THE ROLE OF THE GAS TURBINE IN CANADA'S DEVELOPMENT AND DEFENCE

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SUMMARY

There are innumerable needs, in Canada's development and defence, for large numbers of small portable power plants for purposes of transport, machinery drives, electricity generation, etc. Such power plants must above all things be rugged and reliable, light and compact and capable of efficient operation in the most severe arctic conditions.

In this report the uses and requirements of such power plants are discussed. The ability of existing gasoline and diesel engines to meet these requirements is shown to be inferior to that of a gas turbine designed conservatively in the light of present day knowledge. The gas turbine engine is peculiarly well suited to Canadian problems by virtue of its large increase in both power output and efficiency in cold weather, by its demonstrated ease of starting under extreme conditions, and by its ability to burn almost any liquid fuel.

A design is proposed which could be made in three aerodynamically similar sizes, namely 200 H.P., 400 H.P. and 800 H.P., which it is suggested would meet the great majority of Canadian requirements. These engines will have thermal efficiency comparable with gasoline engines, while burning any liquid fuel, irrespective of octane or cetane numbers. Their weight and size will be much smaller than for existing engines, while experience in the Air Force and elsewhere with turbine engines, proves that maintenance is much simpler and cheaper than with reciprocating engines.

The fact that the three different sizes of engines are aerodynamically similar, simplifies development considerably. By starting with the smallest engine first, the aerodynamic and mechanical design can be proved most cheaply, and both aerodynamic and mechanical design become simpler in the larger sizes.

A planned development programme is put forward, and provided that the number of engines required is not less than 500, it is anticipated that the unit cost of

production, including development costs, would be less than that of competitive reciprocating engines.

It is proposed that the design and initial development of the 200 H.P. engine should be carried out by this laboratory, where the required technical knowledge is available, and where staff are trained in the type of work involved. The cost of development to the stage where mass production can proceed, will be about $500,000, which should be borne either by the Federal Government, as an investment for development and defence, or by industrial concerns interested in the manufacture or use of the engines. Perhaps preferably, the cost would be borne jointly.

It may be suggested that work of this type would be done better either in the U.S.A. or U.K. The writer does not believe this. Experience in the late war has surely exploded the myth that Canada does not do a good job. In any event, there is a very considerable market for such an engine. Why should this be paid for in U.S. currency rather than Canadian? Finally, it is a matter of national prestige that an engine which can play such an important part in Canadian development and defence, should be a Canadian product.

The report is divided into three parts:-

I. **Power needs for Canada, and a review of the performance of various power plants.**

II. **A gas turbine to meet the needs.**

III. Development of the gas turbine.

Appendix. Aerodynamic design of the gas turbine.

PART I

POWER NEEDS FOR THE DEVELOPMENT OF CANADA

It appears that power needs for Canadian development can be classified under four main headings.

a) Transport.

The rapid construction of roads and railroads necessitates the use of large numbers of earth moving machines, such as bulldozers, graders, power shovels and dump trucks, etc. These must all be mobile and many of them require power for operation as distinct from and as well as power of movement.

In the absence of roads, tracklaying vehicles and other special types of transport vehicles such as logging trucks are used.

Power is required for transport, both truck and coach on the roads, and locomotive power will be required on railways. Water transport may be employed, but again suitable power must be available.

Apart from locomotives and vessels, and possibly special construction machinery, the power output required for all these purposes is about 200 H.P. In many cases the power demand may increase at low temperatures.

b) Settlements.

Wherever a settlement is to be located, electric power will be required for community services. Particularly in developing new country it is probable that many settlements will only be of a temporary nature, so that any power unit used for electricity generation must be a portable unit which can easily be brought in with the first settlers, and as readily moved on if and when the need for the settlement in that particular location vanishes.

c) Exploration of Natural Resources.

For every mine or oil well which is a success, there are probably at least fifty which turn out, after preliminary operation, to be non-productive.

Nevertheless, all chances must be explored and the difficulty and cost of such work can be considerably lowered if a portable power unit is available which can be carried easily to the scene of operations, if necessary by sleigh or aeroplqne. In addition, of course, power for domestic use is required.

In logging, power is required for felling and moving the trunks, and again no permanent installation is required.

d) Processing of Resources.

In many instances, were plentiful power available at the scene where raw materials are discovered, preliminary processing could be carried out on the site, thus avoiding unnecessary transportation costs, particularly when developing sites a long way from railhead.

This brief review is far from being complete, but points out some of the more obvious cases where power is required. Power, of course, is being used at present, but better power, in the sense that it would be more easily transported, cheaper to buy and keep operating, can obviously play a great part in accelerating the development already proceeding, and make possible new ventures, presently impractical.

POWER NEEDS FOR THE DEFENCE OF CANADA

Many of the needs cited for development apply equally for defence. Transport and electric power, for camps, radar, and repair or overhaul bases are of obvious importance. In addition, we may add armoured fighting vehicles and gun tractors. We exclude the flying side of aviation from our discussion as the aircraft engine is highly specialized, but there are many needs of power in connection with air force "housekeeping". Likewise, large Naval vessels are outside our scope, but there is need of compact, light power units for high speed motor boats or launches.

REQUIREMENTS TO BE MET BY POWER PLANTS.

From the above discussion we may frame certain requirements to be met by power plants.

(1) For many purposes, what is really required is a unit for driving an electric generator.

(2) Transport in its various forms is the general exception to this rule, although some forms, e.g., locomotives, can be best run with some form of electric drive. However, for ordinary heavy transport or tractors a drive is required which will provide high torque at low speed.

(3) Ruggedness and reliability.

(4) Ease of maintenance.

(5) Easy starting in cold weather.

(6) Low fuel and oil consumption.

(7) Ease of supply of fuel and oil.

(8) Power preferably increasing at low temperatures.

(9) Light weight and compactness.

Any comment on these points, especially the last seven, seems superfluous. In the following sections, the ability of three different types of power plants to meet them will be discussed.

THE GASOLINE ENGINE.

The familiar gasoline engine is well developed and a very satisfactory power unit. The principal criticisms that may be made are:-

(1) Difficult cold weather starting, as a result of increased starting torque requirements, difficulty of fuel evaporation and increased internal resistance of starting batteries.

(2) Liquid cooling is undesirable where extreme weather conditions are likely to be encountered.

(3) Poor torque characteristics, necessitating speed reducing gears for transport applications.

(4) Complete dependence on electricity for starting and ignition is undesirable.

(5) In extremely cold weather, special fuels and oils may be required, introducing supply problems.

The thermal efficiency at full load is about 25%, while neither the efficiency nor the power output respond markedly to low temperatures. Although fairly compact, gasoline engines for commercial service rarely weigh less than 5 lb/BHP and 4 lb/BHP is exceptional.

THE DIESEL ENGINE.

Most of the criticisms of the gasoline engine apply in more force to the Diesel type. In particular, the difficulty of producing fuel with a low pour point and high cetane number, renders operation at low temperatures very difficult. The increased thermal efficiency, at 35%, is offset to some extent by increased lubricating oil consumption. The Diesel engine is always bulkier and heavier than a gasoline engine of the same power.

The Diesel engine can be made independent of electricity, but air starting involves more weight and bulk, and more complication. Maintenance of fuel injection pumps requires skilled labour.

THE GAS TURBINE.

The gas turbine seems to be particularly well suited to Canadian operation, especially at low temperatures. The mechanical simplicity and absence of reciprocating parts means that, fully developed, it can be more rugged and reliable than the reciprocating engine. Even at this early stage experience in the Air Force, and with railroad units, confirms this. The absence of a multiplicity of bearings and reciprocating parts means that the torque required for starting does not increase due to oil congealing in cold weather. Starting, at any rate in sizes up to 2000 H.P., can be effected, if need be, by slow burning cartridges, rendering operation independent of electricity.

By using a simple heat exchanger, thermal efficiencies of the order 20-25% can be attained, while consumption of lubricating oil is negligible. A most important feature is its ability to burn a wide range of cheap fuels irrespective of octane or cetane number, while in emergency, any liquid fuel can be used.

The power developed, and the efficiency, rise rapidly as the temperature falls, while the turbine can be designed to have a stalling torque 100% greater than the full load torque, giving ideal characteristics for traction. Since the turbine is essentially a high speed machine, high speed generators can be coupled to it, to produce a compact plant. The turbine is considerably more compact, and lighter, than any of its competitors, making it highly attractive for a transportable, or transport engine.

PART II

The conclusion arrived at from Part I is that the gas turbine can meet the requirements of Canadian development and defence better than either the gasoline or the diesel engine. In this section we outline a type of turbine engine that would be capable of undertaking a wide range of duties, and outperform its rivals at all of them.

SIZE OF UNIT.

It appears that a unit of about 200 H.P. will be suitable for a wide range of application in transport and road building machinery, and for power generation. For other generator sets, switching locomotives, armoured fighting vehicles, boats, etc., units of 400 H.P. and 800 H.P. would be suitable. It is suggested that units in these three sizes would cater for the vast majority of applications. There appears to be no point in making units in closer sizes, and by keeping the number down, maintenance and the supply of spares is enormously simplified.

All three units would be aerodynamically similar, the only difference being in actual physical size, and linear dimensions will increase roughly as the square root of the horsepower, i.e., the 800 H.P. engine will be twice the size of the 200 H.P. unit.

In the following sections a design for the 200 H.P. unit is outlined.

200 H.P. GAS TURBINE ENGINE.

In considering the design of the engine, the essential considerations have been simplicity and reliability. Figs. 1 and 2 show a project layout. It should be emphasized that this does not represent a finished mechanical design. It is the result of a project investigation to find the best form of engine, and although correct in general proportions, the detailed design has not yet b been made. Enough work has been done to be sure that there are no unknown or insoluble problems.

Essentially, there is a single shaft carrying at one end the compressor and at the other the turbines, and the shaft is coupled via a gearbox to the load. The air delivered by the compressor is discharged through two diffusers to the heat exchanger through which it finds its way to the entry to the two combustion chambers which are mounted in the same annulus as the heat exchanger tubes. Turning 180° to enter the flame tube the air is heated and passes via another 180° bend to the turbine entry volute. Two axial flow turbines are used, and after leaving them, the exhaust gas passes through the long diffuser inside the heat exchanger, before being turned through 180° to enter the heat exchanger tubes, from which it passes out to the atmosphere.

The aerodynamic design is outlined in the appendix.

COMPRESSOR.

A centrifugal compressor is chosen as being the simplest and cheapest to make and these considerations outweigh the increased efficiency which might be anticipated with an axial compressor. Furthermore the compressor is similar to well known aircraft engine superchargers, while, to the writer's knowledge, no successful axial compressor of the size required has yet been built.

COMBUSTORS.

Two combustors are used in the interests of a compact design, and are similar to those used in aero-turbines, or oil burning railroad turbines, but both thermal and aerodynamic loadings are low.

HEAT EXCHANGER.

A simple straight tube heat exchanger is used. It is designed for counter flow, and to have a thermal ratio of 0.7 at full load, rising to about 0.75 at part load.

TURBINE.

A two stage axial flow turbine is used. The stages are similar to, but less highly stressed than those used in jet propulsion engines or exhaust turbine supercharger units. The arrangement of the unit leaves ample space for a diffuser to recover most of the kinetic energy remaining at the turbine exhaust.

REDUCTION GEAR.

The ratio of the reduction gear will depend upon whether an electrical generator is to be driven, or a vehicle. In either case plain spur gearing will be used.

MECHANICAL.

Basically, there are only two bearings and one rotating part in the engine, excluding the reduction gear. In the 200 H.P. unit the rotational speed of the engine will be 25-30,000 RPM, for 400 H.P. 20,000 RPM, and for 800 H.P. 14,000 RPM. These speeds, of course, seem very high, but it must be remembered that they are no higher than speeds which have been used for many years for superchargers and turbines, and that torques and stresses are low. The two bearings carry little applied load, and will be lubricated by oil mist. The actual bearing peripheral speeds are well inside known practice. Both bearings and turbine discs will be cooled by air bled from the compressor.

In the reduction gear, the high speed means low torque and small diameters so that pitch line speeds and tooth loadings are well within known practice.

The basic feature of the design is ease of maintenance, and it will be observed that removal of the rear cover of the heat exchanger, which is not a pressure joint, immediately makes the exchanger tubes accessible for cleaning, and the flame tubes may easily be withdrawn.

STARTING.

Starting may be electrical initially, but at a later stage it is proposed to start using slow burning cartridges to provide power to spin the turbine. The method is presently undergoing extensive development.

CONTROL.

Only one control is required, namely a throttle valve in the fuel supply line. A top speed and temperature governor are also required. A simple centrifugal governor looks after top speed whilst it is proposed to use a temperature sensitive element in the exhaust diffuser as a top temperature controller.

AUXILIARIES.

The auxiliaries required are fuel and oil pumps, and electric generator if battery starting is employed. They will be driven by accessory gears in the main reduction gear box.

POWER TAKE OFF.

In Fig. 1 a simple spur gear is shown, and the final output shaft will run at about 10,000 RPM for direct coupling to a generator. It should be emphasized that all early Parsons turbines units built 40 or more years ago used generators at speeds up to 18,000 RPM. We wish to use the high speed to keep the size and weight down, but if desired, a two train gearbox can be used with a bulkier low speed generator.

Electrical transmission is suitable for many applications to mobile machinery, where the use of individual motors for each drive avoids gearboxes and clutches. In simple transport applications we have the choice of altering our unit to give a free power turbine which will have suitable torque characteristics, or use some form of torque multiplication. It is thought preferable initially to adhere to one design of turbine for all units, and simply use a two train gearbox to bring the final drive shaft speed down to 3,000 or 4,000 RPM, and drive through a hydraulic torque converter such as is used on caterpillar tractors, which are powered by virtually constant speed diesel engines.

MAINTENANCE.

Experience with other gas turbines shows that little trouble is met by rotating parts. There is only the one shaft and two bearings and a simple gearbox, and design is conservative. More frequent maintenance will be required of the heat exchanger and combustors. The design chosen however, is specially aimed at this point, and is arranged so that, even in cold weather, and working with gloved hands, cleaning of the tubes or replacement of the flame tube may be easily effected. Furthermore, the layout is so arranged as to permit easy dismantling in the field.

WEIGHT.

Rough weight estimates suggest that the nominal 200 H.P. engine should weigh about 500 lbs. This is much better than other engines and if it is remembered that in fact the engine produces 380 H.P. at low temperatures, it is very light indeed.

PERFORMANCE.

The engine is designed on a conservative aerodynamic basis as specified in the appendix. Tables I and II give performance figures for the nominal 200 H.P. unit.

TABLE I

Ambient Air Temp. deg. F.	Brake Horse Power	Thermal Efficiency percent
+ 60	170	17.7
+ 40	200	19.3
+ 20	236	21.4
0	268	22.6
- 20	310	24.8
- 40	377	27.2

(Table II on following page)

TABLE II

Percentage Full Load Power	Percentage Full Load Efficiency
120	111
100	100
80	85
60	67
40	47

SUMMARY OF PART II

On paper, and confirmed by gas turbine experience in other fields, a simple unit can be built that will fulfill the requirements of the development of Canada. As the one power plant would be so versatile, the spares problem would be drastically simplified, and combined with the accessibility, and ease of maintenance which has been designed for, should render field operation simpler than that of any conventional engine.

The power characteristics are ideally suited to cold weather operation, the efficiencies are comparable with those of any gasoline engine, while burning almost any liquid fuel.

<u>P A R T   III</u>

DEVELOPMENT OF THE GAS TURBINE.

In the whole layout of the project, great care has been taken to ensure that a design is possible in which stresses and temperatures are low, compared with other turbine units having a good record in service.

By aeronautical standards we have been very conservative, and furthermore, considerable experience has now been obtained on non-aeronautical applications of the gas turbine, with conspicuous success. In turbo-superchargers for Diesel engines, locomotives, oil refining power plants and the Velox boiler, the inherent simplicity and reliability of the turbine have been thoroughly substantiated.

Turning now to the proposed engine, the principal difficulties foreseen are:

(1) Design of seals and clearances.

(2) Lubrication.

(3) Long life for combustion equipment.

Careful design backed up by adequate testbed running is the answer to these, and with reference to the combustion chambers, great care has been taken to make the flame tubes readily accessible for inspection or replacement, while by sticking to one type of engine, it is easy to maintain necessary spares.

It is evident that the cost of developing an engine such as that described, up to the point where mass production might be considered, is no small item. To make any cost estimate at this stage is highly speculative and the only information available is in a paper by F. R. Banks. The writer estimates, very roughly, that the cost of designing and building two prototype engines would be about $150,000, including spare and replacement parts.

Any estimate of development time is speculative, but taking all things into account, a figure of 5,000 hrs. running, appears reasonable, and would cost, say, $150,000.

The total, therefore, is about $300,000; to this must be added the cost of necessary component rig tests, and overhead costs, which would probably bring the total to between $400,000 and $500,000. However, this preliminary estimate is merely an intelligent guess to guide planning. More detailed estimates must wait until the design is a little further on. Supposing $500,000 to be reasonable, this amounts on 500 engines to $1,000 per engine.

The cost of an "expendable" diesel engine of 190 H.P. continuous rating is about $8,000 to $10,000. Such an engine will run to 250 H.P. for short periods, but has no increase of power with cold weather as has the gas turbine. It would appear reasonable, in a batch of 500 engines, to bring the cost per turbine engine to something between $5,000 and $10,000, so that even allowing for the development costs, the turbine would be competitive, if not cheaper, in price, as well as being superior in all other respects.

Apart therefore, from any military considerations, the proposal bears very close investigation as a commercial, money making, project. It is felt that the fact that the gas turbine so exactly meets the specialized Canadian needs, is a reason why such a unit should in fact be developed in Canada, rather than following behind the American and British.

A DEMONSTRATION ENGINE.

The Gas Dynamics Laboratory at McGill University has in its possession a stock of superchargers, combustion chambers, and reduction gears which could form the nucleus of a demonstration engine. The supercharger, being designed for another purpose, is not as efficient as can be made, but would serve, and is of a size not too far different from that which would be required for the prototype unit.

To assemble the engine, it will be necessary to design and build new turbines and suitable ducting. Some detailed estimates are being prepared, but it is anticipated that it would cost about $20 - 25,000 to build and demonstrate such an engine.

THE LARGER ENGINES.

Once the 200 H.P. engine had been produced, the production of 400 and 800 H.P. sizes presents no large difficulty. In going to larger sizes, more favourable Reynolds' numbers assist aerodynamically, machining errors are of less significance and rotational speeds come down.

DEVELOPMENT PROGRAMME.

The following programme is proposed:

(1) Continuation of the design investigation now in hand and completion of mechanical design work.

(2) Investigation of electrical requirements and the design of the necessary electrical equipment.

(3) Assembly of demonstration engine. Manufacture of two prototype engines of 200 nominal H.P.

(4) Tests of component parts of prototype engine, followed by development running of the complete engines. Field service trials.

(5) Production of 200 H.P. engines in quantity.

(6) Design and prototype manufacture of 400 and 800 H.P. engines.

It is felt that a programme of this sort can best be carried out by this laboratory, working in close concert with the manufacturers, the users and the Government.

The financing can be considered in three phases:

(1) Federal support as an essential defence investment.

(2) Federal support as an investment for Canadian development.

(3) Support by private industry interested in the manufacture of the engines.

It is probable that a combination of all three is desirable.

APPENDIX

OUTLINE OF AERODYNAMIC DESIGN

GENERAL.

For a 200 H.P. engine of this type, a single stage centrifugal compressor is almost mandatory. Both manufacturing and aerodynamic difficulties rule out an axial compressor. Use of a two stage compressor gives little increase in efficiency and reduces turbine blade heights undesirably.

A compressor efficiency of 70 percent is readily attainable with such a compressor and choice of the design temperature rise is governed by operation at low temperatures and by turbine design. In the present case the temperature rise, giving the optimum design, was 315°F.

GENERAL ASSUMPTIONS.

a) Compressor temperature rise 315°F.

b) Compressor efficiency 70 percent.

c) Turbine efficiency 85 percent.

d) Maximum turbine temperature 1460°F.

e) Combustion chamber loss 0.5 p.s.i.

f) Heat exchanger loss 1.5 p.s.i. (cold side)

g) Heat exchanger loss 0.3 p.s.i. (hot side)

h) Heat exchanger thermal ratio 0.7

i) Exhaust kinetic energy loss 7 B.t.u's per lb.

COMPONENT DESIGN.

All components are designed with the above assumptions, to give an output of 200 H.P. with air temperature + 40°F., and air pressure 14.7 p.s.i.

COMPRESSOR.

Tip diameter	10.7"	R.P.M.	30,000
Tip width	0.400"	Tip speed	1,400 ft./sec.
Eye diameter	6.16"	Diffuser throat area	3.9 sq.in.
Hub diameter	2.37"	Diffuser vane angle	17.0°.

COMBUSTION CHAMBER.

2 chambers each with maximum diameter 8.0", length not less than 24.0".

TURBINES.

Blade root speed	940 ft./sec.	
Root diameter	7.11"	
Entry annulus area	20.9 sq.in.	
Exit annulus area	22.1 sq.in.,	first stage.
Exit annulus area	30.6 sq.in.,	second stage.
Final discharge velocity	880 ft./sec.	

HEAT EXCHANGER.

2900 tubes, 0.25" i/d, 2.8' long.

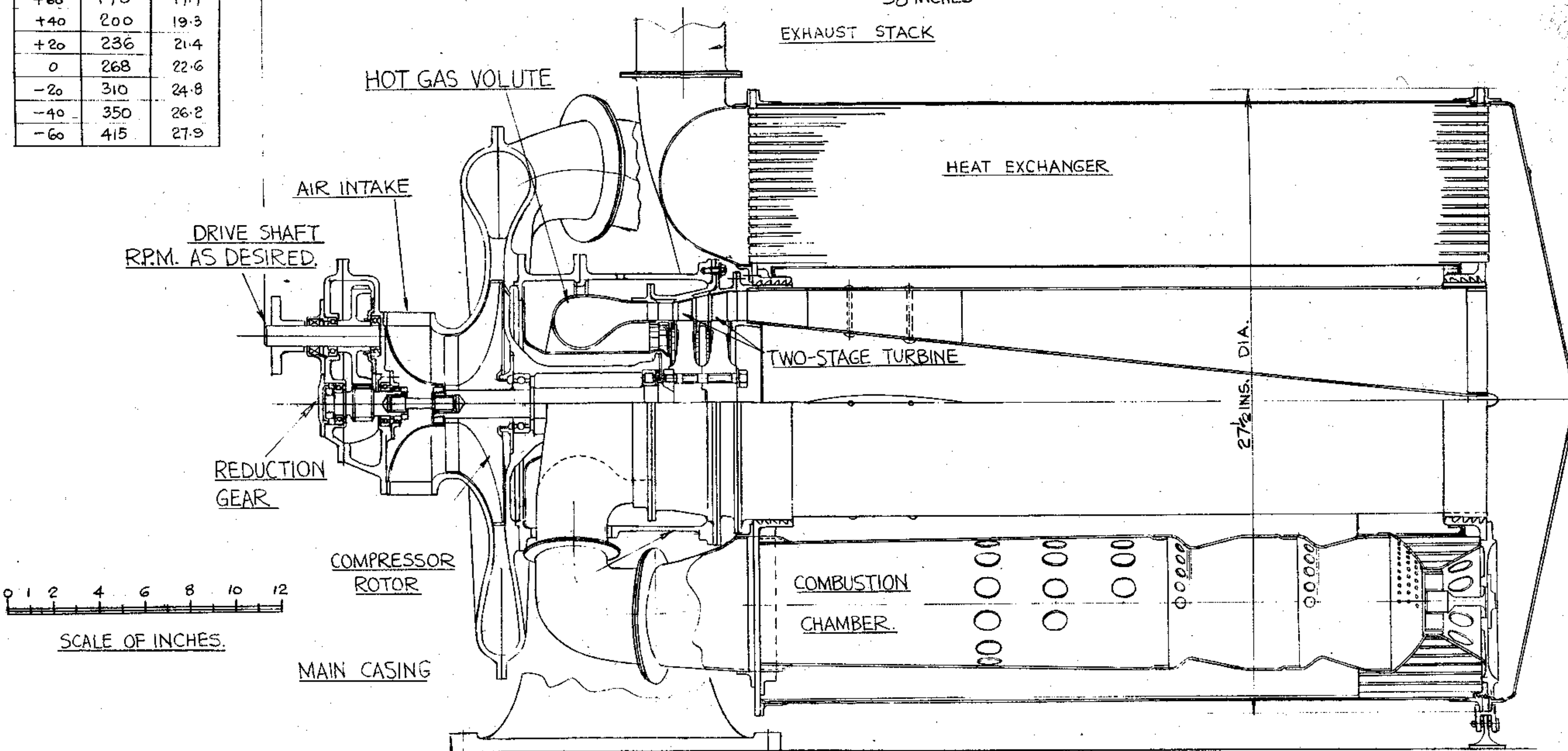
Total gas flow area	1 sq.ft.
Total air flow area	0.5 sq.ft.
Gas pressure loss	0.292 p.s.i.
Air pressure loss	1.24 p.s.i.

NOTE:

Any or all of these dimensions may be altered slightly as the design investigation proceeds. In particular, it is anticipated that the RPM can be decreased to about 25,000 RPM, with a slight increase in compressor and turbine diameters.

PERFORMANCE.

AIR TEMP. °F	B.H.P.	THERM. EFFCY PERCENT.
+60	170	17.7
+40	200	19.3
+20	236	21.4
0	268	22.6
−20	310	24.8
−40	350	26.2
−60	415	27.9



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DRAWN	A.R.E.
APPROVED	
DATE	8-3-49

SCHEME FOR 200 B.H.P. GAS TURBINE POWER UNIT. Fig. 1.

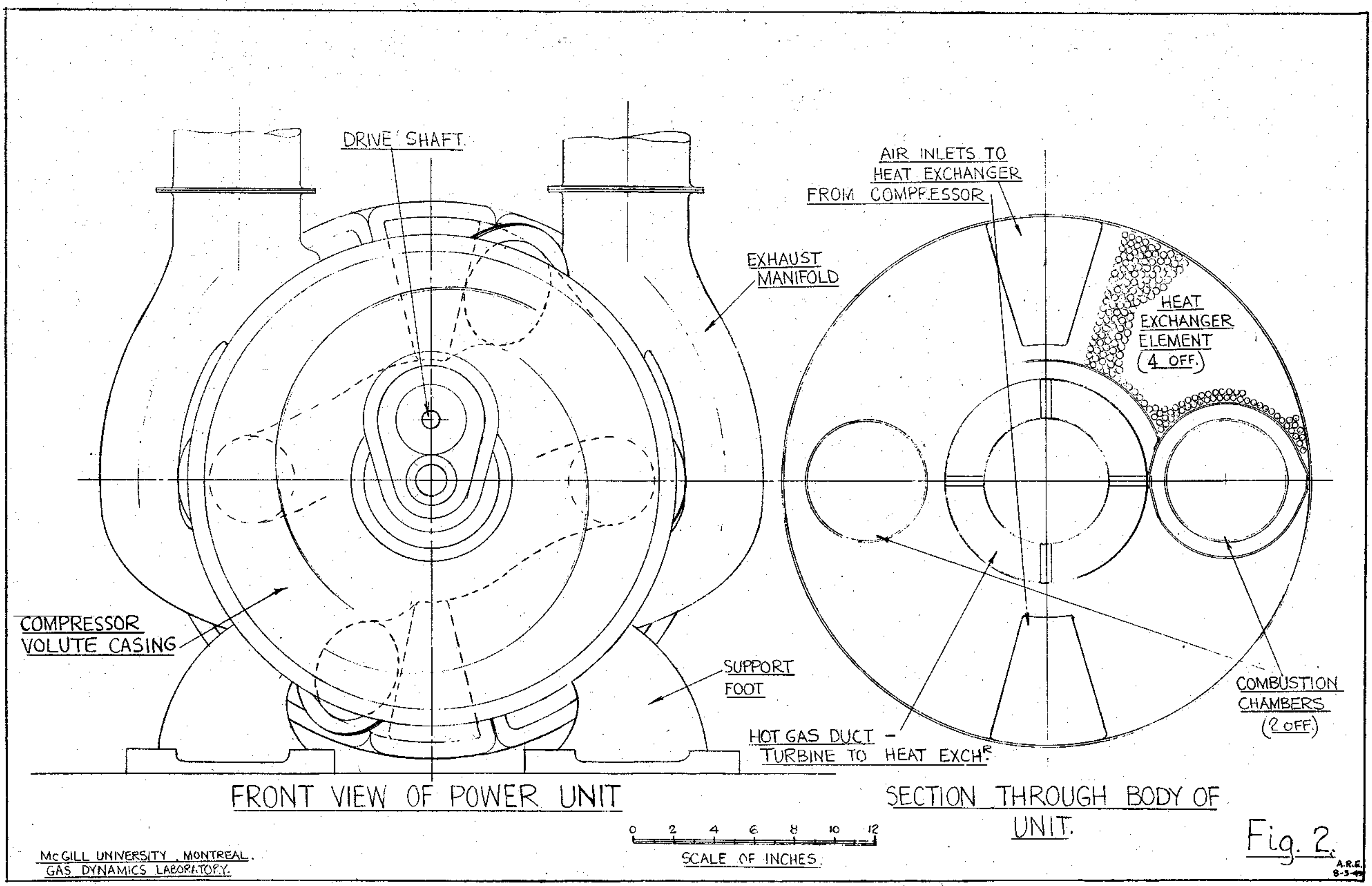
DRIVE SHAFT
AIR INLETS TO HEAT EXCHANGER FROM COMPRESSOR
EXHAUST MANIFOLD
HEAT EXCHANGER ELEMENT (4 OFF)
COMPRESSOR VOLUTE CASING
SUPPORT FOOT
HOT GAS DUCT - TURBINE TO HEAT EXCH^R
COMBUSTION CHAMBERS (2 OFF)
FRONT VIEW OF POWER UNIT
SECTION THROUGH BODY OF UNIT.
0 2 4 6 8 10 12
SCALE OF INCHES.
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Fig. 2.