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LIGHTWEIGHT DIESEL AIRCRAFT ENGINES FOR GENERAL AVIATION

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SUMMARY

This design study reintroduces the diesel engine as an aircraft powerplant. A methodical design study was conducted to arrive at new diesel engine configurations and applicable advanced technologies. Two engines are discussed and the description of each engine includes concept drawings. A performance analysis, stress and weight prediction, and a cost study were also conducted. This information was then applied to 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 shows a vast improvement over current gasoline-powered aircraft. At the completion of this basic study, the program was expanded to evaluate a third engine configuration. This third engine incorporates the best features of the original two, and its design is currently in progress. Preliminary information on this engine is presented.

INTRODUCTION

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 (400 HP) diesel for a twin engined airplane and a 149 kW (200 HP) diesel for a single engined aircraft.

The study consisted of three major phases:

1. Technology Analysis.

   A survey of available aviation and automotive sources was conducted to identify new developments which offer potential benefits to an aircraft engine. These technologies were ranked and then evaluated 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 Step 2 were then used in an engine-aircraft integration study to determine the performance improvement of an airplane equipped with these diesel engines.

Some of the technologies which were applied in these engine designs are anticipated to be available in the late 1980's. These technologies result in high level of performance and, although advanced, are not untried. The adiabatic engine, the catalytic combustor, and the high speed alternator envisioned 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 concepts were included primarily to show what may be ultimately possible. However, alternate less advanced solutions are also given which will result in a small reduction of performance when compared to the ultimate; but nevertheless will result in a powerplant which far outperforms the current gasoline aircraft.

RESULTS AND DISCUSSION

Advantages of the Diesel Engine

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 in fact the engine could run adequately at a much lower compression ratios. New technologies make it possible to combine good startability with low firing pressures at full load. This study shows that the weight of the diesel can be reduced below that of current gasoline aircraft engines.

The diesel engine offers other advantages in addition to low fuel consumption, i.e.:

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. Multi-fuel capability.
5. No carburetor icing problems.
6. Improved altitude performance.
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. No electrical interference from ignition system

Previous Aircraft Diesel Engines

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

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

Some observations can be made from these tables. Average specific weight values are:

4-Stroke cycle engines	.710 kW/Kg
2-Stroke cycle engines	.926 kW/Kg
Aircooled engines	.783 kW/Kg
Liquid-cooled engines	.923 kW/Kg

The numbers indicate that a 2-stroke cycle engine can be expected to be lighter than a 4-stroke cycle engine. A comparison of aircooled and liquid cooled engines would seem to favor the liquid-cooled engine. However, the engine weights of liquid-cooled engines tabulated do not include the weight of the cooling package. With this modification, the corrected values then become:

Aircooled engines	.783 kW/Kg
Liquid-cooled engines	.805 kW/Kg

New Engine Design Study

- 298 kW Engine -

In addition to considering the historical background of aircraft diesel engines, a literature search was made and a technology base was established to evalute any concepts that may be considered for an all new engine design.

The following criteria were observed in considering any new ideas:

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 1979 EPA 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 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.

Design attributes that had to be considered included:

Performance, weight, size, C. G., fuel economy, reliability, multi-fuel capability, noise, life cycle cost, component costs, and technology required.

Figure 1 is a flow chart that shows the different possible combinations of design features that were considered and evaluated within the frame work outlined above.

A detailed description of each of these features is beyond the scope of this paper, but was included in the original basic study. The evaluation then resulted in the technologies that follow from Figure 1 by taking the high score items along the "common to all versions" and "radial 2-stroke cycle" lines.

Common to All Versions Line	Radial 2-Stroke Cycle Line
Open Chamber	Individual Cylinders
Ceramic Pistons	Low Compression Ratio
Insulated Exhaust Manifolds	Geared Prop Drive
No Cylinder Cooling	Loop Scavenge
Tool Steel Piston Rings	Independent Turbo Loop
Composite Connecting Rods	Catalytic Combustor
Synthetic Lube Oil	
High Pressure Fuel Injection	
Electronic Controls	
Conventional Oil Filter	

Conventional Fuel Filter
Pendulum Damper

The engine concept was then laid out around these features.

Figure 2 shows an artist rendering of the proposed 298 kW 6-cylinder engine. Figure 3 shows the schematic of this engine. The design incorporates the technologies which were defined before.

The chosen system uses the 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.

The cylinder liner and piston top are ceramics and, therefore, cylinder cooling will not be required. Tool steel piston rings will be required. Cooling air will be used only for the aftercooler, oil cooler, and the fuel injectors. The exhaust ports will be oil cooled.

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.

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 two-way valve is placed in the intake manifold. To start the engine, this valve is in the vertical position of 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 the maximum turbo speed, and the starter now runs as an alternator. Hot, high pressure air will flow to the engine when the two-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 cold days. 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.

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 during cranking. Thus, with this low compression ratio, the firing pressures are held down to 9650 kPa (1400 psig) at full load resulting in low engine weight.

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

3. Hot start problems are eliminated.

4. 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.

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

The use of synthetic oil is required in this engine design due to the hot cylinders. The synthetic oil can take higher temperatures and requires fewer changes than conventional petroleum bases oils. 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 relatively high oil consumption which is inherent to 2-stroke cycle engines.

The engine design concept is shown in Figures 4 through 8. 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 to interfere with the scavenging of the previous cylinder in the firing sequence. The piston tops are ceramic.

The small end of the connecting rods is designed to allow free rotation of the piston. This should reduce the wear rate of the piston rings. The big end of the connecting rods is 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 inertias 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.

Immediately in front of the first main bearing are 6 individual injection pumps, operated by a single lobed cam ring. Individual pumps were chosen to improve engine realiability - failure of one pump still leave 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 8 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.

The operating parameters for the 298 kW engine are shown in Table III and the sea level performance curve is included as Figure 9.

In addition to the performance projections, detailed calculations were made of weights, torsional vibrations, power component stresses, turbomachinery sizing, cooling requirements, and projected costs to manufacture.

Results of each of these studies are very favorable for the diesel engine, however, these details are beyond the scope of this presentation.

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. NOx concentration will be minimized due to the relatively low peak pressures (9650 kPa) and lower peak temperatures.

3. Smoke levels should be relatively low since the minimum trapped A/F ratio will always be on the order of at least 24:1.

As with emissions, only qualitative evaluations were made of the anticipated engine noise as listed below:

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.

As was described earlier, this engine's feasibility relies heavily on new technology. 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.
8. Efficient fuel injection systems.

A comparison of the 298 kW engine was made with the 4-stroke cycle GTSIO-520-H gasoline engine.

Table IV shows this comparison in a tabular form.

Figure 10 is a size comparison. The frontal area of the diesel en[illegible] 78% of that of a comparable gasoline engine.

- 149 kW Engine Design -

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 east of maintenance carry more weight than in the case of the corporate aircraft.

The engine will be easier to develop and manufacture.

Figure 11 shows an artist rendering of the proposed engine.

Figure 12 shows the schematic of the 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.

Calculations of the heat transfer through cylinder walls, as well as single cylinder engine tests have confirmed that the heat flux is highest through the cylinder walls surrounding the combustion chamber (when the piston is in top dead center). The maximum gas temperature to which the cylinder wall is locally 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 predicted that most 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. Using this approach results in an increase of cooling drag when compared to uncooled cylinders; but eliminates the need for ceramic components, thus making the engine a much more viable alternative for nearer term applications.

Since this smaller engine does not have the independent turbocharger loop, low compression ratio pistons cannot be utilized. Other means must be found to keep firing pressures down to 9,650 kPa. It becomes 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 larger 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. This is not the case here, therefore for this case a variable compression ratio piston is recommended.

The VCR piston, Figure 13 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. Even the 17:1 compression ratio, however, 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.

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.

It also 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. The engine reliability is somewhat improved by this approach due to fewer parts required.

The chosen BMEP of approximately 1200 kPa is 100 kPa higher than the BMEP of the larger 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 cylinder. It should, therefore, be possible to obtain this higher BMEP without an increase of cylinder temperatures. The detailed cycle calculations bear this out.

The 149 kW engine concept design then is shown in the Figures 14 through 18.

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 the slipper type. The big ends 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 essential in this engine because of lower cylinder temperatures (compared to the ceramic), but may be advantageous 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 forced the use of 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 still results in a lighter engine than the geared drive.

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. Two versions of the engine were drawn. One, as shown, for an aircraft with fixed landing gear. A second version of the engine was drawn which accommodates a retractable nose gear. The coolers are moved outboard and the turbocharger raised to provide space between cylinders #2 and #3 for the nose gear strut.

Table V presents the operating parameters of the 149 kW engine concept and Figure 19 shows the projected fuel consumption curve for this engine.

As with the 298 kW engine, calculations were made to define power component stresses, turbocharger and cooler sizing, torsional vibration definition, as well as cost and weight projections.

Table VI and Figure 20 are presented to show comparisons with today's state-of-the-art gasoline engines.

Again, as with the larger engine, all comparisons favor the diesel engine.

Engine/Airframe Integration

This study was conducted as a subcontract 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.

Engine Installation

Installation design layouts were made which show the 298 kW diesel mounted on a twin engine airplane and the 149 kW engine installed in a single engine aircraft with retractable landing gear. The Figures 21 through 23 show the twin engine installation; the Figures 24 through 26 show the single engine installation. Figure 27 and 28, the three view drawings, are based on the wing areas indicated by the performance synthesis program, the engine drawings and standard airplane proportions. Some pertinent features about the installation are as follows:

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.

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.

Aircraft Configurations

Three view sketches of the airplane are shown in the Figures 27 and 28. Following are some characteristics of both planes:

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 27). 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)	(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 28 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 = .79a
Prop speed at economy cruise	1,800 rpm

Tip speed at economy cruise	201 m/sec
Prop ground clearance	356 mm

2. 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 -	(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

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. 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 sufficient 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.

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 powerplant 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 and the twin 298 kW engine airplanes.

The results of the aircraft performance simulation program are shown in the Tables VII and VIII.

Table VII 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

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Table VIII 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.

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.

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 air-frame 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 600 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 IX and X for the twin and single engine airplanes, respectively.

The columns headed "gasoline" refer to the airplanes for equivalent size to the diesels but with the 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 tables show the considerable overall cost advantages of the diesel powered airplanes. Gasoline airplanes of equivalent size cost less initially but this advantage is not sufficient 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.

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 twin and single engine airplanes. These calculations indicated that a two-blade, 84 inch diameter, constant speed propeller will work for the single engine airplane. The propellers indicated for the twin are 81 inch three-blade. Estimates of 1000 ft. 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), 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.

186 kW (250 HP) Engine Configuration

A third engine configuration is currently under evaluation and design definition. This engine is rated at 186 kW (250 HP) net shaft power at 25,000 ft. cruise altitude. Table XI outlines the pertinent features of this engine configuration. Engine specifications are summarized in Table XII.

As shown in this table, a cruise fuel consumption value of .36 lb/hp-hr is projected for this engine. Some pertinent data comparing this projected fuel consumption with other engines is shown in Table XIII. Note that the projected value is relatively conservative compared to actual running engines, confirming the fact that an engine such as proposed is within reach.

CONCLUSIONS

A study indicates that the diesel engine promises to be a superior powerplant for general aviation aircraft for the following reasons:

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.

5. The independent turbo loop provides:

   - Easy cold and hot starts
   - Can crank engine indefinitely
   - Electric power available independent of engine operation (APU mode)
   - Reduced battery capacity
   - Cabin cooling or heating available while aircraft is on the ground

6. The radial cylinder configuration results in:

   - Low engine weight
   - Reduced engine friction
   - Absence of piston inertia forces
   - Compactness of the power package

7. The two-stroke cycle feature results in:

   - Weight reduction
   - Improved reliability due to fewer parts
   - Reduced frontal area

8. The following key technologies will be required to demonstrate the feasibility of the engines proposed in this study:

1985 (250 HP Engine)

- Combustion/scavenging in 2-cycle loop scavenged system
- High pressure ratio, high efficiency turbocharger
- High pressure fuel injection system
- High speed starter/alternator.

1985-2000 (400 HP Engine)

- All of the above
- Ceramic components
- Advanced lubricants (solids, air bearings, etc.)
- Catalytic combustor

TABLE I
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° A	2	liquid	12	[illegible]	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	135	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 II
Specific Data of Previous Aircraft Diesels

Make	Cycle	S/B	BMEP kPa	Piston Speed m/sec	Piston Heat Load kW/cm²	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

TABLE III
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	

TABLE IV
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

TABLE V
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	˚00 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	

TABLE VI
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.[illegible]

TABLE VII
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 VIII
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	[illegible]8 (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	294/21[illegible]	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.

TABLE IX
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 X
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 XI

250 Horsepower Engine Configuration Features

Combined best features of 400 and 200 horsepower without high risk ceramic components.

Radial/geared

2-Stroke

4-Cylinder

Independent turbocharger loop

Conventional combustor

High pressure turbocharger (8:1)

TABLE XII

250 Horsepower Engine Configuration Specification

Displacement:	246 inches^3
Rated Speed:	3500 RPM
Power:	250 Net Horsepower at 25,000 ft.
	360 Net Horsepower at Sea Level
BSFC:	.3[illegible] lb/hp-hr at Cruise
Weight:	384 lb.

TABLE XIII

Basis For Fuel Consumption Projections

1. Analytical fuel/air cycle calculations.

2. Verified by past published data on both 2 and 4 cycle diesel engines of similar features (low C.R. and high boost).

A.	4-Cycle-AVCR-1360		
	8:1 C.R.	250 BMEP	.395 BSFC
	4-Cycle-LCR-1790		
	11:1 C.R.	263 BMEP	.373 BSFC
B.	2-Cycle-Napier Nomad		
	Base Engine	205 BMEP	.388 BSFC
	With Turbocompounding		.345 BSFC
	2-Cycle-Junkers Jumo		.345 BSFC
	2-Cycle-DDAD-8V92T	110 BMEP	.383 BSFC
	2-Cycle-McCulloch	153 BMEP	.399 BSFC
		Average	.375

3. Additional features of proposed engine favoring improved fuel consumption.

   A. Reduced friction - only two-main bearings, no valve train, no mechanical blower.

   B. Signi[illegible]ly improved injection systems and turbomachinery ava[illegible] with modern technology.

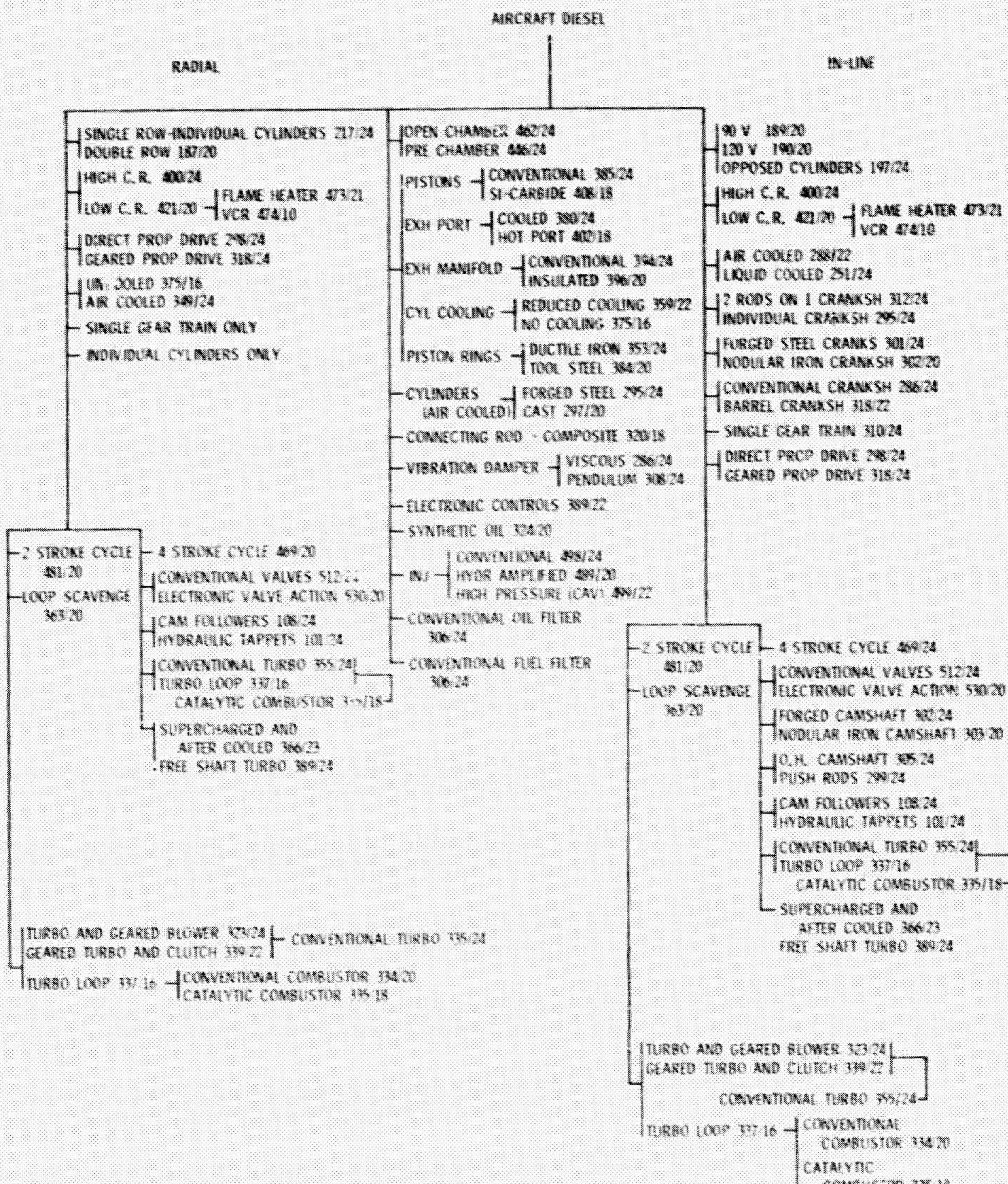

AIRCRAFT DIESEL
RADIAL
IN-LINE
SINGLE ROW-INDIVIDUAL CYLINDERS 217/24
DOUBLE ROW 187/20
HIGH C.R. 400/24
LOW C.R. 421/20
FLAME HEATER 473/21
VCR 474/10
DIRECT PROP DRIVE 298/24
GEARED PROP DRIVE 318/24
AIR COOLED 349/24
SINGLE GEAR TRAIN ONLY
INDIVIDUAL CYLINDERS ONLY
2 STROKE CYCLE 481/20
LOOP SCAVENGE 363/20
4 STROKE CYCLE 469/20
CONVENTIONAL VALVES
ELECTRONIC VALVE ACTION 530/20
CAM FOLLOWERS 108/24
HYDRAULIC TAPPETS 101/24
CONVENTIONAL TURBO 355/24
TURBO LOOP 337/16
CATALYTIC COMBUSTOR
SUPERCHARGED AND AFTER COOLED 366/23
FREE SHAFT TURBO 389/24
TURBO AND GEARED BLOWER 323/24
GEARED TURBO AND CLUTCH 339/22
CONVENTIONAL TURBO 335/24
TURBO LOOP 337/16
CONVENTIONAL COMBUSTOR 334/20
CATALYTIC COMBUSTOR 335/18
OPEN CHAMBER 462/24
PRE CHAMBER 446/24
PISTONS
CONVENTIONAL 385/24
SI-CARBIDE 408/18
EXH PORT
COOLED 380/24
HOT PORT 402/18
EXH MANIFOLD
CONVENTIONAL 394/24
INSULATED 396/20
CYL COOLING
REDUCED COOLING 359/22
NO COOLING 375/16
PISTON RINGS
DUCTILE IRON 353/24
TOOL STEEL 384/20
CYLINDERS (AIR COOLED)
FORGED STEEL 295/24
CAST 297/20
CONNECTING ROD - COMPOSITE 320/18
VIBRATION DAMPER
VISCOUS 286/24
PENDULUM 308/24
ELECTRONIC CONTROLS 389/22
SYNTHETIC OIL 324/20
INJ
CONVENTIONAL 498/24
HYDR AMPLIFIED 489/20
HIGH PRESSURE (CAV) 499/22
CONVENTIONAL OIL FILTER 306/24
CONVENTIONAL FUEL FILTER 306/24
90 V 189/20
120 V 190/20
OPPOSED CYLINDERS 197/24
HIGH C.R. 400/24
LOW C.R. 421/20
FLAME HEATER 473/21
VCR 474/10
AIR COOLED 288/22
LIQUID COOLED 251/24
2 RODS ON 1 CRANKSH 312/24
INDIVIDUAL CRANKSH 295/24
FORGED STEEL CRANKS 301/24
NODULAR IRON CRANKSH 302/20
CONVENTIONAL CRANKSH 286/24
BARREL CRANKSH 318/22
SINGLE GEAR TRAIN 310/24
DIRECT PROP DRIVE 298/24
GEARED PROP DRIVE 318/24
2 STROKE CYCLE 481/20
LOOP SCAVENGE 363/20
4 STROKE CYCLE 469/24
CONVENTIONAL VALVES 512/24
ELECTRONIC VALVE ACTION 530/20
FORGED CAMSHAFT 302/24
NODULAR IRON CAMSHAFT 303/20
O.H. CAMSHAFT 305/24
PUSH RODS 299/24
CAM FOLLOWERS 108/24
HYDRAULIC TAPPETS 101/24
CONVENTIONAL TURBO 355/24
TURBO LOOP 337/16
CATALYTIC COMBUSTOR 335/18
SUPERCHARGED AND AFTER COOLED 366/23
FREE SHAFT TURBO 389/24
TURBO AND GEARED BLOWER 323/24
GEARED TURBO AND CLUTCH 339/22
CONVENTIONAL TURBO 355/24
TURBO LOOP 337/16
CONVENTIONAL COMBUSTOR 334/20
CATALYTIC COMBUSTOR 335/18

Figure 1

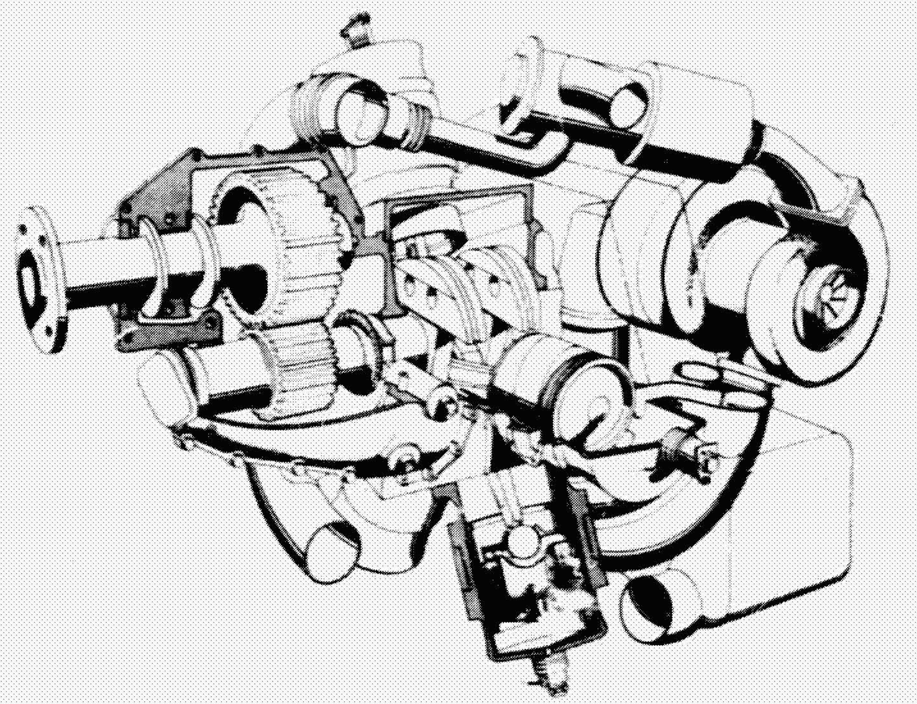


FIGURE 2 298 kW DIESEL AIRCRAFT ENGINE

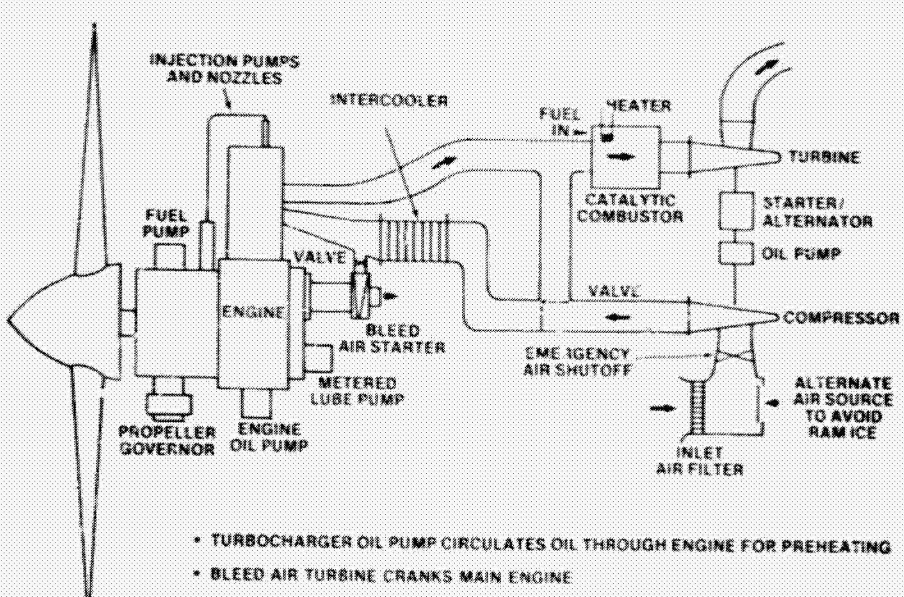


FIGURE 3 SCHEMATIC 2-STROKE ENGINE WITH INDEPENDENT TURBO LOOP/HOT ENGINE CONFIGURATION—NO COOLING/LOW COMPRESSION RATIO PISTONS

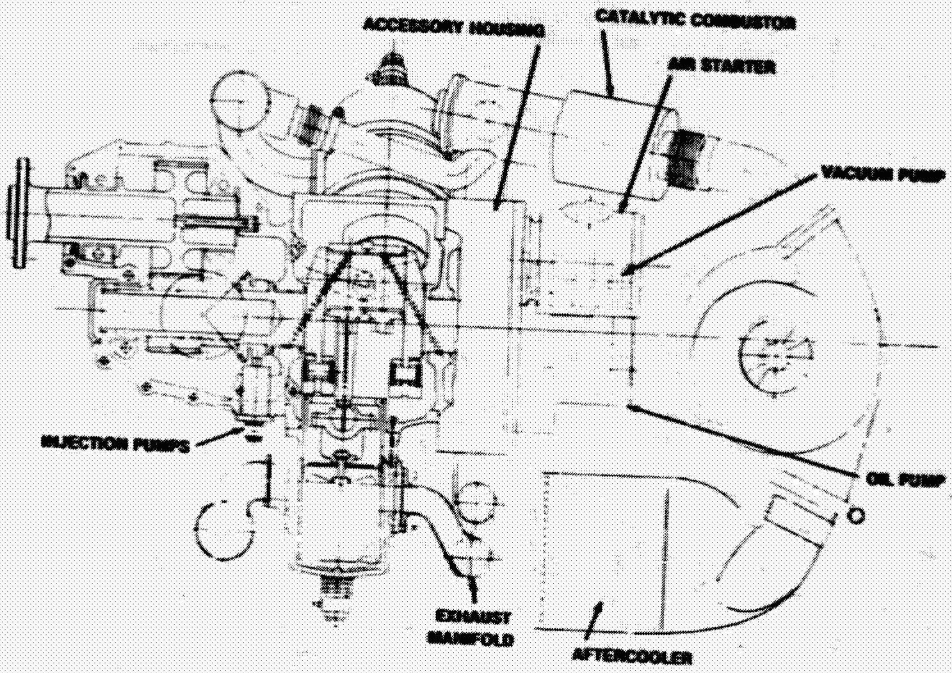


FIGURE 4 298 kW AIRCRAFT DIESEL —LONGITUDINAL SECTION

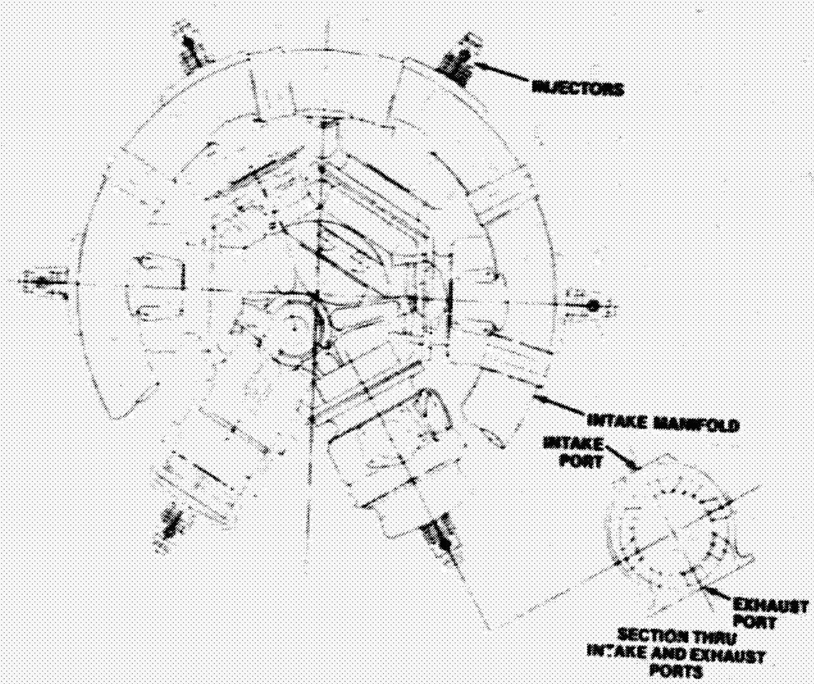


FIGURE 5 8 kW AIRCRAFT DIESEL —CROSS SECTION

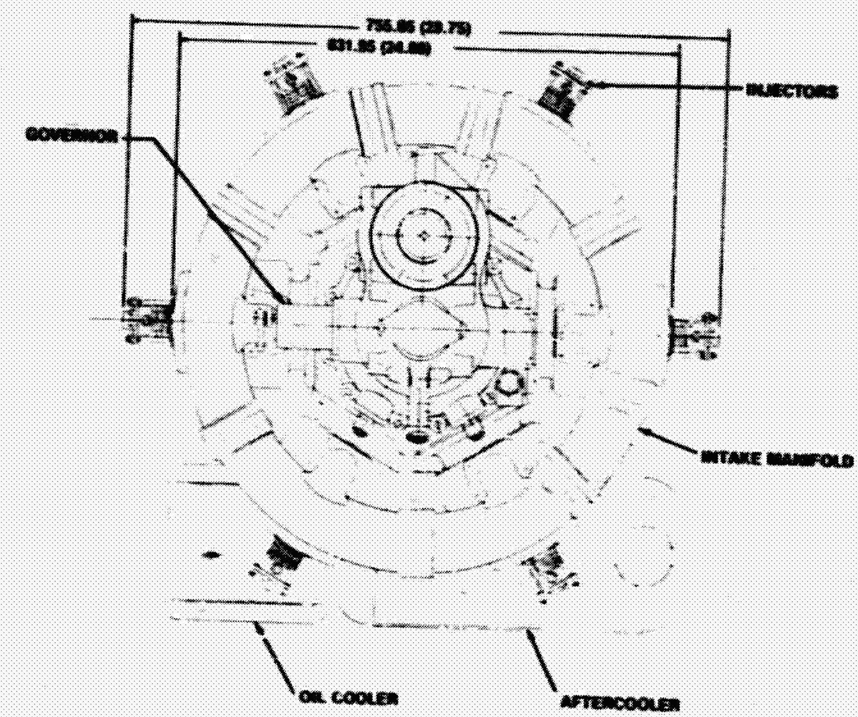


FIGURE 6 25[illegible]W AIRCRAFT DIESEL—FRONT VIEW

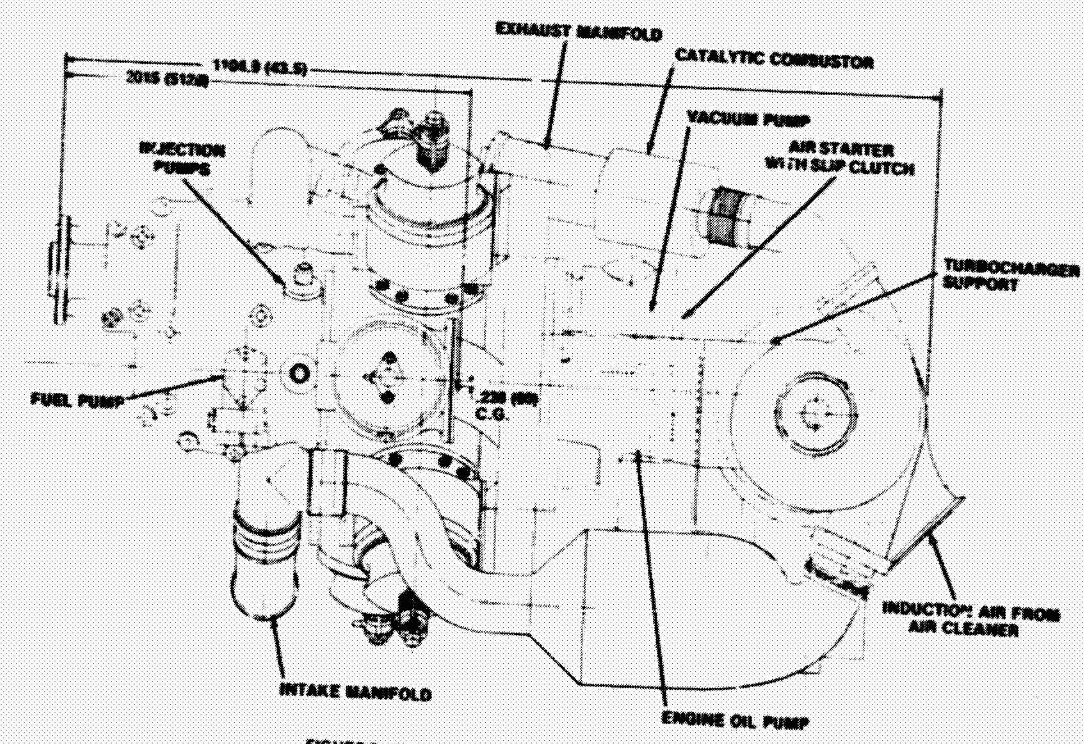


FIGURE 7 298 kW AIRCRAFT DIESEL—SIDE VIEW

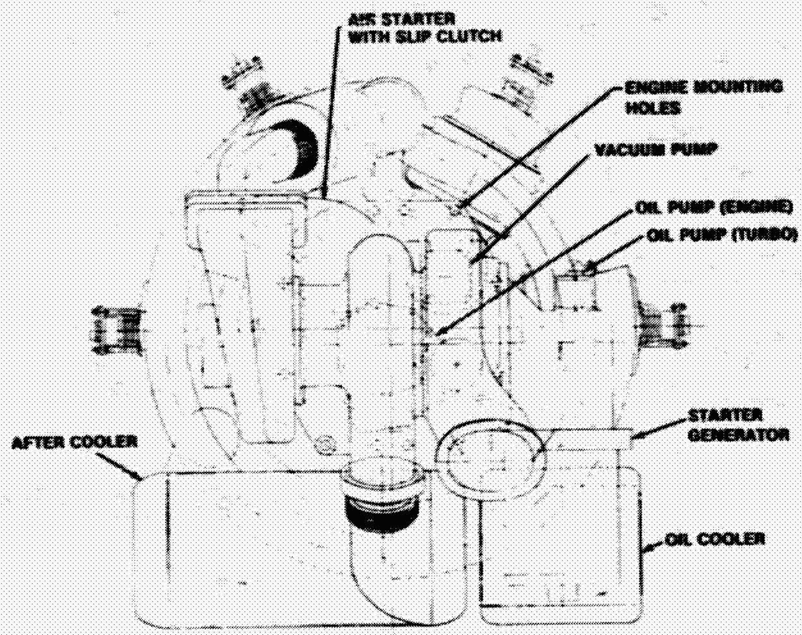


FIGURE 8 298 kW AIRCRAFT DIESEL—REAR VIEW

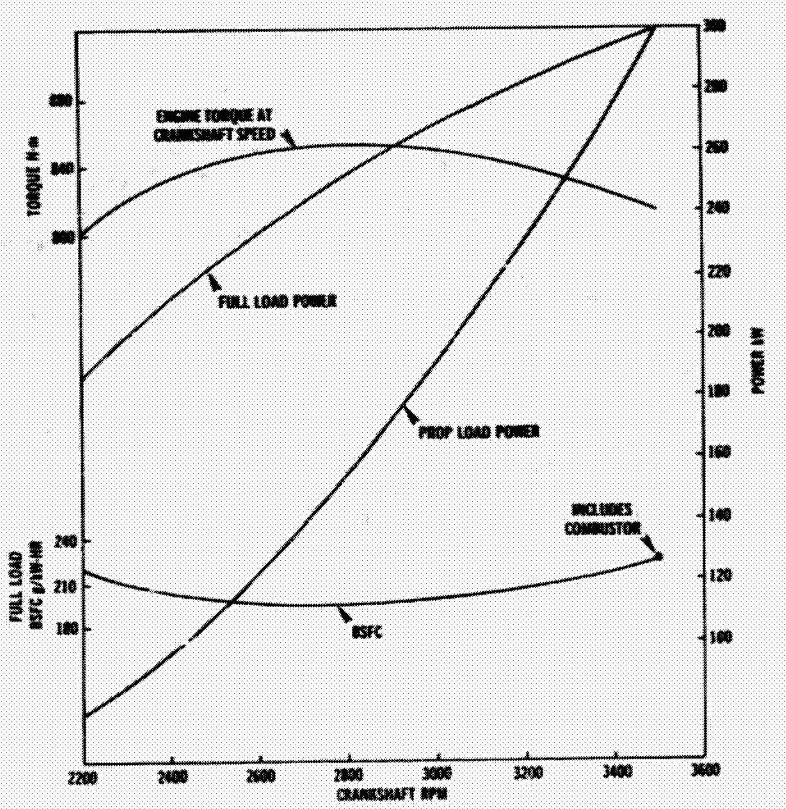


FIGURE 9 SEA LEVEL PERFORMANCE 6-CYLINDER RADIAL AIRCRAFT DIESEL ENGINE

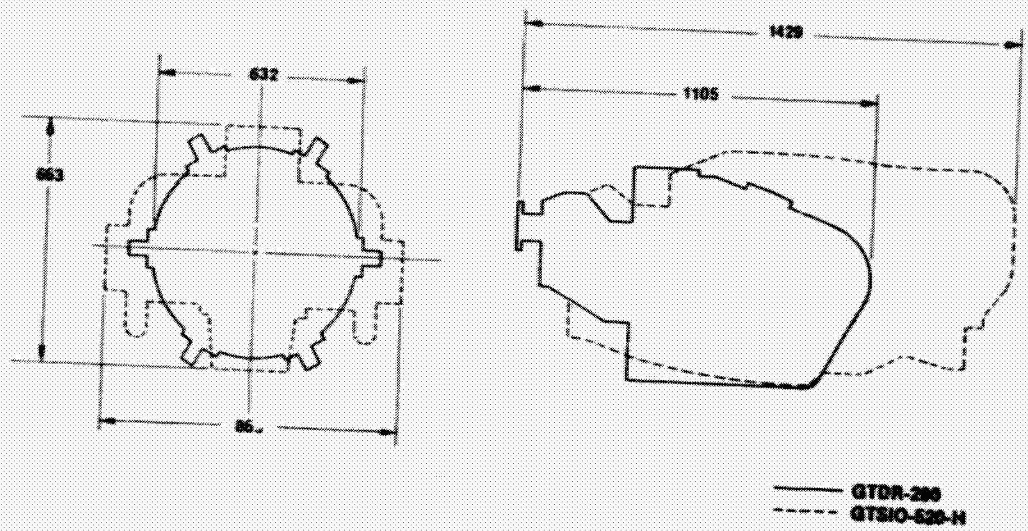


FIGURE 10 SIZE COMPARISON GTSIO-520-H AND GTDR-290 AIRCRAFT DIESEL ENGINE

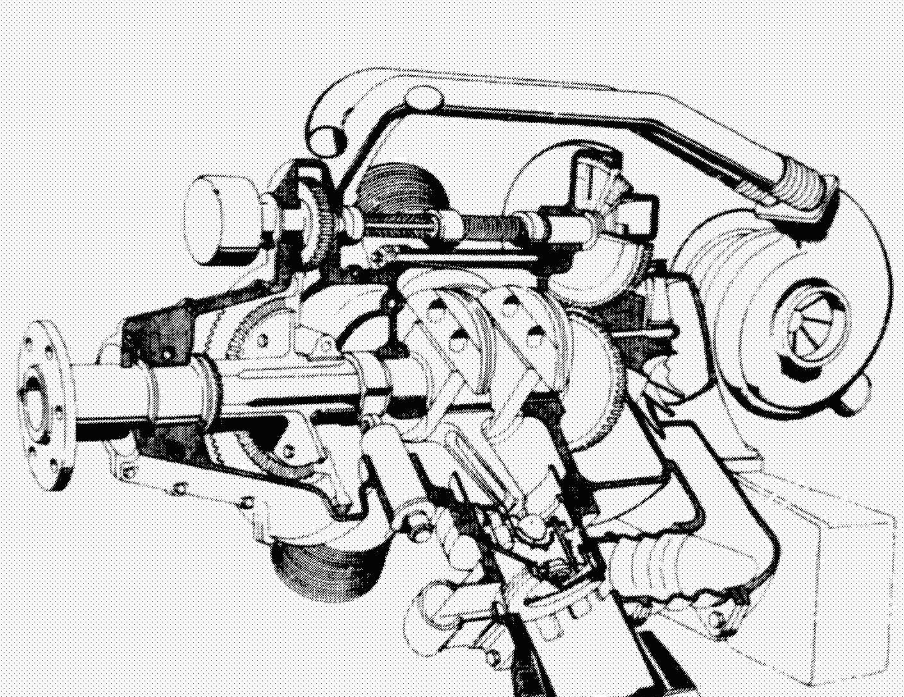


FIGURE 11 149 kW, 4-CYLINDER DIESEL AIRCRAFT ENGINE

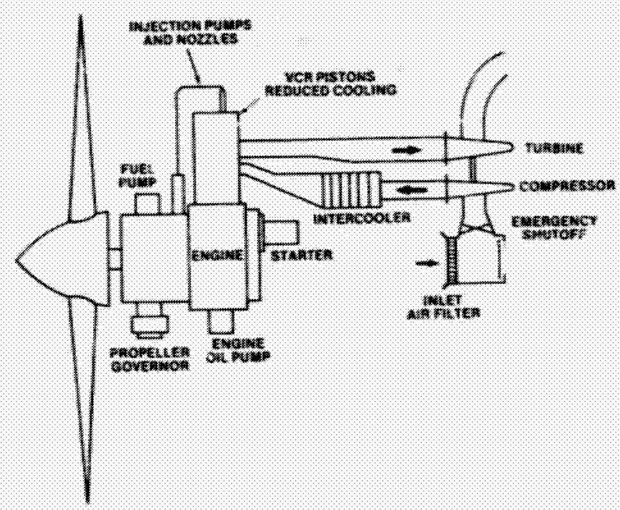


FIGURE 12 SCHEMATIC 2-STROKE TURBOCHARGED ENGINE REDUCED COOLED/VCR PISTONS

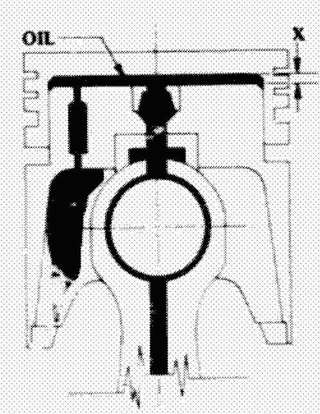


FIGURE 13 VARIABLE COMPRESSION RATIO PISTON

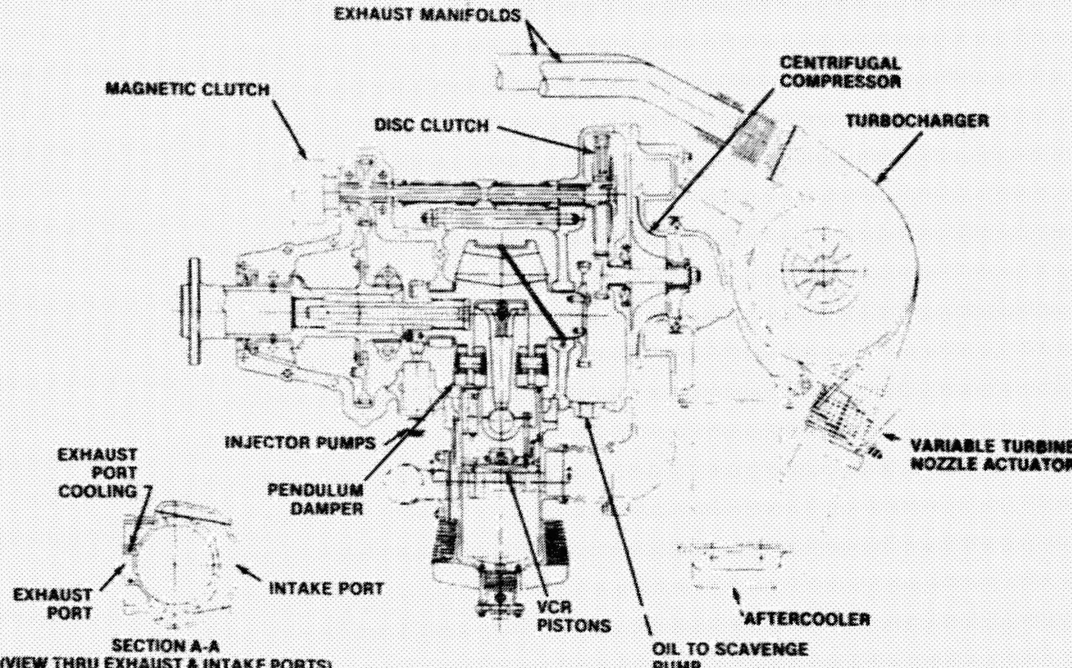


FIGURE 14 149 kW AIRCRAFT DIESEL—LONGITUDINAL SECTION

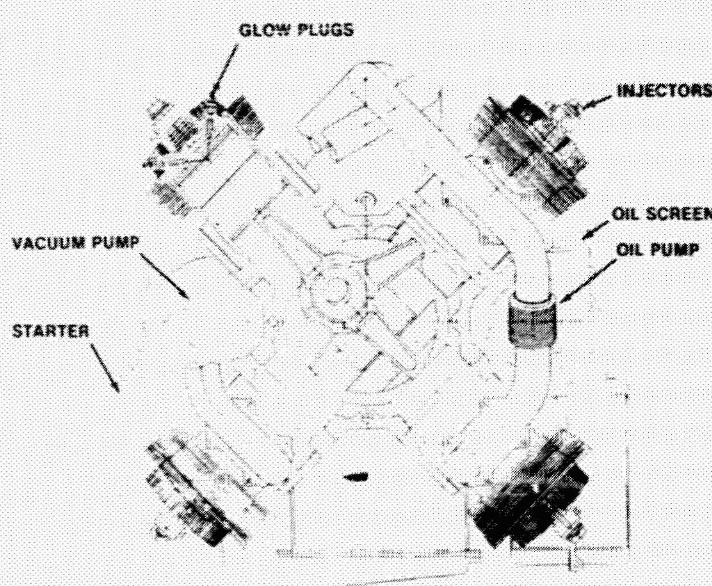


FIGURE 15 149 kW AIRCRAFT DIESEL—CROSS SECTION

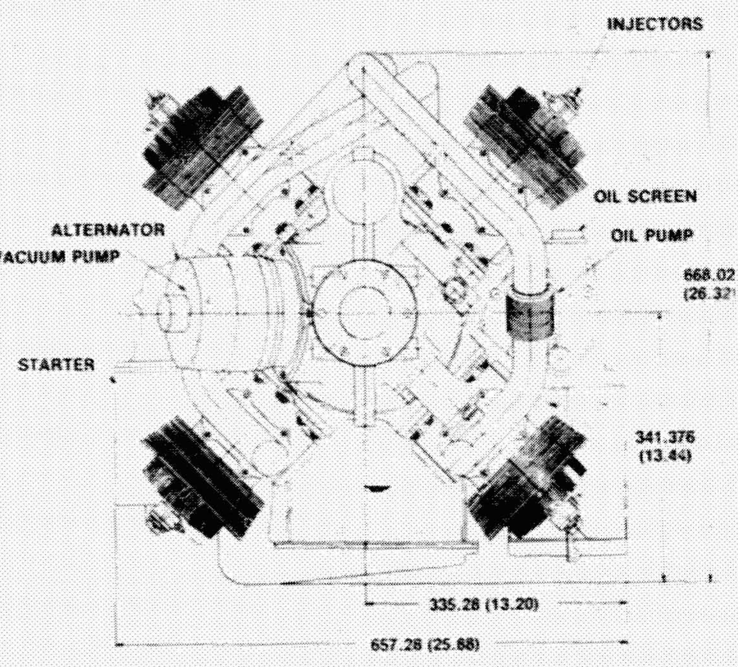


FIGURE 16 149 kW AIRCRAFT DIESEL—FRONT VIEW

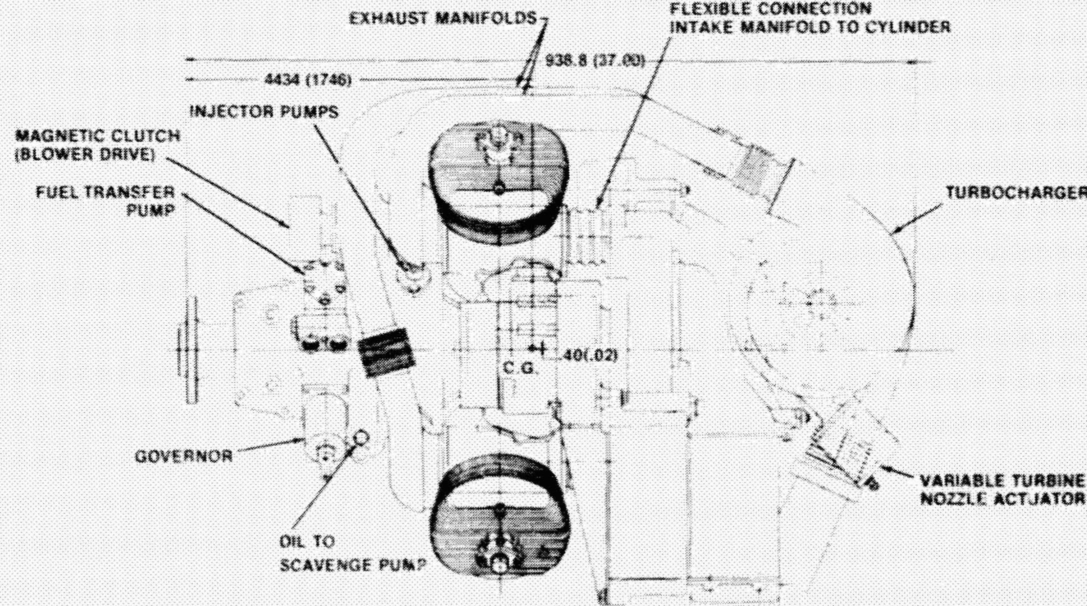


FIGURE 17 149 kW AIRCRAFT DIESEL—SIDE VIEW

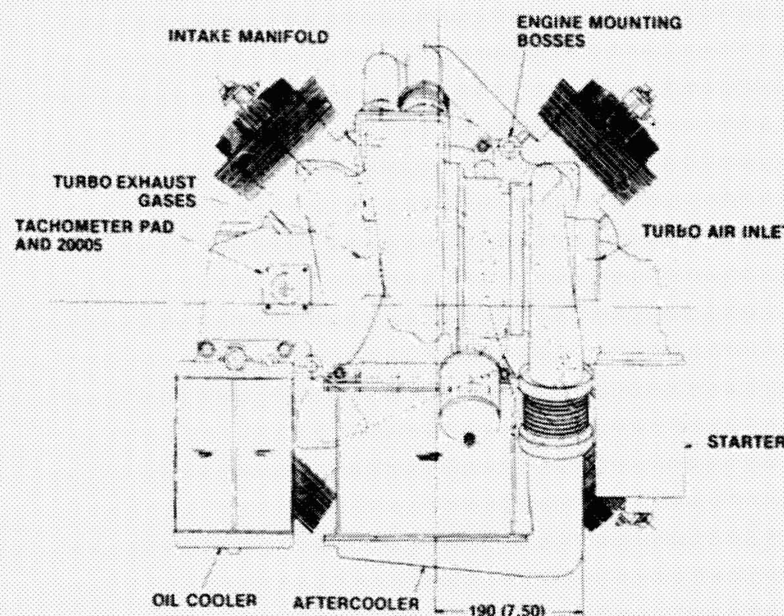


FIGURE 18 149 kW AIRCRAFT DIESEL—REAR VIEW

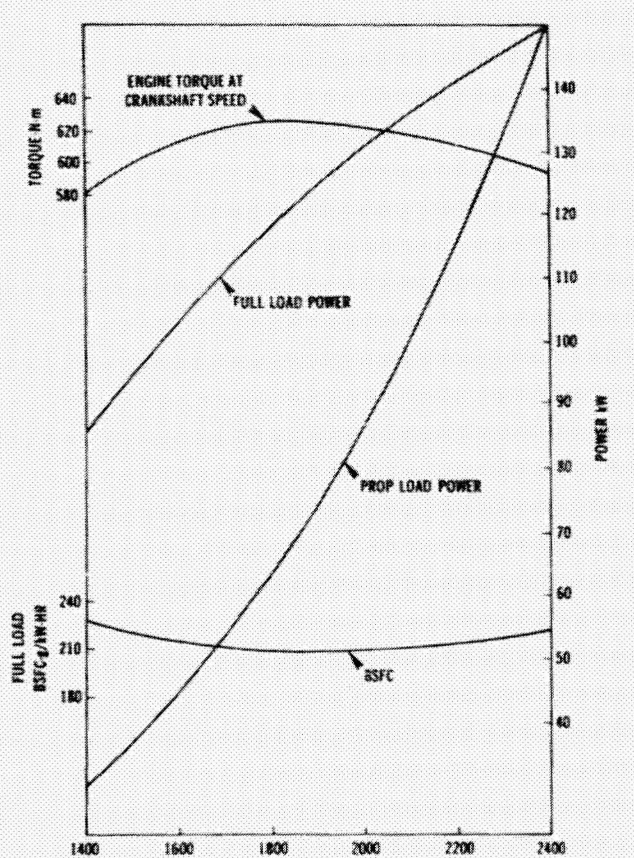


FIGURE 19 SEA LEVEL PERFORMANCE 4-CYLINDER RADIAL AIRCRAFT DIESEL ENGINE

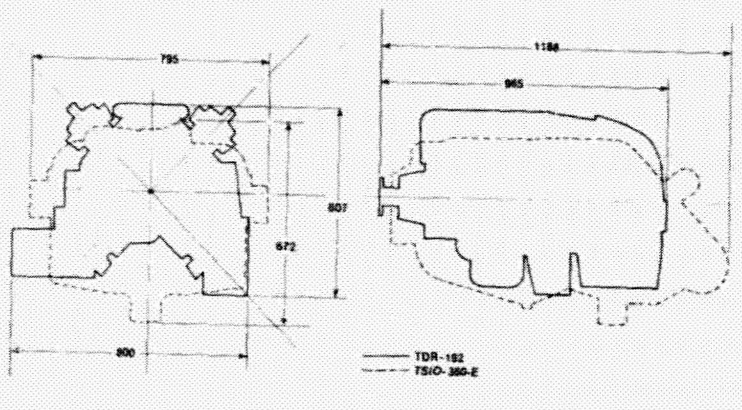


FIGURE 20 SIZE COMPARISON TSIO-360E AND TDR-192 AIRCRAFT DIESEL ENGINE

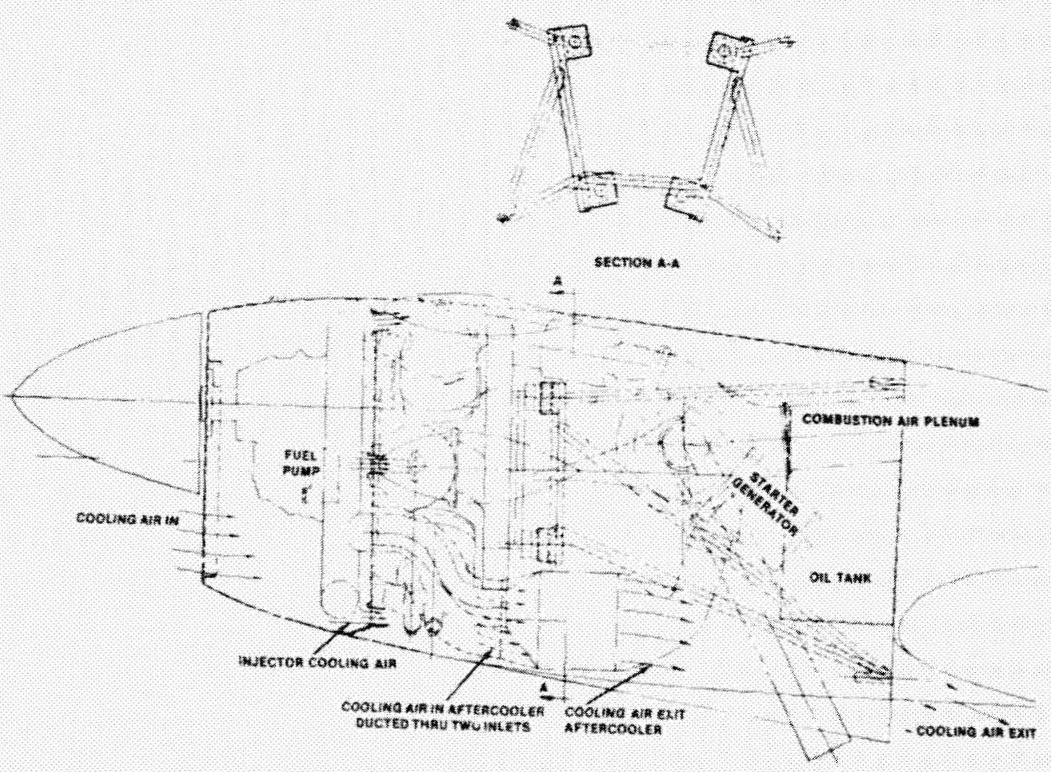


FIGURE 21 SIDE VIEW TWIN INSTALLATION

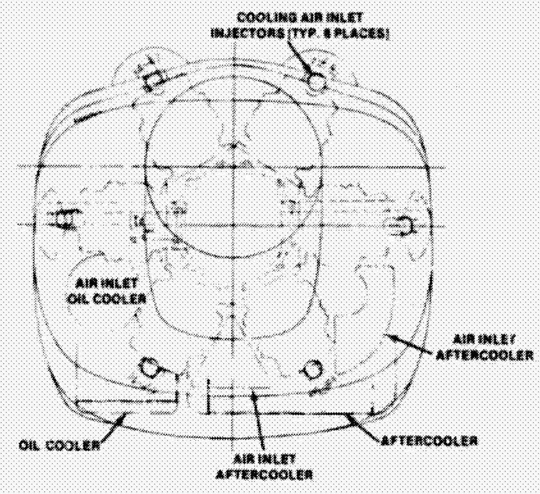


FIGURE 22 FRONT VIEW TWIN INSTALLATION

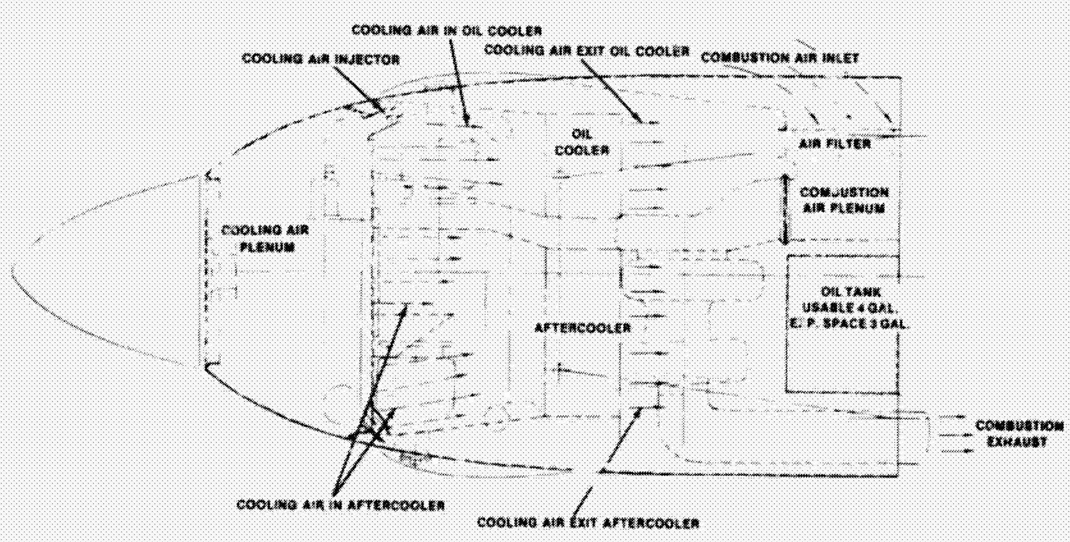


FIGURE 23 TOP VIEW TWIN INSTALLATION

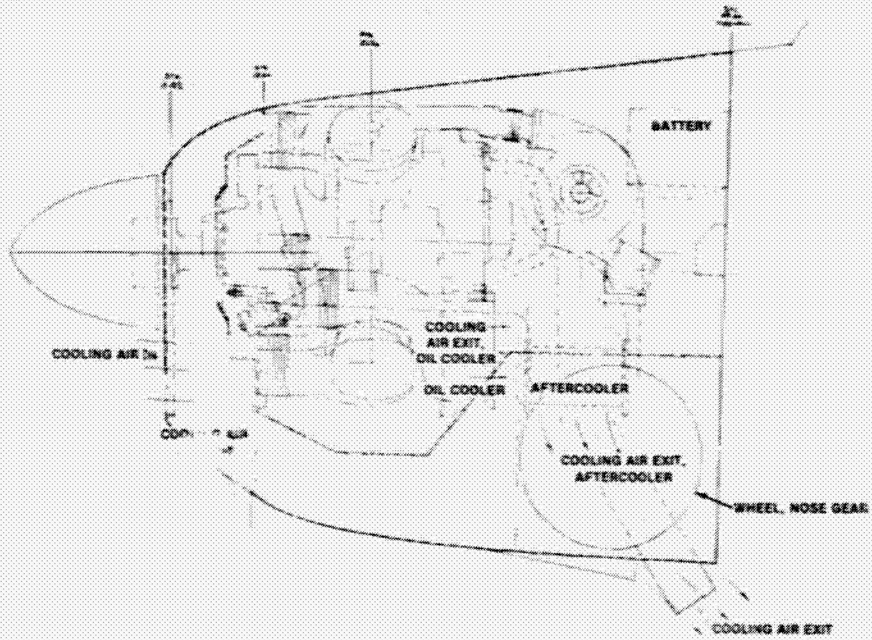
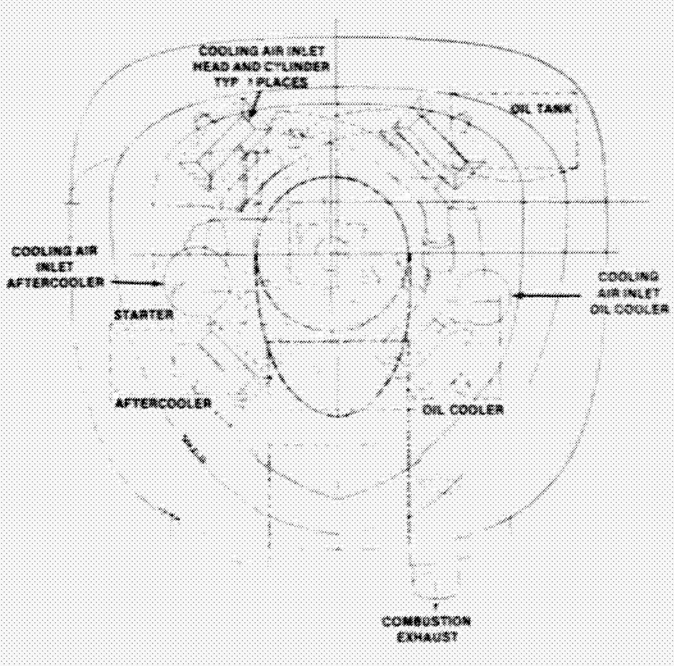


FIGURE 24 SIDE VIEW SINGLE INSTALLATION



FRONT 25 FRONT VIEW SINGLE INSTALLATION

C-4

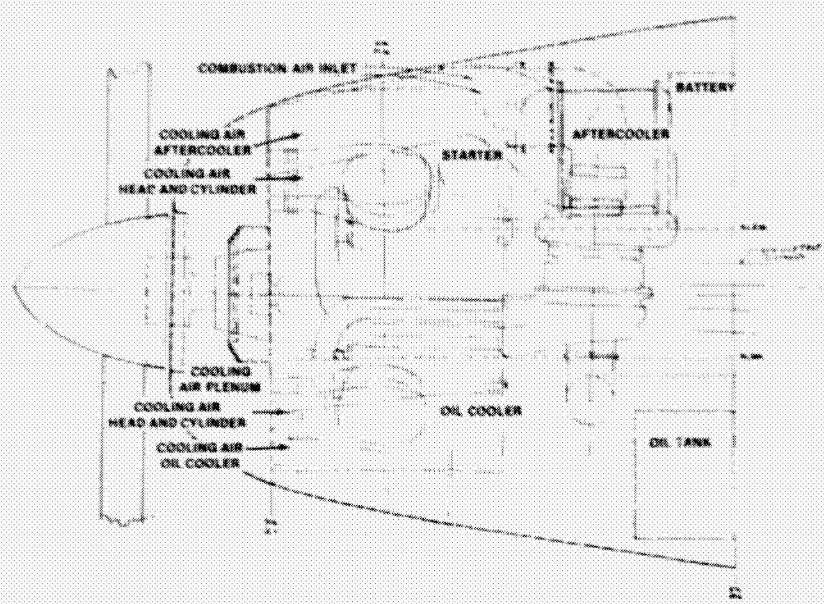


FIGURE 26 TOP VIEW SINGLE INSTALLATION

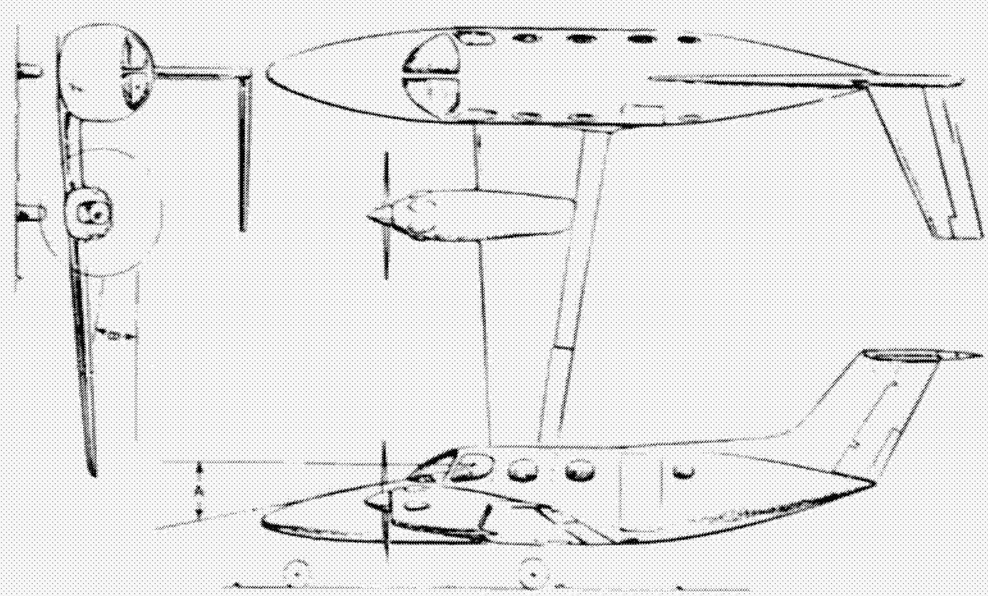


FIGURE 27 TWIN ENGINE AIRCRAFT CONFIGURATION

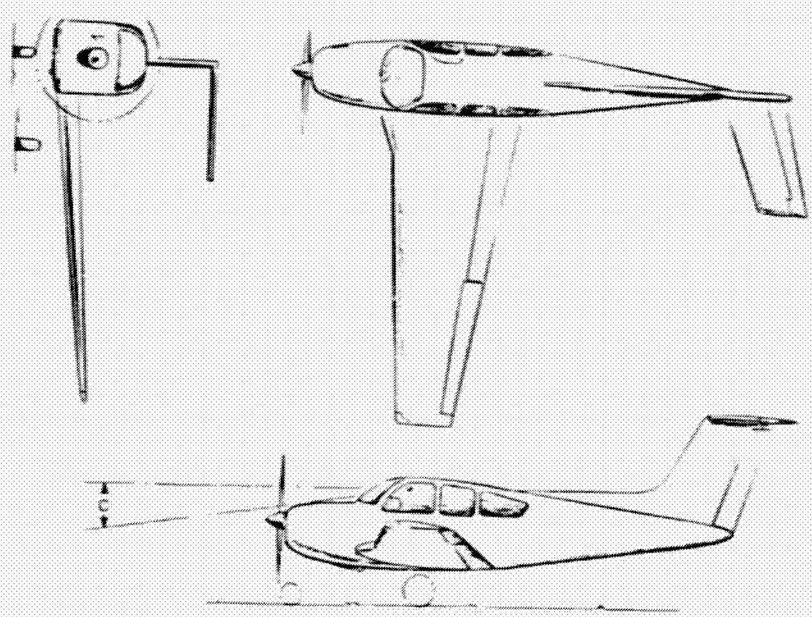


FIGURE 28 SINGLE ENGINE AIRCRAFT CONFIGURATION