installation in the ship. Concerning the usefulness of shop trials of the complete machine, he said that his company endorsed the view set out in the paper that this form of testing was essential so that, as far as possible, complete compatibility could be ensured prior to the units being installed in the vessel, thus keeping sea trial time and any subsequent modifications, costs and delay to a minimum.

During the tests at the works, the power absorbed on Set 1 had been 64 hp and on Set 2, 67 hp, and following from this the estimated losses at full speed and load were such as to give a gearbox efficiency of 98·2 per cent.

Allen epicyclic gearboxes for powers up to 15 MW were being used for steam and gas turbine/generator applications in both land and marine installations. To date, over 700 gearboxes had been supplied for these purposes, whilst well over 200 had been built as propulsion units for gas turbine propelled vessels.

DR. A. W. DAVIS, C.Eng., M.I.Mar.E. thought that the paper would in due course be looked upon as one of the significant papers on the subject in its early days. It had come at a time when it was difficult to get very excited about the subject in marine circles, but that fact did not in any way, in his view, minimize the importance of the information that had been put before the Institute.

He said that he remembered being regarded as anything but "on the ball" when he had said, around 1950, that he did not see a lot of future for the gas turbine at sea. This was now nonsense, but in view of the many difficulties that are so slowly being uncovered and overcome he was not ashamed of having made such a statement 20 years ago. In another 20 years he believed that the paper would be looked upon as being of very broad interest and the Navy might well be looking upon it that way.

The key to the matter was fuel. The Navy were in the position of being able to use the taxpayers' fuel, and he supposed that in Canada it was the taxpayer who broke ice.

A prominent ship had come on the seas a few months previously which had been heralded as the first of a new age, which was a kind of contradiction of all that had happened in the last decades, but it remains for the economics of operation of such vessels to be revealed by the choice of machinery for subsequent tonnage.

Another feature he mentioned was the ruggedness of the unit. A comparison had recently been made between a gas turbine first stage blade for an industrial turbine and one for an aircraft turbine, and they had not really both been identifiable as being the same thing. Although one had become familiar with the discussion between these two types of machine, he thought a few words by the author on the gas turbine itself would be helpful to emphasize its ruggedness.

In conclusion, he said that he had been glad to hear that Mr McCullum had obtained some operating experience after 28 January, 1970, and he thought it would add greatly to the value of the paper if this could be included in the answer to the discussion.

MR. R. COATS, C.Eng., M.I.Mar.E. said that he would be interested to know how the enamel covering for the stainless steel of the compressor blades was performing, and whether this enamel was liable to crazy crack in any way in service under thermal cycling. Admittedly it was the compressor they were dealing with, but it would have to deal with a certain range of temperature. One thing that he foresaw was that if crazy cracking did occur it would have a disastrous effect on the fatigue life of the parent material.

He also asked how the enamel coating stood up to the spent catalyst that was used for cleaning the compressor blades.

He said that he was interested in the ceramic aluminium coating for the compressor discs and the exhaust bearing supports, and asked the author if he could give more information on it. He supposed that these supports were the arms that cut across the exhaust space in the hot gas stream.

A previous speaker had referred to the shock aspect of icebreaking, and the paper had said that $1g$ was the design criterion for the strength of the machine. This did not seem to be a very onerous requirement. In fact, he thought this was what all machines would naturally be designed for, except that in marine service it had been the practice, without considering any shock loading arising from special circumstances such as explosions, and so on, to design for $1\frac{1}{2}g$. However, if there were any particular naval requirements then it had to be related to very much higher values.

If that were the only shock requirement then he would not have thought that it was necessary to change the nodular iron to steel, but perhaps this was a naval requirement.

This particular application seemed to be a very good one for trying out a gas turbine in that one was not putting all one's eggs in one basket. One had got the Diesel engines if anything went wrong with the gas turbine, although, as the author had mentioned, in this case it turned out to be the other way round.

He was not quite sure what the relationship between the Diesel engines and the gas turbines was. Were the Diesel engines meant to be cruising engines and the gas turbine a booster engine, or were they both used together? He also asked what power the Diesel engine had compared with the gas turbine. He said that he was very interested in the electrical transmission aspect.

The point about the transient re-generation of energy when the ship was slowing down after a high speed operation was a very important one, and various means had been considered for absorbing this energy. His company had been looking into a scheme for a similar application by generating electricity as a.c. and using d.c. meters, with a thyristor conversion scheme to change from a.c. to d.c. In that case it seemed to be possible to absorb this re-generated energy in the thyristor system.

His next point was related to quite a different concept altogether. It seemed to him that for an application such as an icebreaker, and particularly for this level of power, it would have been a good arrangement to have incorporated an hydraulic reversing transmission in conjunction with mechanical gearing, and to have eliminated the electrics altogether. By such a means one could have achieved all the manoeuvring facility that the electrical scheme provided at a much cheaper cost and at a much higher efficiency. He wondered if the author could say something about the deliberations that had led to the choice of electrical transmission in the first place.

With regard to starting by means of the main generator, he said that on his company's gas turbine they would normally incorporate a starting motor for marine purposes of about 400 to 500 hp, situated at the compressor end of the machine. This was a perfectly standard arrangement. It was difficult for him to understand why, when apparently a standard gas turbine had been used, it did not incorporate a starting motor or a starting device of its own. He wondered why the main generator had been brought into use for starting the turbine.

He concluded by thanking the author for an interesting paper and wished him all success. He also looked forward to further reports on performance in due course.

Correspondence

MR. J. MCNAUGHT, C.Eng., M.I.Mar.E., Chairman of the Papers and Technical Committee, wrote that because of remarks made by contributors about the use of S.I. units, it was considered that some comments should be made about the present position.

In January 1970 it had been decided to adopt S.I. units with Imperial units in brackets, for papers presented after an agreed date, which had become September 1971. It had also been decided to follow the recommendations laid down by the British Standards Institution in their publication "The Adoption of the Metric System in the Marine Industry PD 6430".

The subject had again been reviewed by the Papers Committee and the following was decided:

a) Until the end of the 1972/73 session both units would be given where practicable with the preferred S.I. units being quoted first.

b) From April 1973 until the end of 1975/76 session, preferred S.I. units only would be quoted, but some exception would be made for units of power, pressure and some compound units.

c) After April 1976 S.I. units only would be used.

The above policy would be implemented in a flexible manner. The important consideration was that technical papers should continue to be interesting and comprehensible to the wide membership of the Institute.

It would not be possible to implement this policy in full in *Marine Engineers Review* until such time as all advertisements and abstracts were written wih S.I. units.

The following are the details of the B.S.I. publications:

1) Adoption of the Metric System in the Marine Industry PD 6430 January 1969 incorporating the amended issue in October, 1970 (A.M.D. 608). Price: £1

2) PD 6430/1 dated December 1970 Price: 60p which includes the appendices only from the main pamphlet.

Both these publications can be obtained from the British Standards Institution, Sales Branch, 101/113 Pentonville Road, London, W.1.

Author's Reply

In reply to Lt. Cdr. Randles, Mr. McCullum said that he had had no reports of icing of the turbine in application. With the aid of an illustration he pointed out two things about the possibility of icing. First of all, it would be noted that the turbine bearing was outside the air path into the turbine. Therefore there was not a support structure at the inlet to support the bearing on which, through a range of temperature and humidity, it was possible to have ice built up due to the cooling of the humid air on the cold structure. The first row stationary blade or inlet guide vein would be a location for the build up of frost type ice. In industrial experience in the prairie part of Canada and almost throughout the range to British Columbia there had been ice built up on this. However, the chief effect of that had been to throttle the air inlet and reduce the turbine capability. In general, the operators kept the machine in service. The principal reason for this was that they needed the power because it was winter, and it was in population service or electrical service and that was the period of greatest demand for power or electricity.

The other chief source of ice damage in the application of turbines was where condensation or rain or snow had been allowed to accumulate in inlet ducting systems or in the silencer arrangement, and when the turbine was not in use that material or location was in freezing ambient and the condensate water or snow might have melted at some time and run down and accumulated in low spots as water. His company emphasized as strongly as they could to others, that if they were responsible for the design of the inlet system they should minimize the possibility of the water dropping in low spots, and where the low spot was necessary they should have a drain and the drain should be heated so that it did not freeze. Frost build up could be very rapid, and at times it had caused the operators to shut down the turbine. His company's experience was, without exception, that when there was frost build up on the inlet guide vein of the turbine which then broke loose and passed through the turbine, it had caused no visible damage. He was talking about machines in the 10 000 hp to 30 000 hp range. The damage on the inlets of turbines had been caused where water had been allowed to accumulate in a low spot in the ducting and had not drained, and on start-up the pocket of ice had been jarred loose and swept up in the airstream and had moved into the turbine, striking the inlet guide vein and breaking up into relatively hard pieces. This certainly damaged the first row moving blades and occasionally the second row moving blades. They had had their most serious cases of this in British Columbia, where there was a fairly humid atmosphere. They had not seen damage beyond the second row compressor stage. His company's official recommendation was that if that happened, the machine should be shut down and the turbine blades repaired or replaced so that one got a full pressure ratio over the turbine for the temperature that one was still running at. Operators had been known to continue operating the machine after moving away, but there had been only one or two instances of that.

Referring to Mr. Webb's comments on the protection of the inlet system, he said that the air inlet was passed through an inertial type filter. There was a trash screen at the top of the inlet system. That was the only physical separator that was located in the system other than levers or doors at the inlet when the turbine was not in use.

With regard to the degree of silencing, the numbers in the paper were for an unsilenced machine and without the benefit of the silencing effect that went with heat insulation on the body of the turbine or on the exhaust manifold.

On the question about depth of ice, this could be any level, and in the St. Lawrence River it went to a depth of 40 to 50 ft of ice. This was ice that started out as cakes floating on the river which, when they reached a point of congestion, piled up one on top of another and forced their way practically to the bed of the river. This, in turn, created flooding. The icebreaker did not go through this forward; it turned around and drilled its way through backwards.

With regard to shock, 1*g* was specified, although there were times when the ship saw more than that. The Coast Guard in Canada had fully instrumented its largest operational icebreaker.

He appreciated Mr. de Ville's comments on gearing. As he had said in the paper, the performance of that gear had been fundamental to the successful performance of the equipment.

Dr. Davis had raised a number of comments on the turbine ruggedness and had referred to aircraft type gas turbines. He thought it fair to say that an aircraft gas turbine might not have been acceptable aboard the ship unless it had been built with sufficient thickness of wall to contain parts that might fly loose under some circumstances. There were aircraft gas turbines that were doing a good job aboard ship, but it should be remembered that the icebreaker went many miles away from anywhere, where it could not be reached by any other ship, and conservatism permeated the whole design philosophy and specification philosophy.

Dr. Davis was quite correct in surmizing that the taxpayer paid for the oil and the ship.

Author's Reply

Mr. Coats' comments and questions had been extremely important. With regard to the survival of the compressor, the disc and the turbine exhaust coating, he said that he thought they had done the right thing and that they were not going to have the kind of problem Mr. Coats very properly suggested could arise.

Mr. Coats was quite right in his suggestion that there was a modest degree of shock to withstand.

The substitution of steel for nodular iron had been just another note of conservatism. The same comment would apply to the electric transmission aspect. They were fairly competent in the care and operation of large ships with direct current electric transmissions in the Canadian Coast Guard. Direct current electric transmission had gained acceptance a few jumps ahead of controllable or variable or reversible pitch propeller systems and in icebreaking duty it was used because of conservatism.

Someone had commented that having an electric drive system was a good way to escalate a gas turbine in an icebreaker along with Diesels to get some experience. That had been precisely the view of the Coast Guard at the time. The role of the Diesels was that they had about the same hp rating and they could drive the ship during most of its operations. The role of the gas turbines was to provide a booster, although they did provide power when the Diesels were not available due to an unfortunate accident. Perhaps hydraulic reversing machinery would appear later, but it was a case of the gas turbine being tried in an icebreaker and the other variables being kept to a minimum.

He agreed that a separate starter device if added to the end of the turbine would certainly be an increase in length.

Related Abstracts

Gas turbines for marine propulsion

Recent improvements in gas turbine technology can be expected to lead to a range of new engines, some of them derived closely from aero engines, others developed *ab initio* for the industrial and marine environment.

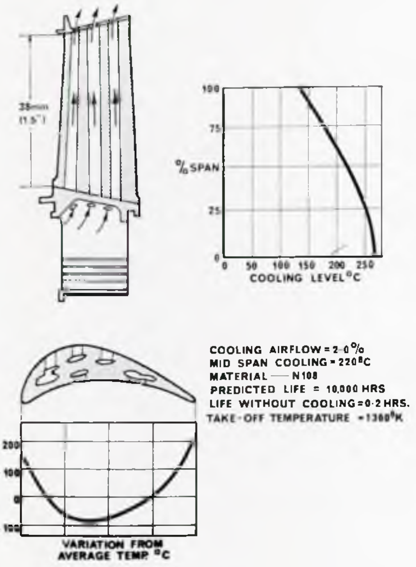


Fig 1—*Typical cooled turbine blade*

A typical modern cooled blade design is shown in Fig. 1. It has elliptically shaped cooling holes. Cooling air enters the blade from both sides of the root and exhausts from the tip. The cooling airflow used is two per cent of the main turbine flow and reduces the midspan average blade temperature by 200°C.

Improvements have also been made in the methods of introduction of cooling air into the blade roots. One such method is shown in Fig. 2. Pre-swirl nozzles impart a tangential component to the cooling air so that it enters the blade root cleanly. This results in a lower cooling air temperature than would be given with an inefficient entry to the blade root.

Prior to the introduction of the cooled blade, the turbine entry temperature of aircraft engines rose at a rate of approximately 10°C per annum as a result of improvements in materials. With cooling, the rate of increase has been raised to almost 30°C per annum. Transferred to the industrial scene, the latter figure would imply rates of increase of power six per cent and of efficiency two per cent per annum. The introduction of the air-cooled turbine blade has doubled the potential rate of improvement over that which was possible before.

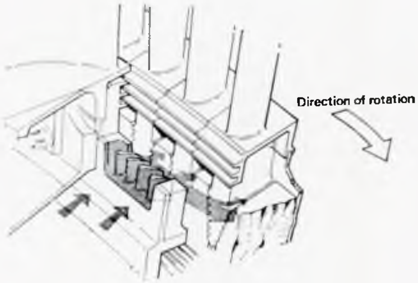


FIG. 2—*Method of supplying cooling air to turbine blades*

A significant penetration of the merchant marine market by the gas turbine can be expected in the near future, partly due to engine improvements and partly due to changes in the requirements of ship design. The size and speed of ships are both increasing, creating the demand for more power. An increasing amount of cargo is carried in containers and experience to date suggests that the average full container is well below its maximum permitted weight. There is a trend towards lighter loaded weights. The number of containers that can be loaded is thus determined by the available space in the ship. Shorter stays in port are also required in container ship operation and the availability of the ship to operate a scheduled service is important. The gas turbine can meet all these requirements. Typical of the future engines suited to this application is the Marine RB.211 derived from the engine for the Lockheed Tristar airbus. This engine produces over 15 MW (20 000 hp) at its service rating with a specific fuel consumption in the region of 183 g/bhp-h (0·4 lb/hp-h). It uses more fuel than a Diesel engine of the same power. It burns distillate fuel, moreover, and this means that the fuel costs are higher unless special situations exist, as in liquefied natural gas carriers.—*Marine Engineer and Naval Architect, November 1971, Vol. 94, pp. 452–454.*