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150 and 300 kW Lightweight Diesel Aircraft Engine Design Study

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1.0 SUMMARY

Energy conservation, uncertainties of fuel supply and limited availability of high octane gasoline, have renewed the interest in the diesel aircraft engine, since its fuel economy is better than any type of aircraft engine currently in production.

Aircraft diesel engines have been developed before, notably the Junkers "JUMO," the Napier "NOMAD" and the McCulloch TRAD 4180. Of these, only the Junkers opposed piston, 2-stroke cycle engine ever reached the production stage. The Napier Nomad was a 2-stroke cycle, turbocompounded design. Its complexity and the fact that it invaded the territory of turbine engines probably accounted for its demise. The McCulloch engine came close to flying when the program was terminated for non-technical reasons.

New technologies, now under active development, will result in even better fuel economies than can be obtained with current state-of-the-art diesel engines. These technologies also make it possible to develop a powerplant which is more compact and lighter than current gasoline aircraft engines.

Two engines were investigated in the study, a 298 kW diesel for a twin engined airplane and a 149 kW diesel for a single engined aircraft.

The study consisted of three major phases:

1. Technology Analysis.
   All in-depth survey of available aviation and automotive sources was conducted to identify new developments which offer potential benefits to an aircraft engine.

   The technology base includes definition of:

   A. Existing automotive diesel technology, extrapolated to the expected level in the late 1980's.

   B. Existing and extrapolated aircraft engine technology.

   C. On-going diesel aircraft engine developments.

   These technologies were then evaluated and ranked on the basis of performance and adaptability.

2. Engine Concept Design.
   The technologies which were chosen as a result of the evaluation and ranking process were applied to the design of the 149 and 298 kW engines. Performance, stress, weight. and cost calculations were made concurrently.

3. Engine/Aircraft Integration Study.
   The results of Phase 2 were then used in an engine-aircraft integration study to determine the performance improvement of an airplane equipped with diesel engines.

The study indicates that the diesel promises to be a superior powerplant for general aviation aircraft. The following tabulation, in which the 298 kW diesel is compared to a comparable gasoline aircraft engine shows a reduction of fuel flow, a smaller package and reduced engine weight; see Table I.

TABLE I
Diesel vs. Gasoline Engine

		4-Cycle GTSIO-520-H	2-Cycle Diesel
Configuration		6-Cyl. opposed	6-Cyl. radial
Bore x Stroke	mm	133.35 x 101.60	100 x 100
Displacement	liter	8.514	4.712
Take-off Power	kW	279.64	298.28
RPM at Take-off		3400	3500
Fuel Flow at Take-off	kg/hr	119.07	67.13
65% Cruise Power	kW	181.76	193.88
Fuel Flow at Cruise	kg/hr	49.75	37.74
Dimensions:			
Length	mm	1657	1105
Width	mm	865	632
Height	mm	680	660
Dry Weight	kg	262	207

The superior characteristics of the diesel powerplant result in a much improved aircraft performance. The following tabulation shows the performance of a twin engine aircraft equipped with gasoline engines or diesels. Payload is increased by 8% and, simultaneously, the range is extended by 50%:

TABLE II
Aircraft Performance

		Gasoline Powered	Diesel Powered
Rated Power	kW	298	298
Max. Take-off Weight	kg	3671	3671
Std. Empty Weight	kg	2380	2294
Useful Load	kg	1291	1377
Useable Fuel	kg	609	652
Payload	kg	683	726
Max. Cruise Speed	km/hr	454	472
Range	km	1805	2592

A similar performance improvement is obtained with the 4-cylinder 149 kW diesel engine.

The technologies which result in this high level of performance are, although advanced, not untried. The adiabatic engine, the catalytic combustor and the high-speed alternator are currently under development under various contracts. It should be noted here that, although the concept engine proposes the use of ceramic combustion system components, the use of such materials for "man rated" aircraft may be 20 years away. These were included primarily to show what may be ultimately possible. However, alternate solutions are given which will result in a small reduction of performance but nevertheless will result in a power plant which far out performs the gasoline aircraft engine.

2.0 INTRODUCTION

2.1 Advantages of the Diesel Engine

The current trend of ever increasing fuel prices and the dependence on imported fuel dictate the use of powerplants that offer the best in fuel economy. The diesel engine has always been burdened with the stigma of being heavy, thus offsetting its advantage of low fuel consumption for aircraft applications. If it is possible to build an engine that combines low fuel consumption and low weight, then that engine becomes a very attractive aircraft powerplant. Old and once discarded concepts can become attractive by applying new technologies.

A conventional diesel engine requires high compression ratios for starting and low load operation. This results in high firing pressures at full load when the engine could run at a much lower compression ratio. New technologies make it possible to combine good startability with low firing pressures at full load. The study shows that the weight of the diesel can be reduced below that of current gasoline aircraft engines.

The diesel engine offers more advantages in addition to low fuel consumption:

1. Lower operating cost:
   - Lower cost of fuel
   - Reduced maintenance
   - Extended TBO

2. Greatly reduced fire and explosion hazard.

3. Better in-flight reliability. No ignition and mixture control problems.

4. Multifuel capability. The engine will be capable of burning a variety of fuels, to be discussed in detail in Section 3.1.4.

5. No inlet icing problems.

6. Improved altitude performance. The 298 kW engine will be capable of continuous full power operation at 6150 m. altitude.

7. Safe cabin heating from exhaust stacks, less danger of carbon monoxide.

8. Exact fuel metering indicator. The rack position determines the fuel flow.

9. Fewer controls for the pilot:
   - No mixture control
   - No inlet heat control
   - No manual waste gate
   - No mandatory power reduction.

10. No electrical interference from ignition system.

2.2 Previous Aircraft Diesel Engines

Table III shows a listing and design data of aircraft diesel engines. No clear trends follow from this tabulation Seven of the thirteen engines have a radial configuration, seven were air-cooled, eight were 2-stroke cycle.

The tabulation becomes more meaningful if specific ratios are used. See Table IV.

Formulas used in the tabulations are:

2-Stroke cycle power:

$$\mathrm{kW} = \frac{\mathrm{BMEP} \times D \times \mathrm{RPM}}{60{,}000}$$

4-Stroke cycle power:

$$\mathrm{kW} = \frac{\mathrm{BMEP} \times D \times \mathrm{RPM}}{120{,}000}$$

BMEP is expressed in kPa

Engine displacement D in liters

Piston speed $$v_p = \frac{s \times \mathrm{RPM}}{30} \text{ m/sec}$$

s = stroke in meters

Some observations can be made from the Tables III and IV. Average specific weight values are:

4-Stroke cycle engines	1.408 kg/kW
2-Stroke cycle engines	1.071 kg/kW
Air-cooled engines	1.277 kg/kW
Liquid-cooled engines	1.082 kg/kW

The numbers indicate that a 2-stroke cycle engine can be expected to be lighter than a 4-stroke cycle engine. A comparison of air-cooled and liquid engines would seem to favor the liquid-cooled engine. However, the engine weights of liquid-cooled engines do not include the weight of the cooling package, which accounts for approximately .160 kg/kW. The corrected values then become:

Air-cooled engines	1.277 kg/kW
Liquid-cooled engines	1.242 kg/kW

TABLE III
Previous Aircraft Diesels

Make	Model	Config.	Cycle	Cooling	No. Cyl.	Bore mm	Stroke mm	Displ. ℓ	Compr. Ratio	Power kW	RPM	Wgt. kg	Year
1. Packard	DR980	Radial	4	air	9	122	152	16.1	16:1	174	2050	231	1930
2. Guiberson	A980	Radial	4	air	9	122	152	16.1	14.7:1	155	2050	231	1931
3. Deschamps		30° **Λ**	2	liquid	12	152	229	50.5	16:1	1000	1750	1089	1934
4. Bristol	Phoenix	Radial	4	air	9	146	190	28.75	14:1	318	2000	494	1934
5. Zbrojovka	ZOD	Radial	2	air	9	120	130	13.2	15:1	207	1600	297	1935
6. Hispano	Clerget 14F2	Radial	4	air	14	140	160	34.5	15:1	518	2200	600	1935
7. Salmson	SH18	Radial	2	air	18	118	150	29.5	16:1	481	1700	567	1935
8. Mercedes	OF2	60° **V**	4	liquid	12	165	210	53.9	15:1	592	1790	935	1935
9. Junkers	204	Opposed	2	liquid	6	120	2 x 210	28.75	17:1	570	1800	750	1935
10. Junkers	205	Opposed	2	liquid	6	105	2 x 160	16.6	16:1	444	2200	510	1936
11. Junkers (1)*	207 Turbo	Opposed	2	liquid	6	105	2 x 160	16.6	16:1	740	3000	649	1938
12. Napier (2)*	Nomad	Flat	2	liquid	12	152.4	187.33	41.0	16:1	1984	2050	1624	1953
13. McCulloch (3)*	TRAD-4180	Radial	2	air	4	98.43	98.43	3.0	15:1	150	2850	149	1970

*Numbers in parentheses refer to list of references at the end of this report.

TABLE IV
Specific Data of Previous Aircraft Diesels

Make	Cycle	S/B	BMEP kPa	Piston Speed m/sec	Piston Heat Load kW/cm^2	Spec. Power kW/ℓ	Spec. Wgt. kW/kg
Packard	4	1.246	633	10.39	.165	10.81	.75
Guiberson	4	1.246	564	10.39	.147	9.63	.67
Deschamps	2	1.507	679	13.36	.459	19.80	.92
Bristol	4	1.301	664	12.67	.211	11.06	.64
Zbrojovka	2	1.083	588	6.93	.203	15.68	.70
Hispano	4	1.143	819	11.73	.240	15.01	.86
Salmson	2	1.271	575	8.50	.244	16.31	.85
Mercedes	4	1.273	736	12.53	.231	10.98	.63
Junkers 204	2	1.750	661	12.60	.420	19.83	.76
Junkers 205	2	1.524	729	11.73	.427	26.75	.87
Junkers 207	2	1.524	892	16.00	.712	44.58	1.14
Napier	2	1.229	1416	12.80	.906	48.39	1.22
McCulloch	2	1.000	1053	9.35	.493	50.00	1.01

2.3 Scope of the Project

The purpose of the study is the conceptual design of two advanced diesel aircraft engines and the integration of these engines into airframes which are optimized for their use. One engine of 149 kW is designed to power a light single engine aircraft, the other of 298 kW is designed to power a heavy twin engine aircraft. The engines are designed to result in aircraft performance as shown:

Aircraft Characteristics	Single Engine	Twin Engine
Design Payload	2 passengers 181 kg	3 passengers 272 kg
Max. Payload	4 passengers 363 kg	6 passengers 544 kg
Design Speed km/hr	240	400
Design Range km	1370	1610
Design Cruise Alt. m	3050	6100
Take-off to 15 m (standard day)	520	1100
Climb Requirement	FAR Part 23	FAR Part 23

The results of a "GATE" computer simulation show that the aircraft will exceed these requirements by a wide margin.

2.4 Relative Merit of this Project to the General Field

Sizeable reductions in fuel consumption — 47% at take-off and 29% at 65% cruise power are projected for the proposed 298 kW design. This results from the use of ceramics (uncooled cylinders) and a high efficiency, high pressure ratio turbocharger. These techniques when developed can be equally applied to any diesel powerplant to obtain reductions in fuel consumption from present levels.

Other technologies which are applicable to the general diesel field are:

- The catalytic combustor
- The high speed starter/alternator
- Operation of the turbocharger independent of the engine

2.5 Significance of the Project

The importance of the program is the contribution this new engine will make in reducing the fuel consumption of general aviation aircraft. Also, the capability of the proposed engines to operate on a variety of fuels will make the diesel-engined aircraft less vulnerable to local scarcities of a particular fuel.

The significance of the program goes beyond aircraft engines since the technologies to be developed in this program would be applicable to other fields as well.

3.0 ENGINE DESIGN STUDY

3.1 Technology Analysis

3.1.1 Literature Search

An in-depth survey of available aviation and automotive sources was conducted to identify new or expected developments which offer potential benefits to a general aviation aircraft engine. A listing of this material is enclosed with this report as Appendix A.

3.1.2 Definition of the Technology Base

Following a study of the literature, a schematic, Figure 3-1, was made which shows all the technologies and the interrelationship of configurations that can be considered for an advanced diesel aircraft engine. The methodology of evaluation and ranking is presented in the definition of design approaches section.

1. **Engine Configuration.**
   Piston engines have been built in radial and in-line configurations. The radial engine has a weight advantage, the in-line engine has reduced frontal area.

2. **2-Stroke Cycle vs. 4-Stroke Cycle.**
   The following 2-stroke cycle scavenge systems were considered, see Figure 3-2:

   A. Loop Scavenging. This is a valveless configuration in which the piston controls both intake and exhaust timing events by covering and uncovering of two sets of ports located near the bottom end of the piston stroke.

   B. Uniflow Scavenging. This is a system where fresh air is admitted at one end of the cylinder and exhaust gas is discharged at the other end. No short circuiting of air flow between intake and exhaust ports is possible with this system. Three arrangments are possible for uniflow scavenging:
      - Opposed pistons
      - Twinned cylinders
      - Inlet ports and exhaust valves

3. **Combustion Systems.**
   Four systems were considered — Figure 3-3.

   - Direct injection.

   - Prechamber, where the fuel is injected and ignited in a high turbulence system.

   - MAN System. Essentially a prechamber built into the piston.

   - NAHBE System. (4)* (Naval Academy Heat Balanced Engine). This system is based on a pressure exchange between an annular space in the piston and the main combustion chamber.

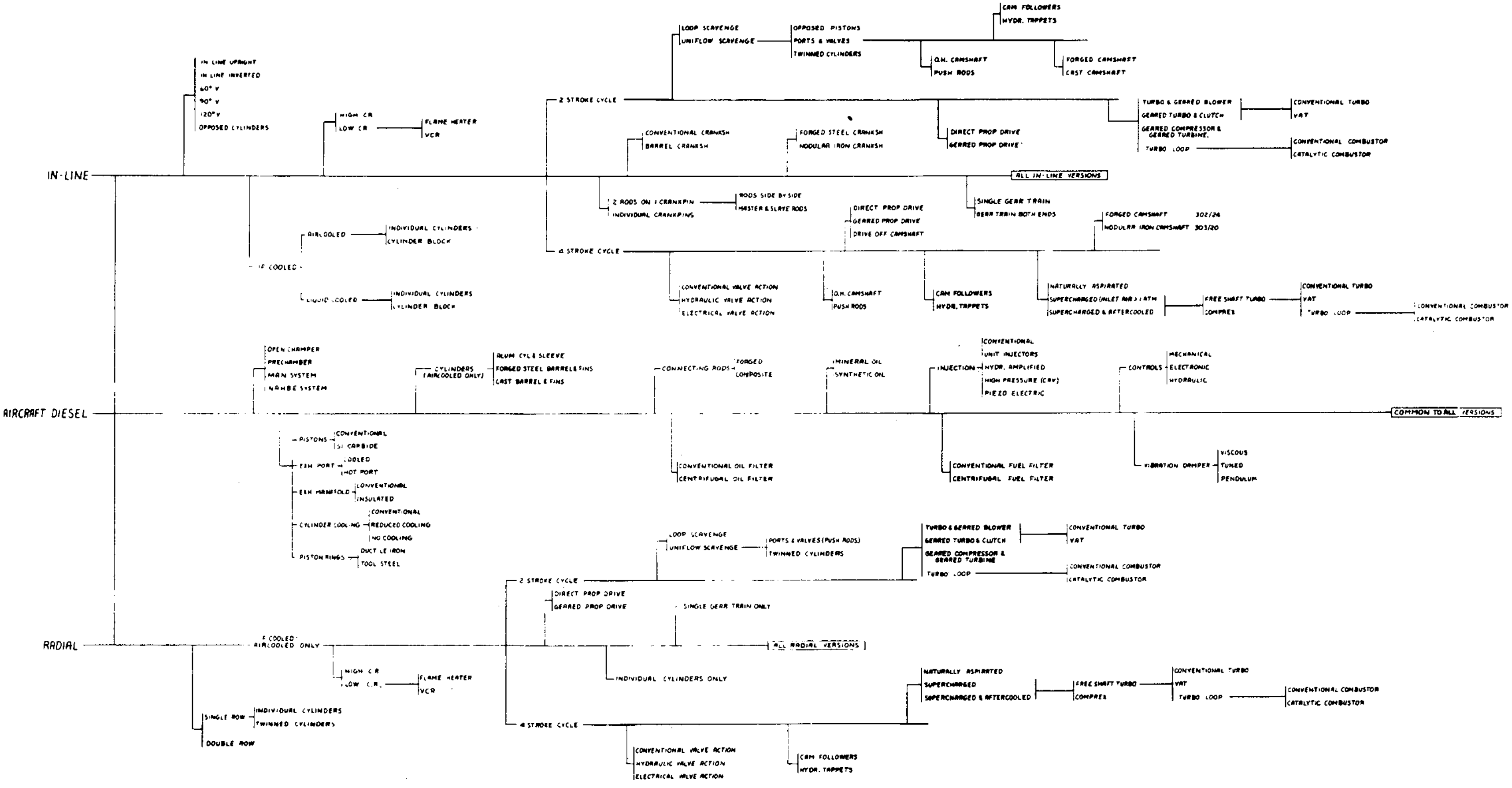

FIGURE 3-1 AIRCRAFT DIESEL DESIGN APPROACHES

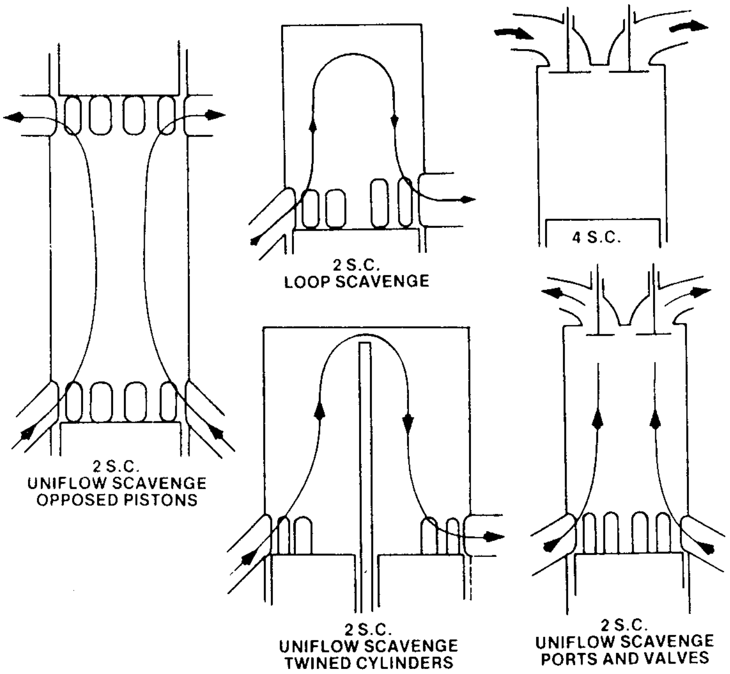

FIGURE 3-2 SCAVENGE SYSTEMS

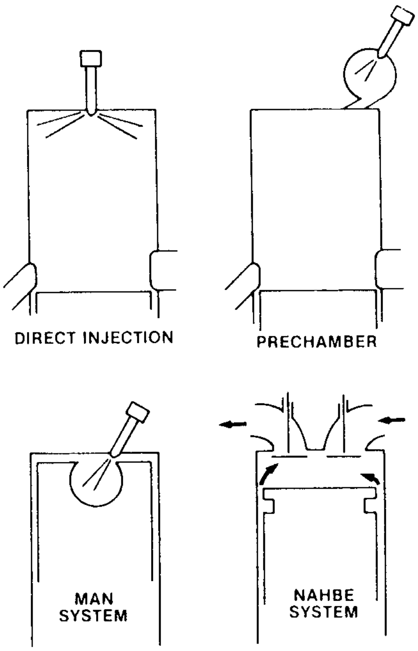

FIGURE 3-3
COMBUSTION SYSTEMS

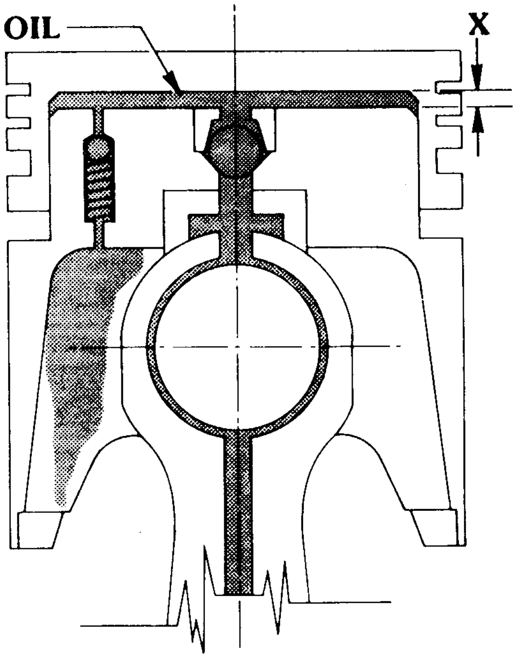

FIGURE 3-4
VARIABLE COMPRESSION RATIO PISTON

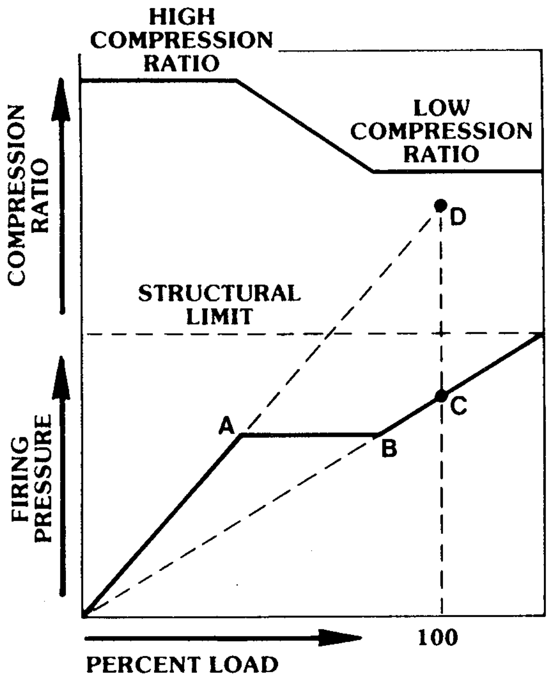

FIGURE 3-5
COMPRESSION RATIO AND FIRING PRESSURE

4. **Compression Ratio.**
A low compression ratio results in low firing pressures and thus a lighter engine. The disadvantage is that the compression temperature becomes too low for ignition at starting and idle operation. Several methods are available to overcome this problem:

- A flame heater in the intake manifold.

- A combustor in the exhaust manifold to accelerate the turbocharger at low engine speeds.

- Variable compression ratio piston, Figure 3-4 (5)*. Regulation of the maximum pressure in the oil chamber results in a limitation of cylinder firing pressures. The firing pressure at full load is indicated by point C, Figure 3-5. Without VCR this would have been point D.

5. **Crankshaft Configurations.**
A conventional crankshaft consists of main journals, crankpins, and cheeks. A barrel crankshaft has main journals and cheeks combined into large discs. This results in a shorter shaft and a higher torsional natural frequency.

6. **Injection Systems:**

- Conventional, consisting of injection pumps and pressure operated injectors.

- Unit injectors. Pumps and injectors are combined in one unit.

- Hydraulically amplified injectors (UFIS).

- High pressure system (CAV. (6)*

- Piezo-electric operation.

7. **Degree of Cooling.**
Tests at TCM/GPD on air-cooled cylinders have shown that the cooling air flow can be reduced without harmful effects to the integrity of the cylinders. In aircraft engines this results in a reduction of the cooling drag.

A program is in progress to develop an engine without cylinder cooling, the "Adiabatic" diesel engine. (7)* This program is under way at Cummins Engine Co. and is sponsored by the U.S. Army Tank Automotive Research & Development Command. The cylinder and piston temperatures necessitate the use of ceramics.

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*Numbers in parentheses refer to list of references at the end of this report.

8. Turbocharging Systems for 2-Stroke Cycle.

A. Turbocharger and Geared Blower. The 2-stroke cycle requires a positive pressure differential between intake and exhaust manifolds in order to accomplish the scavenging of the cylinders. The turbocharger, however, produces a negative pressure ratio at low engine power. A geared blower, therefore, is required for starting and low load operation. A clutch can be provided to disengage the blower once the turbocharger comes up to speed.

B. Geared Turbocharger and Clutch. In this case, the turbocharger is mechanically connected with the crankshaft. The clutch provides free shaft operation when the turbocharger is capable to provide a positive pressure ratio.

C. Geared Compressor and Geared Turbine. This system guarantees adequate air flow to the cylinders, while any excess exhaust gas energy not needed to drive the compressor becomes useful shaft energy.

D. Comprex. (8)* Figure 3-6. This is a device in which the pressure pulses of the exhaust gases are directly transferred to the induction air. The rotor is mechanically driven but no mechanical energy is required to compress the air.

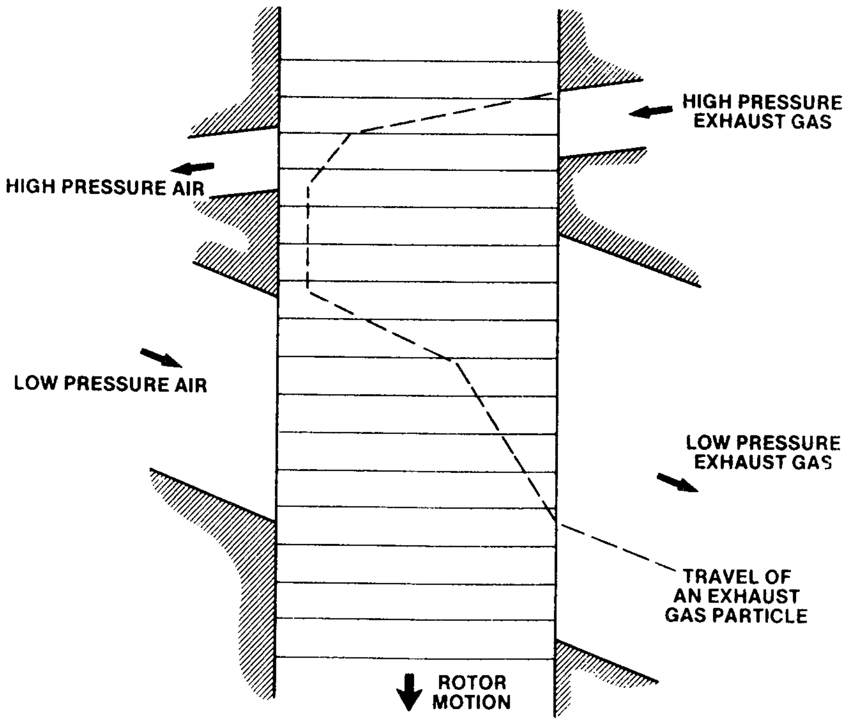


FIGURE 3-6 COMPREX SUPERCHARGER

E. Turbocharger Operation Independent of Engine Operation. (9)* In this system, a starter motor engages with the turbocharger. An injector and combustor are located between the compressor and the turbine. Similar to a gas turbine, at some speeds the system will become self-sustaining without the aid of the starter motor. The high pressure, high temperature air from the compressor will then be utilized to start the engine. The system will be explained in more detail when the 298 kW engine is described.

F. Differential Compound. Figure 3-7. This system compensates for a sudden increased power demand on the output shaft. This demand will slow the output shaft down and at a constant engine speed will result in a speed increase of the compressor. The resulting higher intake manifold pressure means a higher engine torque capability to meet the increased power demand.

G. Diesel Rankine Compound Engine: (10)* This system utilizes the heat energy in the exhaust gases for a secondary steam cycle. The steam is expanded in a turbine which is mechanically linked to the engine output shaft.

9. Turbocompounding. Figure 3-8.
Exhaust gas first expands in the first stage free-shaft turbine which drives the compressor. The second stage turbine is mechanically connected with the engine crankshaft.

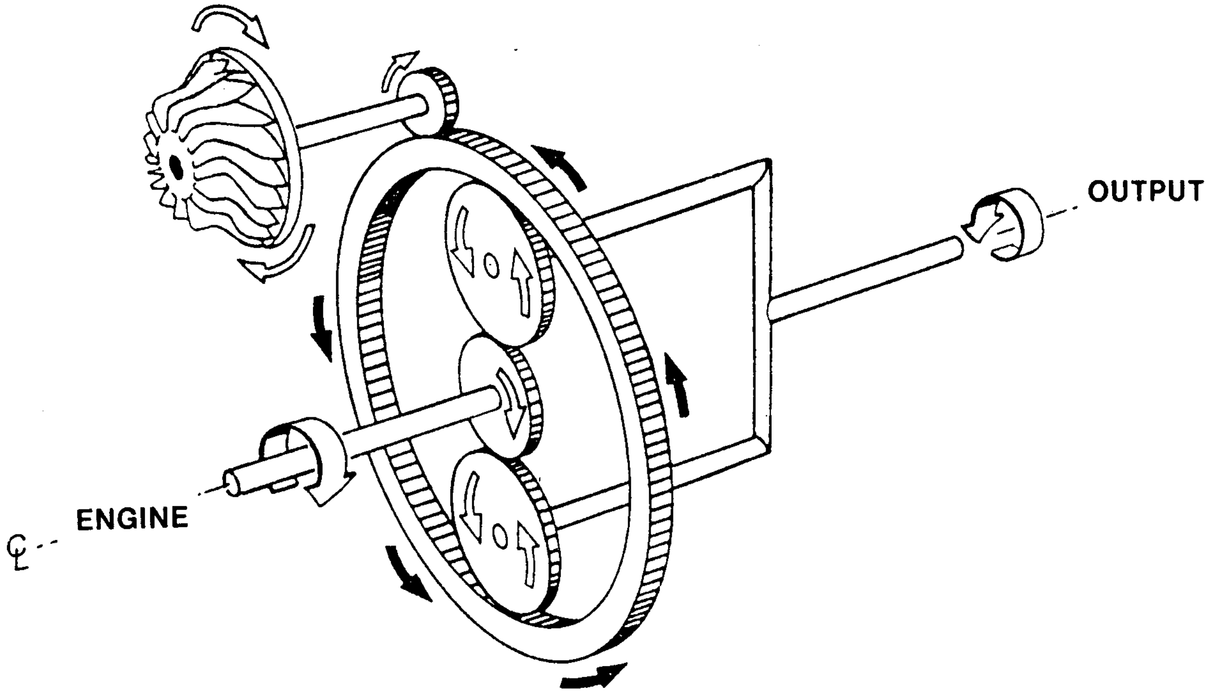


FIGURE 3-7 DIFFERENTIAL GEARED DRIVE

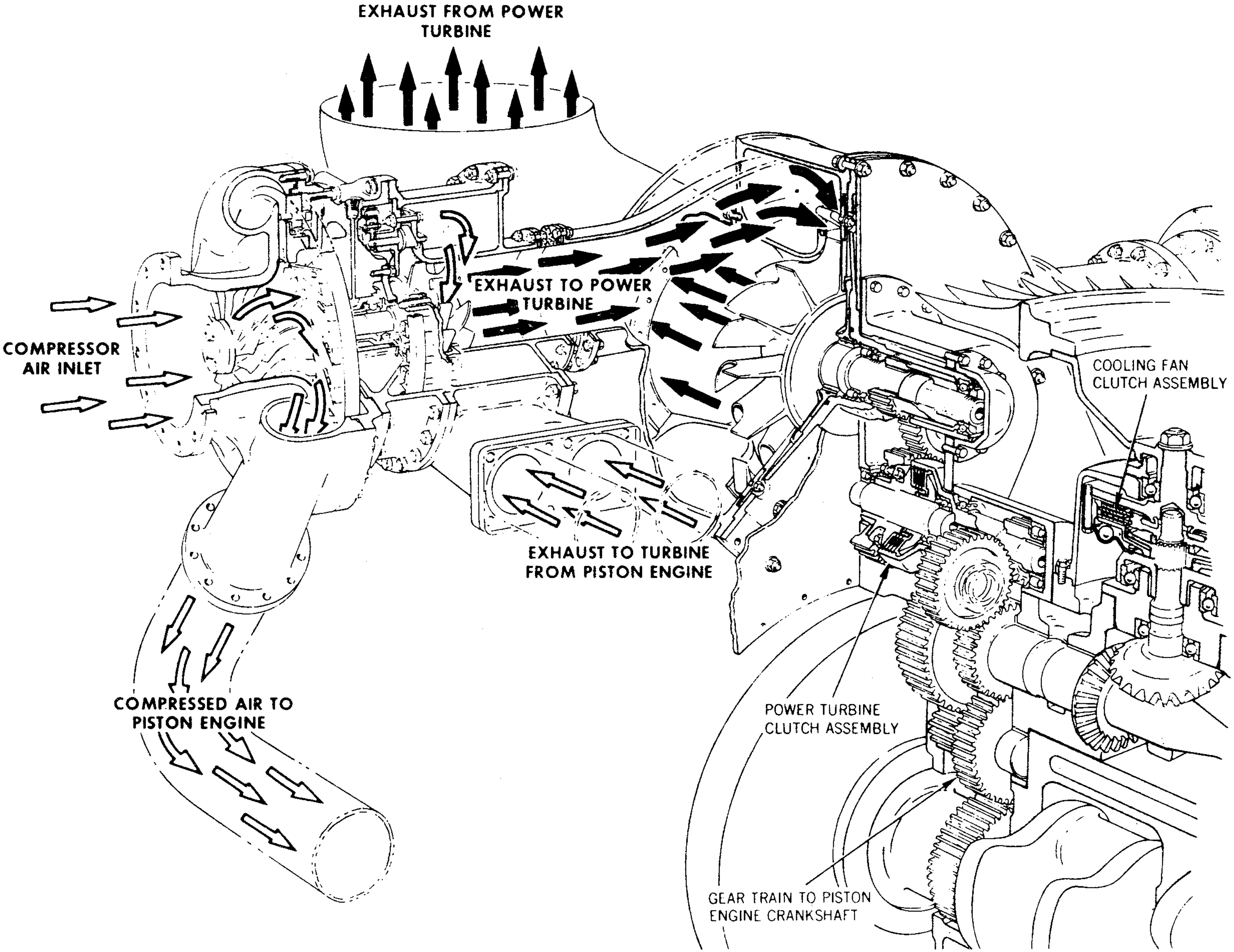


FIGURE 3-8 TURBOCOMPOUNDING

10. Catalytic Combustor. Figure 3-9.

The catalytic combustor consists of a fuel injector, igniter, flame holder and a catalyst. An infrared surface heater, capable of generating sufficient heat to activate the catalyst could be incorporated. The catalytic combustor performs several functions:

- It provides the means to run the turbocharger independent of the engine.
- It provides additional thermal energy to the turbocharger turbine at maximum power operation.
- It reduces exhaust emissions.

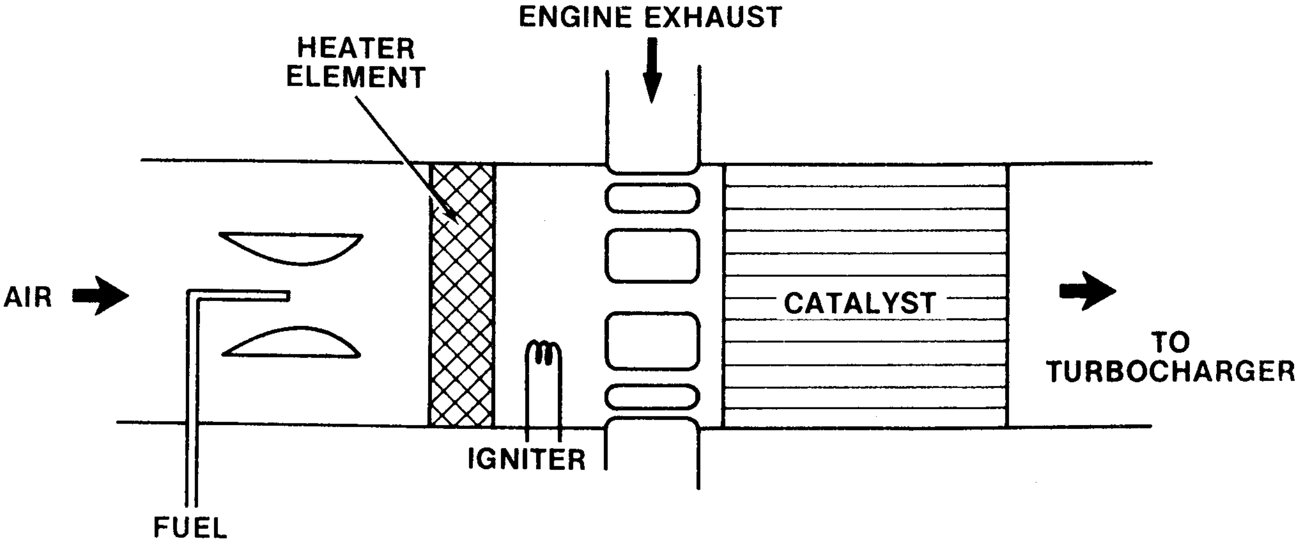


FIGURE 3-9 CATALYTIC COMBUSTOR

11. Variable Area Turbocharger (VAT). Figure 3-10.

A. Compressor Section. High pressure ratio turbochargers are severely limited in flow range unless some form of flow regulation is applied to the compressor section. The problems are surge and choking in the inducer and diffuser. Flow limits can be increased if the area which is choked can be increased. Similarly, surge flow limits can be reduced if the area where surge occurs can be reduced. The variable diffuser vane concept can provide the combination of high pressure ratios, high efficiencies and a wide flow range.

B. Turbine Section. The function of the turbine is to meet the varying power demands of the compressor. In order to meet the wider range of the variable compressor diffuser, it is necessary to provide a variable area nozzle on the turbine.

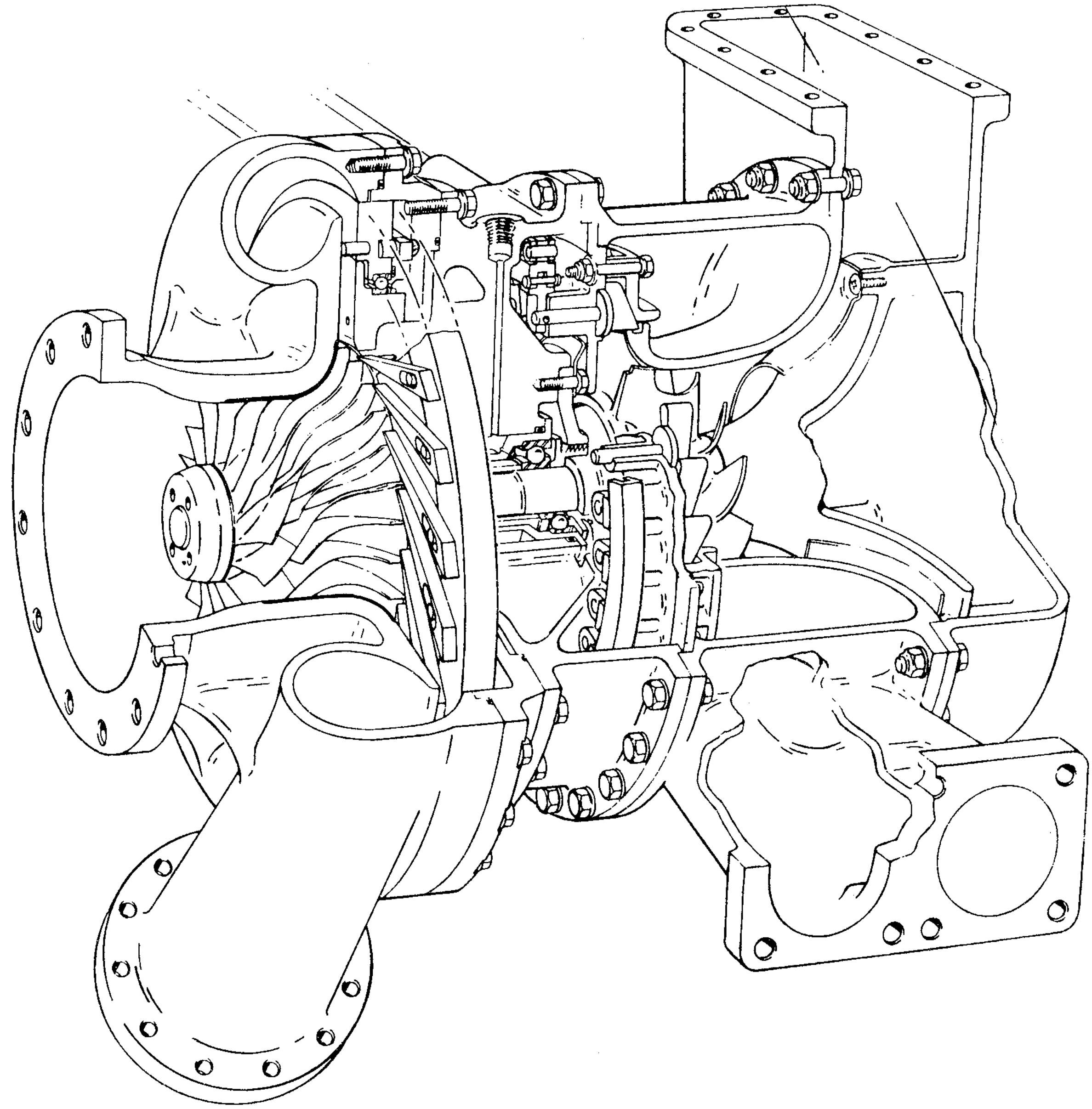


FIGURE 3-10 VARIABLE AREA TURBOCHARGER

3.1.3 Definition of the Design Approaches

An evaluation and ranking procedure of the technology base was devised to arrive at a definition of the design approaches for both engines. It was not possible due to time limitations to use the NASA Systems Engineering Decision Algorithm. Instead, a simplified ranking procedure was used.

The following criteria were observed:

1. The engine must be a piston-crankshaft type powerplant.
2. Be compatible with conventionally designed aircraft (size and drag).

3. Allow manufacture of an experimental model in five years.
4. Be ready for production in the late 1980's.
5. Meet EPA 1979 emission standards (guide reference only).
6. Have multi-fuel capability.
7. Have engine performance comparable to current aircraft engine.
8. Have lower BSFC than present engines.
9. Maximum specific weights of .852 kg/kW for the 298 kW engine and 1.095 kg/kW for the 149 kW engine.
10. Life cycle costs equal or less than present aircraft engines.
11. Avoid problem areas encountered in current aircraft engine designs.

3.1.4 Criteria Attributes

1. **Performance.** The engines must be capable of meeting the propulsion requirements for a given air frame application.

2. **Weight, Size and Center of Gravity.**

   A. Weight. Engine weight must be held to a limit where aircraft performance is not adversely affected. Any extra weight relative to current engines will require redesign of engine mounts and possibly wing design.

   B. Size. Those dimensions or areas which determine the contribution of the powerplant to the overall drag of the aircraft are considered most critical.

   C. Center of Gravity. A large deviation of the center of gravity relative to current aircraft engines must be avoided. Such a deviation would affect the flight characteristics of the aircraft and would require a redesign of the airframe.

3. **Fuel Economy.** Brake specific fuel consumption will be used as a criterion of fuel economy. For this study acceptable BSFC targets at 65% cruise power will be:

   A. 275 g/kW-hr for the 149 kW engine

   B. 245 g/kW-hr for the 298 kW engine

4. **Multi-Fuel Capability.** The design goal of the study is efficient operation on diesel fuel and jet fuels, specifically automotive diesel fuels DF1 and DF2, turbine fuels JP4, JP5 and Jet A and kerosine. Operation on gasoline is possible only if an additive or lube oil is mixed with the gasoline. Engine design modifications may be developed that would allow the installation of a heater in the intake manifold. With such a device low cetane fuels may be used; however, power output and engine life would be negatively effected under the circumstances and operation in this mode should not be considered routine.

5. **Reliability.** Reliability is defined as the probability that a subsystem or component will perform satisfactorily for the projected life of the engine or between times of inspection or overhaul.

6. **Noise.** Engine-related noise will be held at or below the level of current aircraft engines.

7. **Technology.** Technology is defined as the level of available knowledge regarding the functioning of a proposed subsystem or component.

8. **Life Cycle Costs.** Life cycle costs include all costs related to the operation of the engine over the life of the engine, such as fuel, oil, inspections, maintenance, and overhauls.

9. **Component Costs.** This criterion relates to the initial cost of components. It includes manufacturing costs and the launching costs, such as R&D, and tooling.

10. **Integration.** Integration is defined as the capability of the proposed design approach to be integrated into the overall engine design, as well as the ability to adapt the engine to conventional airframes. The engine's cooling characteristics in the installed environment will be considered an important facet of this criterion. The center of gravity of the proposed powerplant will also be considered in this category.

3.1.5 Ranking Priorities

Decision criteria were divided into three major groups:

1. Highest priority is given to those criteria which determine that the engine is compatible with conventional airframes and that it has improved fuel economy when compared to current aircraft engines. Included in this category are:
   - Performance
   - Weight
   - Size
   - Fuel Economy

2. Next highest priority is given to those criteria that make the diesel engine a more attractive aircraft powerplant than current gasoline engines:
   - Multi-Fuel Capability
   - Reliability
   - Emissions
   - Noise
   - Technology

3. The following criteria are important but not to the degree attached to the previous categories:
    - Costs
    - Integration
    - Cooling
    - Drag

3.1.6 Rating of Criteria

The rating system was used as a guide to identify those technologies which offer the most significant payoff, Table V.

TABLE V
Weighting Factors

Factor	Max. Weighting Factor	x Priority	=	Max. Points Assigned
Performance	10	10		100
Component Weight	2	10		20
Effect on Engine Weight	10	10		100
Effect on Engine Size	10	10		100
Effect on Fuel Economy	10	9		90
Engine Friction	4	2		8
Multi-Fuel Capability	8	8		64
Reliability	8	7		56
Emissions	6	6		36
Noise	6	5		30
Technology	6	4		24
Life Cycle Cost	4	3		12
Component Cost	4	2		8
Effect on Engine Cost	4	2		8
Integration	4	1		4
Cooling	4	2		8
Drag	4	1		4
		Total any item		672 points

3.1.7 Logic of Ranking

Following is the reasoning that went into the assignment of points:

1. **Engine Configuration.**

    A. Cylinder Arrangement.

    a. Weight.

    - In Line. Increased weight due to longer crankcase and longer crankshaft.
    - 60°, 90°, and 120°V. Heavier crankcase than opposed cylinders due to direction of rod forces, resulting in heavier main bearing area construction.

- Radial Single Row. Lightest crankcase.
- Radial Double Row. Heavier crankcase than single row.

b. Size. Same frontal area for Vee engines and opposed cylinders. Minimum overall size for radial single row.

c. Engine Friction. Engine friction will vary with the number of crankshaft bearings.

d. Technology

- In Line. No problems.
- 60°, 90°, and 120°V. Crankcase harder to design due to direction of forces relative to main bearings.
- Opposed Cylinders. No problems.
- Radial Single Row. No problems.
- Radial Double Row. No problems.
- Radial Twinned. Little experience to count on.

e. Life Cycle Cost.

- In Line. Easy maintenance.
- Vee Engines. Less accessibility of components inside Vee.
- Opposed Cylinders. Easy maintenance.
- Radial Single Row and Twinned Cylinders. Very accessible for maintenance.
- Radial Double Row. Less accessible.

f. Engine Costs. Points assigned proportional to engine weight and complexity.

g. Integration.

- 120°V and opposed cylinders come closest to current gasoline engines. 60° and 90°V. Probably more difficult to integrate with current airframes.
- In Line. Longer than current gasoline engines.
- Radial. Totally different configuration than current aircraft engines.

h. Cooling.

- Single Row Radial. Best cooling conditions.
- Single Row Twinned. Less cooling between twinned cylinders.
- Double Row Radial. Slightly less cooling of the 2nd row.
- In Line. Reduced cooling rear cylinders.

B. Air-Cooled. In-Line Configuration, Cylinders in One Block.

a. Weight. Continuous fins and one-piece mounting flange add more weight to cylinder block.

b. Reliability. Portion of combustion load is absorbed by cylinder hold-down bolts of adjacent cylinders in the case of a cylinder block.

c. Technology. The larger cylinder block presents more casting problems than individual cylinders.

d. Life Cycle Costs. Cheaper to replace an individual cylinder in case of scuffing.

C. Liquid Cooled. In-Line Configuration, Individual Cylinders.

a. Weight. A cylinder block allows closer spacing of the cylinders. Also, no walls separate the cylinders. Same arguments apply to size.

b. Reliability. Individual cylinders require coolant connections and thus a chance of leaks.

c. Component and engine costs lower in case of cylinder blocks due to simultaneous machining of all cylinders.

D. Propeller Drive

a. Drive off the camshaft results in low engine weight and size since it allows a high engine speed and thus a lower piston displacement. Also, the gear train is simplified. However, potential severe vibration problems in engines of this type imply an intense R&D effort.

b. Drive off the crankshaft results in a low engine speed and thus a large engine displacement, reflected in the weight, size, engine cost and integration factors.

c. The geared prop drive falls between the aforementioned versions.

2. Power Train.

A. Type of Crankshaft. The barrel crankshaft has the main journal and the cheeks combined into a single disc. It allows much closer spacing of the cylinders and results in a high natural frequency of the crankshaft system. Consequently, engine weight, size, and cost are reduced.

B. Crankshaft Material. Advantage of nodular iron is reduced weight and manufacturing cost. Stress calculations will determine the feasibility of a cast crankshaft.

C. Crankpin Arrangement. Individual crankpins for all cylinders, required to obtain even firing of an opposed 6-cylinder engine, results in increased cylinder spacing and, therefore, increased engine weight, size and cost.

D. Connecting Rod Configuration. Master and link rods result in reduced cylinder spacing.

E. Effect of Compression Ratio. High C.R. results in heavier components and increased engine weight. BSFC is lower due to higher thermal efficiency. The requirement of VCR pistons or a flame heater system in the case of the low C.R. engine resulted in lower factors for technology and life cycle cost.

F. Piston Material. Composite material will be considered in the case of an adiabatic engine, resulting in a lighter engine and lower BSFC.

G. Connecting Rod Material. Lighter composite rods will reduce average bearing loads and increase natural frequency of the crankshaft system.

H. Cylinder Construction. Current construction of cylinders, aluminum with a steel sleeve, is probably inadequate for diesel operation. Best construction is a forged steel barrel with cast-on fins. Compromise is a cast barrel, which is less expensive to manufacture.

I. Piston Ring Material. Composite material to be considered in the case of an adiabatic engine. Ductile iron becomes inadequate at higher operating temperatures.

J. Gear Train Location. Advantage can be taken of the offset of opposing cylinders when gear trains are located at both ends of the engine, resulting in reduced engine length. However, more gears mean increased weight and less reliability.

3. Induction System.

A. 4-Stroke vs. 2-Stroke Cycle. The simplicity or absence of the valve train in the case of 2-stroke cycle engine results in significantly reduced weight and size and more reliability. However, more effort is required to develop optimum scavenge conditions.

B. 2-Stroke Cycle Systems. Loop scavenging is the simplest but also the least efficient system. Opposed piston uniflow, although very efficient has the disadvantage of complexity due to two crankshafts and related gearing. Twinned cylinders offer an advantage in weight and size but disadvantages of high pumping losses between the cylinders and an extensive combustion chamber development program. Uniflow with inlet ports and exhaust valve has the disadvantage of requiring a camshaft and camshaft drive and as a result increased frontal area.

C. Types of Valve Actuation. Hydraulic valve action requires pumping elements and valve actuators. Wave propagation between pump and cylinder results in valve timing which varies with engine speed. Reliability suffers because of possible leaks of fittings. Electrical valve action has advantages of simplicity and compactness.

D. Overhead Camshaft vs. Push Rods. The overhead camshaft eliminates push rods and rocker arms. Also, the natural frequency of the valve train is higher which reduces the chance of separation.

E. Camshaft Material. Nodular iron is preferred because of lower cost and reduced weight. Stress calculations will decide whether a cast camshaft can be utilized.

F. Cam Followers vs. Hydraulic Tappets. Cam followers are preferred because of lower cost and higher reliability.

4. Exhaust System.

A. Cooled vs. Hot Exhaust Port. The hot exhaust port is to be considered in particular in the case of the adiabatic engine. Much development work needs to be done if the engine is equipped with exhaust valves to provide valve cooling and to ensure proper seating of the valve.

B. Exhaust Manifold. The insulated exhaust manifold will be considered in conjunction with the adiabatic engine.

5. Cooling System.

A. Liquid Cooling vs. Air Cooling. Reliability of the liquid cooled engine has been rated low because of the possibility of cooling system leaks.

B. Degree of Cooling. The highest score obviously goes to the adiabatic engine. The technology factor scores low due to the amount of development work that needs to be done to make such a system feasible. Reduced Cooling: TCM has done considerable work on reduction of the cooling air flow around air-cooled cylinders. It was found that the cylinder cooling can be greatly reduced from current practice without harmful effect. Piston rings appear to be the critical item when the cooling is reduced.

6. Combustion System.

A. Combustion Chamber Design.

a. Open Chamber. The open chamber scores highest in most categories except multi-fuel capability and emissions.

b. Prechamber System. The prechamber system is mainly used in applications where emissions and multifuel capability are prime considerations. However, the pumping losses between prechamber and main chamber and the heat loss of the prechamber result in a higher fuel consumption.

c. MAN System. The MAN system in a broad sense could be considered to be a prechamber system, and has most of the advantages and disadvantages of the prechamber engine. An added disadvantage of the MAN system is the high heat load on the piston, which practically limits the BMEP to 1000 kPa.

d. NAHBE System. Not enough is known about the endurance features of this engine. Obvious disadvantages of this system are high pumping losses between the main combustion chamber and the annular chamber in the piston and the lack of cooling of the upper part of the piston.

B. Methods to Obtain Low Compression Ratio at Full Load. Flame Heater System. In this case, the engine has a fixed, low compression ratio. Starting, idling and low load operation require preheating of the induction air in order to obtain the ignition temperature of the fuel at the end of the compression stroke. Development work needs to be done to ensure a very reliable heater system. The main disadvantage of this system is that the engine will die if the flame heater system fails during low load operation, with no possibility of restarting the engine without the heater.

VCR Approach. The engine starts and idles at a high compression ratio. The VCR piston gradually lowers the compression ratio as the engine load increases. Disadvantages are the heavier pistons and the resultant somewhat lower natural frequency of the crankshaft system. Failure of the VCR function may result in excessive firing pressures and the failure of a cylinder but does not affect the operation of the remaining cylinders.

7. Lubrication System.

A. Type of Oil. Synthetic oil is probably a must in the case of the adiabatic engine. The technology factor for synthetic oil has been reduced to indicate that more experience with this type of oil is required in our particular application.

B. Type of Oil Filter. The centrifugal oil filter has been in use on board of diesel powered ships for more than 50 years. The centrifugal filter prolongs the life of the oil indefinitely. The problem in the case of the aircraft engine is the development of a compact, lightweight, and very reliable unit. Such a filter does not now exist.

8. Injection System.

A. Systems.

a. Conventional System. Most commercial systems operate at 55,000 - 83,000 kPa line pressures. These systems are well developed and reliable. Unit injectors offer an advantage of simplicity but have a disadvantage in bulkiness of the injector.

b. Hydraulic Amplified Systems. Best known is the UFIS System. Its advantages are superior injection characteristics resulting in a very low BSFC. Disadvantages are complexity and bulkiness, which at the present state-of-the-art make the system feasible only for large engines.

c. High Pressure System. This system involves line pressures over 110,000 kPa. The high rate of injection and short duration of injection result in heat release during a period of the highest instantaneous thermal efficiency and thus in a low BSFC. Endurance testing of this system will be required to prove its durability.

d. Piezo-Electric System. This system will have a place in the engine if electronics are used in the control system. The system will have much of the advantages of the hydraulically amplified system but with less bulkiness and complexity. Disadvantage of this system is the state-of-the-art. Much development and endurance testing must be done to prove its validity.

B. Type of Fuel Filter.

The same arguments mentioned under oil filters apply to the fuel filter. Considering the life of a fuel filter, the arguments in favor of a centrifugal fuel filter are probably even weaker.

9. Controls.

Mechanical controls have the advantage of proven reliability and a high degree of technology.

Electronic controls have the advantage of being able to handle a much more complex input of variables and thus result in a much better engine response to varying conditions. Weight and size of this system are expected to be superior and the BSFC is expected to be lowest. Hydraulic controls are expected to be heavier and bulkier and to have the lowest degree of reliability.

10. Control of Torsional Vibrations.

Pendulum Dampers. These dampers have the advantage of minimum weight and a very high degree of reliability. The disadvantage, same as in the case of tuned damper, is that they are tuned to one order of vibration. Still, we consider the pendulum dampers superior to the rubber and viscous dampers. The rubber damper will lose its effectiveness in time due to deterioration of the rubber. Also, the tuning effect depends on the spring rate of the rubber, which is affected by ambient temperature. The same is true in the case of the viscous damper.

11. Basic 4-Stroke Cycle Systems.

A. Supercharging. This is any system that will increase the intake manifold pressure above atmospheric. Supercharged and aftercooled operation results in the highest density of the induction air, consequently, more fuel can be burned per liter of displacement.

B. Type of Supercharging. The free shaft system, or conventional turbocharging is compact and the technology well in hand. Disadvantage is that the turbocharger acts as a restriction in the induction system at idle and low engine loads. This is avoided in the coupled system, where the turbocharger is mechanically coupled to the crankshaft. The coupled system, however, has the disadvantage of the weight, bulk and complexity of a high speed gear train.

The comprex, a mechanically driven, gas dynamic pressure exchanger avoids the disadvantages of the turbocharger. Early disadvantages of the comprex, such as limited speed range, low efficiency and exhaust gas recirculation have been partially overcome. By its nature, the comprex has an optimum efficiency at one speed. Therefore, the comprex would be optimized for the aircraft's cruise speed. The comprex utilizes the exhaust gas energy to compress the air, therefore, the energy to drive the unit is minimal. The technology factor is low because much endurance testing needs to be done.

C. VAT and Independent Turbocharger Operation vs. Conventional Turbocharging. Independent turbocharger operation offers a concept for very high supercharging without excessive exhaust port temperatures. BMEP's up to 3450 kPa may be expected, resulting in a very small piston displacement. Disadvantages are the complexity of the system and lack of experience. The variable area turbocharger-VAT has the advantage of better matching of turbocharger and engine. The BSFC is lower and the engine torque remains high at low engine speeds. Disadvantage of the VAT is the weight and bulk of the control system.

D. Types of Combustors. The combustor provides turbine power at start, idle and low engine load conditions. Thus, the compression ratio of the basic engine can be lowered resulting in reduced mechanical loads on the engine. Advantages of the catalytic combustor are a wide range of operation, reduced emissions, simple control by modulation of the fuel and the fact that re-ignition does not require a pilot. The latter is a very important advantage in the case of aircraft operation.

E. Turbocompounding, Differential Compound and Organic Rankine Systems. Turbocompounding has the advantage of a higher overall thermal efficiency of the engine system but the disadvantage of the complexity of the high speed gear train.

Differential compounding produces higher torques at reduced engine speeds but this is not a particular advantage in the case of aircraft engines.

The organic Rankine system has the advantage of extracting all available energy from the exhaust gases. The result is a 15% improvement of the BSFC. Disadvantage is the complexity and weight of the system and lack of proven reliability.

12. Basic 2-Stroke Cycle Systems.

Most of the systems have already been discussed. Condition for 2-stroke cycle operation is an intake manifold pressure which is higher than the exhaust manifold pressure throughout the engine operating range.

The turbocharger and geared blower combination is the conventional approach for high output 2-stroke cycle engines. Disadvantages are the bulkiness of the system and power required to drive the blower. The BSFC consequently is higher but the advantage is that it is a proven system.

A geared turbocharger and clutch combination overcomes the disadvantage of the turbocharger at low engine speeds but has the disadvantage of a high speed gear train.

Another scheme consists of a geared compressor and separately geared turbine. Advantages are a positive ΔP throughout the engine speed range and better utilization of the exhaust gas energy. Disadvantage is the complexity of the system.

The total points for each item were then entered on the matrix chart, Figure 3-11. The first number represents the total minus technology points, the second technology. The value given to technology represents the current state-of-the-art. Any value less than 24 indicates that some development will be required. By listing technology separately the possibility is avoided that an attractive design approach might be rejected on account of a low technology value.

3.2 Choice of Engine Configuration and Technologies.

3.2.1 Initial Elimination of Items From the Flow Chart [Figure 3-11]:

1. 2-Stroke Cycle Comprex: Comprex cannot produce boost/back pressure ΔP required for 2-stroke cycle operation.

2. Coupled Turbocharged Systems: Considered too complex and too heavy relative to the benefits in the case of small powerplants.

3. In-Line Configurations: Too long, too heavy.

4. 60°V Configuration: Insufficient space inside V for injection pump and intake manifolds.

5. Cylinder Block Air-Cooled In-Line Engines: Too complex, probably too heavy. High replacement costs in case of a cylinder failure.

6. Liquid-Cooled In-Line: Too prone to leakage problems. Weight penalty of radiator, water pump and hose connections.

7. Uniflow Scavenging: Complexity and weight disadvantage are not justified when compared to valveless loop scavenging.

8. Master and Slave Rods: Difficult to use in combination with VCR pistons. Very high unit pressures between secondary pins and pin bores in master rod in case of high diesel combustion pressures.

9. Prop Drive Off Camshaft: Results in very high crankshaft and camshaft stresses due to torsional vibrations.

10. Gear Train Both Ends of Camshaft: Increased weight and less reliability offset the advantage of some reduction in engine length.

11. VAT: Purpose of VAT is to broaden efficient operation of the turbocharger over a wide range of engine speeds, not required in aircraft operation. A variable turbine nozzle may·be required to maintian a positive boost/B.P. Δ P throughout the engine load range in 2-stroke cycle operation.

12. Geared Compressor and Geared Turbine: Rejected because of complexity, weight penalty, and unreliability of 2-high speed gear trains.

13. Conventional Combustor: Rejected because of higher level of emissions compared to catalytic combustor.

14. MAN System: Developed for multi-fuel operation. High heat load on piston limits BMEP.

15. NAHBE System: High pumping losses and lack of cooling of the upper part of the piston.

16. Aluminum Cylinder and Cast-in Steel Sleeve: Structurally inadequate for the higher firing pressures of a diesel engine. Some new aluminum alloys will be explored in detailed study.
    - Gasoline engine 4100-5500 kPa
    - Diesel engine 8300-9650 kPa

17. Conventional Cylinder Cooling: The use of improved materials permits a large reduction of the cooling air flow with a resultant reduction of the cooling drag.

18. Twinned Cylinders: High flow losses can be expected in the narrow internal passage between the cylinders. Any air-swirl will be lost during passage from one cylinder to the twin cylinder with an adverse effect on combustion.

19. Centrifugal Filters: A compact, lightweight and very reliable unit will be required for aircraft use. Such a filter does not now exist.

20. Connecting Rod: The technique of producing lightweight composite rods is available and should be applied to the aircraft engine rather than steel forgings.

21. Hydraulic Valve Activation: Hydraulic valve action has disadvantages of complexity (pumping elements and actuators) and reliability — possibility of leaks. Valve timing will have to vary with engine speed which would require a complex control system.

22. Mineral Oil: Expected high oil temperatures will result in a very short period between oil changes.

23. Naturally Aspirated System: Low BMEP would result in a large piston displacement.

24. Supercharged, without Aftercooling: Aftercooling will be required when operating at the higher pressure ratios.

25. Unit Injectors: (Pump and Injector as One Unit) Rejected because of weight and size. The resultant large frontal area would add to drag loss.

26. Piezoelectric Injection: Rejected because of size, cost, reliability, and only marginal advantages.

27. Controls: Electronic controls will be applied because of the complex input of variables that can be handled, resulting in a much better engine response to varying operating conditions.

28. Tuned Damper: Rejected because of the temperature effect on the rubber (also may not be required for radial engine).

Figure 3-12 is the resultant simplified matrix. This chart still represents too many possibilities.

3.2.2 Choice of Engine Configuration

Figure 3-13 shows all possibilities of opposed and V engines, 2-stroke and 4-stroke cycle. Shown are:

1. Firing orders.
2. Firing intervals, which indicate smoothness of operation.
3. Number of main bearings, which has a large effect on engine weight. Several configurations can be eliminated because of excessive torque fluctuations and too many main bearings for a given number of cylinders.

Tables VI and VII show the first step in the elimination process of cylinder configurations.

The remaining candidates of Tables VI and VII are shown in Table VIII and were checked for unbalanced piston and rod inertia forces. Only two possible in-line candidates remain:

- 135° V8 2-stroke cycle
- 90° V8 4-stroke cycle

Table IX lists the candidates for radial engines. The rotating and primary inertia can easily be balanced by counterweights on the crank cheeks opposite the crankpin.

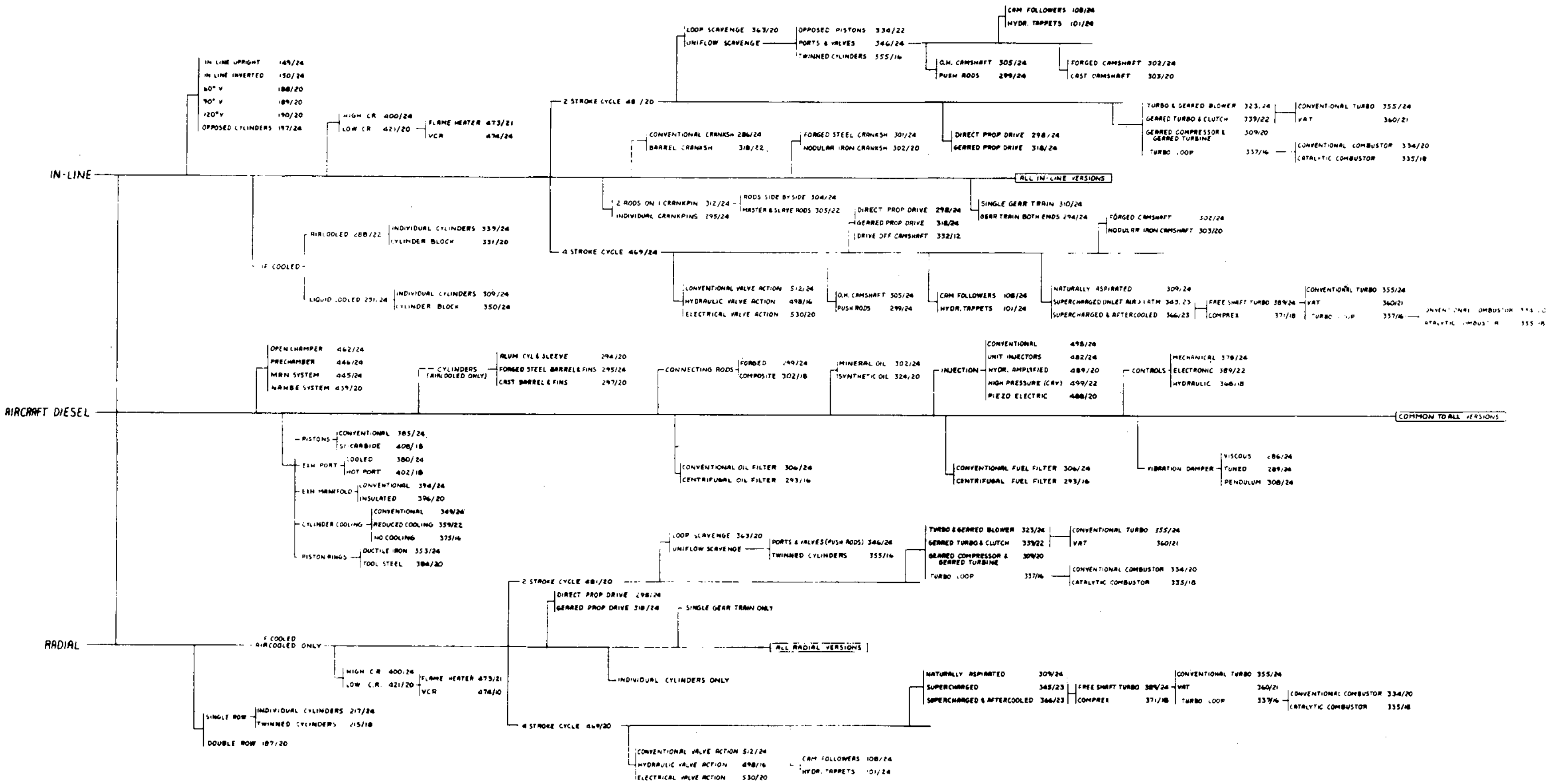


FIGURE 3-11 RANKING OF DESIGN APPROACHES

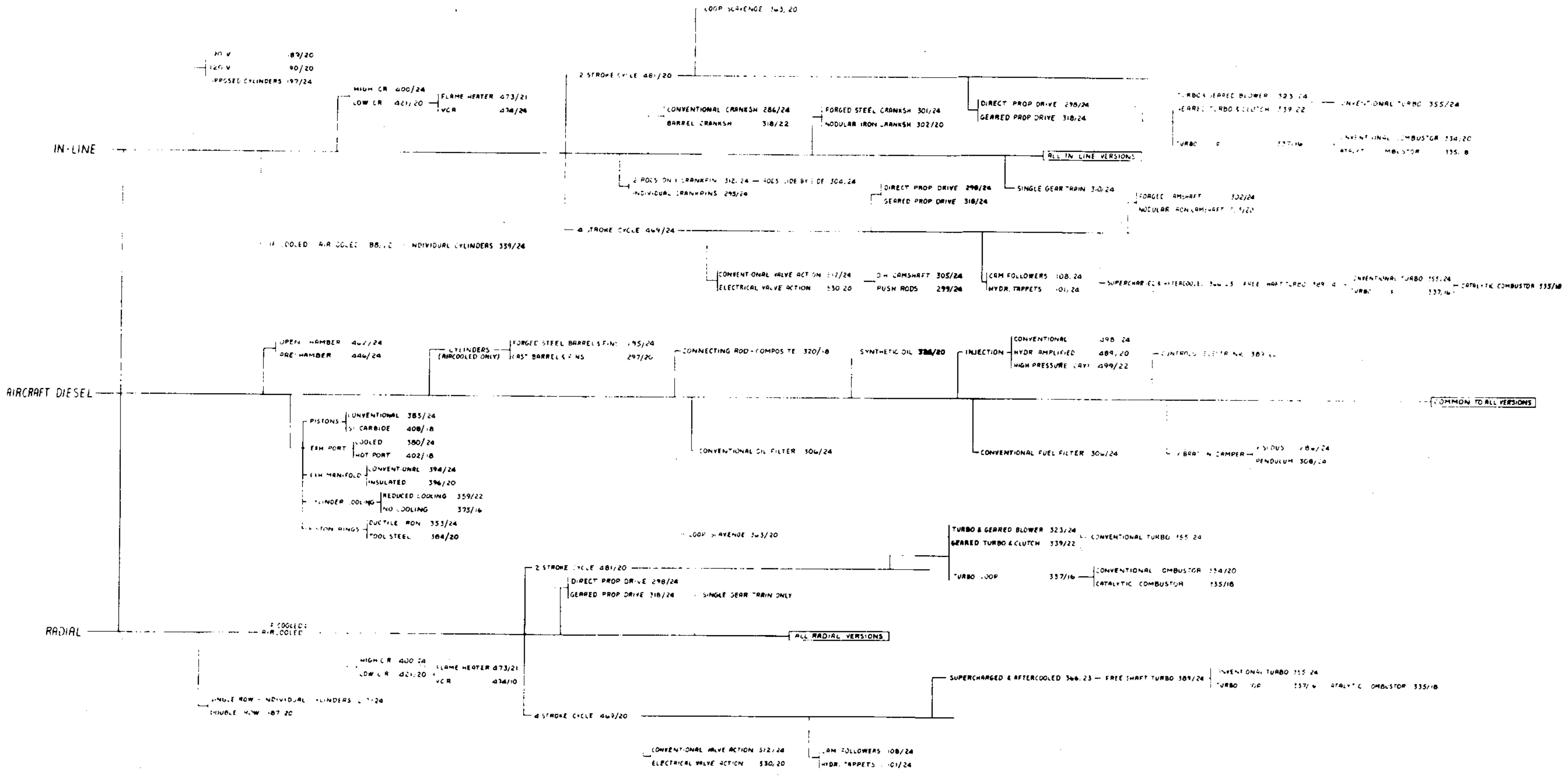


FIGURE 3-12 AIRCRAFT DIESEL DESIGN APPROACHES-SIMPLIFIED MATRIX

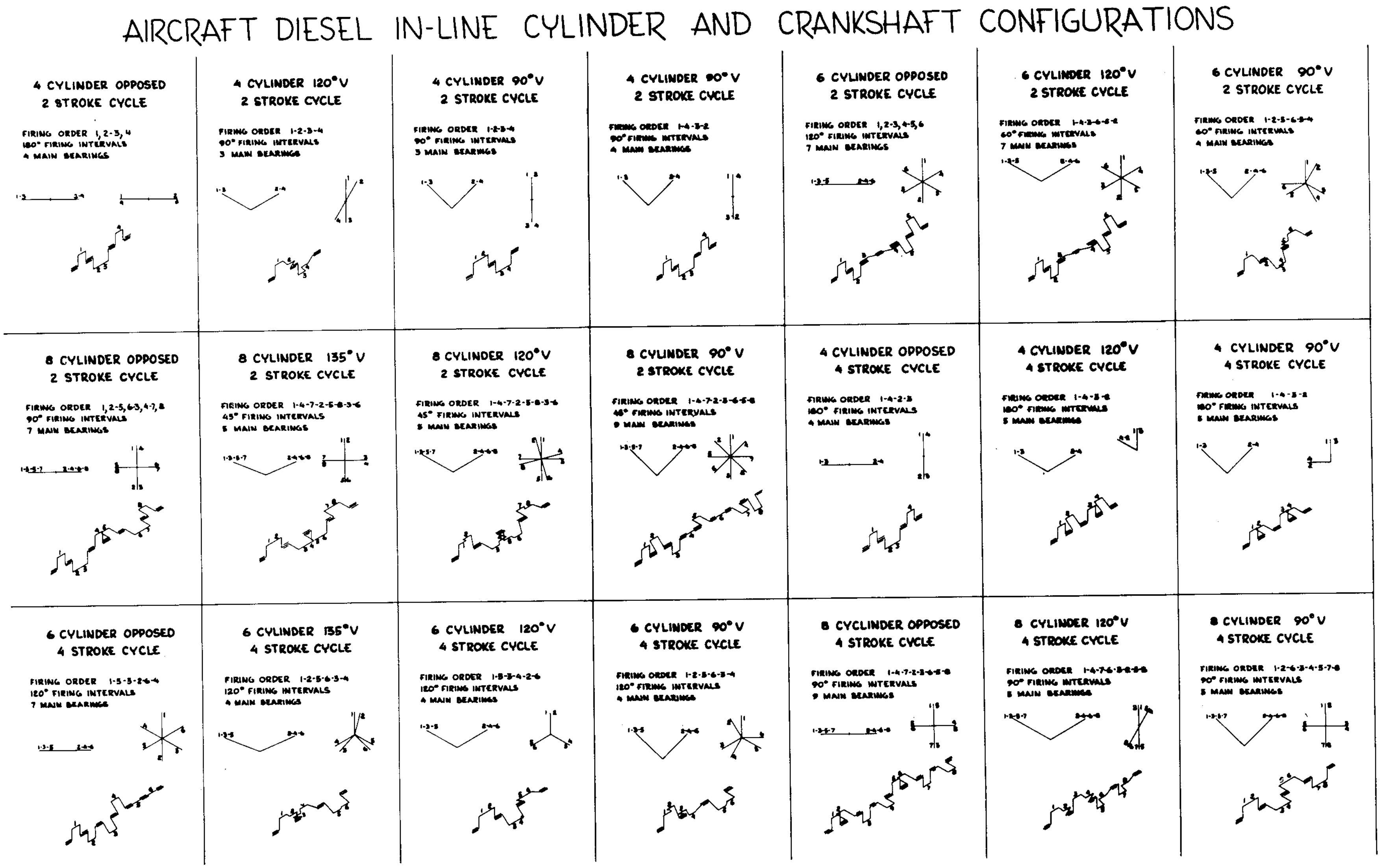


FIGURE 3-13 AIRCRAFT DIESEL CYLINDER CONFIGURATION

TABLE VI
Selection of 2-Stroke Cylinder Configurations — Step I In-Line and V Engine

	No. of Main Bearings	Objections
Flat 4	4	Large torque fluctuations.
120° V4	3	
90° V4	3 or 4	
Flat 6	7	Large torque fluctuations.
120° V6	7	Too many mains — heavy crankcase.
90° V6	4	
Flat 8	7	Too many mains.
135° V8	5	
120° V8	5	Stepped crankpins compared to 135° V8.
90° V8	9	Too many mains.

TABLE VII
Selection of 4-Stroke Cylinder Configurations — Step I In-Line and V Engine

	No. of Main Bearings	Objections
Flat 4	4	2 Torque fluctuations per rev. Can resonate with 2-bladed prop.
120° V4	5	Too many mains.
90° V4	5	Too many mains.
Flat 6	7	Too many mains.
135° V6	4	Stepped crankpins compared to 120° V6.
120° V6	4	
90° V6	4	Stepped crankpins.
Flat 8	9	Too many mains.
120° V8	5	
90° V8	5	

TABLE VIII
Selection of Cylinder Configurations — Step II In-Line and V Engine

INTERTIA FORCES AND MOMENTS

	FORCES			MOMENTS			
	Rot.	Prim.	Sec.	Rot.	Prim.	Sec.	Objections
2-Stroke Cycle							
120° V4	0	0	$\neq 0$	$\neq 0$	$\neq 0$	$\neq 0$	secondary unbalance
90° V4	0	0	$\neq 0$	0	0	$\neq 0$	secondary unbalance
90° V6	0	$\neq 0$	0	$\neq 0$	$\neq 0$	$\neq 0$	primary unbalance
135° V8	0	0	0	$\neq 0$	$\neq 0$	0	
4-Stroke Cycle							
120° V6	0	$\neq 0$	$\neq 0$	$\neq 0$	$\neq 0$	0	secondary unbalance
120° V8	0	0	$\neq 0$	$\neq 0$	$\neq 0$	0	secondary unbalance
90° V8	0	0	0	$\neq 0$	$\neq 0$	0	

TABLE IX
Radial Cylinder Configurations

RULE:

2-Stroke Cycle: Any number of cylinders per row.
4-Stroke Cycle: Uneven number of cylinders per row.

INERTIA FORCES:

Rotating: Constant, in direction of crank radius.
Primary: Constant, in direction of crank radius.
Secondary: Zero resultant force.

Maximum number of cylinders per row is 4 due to limited bearing area of slipper connecting rods.

Candidates:

3-Cylinder single row	4-stroke cycle
6-Cylinder double row	4-stroke cycle
4-Cylinder single row	2-stroke cycle
6-Cylinder double row	2-stroke cycle

3.2.3 Comparison of 2-Stroke Cycle Operation vs. 4-Stroke Cycle

Loop scavenge 2-stroke cycle operation offers the following advantages over 4-stroke cycle:

1. Higher specific power (kW/ℓ)
2. Weight reduction due the absence of the valve mechanism, camshaft and camshaft drive.
3. Reduction of frontal area due to the elimination of the overhead valve mechanism.
4. Improved reliability due to fewer parts .
5. Higher engine speeds are possible due to the absence of a valve mechanism.
6. Less engine torque variation.
7. To be discussed in a later section (3.3.2), the 298 kW version is proposed to have uncooled cylinders. Valve problems in an uncooled cylinder will probably be unsurmountable; therefore, elimination of the valves is essential.

Disadvantages of 2-stroke cycle are:

1. Scavenging of the cylinders requires a positive pressure difference between intake and exhaust manifolds under all operating conditions. This means the addition of a mechanical blower in the case of conventional turbocharged 2-stroke cycle engines.

2. 30% more airflow required for scavenging of the cylinders.
3. Higher mean cycle temperature which results in a higher thermal loading of cylinders and piston rings and raises and NOx emissions.
4. Higher oil consumption due to loss of oil through the exhaust ports.
5. More development time required to optimize the scavenging.
6. Cooling of the exhaust ports is required.

The choice is the 2-stroke cycle system:

1. The advantages listed above are of critical importance in the specific case of an aircraft engine:
    A. Weight reduction
    B. Reduced frontal drag
    C. Improved reliability
2. The best known diesel aircraft engines that were ever produced or fully developed were 2-stroke cycle engines:
    A. The German opposed piston, uniflow scavenged Junkers "JUMO."
    B. The British loop scavenged Napier "NOMAD."
    C. The McCulloch loop scavenged radial TRAD 4180.

3.2.4 Final Engine Configurations

The following candidates are left (all 2-stroke cycle):

1. 135° V8
2. 4-Cylinder single row radial
3. 6-Cylinder double row radial

This leaves only one in-line candidate to cover both the 149 kW and 298 kW. This configuration is alright for the 298 kW version but too complex for the 149 kW engine. Our final choice, therefore, is the radial configuration as follows:

1. A 149 kW 4-cylinder single row — 2 stroke cycle.
2. A 298 kW 6-cylinder double row — 2 stroke cycle.

3.2.5 Choice of Technologies

The technologies now follow from Figure 3-12 taking the high score items along the "common to all versions" and "radial 2-stroke cycle" lines.

Common to All Versions Line

- Open chamber
- Ceramic pistons
- Insulated exhaust manifolds
- No cylinder cooling
- Tool steel piston rings
- Composite connecting rods
- Synthetic lube oil
- High pressure fuel injection
- Electronic controls
- Conventional oil filter
- Conventional fuel filter
- Pendulum damper

Radial 2-Stroke Cycle Line

- Individual cylinders
- Low compression ratio
- Geared prop drive
- Loop scavenge
- Independent turbo loop
- Catalytic combustor

3.3 The 298 kW 6-Cylinder Engine

Figure 3-14 shows an artist rendering of the proposed engine. Figure 3-15 shows the schematic of the engine. The design incorporates all the technologies which were defined before.

3.3.1 2-Stroke Cycle

The chosen system is Curtis loop scavenging. The intake ports and intake manifold are located at the propeller side of the engine, exhaust ports and exhaust manifold at the back end.

3.3.2 Uncooled Cylinders

The cylinder liner and piston top are ceramics. Tool steel piston rings will be required. Cooling air will be required only for the aftercooler, oil cooler and the cylinder fuel injectors. The exhaust ports will be oil cooled.

3.3.3 Injection System

Each cylinder receives fuel from a separate injection pump located in front of the cylinder (cool side of the engine). Failure of one pump still leaves 5/6 of engine power available. A high injection line pressure will be required to limit injection duration at high engine speeds.

3.3.4 Independent Turbocharger Operation

The turbocharger can run independent of the engine. For that purpose a high-speed starter/alternator and an oil pump are mounted on the turbocharger. A 2-way valve is placed in the intake manifold. To start the engine this valve is in the vertical position of

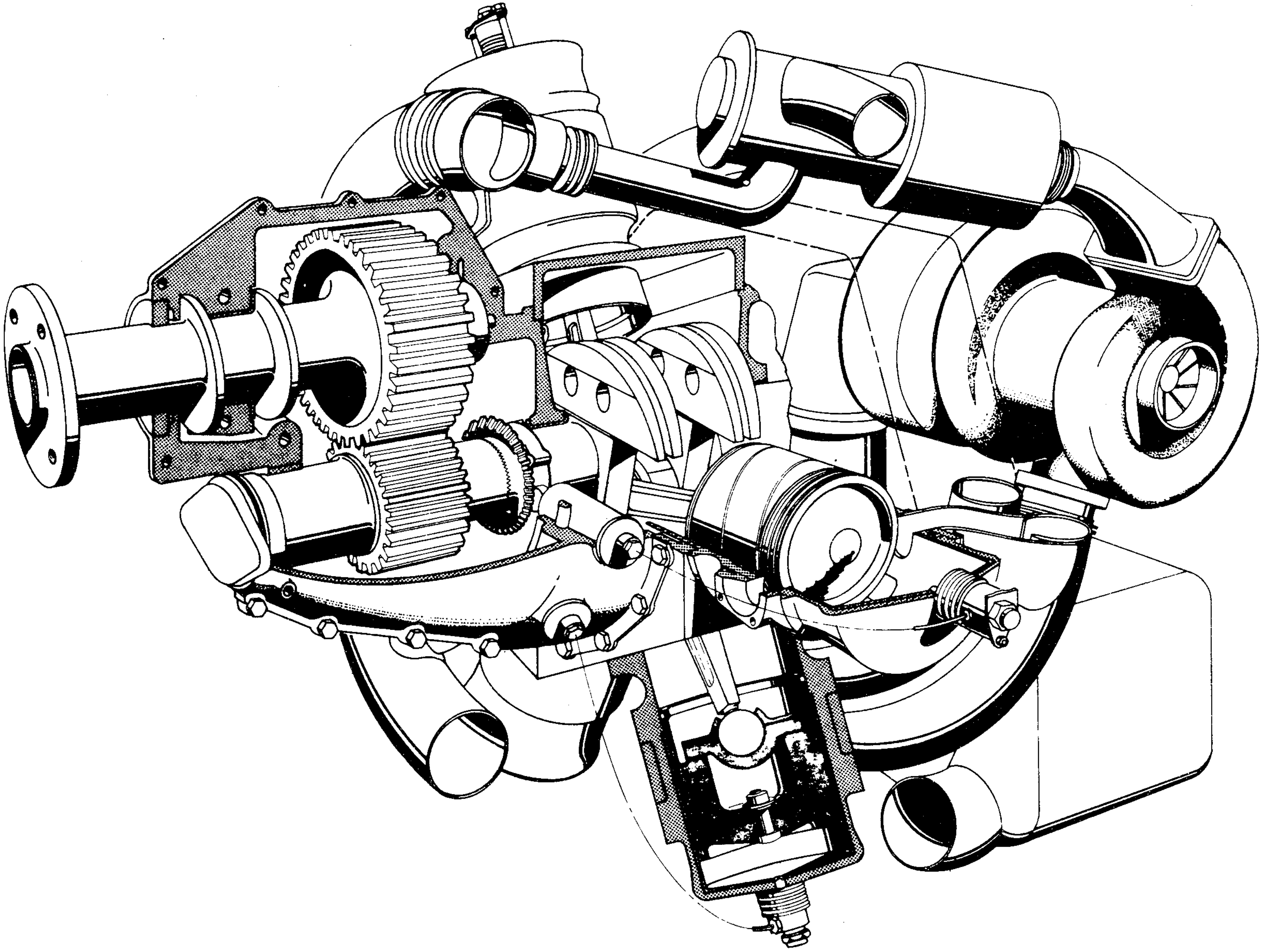
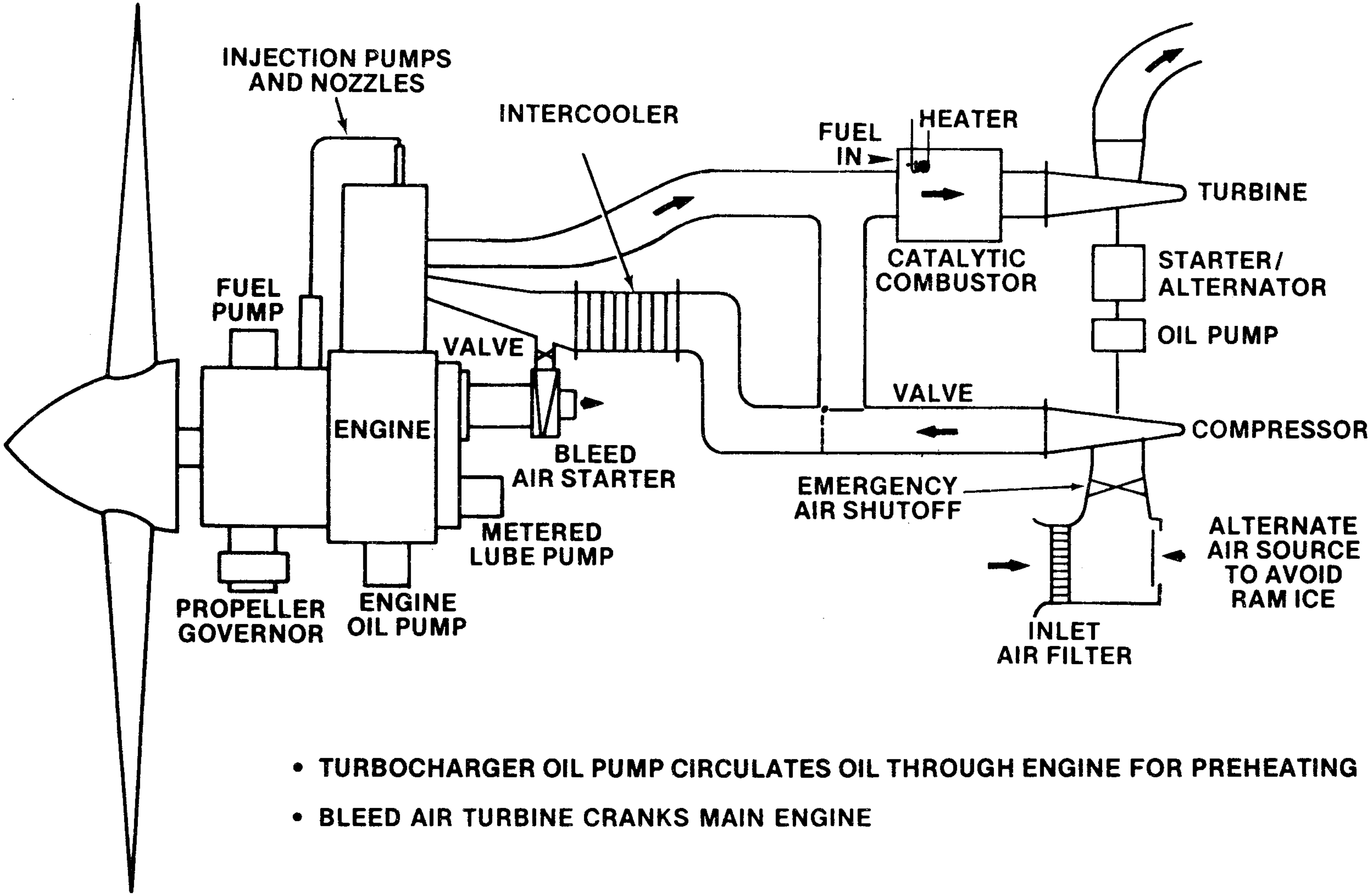


FIGURE 3-14 298 KW DIESEL AIRCRAFT ENGINE



- **TURBOCHARGER OIL PUMP CIRCULATES OIL THROUGH ENGINE FOR PREHEATING**
- **BLEED AIR TURBINE CRANKS MAIN ENGINE**

FIGURE 3-15 SCHEMATIC 2-STROKE ENGINE WITH INDEPENDENT TURBO LOOP/HOT ENGINE CONFIGURATION—NO COOLING/LOW COMPRESSION RATIO PISTONS the schematic, which results in a turbocharger loop independent of the engine. Combustor fuel is ignited by the heater. This heater can be turned off as soon as the catalyst becomes sufficiently hot. The cycle will become self-sustaining at approximately 1/3 of maximum turbo speed, and the starter now runs as an alternator. Hot, high pressure air will flow to the engine when the 2-way valve is partially opened. The cylinder intake ports are opened during approximately 120 crank-degrees, so hot air can flow through two cylinders for preheating on an extreme cold day. The high pressure air will next be admitted to the engine-mounted bleed air starter to crank the engine. The whole sequence would be automatic on a production engine.

This system offers many advantages:

1. The availability of hot induction air at start reduces the need for a high compression ratio. The engine will start and idle at a 10:1 compression ratio provided this hot high pressure air is available to it. Thus, with this low compression ratio, the firing pressures are held down to 9650 kPa at full load resulting in low engine weight.

2. The engine will start easily under extreme cold conditions, a problem with current gasoline engines.

3. Hot start problems are eliminated.

4. Easy restart is available while airborne.

5. The engine can be shut-off and the turbocharger kept running when the aircraft is on the ground for some period. Meanwhile, electric power, cabin heat or air conditioning remain available. This in effect converts the turbocharger into an APU.

6. The battery requirement is greatly reduced since engine cranking is accomplished by air pressure.

7. Activation of the heater greatly reduces the turbocharger response time to engine power changes.

3.3.5 Synthetic Oil

The use of synthetic oil is required due to the hot cylinders. Over the long term perhaps a method can be found to generate an airfilm between pistons and cylinder walls, in effect, using air bearing technology. This would also reduce the expected high oil consumption which is inherent to 2-stroke cycle engines.

3.3.6 Initial Performance Parameters

Table X shows the full power performance of three aircraft diesel engines. For comparison a BMEP of approximately 1100 kPa and a stroke/bore ratio = 1 were chosen for the study engine.

The engine characteristics become:

Number of cylinders	6
Take-off power	298 kW
Engine speed at T.O.	3500 rpm

BMEP	1085 kPa
Displacement	4.71 liter
Cylinder bore	100 mm
Stroke	100 mm
Piston speed	11.67 m/sec.
Propeller drive	geared

The study is aimed more at the best possible fuel economy and reliability than the highest possible power output.

TABLE X
Performance of 2-Stroke Cycle Aircraft Diesel Engines

	No. Cyl.	Bore mm	Stroke mm	Ratio S/B	Displ. ℓ	Engine Speed RPM	Power kW	BMEP kPa	Piston Speed m/sec.	Total Piston Area CM^2	Spec. Power kW/cm^2	Spec. Power kW/ℓ	Weight kg	Spec. Wt. kW/kg	BSFC g/kW·hr.
McCulloch	4	98.425	98.425	1.000	3.00	2850	150	1052.6	9.35	304.3	.493	50.00	149	1.001	243
Napier-Nomad	12	152.4	187.325	1.229	41.00	2050	1984	1416.3	12.80	2189.0	.906	48.40	1624	1.222	213
Junkers-Jumo	6	105.0	2 x 160	1.524	16.62	3000	740	890.5	16.00	1039.1	.712	44.52	649	1.140	213

Average BMEP	1119.8 kPa	(162.4 psi)
Average Piston Speed	12.72 m/sec.	(2504 fpm)

3.3.7 Engine Concept Design

The engine concept is shown in the Figures 3-16 through 3-20. The cylinders are arranged in two offset banks of three cylinders each, acting on a single crankpin. The rotating and reciprocating inertias are 100% balanced by counterweights on the crank cheeks. The pendulum dampers are mounted to the counterweights and will be tuned for the 4-1/2 and 6th orders. The cylinders are uncooled and provided with ceramic liners. The intake ports and the intake manifold are located at the front side—the cool side of the engine. The exhaust ports and exhaust manifolds are located at the backside—the hot side of the engine. Two exhaust manifolds are required to prevent the exhaust pulse of one cylinder from interfering with the scavenging of the previous cylinder in the firing sequence. The piston tops are ceramic.

The small ends of the connecting rods are designed to allow free rotation of the pistons.This should reduce the wear rate of the piston rings. The big ends of the connecting rods are designed as a slipper, i.e., each rod contacts only 1/3 of the circumference of the crankpin. This is possible for 2-stroke cycle engines because the combined load of gas pressure and inertia is always directed toward the crankpin. The bearing material will initially be conventional, but a study could be conducted later of self-lubricating and gas bearings to eliminate the need for oil in the crankcase. The oil to be used initially is a synthetic oil which can take higher temperatures and requires fewer changes than conventional petroleum based oils.

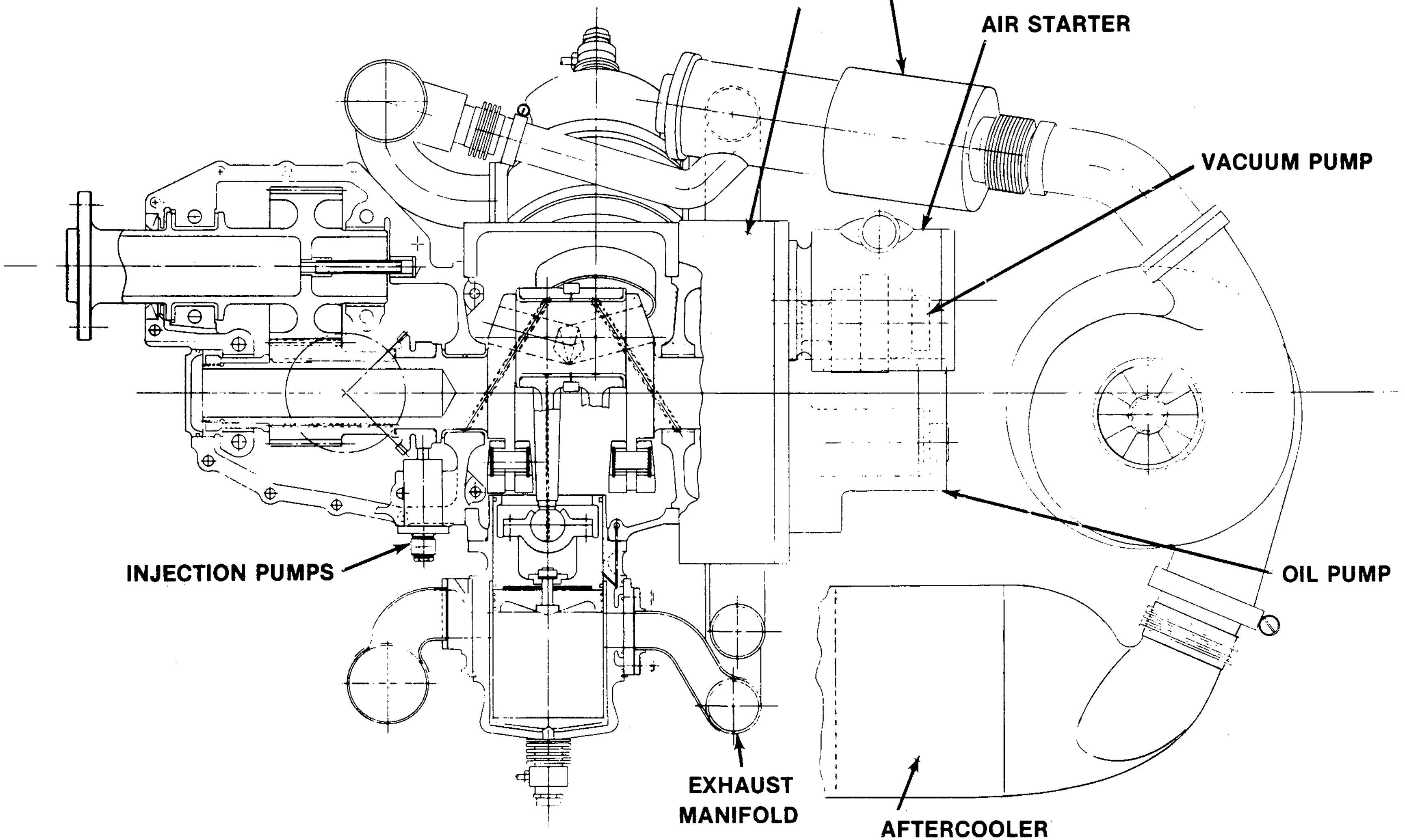


FIGURE 3-16 298 kW AIRCRAFT DIESEL—LONGITUDINAL SECTION

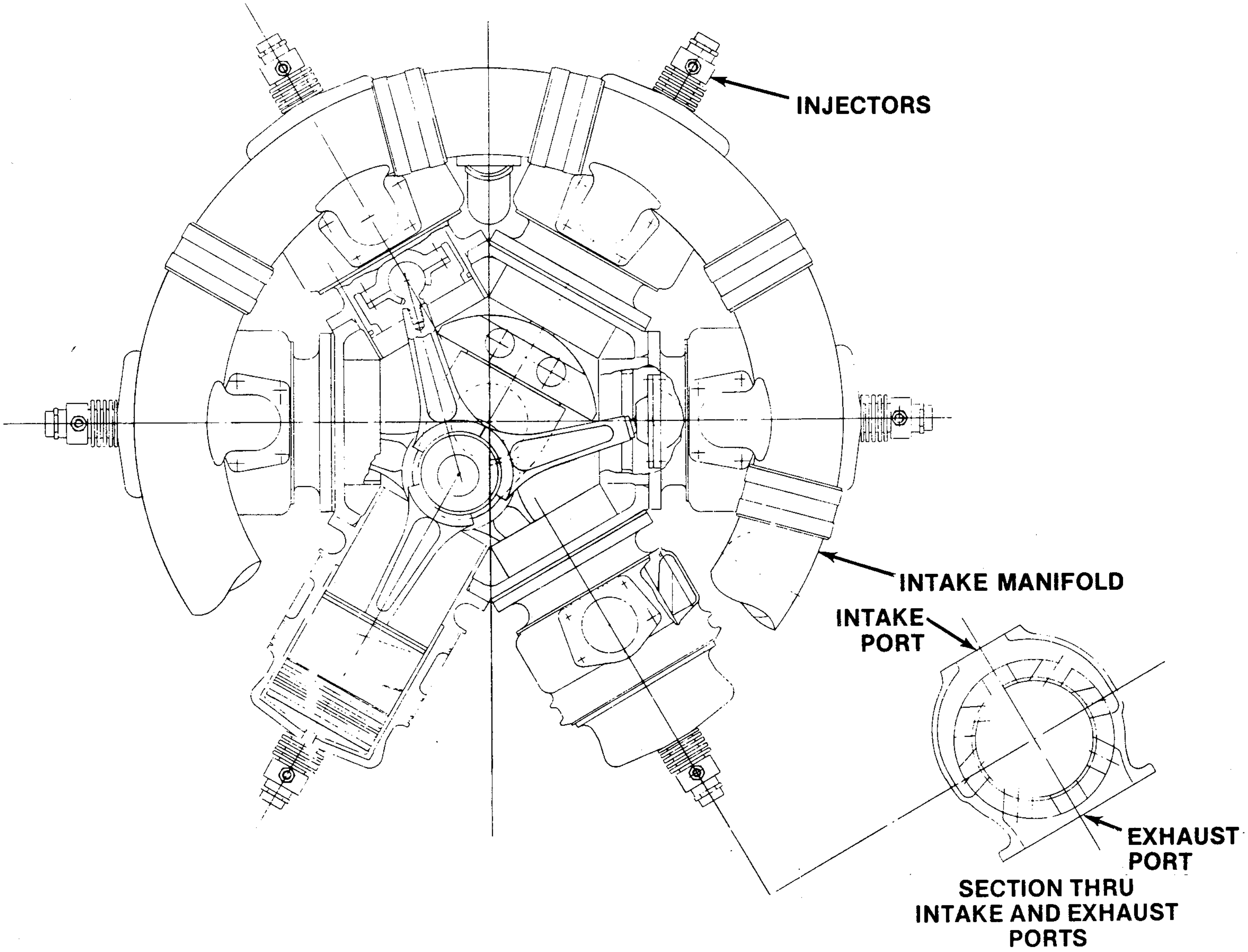


FIGURE 3-17 298 kW AIRCRAFT DIESEL—CROSS SECTION

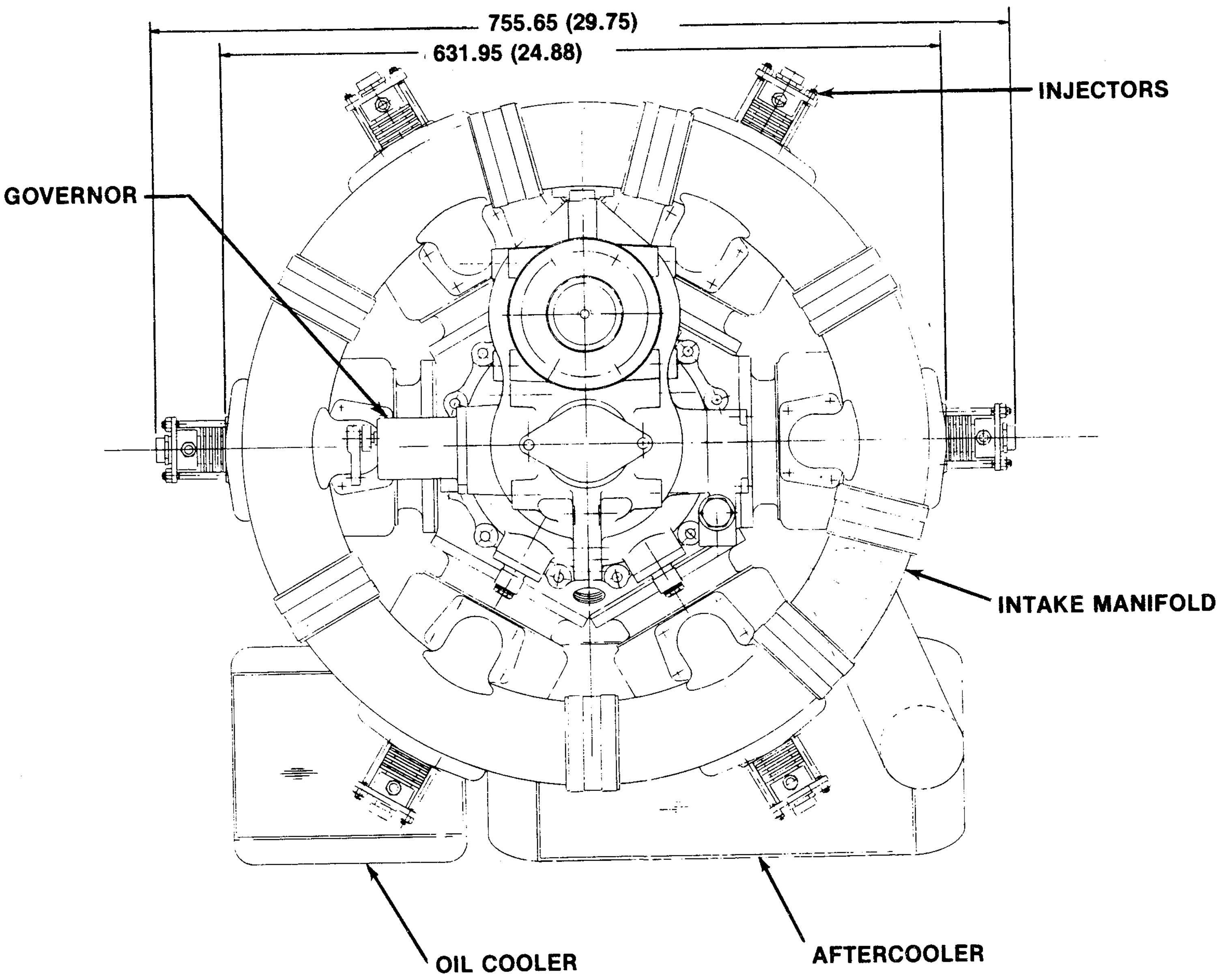


FIGURE 3-18 298 kW AIRCRAFT DIESEL—FRONT VIEW

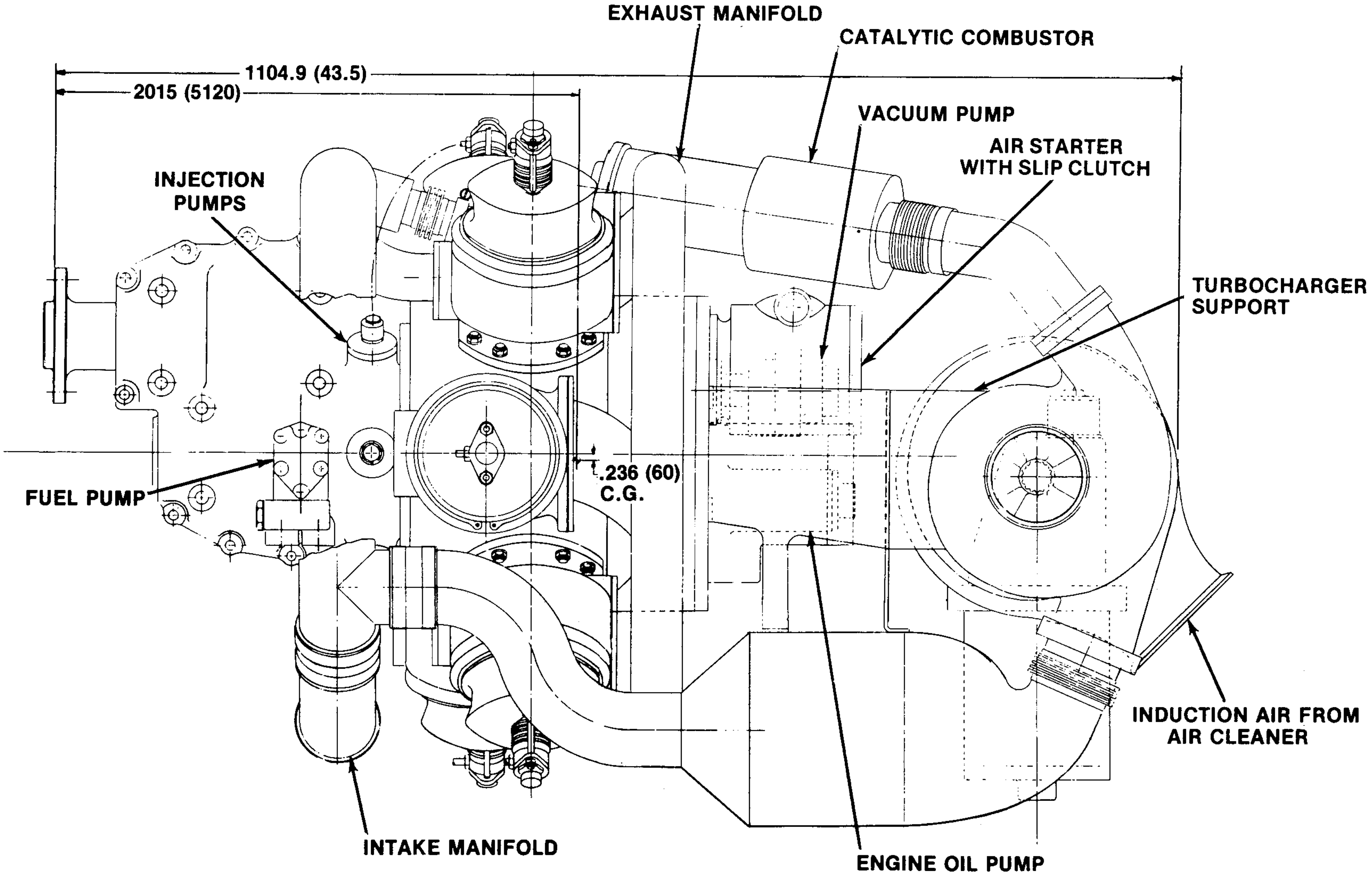


FIGURE 3-19 298 kW AIRCRAFT DIESEL—SIDE VIEW

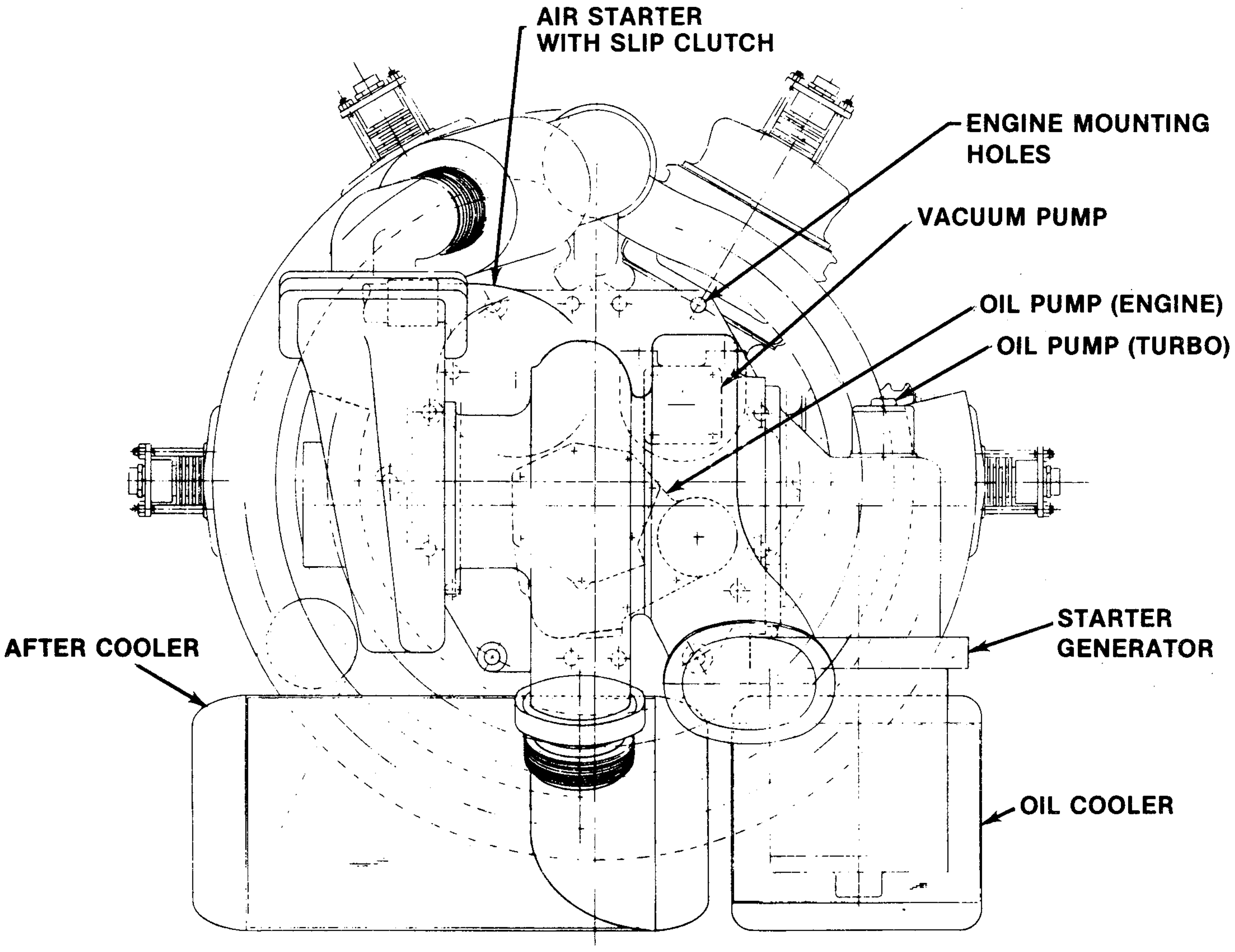


FIGURE 3-20 298kW AIRCRAFT DIESEL—REAR VIEW

Immediately in front of the 1st main bearing are 6 individual injection pumps, operated by a single lobed cam ring. Individual pumps were chosen to improve engine reliability — failure of one pump still leaves 5 cylinders operable. Also, all fuel lines can have the same length resulting in the same injection timing for all cylinders.

A bevel gear in front of the cam ring drives the prop governor and the fuel priming pump.

A gear reduction reduces the crankshaft speed of 3500 rpm at take-off down to 2300 rpm propeller speed.

At the back of the crankcase is an accessory housing which contains the gearing for the engine oil pump, the vacuum pump, and the bleed air starter. The air starter drive is provided with a slip clutch to prevent engine damage in the case of a hydrostatic lock in one of the cylinders (accumulation of fuel due to the leakage of a fuel injector). Four engine mounting points are provided on the accessory housing. Above the accessory case is the catalytic combustor assembly. Leading to it are the two exhaust manifolds and the air bypass for operation in the APU mode.

The turbocharger is located behind the accessory housing. Figure 3-20 shows the turbine to the left and the compressor in the center. To the right is a gear housing with the high speed alternator and turbo oil pump drives.

The aftercooler and oil cooler are located below the engine accessories.

The engine will operate with a dry sump.

Speeds of accessories are shown in Table XI.

TABLE XI
Accessory Speeds

Engine	3500 rpm
Propeller	2300 rpm
Governor	3500 rpm
Fuel Transfer Pump	3500 rpm
Engine Oil Pump	3500 rpm
Vacuum Pump	3500-4200 rpm
Air Starter	max. 10000 rpm (40 to 1 reduction)
Tachometer	1750 or 3500 rpm
Alternator	35000 rpm (At 70,000 rpm turbo speed)
Turbo Oil Pump	8000 rpm

3.3.8 298 kW Engine Operating Data (11)* (12)*

Operating parameters have been calculated for the 298 kW engine and are shown in Table XII.

TABLE XII
Operating Parameters — 298 kW Engine

	Take-off	100% Power Cruise	65%Power Cruise	
Altitude	0	6,096	6,096	meters
Power	298	298	194	kW
RPM	3,500	3,500	2,675	
Displacement	4.71	4.71	4.71	liters
Bore x Stroke	100 x 100	100 x 100	100 x 100	mm
BMEP	1,085	1,085	923	kPa
Compressor Pressure Ratio	4.06:1	8.30:1	6.25:1	
Nominal Compression Ratio	13.185:1	13.185:1	13.185:1	
Effective Compression Ratio	10.0:1	10.0:1	10.0:1	
Barometric Pressure	101.4	46.4	46.4	kPa
Ambient Temperature	15.5	– 25	– 25	°C
Intake Manifold Pressure	402.4	370.2	277.6	kPa
Intake Manifold temperature	116	116	116	°C
Exhaust Manifold Pressure	309.5	284.8	245.5	kPa
Scavenge System	Curtis Loop	Curtis Loop	Curtis Loop	
Scavenge Ratio	1.3	1.3	1.3	
Ratio Boost/Back Pressure	1.3	1.3	1.131	
Height Intake Ports	20.65	20.65	20.65	mm
Height Exhaust Ports	26.14	26.14	26.14	mm
Intake Ports Open/Close	61°47′	61°47′	61°47′	BBDC/ABDC
Exhaust Ports Open/Close	69°39′	69°39′	69°39′	BBDC/ABDC
BSFC-engine	206.8	212.9	194.6	g/kW-hr.
BSFC-combustor	18.2	6.1	0	g/kW-hr.
BSFC-powerpack	225.0	219.0	194.6	g/kW-hr.
Fuel Flow Powerpack	67.1	65.3	37.8	kg/hr
Air Density	.00279	.00256	.00205	kg/ℓ
Air/Fuel Ratio	27.50	24.59	25.47	

3.3.9 P-V Diagrams

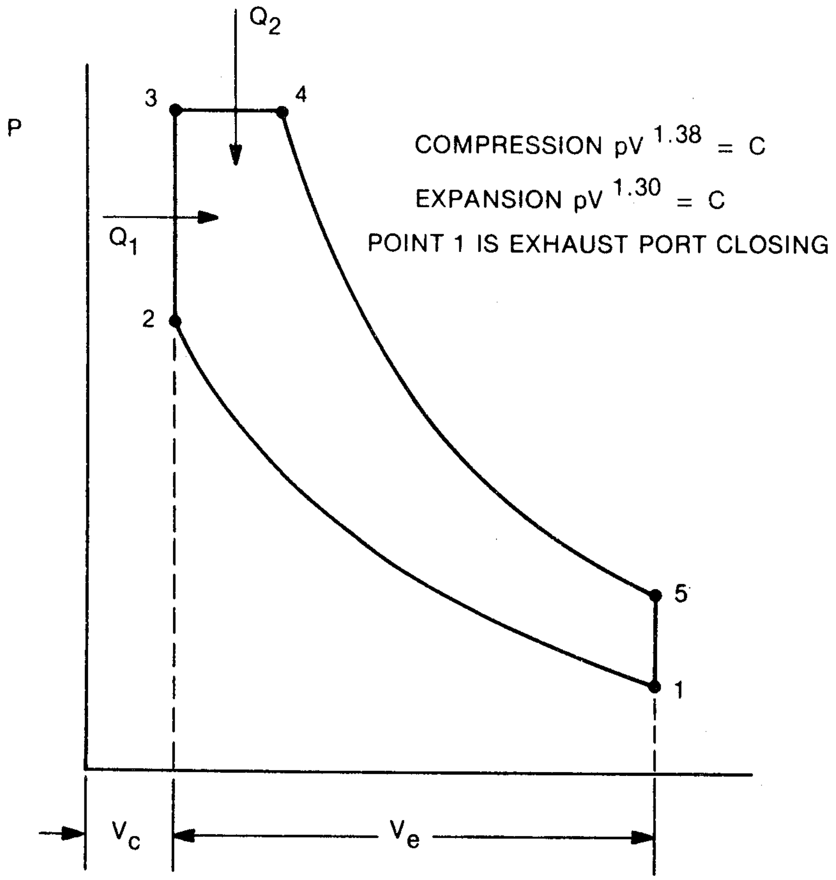
Air cycle performance data has been calculated for the proposed engine. Figure 3-21 illustrates the points calculated on the P-V diagram. Specific data points for three operating conditions are given in Table XIII.

TABLE XIII
Air-Cycle Performance

	Take-off	100% Power Cruise	65% Power Cruise	
P_1	356	328	262	kPa
V_1	.645	.645	.645	liter
T_1	171	171	171	°C
P_2	8,540	7,850	6,270	kPa
V_2	.064	.064	.064	liter
T_2	792	792	792	°C
P_3	9,650	8,970	7,390	kPa
V_3	.064	.064	.064	liter
T_3	932	888	982	°C
P_4	9,650	8,970	7,390	kPa
V_4	.110	.115	.111	liter
T_4	1,783	1,900	1,882	°C
P_5	970	960	750	kPa
V_5	.645	.645	.645	liter
T_5	937	1023	997	°C
Fuel/Cyl./Rev.	.0000490	.0000504	.0000390	kg
Air in Cylinder	.00135	.00124	.00099	kg
Q/Cyl./Rev.	.502	.516	.400	kcal
Q_1	.053	.053	.053	kcal
Q_2	.450	.463	.347	kcal
IMEP	1,339	1,357	1,069	kPa
Mech. Eff. (engine)	81	80	86	%
Turbine Pressure Ratio	3.052	6.137	5.290	
Compressor Pressure Ratio	4.066	8.300	6.250	
Compressor Efficiency	78	79	80	%
Turbine Efficiency	77	77	79	%
Mechanical Efficiency	98	98	98	%
Overall Turbo Efficiency	59.6	60.0	62.3	%
Required TIT	616	594	458	°C
Available TIT from Engine	533	569	572	°C
FLOWS:				
Weight Pure Air	.472	.434	.266	kg/sec
Weight Fuel	.017	.018	.010	kg/sec
Weight Exhaust Gas	.489	.452	.276	kg/sec
Weight Scavenge Air	.142	.130	.080	kg/sec

The Figures 3-22 thru 3-24 show the schematics of these three operating conditions.

Figure 3-25 shows the engine performance curves.



COMPRESSION $pV^{1.38} = C$

EXPANSION $pV^{1.30} = C$

POINT 1 IS EXHAUST PORT CLOSING

Vc = CLEARANCE VOLUME

Ve = EFFECTIVE STROKE

FIGURE 3-21 ENGINE INDICATOR DIAGRAM

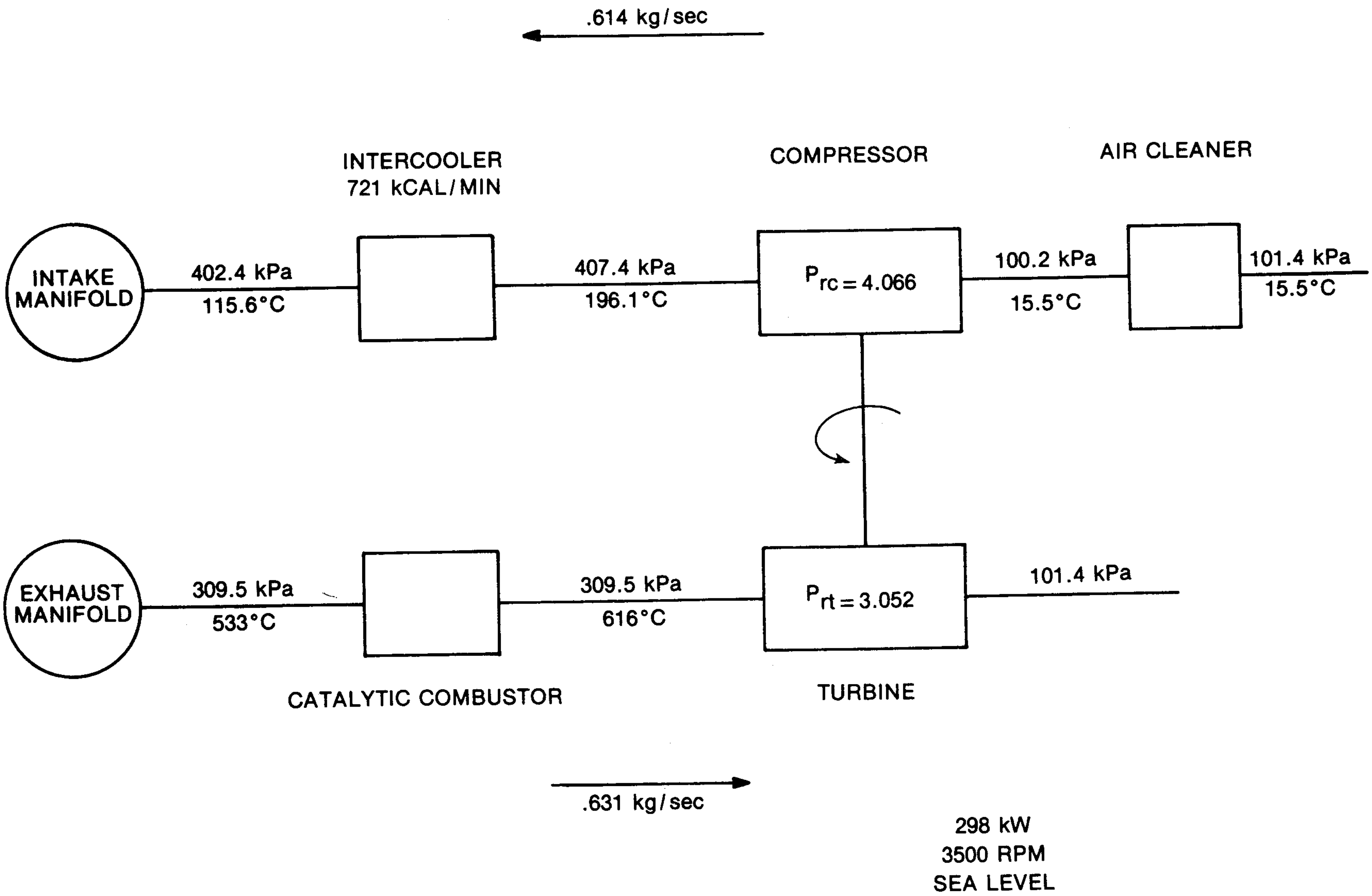


FIGURE 3-22 OPERATING SCHEMATIC—TAKE-OFF

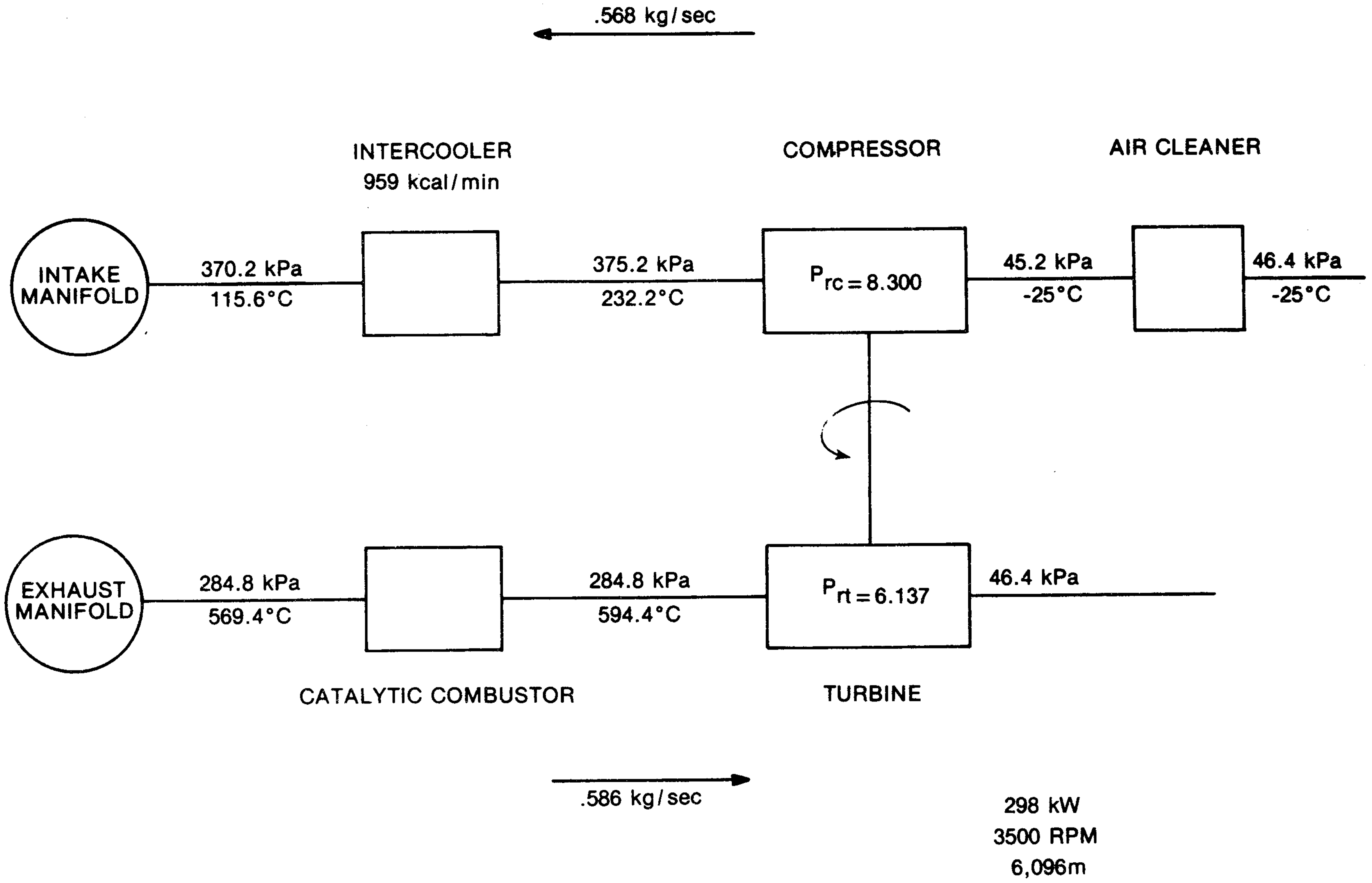


FIGURE 3-23 OPERATING SCHEMATIC—100% CRUISE POWER

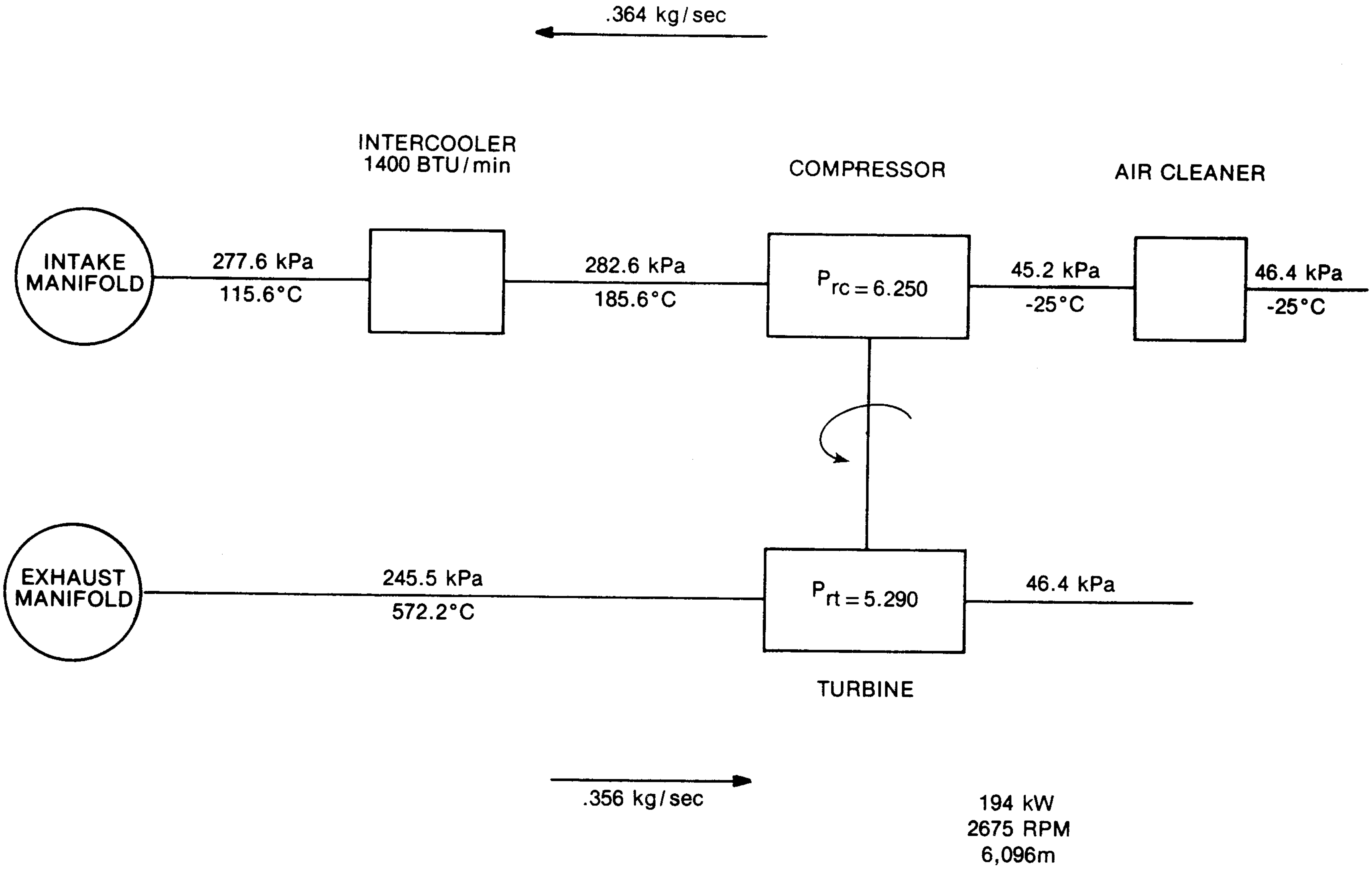


FIGURE 3-24 OPERATING SCHEMATIC—65% CRUISE POWER

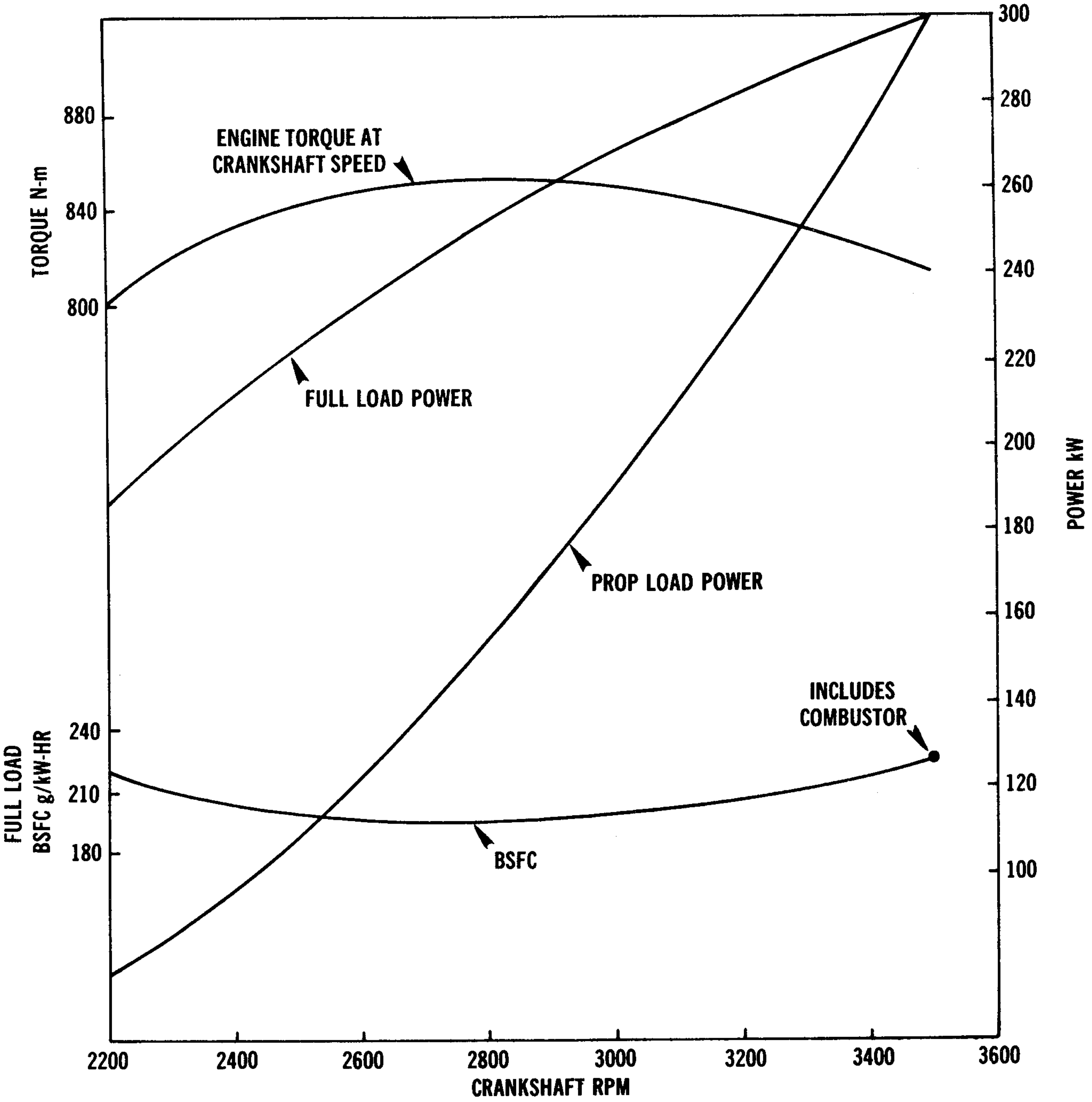


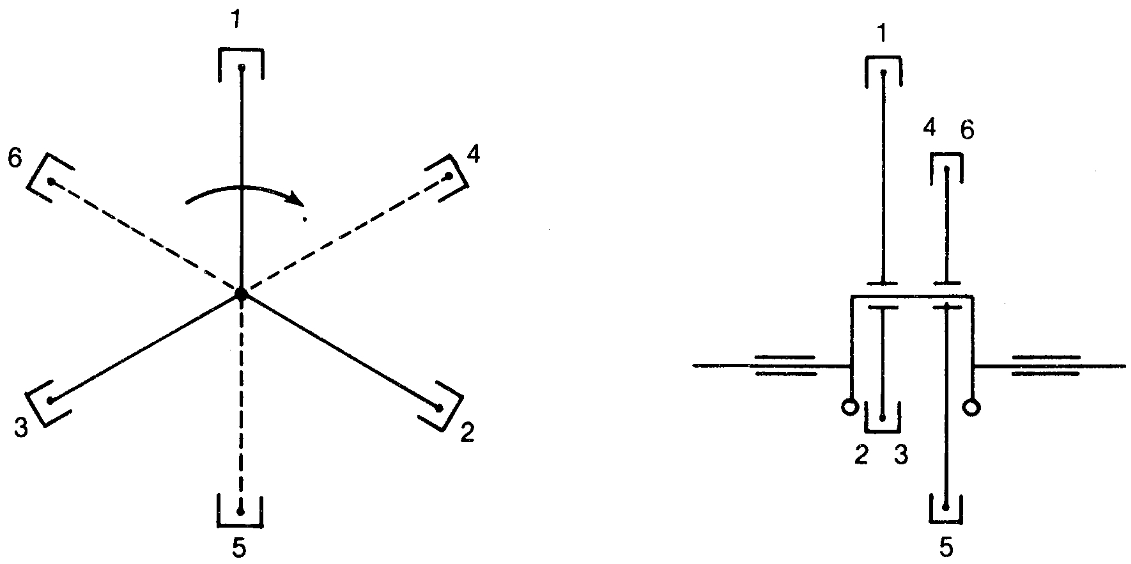
FIGURE 3-25 SEA LEVEL PERFORMANCE 6-CYLINDER RADIAL AIRCRAFT DIESEL ENGINE

3.3.10 Stress Calculations

All calculations were based on a 9650 kPa firing pressure. This pressure occurs only for short periods during take-off. Most fatigue cycles occur during cruise operation when the firing pressures and, therefore, the stresses are much lower. This results in an extra safety factor.

Figure 3-26 shows the cylinder configuration. The cylinders are arranged in two rows of cylinders. The offset of the two rows is determined by the width of a connecting rod.

The firing order is 1, 4, 2, 5, 3, 6 with even 60° firing intervals.



FIRUGE 3-26 CYLINDER CONFIGURATION

1. Power Train Data

Weight Piston Assembly:

Ceramic top	.35 kg
Hold-down bolt	.25 kg
Aluminum piston	.88 kg
Piston rings	.12 kg
Total Piston	1.60 kg
Composite connecting rod	.20 kg
Slipper rings	.44 kg
Counterweights	9.28 kg
Total reciprocating WR	24.9 kg-cm
Total rotating WR	25.0 kg-cm
Total counterweight WR	49.5 kg-cm
Balance	100%

2. Crankshaft Stresses

A. Crankpin Fillet Radius:

Max. principal bending stress	559 MPa
Max. principal shear stress	120 MPa

B. Main Bearing Fillet Radius:

Max. principal bending stress	87 MPa
Max. principal shear stress	60 MPa

C. Material:

AMS 6415

Ultimate tensile strength (min)	1034 MPa
Endurance strength (machined & peened)	552 MPa

3. Connecting Rod Stresses and Bearing Pressures

A. Connecting Rod

Max. compressive stress	291 MPa
Min. compressive stress	35 MPa
Graphite-epoxy fatigue strength	390 MPa
Crankpin bearing unit load	40 MPa
SAE-794 leaded bronze max. unit load	69 MPa
Piston ball joint (30 mmø) unit load	95 MPa
Note: (w/o oil groove on ball)	

B. Main Bearing (65 mmø x 30 mm length)

Peak unit load	22 MPa
Min. unit load	16 MPa

The Figures 3-27 and 3-28 show the main bearing load diagram and the crankshaft and connecting rod stresses.

4. Cylinder Barrel Stresses

Cylinder wall hoop stress	63 MPa
Cylinder wall longitudinal stress	32 MPa

8-Cylinder hold down studs

M10X1.5 — 6g Grade 8 (Proof load 40,430 N/stud)

Torque to 75% proof load: 30,320 N/stud

Peak dynamic load: 1,490 N/stud

Material	**Sintered Alpha SiC**	**Steel**
Flexural strength at 1000°C	442 MPa	455 MPa
Density	3.16 g/cc	7.86 g/cc
Thermal Expansion Coefficient RT-700°C	4.02 x 10^{-6}/°C	11.4 x 10^{-6}/°C
Thermal conductivity at 600°C	.045 kcal/m-hr-°C	37.2 kcal/m-hr-°C

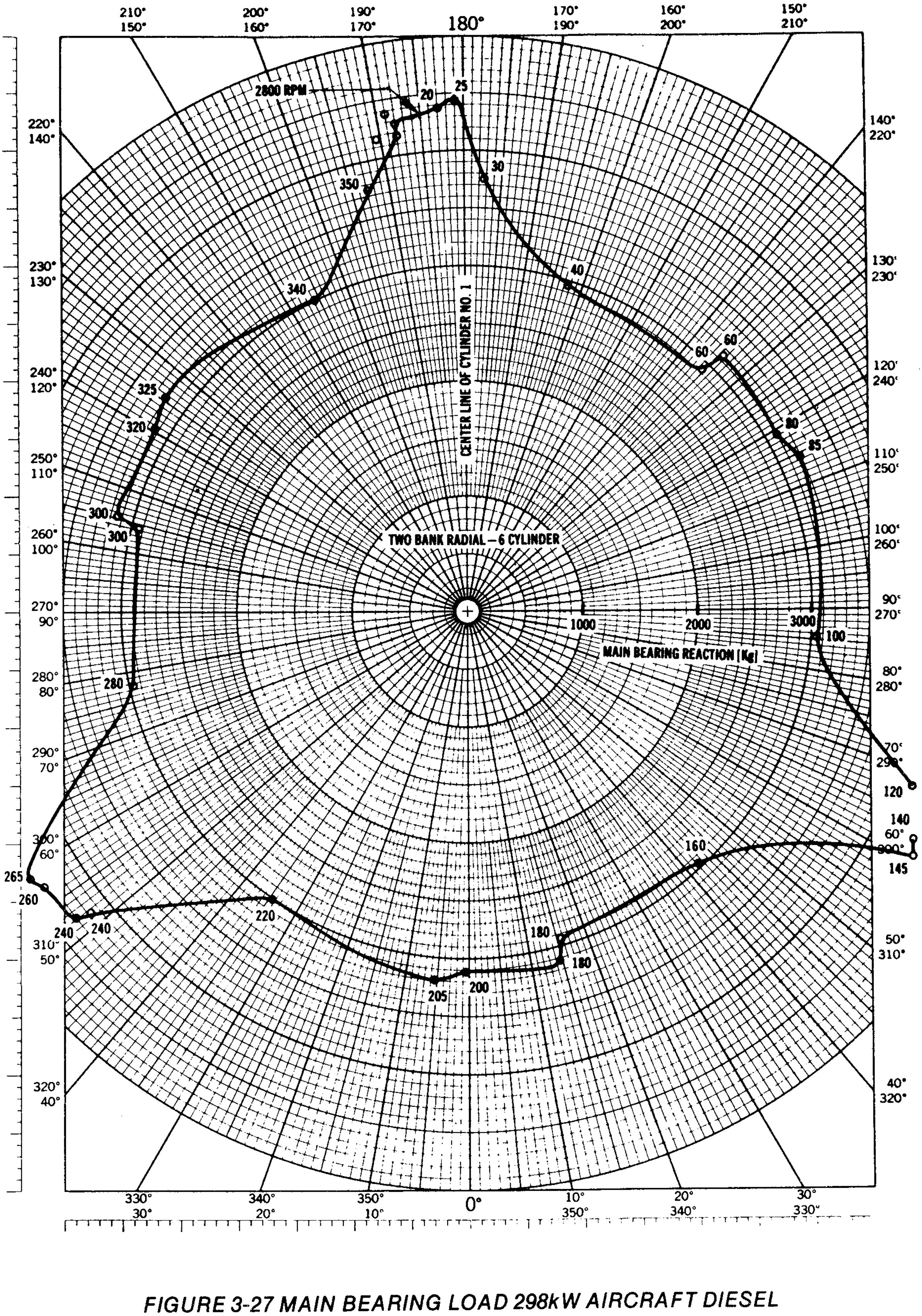


FIGURE 3-27 MAIN BEARING LOAD 298kW AIRCRAFT DIESEL

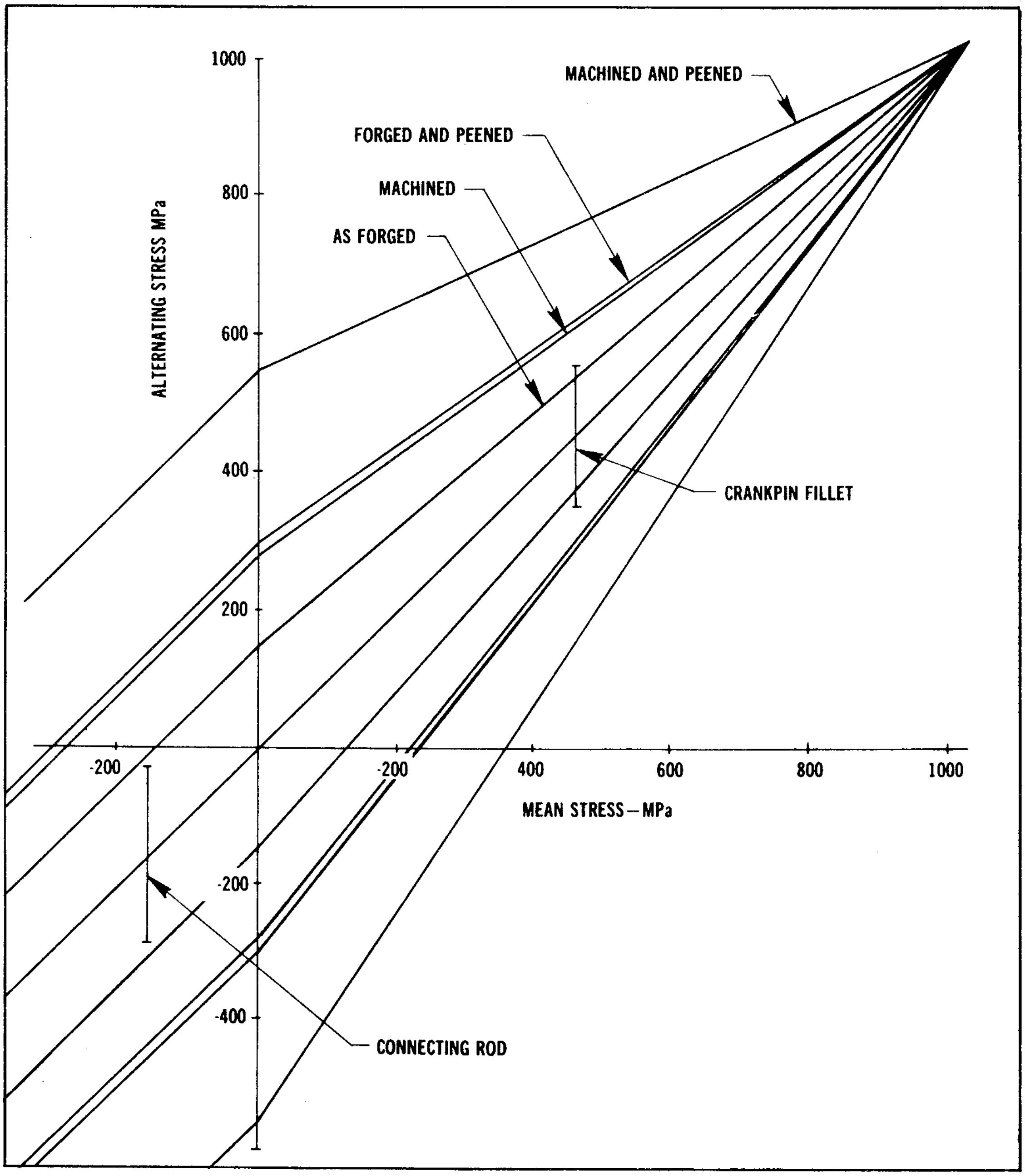


FIGURE 3-28 CRANKSHAFT AND CONNECTING ROD STRESS

5. **Natural Frequencies Crankshaft System**

First mode's natural frequency — 220 Hz

1st Order	13,200 rpm
3rd Order	4,400 rpm
4-1/2 Order	2,930 rpm
6th Order	2,200 rpm

Pendulum dampers to be tuned for 4-1/2 and 6 Orders.

6. **Propeller Drive Gear Stresses**

A. Driven Gear
38T/7P (20° P.A.)
63.5 mm face width

B. Drive Gear
25T/7P (20° P.A.)
63.5 mm face width

Wear stress	1,400 MPa
Bending stress	346 MPa

Note: Overload factor taken as 1.0
Power transmitted — 304 kW at 3500 rpm

C. Material AMS 6260
Case carburized and hardened (R_c60)
AGMA allowable bending stress 414 MPa
AGMA allowable wear stress 1465 MPa

3.3.11 Projection of Fuel Consumption

A comparison is made with the TCM/GPD AVCR/VAT 1360 high output 4-stroke cycle air-cooled diesel engine. This engine delivers 1120 kW at 2600 RPM. The engine was chosen because its BMEP of 2317 kPa is approximately twice that of the aircraft diesel, which is 1085 kPa. (A 4-stroke cycle engine of the same displacement and speed has to have double the BMEP of a 2-stroke cycle engine in order to deliver the same power.)

1. Measured AVCR-1360 performance data:

BSFC = .252 kg/kW-hr at 2600 RPM.
Fuel flow 282 kg/hr (heating value 10,250 kcal/kg).
Energy input 48,230 kcal/min.
Heat equivalent of 1120 kW is 16,030 kcal/min or 33.2% of total energy.

AVCR-1360 cooling losses:

Cylinders	6,300 kcal/min
Oil Coolers	2,140 kcal/min
Aftercoolers	4,940 kcal/min
Total	13,380 kcal/min = 27.7%

Exhaust energy loss 17,410 kcal/min = 36.1%
Radiation 1,410 kcal/min = 3.0%

2. Projection of an AVCR-1360 with uncooled cylinders:

The absence of cylinder cooling changes the energy balance by 6,300 kcal/min. Approximately 55% of it or 3,465 kcal/min. can be recovered as usable energy. The rest, 2,835 kcal/min. goes out the tailpipe. The new energy balance becomes:

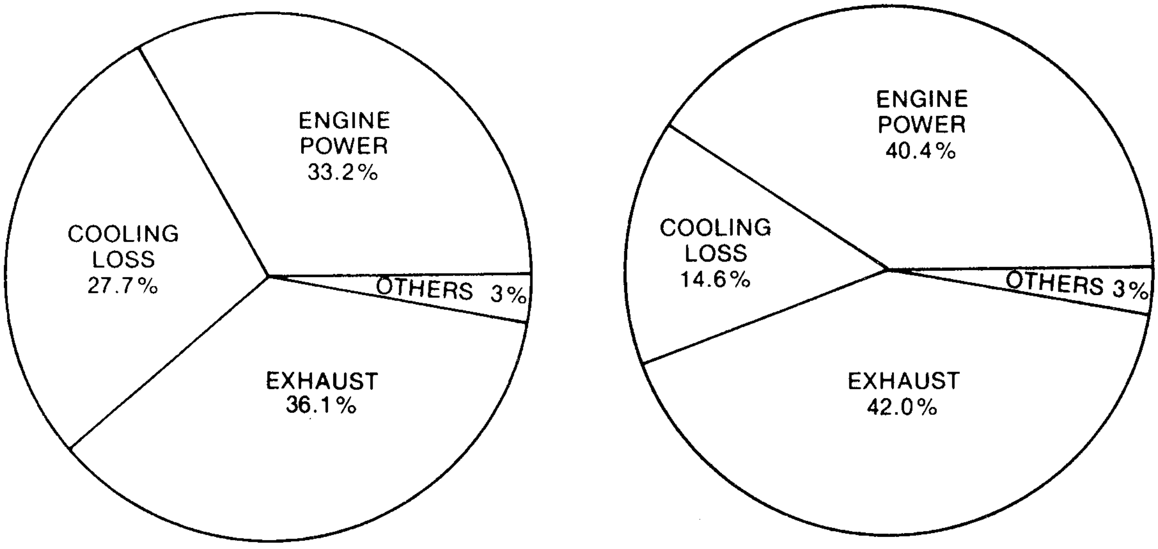
Engine power 16,030 + 3,465 = 19,495 kcal/min. = 40.4%
or 1360 kW
Cooling loss 2,140 + 4,940 = 7,080 kcal/min. = 14.6%
Exhaust loss 17,410 + 2,835 = 20,245 kcal/min. = 42.0%
Radiation 1,410 kcal/min. = 3.0%
Total 48,230 kcal/min.

Fuel flow is unchanged at 282 kg/hr

New BSFC $\frac{282}{1360}$ = .207 kg/kW-hr

Improvement factor $\frac{.207}{.252}$ = .821

Figure 3-29 shows the energy distribution with conventional cooling and a simulated AVCR-1360 adiabatic engine.



CONVENTIONAL AIR COOLING AVCR-1360

UNCOOLED CYLINDERS SIMULATED AVCR-1360

FIGURE 3-29 HEAT BALANCE COMPARISON

3. Compare to a conventional turbocharged 2-stroke cycle 8V-92T Detroit Deisel Allison engine:

   Minimum BSFC = .229 kg/kW-hr (published data)
   At rated power BSFC = .231 kg/kW-hr (published data)
   Applying the BSFC improvement factor yields .821 x .229 = .188 kg/kW-hr

4. This probably represents an overly optimistic number for a 2-stroke cycle engine. Therefore, a more conservative 15% improvement in BSFC over conventionally cooled engines or .85 x 229 = 194.6g/kW-hr at 65% power is projected.

5. Estimate of BSFC at take-off:

   Maximum power BSFC increase over minimum fuel consumption for several engines:

	ΔBSFC g/kW-hr
4-Stroke cycle VAT 1360	18.25 (data)
4-Stroke cycle Cummins LCR-V-903	12.17 (projection)
4-Stroke VAT 1790 low C.R.	12.17 (data)
2-Stroke Cycle GM 8V 92T	6.08 (data)
2-Stroke Cycle Napier Nomad	6.08 (data)

This led to the projection of a 206.8 g/kW-hr BSFC at take-off power.

The BSFC at 100% power cruise condition is expected to be higher than at take-off, 212.9 g/kW-hr, due to a lower air/fuel ratio.

These BSFC's refer to the engine only and do not include the combustor fuel flow.

3.3.12 Energy Balance Turbocharger — Take-Off

Turbine pressure ration $P_{rt} = 3.052$

Compressor pressure ratio $P_{rc} = 4.066$

Efficiencies:

	Adiabatic	**Polytropic**
Compressor	.78	.818
Turbine	.77	.744
Mechanical	.98	.98
Overall polytropic efficiency S =	.596	
$\sqrt{S} =$	.772	

1. Required turbine inlet temperature Tit follows from

$$P_{rt} = \left[1 - \frac{.875 \left(P_{rc}^{\frac{.286}{\sqrt{S}}} - 1 \right)}{\frac{T_{it}}{T_{ic}}} \right]^{\frac{-4}{\sqrt{S}}}$$

Compressor inlet temp. Tic = 273 + 15.5 = 288.5°K
Required Tit = 888.9°K

2. Available turbine temperature.

   The gas in the exhaust manifold is a mixture of exhaust gases and scavenge air.

   Exhaust gas conditions at exhaust port opening — See paragraph 3.3.9.

   $P_5 = 970$ kPa
   $T_5 = 937 + 273 = 1210°K$

   The gas expands to exhaust manifold pressure (309.5 kPa), resulting in a reduced temperature of 909.4°K.

   The scavenge air will heat up in the cylinder to 444.4°K.

   The mixing of exhaust gas and scavenge air results in a mixing temperature of 806.7°K.

3. The combustor must heat the gas from 806.7°K to 888.9°K in order to provide the turbine energy balance.

4. The resultant increases of the BSFC due to the combustor operation are:

   A. Take off BSFC = 18.2 g/kW-hr

   B. 100% power cruise BSFC = 6.1 g/kW-hr

   C. 65% power cruise BSFC = 0 g/kW-hr

5. Turbocharger parameters:

   A. Compressor:
   Wheel diameter 134.62 mm
   Speeds:

	Take-Off	100% Cruise Power	65% Cruise Power
Shaft RPM	70,052	88,906	83,630
Tip Speed m/sec	494	627	589

   B. Turbine:
   Wheel diameter 127.00 mm

3.3.13 Cooling Requirements

1. Aftercooler:

	Take-Off	100% Cruise Power	65% Cruise Power
Air Flow kg/sec	.614	.568	.364
Δt °C	80.5	116.6	70.0
Heat Rejection kcal/min	721	966	371

2. Oil Cooler:

Comparison with some existing engines of comparable specific power:

A. VHO — Caterpillar very high output 8-cylinder water-cooled diesel, 4-stroke cycle, 477 kW, oil-cooled pistons.

B. AVCR-1100 — Teledyne Continental Motors high output 12-cylinder, 4-stroke cycle, 932 kW, VCR pistons.

C. GTSIO-520 — 6-cylinder air-cooled gasoline engine, 324 kW, 4-stroke cycle.

D. TSIR-5190 — McCulloch, 5-cylinder liquid-cooled gasoline engine, 2-stroke cycle, 201 kW.

TABLE XIV
Comparative Oil Cooler Data

		Heat Rejection		Oil Flow		Spec. Flow		Δt
Engine	**kW**	**kcal/min**	**kcal/min-kW**	**ℓ/min**	**kg/min**	**ℓ/min-kW**	**kg/min·kW**	**°C**
VHO	477	806	1.69	208.2	172.1	.44	.36	8.5
AVCR	932	1714	1.84	280.1	231.6	.30	.25	13.4
GTSIO	324	413	1.27	46.6	38.5	.14	.12	19.5
TSIR	201	328	1.63	18.9	15.6	.09	.08	38.1

Weight of oil .827 kg/ℓ.

Spec. heat of oil .55 kcal/kg/°C.

Choice of Aircraft Diesel Oil Cooler Parameters:

A. Spec. heat rejection 1.35 kcal/min/kW which is:
- Lower than VHO — aircraft diesel has no piston cooling jets.
- Lower than AVCR — aircraft diesel has no VCR pistons.
- Higher than GTSIO — aircraft diesel is 2-stroke cycle.
- Higher than TSIR — aircraft diesel has no piston cooling.

Projected heat rejection 298 kW diesel
Q = 298 x 1.35 = 403 kcal/min.

B. Spec. flow rate .178 1/min/kW
- Lower than VHO — no oil required for piston cooling.
- Lower than VCR — no oil required for VCR pistons.
- Higher than GTSIO — aircraft diesel is 2-stroke cycle.
- Higher than TSIR — Δt of the TSIR is too high.

Projected oil flow rate 298 kW diesel
298 x .178 = 53 ℓ/min.

3. Fuel Injectors

Expected heat rejection per injector
25 kcal/min.

4. Cooling Requirements:

The total cooling requirements for the 3 modes of operation are shown in Table XV.

TABLE XV
Cooling Requirements

	Take-Off	100% Power Cruise	65% Power Cruise
Aftercooler kcal/min	721	966	371
Oil cooler kcal/min	403	403	262
Injectors kcal/min	150	150	98
Total kcal/min	1,274	1,519	731
Fuel flow kg/hr	67.1	65.3	37.8
	Heating value 10,250 kcal/kg		
Total energy kcal/min	11,463	11,155	6,458
% cooling of total energy	11.1	13.6	11.3

3.3.14 Anticipated Maximum Surface Temperatures of Engine Components

Crankcase	150°C (synthetic oil)
Aftercooler (peak)	230°C w/o insulation
Compressor housing	230°C w/o insulation
Turbine housing (will be radiation shielded)	595°C w/o insulation
Turbine housing	290°C with insulation
Exhaust manifolds	150°C with insulation
Combustor surface	150°C with insulation
Intake manifolds	95°C
Cylinders	150-175°C

3.3.15 Weight of the 298 kW Diesel

A detailed analysis indicates an expected weight of 207.5 kg. This is dry weight and includes all accessories except the filters.

The weight of a comparable gasoline aircraft engine, the GTSIO-520-H is 262.4 kg. Specific component weights are listed in Table XVI.

3.3.16 Initial Cost of the 298 kW Diesel

The method followed here assumes a certain cost per kg of material. See Table XVI.

TABLE XVI
298 kW
Initial Cost — Aircraft Diesel

Part	Reasoning	A Technology &/or Mat. Factor	B Weight kg	A x B Eval. No.
Prop Gear Housing		1.00	16.06	16.06
Crankshaft		1.00	10.41	10.41
Counterweights	Tungsten, high $/kg.	2.00	4.56	9.12
Prop Drive Gears		1.00	9.98	9.98
Crankcase Assy.		1.00	6.54	6.54
Accessory Housing		1.00	3.96	3.96
Accessory Drive Gears		1.00	4.00	4.00
Pistons	High technology	5.00	7.48	37.40
Connecting Rods	High material cost, partially offset by simplicity	1.50	5.62	8.43
Piston Rings	High technology	5.00	.69	3.47
Cylinder Assys.	Ceramic liner, otherwise simplified	2.00	34.90	69.79
Injection System	Closer tolerances	1.50	5.74	8.61
Intake System		1.00	9.49	9.49
Exhaust Manifold		1.00	12.11	12.11
Fuel Pump		1.00	1.16	1.16
Governor		1.00	.91	.91
Vacuum Pump		1.00	.91	.91
Oil Pumps		1.00	5.95	5.95
Starter/Generator (total package)		2.50	6.37	15.93
Oil Cooler		1.00	2.73	2.73
Aftercooler		1.00	4.55	4.55
Turbocharger	High performance	2.00	15.91	31.82
Balance Engine Parts		1.00	37.47	37.47
			207.50	310.85

Column A represents a technology and/or material factor which expresses the effect of advanced technology on component cost per kg when compared to current production costs.

Column B shows the calculated weights of components of the proposed engine. The third column then represents the cost ratio of advanced diesel and current technology components.

1. Weight Factor:

Weight diesel	207.5 kg
Weight gasoline engine	262.4 kg

Weight ratio $\frac{207.5}{262.4} = .791$

2. Overall engine technology and material factor:

$$\frac{\text{Total A x B}}{\text{Total B}} = \frac{310.85}{207.50} = 1.498$$

3. Overall cost ratio diesel vs. current gasoline engine:
   .791 x 1.498 = 1.185

3.3.17 Emissions

Emissions were not quantitatively addressed, however, the following qualitative statements are valid:

1. Hydrocarbons and carbon monoxide will be oxidized by the use of a catalytic converter.
2. NO_x concentration will be minimized due to the relatively low peak pressures (9,650 kPa) and lower peak temperatures.
3. Smoke levels should be relatively low since the minimum trapped A/F ratio will be on the order of 24:1.

3.3.18 Noise

As with emissions only, qualitative evaluations were made of the anticipated engine noise as listed below: (propeller noise is covered elsewhere in this report)

1. The catalytic combustor and insulated exhaust stacks in series with the turbocharger should minimize direct combustion noise.
2. The absence of cylinder cooling fins should reduce externally generated vibratory noise.
3. The absence of valves, rocker arms, push rods, and camshaft should minimize internally generated mechanical noise.
4. The geared drive will allow a relatively low propeller speed, thereby reducing prop generated noise.
5. Two-stroke cycle operation, however, tends to offset some of the gains noted above.

3.3.19 Risk Areas Associated With the Selected Design

Following are the areas where existing technologies need to be advanced to make such an engine feasible:

1. Piston rings — operating in uncooled cylinders.
2. Cylinders — ceramic components and their interface with metallic hardware.
3. Turbo starter/alternator operating at high speeds.
4. Catalytic combustor and its associated controls.
5. Cooling of the cylinder exhaust ports.
6. Piston lubrication.
7. Spherical connecting rod end.

Development programs in all these areas are in progress at NASA and TARADCOM (Army).

3.3.20 Proposed Development Program for the 298 kW Diesel Engine

Should the development of such an engine be undertaken, a detailed development program would be recommended based on the following problem areas:

1. **Two-Cycle Performance Demonstration.**
   A. Design and procurement of hardware.
   B. Flow modeling.
      a. Port configuration
      b. Scavenge ratios
      c. Timing variations (ports)
      d. Air utilization
      Note: This activity may be deleted. Cost/benefit evaluation in process.
   C. Combustion development (SCTE) — standard cooled cylinder.
      a. Piston configurations
      b. Injection characteristics
         - Spray patterns
         - Timing optimization
         - Emissions
         - Smoke
         - BSFC

2. Adiabatic (uncooled) Operation

A. Materials evaluations and selection.

  a. Ceramic piston

  b. Ceramic cylinder liner

  c. Piston ring materials

  d. Solid lubricants

B. Design and procurement of hardware.

C. SCTE demonstration.

  a. Integrity of ceramic components

  b. Demonstration of adequate piston ring sealing and life

  c. Port cooling

  d. Piston lubrication

  e. Injection nozzle cooling

  f. Performance
    - BSFC
    - Emissions
    - Smoke
    - Oil consumption

3. Turbocharger Development

A. Design and procurement of hardware.

B. Compressor bench test.

  a. Operation at
    - High specific speed
    - High pressure ratios
    - High flow factors

  b. Variable diffuser (if necessary)

  c. Maximized efficiencies

C. Turbine bench test.

  a. Operation at
    - Variable turbine back pressure (altitude)
    - High tip speeds (640 m/sec)
    - TIT 815°C
    - Very high efficiencies

  b. Pulse recovery versus steady flow turbine housings

D. Bench test of complete turbocharger.

E. Combustor bench test.

  a. Efficiencies

  b. Emission control (catalyst)

  c. Reliability

  d. Life

  e. Controls

  f. Effect on pulse recovery

4. Support Hardware

A. Design and procurement of hardware.

B. Test of

  a. High speed starter/alternator

  b. Bleed air starting system

  c. Composite rods

  d. Injection equipment

  e. Synthetic and solid lubricants

  f. Catalyst ignition system

  g. Electronic controls for
    - Combustor operation
    - Injection control
    - Prop control interface

  h. Aftercooler

  i. Oil cooler

  j. High speed gear train

5. **Multi-Cylinder Demonstration**
   - A. Design and procurement of hardware
   - B. Performance and system integration
     - a. Scavenge characteristics
     - b. Startability (cold and hot)
     - c. BSFC
     - d. Emissions
     - e. Reliability
     - f. Altitude operation
   - C. Demonstrate design integrity
     - a. Assembly
     - b. Torsional characteristics
     - c. Structural integrity
   - D. FAA type testing
     - a. Safety
     - b. Durability
     - c. Reliability

This type of program could possibly be completed in a 5-6 year time frame and result in a flyable demonstrator engine.

3.3.21 Alternate Technologies

Failure to attain all targets of the development program would not mean a failure of the whole program. The alternate technologies, although less ambitious, will still result in a diesel powerplant which is superior to existing aircraft engines. Some of the alternate solutions are outlined below:

1. Uncooled cylinders:

   Alternate: Apply limited cooling to avoid need for ceramics.

   The penalties are:

   - A. Increased fuel consumption (still much lower than gasoline engines).
   - B. Increased cooling drag.

2. High speed alternator:

   Alternate: Drive the alternator off the engine.

   The penalties are:

   A. A larger, heavier alternator.

   B. Separate, declutchable turbostarter required.

3. Catalytic combustor:

   Alternate: Conventional combustor and ignitor.

   The penalties are:

   A. The ignitor must remain turned on whenever the combustor is operating.

   B. Emissions level of the engine might be higher.

3.3.22 Comparison of the 298 kW Aircraft Diesel and a Comparable Current Gasoline Engine.

A comparison is made with the 4-stroke cycle GTSIO-520-H gasoline engine.

Table XVII shows this comparison in a tabular form.

Figure 3-30 is a size comparison. The frontal area of the diesel engine is 78% of that of a compatable gasoline engine.

TABLE XVII
Comparison of GTSIO-520-H Gasoline and GTDR-290 Aircraft Diesel Engine

	4-Stroke Cycle GTSIO-520-H Gasoline Engine	2-Stroke Cycle GTDR-290 Diesel Engine
Configuration	6 cyl. opposed	6 cyl. radial
Displacement ℓ	8.52	4.71
Take-off RPM	3400	3500
Rated max. take-off power kW	280	298
Rated max. for cruising kW	210	298
Prop speed at take-off RPM	2278	2345
BSFC g/kW-hr:		
Take-off	425.8	225.1
100% power cruise	—	219.0
65% power cruise	273.7	194.6
Dimensions:		
Length mm	1429	1105
Width mm	865	632
Height mm	663	660
Engine weight dry, kg	262.4	207.5

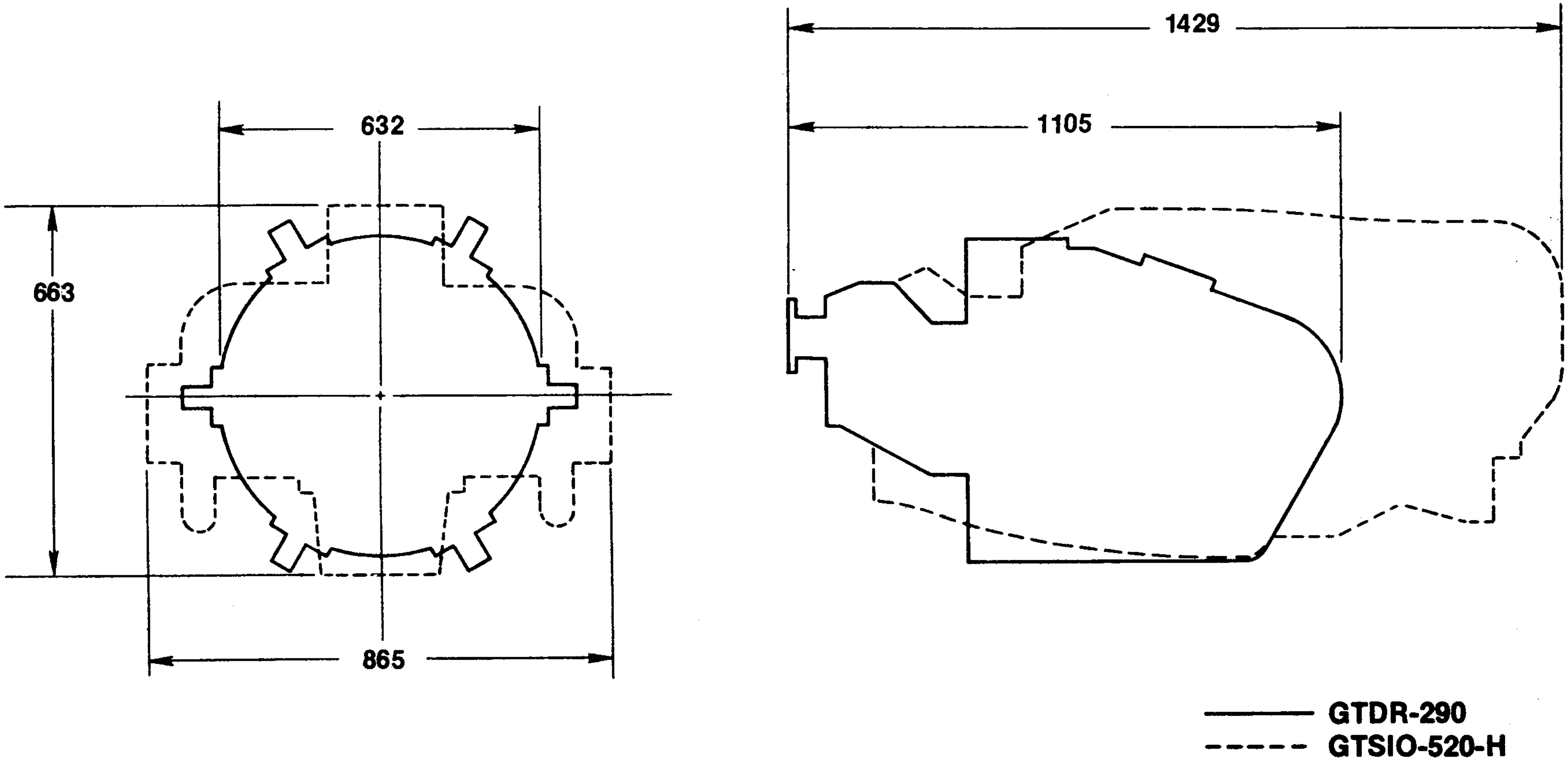


FIGURE 3-30 SIZE COMPARISON GTSIO-520-H AND GTDR-290 AIRCRAFT DIESEL ENGINE

3.4 The 149 kW 4-Cylinder Engine

1. Different design philosophy was applied to the 149 kW engine:

   A. To find out how other technologies will affect the configuration and performance of a diesel aircraft engine.

   B. To avoid the 149 kW concept from being a scaled down version of the larger powerplant. Chances are that at the conclusion of the development program only one type of configuration will emerge, differing only in size and adaptation details from one engine to another.

   C. The technologies applied to the 149 kW engine are not as far advanced as in the case of the 298 kW engine. The 149 kW engine will primarily serve the private owner market where initial cost and ease of maintenance carry more weight than in the case of the corporate aircraft.

   D. The engine will be easier to develop and manufacture.

Figure 3-31 shows an artist rendering of the proposed engine.

Figure 3-32 shows the schematic of the engine.

3.4.1 Technologies Applied to the 149 kW Engine

The following features are incorporated in the 149 kW design concept:

1. Radial configuration.
2. Two-stroke cycle Curtis loop scavenging.
3. Minimum cylinder cooling — reduced fin area.
4. Variable compression ratio pistons (VCR).
5. Mechanically driven centrifugal blower, declutched when not needed.
6. Glow plug starting aid in cylinders.
7. Conventional starter and alternator.
8. Conventional exhaust system (no combustor).
9. Direct propeller drive.

3.4.2 Minimum Cylinder Cooling

Calculations of the heat transfer through cylinder walls and confirmed by tests at TCM/GPD show that the heat flux is highest through the cylinder walls which surround the combustion chamber (when the piston is in top dead center). The maximum gas temperature to which the cylinder wall locally is exposed drops off fast as the piston travels downward, resulting in a lower local average cycle gas temperature and, therefore, a reduced heat flux. It can be safely said that all cooling fins below the piston ring belt (piston in TDC) can be eliminated without an appreciable effect on cylinder wall, piston and piston ring temperatures.

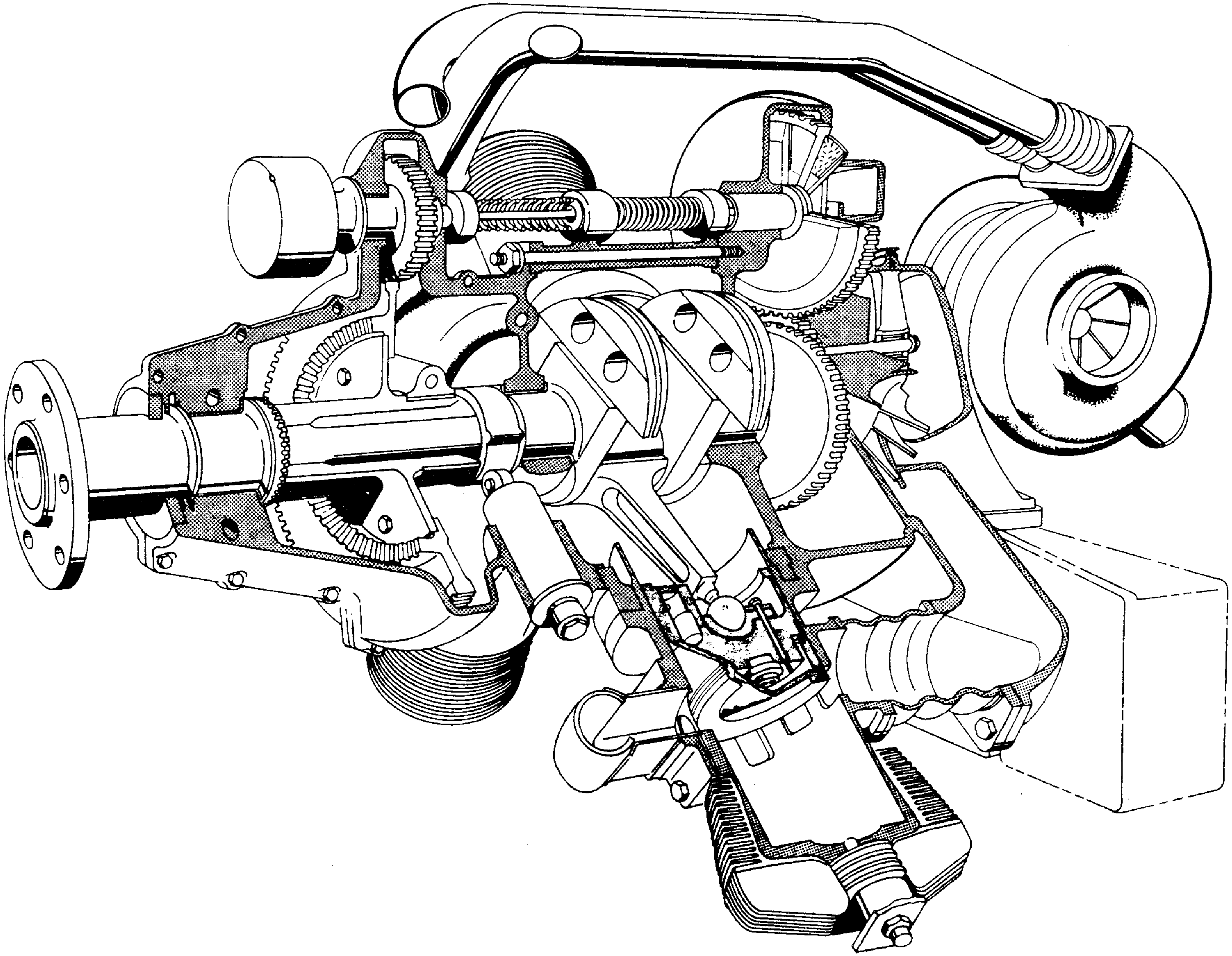


FIGURE 3-31 149 kW, 4-CYLINDER DIESEL AIRCRAFT ENGINE

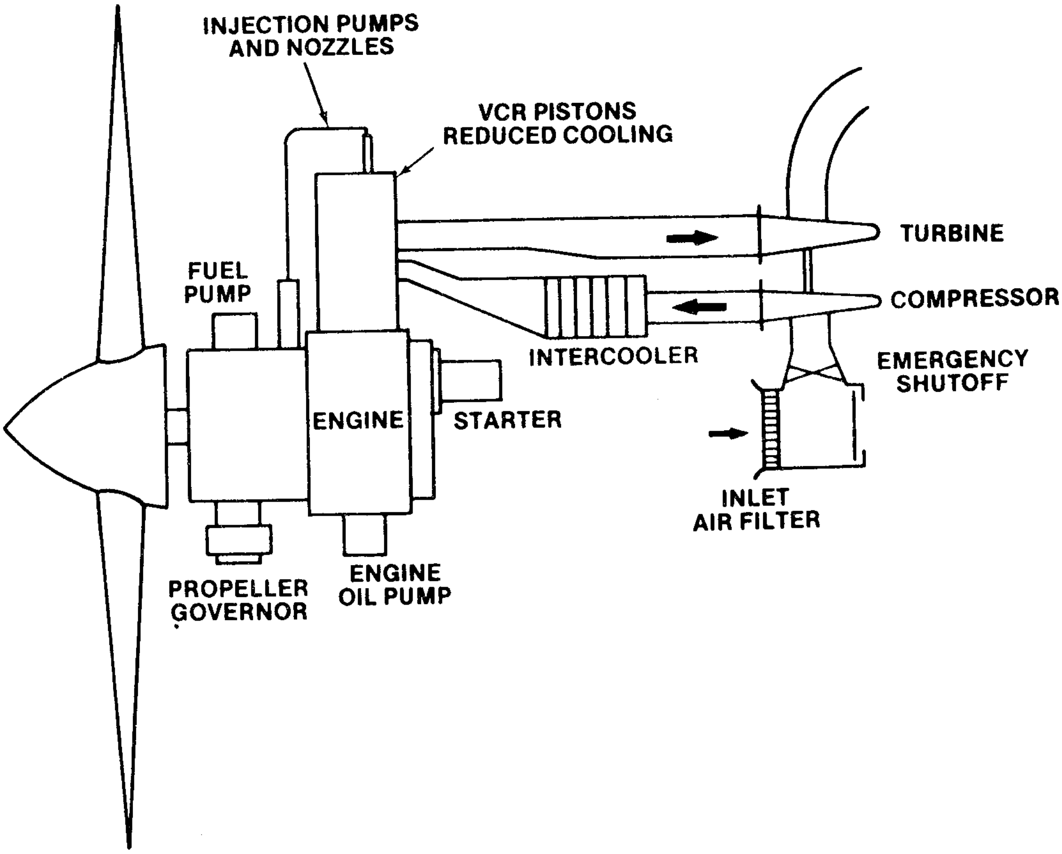


FIGURE 3-32 SCHEMATIC 2-STROKE TURBOCHARGED ENGINE REDUCED COOLED/VCR PISTONS

This approach results in an increase of cooling drag when compared to uncooled cylinders but eliminates the need for ceramic components as was recommended for the 298 kW engine.

3.4.3 Variable Compression Ratio Pistons

To keep firing pressures down to 9,650 kPa it is necessary to reduce the compression ratio under load to 10:1. However, the engine cannot be started or run idle at such a low compression ratio. In the case of the 298 kW engine, this was solved by means of the independent turbocharger loop which provides intake air of sufficient pressure and temperature to start the engine and the catalytic combustor which keeps the turbocharger at a high speed during engine idle operation. That is not the case here, therefore for this case a variable compression ratio piston is recommended.

The VCR piston—Figure 3-33, varies the compression ratio from 17:1 at start and low load to 10:1 at full load. This high C.R. is sufficient under normal ambient conditions to start the engine.

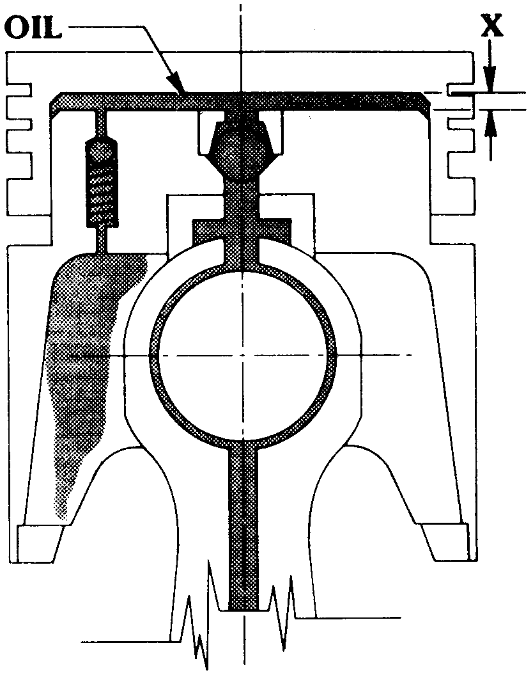


FIGURE 3-33 VARIABLE COMPRESSION RATIO PISTON

3.4.4 Mechanically Driven Centrifugal Blower

Scavenging of a 2-stroke cycle cylinder requires that the intake manifold pressure exceeds the exhaust manifold pressure at any load and engine speed. The turbocharger, however, produces a negative Δp at low load. This is no problem for 4-stroke cycle engines where the piston does the scavenging. The 2-stroke cycle engine without a combustor requires an engine driven blower to produce a positive Δp across the cylinders at low loads. The blower will be disconnected at the load point where the turbocharger provides a positive Δp.

3.4.5 Glow Plug Starting Aid in Cylinders

Even the 17:1 compression ratio does not provide a sufficiently high compression temperature to ignite the fuel at very low ambient temperatures. Operation of the glow plug may be required to assure good startability. It is also intended that glow plug operation would automatically be in effect at low throttle settings. This would be an added safety feature to assure absolutely no misfiring during descent mode operation.

3.4.6 Direct Propeller Drive

1. It became obvious early in the design phase of the 149 kW engine that a direct drive would result in a smaller engine package and a weight reduction.

2. The engine reliability is improved by this approach due to fewer parts.

3.4.7 Initial Performance Parameters

The chosem BMEP of approximately 1200 kPa is 100 kPa higher than the BMEP of the 298 kW engine. The much lower crankshaft speed dictated by the direct propeller drive will result in better scavenging and, hence, a larger amount of air trapped in the cylinders. We should, therefore, be able to obtain a higher BMEP without an increase of cylinder temperatures. The detailed cycle calculations (temp. T_4 of the p-V diagrams) bear this out. A stroke/bore ratio = 1 was chosen.

The engine characteristics become:

Number of cylinders	4
Take-off power	149 kW
Engine speed at T.O.	2400 RPM
BMEP	1187 kPa
Displacement	3.14 liter
Cylinder bore	100 mm
Stroke	100 mm
Piston speed	8.00 m/sec
Propeller drive	Direct

The piston speed is very comfortable and will result in long piston ring life.

3.4.8 Engine Concept Design

The engine concept design is shown in the Figures 3-34 through 3-38. The cylinders are arranged in one bank of four cylinders. The rotating and reciprocating inertias are 100% balanced. The cylinders have a limited number of cooling fins to cool the combustion chamber. The necessity for a gear driven blower at the back side of the engine made it more practical to have the cylinder intake port at the back side and the exhaust manifolds at the front. The exhaust manifolds will be insulated to avoid radiation to the injection pumps. Two exhaust manifolds are required to avoid pulse interference between cylinders. The connecting rods are executed as slipper rods. The big ends of the rods are wider than in the case of the 298 kW engine to compensate for the reduced circumferential contact length.

The use of synthetic oil is not contemplated because of lower cylinder temperatures but may be feasible to extend the periods between oil changes. Four individual injection pumps are provided driven off a single lobe cam ring. The centrifugal blower is driven off the propeller shaft through a lay shaft which is located above the crankcase between the cylinders #1 and #4. This arrangement was chosen rather than a drive from the rear end to avoid torsional problems. The nodal point lies close to the largest inertia member of the crankshaft system, that is the propeller. Putting the blower drive gear near this point reduces the input of torsional amplitudes into the blower drive. The lay shaft, which is a quill shaft, further isolates the blower from the crankshaft vibrations. However, this feature also necessitates a direct propeller drive. To put a propeller reduction gearing in front of the blower drive would have led to an unacceptable length of the engine. A weight analysis for this particular engine showed that the direct drive with the inherent larger piston displacement results in a lighter engine than the indirect drive.

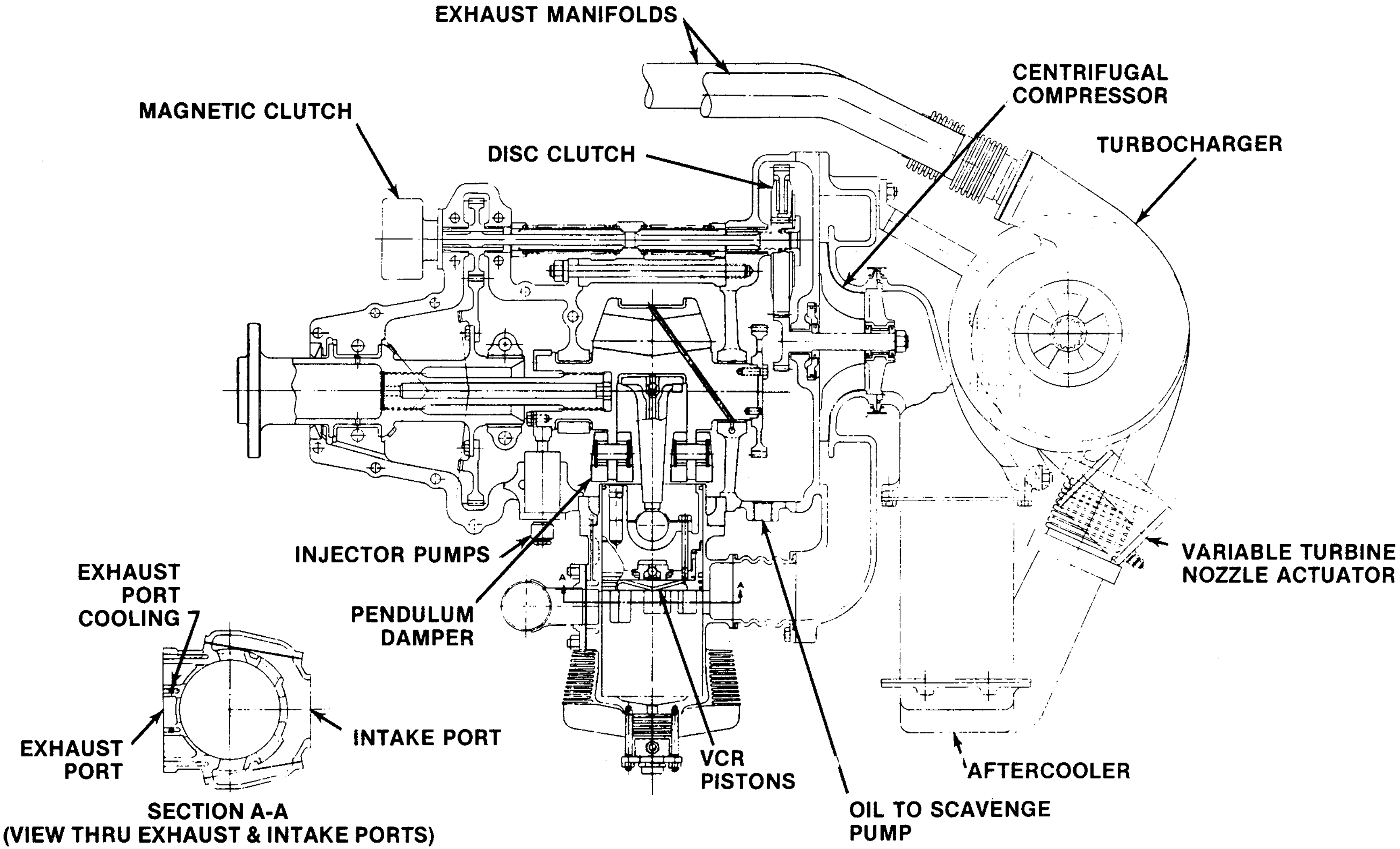


FIGURE 3-34 149 kW AIRCRAFT DIESEL—LONGITUDINAL SECTION

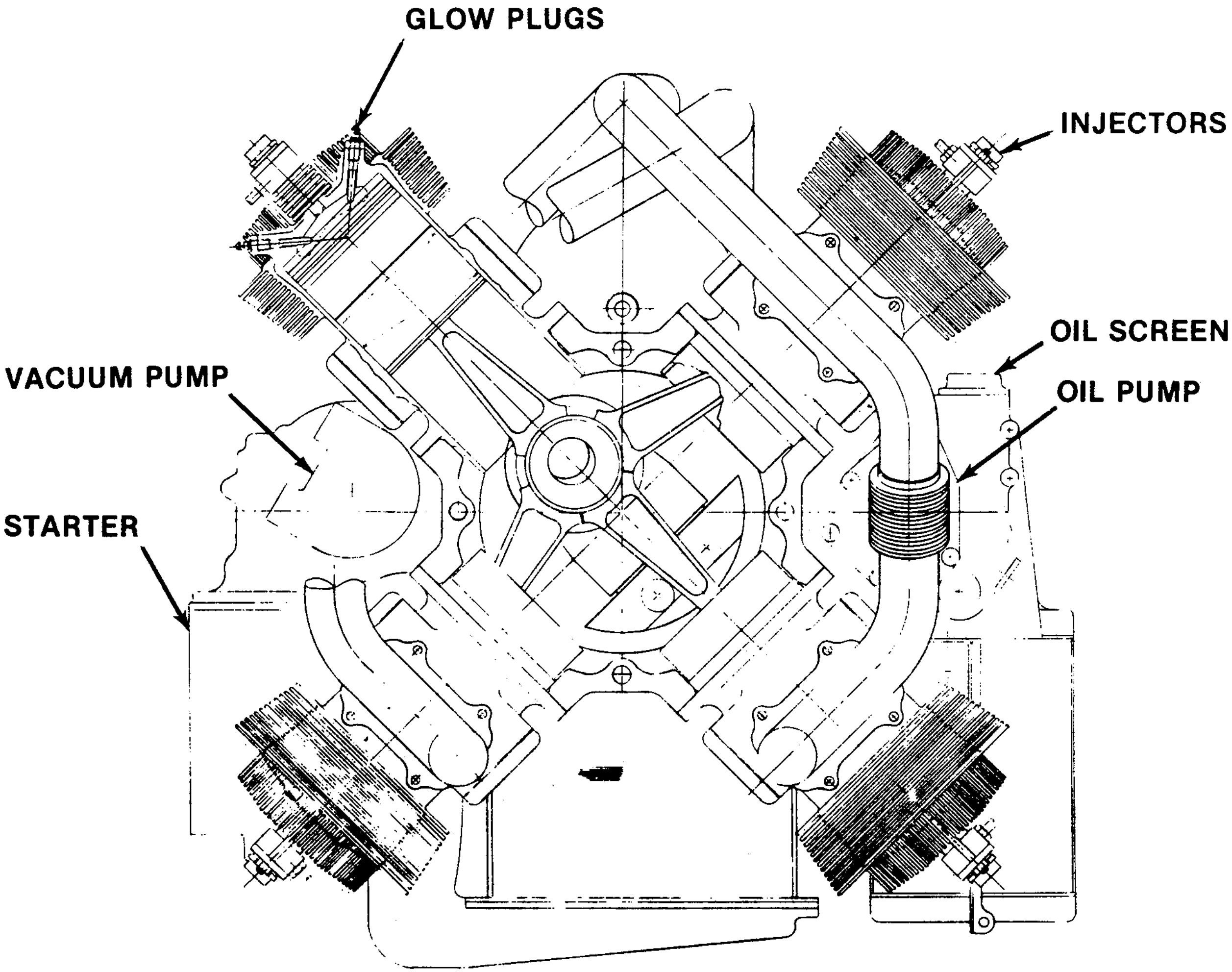


FIGURE 3-35 149 kW AIRCRAFT DIESEL—CROSS SECTION

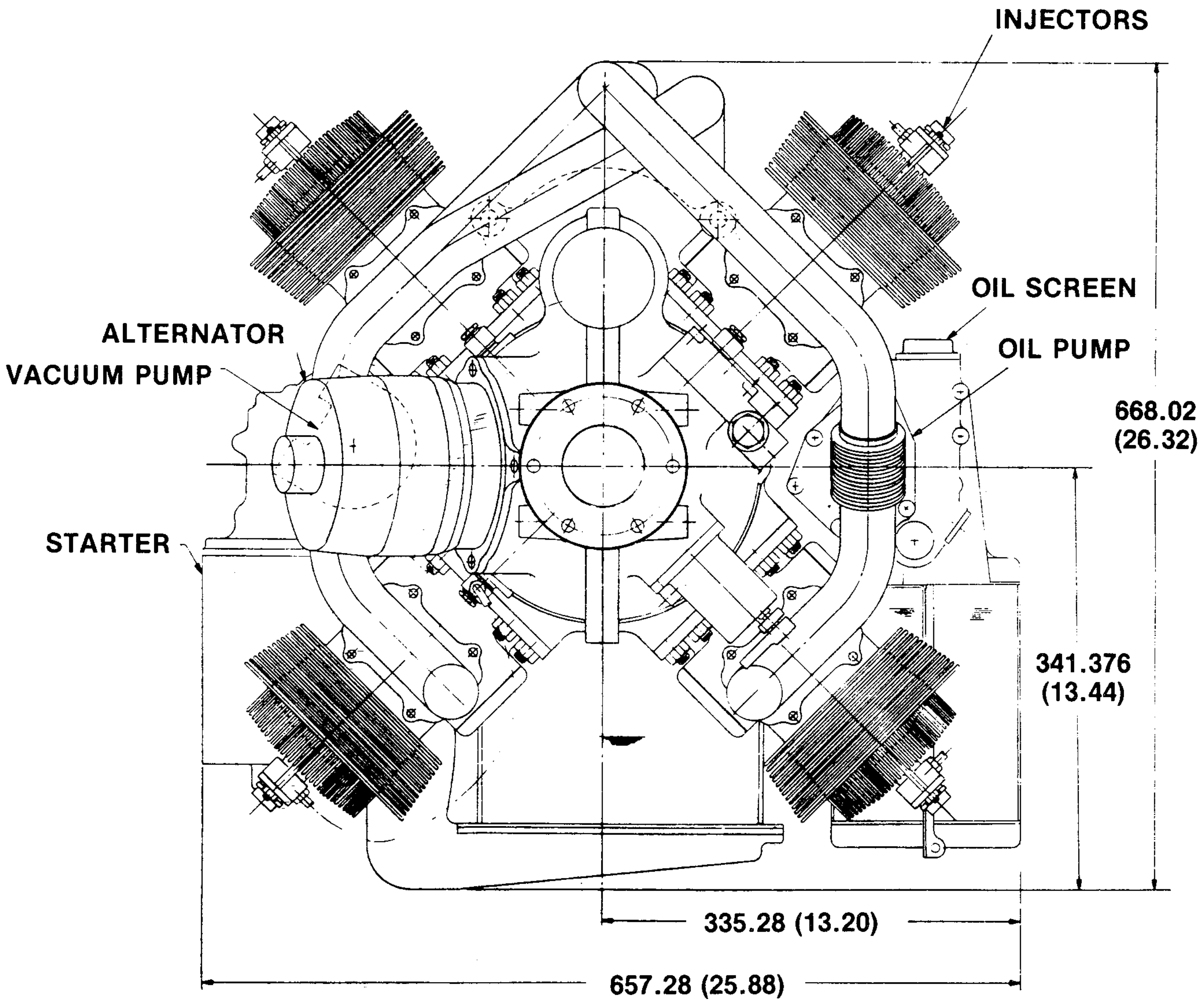


FIGURE 3-36 149 kW AIRCRAFT DIESEL—FRONT VIEW

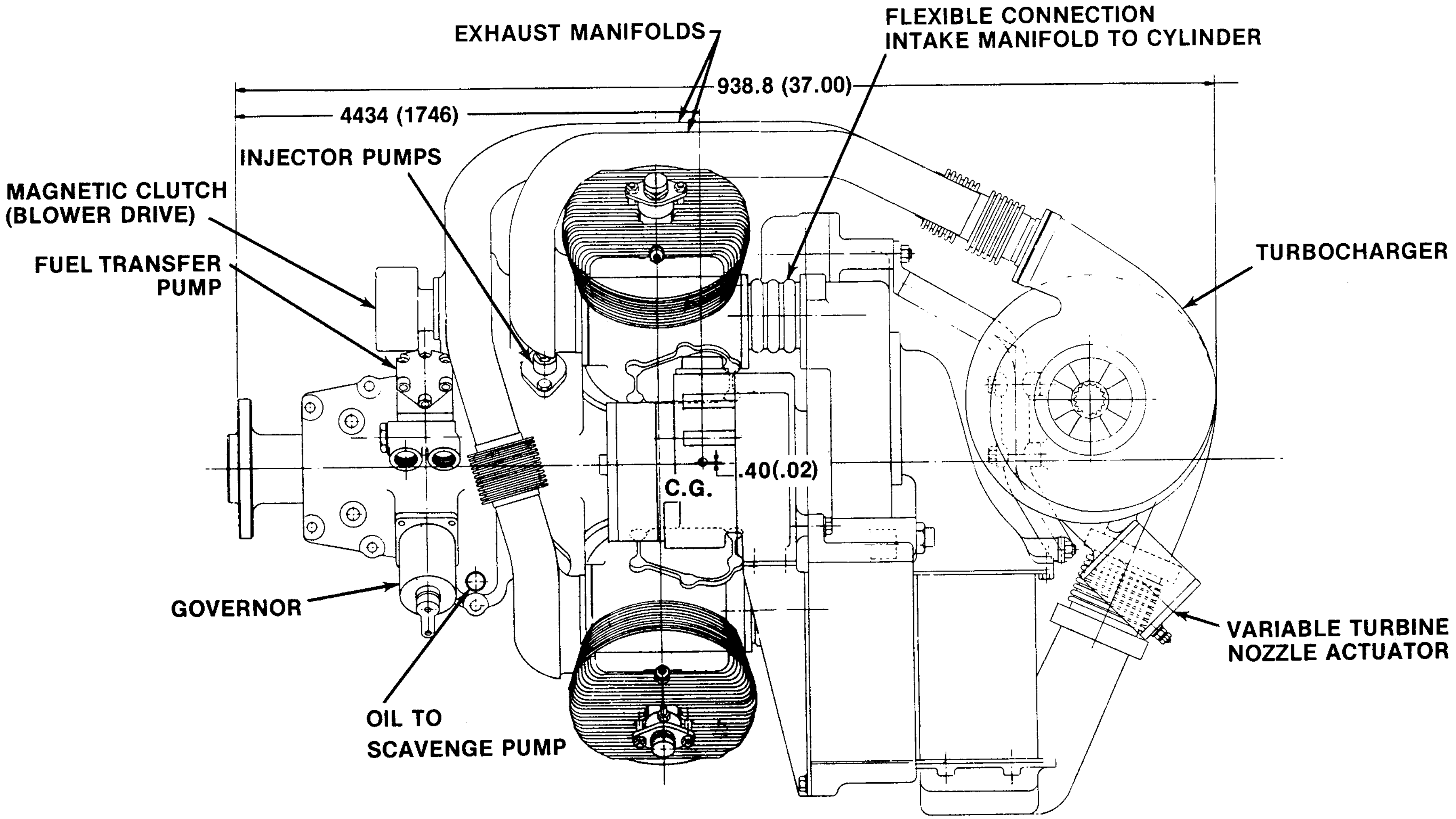


FIGURE 3-37 149 kW AIRCRAFT DIESEL—SIDE VIEW

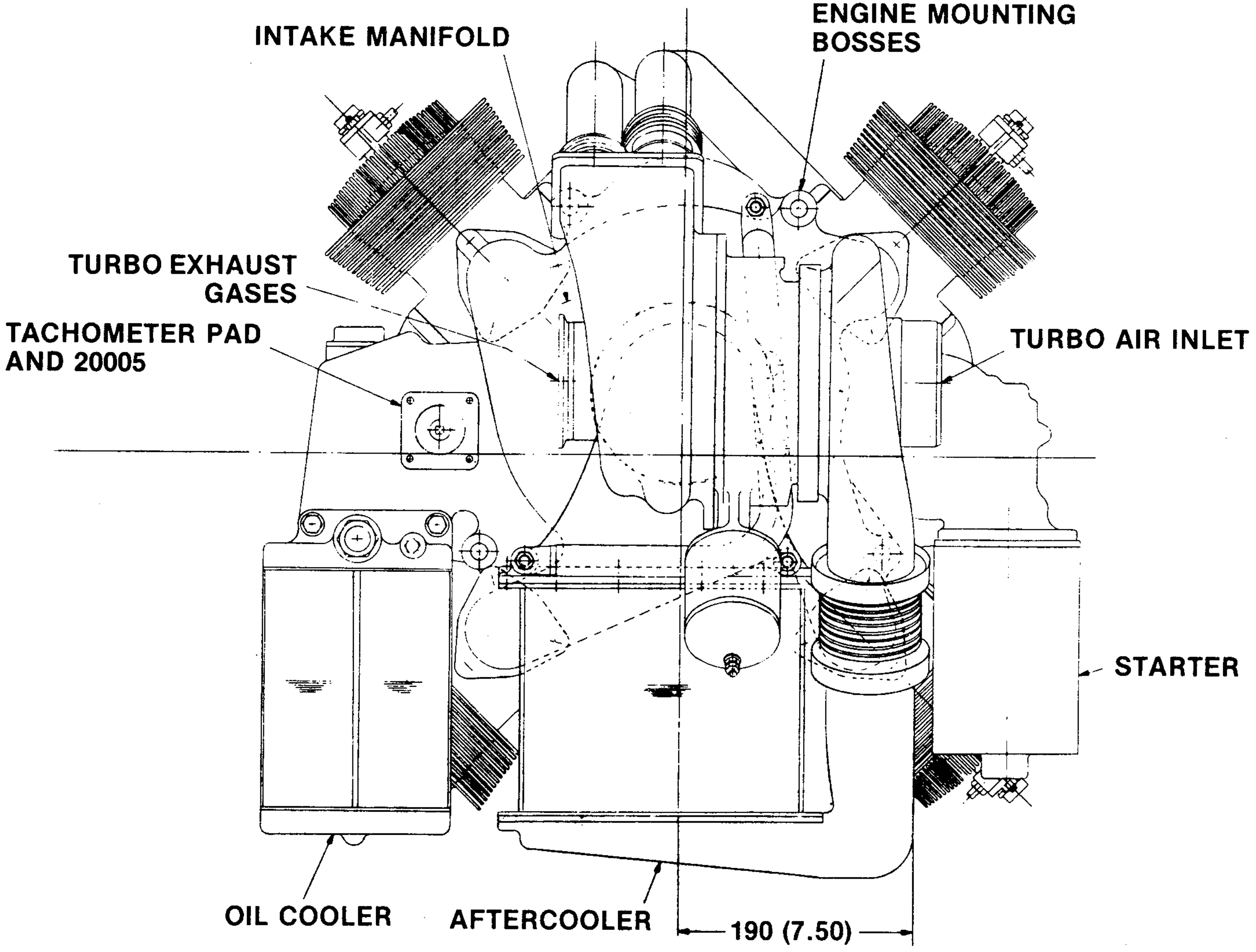


FIGURE 3-38 149 kW AIRCRAFT DIESEL—REAR VIEW

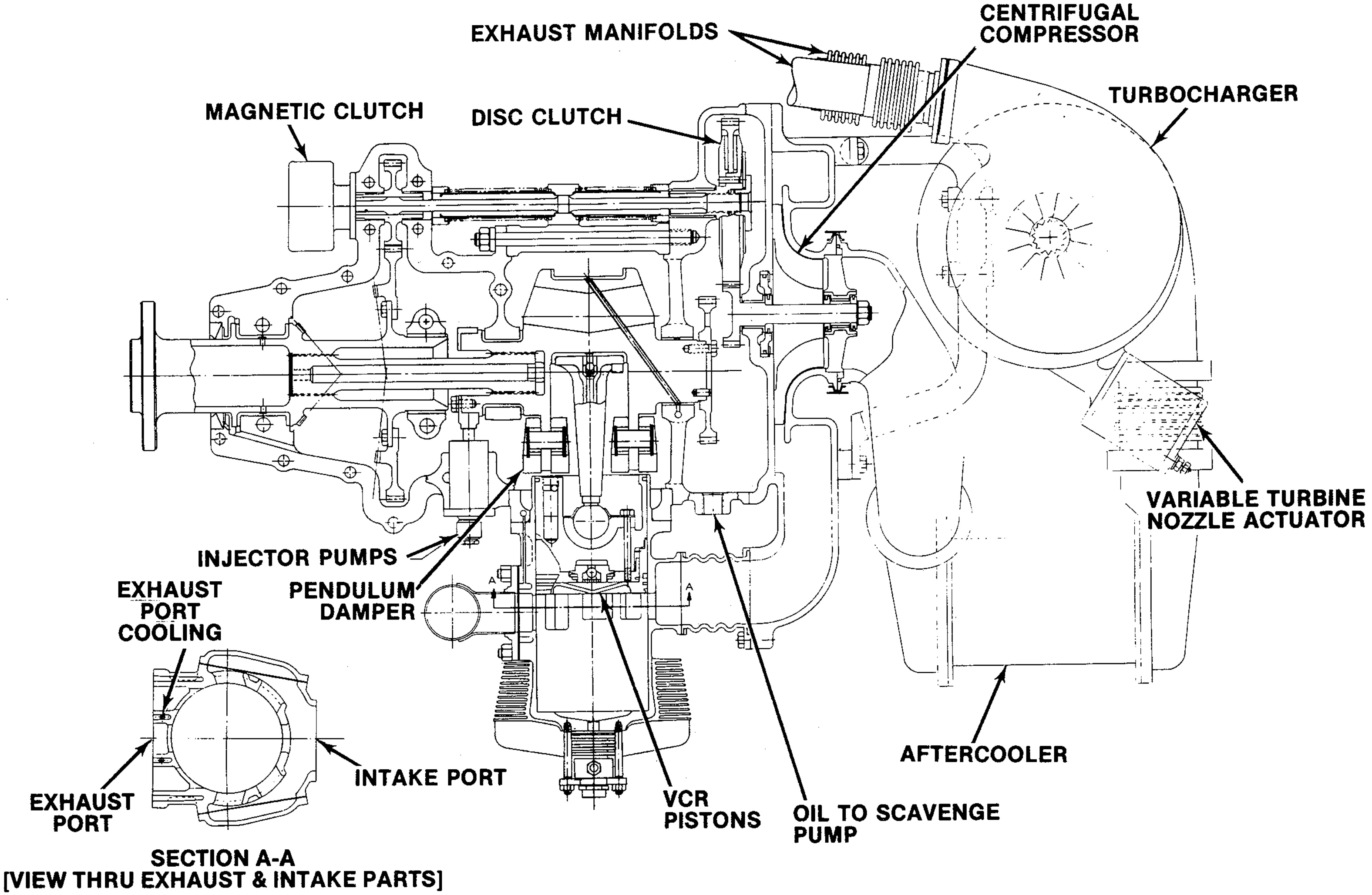


FIGURE 3-39 149 kW AIRCRAFT DIESEL—LONGITUDINAL SECTION

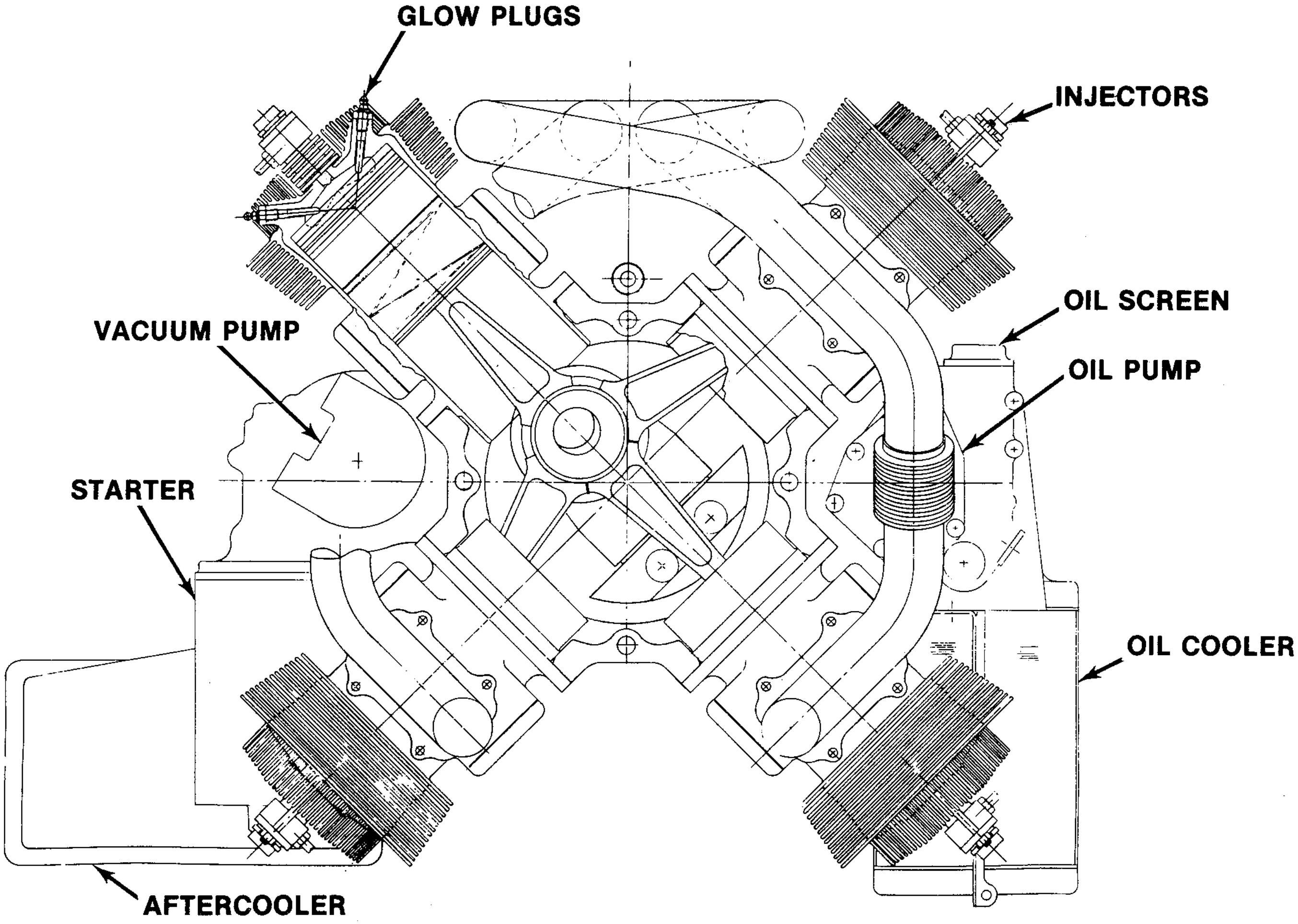


FIGURE 3-40 149 kW AIRCRAFT DIESEL—CROSS SECTION

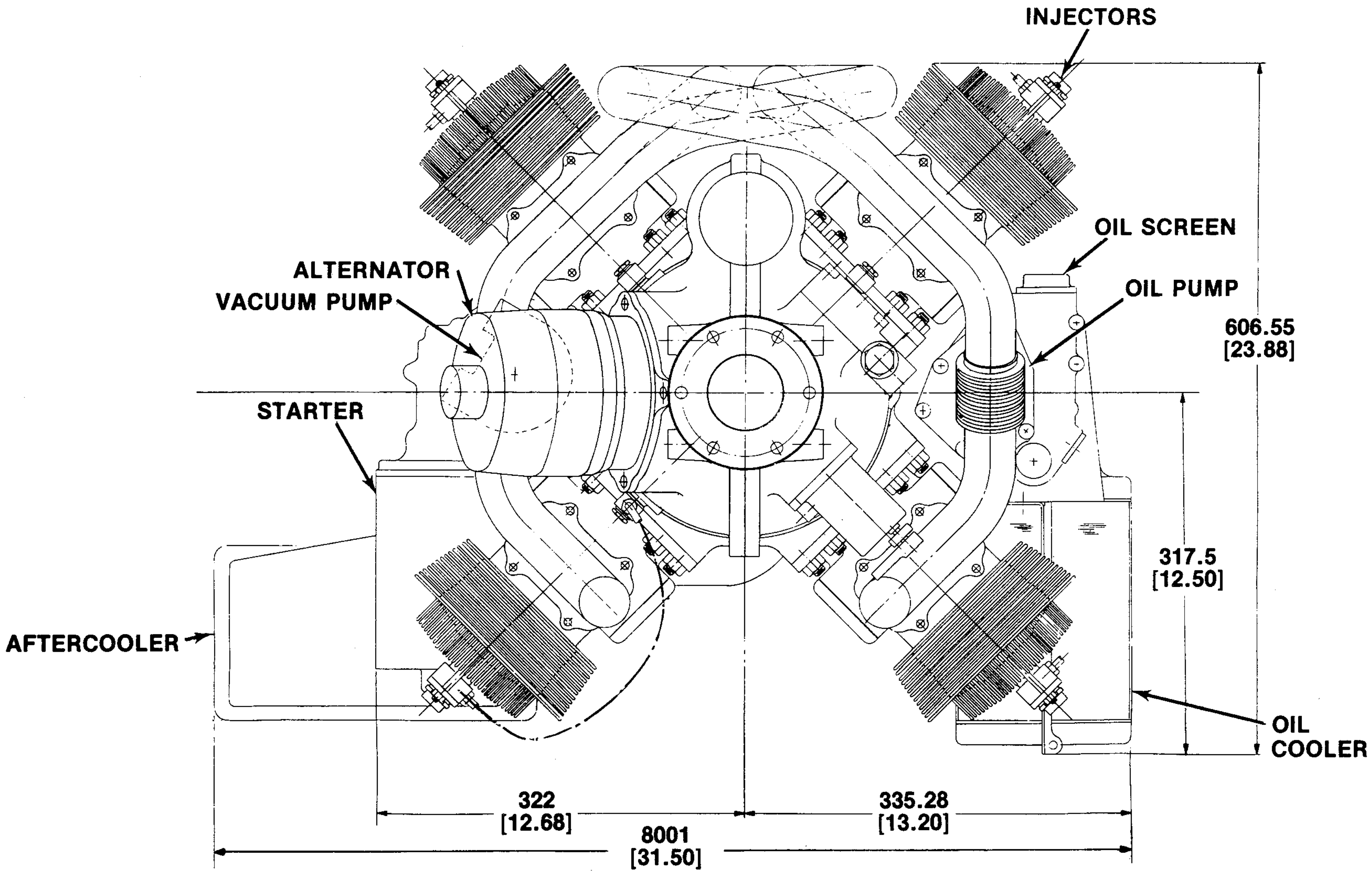


FIGURE 3-41 149kW AIRCRAFT DIESEL—FRONT VIEW

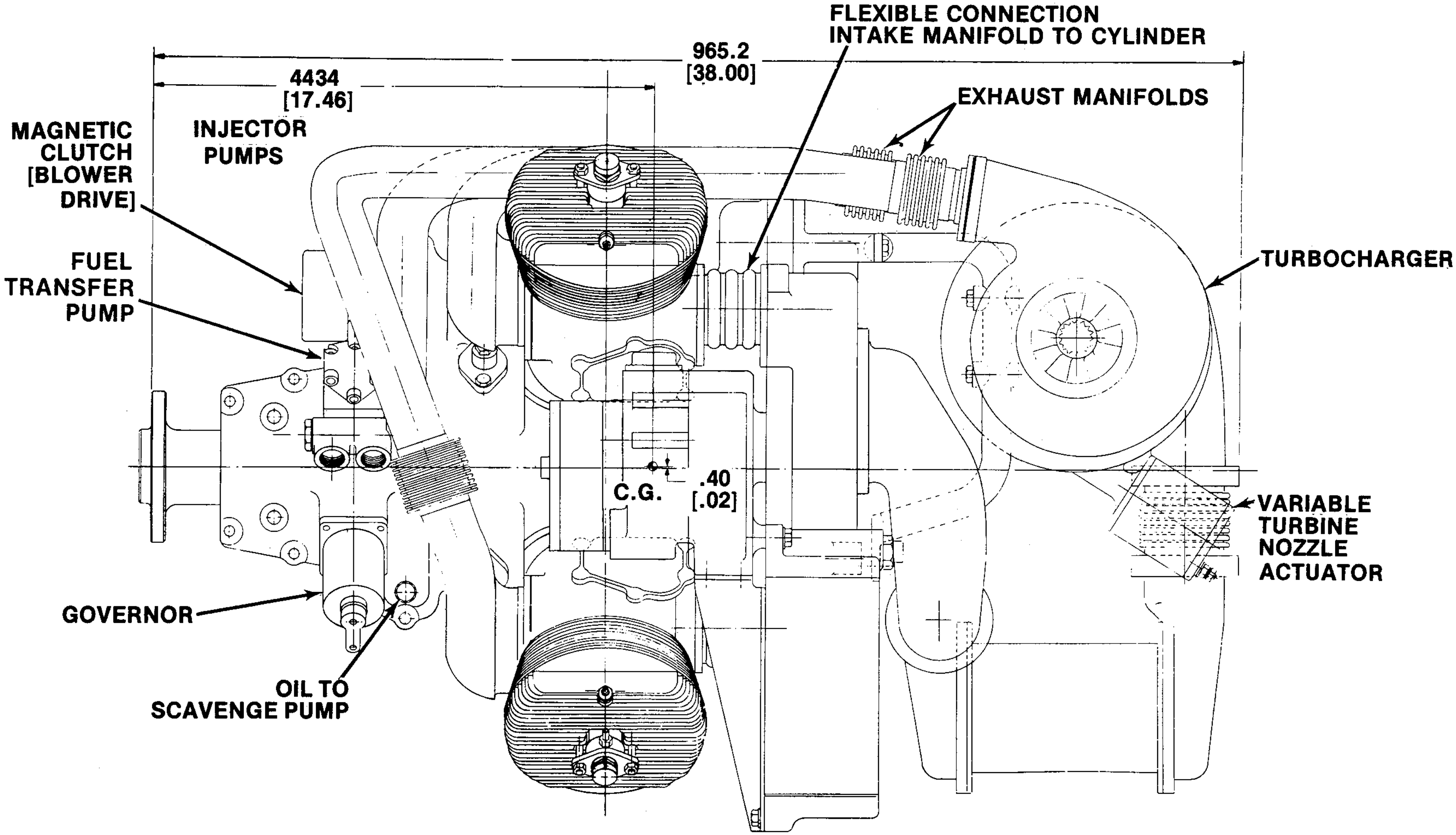


FIGURE 3-42 149 kW AIRCRAFT DIESEL—SIDE VIEW

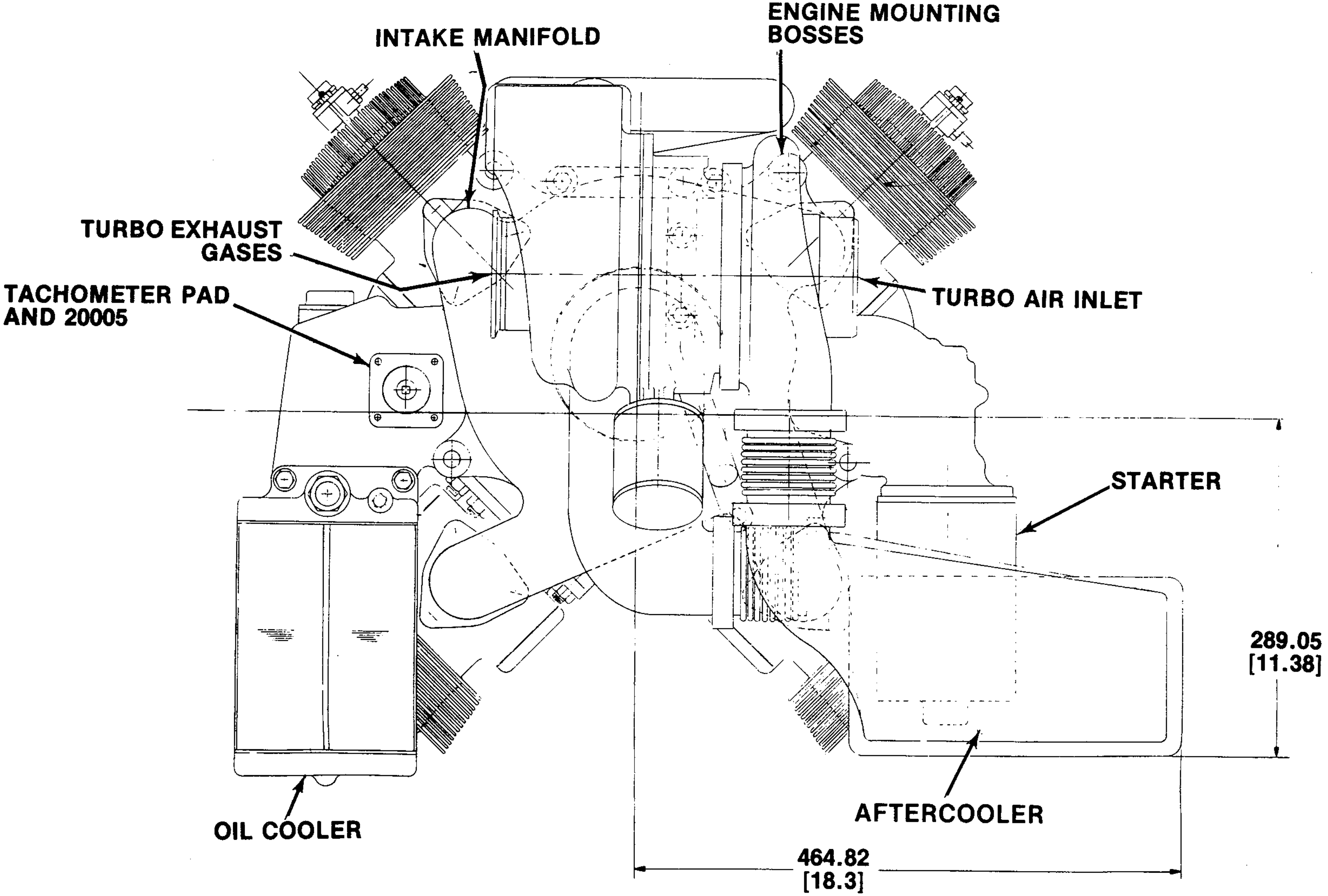


FIGURE 3-43 149 kW AIRCRAFT DIESEL—REAR VIEW

The blower drive is provided with two clutches. One, the magnetic clutch, disengages the blower drive once the turbocharger has come up to speed. The location of the magnetic clutch is such that as much of blower drive as possible is disengaged to prevent unnecessary drag on the engine. A disc type slip clutch is provided to prevent large torsional amplitudes as they occur at low engine speeds due to cyclic irregularity from reaching the blower. The turbocharger is mounted behind the engine as are the oil cooler and the aftercooler.

A second version of the engine was drawn, Figures 3-39 through 3-43, which accommodates a retractable nose gear. The coolers are moved outboard and the turbocharger is raised to provide space between Cylinders #2 and #3 for the nose gear strut. The increased width of the engine is no problem since it occurs near the fire wall where the width of the fuselage is determined by the side-by-side cabin seating arrangement.

3.4.9 149 kW Engine Operating Data

The following operating parameters have been calculated for the 149 kW engine:

TABLE XVIII
Engine Operating Parameters

	Take-off	100% Power Cruise	65% Power Cruise	
Altitude	0	3,048	3,048	meters
Power	149	149	97	kW
RPM	2400	2400	1800	
Displacement	3.14	3.14	3.14	liters
Bore x Stroke	100 x 100	100 x 100	100 x 100	mm
BMEP	1,187	1,187	1,029	kPa
Compressor Pressure Ratio	4.16:1	6.10:1	4.13:1	
Compression Ratio	Variable	Variable	Variable	
Max. C.R.	17:1 (effective)			
Min. C.R.	10:1 (effective)			
Barometric Pressure	101.4	69.6	69.6	kPa
Ambient Temperature	15.5	−5	−5	°C
Intake Manifold Pressure	411.8	411.8	280.9	kPa
Intake Manifold temperature	116	116	116	°C
Exhaust Manifold Pressure	316.8	316.8	255.4	kPa
Scavenge System	Curtis Loop	Curtis Loop	Curtis Loop	
Scavenge Ratio	1.3	1.3	1.3	
Ratio Boost/Backpressure	1.3	1.3	1.1	
Height Intake Ports	20.13	20.13	20.13	mm
Height Exhaust Ports	27.15	27.15	27.15	mm
Intake Ports Open/Close	± 61°	± 61°	± 61°	BBDC/ABDC
Exhaust Ports Open/Close	± 71°	± 71°	± 71°	BBDC/ABDC
BSFC	222.0	228.1	209.8	g/kW-hr.
Fuel Flow	33.1	34.0	20.3	kg/hr.
Air/Fuel Ratio	26.6	26.0	24.0	

3.4.10 P-V Diagrams

Following are calculated air cycle performance data for the proposed 149 kW engine. Figure 3-21 illustrates the points calculated on the P-V diagram.

Compression $pV^{1.37} = C$

Expansion $pV^{1.285} = C$

TABLE XIX
Air Cycle Performance

	Take-off	100% Power Cruise	65% Power Cruise	
P_1	364	364	268	kPa
V_1	.637	.637	.623	liter
T_1	149	149	138	°C
P_2	8,540	8,540	8,540	kPa
V_2	.064	.064	.050	liter
T_2	717	717	773	°C
P_3	9,650	9,650	9.650	kPa
V_3	.064	.064	.050	liter
T_3	846	846	911	°C
P_4	9,650	9,650	9,650	kPa
V_4	.118	.120	.095	liter
T_4	1,803	1,829	1,975	°C
P_5	1,110	1,120	830	kPa
V_5	.637	.637	.623	liter
T_5	1,012	1,032	1,032	°C
Fuel/Cyl./Rev.	.0000576	.0000590	.0000472	kg
Air in Cylinder	.00192	.00192	.00142	kg
Q/Cyl./Rev.	.590	.605	.484	kcal
Q_1	.052	.052	.041	kcal
Q_2	.538	.552	.443	kcal
IMEP	1,539	1,582	1,416	kPa
Mech. Eff. (engine)	77	75	73	%
Turbine Press. Ratio	3.123	4.549	3.667	
Compressor Pressure Ratio	4.156	6.101	4.126	
Compressor Efficiency	81.5	80.5	79	%
Turbine Efficiency	80.5	79.5	78	%
Mechanical Efficiency	98	98	98	%
Overall Turbo Efficiency	64.3	62.7	60.4	%
Required TIT	352	362	374	°C
Fuel Flow	33.1	34.0	20.3	kg/hr.
Air Density	.00301	.00301	.00227	kg/ℓ
FLOWS:				
Weight Pure Air	.245	.245	.142	kg/sec
Weight Fuel	.009	.0095	.006	kg/sec
Weight Exhaust Gas	.254	.2545	.148	kg/sec
Weight Scavenge Air	.073	.073	.043	kg/sec

The Figures 3-44 through 3-46 show the schematics of the three operating conditions.

The engine performance curves are shown in Figure 3-47.

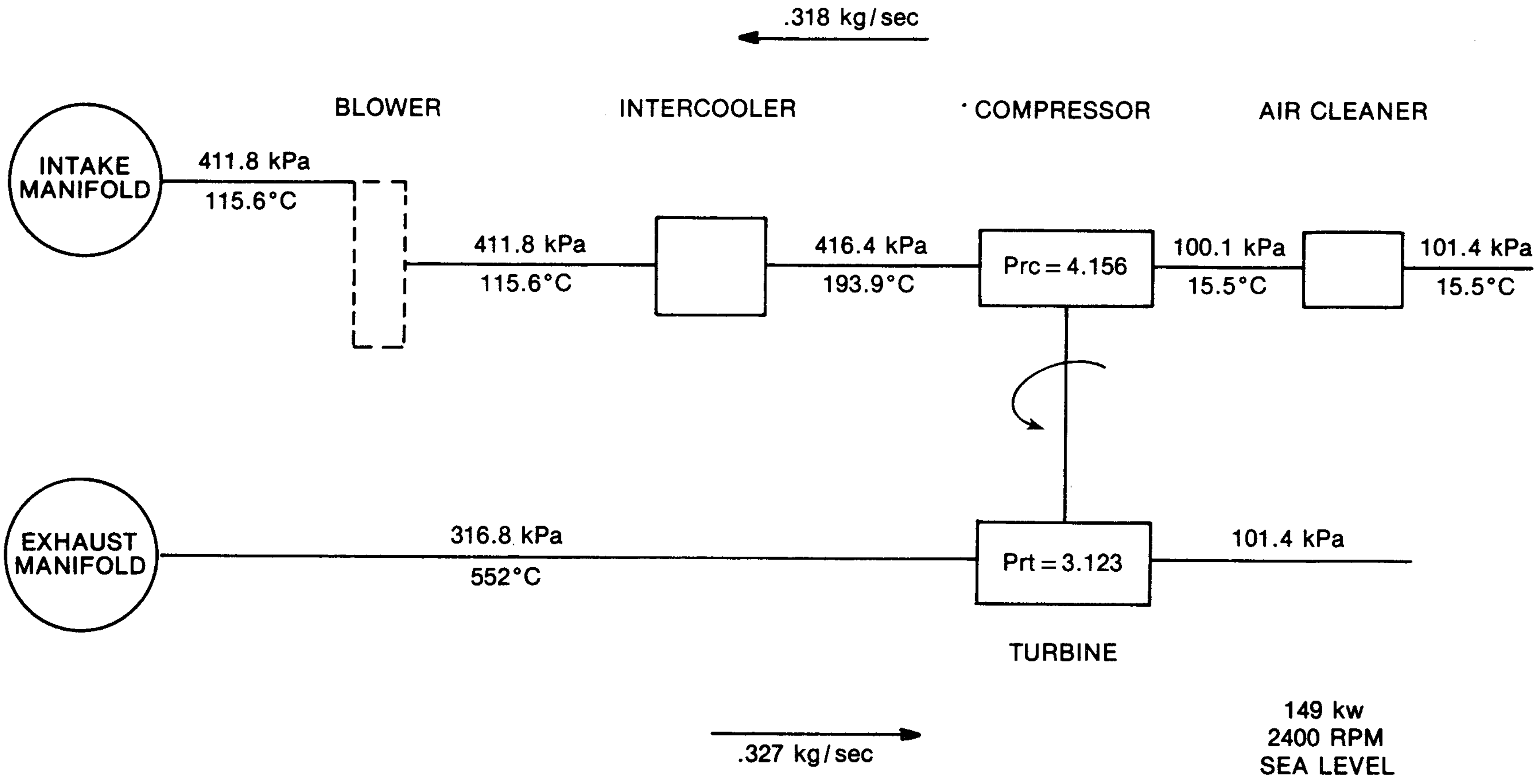


FIGURE 3-44 OPERATING SCHEMATIC—TAKE-OFF

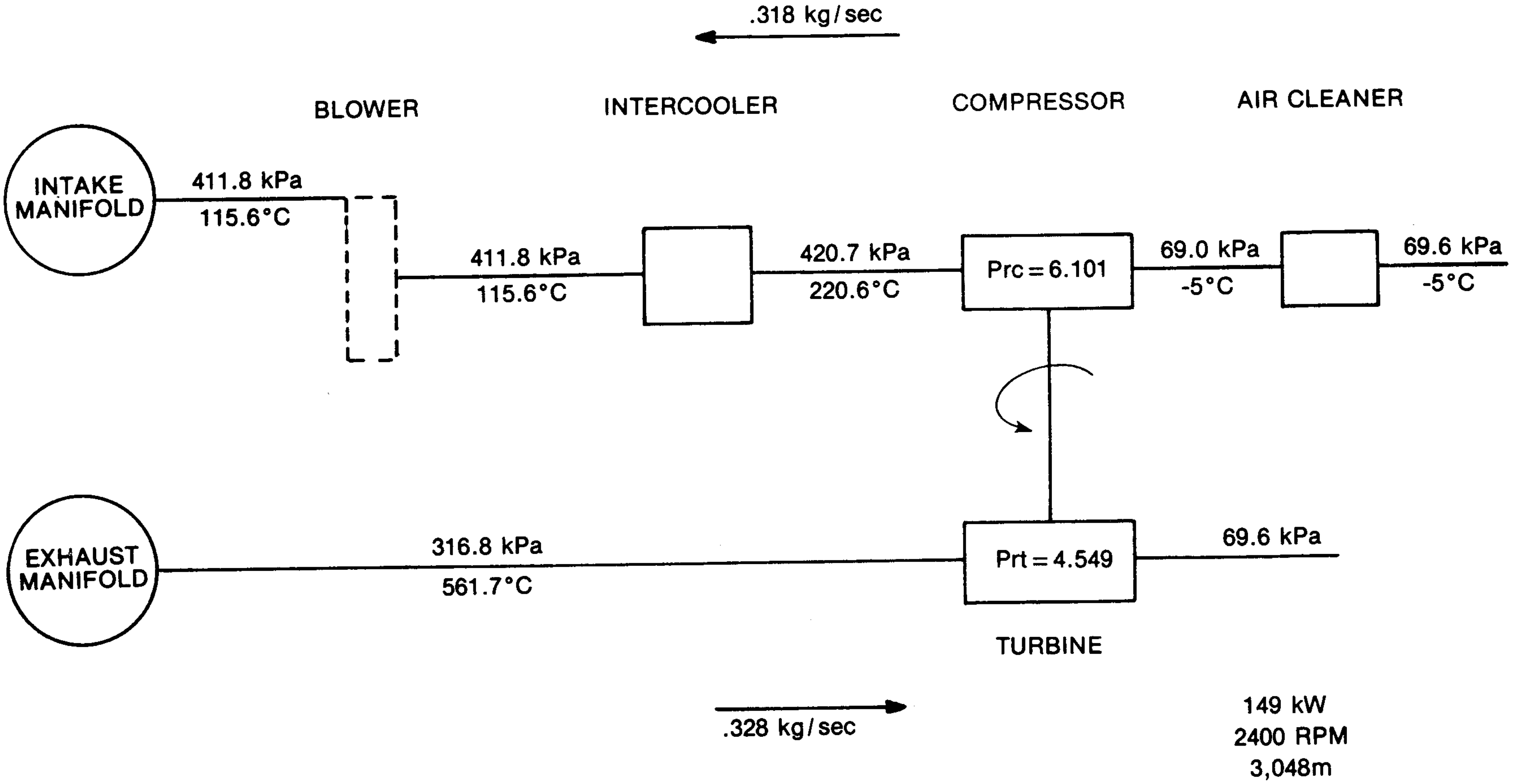


FIGURE 45 OPERATING SCHEMATIC—100% CRUISE POWER

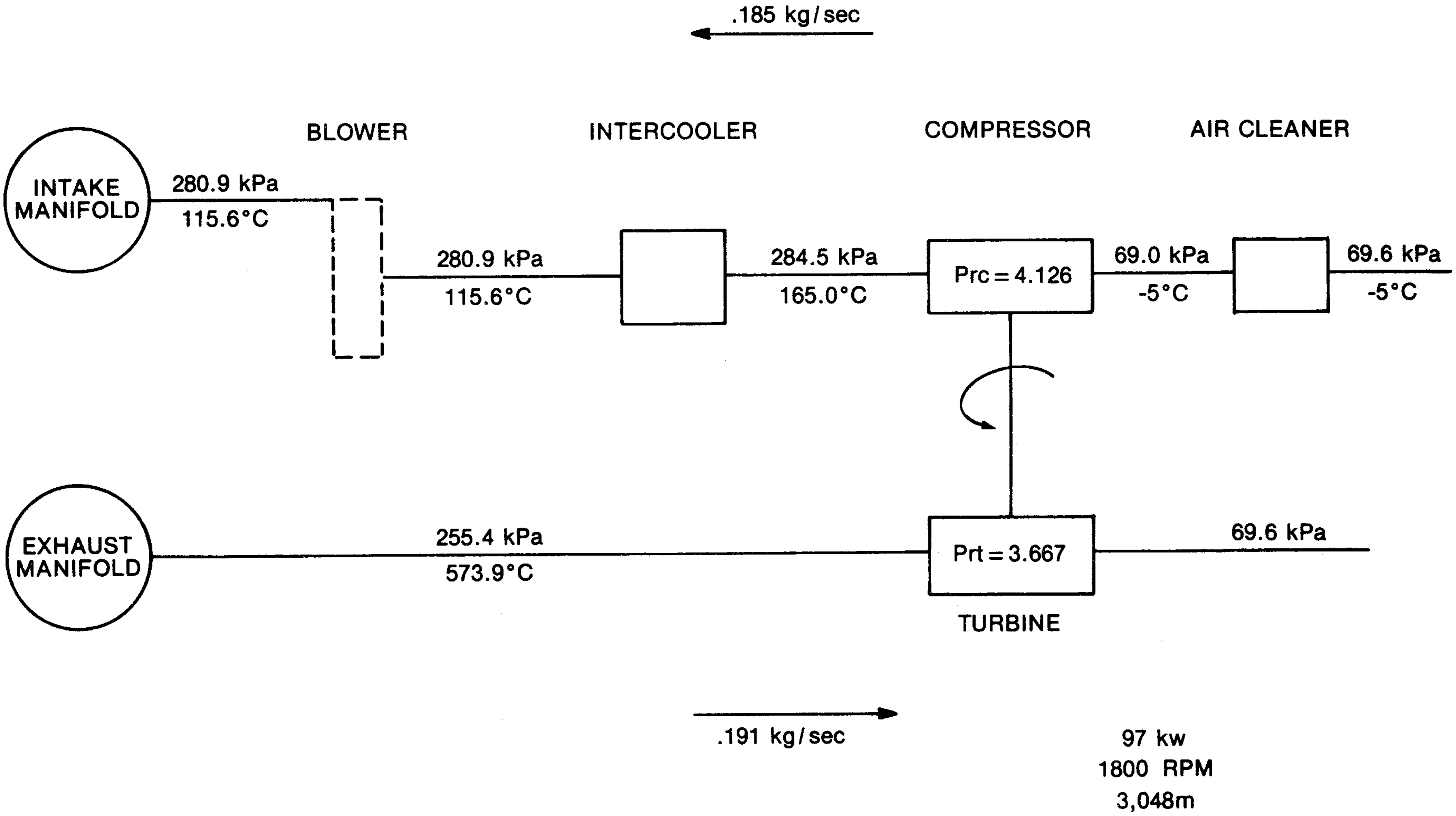


FIGURE 3-46 OPERATING SCHEMATIC—65% CRUISE POWER

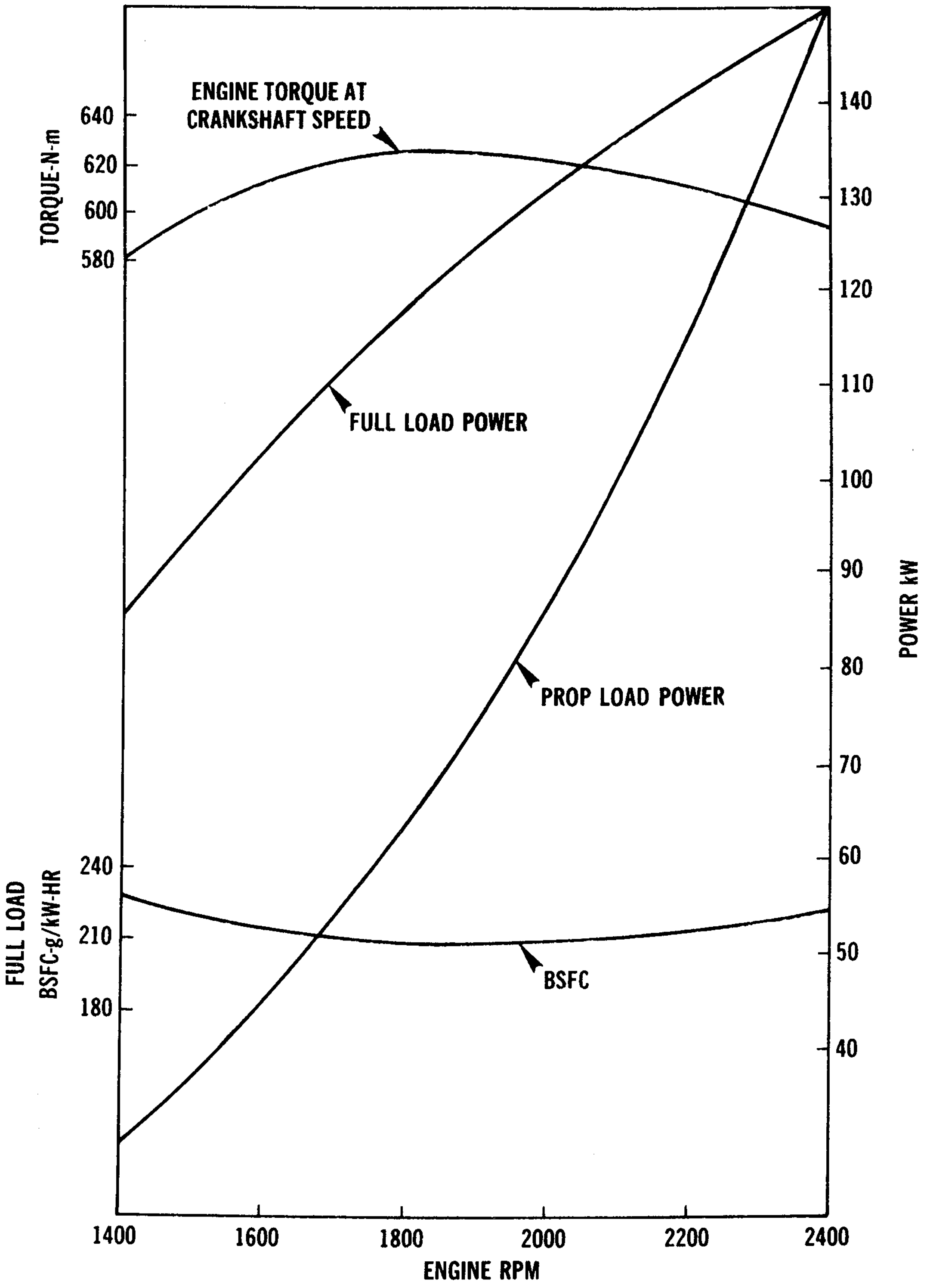


FIGURE 3-47 SEA LEVEL PERFORMANCE 4-CYLINDER RADIAL AIRCRAFT DIESEL ENGINE

3.4.11 Stress Calculations

All stress calculations are based on a 9650 kPa firing pressure. Figure 3-48 shows the cylinder arrangement. The cylinders are in one plane. The firing order is 1, 2, 3, 4 with even 90° firing intervals.

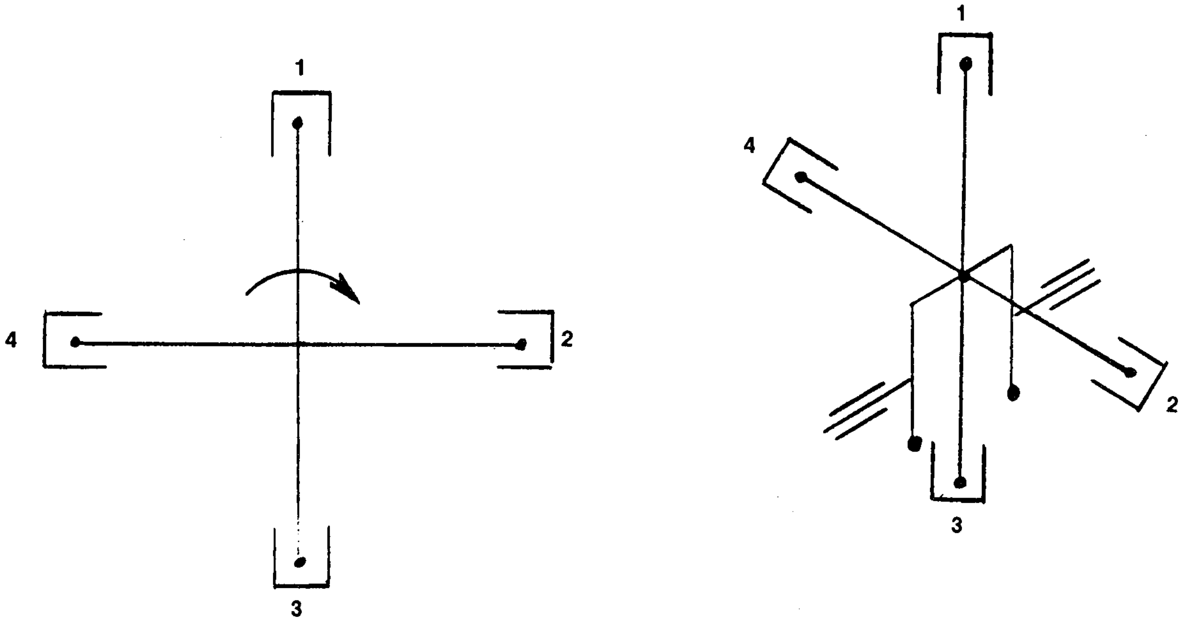


FIGURE 3-48 CYLINDER ARRANGEMENT

1. Power Train Data

Weight piston assembly:	
Ring carrier assembly	.93 kg
Pin carrier assembly	1.86 kg
Total piston	2.79 kg
Composite connecting rod	.33 kg
Slipper rings	.19 kg
Counterweights	7.70 kg
Total reciprocating WR	27.9 kg-cm
Total rotating WR	20.8 kg-cm
Total counterweight WR	47.1 kg-cm
Balance	100%

2. Crankshaft Stresses

A. Crankpin Fillet Radius	
Max. principal bending stresses	584 MPa
Min. principal shear stresses	128 MPa
B. Power Transmission Shaft	
Nominal shear stress	174 MPa
C. Material	
AMS 6415	
Ultimate tensile strength (min)	1034 MPa
Endurance strength (machined & peened)	552 MPa
D. Blower Quill Shaft	
Max. power transmission capacity	39 kW

3. Connecting Rod Stresses and Bearing Pressures

A. Connecting Rod	
Max. compressive stress	214 MPa
Min. compressive stress	27 MPa
Composite material fatigue strength	391 MPa
B. Crankpin Bearing Unit Load	28 MPa
SAE 794 leaded bronze max. unit load	69 MPa
C. Piston ball joint (30 mmø) unit load (Note: w/o oil groove on ball)	91 MPa
D. Main Bearing (55 mmø x 28 mm length)	
Peak unit load	21 MPa
Min. unit load	6 MPa

The Figures 3-49 and 3-50 show the main bearing load diagram and the crankshaft and connecting rod stresses.

4. Cylinder Barrel Stresses

A. 8-Cylinder Hold Down Studs	
M10X1.5 — 6g Grade 8 (proof load 40,430 N/stud)	
Torque to 75% proof load	30,320 N/stud
Peak dynamic load:	1,490 N/stud
B. Cylinder Wall Hoop Stresses	63 MPa
C. Cylinder Wall Longitudinal Stresses	32 MPa
D. Material: Steel	
Min. flexural strength at 1000°C	455 MPa

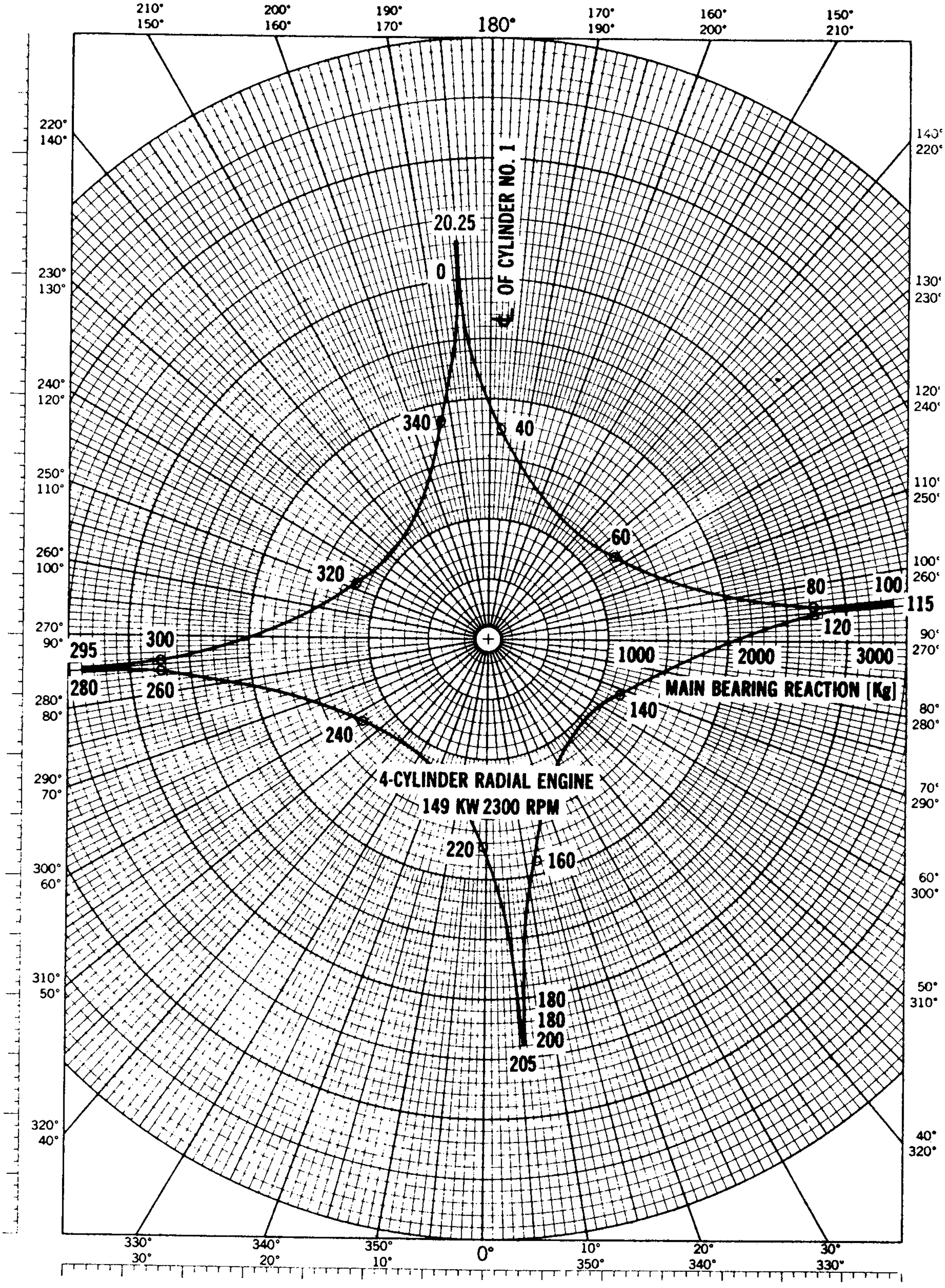


FIGURE 3-49 MAIN BEARING LOAD 149 kW AIRCRAFT DIESEL

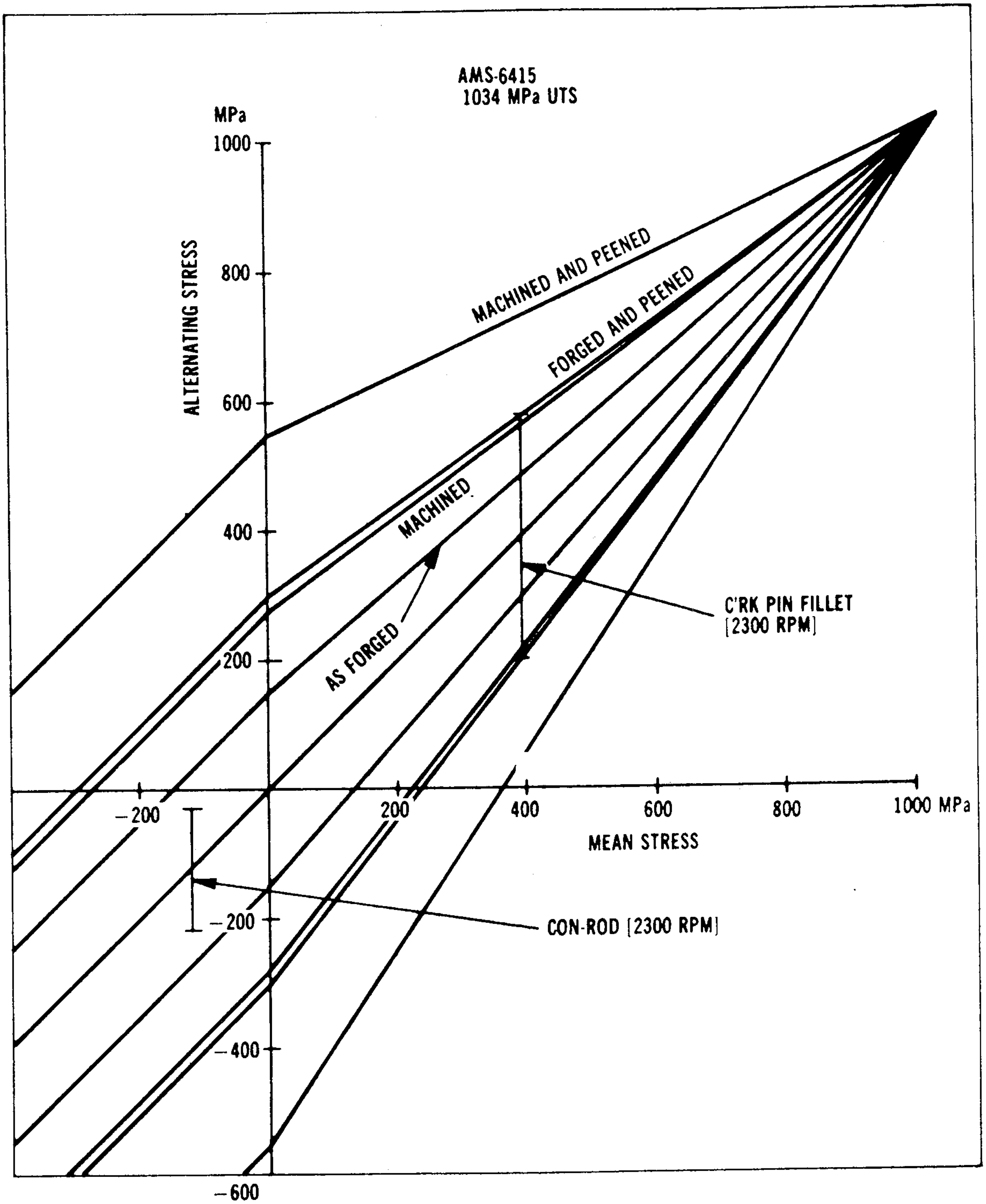


FIGURE 3-50 CRANKSHAFT AND CONNECTING ROD STRESS

5. Natural Frequencies Crankshaft System

A. First Mode's Natural Frequency		16 Hz
1st Order	974 rpm	
B. 2nd Mode's Natural Frequency		78 Hz
1st Order	4655 rpm	
2nd Order	2327 rpm	
4th Order	1164 rpm	

Pendulum dampers to be tuned for 2nd and 4th orders.

3.4.12 Projection of Fuel Consumption

Reference: Paragraph 3.3.11.

Baseline for the projections of BSFC was the 2-stroke cycle 8V92T Detroit Diesel Allison engine:

Min. BSFC = 229 g/kW-hr

In the case of the 298 kW engine a 15% BSFC improvement was projected due to the uncooled cylinders, resulting in a 65% cruise power BSFC (best economy) of .85 x 229 = 194.6 g/kW-hr.

For the 149 kW engine with partially cooled cylinders a 8.5% gain is projected resulting in a minimum BSFC = .915 x 229 = 209.8 g/kW-hr BSFC.

Projected BSFC's g/kW-hr:

	298 kW Engine	**149 kW Engine**
65% Cruise Power	194.6	209.8
Take-off Power	194.6 + 12.2 = 206.8	209.8 + 12.2 = 222.0
100% Cruise Power	194.6 + 18.3 = 212.9	209.8 + 18.3 = 228.1

These values were used in Paragraph 3.6.9.

3.4.13 Cooling Requirements

Reference: Paragraph 3.3.13

1. Aftercooler

	Take-off	**100% Cruise Power**	**65% Cruise Power**	
Air Flow	.318	.318	.185	kg/sec
Δt	78.3	105.0	49.4	°C
Cp	.243	.243	.243	kcal/kg-°C
Heat	363	487	133	kcal/min

2. Oil Cooler

Specific heat rejection of the VHO is 1.69 kcal/min/kW

Heat at 149 kW: Q = 149 x 1.69 = 252 kcal/min.

	Take-off	100% Cruise Power	65% Cruise Power
Q kcal/min	252	252	164

3. Cylinders

Reference: Paragraph 3.3.11

A. Fully Cooled AVCR-1360:
Q = 6,300 kcal/min at 1120 kW
Spec. heat 5.625 kcal/min/kW

B. Limited Cooled TDR–192 aircraft diesel:
40% reduction of cylinder heat load
Q = .60 x 5.625 x 149 = 504 kcal/min

	Take-off	100% Cruise Power	65% Cruise Power
Q kcal/min	504	504	327.6

The heat balance is shown in Table XX. Figure 3-51 shows a heat balance comparison of the 6-cylinder uncooled, and the 4-cylinder partially cooled aircraft diesels.

A comparison of the Figures 3-51b and 3-51-c shows that in the case of the 298 kW a large portion of the cooling loss reduction ends up in the exhaust gases. This is why Cummins Engine Company decided on turbocompounding of their adiabatic diesel engine to utilize this energy. Turbocompounding of the aircraft diesel was rejected for the following reasons:

a) Increased weight of the powerplant.

b) Reduced reliability of the high speed gear train.

The penalty is a somewhat higher BSFC.

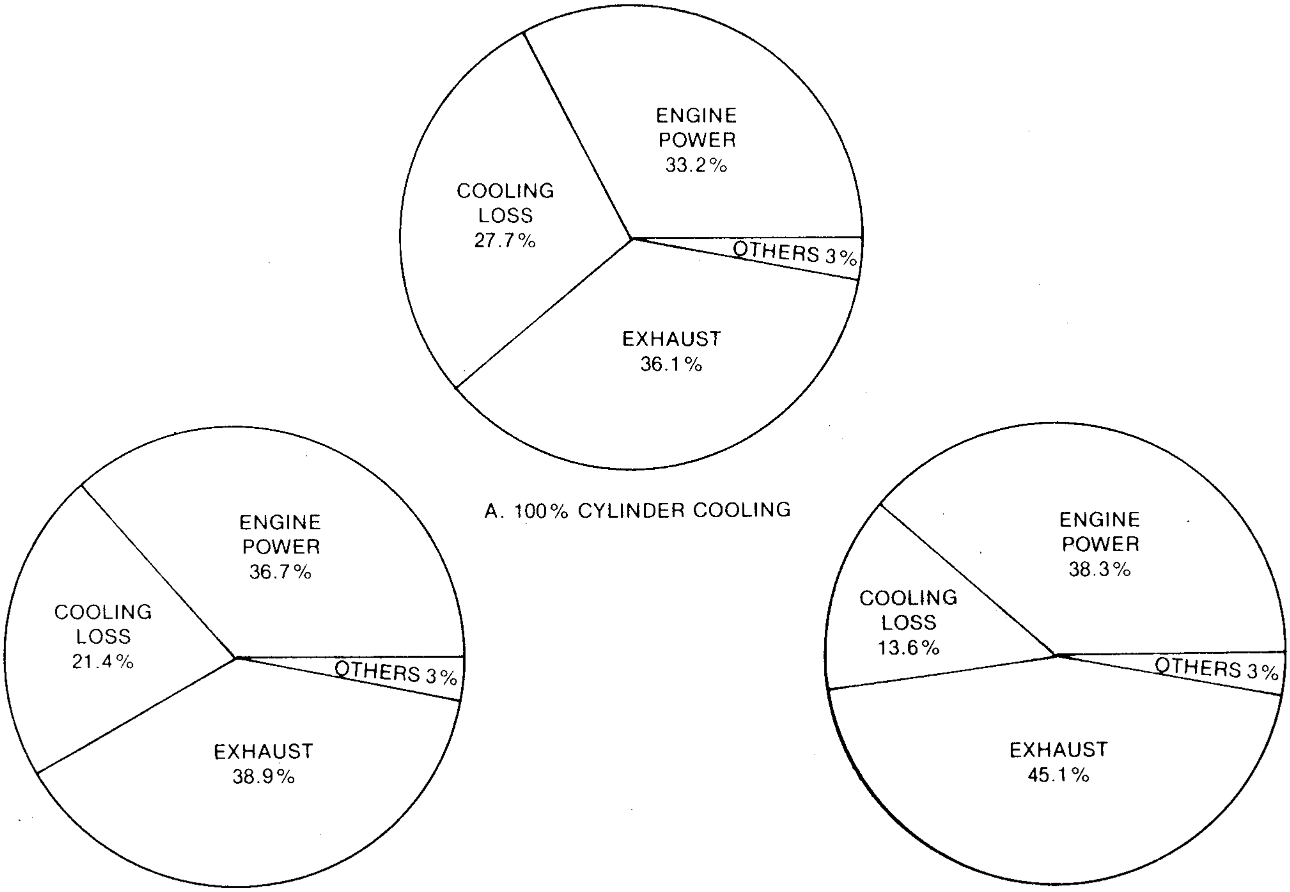
3.4.14 Anticipated Maximum Surface Temperatures of Engine Components

Crankcase	150°C
Aftercooler (peak)	195°C w/o insulation
Compressor housing	195°C w/o insulation
Turbine housing	510°C w/o insulation
(will be radiation shielded)	
Turbine housing	230°C with insulation
Exhaust manifolds	150°C with insulation
Intake manifolds	95°C
Cylinder	230-245°C

TABLE XX

Heat Balance 149 kW Engine

	TAKE-OFF	100% POWER CRUISE	65% POWER CRUISE
Aftercooler kcal/min	363	487	133
Oil cooler kcal/min	252	252	164
Cylinders kcal/min	504	504	327.6
Total cooling kcal/min	1,119	1,243	625
Fuel flow kg/hr	33.1	34.0	20.3
Total energy kcal/min	5,667	5,812	3,475
Engine power kcal/min	2,134	2,134	1,389
Exhaust gas kcal/min	2,244	2,261	1,357



A. 100% CYLINDER COOLING

B. 60% CYLINDER COOLING
149 kW DIESEL
100% CRUISE POWER

C. NO CYLINDER COOLING
298 kW DIESEL
100% CRUISE POWER

FIGURE 3-51 HEAT BALANCE COMPARISON

3.4.15 Turbocharger Operation

The turbocharger data for the 3 modes of operation are shown in Table XXI.

3.4.16 Blower Operation

Assume crank-up to 600 rpm. Required pressure ratio across cylinder ports is 1.01. Required blower tipspeed 41.1 m/sec. Blower diameter 177.8 mm.

Blower speed is 4500 rpm at 600 rpm crankshaft speed.

Temperature increase in blower:

$$\Delta T = \frac{.289}{.60} (1.01^{.286} - 1) = 1.4°C$$

Intake manifold temperature 16.9°C

Temperature at the end of compression in the cylinder:

$$T = (273 + 16.9) \times 17^{.37} = 827°R = 554°C$$

Fuel ignition temperature is approximately 590°C, therefore, glow plugs are required for start and restart.

3.4.17 Weight of the 149 kW Diesel

A detailed analysis indicates an expected weight of 163.2 kg. This dry weight includes all accessories.

Specific component weights are listed in Table XXII.

The weight of a comparable gasoline aircraft engine, the TSIO-360-E is 174.6 kg.

3.4.18 Initial Cost of the 149 kW Diesel

Method followed is the same as described in Paragraph 3.3.16. See Figure 3-52.

1. Weight Factor:
   Weight diesel 163.2 kg
   Weight gasoline engine 174.6 kg
   Weight ratio $\frac{163.2}{174.6} = .935$

2. Technology and Material Factor:
   $$\frac{\text{Total A x B}}{\text{Total B}} = \frac{212.71}{163.20} = 1.303$$

3. Overall Cost Ratio Diesel vs. Current Gasoline Engine:

   $.035 \times 1.303 = 1.218$

TABLE XXI
Turbocharger Data

	Take-off	100% Power Cruise	65% Power Cruise	
Compressor Ratio P_{rc}	4.156	6.101	4.126	
Turbine Ratio P_{rt}	3.123	4.549	3.667	
EFFICIENCIES:				
— Compressor	.842	.834	.817	
— Turbine	.775	.768	.752	
— Mechanical	.980	.980	.980	
— Overall	.640	.627	.604	
Air Flow	.318	.318	.185	kg/sec
Exhaust Gas	.327	.328	.191	kg/sec
Compressor Inlet Press.	101.4	69.6	69.6	kPa
Compressor Inlet Temp.	15.5	−5	−5	°C
Compressor Discharge Temp.	193.9	220.6	165.0	°C
Turbine Inlet Temp.	552.0	561.7	573.9	°C
Mechanical Blower Operation	no	no	no	
Exducer Diam.	76.2	76.2	76.2	mm
Turbine Rotor	101.6	101.6	101.6	mm
Compressor Wheel	114.3	114.3	114.3	mm
$N/\sqrt{\theta}$	79,170	89,840	77,515	

3.4.19 Emissions

1. Hydrocarbons and carbon monoxide will be comparable to current 2-stroke cycle engines. A catalytic converter may be added downstream of the turbocharger if future regulations mandate lower HC and CO levels.

2. NOx concentration will be minimized due to the relatively low peak pressures (9,650 kPa) and lower peak temperatures.

3. Smoke levels should be relatively low since the minimum trapped A/F ratio will be on the order of 25:1.

3.4.20 Risk Areas Associated with the Selected Design

Following are the areas where existing technologies need to be advanced:

1. VCR piston — develop for 2-stroke cycle operation.

2. Cylinders — reduced cooling air flow.

3. Piston rings — operating in reduced cooled cylinders.

4. Cooling of cylinder exhaust ports.

5. Piston lubrication.

6. Spherical connecting rod end.

TABLE XXII
Initial Cost 149 kW Aircraft Diesel

Part	Reasoning	A Technology &/or Mat. Factor	B Weight kg	A x B Eval. No.
Crankshaft		1.00	4.50	4.50
Counterweights	Tungsten	2.00	6.68	13.36
Quill Shaft		1.00	2.71	2.71
Prop Shaft		1.00	4.95	4.95
Pistons	2-Stroke cycle VCR	2.50	10.75	26.86
Piston Rings	Elevated temperature	2.50	.24	.59
Connecting Rods	Composite material	1.50	1.92	2.88
Cylinders	Limited cooling	1.50	29.67	44.51
Injection System	Tight tolerances	1.50	3.58	5.38
Front Acc. Gears		1.00	3.08	3.08
Front Housings		1.00	10.57	10.57
Blower Drive		1.20	5.25	6.30
Crankcase		1.00	5.35	5.35
Rear Acc. Gears		1.00	1.57	1.57
Intake System		1.00	5.58	5.58
Blower		1.00	.66	.66
Exhaust Manifolds		1.00	.66	.66
Aftercooler		1.00	3.76	3.76
Turbocharger		1.50	15.45	23.17
Oil Pump		1.00	5.46	5.46
Vacuum Pump		1.00	.91	.91
Governor		1.00	.91	.91
Alternator		1.00	4.88	4.88
Fuel Pump		1.00	1.16	1.16
Starter		1.00	3.54	3.54
Oil Cooler		1.00	2.35	2.35
Balance Parts		1.00	27.06	27.06
			163.20	212.71

3.4.21 Proposed Development Program for the 149 kW Diesel Engine

Following is a detailed program that is recommended for the development of this engine:

1. **2-Cycle Performance Demonstration**
    - A. Design and procurement of hardware.
    - B. Flow modeling.
        - a. Port configuration
        - b. Scavenge ratios
        - c. Timing variations (ports)

d. Air utilization
Note: This activity may be deleted. Cost/benefit evaluation in process.

C. Combustion development (SCTE) — standard cooled cylinder.

a. Piston configurations

b. Injection characteristics
- Spray patterns
- Timing optimization
- Emissions
- Smoke
- BSFC

2. Reduced Cylinder Cooling Operation

A. Materials evaluation and selection.

a. Cooling fins configuration

b. Piston ring materials

c. Solid lubricants

B. Design and procurement of hardware.

C. SCTE demonstration.

a. Cylinder integrity

b. Demonstration of adequate piston ring sealing and life

c. Port cooling

d. Piston lubrication

e. Injection nozzle cooling

f. Performance
- BSFC
- Emissions
- Smoke
- Oil consumption

3. VCR Piston Development

A. Design and procurement of hardware.

B. Bench test.

C. SCTE demonstration.

  a. Performance tests

  b. Endurance testing

4. Turbocharger Development

A. Design and procurement of hardware.

B. Compressor bench test.

  a. Operation at:
    - High specific speed
    - High pressure ratios
    - High flow factors

  b. Maximized efficiencies

C. Turbine bench test.

  a. Operation at:
    - Variable turbine back pressure (altitude)
    - High tip speeds
    - High efficiencies

  b. Optimization of variable nozzle area operation

  c. Development of nozzle control actuator

D. Bench test of complete turbocharger

5. Support Hardware

A. Design and procurement of hardware.

B. Test of:

  a. Composite rods

  b. Blower drive and declutch system

  c. Injection equipment

  d. Lubricants

  e. Electronic controls for
    - VAT turbocharger
    - Blower declutching
    - Injection control
    - Prop control interface

    - f. Aftercooler
    - g. Oil cooler

6. Multi-Cylinder Demonstration

- A. Design and procurement of hardware.
- B. Performance and system integration.
    - a. Scavenge characteristics
    - b. Startability (cold and hot)
    - c. BSFC
    - d. Emissions
    - e. Reliability
    - f. Altitude operation
- C. Demonstrate design integrity.
    - a. Assembly
    - b. Torsional characteristics
    - c. Structural integrity
- D. FAA Type Testing.
    - a. Safety
    - b. Durability
    - c. Reliability

3.4.22 Comparison of the 149 kW Aircraft Diesel and a Comparable Current Gasoline Engine

A comparison is made with the 4-stroke cycle TSIO-360-E gasoline engine.

Table XXIII shows this comparison in a tabular form.

Figure 3-52 is a size comparison.

TABLE XXIII
Comparison of TSIO-360-E Gasoline and TDR-192 Aircraft Diesel Engine

	4-Stroke Cycle TSIO-360-E Gasoline Engine	2-Stroke Cycle TDR-192 Diesel Engine
Configuration	6 cyl. opposed	4 cyl. radial
Displacement ℓ	5.91	3.14
Take-off RPM	2800	2400
Rated max. take-off power kW	149	149
Rated max. for cruising kW	112	149
Prop drive	direct	direct
BSFC g/kW-hr:		
Take-off	377.1	222.0
100% power cruise	—	228.1
65% power cruise	267.6	209.8
Dimensions:		
Length mm	1188	965
Width mm	795	800
Height mm	672	607
Engine weight dry, kg	174.6	163.2

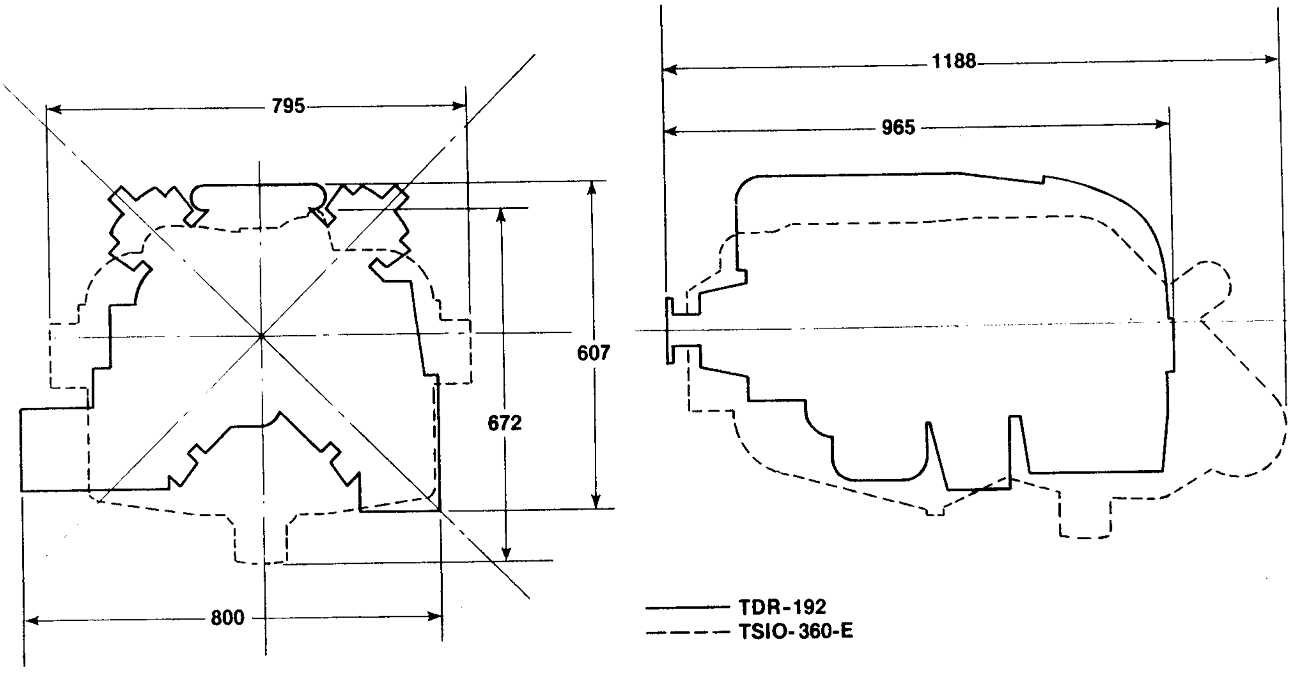


FIGURE 3-52 SIZE COMPARISON TSIO-360E AND TDR-192 AIRCRAFT DIESEL ENGINE

4.0 ENGINE/AIRFRAME INTEGRATION

This study was conducted by Beech Aircraft Corp. to evaluate the integration of the proposed diesel aircraft engines into future airframes and to determine the effect of the engine on aircraft performance and operating costs. The results were then compared with corresponding data for current production type gasoline engine powered aircraft.

4.1 Engine Installation

Installation design layouts were made which show the 298 kW diesel—Figures 3-16 through 3-20—mounted on a twin engine airplane and the 149 kW engine, Figures 3-39 through 3-43, installed in a single engine aircraft with retractable landing gear.

The Figures 4-1 through 4-3 show the twin engine installation, the Figures 4-4 through 4-6 show the single engine installation.

4.1.1. Description of the layouts

1. Engine mounts are of two basic types — cantilever and bed mount. A cantilever mount from the firewall was used in the twin and a bed mount incorporating the nose gear support structure was used in the single. "Dynafocal" type mounts would be used with the cantilever method to minimize vibration transmission to the airframe.

2. The induction system in both cases would be a NACA flush inlet, ducting and an air filter. Alternate air would be available to the engine through a door operated by differential pressure.

3. Both engines have a dry oil sump and require external oil tanks mounted in the engine compartments.

OIL SYSTEM DATA

Engine	Oil Flow 1/min.	Oil Capacity — Liters		
		Engine	Sump Tank	Total
298 kW Diesel	53	4	15.5	19.5
149 kW Diesel	34	2	9.5	11.5

4. Both engines would have cooling air inlets providing air to a plenum chamber. Ducts from the plenum would direct air to individual cylinders, oil coolers, aftercoolers and fuel injectors as needed. On the single, cooling air exits are outboard of the nose gear on the lower side of the cowling. Exits from the twin nacelle would be at the lower aft end.

5. The installation drawings were done in enough detail to indicate the features noted above and to provide reasonable assurance that no major installation problems would be encountered with the proposed diesel engine concepts.

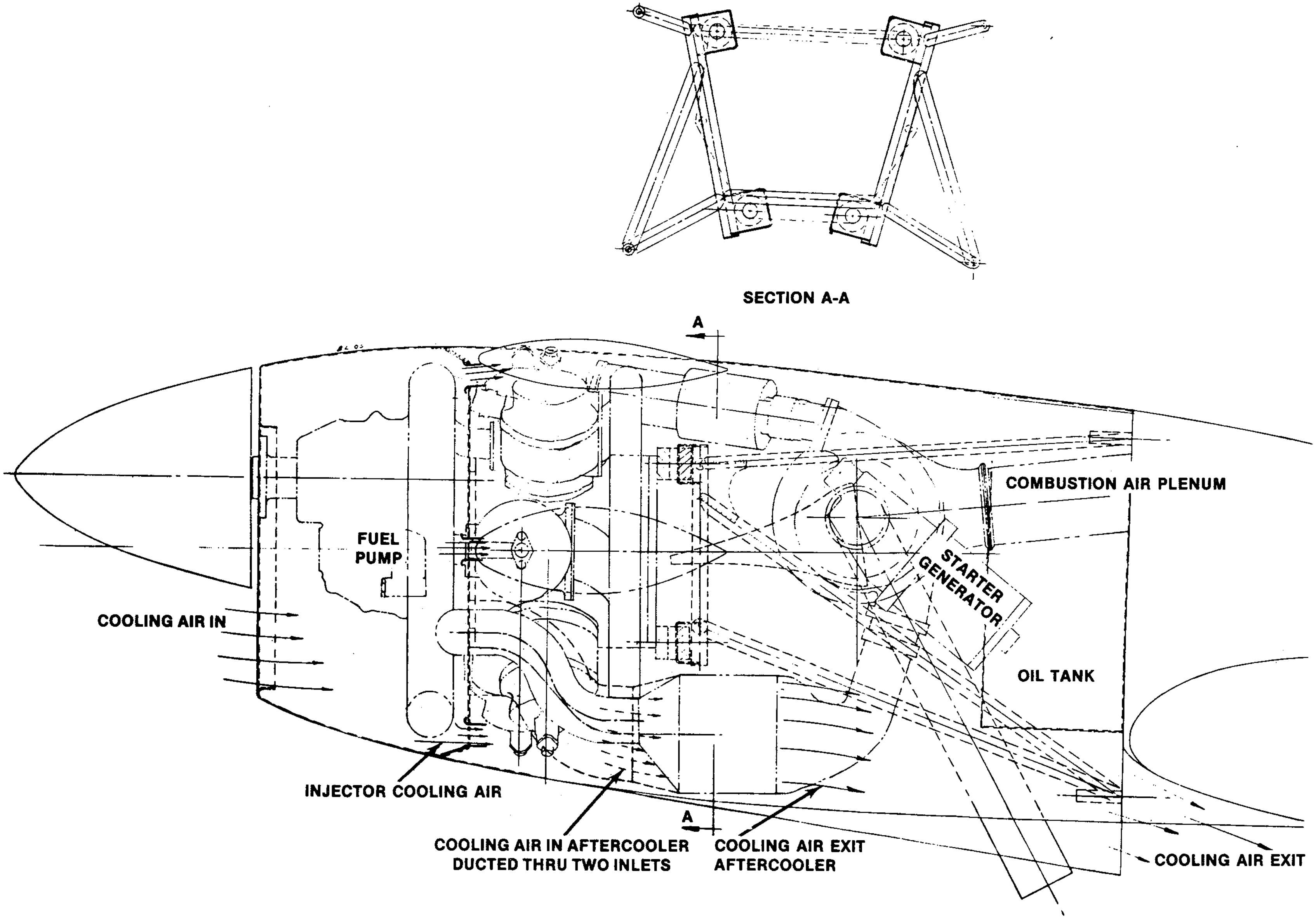


FIGURE 4-1 SIDE VIEW TWIN INSTALLATION

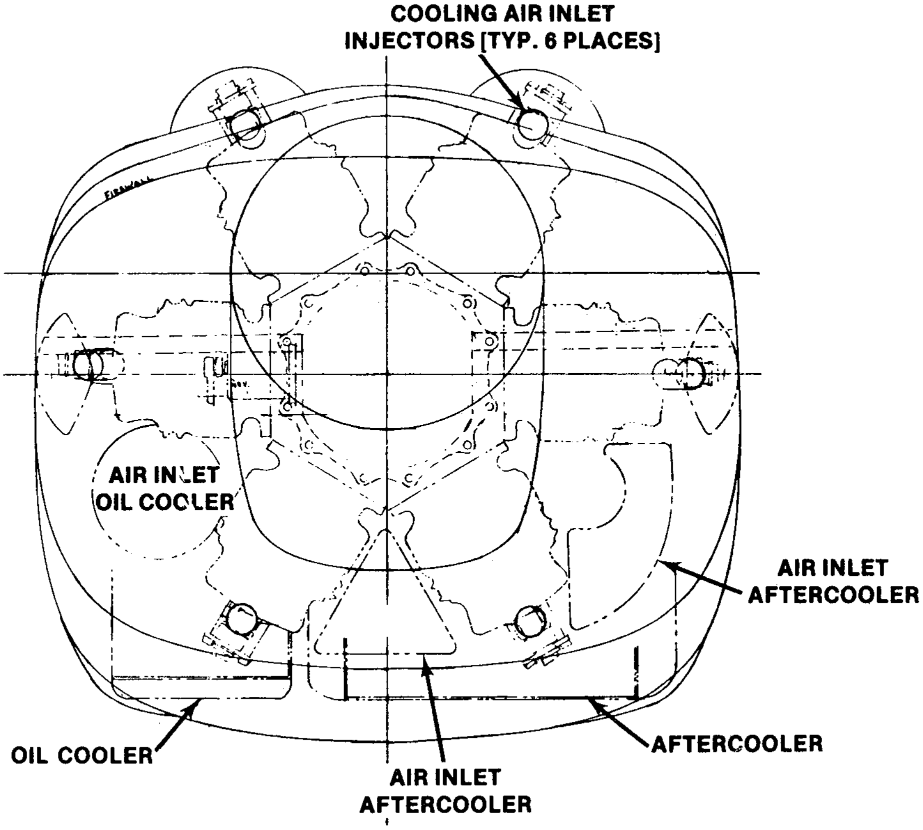


FIGURE 4-2 FRONT VIEW TWIN INSTALLATION

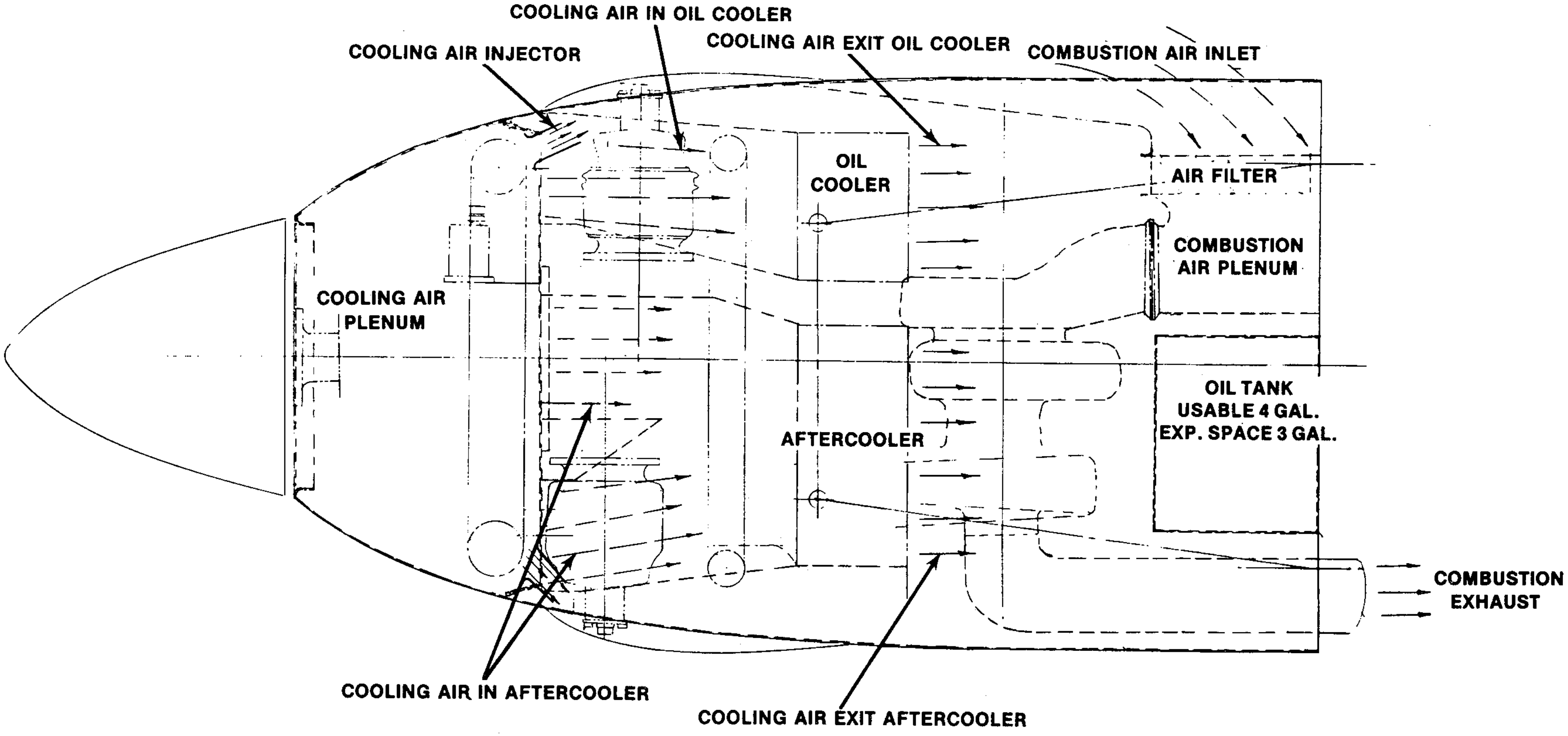


FIGURE 4-3 TOP VIEW TWIN INSTALLATION

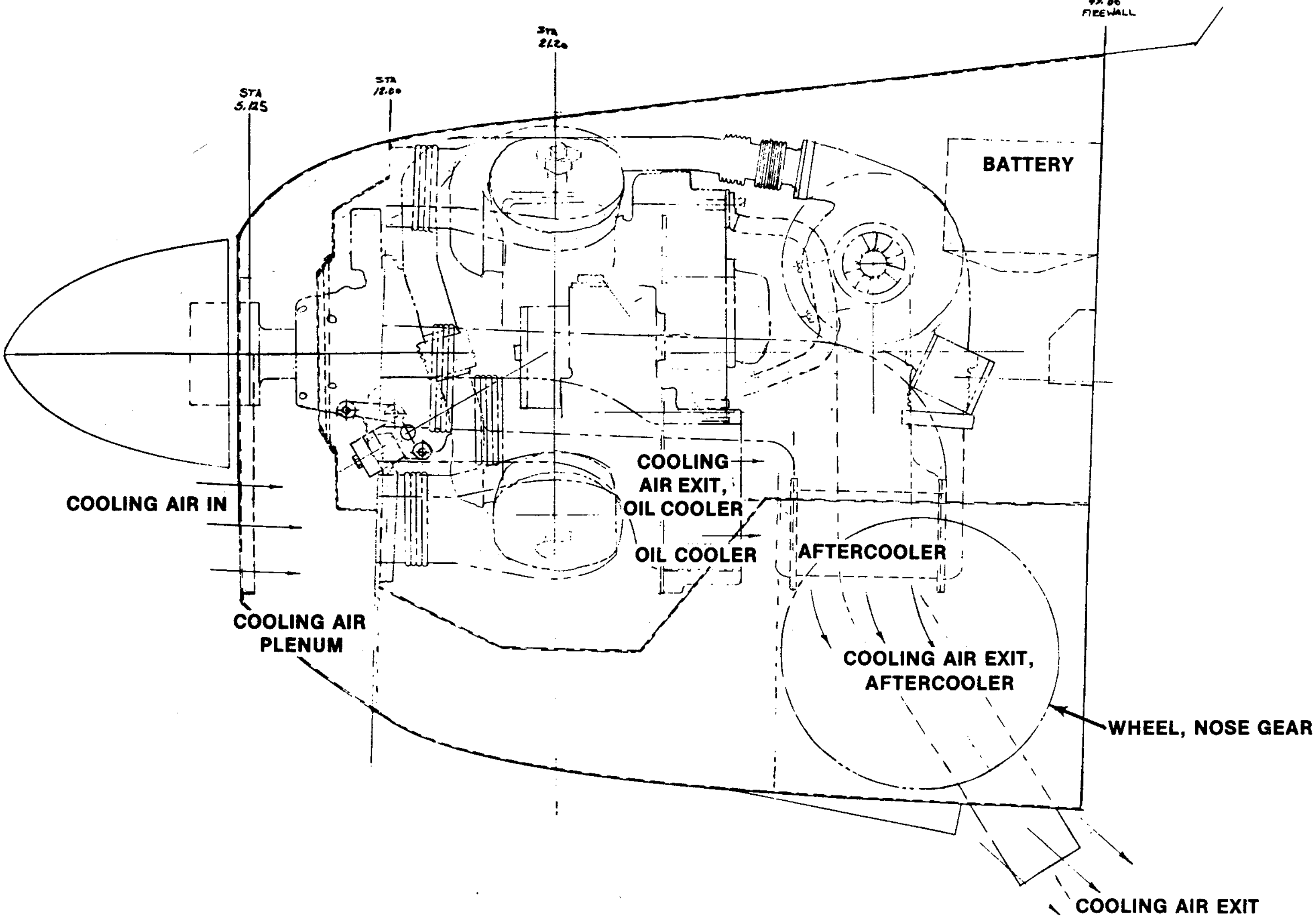


FIGURE 4-4 SIDE VIEW SINGLE INSTALLATION

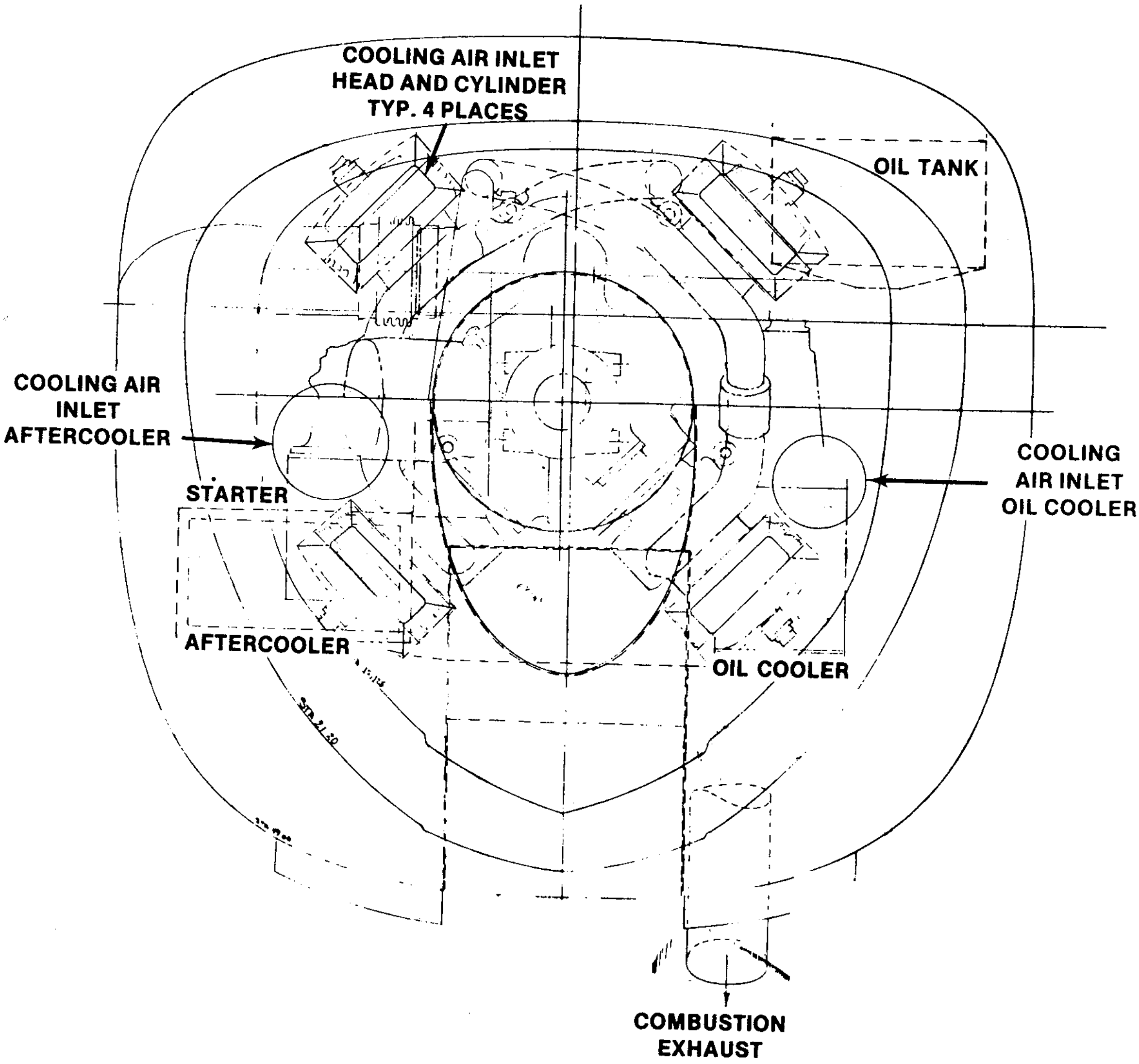


FIGURE 4-5 FRONT VIEW SINGLE INSTALLATION

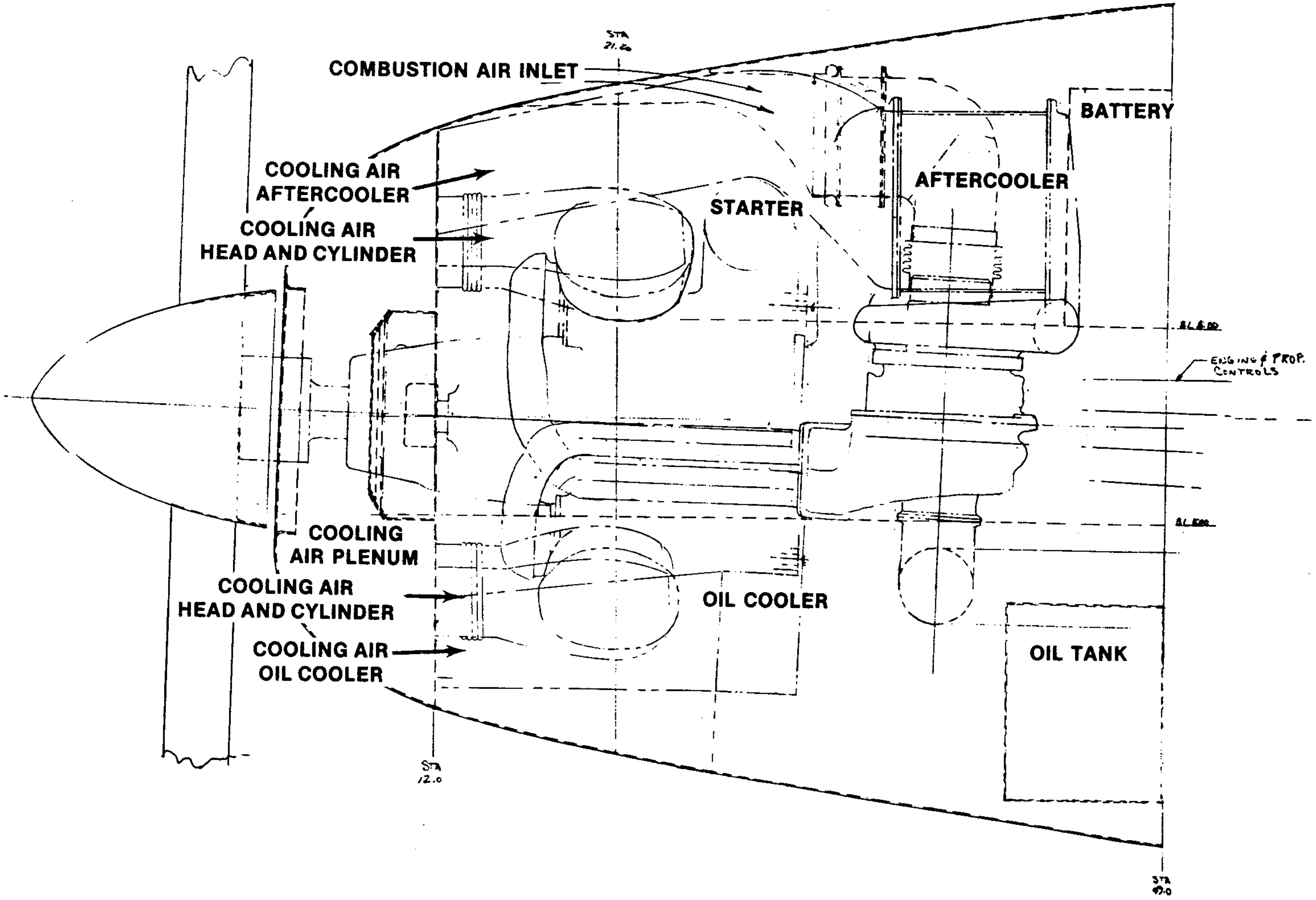


FIGURE 4-6 TOP VIEW SINGLE INSTALLATION

4.2 Aircraft Configurations

Three view sketches of the airplanes are shown in the Figures 4-7 and 4-8. Following are some characteristics of both planes:

4.2.1 Twin Engine Airplane

Figure 4-7 shows the twin engine aircraft. The sketch yields the following information:

1. **Propeller Data**

Prop. diameter	2.057 m
Prop. speed at take-off	2,345 rpm
Tip speed at take-off	253 m/sec = .74a

a = Velocity of sound = $20.06\sqrt{T}$ m/sec (T in °K)

At standard ambient temp. 15.5°C

$a = 20.06\sqrt{273 + 15.5} = 341$ m/sec

Prop. speed at economy cruise	1,790 rpm
Tip speed at economy cruise	193 m/sec
Prop. ground clearance	330 mm

2. **Sight Angles**

The pilot's sight angles for the twin are indicated by A and B (Figure 4-7). The centerline angle over the nose, A, as indicated is about 12°. If the airplane were lofted, the angle from the pilot's actual eye position would be about 18° which is considered more than adequate. The smallest lateral angle B is 10°. This is also more than adequate, especially compared to some current piston engine twins with larger nacelles.

3. **Aircraft Data**

			Twin Engine Diesel	**Twin Engine Gasoline**
Airframe minus engine	(a)	kg	1,860	1,860
Engines (2) Figure 3-36	(b)	kg	415	525
Empty weight (a) + (b)	(c)	kg	2,275	2,385
Payload	(d)	kg	726	671
Fuel load	(e)	kg	653	598
Useful load (d) + (e)	(f)	kg	1,379	1,269
Max. take-off weight (c) + (f)		kg	3,654	3,654
Wing span		m	13.05	13.05
Length		m	11.89	11.89
Tail height		m	3.87	3.87
Tail span		m	5.09	5.09
Wing area		m^2	22.39	22.39

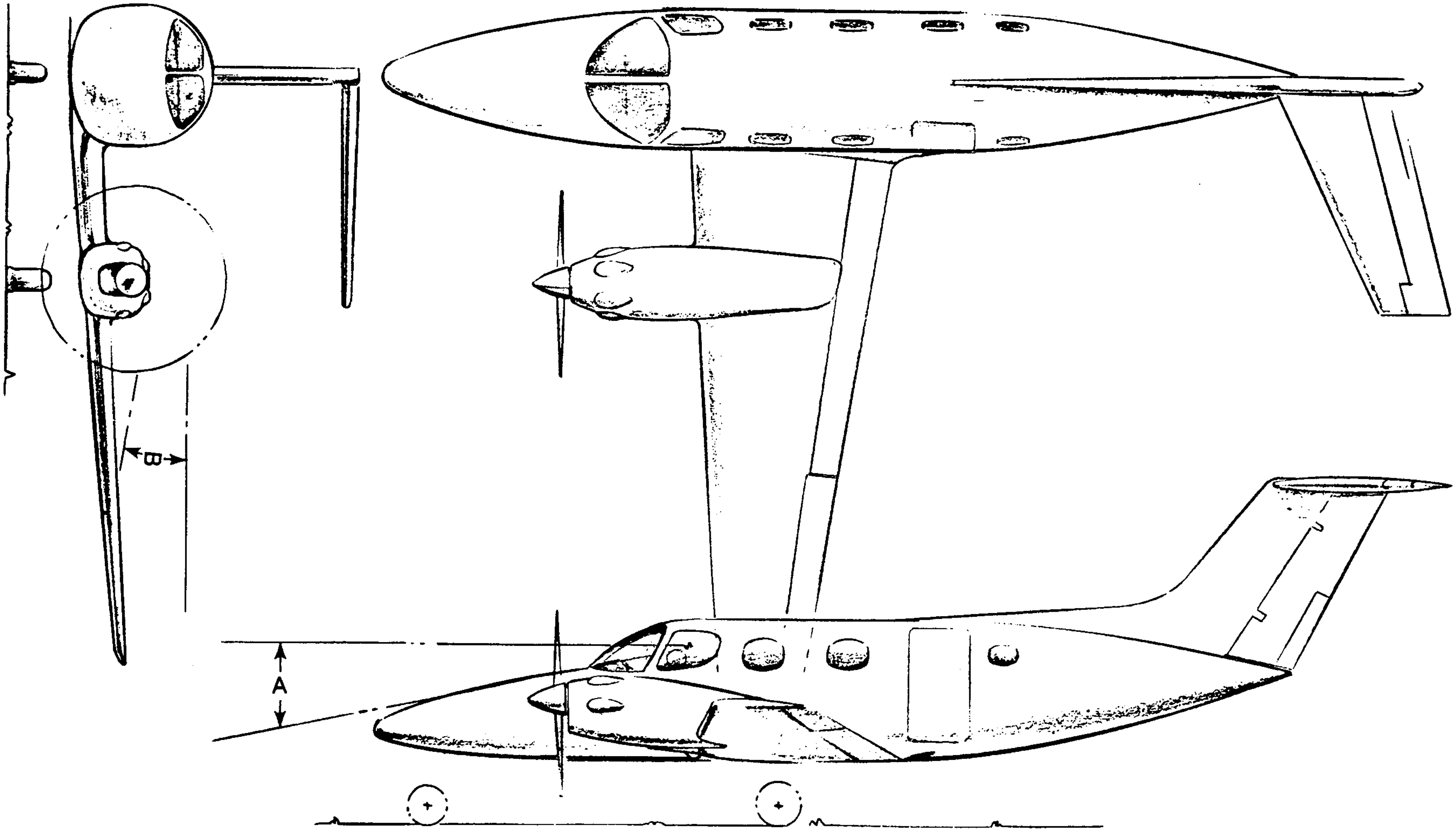


FIGURE 4-7 TWIN ENGINE AIRCRAFT CONFIGURATION

4.2.2 Single Engine Airplane

Figure 4-8 shows the single engine aircraft. Characteristics are:

1. Propeller Data:

Prop. diameter	2.134 m
Prop. speed at take-off	2,400 rpm
Tip speed at take-off	268 m/sec = .79 a
Prop. speed at economy cruise	1,800 rpm
Tip speed at economy cruise	201 m/sec
Prop. ground clearance	356 mm

2. Sight Angles

The centerline angle over the nose for the single engine airplane, C, is 9°. This should correspond to actual pilot's viewing angle of about 12°. This is probably adequate, especially when compared to some of today's long nose single engine aircraft.

3. Aircraft Data

			Single Engine Diesel	Single Engine Gasoline
Airframe minus engine	(a)	kg	667	667
Engine — Figure 3-58	(b)	kg	162	175
Empty weight (a) + (b)	(c)	kg	829	842
Payload	(d)	kg	340	333
Fuel load	(e)	kg	180	174
Useful load (d) + (e)	(f)	kg	520	507
Max. take-off weight (c) + (f)		kg	1,349	1,349
Wing span		m	11.16	11.16
Length		m	8.66	8.66
Tail height		m	3.14	3.14
Tail span		m	3.78	3.78
Wing area		m^2	17.74	17.74

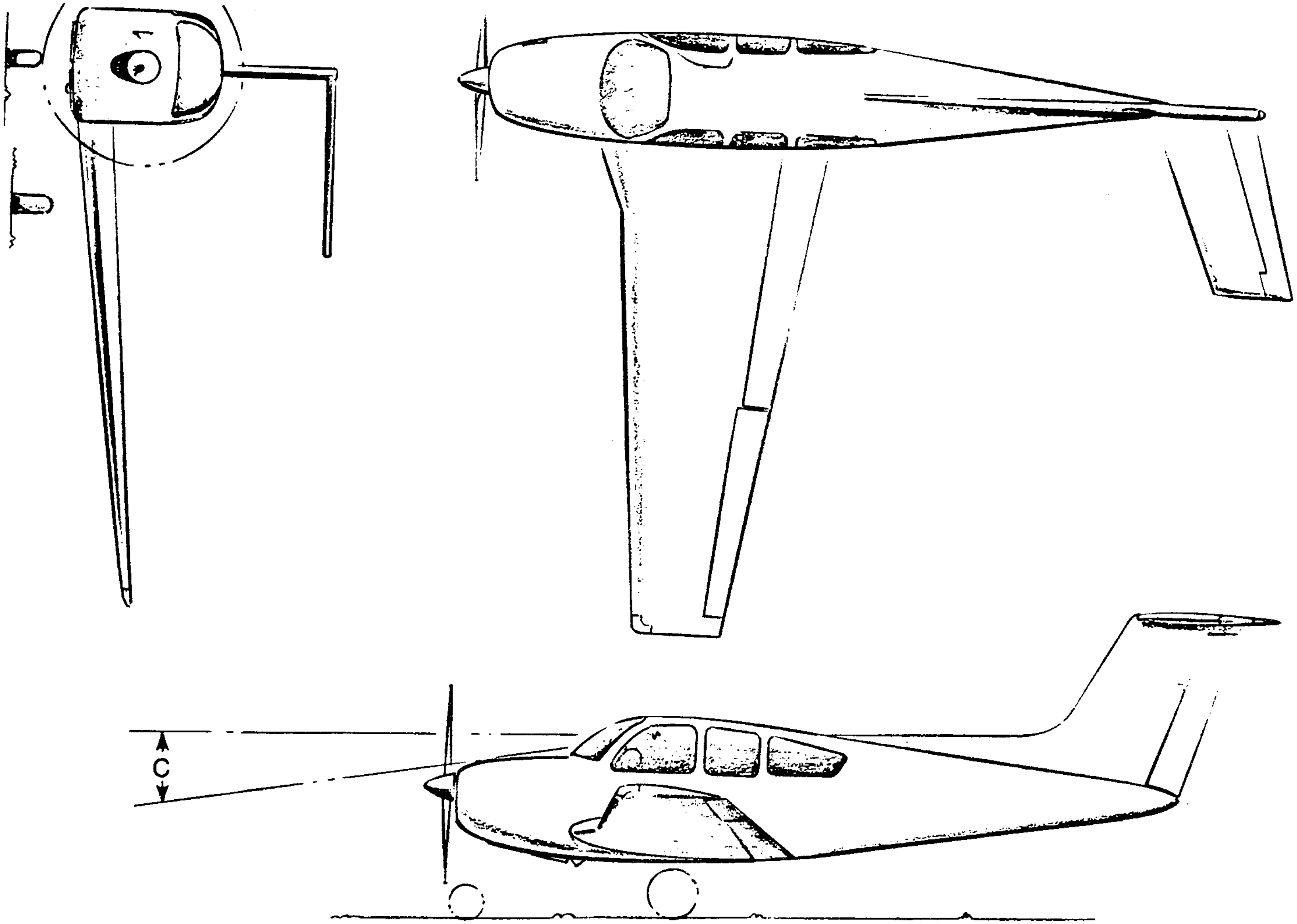


FIGURE 4-8 SINGLE ENGINE AIRCRAFT CONFIGURATION

4.3 Aircraft Performance Evaluation

The major tool used in the airplane design synthesis was a somewhat modified version of the synthesis method originally developed for the NASA GATE (General Aviation Turbine Engine) Study. (13)* The process was simplified for this purpose since take-off and cruise power could be specified as program inputs. The program is not accurate enough nor does it account for enough variables to actually design airplanes, but it is considered adequate to indicate trends in relative size and performance for airplanes theoretically equipped with different engines. The main point to bear in mind when looking at the results of the program is that the objective is to provide an indication of the differences in performance and cost between diesel and gasoline powered airplanes. The methods used in estimating throughout are no better than 5 to 10% accurate, but the uniform assumptions and methods used in all cases would make the resulting differences good indications of the trends to be expected. This is the proper objective for a conceptual investigation.

4.3.1 Program Input Data

The data needed by the program can be put in three broad classifications:

1. **Desired Airplane Mission Profile:**

   A. Payload.

   B. Range and speed at cruise altitude.

   C. Take-off and landing distances.

   Mission Profile:

		149 kW Single	**298 kW Twin**
Cruise speed	km/hr	324	474
Altitude	m	3,048	7,620
Range	km	1,481	2,592
Payload	kg	340	726
Take-off distance	m	579	701
Landing distance	m	369	677
Cruise power	kW	149	243
Take-off power	kW	149	298

2. **Engine Performance Data:**

   A. Take-off power.

   B. Cruise power and fuel consumption at the specified cruise altitude.

   C. Engine weight and geometry.

   D. Propeller drive shaft speed for use in calculating propeller diameter and propulsive efficiency.

   E. Induction airflows.

   F. Cooling requirements.

The following tabulation gives the specific program input data:

		149 kW		298 kW	
		Diesel	**Gasoline**	**Diesel**	**Gasoline**
BSFC	g/kW-hr	228	268	213	286
Altitude	m	3,048	3,048	7,620	7,620
Speed	km/hr	315	315	444	444
Power	%	100	75	81.5	75
Proposed	rpm	2,400		2,300	

The 298 kW develops full power up to 6,096 m. Above that altitude the power drops off in proportion to the ambient air density.

Engine weight data:

		149 kW	298 kW
Gasoline	kg	175	262
Diesel	kg	163	207
Difference	kg	12	55

Cooling air estimates

Engine cooling air requirements are used to calculate cooling air inlet areas, exit areas and momentum drag. Piston engine experience indicates that an inlet velocity ratio between the inlet and free stream of .4 is desirable ($\frac{v_1}{v_0} = .4$).

Similarly an exit velocity ratio of .3 is indicated ($\frac{v_{ex}}{v_o} = .3$).

The inlet and exit areas are calculated using:

$$A = \frac{V}{v}$$

where

A = area m^2

V = airflow volume m^3/sec

v = airflow velocity m/sec

Airflow volume V is determined from the weight W_A:

$$V = \frac{W_A}{d}$$

where

W_A = weight airflow kg/sec

d = air density kg/m^3

Weight flow is determined by the required heat rejection rates:

$$W_A = \frac{Q}{c_p \quad T} \quad \text{where}$$

Q = heat rejection rate kcal/sec

c_p = spec. heat of air at constant pressure
= .24 kcal/kg/°C

ΔT = temp. rise of cooling air across heat exchanger
= 55.6°C

In calculating the cooling exit areas, a 4.4°C temperature rise was used in addition to the 55.6°C rise across the heat exchangers. This allowed for ram rise and radiation heating. Exit density used in calculating exit areas was determined by temperature ratio.

$$d_{ex} = d \frac{T}{T_{ex}} \quad \text{where}$$

d_{ex} = exit density kg/m^3

T_{ex} = exit temperature °K

d = density ambient air kg/m^3

T = temp. ambient air °K

The change in momentum of the air flowing through the heat exchangers in the engine compartment induces a drag force on the airplane. This is best represented in terms of thrust power required to provide the cooling air flow. It is a function of the velocity of the airplane and the atmospheric conditions:

TABLE XXIV
Data for Cooling Air Duct Sizing and Cooling Air Momentum Drag Calculation

100% Power Cruise (Standard Ambient)

Engine Type		**Diesel**	**Gasoline**	**(1) Diesel**	**(1) Gasoline**
Rated Power	kW	149	149	298	298
Cruise Power	kW	149	112	298	224
Speed	km/hr	330	315	439	444
Altitude	m	3,048	2,134	6,096	7,620
Cooling	kcal/min				
Oil Cooler		252	363	403	255
After Cooler		390	—	959	363
Cylinders		504	762	—	762

Engine Type		Diesel	Gasoline	(1) Diesel	(1) Gasoline
Fuel Injectors		—	—	151	—
Total Heat Rejection	kcal/min	1,146	1,125	1,513	1,380
Induction Airflow	kg/sec	.32	.14	.56	.23
Inlet Area	cm^2	432	—	593	—
Exit Area	cm^2	701	—	980	—
(2) Drag (thrust kW)		10.2	8.2	21.8	20.9
(3) Cooling f	m^2	.030	.025	.037	.040

(1) Each Engine
(2) At altitudes and speeds listed.
(3) Equivalent flat plate area for use at any altitude and speed.

$$\text{Thrust power} = \sum \frac{W_A \; v_o \, (v_o - v_{ex})}{102} \;\; \text{kW}$$

Input data and the results of the calculations are shown in Figure 4-8.

It should be noted that the cooling data for the gasoline engine refer to 75% cruise power while the diesel data apply to 100% cruise power. For a fair comparison the gasoline data should have been 33% higher.

3. Aerodynamic Characteristics and Weight Data:

These values are supplied by the program aerodynamicist using experience with the class of airplane being considered and the desired characteristics of the new design. These data include life and drag coefficients and the coefficients for an airplane weight calculation. Other values needed are tail size parameters, reserve fuel, air density, and constants used in take-off and landing distance calculations. Many of the constants and coefficients used are empirical. Some of the important values are shown in the following table:

TABLE XXV
Aerodynamic Constants and Coefficients

		(1) Single Engine Aircraft	Twin Engine Aircraft
C_L Max. Landing		2.19	1.87
C_L Max. Take-off		1.43	1.48
f Total Diesel (2)	m^2	.30	.50
f Diesel-f-Gasoline			
Cooling:	m^2	.0046	−.0033(5)
Nacelle size	m^2	—	.0084(5)
Reserve fuel(6)	hours	.75	.82
$\Delta C_D / \Delta C_L{}^2$ (3)		.0655	.0597
η_p Cruise(4)		.85	.85

(1) The data are for diesel and gasoline airplanes of constant size. The larger airplanes for constant mission comparisons are scaled up as required from this basis.
(2) Equivalent flat plate area used to calculate profile drag.
(3) Induced drag factor.
(4) Propeller Efficiency $= \frac{\text{thrust power}}{\text{shaft power}}$
(5) Each engine.
(6) Includes allowance for climb, take-off and reserve.

In the case of the diesel twin, the drag was decreased by about 2% to allow for the smaller frontal and wetted area relative to the gasoline engine nacelle. The projected frontal area of the single engine airplane does not change since the cabin cross section stays the same.

The airplane size parameters obtained when the program is run using the above information include wing area, gross weight and fuel weight. Sets of data made up of inputs and resulting outputs allow synthesized airplanes of different sizes and with different engines to be compared. The process is very simplified and is by no means a complete airplane design process but it does allow preliminary concepts to be evaluated side by side on the basis of the same set of assumptions.

4.3.2 Calculation Method

1. A trial airplane weight is selected.

2. Wing area required for landing is calculated using an empirical relation containing weight, wing lift and required landing distance.

3. Wing area required for take-off is calculated using an empirical relation containing weight, wing lift, power and required take-off distance.

4. Using the larger wing area from 2 or 3, cruise drag is calculated accounting for wing area, tail area, fuselage size, nacelle size and miscellaneous items.

5. Cruise power required is calculated to meet the speed requirement.

6. Fuel required to meet the range is then calculated.

7. Airplane weight is then calculated using an empirical relation accounting for fuel weight, payload, wing area and power.

8. The weight calculated in Item 7 is compared with the trial weight of Item 1. If different, a new trial weight is selected and the process repeated.

Using the data and methods described, hypothetical gasoline and diesel powered airplanes were synthesized and compared in two ways. In one case, the airframe was held constant and the mission profile was allowed to change when the power plant type changed. In the other case, the mission requirements were held constant and the airplane needed to perform that mission changed size as necessary to meet the mission requirements. These comparisons were made for both the single 149 kW engine and twin 298 kW engine airplanes.

4.3.3 Results of the Simulation Program

The results of the aircraft performance simulation program are shown in the Tables XXVI and XXVII.

Table XXVI shows the differences in aircraft performance for a fixed airplane size.

The fixed parameters are:

- Max. take-off weight
- Max. landing weight
- Take-off distance
- Landing distance
- Stall speed
- Wing area

The advantages of the diesels with their high cruise power output and low fuel consumption can be readily seen in the basic parameters of range, speed, and payload.

TABLE XXVI
Comparison Gasoline and Diesel Aircraft Engines
Airplane Size Fixed, Variable Performance

		Single-Engine Diesel*	Single-Engine Gasoline*	Twin-Engine Diesel*	Twin Engine Gasoline*
Rated power	kW/RPM	149/2400	149/2600	298/2300 (ea)	298/2267 (ea)
Max. take-off weight (gross)	kg	1349	1349	3654	3654
Max. landing weight	kg	1349	1349	3654	3654
Standard empty weight	kg	829	842	2275	2385
Useful load	kg	520	508	1378	1269
Usable fuel	ℓ/kg	251/180	241/174	908/653	832/598
Payload (with full fuel)	kg	340	334	726	671
Altitude —m/% power		3048/100%	3048/75%	7620/81.5%	7620/75%
Max. cruise speed	km/hr	324	291	474	448
Range	km	1481	1468	2592	1726
Altitude — m/% power		3048/75%	3048/75%	7620/81.5%	7620/75%
Speed	km/hr	289	291	474	448
Range	km	1968	1468	2592	1726
Take-off distance (normal, OV. 15 m)	m	579	579	701	701
Landing distance (normal, OV. 15 m)	m	369	369	677	677
Stall speed (landing)	km/hr	85	85	135	135
Wing area	m^2	17.7	17.7	22.4	22.4

*All engines are turbocharged.

Table XXVII shows the differences in airplane size for a fixed performance.

The fixed parameters are:

- Payload
- Max. Cruise Speed
- Range

The gasoline powered airplanes are bigger and considerably less efficient.

TABLE XXVII
Comparison Gasoline and Diesel Aircraft Engines Performance Fixed, Variable Airplane Size

		Single-Engine Diesel*	Single-Engine Gasoline*	Twin-Engine Diesel*	Twin-Engine Gasoline*
Rated power	kW	149	198	298 (ea)	414 (ea)
Max. take-off weight (gross)	kg	1349	1525	3654	4981
Max. landing weight	kg	1349	1525	3654	4981
Standard empty weight	kg	829	973	2275	3140
Useful load	kg	520	552	1378	1842
Usable fuel	ℓ/kg	251/180	294/211	908/653	1552/1116
Payload (with full fuel)	kg	340	340	726	726
Altitude — m/% power		3048/100%	3048/75%	7620/81.5%	7620/75%
Max. cruise speed	km/hr	324	324	474	474
Range	km	1481	1481	2592	2592
Altitude — m/% power		3048/75%	3048/100%	7620/81.5%	7620/75%
Speed	km/hr	289	324	474	474
Range	km	1968	1481	2592	2592
Take-off distance (normal, OV. 15 m)	m	579	564	701	701
Landing distance (normal, OV. 15 m)	m	369	427	677	689
Stall speed (landing)	km/hr	85	93	135	135
Wing area	m^2	17.7	17.0	22.4	29.9

*All engines are turbocharged.

4.4 Operating Cost Estimates

Production costs were estimated by assuming that new airplanes would be designed and equipped with the diesel engines and, alternatively, compatible gasoline engines. Development, material and labor costs were chosen to be of roughly the correct magnitude, but are intended primarily to illustrate cost differences due to using diesel instead of gasoline engines. Operating cost estimates were made using figures obtained from current estimates of average operating costs.

4.4.1 Airplane Acquisition Cost Estimates

The acquisition cost estimates were based on information from the airplane synthesis process. The airplane empty weights were the main parameters used with FY79 rates for labor, material costs and OEM engine costs. The estimating methods used are based on historical data and "learning curve" theory. An airframe weight was estimated from the operating empty weight. This was used with estimating data to get material weights to which material cost could be applied. Manhour per pound data were used to get labor content to which labor rates were applied. A production run of 6000 units was used to amortize assumed development costs and to locate factors on the learning curves. When a basic factory cost was summed up, assumed manufacturer's and dealer's mark-ups were applied. Costs were included for currently typical optional equipment and avionics selections. The final total represented a dealer's price tag figure for a typically equipped airplane. Both the single and the twin were considered to be all new designs. The same sets of reasonably realistic assumptions were used throughout so the results are quite adequate for looking at differences between gasoline and diesel airplane prices within the overall accuracy of this study. Acquisition price percentage changes from the diesel to the gasoline engine powered airplanes is shown on the cost summaries. See Tables XXVIII and XXX for the single and twin engine airplanes, respectively.

The factors used in calculating these costs are summarized in the Tables XXIX and XXXI.

TABLE XXVIII
Cost Summary
Single Engine

Use 500 Hours/Year

Airplane		**Diesel**	**Gasoline**	**Equal Plane Performance Gasoline***
Acquisition cost		Base	−4%	+11%
Fuel	$/hr	8.54	9.90	13.20
Oil	$/hr	.43	.38	.51
Inspection & maintenance				
Airframe	$/hr	2.59	2.59	2.59
Engine	$/hr	4.00	2.59	2.59
Propeller	$/hr	.30	.30	.30
Engine exchange	$/hr	4.28	7.57	10.09
Hangar rental	$/hr	2.40	2.40	2.40
Insurance	$/hr	5.90	5.90	6.54
Total DOC/Hr.	$/hr	28.44	31.63	38.22
Total per year	$	14220	15815	19110
Total for 5 years	$	71100	79075	95550

*Bigger airplane required to do the same job as the diesel.

TABLE XXIX
Main Operating Cost Factors Summary
Single Engine

Factor		Diesel	Gasoline	Equal Plane Performance Gasoline
Cruise speed @ 3048 m	km/hr	324	291	324
Total cruise power output	kW	149	112	149
BSFC	g/kW/hr	228	268	268
Fuel density	kg/ℓ	.81*	.72	.72
Fuel cost	$/ℓ	.20*	.24	.24
Oil density	kg/ℓ	.87	.87	.87
Oil cost	$/ℓ**	1.11	1.11	1.11
Engine exchange cost	$	12841	10604	14103†
Time between overhauls	hours	3000	1400	1400

*Jet fuel.

**Oil consumption is 1% of fuel consumption.

†$/Rated kW ratio ($\frac{198}{149}$) from 149 kW gasoline engine.

TABLE XXX
Cost Summary
Twin Engine

Use 1000 Hours/Year

Airplane		Diesel	Gasoline	Equal Plane Performance Gasoline*
Acquisition cost		Base	−3%	+7%
Fuel	$/hr	26.79	42.30	58.69
Oil	$/hr	6.98	1.53	2.13
Inspection & maintenance				
Airframe	$/hr	9.20	9.20	9.20
Engine	$/hr	13.80	13.80	13.80
Propellers	$/hr	2.00	2.00	2.00
Engine exchange	$/hr	19.82	34.84	48.34
Hangar rental	$/hr	3.30	3.30	3.30
Insurance	$/hr	6.18	5.99	6.59
Total DOC/Hr.	$/hr	88.07	112.96	144.05
Total per year	$	88070	112960	144050
Total for 5 years	$	440350	564800	720250

*Bigger airplane required to do the same job as the diesel.

TABLE XXXI
Main Operating Cost Factors Summary
Twin Engine

Factor		Diesel	Gasoline	Equal Plane Performance Gasoline
Cruise speed @ 7620 m	km/hr	474	448	474
Total cruise horsepower	kW	501	447	620
BSFC	g/kW/hr	213	286	286
Fuel density	kg/ℓ	.81*	.72	.72
Fuel cost	$/ℓ	.20*	.24	.24
Oil density	kg/ℓ	.94**	.87	.87
Oil cost	$/ℓ†	6.34**	1.11	1.11
Engine exchange cost	$	24775	20907	29008††
Time between overhauls	hours	2500	1200	1200

*Jet fuel.

**Synthetic oil.

†Oil consumption is 1% of fuel consumption.

††$/Rated kW ratio ($\frac{414}{298}$) from 298 kW gasoline engine.

The columns headed "gasoline" refer to the airplanes of equivalent size to the diesels but with these mission capability as indicated in the performance estimates. The "equal plane performance gasoline" column refers to the airplanes that will do the same missions as the diesels but are bigger and less efficient.

The cost summary pages show the considerable overall cost advantage of the diesel powered airplanes. Gasoline airplanes of equivalent size cost less initially but this advantage is not significant in view of the reduced mission capability and higher overall costs. The biggest factors in raising the gasoline airplanes operating costs are fuel and overhaul expense, as indicated.

4.5 Propeller Noise Estimates

Propeller performance estimates were made to get some idea of the propeller sizes needed to realize a cruise propulsive efficiency of .85 for both the single and twin engine airplanes. These calculations indicated that a two-blade, 2134mm diameter, constant speed propeller will work for the single engine airplane. The propellers indicated for the twin are 2057mm three-blade. Estimates of 305m flyover noise predict values of 72 dB(A) for the single and 74 dB(A) for the twin. These compare favorably to the limits of 77.5 dB(A) and 80 dB(A), respectively. Limits are based on airplane weight as set out in FAR 36, Appendix F. A favorable correction factor can reasonably be expected, creating a greater margin relative to the limits. The correction factor is based on detailed take-off performance estimates that are beyond the scope of this study. Even without correction factors, the noise regulations appear to present no problem for the conceptual diesel airplanes.

5.0 CONCLUSIONS

The study indicates that the diesel engine promises to be a superior powerplant for general aviation aircraft.

1. The diesel engine offers high cruise power at altitude and low fuel consumption. This will result in improved range, high cruising speed and more payload for a diesel engined aircraft.
2. The diesel powered airplane has a considerable overall cost advantage. Gasoline airplanes of equivalent size cost less initially, but this advantage is offset by reduced mission capability and higher operating costs.
3. The diesel engine presents no installation problems. Although the radial configuration is different than current gasoline engines, the mounting to the airframe is essentially the same and requires no major airframe modifications.
4. The engine can run on diesel fuel and jet fuel.
5. The independent turbo loop provides these features:
    A. Easy cold and hot starts.
    B. Can crank engine indefinitely.
    C. Electric power available independent of engine operation (APU mode).
    D. Reduced battery capacity.
    E. Cabin cooling or heating available while aircraft is on the ground.
6. The radial cylinder configuration results in:
    A. Low engine weight.
    B. Reduced engine friction.
    C. Absence of piston inertia forces.
    D. Compactness of the power package.
7. The two-stroke cycle feature results in:
    A. Weight reduction.
    B. Improved reliability due to fewer parts.
    C. Reduced frontal area.

8. Alternate solutions are available for the high risk technologies:

   A. Limited cylinder cooling can be substituted for uncooled cylinders which require the use of ceramic components.

   B. A conventional combustor can be substituted for the catalytic combustor.

   C. An engine driven alternator can replace the high speed turbo driven alternator.

6.0 RECOMMENDATIONS

The program has shown the feasibility of the diesel engine as a powerplant for general aviation aircraft. the technologies which were applied to the engine designs are currently under development under various Government contracts but require more experience and adaptation to an aircraft engine. It is recommended that development programs be initiated starting with single cylinder test engines and leading to full scale multi-cylinder engines for test cell performance and testing and eventual flight experience.

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APPENDIX A

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APPENDIX B
Metric Conversion Factors

From:	Multiply by:	To:
kW	1.341	HP
mm	.0394	inch
liters cu. dm	61.024	in^3
kg	2.2046	lb
km	.6214	mile
kPa	.145	psi
m/sec	196.85	fpm
kW/kg	.6083	HP/lb
kW/cm^2	8.656	HP/in^2
kW/liter	.022	HP/in^3
km	.5401	nautical mile
g/kW-hr	.00164	lb/HP-hr
kg/l	62.453	lb/ft^3
kcal	3.9683	BTU
N-m	.7375	ft-lb
MPa	145	psi
kcal/min-kW	2.959	BTU/min-HP
m	3.2808	ft
liter	.264	gallon
kcal/kg	1.8	BTU/lb
kW	56.826	BTU/min

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16. Abstract

This design study reintroduces the diesel engine as an aircraft powerplant. A methodical study was conducted to arrive at engine configurations and applicable advanced technologies. Two engines are discussed, a 300 kW six-cylinder engine for twin engine general aviation aircraft and a 150 kW four-cylinder engine for single engine aircraft. The description of each engine includes concept drawings, a performance analysis, stress and weight data, and a cost study. This information was used to develop two airplane concepts, a six-place twin and a four-place single engine aircraft. The aircraft study consisted of installation drawings, computer generated performance data, aircraft operating costs, and drawings of the resulting airplanes. The performance data show a vast improvement over current gasoline-powered aircraft. A second report, NASA CR-3261, covers a design, performance, and cost study of a 186 kW aircraft diesel engine applicable to single and twin engine aircraft. A 5 year program consisting of component development and single-cylinder and multicylinder performance and endurance tests of the 186 kW engine is covered in CR-3261.

17. Key Words (Suggested by Author(s))
Aircraft diesel engine; Diesel aircraft engine; Advanced engines; Adiabatic diesel engine; Diesel with independent turbocharger loop; High speed starter/alternator for aircraft diesel; Two-stroke cycle aircraft diesel; Radial diesel aircraft engine

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