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Propulsion Power Plants for Large Icebreakers with Special Reference to Gas Turbine Applications

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The Canadian Government, Ministry of Transport, initiated a Study of the Application of Gas Turbines to Canadian Coast Guard Vessels in 1972, which was completed in early 1974. This paper discusses the results of our findings and also new data now being used in design studies for heavy Icebreakers of Polar Class.

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S. ROSSI C. KLOP

INTRODUCTION

A number of papers have been presented on the applicability of gas turbines for ships' propulsion, and an ever-growing number of gas turbine driven ships are now in service or are being built by shipyards around the world.

To name a few:

1 Naval Vessels:
   (a) DDH Class Destroyers (Canada)
   (b) Yarrow Frigate (British)
   (c) Guided Missile Destroyer Type 42 (U.S.A.)
   (d) PEDER SKRAM (Denmark)

2 Merchant Vessels:
   (a) GTS ADM. WM. M. CALLAGHAN
   (b) Sea Train Vessels
   (c) Iron MONARCH
   (d) Chevron Tanker

3 Icebreakers:
   (a) NORMAN McLEOD ROGERS (Canada)
   (b) POLAR STAR (USA).

After the initial problems encountered especially on the "CALLAGHAN" and the SEA TRAIN VESSELS, these propulsion plants now are operating efficiently. Low maintenance is reported by the various owners and downtime is at a minimum or nonexistent. In other words, the marinized gas turbine has proved to be a reliable prime mover for naval vessels and merchant marine ships.

For icebreaking vessels, however, the only experience with gas turbines as prime movers to date was accumulated on the "C.C.G.S. McLEOD ROGERS" in which single-shaft heavy-duty gas turbine generator sets are installed to provide boost power in a dc-dc propulsion electric drive configuration.

Because of the ever-growing need of icebreaking operation in the world, it became obvious there was a need for a study on the suitability of the gas turbine as a prime mover for a wide range of icebreaker applications, and in 1972, the Canadian Coast Guard ordered a "Study of the Application of Gas Turbines to Canadian Coast Guard Vessels." This study was aimed at assessing the suitability of gas turbines for propulsion duty in existing and planned vessels, and in the early part of 1974, the study, in a five-phase format, was completed. It would be impossible to present here all the findings from this study or the groundwork done for the preliminary design of a Polar Icebreaker presently on the drawing boards. This paper, therefore, will look only at the acceptability of the gas turbine as a prime mover in large icebreakers.

Because this type of vessel differs from other ships, the analysis of prime mover suitability must first take into account the vessel design requirements. These requirements are briefly examined.

TYPICAL VESSEL CHARACTERISTICS

The principal particulars for the class of icebreaking vessel under study have been established as:

Length between perpendiculars	500 ft-0 in.
Breadth, maximum	104 ft-0 in.
Breadth, maximum or load W.L.	100 ft-0 in.
Depth of hull	52 ft-0 in.
Design draft, deepest	35 ft-0 in.
Displacement, long tons	26,000
Economical speed knots	17
Corresponding shp for economical speed	15,000
Corresponding range (nautical miles)	44,000

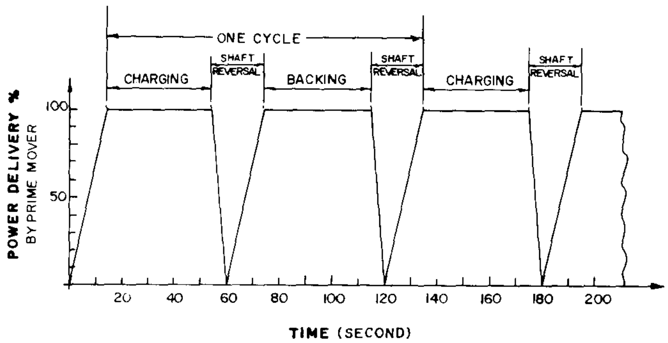

Fig. 1 Hypothetical power profile of the main propulsion system of an icebreaker during heavy ramming

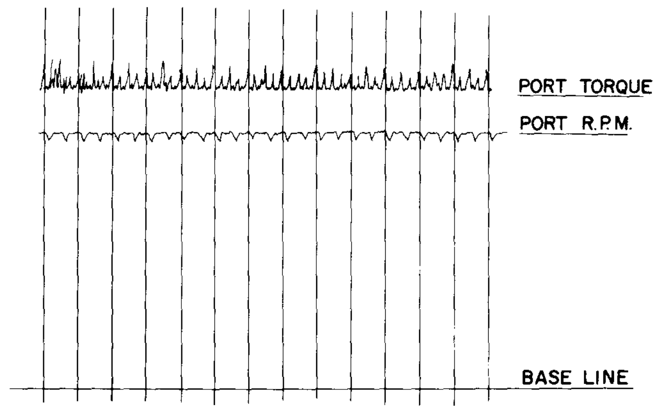

Fig. 2 Shaft torque and rpm fluctuations as measured on c.c.g.s. labrador

Shp required for breaking land-fast ice of 3-ft thickness ------	27,000
Shp required for heavy ice-breaking -----------------------	81,000

MISSION PROFILE

A typical mission profile developed by the Canadian Coast Guard for a heavy icebreaker is as follows:

The ship will be used in the Arctic 10 months a year and will be back from Northern operation only for refit and drydocking.

Total time underway will be 4500 hr or 450 hr per month.

	Power Used	Percent of Time
Full power available 30 percent of the time (135 hr/month)	100	60
	80	15
	60	10
	40	10
	Idle stop	5
Two-thirds of full power available 40 percent of the time (180 hr/month)	100	60
	80	15
	60	10
	40	10
	Idle stop	5
One-third of full power available 30 percent of the time (135 hr/month)	100	40
	80	40
	60	10
	40	5
	Idle stop	5

POWER PROFILE

A hypothetical power profile of the main propulsion system of a heavy icebreaker during ramming was developed and is shown in Fig. 1

It would be possible for this duty cycle to be experienced for long periods of time.

POWER FLUCTUATIONS DURING CONTINUOUS ICEBREAKING AT THREE KNOTS

The large icebreaker will be designed to break ice continuously at three knots through an ice thickness commensurate with its class.

The Polar Icebreaker now in the design state will have a light ice-breaking power level designed to enable the vessel to break 36 in. of ice continusouly at three knots and a full power capability to continuously break 6 to 8 ft thick ice at three knots.

Power fluctuations caused by ice torque variations when milling through ice have been measured during icebreaking tests. Fig. 2 shows an actual graph taken on the icebreaker "LABRADOR" when in service in Resolute Bay.

This graph shows torque fluctuations of plus 5 percent to minus 10 percent from full power as each propeller blade hits the ice when proceeding at three knots.

In other ships' tests, the measurements taken show, in extreme cases, that propeller loads can fluctuate between 60 and 140 percent of full load torque at 2-sec intervals when proceeding through heavy ice.

PROPELLER JAMMING IN ICE

When the vessel is operating in heavy ice, the propeller may stall because of the very high ice-induced torque values. This possible condition is the reason for a design requirement which needs all shafting, gearing, propellers, etc. to be designed to withstand forces applied

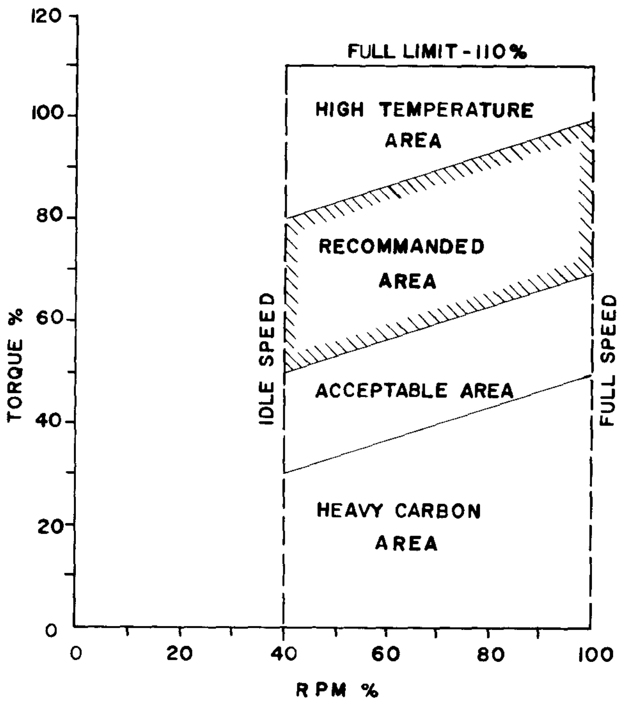

Fig. 3 Typical diesel engine characteristics

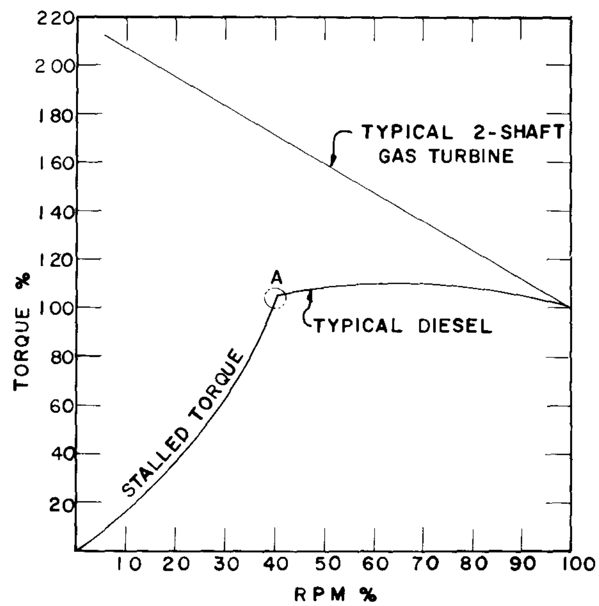

Fig. 4 Typical diesel and gas turbine torque-rpm graph

when the propeller is stopped in one second with prime mover operating at full power.

Also, the propulsion plant must be capable of providing high torque with the propeller in near stalled condition at very low shaft rpm.

PROPULSION POWER PLANTS

The foregoing parameters impose certain restrictions on the choice of propulsion plants for icebreaking vessels.

The two basic propulsion power plants being considered for Canadian Coast Guard icebreakers are:

(a) Geared propulsion with C.P. propeller;
(b) Electric propulsion with F.P. propeller.

In the geared propulsion, the prime mover is either a diesel or a gas turbine or a combination of both.

Electric propulsion power can be generated either by diesel, gas turbine, steam turbine generator sets, or a combination of these. In all cases, the propulsion motor is a d-c electric motor; however, an ac-ac propulsion system with C.P. propeller is still being analyzed.

In this paper, we are mainly concerned with the choice of prime movers so let us examine in some detail the pro's and con's of using any given prime mover in either geared or electric propulsion.

(a) Geared Propulsion, Diesel Engine or Gas Turbine as Prime Mover

A typical diesel engine characteristic and a typical diesel engine and gas turbine torque versus rpm curve are shown in Figs. 3 and 4. Fig. 3 shows the recommended area in which the diesel engine should run for long life and low maintenance.

Fig. 4 shows that if a diesel engine drives the propeller through a reduction gearbox, 100 percent torque will be available at 100 percent rpm; when the ship encounters ice and the propeller slows down because of increasing ice torque, the rpm will drop, thus demanding more fuel for the diesel until the engine is producing approximately 110 percent torque. Further slowing down of the propeller will slow the engine until point A is reached and any further drop in rpm will stall the diesel. If the diesel engine is kept connected to the propeller system, it will not be able to re-start until ice-induced torque values drop below available starting torque.

The characteristics of a gas turbine are completely different for a similar mode of operation. The free turbine type of gas turbine engine has a large range of normal con-

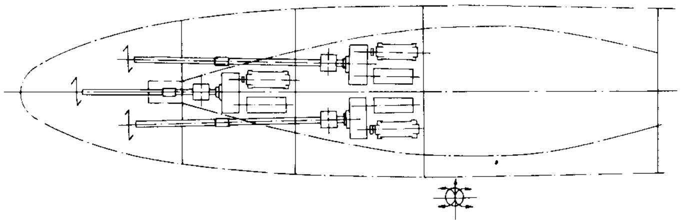

Fig. 5 Arrangement 1

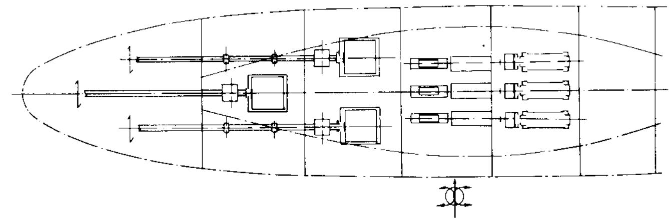

Fig. 6 Arrangement 2

tinuous operation. This makes it easily adaptable as a prime mover for almost any duty.

The load applied to the free turbine has no significant effect on the gas generator and at constant fuel flow, the airflow and gas power produced remain about constant, irrespective of the speed of the free power turbine. Under these conditions, the power and torque developed by the free power turbine vary with rpm in accordance with the normal turbine efficiency curve as shown. The result is, that if the free power turbine speed is reduced, its output torque capability is increased as is the case with steam turbines and d-c electric motors.

From this, it can be seen that the gas turbine is a more suitable prime mover for direct drive on icebreakers than diesel engines. However, it is possible to install a flexible disconnect coupling between the diesel engine and the gearbox with built-in over torque disconnect capability, thus making the diesel-geared propulsion system not completely unacceptable. Various types of these couplings are on the market, one accpetable one being a pneumatic actuated clutch combined with a flexible coupling. The coupling acts as a cushion between the propeller and the diesel prime mover absorbing part of the torque fluctuation with propeller milling through ice while the disconnect clutch will protect the diesel from stalling when too high ice torque values are encountered.

Further investigations related to the Mission Profile have led to the conclusion that for high-powered icebreakers two levels of continuous power should be available, one to cater for high-powered heavy ice-breaking duty and one to take care of the cruising and light icebreaking mode.

Our naval architects have studied the relationship between hull size versus the cruising and light icebreaking power requirements from which it has been established that the cruising power can be assumed to be approximately one-third of the heavy icebreaking power requirement; i.e., on a 90,000-shp ship, the cruise power requirements would be 30,000 shp, and on a 75,000 shp ship, the cruise power would be 25,000 shp. Another conclusion, which affects the choice of prime mover, was that on icebreakers a triple screw configuration is preferred based on thrust, maneuverability, redundancy, vulnerability, and space. Also, it was determined that power distribution among shafts should be equal.

This decision was based on considerations regarding redundancy, vulnerability, maneuvering ability, and plant layout.

Greater power on the wind screws would create a considerable loss of power if one wing screw would be inoperable.

Greater power on the center screw would increase the maneuverability, but in the icebreaking mode tends to "starve" the wing screws.

The scope of this paper does not allow us to go into the complete analysis leading to these conclusions, or discuss the considerations regarding the adoption of C.P. propellers. It suffices to say that it was concluded that gearboxes and controllable pitch propellers are acceptable for icebreaking vessels provided, of course, they are specially designed to meet the rigorous duty of these vessels.

In order to utilize to the best advantage the low SFC characteristics of the diesel engine, these should be used in the cruising mode while the good torque-rpm characteristics of the gas turbine should be used for heavy icebreaking.

Thus, a typical propulsion set was arrived at consisting of one high powered gas turbine, one diesel engine of approximately one-third power driving a C.P. propeller through a suitable double input, single output reduction gearbox. Fig. 5 shows a typical layout of an icebreaker with triple screw geared propulsion plant.

(b) Electric Propulsion with Fixed Pitch Propeller

The electric motor has been, up to now, the preferred mode of propulsion on icebreaking

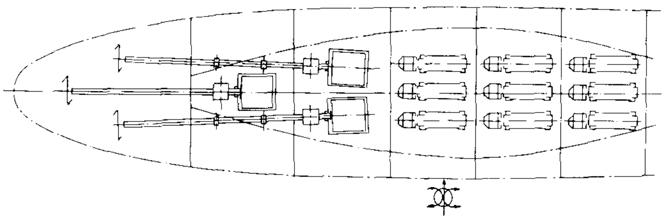

Fig. 7 Arrangement 3

vessels because of the inherent good torque-rpm characteristics, ease of reversing, and speed control of the d-c propulsion motor. Very similar to the gas turbine, the propulsion power torque values go up when propeller rpm goes down until with propeller of very low rpm, still very high torques are available.

Power can be generated by either steam turbines, gas turbines or diesel engines, and, in general, it becomes a matter of choice based on economics, capital cost, fuel consumption, available space, weight, redundancy, or even Owner's preference.

However, on the very high powered icebreakers, the choice becomes rather restricted mainly because of space availability, weight allowance, and fuel consumption.

A 30,000-shp d-c propulsion motor is of such enormous dimension and weight that the vessel must be specially designed to accommodate the propulsion motors alone.

The estimated weight of a double armature d-c propulsion motor is approximately 500 tons each of which the size is approximately 20 ft (6 m) dia and 40 ft (12 m) long and 30 ft (9 m) high.

These motors will take up a large portion of the aft end of the ship, restricting the space availability for the prime movers with associated generators. Thus, on high powered icebreakers, the use of steam turbine driven generators becomes impractical, even impossible, because of physical size of the steam plant alone.

The all-diesel electric arrangement is very tight, and special arrangements had to be made in order to show the arrangement with diesel generators.

It is safe to say that on high powered electric driven icebreakers of a reasonable size, the use of gas turbines as prime movers is the only viable arrangement for the full power heavy icebreaking duties required.

Cruising power, however, should still be provided by diesel generator sets to benefit from the good SFC of the diesels when running at part power.

Figs. 6 and 7 show the difference in space requirements between a CODEOGE arrangement and an all-diesel electric arrangement.

COMPARISON OF ARRANGEMENTS

Having established that gas turbine prime movers are desirable for this type of vessel, it becomes much easier to set up a comparison between the various possible arrangements for an icebreaker of this size.

The propulsion plant of this class of icebreaker must be designed to withstand the most arduous requirements of any machinery system ever built or being built for a ship in the world today. The overall system must be capable of producing high powers, it must be reliable, and it must be capable of being easily maintained to enable the vessel to operate in remote areas for at least 10 months in a year. In addition, it must have enough flexibility and redundancy so that the vessel will be able to accomplish its mission profile in a highly efficient manner.

Although many arrangements were originally examined, only three installations are finally considered in detail in accordance with the following criteria:

1. Hull and machinery characteristics
2. Weight and space consideration
3. Fuel consumption
4. Reliability
5. Redundancy
6. Maintainability
7. Manning requirements
8. Automation
9. Training
10. Cost analysis.

As a result of the study examining arrangements for a typical 81,000-shp power plant, the following overall conclusions are arrived at:

(a) Three-shaft arrangement is selected.

(b) More than one engine per shaft should be used for good redundancy, reliability, and east of maintenance.

(c) The most practical method of obtaining high powers is by the use of marinized aero-derived gas turbines. The consideration for the use of heavy-duty gas turbines for these high powers is being held in abeyance until further experience is obtained by these machines in ice-breaking vessels.

(d) For the very high powers, the gas turbine has an advantage over the diesel engine.

(e) Diesel engines should be used in cruising and light icebreaking mode because specific fuel consumption of these engines is superior to present-day gas turbines.

(f) The diesel engine direct drive is not suitable for heavy icebreaking because of its inherent poor torque characteristics.

(g) Reversing type gearboxes are at present not available for the high power being considered.

(h) Both controllable and fixed pitch propellers are considered suitable for use in appropriate installations.

(i) Electrical transmission systems give more flexibility to the propulsion system. However, they are more expensive, heavier, larger and more maintenance effort is required. Development now being done by industry in electrical systems may reduce the size and weight and possibly some savings in the overall costs for future vessels.

(j) A-c generator with diode or thyristor rectifiers to d-c motors is the recommended propulsion system at the present time.

The following compares the different characteristics for the three arrangements:

Arrangement:	1	2	3
Description (1 shaft only)			
Full power	1GT	1GT	3D
Cruising	1-D	1-D	1-D
Transmission/prop.	CPP	Elec/FP	Elec/FP
Machinery weight (tons)	1770	2445	2790
Space (length)	160 ft/ 49 m	210 ft/ 64 m	250 ft/ 76 m
Annual fuel consumption (tons)	46,100	49,800	34,700
Est. refueling frequency (times per year)	5.5	5.8	4.0
Acquisition costs (x 10^6)	$22.4	$26.9	$27.2
Operational costs (x 10^6)/yr	$4.6	$5.2	$4.0
Life cycle costs (x 10^6)	$97.8	$111.0	$83.3
Mean time between failures (hr)	2919	2796	4240
Reliability (estimated)	0.214	0.200	0.346
Maintainability-order	1	2	3
Automation-order	1	2	3
Manning (engineering only)	21	33	39

SOME OUTSTANDING PROBLEMS

Within the scope of this paper, it is not attempted to prove that all the problems regarding the design of the propulsion system for a Polar Icebreaker are solved.

As an example, when considering the gas turbine as a prime mover, one area of concern still is the ingestion of salt and/or ice from the intake system. This problem seems solved or nearly solved with the more recent applications of filtration/separation, inlet preheating and the continuous research and development of blade design coatings and materials.

One other area of concern is the gas turbine metal thermal stresses caused by icebreaking modes.

During heavy running and repeated changes of power, from full head to full astern, thermal stresses may build up which, when continued for long period, could cause operational problems and equipment damages.

Heavy-duty gas turbine manufacturers would not recommend operating their engines according to the power profile of Fig. 1 without paying a penalty maintenance and/or life expectancy.

Although it is stated that gearboxes and controllable pitch propellers are acceptable for heavy icebreaking, a detailed study of these components will be made before the final specification of the power plant is formulated. Especially, in the case of controllable pitch propellers, a careful analysis will be made of the spindle tongue valves during heavy ice milling in conjunction with automatic pitch changes when in a constant rpm mode of control.

CONCLUSION

In this paper, it was attempted to give the reader an insight into the complexity of selecting a suitable propulsion power plant for a polar icebreaker.

Also the results of a preliminary design study were given and some of the aspects of yet unanswered questions and problems were noted.

Within the confines of a Polar Icebreaking vessel of high powers, reasonable size, good icebreaking, and ice maneuvering capability, the use of gas turbines as prime movers in either a direct mode or in electric propulsion mode is considered highly feasible.