NASA Contractor Report 3261

186 kW Lightweight Diesel Aircraft Engine Design Study

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1.0 SUMMARY

This report describes the design of an aircraft diesel engine capable of developing 186 kW net power at 7620m altitude, utilizing the experience gained from the basic study of the 300 kW and 150 kW aircraft diesel engines. It was conducted as an extension of the original study and compliments that work. The 186 kW design takes expected new developments in aircraft design into account, resulting in a reassessment of the power requirement at the cruise mode of operation.

Based on the results of this analysis, it is possible to project a development program in three phases, resulting in production dates in 1985, 1992 and 2000. The advantages of this approach are:

- A fuel efficient engine will become available at the earliest possible date.
- It results in a gradual, stepwise development of the ultimate power plant.
- It will be possible to retrofit each new version on then existing aircraft. Also, it will be possible to retrofit newly developed components on previous versions of the diesel aircraft engine.

This report follows the format and arrangement of the final report on the original two engines.

2.0 INTRODUCTION

Programs are currently being defined at NASA that are keyed toward improved fuel efficiency of general aviation aircraft. In addition to more efficient power plants, which this study addresses, these programs involve new propeller technology, improved aerodynamics and weight reduction of aircraft through the use of composites. The projected aircraft performance improvements have led to a re-definition of the engine power requirements.

2.1 Scope of the Project

The purpose of this study is the conceptual design of an advanced diesel aircraft engine capable of sustained 186 kW net cruise power at 7620m altitude. The engine will be suitable to power high performance pressurized single and pressurized twin engine aircraft. The level of technology must be such that the engine can be commercially introduced in the late 1980's.

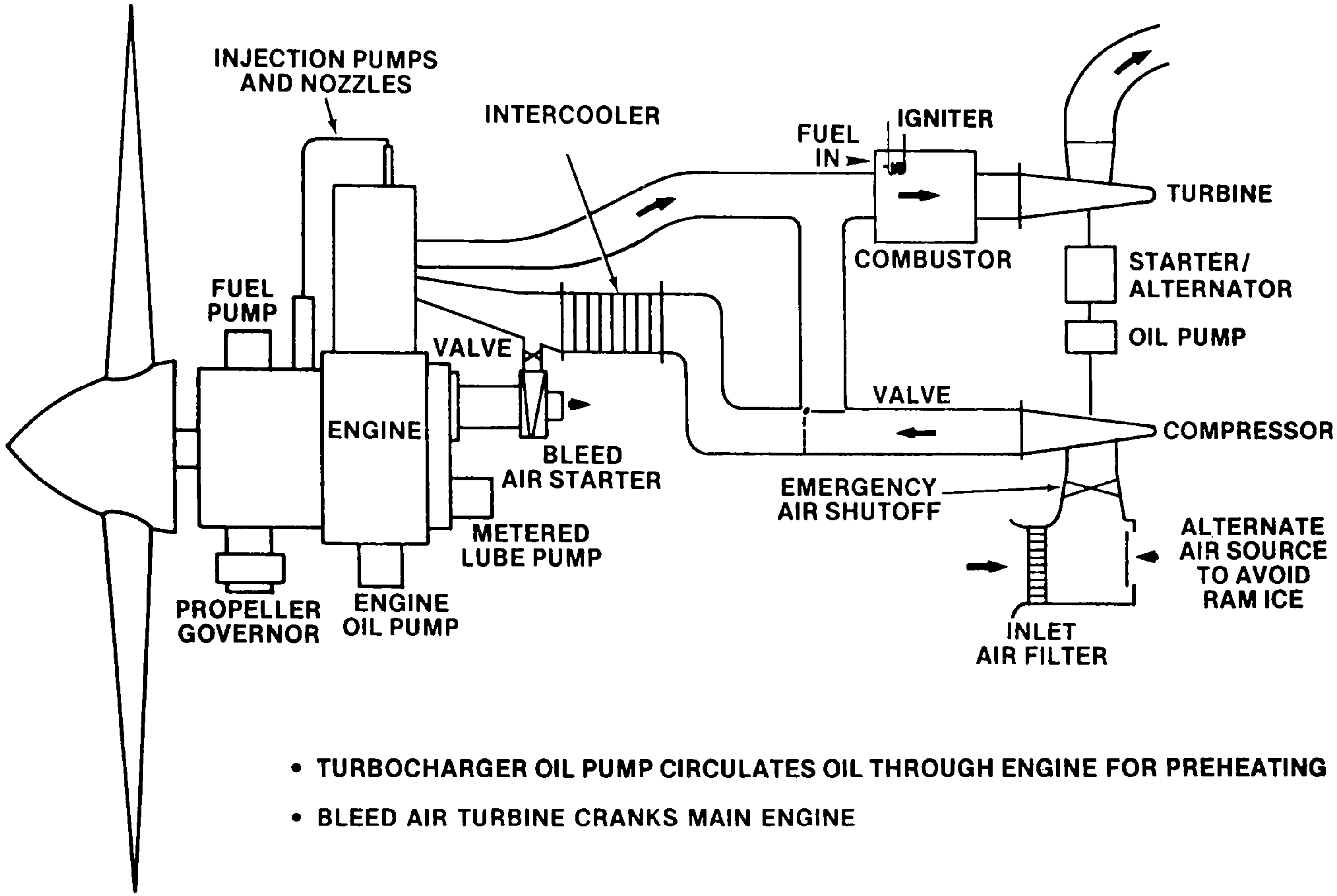
3.0 DESIGN STUDY OF THE 186 kW ENGINE

Figure 3-1 shows the schematic of the engine.

3.1 Engine Features

The design incorporates the following features, most of which have been discussed earlier in the main report.

1. Radial cylinder configuration.
2. Two-stroke cycle, Curtis loop scavenged.
3. Limited cooling of the cylinders within the limitations of conventional materials.
4. Turbocharged and aftercooled.



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

FIGURE 3-1 SCHEMATIC 2-STROKE ENGINE WITH INDEPENDENT TURBO LOOP, REDUCED CYLINDER COOLING, LOW COMPRESSION RATIO.

5. Independent turbocharger loop. This is similar to the previously described 6-cylinder 300 kW engine and eliminates the need for a centrifugal blower.

6. Conventional combustor in the exhaust manifold. The catalytic combustor will be developed for a later production version of the engine.

7. High speed starter/alternator.

8. Bleed air starter.

9. Geared propeller drive.

10. Separate injection pumps for each cylinder.

3.2 Engine Concept Design

The engine concept design is shown in the Figures 3-2 through 3-6. The cylinders are arranged in one bank of four cylinders. The cylinders have a limited number of cooling fins to cool the combustion chamber. The cylinders are held down by means of threaded and toothed rings. This method results in a uniform load on the cylinder mounting flanges and eliminates the current problem of cylinder bore distortion. The intake manifold is located at the front side of the engine. Two elbows per cylinder direct the air to the intake ports. Two exhaust manifolds at the back side of the cylinders are provided to avoid pulse interference between the cylinders. The connecting rods are designed as slipper rods.

The use of synthetic oil is not contemplated because of relatively low cylinder temperatures. The turbocharger is mounted behind the engine as are the oil cooler and the aftercooler. A conventional combustor and igniter are mounted to the exhaust manifold to provide the independent turbocharger loop feature. A propeller reduction gear is provided to combine a low propeller speed and a high engine RPM.

The Figures 3-2 through 3-6 show the engine configurations for twin engine aircraft and single engine aircraft with a fixed landing gear. Another version, not shown, will have the coolers moved outboard to provide space for a retractable nose gear.

3.3 Gross Power Requirements

The net shaft power requirement (input into the propeller) at cruise condition is 186.4 kW at 7620m altitude. An 85% propeller efficiency results in 158.4 kW propulsive power.

Power demand of the accessories:

1. Injection Pump

- Fuel flow approximately 45 kg/hr
- Pump pressure 82,750 kPa
- Pump efficiency 75%
- Pump power 2.31 kW

2. Alternator

- 24V, 100A, 65% efficiency
- Input power 3.73 kW

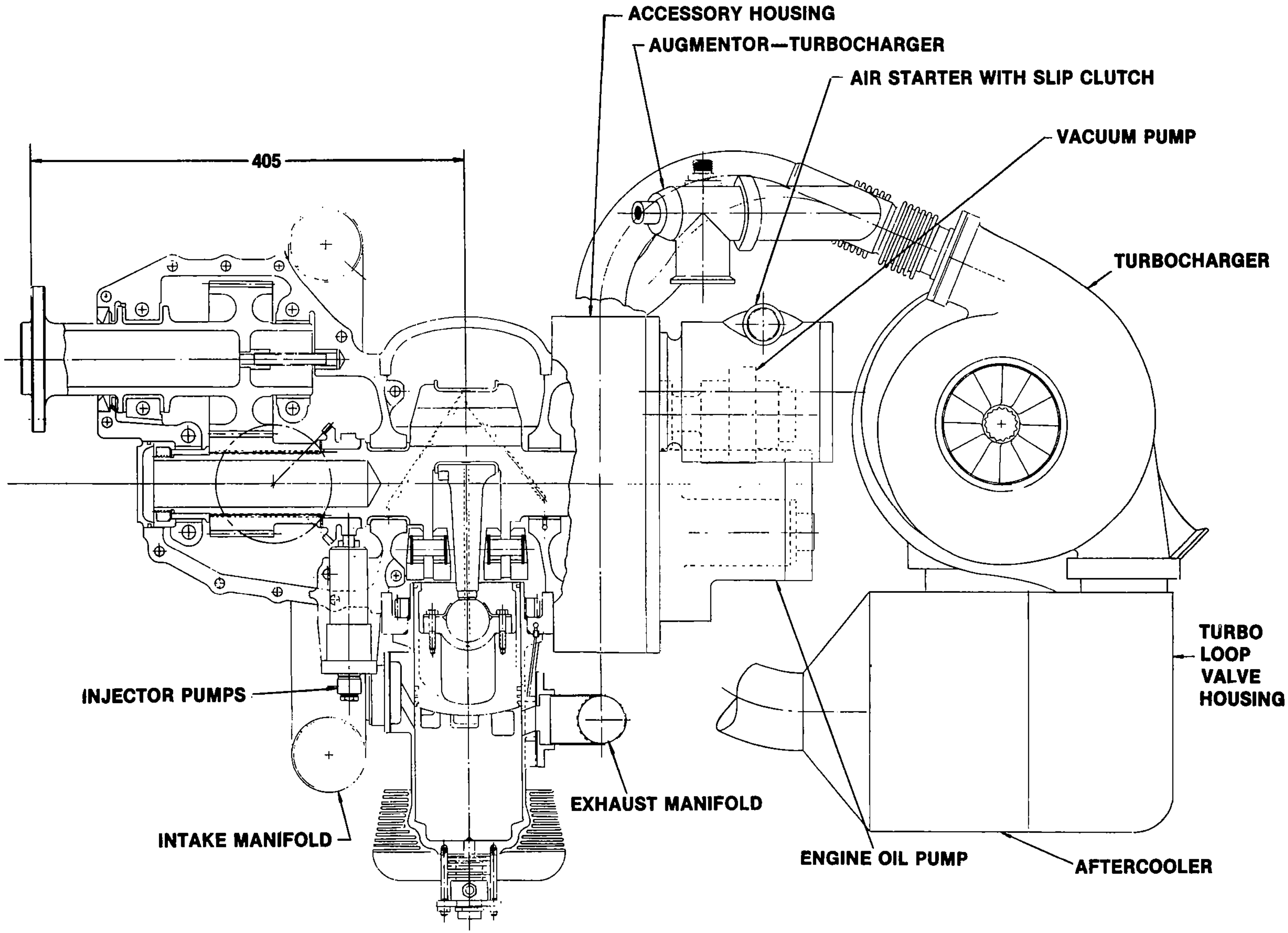
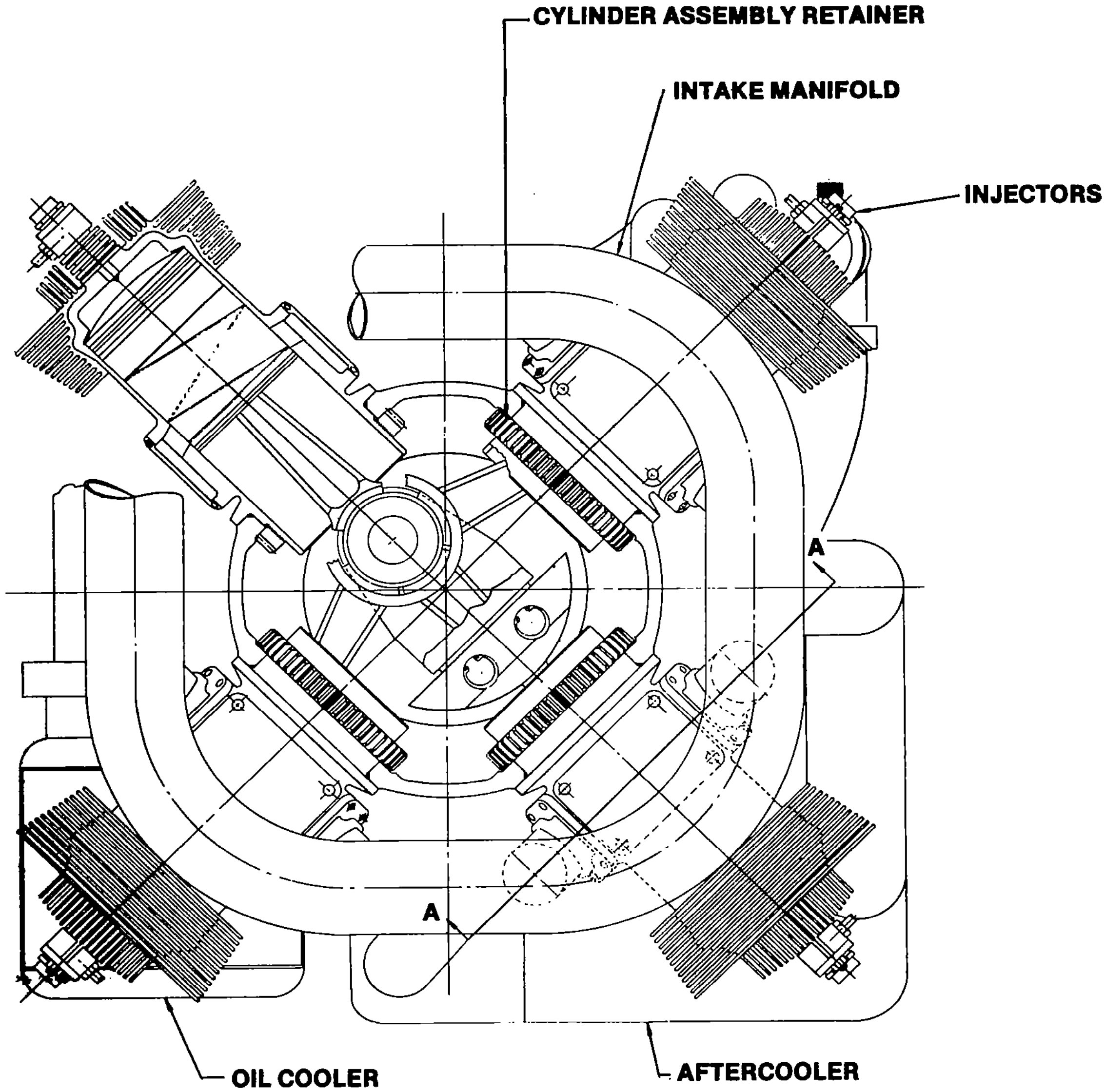
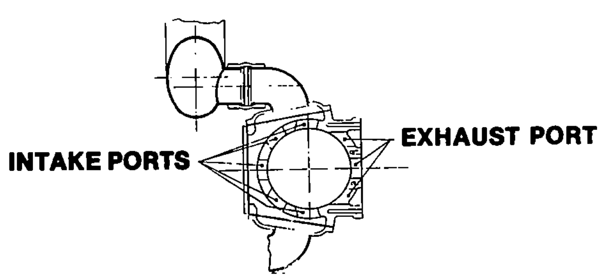


FIGURE 3-2 186 kW AIRCRAFT DIESEL LONGITUDINAL SECTION





SECTION A—A
THROUGH INTAKE AND EXHAUST PORTS

FIGURE 3-3 186 kW AIRCRAFT DIESEL CROSS SECTION

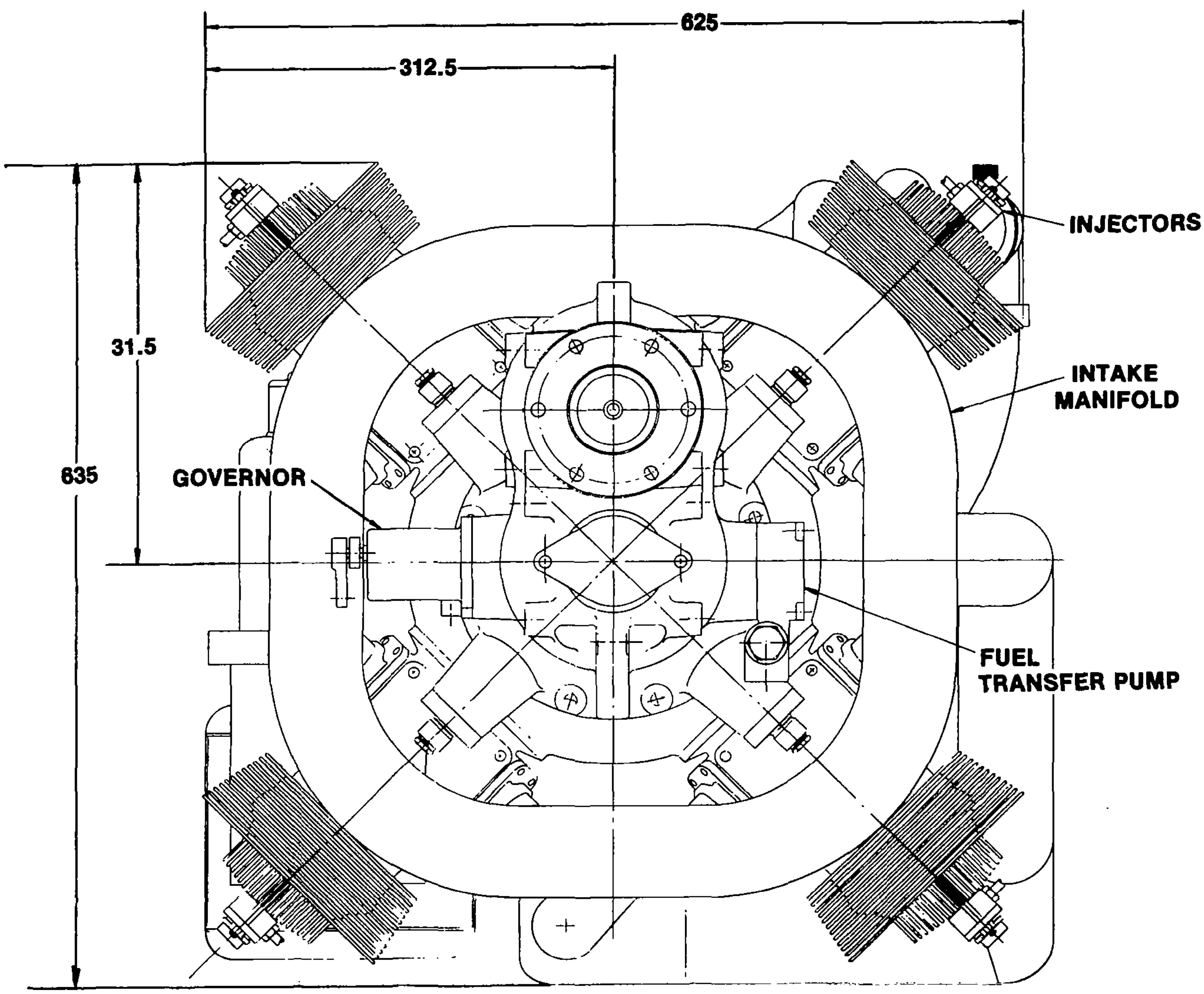


FIGURE 3-4 186 kW AIRCRAFT DIESEL FRONT VIEW

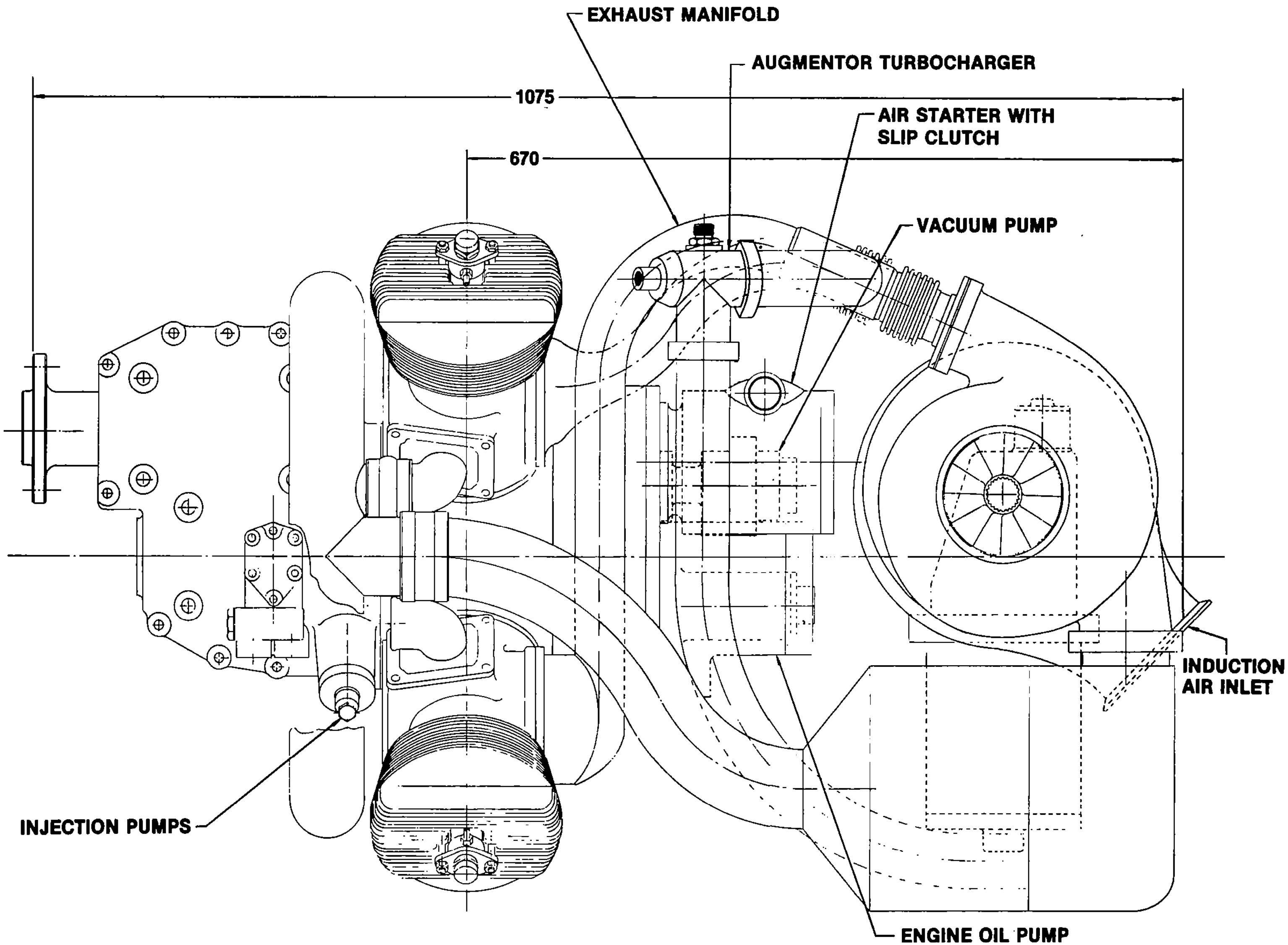


FIGURE 3-5 186 kW AIRCRAFT DIESEL SIDE VIEW

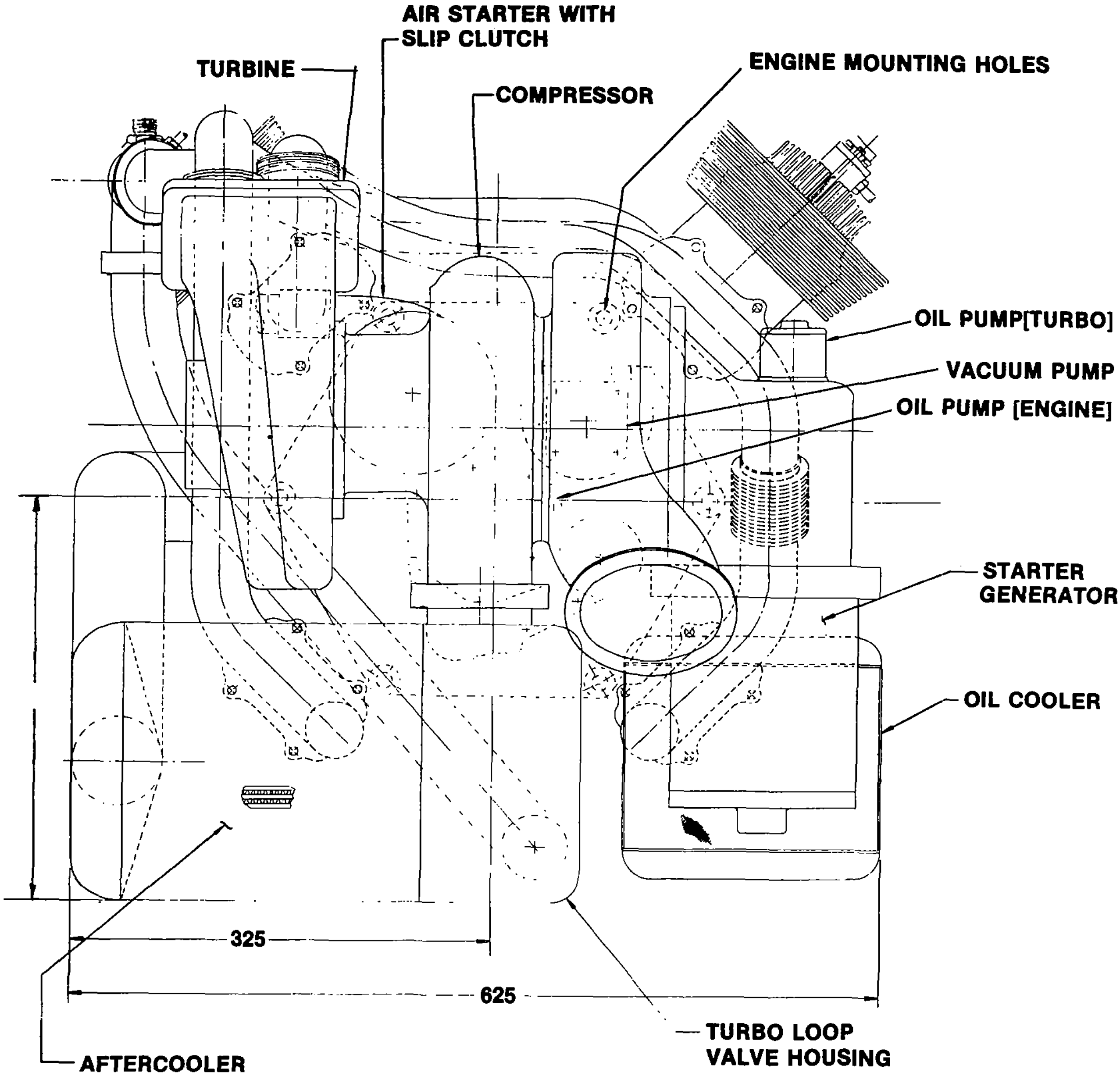


FIGURE 3-6 186kW AIRCRAFT DIESEL REAR VIEW

3. **Cabin Air Pressurization**

   - Cabin air will be supplied by a mechanical blower. Power requirement of the blower is 7.46 kW per engine.

4. **Oil Pump**

   - Specific flow rate—.228 ℓ/min/kW
   - Flow rate—.635 kg/sec
   - Oil Pressure—310 kPa
   - Pump efficiency—60%
   - Power input—.37 kW

5. **Remaining Accessories—.30 kW**

6. **Total all accessories—14.20 kW**

Gross engine power demand at altitude is 186.4 + 14.2 = 200.6 kW.

3.4 Cylinder Configuration

Based on experience gained in the design of the 150 kW and 300 kW engines, it was decided to design a geared 4-cylinder engine.

1. The cylinders of a 4-cylinder engine are larger than those of a 6-cylinder engine, but elimination of 2-cylinders and moving parts, coupled with a shorter crankshaft and a shorter crankcase results in a lighter engine.
2. Fewer parts of a 4-cylinder configuration results in improved reliability.
3. The 4-cylinder configuration adapts easier to a single engine aircraft with retractable nose gear.

3.5 Engine Operating Data

The engine data for three flight conditions are shown in Table I.

TABLE I
Operating Parameters

	Take-Off	Cruise	Economy Cruise	
Altitude	0	7,620	7,620	meters
Power	275.2	200.6	135.3	kW
RPM	3500	3500	2650	
Displacement	4.031	4.031	4.031	liters
Bore x Stroke	108 x 110	108 x 110	108 x 110	mm
BMEP	1170	853	761	kPa
Compressor Pressure Ratio	3.706:1	7.250:1	6.918:1	
Nominal Compression Ratio	13.37:1	13.37:1	13.37:1	
Effective Compression Ratio	10.0:1	10.0:1	10.0:1	
Barometric Pressure	101.4	37.65	37.65	kPa
Ambient Temperature	15.5	-34.4	-34.4	°C
Intake Manifold Pressure	366.3	261.5	252.9	kPa
Intake Manifold Temperature	115.6	115.6	115.6	°C
Exhaust Manifold Pressure	293.1	209.2	226.8	kPa
Ratio $\frac{\text{Int. Press.}}{\text{Exh. Press.}}$	1.250	1.250	1.115	
Scavenge System	Curtis Loop	Curtis Loop	Curtis Loop	
Scavenge Ratio	1.3	1.3	1.3	
Height Intake Ports	21	21	21	mm
Height Exhaust Ports	30	30	30	mm
Intake Ports Open/Close	59°23'	59°23'	59°23'	
Exh. Ports Open/Close	71°10'	71°10'	71°10'	
BSFC	219.0	225.1	206.8	g/kW-hr
Fuel Flow	60.26	45.15	27.99	kg/hr

	Take-Off	Cruise	Economy Cruise	
Scavenge Efficiency	82	82	82	percent
Air Density at Exhaust Port Closing	.00272	.00194	.00203	kg/ℓ
Volume of Pure Air Per Cycle	.668	.668	.668	ℓ
Weight of Pure Air Per Cycle	.00181	.00130	.00136	kg
Air/Fuel Ratio	25.00	24.14	30.00	

3.6 P-V Diagrams

Specific data points for the three conditions are given in Table II.

TABLE II
Air Cycle Performance

	Take-Off	Cruise	Economy Cruise	
P_1	330	235	240	kPa
V_1	.814	.814	.814	liter
T_1	149	149	138	°C
P_2	7729	5516	5626	kPa
V_2	.081	.081	.081	liter
T_2	717	717	691	°C
P_3	8846	6633	6743	kPa
V_3	.081	.081	.081	liter
T_3	860	917	882	°C
P_4	8846	6633	6743	kPa
V_4	.156	.154	.140	liter
T_4	1902	1976	1718	°C
P_5	1061	780	705	kPa
V_5	.814	.814	.814	liter
T_5	1085	1126	934	°C

	Take-Off	Cruise	Economy Cruise	
Coefficient of Compression	1.370	1.370	1.370	
Coefficient of Expansion	1.285	1.285	1.285	
Fuel/Cyl/Rev.	.0000726	.0000544	.0000454	kg
Q/Cyl/Rev.	.744	.558	.465	kcal
Q_1	.067	.067	.067	kcal
Q_2	.677	.491	.398	kcal
IMEP	1496	1126	988	kPa
Mech. Efficiency	78.2	75.8	77.0	Percent
Comp. Press. Ratio	3.706	7.250	6.918	
Comp. Inlet Temp.	+15.5	-34.4	-34.4	°C
Weight Pure Air	.423	.303	.241	kg/sec
Weight Scavenge Air	.127	.090	.072	kg/sec
Comp. Airflow	.550	.393	.313	kg/sec
Fuel Flow	.017	.013	.008	kg/sec
Weight Exh. Gas	.440	.315	.248	kg/sec
Blowdown Temp. Exh. Gas	712	734	636	°C
Turbine Inlet Temp.	586	603	524	°C
Turbo Efficiencies				
Comp. ηac	.78	.77	.78	
Turbine $\eta at/t\text{-}s$	.77	.76	.77	
Compressor ηpc	. 816	.823	.830	
Turbine ηpt	.745	.718	.727	
Mechanical	.98	.98	.98	
Overall s (= ηpc x η pt x ηm)	.596	.579	.591	
$\sqrt{s}$	.772	.761	.769	
Turbine Press. Ratio	2.890	5.557	6.026	
Comp. Inlet Temp.	+15.5	-34.4	-34.4	°C

	Take-Off	Cruise	Economy Cruise	
Required TIT	580	557	481	°C
Available TIT	586	603	524	°C

The figures 3-7 through 3-9 show the schematics of these three operating conditions.

3.7 Turbocharger Operation

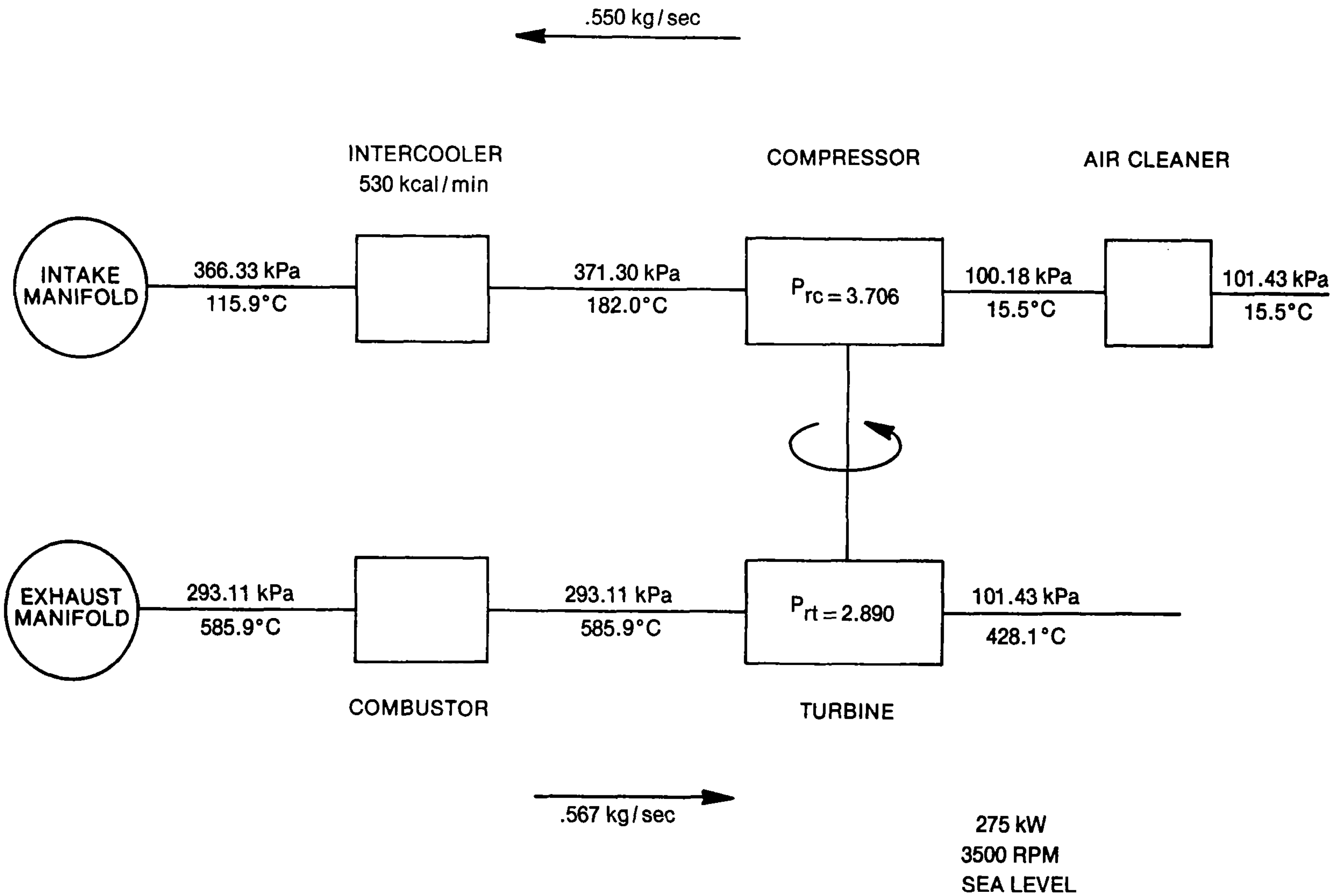
The turbocharger data for the 3 modes of operation are shown in Table III.

The results of the calculations indicate a requirement for a variable turbine nozzle area. A 2-position nozzle setting may be possible which would greatly simplify the control system.

TABLE III
Turbocharger Data

	Take-Off	Cruise	Economy Cruise	
Comp. Press. Ratio	3.706	7.250	6.918	
Turb. Press. Ratio	2.890	5.557	6.026	
Efficiencies		See Table II		
Comp. Airflow	.550	.393	.313	kg/sec
Comp. Inlet Temp.	15.5	-34.4	-34.4	°C
Comp. Discharge Temp.	182.0	199.3	189.3	°C
Intake Manifold Temp.	115.9	115.9	115.9	°C
Aftercooler Heat Load	530.5	477.8	334.2	kcal/min
Comp. Input Power	93.0	93.3	71.0	kW
Bearing Loss	1.8	1.9	1.4	kW
Required Turbine Output Power	94.8	95.2	72.4	kW
Available Turbine Inlet Temp.	586.0	603.2	523.7	°C
Exhaust Gas Flow	.567	.406	.320	kg/sec
C_{pt}	.266	.266	.262	kcal/kg-°C
k	1.346	1.346	1.354	
Available Turbine Shaft Power	99.7	107.3	88.0	kW
φ/φ_o	.988	1 (Design Point)	.752	
Exhaust Energy Factor	.051	.105	.057	

	Take-Off	Cruise	Economy Cruise	
$P_{rt\text{-}t}$	2.80	5.00	5.82	
Turbine Inlet Pressure	293.1	209.2	226.8	kPa
Turbine Outlet Pressure	104.5	41.9	39.0	kPa
Temp. Drop in Turbine	157.8	237.2	229.5	°C
Turbine Discharge Temp.	428.2	365.9	294.3	°C
Exducer Diameter	115	115	115	mm
Exducer Flow Area	75.0	75.0	75.0	cm^2
Area Ratio A/A*	2.095	1.257	1.54	
Exit Mach Number	.284	.551	.420	
Stagnation Temp.	418.7	334.3	277.0	°C
Gas velocity into Rotor	677.3	825.4	821.1	m/sec
Gas Velocity out of Rotor	146.0	265.5	192.6	m/sec
Preferable Exit Velocity is 1.25—1.50 Times Air Speed.				
Turbine Rotor Diameter	152	152	152	mm
Comp. Wheel Diameter	158	158	158	mm
Comp. Tip Speed	457.8	543.8	531.9	m/sec
Comp. Speed $\sqrt{\theta_c}$	55343	65734	64297	rpm
Comp. Inlet Temp.	+15.5	-34.4	-34.4	°C
$\sqrt{\theta_c}$	.977	.888	.888	
Comp. Speed N	54070	58372	57096	rpm
Temp. Correction Factor θ_t	2.84	2.89	2.63	
Press. Correction Factor δ_t	2.89	2.06	2.24	
Corrected Turbine Mass Flow	.331	.225	.155	kg/sec
Nozzle Area	15.29	14.85	10.21	cm 2



FIGURL 3-7 OPERATING SCHEMATIC—TAKE-OFF

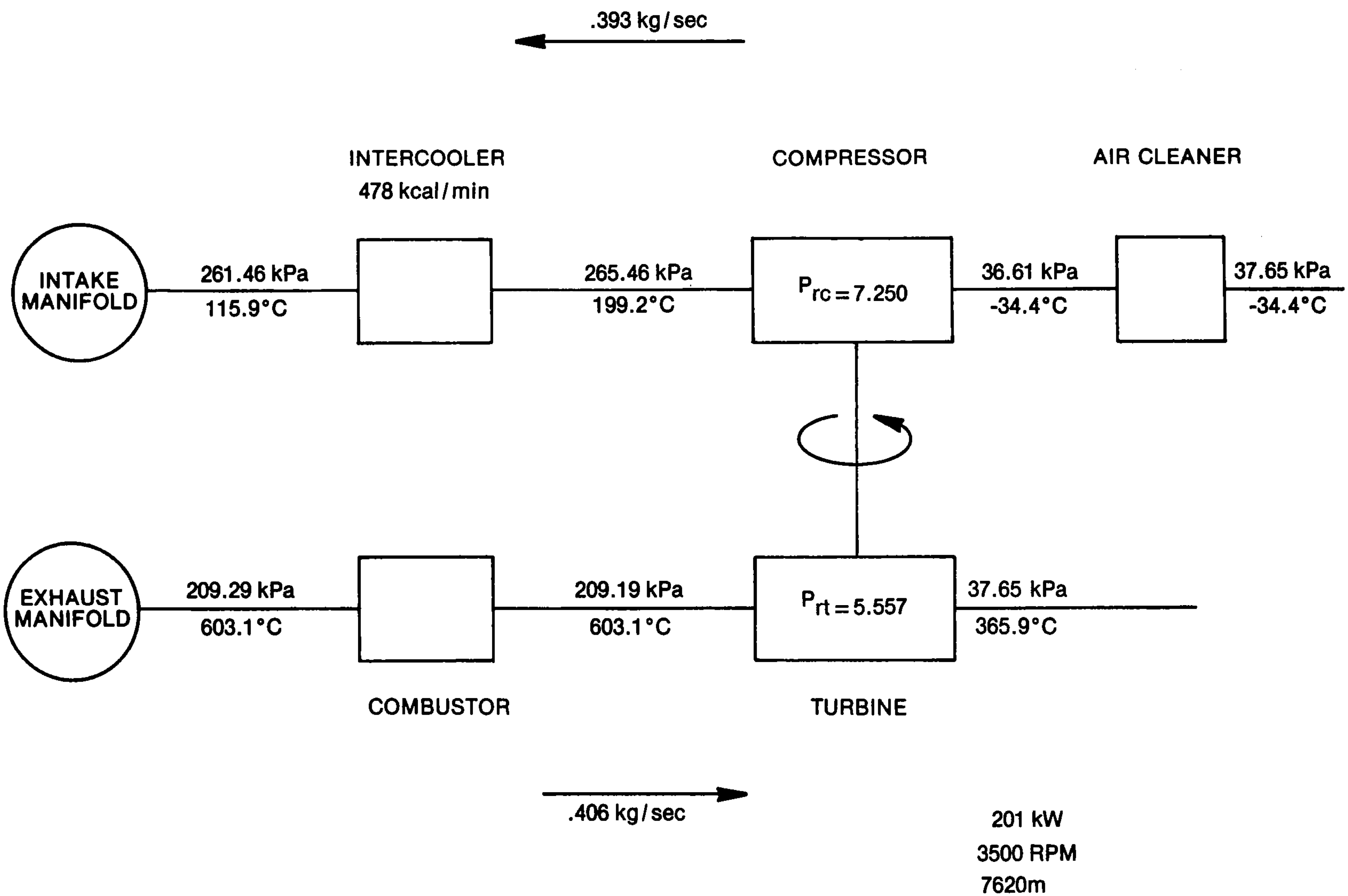


FIGURE 3-8 OPERATING SCHEMATIC—CRUISE POWER

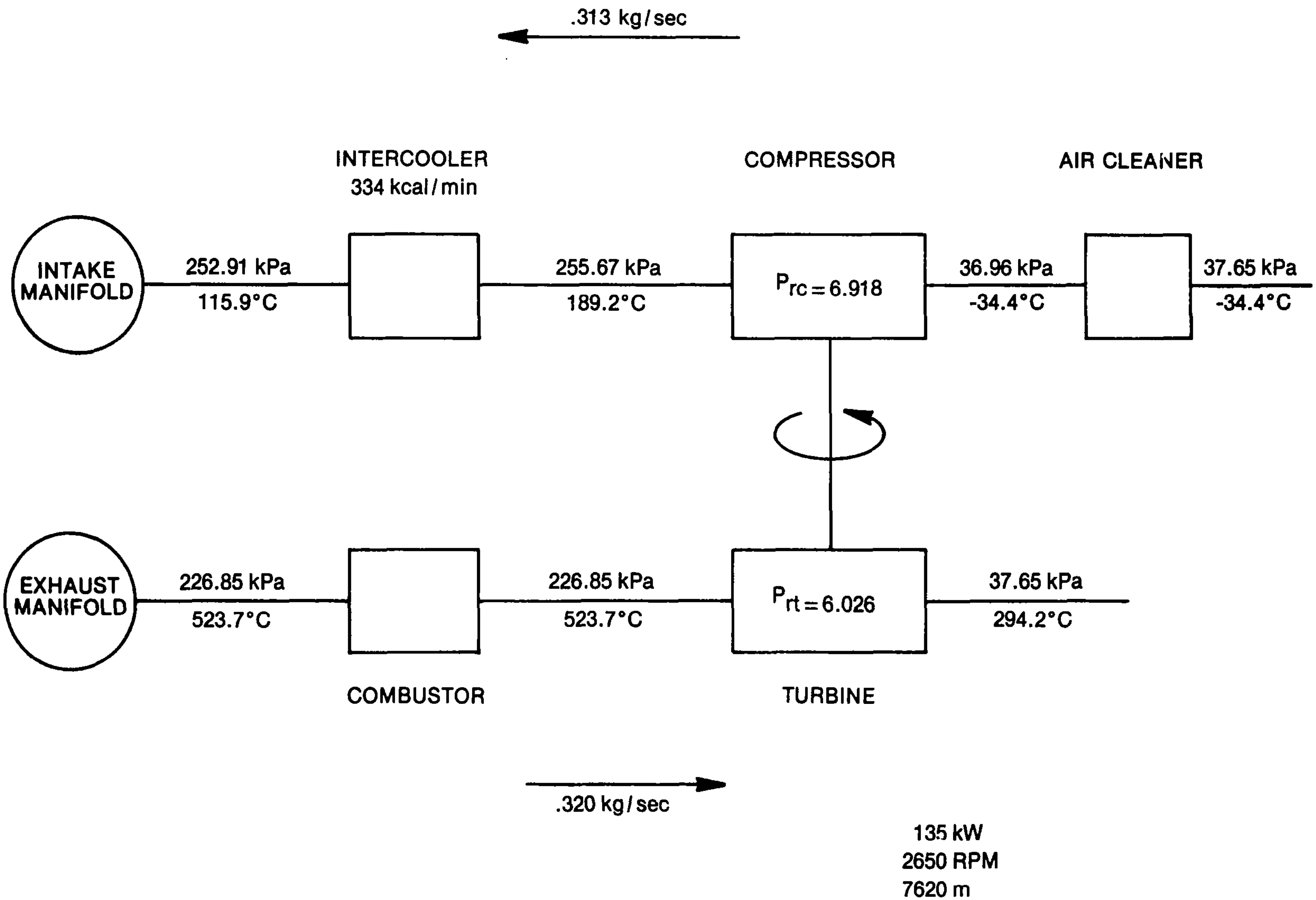


FIGURE 3-9 OPERATING SCHEMATIC—ECONOMY CRUISE POWER

3.8 Weight and Initial Cost

The weight of the engine and the cost relative to a current gasoline aircraft engine are shown in Table IV.

TABLE IV
Weight and Cost of the 186 kW Diesel

	A TECHNOLOGY AND/OR MATERIAL FACTOR	B WEIGHT kg	A X B EVALUATION NUMBER
Proper Gear Housing	1.00	14.80	14.80
Crankshaft	1.00	9.37	9.37
Counterweights	2.00	4.56	9.12
Prop Drive Gears	1.00	9.07	9.07
Crankcase Assembly	1.00	5.44	5.44
Accessory Housing	1.00	3.96	3.96
Accessory Drive Gears	1.00	4.00	4.00
Pistons	1.25	3.34	4.17
Connecting Rods	1.50	3.08	4.62
Piston Rings	2.00	.24	.48
Cylinders	1.50	31.75	47.62
Injection System	2.50	4.08	10.20
Intake System	1.00	9.53	9.53
Exhaust System	1.00	.66	.66
Combustor	1.25	.78	.97
Fuel Pump	1.00	1.16	1.16
Governor	1.00	.91	.91
Vacuum Pump	1.00	.91	.91
Oil Pump	1.00	5.95	5.95
Starter/Generator	2.50	6.37	15.92
Oil Cooler	1.00	2.63	2.63
Aftercooler	1.00	4.08	4.08
Turbocharger	1.75	20.41	35.71
Balance Engine Parts	1.00	27.22	27.22
		174.30	228.50

1. Weight Factor:

Weight diesel 174.30 kg

Weight Gasoline Engine 254.90 kg

Weight Ratio $\frac{174.30}{254.90} = .684$

2. Overall Engine Technology and Material Factor:

$$\frac{\text{Total A\&B}}{\text{Total B}} = \frac{228.50}{174.30} = 1.311$$

3. Overall Cost Ratio Diesel Versus Current Gasoline Engine:

$.684 \times 1.311 = .896$

Two observations can be made:

1. The weight ratio of the 6-cylinder diesel was .791 (Page 71 Final Report). The 4-cylinder configuration, therefore, has resulted in a sizeable weight reduction compared to a 6-cylinder engine of the same displacement.

2. The same applies to engine costs. The 4-cylinder configuration costs 10% less than a current gasoline engine of the same power. A 6-cylinder configuration would have cost more than a current gasoline engine.

4.0 PROPOSED DEVELOPMENT PROGRAM

The projected 1985 production date of the 186 kW engine puts limitations on the technologies that can be developed within this time frame. Development of uncooled cylinders, the catalytic combustor and very high compressor pressure ratios requires much more time. Consequently, the program has been revised to result in three production release dates.

Table V lists the technologies and performance targets of the three versions of the aircraft diesel.

TABLE V
Features and Performance Targets of the Aircraft Diesel Development Program

	PROJECTED PRODUCTION RELEASE DATES		
	1985	**1992**	**2000**
Features			
	Radial	Radial	Radial
	2-Stroke Cycle	2-Stroke Cycle	2-Stroke Cycle
	Limited Cooling (conventional materials)	Limited Cooling (high temperature materials)	No Cylinder Cooling (Ceramics)
	Turbocharged $P_{rc} = 7.25:1$	Turbocharged $P_{rc} = 9.00:1$	Turbocharged and Turbocompounded
	Conventional Lubrication	Air Bearings	Air Bearings

	1985	1992	2000	
Displacement	4.031	4.031	4.031	ℓ
RPM	3500	3500	3500	
Net Cruise Power at 7,620m Altitude	186	257	298	kW
Cruise BSFC	225	197	170	g/kW-hr
Net Take-Off Power	268	369	428	kW
Take-Off BSFC	219			g/kW-hr
Net Economy Power (65% of Cruise Power)	121	167	193	kW
Economy BSFC	206			g/kW-hr
Dry Weight (Including Accessories)	174	186	198	kg
Spec. Weight Based on Cruise Power	.935	.726	.664	kg/kW
Spec. Weight Based on Take-Off Power	.649	.506	.462	kg/kW

The phased development approach has several advantages:

1. A fuel efficient engine will be commercially available at an early date.
2. Fewer technologies will be addressed for each version, which enhances the success of the program.
3. Each successive version can be retrofitted on older aircraft and thus improve the performance of the aircraft.
4. It will be possible to rebuild older engine versions to incorporate the technologies of the next generation.

5.0 CONCLUSIONS

1. The 4-cylinder configuration, although somewhat larger in diameter, offers a distinct weight and cost advantage over a 6-cylinder engine of the same displacement. The radial engine should be designed for a minimum number of cylinders within the available space.
2. The phased development program offers several advantages.
   - A fuel-efficient production engine will be come available much sooner.
   - Fewer technologies need to be developed during each phase thus reducing the risks of the development program.

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15. Supplementary Notes

Final report. Project Manager, Lloyd W. Ream, Engine Systems Division, NASA Lewis Research Center, Cleveland, Ohio 44135.

16. Abstract

The study presented in this report is a continuation and augmentation of the program described in NASA CR-3260, 150 and 300 kW Lightweight Diesel Aircraft Engine Design Study. This report describes the design of an aircraft engine capable of developing 186 kW shaft power at a 7620 m altitude. The 186 kW design takes into account expected new developments in aircraft designs resulting in a reassessment of the power requirements at the cruise mode operation. Based on the results of this analysis a three phase technology development program is projected resulting in production dates of 1985, 1992, and 2000.

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	18. Distribution Statement Unclassified - unlimited STAR Category 07

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