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Liquid Cooled Turbocharged Propulsion System for HALE Application

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ABSTRACT

An unmanned air vehicle (UAV) capable of sustained flight in the upper limits of the tropopause is a relatively new technology which has seen increasing interest during the past decade. Mission lengths for High Altitude Long Endurance (HALE) applications are typically measured in days rather than hours with operating altitudes ranging from 50,000 to 100,000 feet. An Otto cycle propulsion system offers significant performance advantages over other cycles. This paper provides a technical assessment of a liquid cooled turbocharged, reciprocating engine concept capable of meeting the requirements for a HALE vehicle. A properly designed spark ignition engine with a two or three stage series turbocharger system utilizing state-of-the-art aerodynamic design can meet the challenges presented at these altitudes. Several records for long endurance and high altitude flight have already been set with this type of propulsion system. A comparison with other candidate engines will also be made. The ability to operate with low brake specific fuel consumption (BSFC) across a broad operating range will be identified. With sufficiently high exhaust gas temperatures, the addition of a power turbine for turbocompounding can further reduce the BSFC and brake specific air consumption (BSAC). A version of the turbocharged spark ignition engine is capable of providing high thermal efficiency with the least BSAC and minimum turbomachinery weight.

INTRODUCTION

The mission requirements for a HALE air vehicle impose challenges for current technology in several areas, particularly the propulsion system. Compass Cope and Condor are two successful examples of aircraft that integrated the technologies necessary to overcome the challenges presented by HALE flight (2). High propulsion efficiency to minimize fuel consumption and low air consumption to minimize turbomachinery weight are two primary considerations when evaluating candidate engine systems. Teledyne's Voyager 300 (Figure 1) liquid cooled spark ignition engine has demonstrated the capability of thermal efficiencies between 36% and 39% (1). This equates to brake specific fuel consumptions of 0.375 and 0.345 lbs/BHP/hr., respectively. It was a four cylinder Voyager 200 engine which powered the Voyager aircraft (Figure 2) on its historic nine day

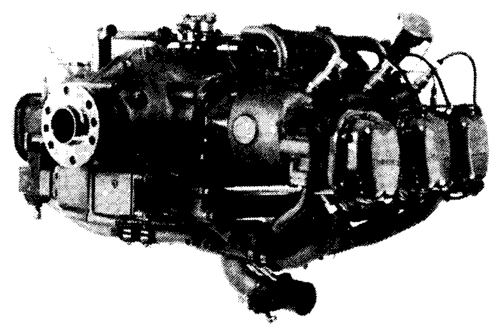

Fig. 1 - Liquid Cooled Voyager® 300 Engine

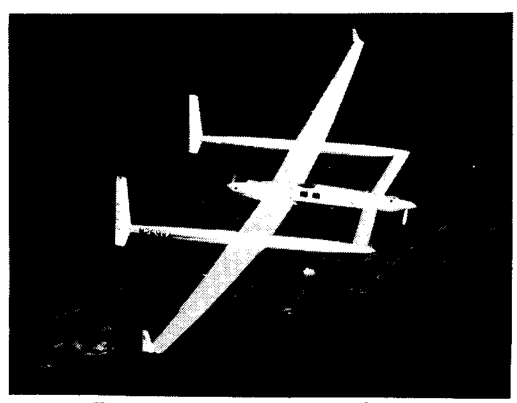

Fig. 2 - Voyager® Aircraft

non-stop, non-refueled flight around the world - a convincing demonstration of the long endurance, low fuel consumption characteristics of the Voyager engine concept. A six cylinder, 300

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cubic inch version was similarly selected to power the Condor (Figure 3), a record setting unique aircraft design developed by the Boeing Company. Liquid cooled spark ignition engines were chosen for both record breaking aircraft due to their high thermal efficiencies and reliability.

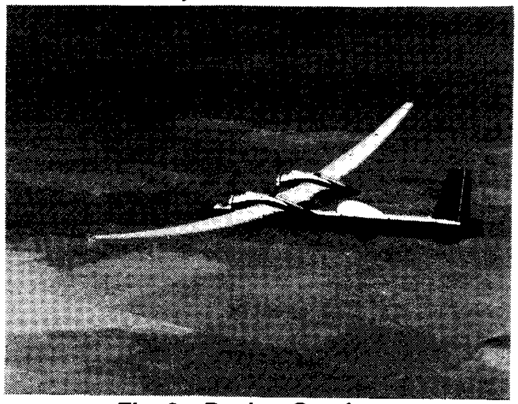


Fig. 3 - Boeing Condor

POWERPLANT ASSESSMENT

Selection of the appropriate propulsion system for a high altitude long endurance aircraft such as the Boeing Condor, or a very long endurance air vehicle such as the Voyager aircraft, is strongly influenced by powerplant efficiencies. Primary considerations include thermal efficiency, air consumption, heat losses, weight, and the ability to operate efficiently at low power. A turbocharged spark ignition internal combustion engine such as the Voyager 200 or 300 series engine operating on aviation gasoline offers an efficient propulsion system strategy for high altitude long endurance flight. This conclusion is based in part upon an assessment of the fuel consumption and combustion airflow characteristics of the candidate engine cycles listed in Table 1.

TABLE 1
CANDIDATE ENGINE CYCLES

- o Spark Ignition Piston Engine
  - Otto Cycle
- o Compression Ignition Engine
  - Diesel Cycle
- o Rotary Internal Combustion Engine
  - Wankel, Stratified Charge
- o Continuous Combustion Gas Turbine
  - Brayton Cycle

THERMAL EFFICIENCY

The single most important criteria for a HALE propulsion system is thermal efficiency, typically expressed as brake specific fuel consumption (BSFC). The significance of specific fuel consumption is best illustrated by the well known Brequet Equation (3, 4) which expresses the relationship between endurance and initial and final air vehicle weights. Endurance is directly proportional to BSFC with the lowest values of BSFC yielding maximum endurance. A 1% decrease in BSFC will affect a 1% increase in endurance. The BSFC criteria forces the air vehicle designer to concentrate on those engines which offer the best possible fuel efficiency. Turbine engines are at a significant disadvantage in this category with cruise fuel consumption for an efficient turboprop more than 20 percent greater than a turbocharged spark ignition engine (2). BSFC characteristics for various piston engines are summarized in Figure 4. Even higher thermal efficiencies are obtainable with turbocompounding as discussed in the following sections.

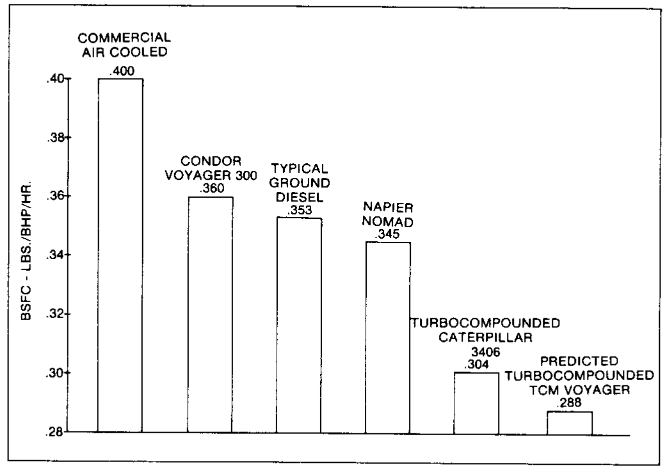


Fig. 4 - Fuel Efficiency of Various Piston Engines

AIR CONSUMPTION

Specific air consumption of internal combustion engines can be expressed as the ratio of combustion airflow to brake horsepower, a term normally identified as BSAC (brake specific air consumption). Based upon a comparison of the combustion airflow characteristics of the above engine cycles, an Otto cycle spark ignition engine offers the lowest specific air consumption which results in the smallest size, and therefore lightest weight turbomachinery. Similarly, the highest value of thrust specific air consumption, TSAC, (ratio of vehicle thrust to combustion airflow) is also obtained. Figure 5 provides a comparison of typical brake specific air consumption (BSAC) values for candidate engine cycles. Even with a Diesel engine which runs on excess air as compared to the spark ignition engine, the turbomachinery size and weight is larger due to the higher air flow at the same horsepower. Stratified charge rotary (Wankel) type

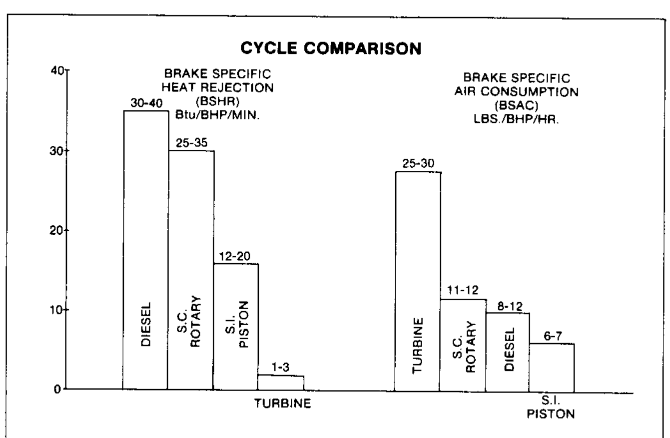


Fig. 5 - Cycle Comparison: BSAC and BSHR

engines have air consumption characteristics closer to the Diesel engine; however, their thermal efficiencies are characteristically lower than either the spark ignition or Diesel engine. The size and corresponding weight of the turbomachinery is directly influenced by the core engine mass airflow requirements.

HEAT LOSSES

Heat losses to coolant and lubricating oil for the spark ignition, Diesel, and Wankel type engines can become a significant consideration at high altitude. Minimum heat losses are desirable to minimize heat sink size and associated cooling drag. As illustrated by Figure 5, a liquid cooled spark ignition engine, such as the Voyager model, is a more attractive choice with substantially lower heat losses as compared to a Diesel candidate. Equally important to the propulsion system thermal balance is the heat dissipation associated with the charge air coolers used to minimize compression work and limit engine intake manifold air temperature.

Liquid cooling has been shown to offer significant advantages for an aircraft piston engine as compared to an air cooled approach (7). Even though air cooled piston engines have a well established successful reputation for commercial and military applications, the air cooled cylinder design concept becomes impractical for adequate cooling at HALE altitudes. Simply stated, a well designed state-of-the-art aerospace quality heat exchanger is a far more effective and efficient heat transfer device in a high altitude environment as compared to a multi-cylinder air cooled engine assembly.

LOW POWER MODULATION

Typical of a long endurance air vehicle, a 40% to 60% power reduction (takeoff to end of cruise) may be required as vehicle weight reduces due to fuel burn. It is obviously desirable for best range and endurance that the propulsion system be capable of operating at reduced power as efficiently as at maximum power. The spark ignition engine offers excellent turndown capability with BSFC actually improving at lower power levels (7). The Diesel engine is not as competitive when evaluated for low power modulation since Diesel engines characteristically have lower exhaust gas temperatures as compared to the spark ignition engine. As power is reduced on the Diesel engine, the point is reached where there is insufficient exhaust gas energy to drive the turbocharger turbines. The result is that Diesel engine minimum cruise power is limited by available exhaust gas energy. Similarly, turbocompounding offers much higher efficiency gains with the spark ignition engine because of its comparatively higher exhaust gas temperatures.

WEIGHT

The fuel fraction of a long endurance aircraft is normally a very large percentage of the total air vehicle weight. Fuel weight can be as much as 75 percent of gross weight, again emphasizing the importance of low fuel burn. Takeoff weight of the Voyager aircraft on its world flight was 9694.5 lbs with 7011.5 lbs of fuel consumed during its nine day flight. Propulsion system weight is estimated to constitute a small fraction, as low as only 10-12 percent of a HALE air vehicle gross weight, and thus represents a second order influence on total aircraft weight. However, weight of the engine system remains an important consideration. Since the power available from a turboprop decreases rapidly with altitude with less than 10 percent of the sea level rating available above 65,000 feet (Figure 6), a very large and heavy turbine engine is required to meet the HALE requirements (2). A turboprop with a sea level rating of near 5500 SHP is required to provide 350 SHP at 65,000 feet, and is estimated to weigh well over 2000 lbs. Weight of an equivalent Voyager 550 system is estimated at 1000 lbs. A reciprocating engine system such as the turbocharged spark ignition engine offers a lighter weight alternative.

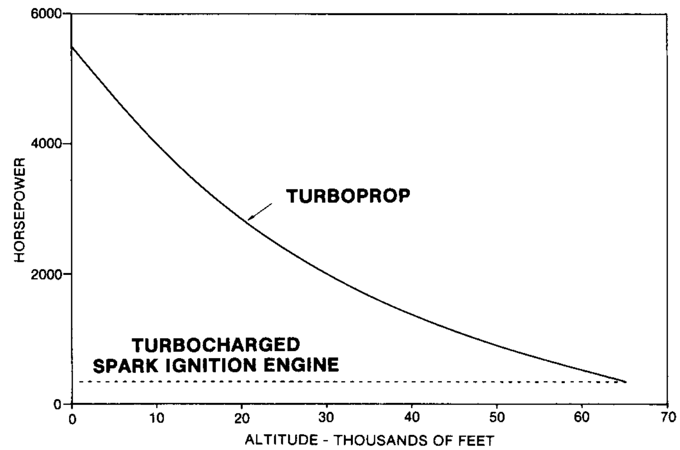


Fig. 6 - Altitude Effects on Horsepower

OTHER CONSIDERATIONS

An important consideration in the selection and sizing of piston type engines for long endurance high altitude applications is the engine size and speed relationship which has a direct influence on fuel consumption and engine life. A larger displacement engine operating at relatively lower speeds is the preferred strategy for best fuel efficiency and longest life, as compared to a smaller displacement engine operating at higher speeds and higher boost levels. The lowest BSFC with the highest reliability and life are achieved with this approach. The higher displacements tend to keep crankshaft speeds low which minimizes frictional horsepower losses resulting in lower fuel consumption. A smaller displacement engine would typically require a higher manifold pressure which increases structural loading and impacts turbomachinery pressure ratio, size, and weight. High speed, highly boosted engines operating at high BMEP levels are typically unable to provide a life equivalent to the lower speed higher displacement aircraft type engines. Aircraft piston engines available today reflect this displacement/speed strategy and are capable of providing TBO's (Time Between Overhauls) in the range of 1500-2000 hours when operated to a general aviation type duty cycle.

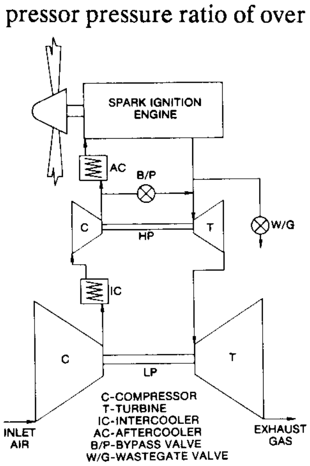
A Diesel type engine or its derivative is also an attractive powerplant candidate; however, a flight weight engine capable of providing the desired thermal efficiencies is not currently available. The biggest advantage offered by a Diesel derivative is improved thermal efficiency as compared to the best spark ignition engine, reference Figure 4. Performance analysis of an advanced on-purpose flight design indicates that a turbocompounded Diesel version offers the potential of obtaining thermal efficiencies near 50%. However, substantially higher heat loss to coolant and oil becomes a detriment with respect to the extreme cooling drag sensitivities at high altitude. Another negative aspect is a heavier engine weight as compared to a spark ignition engine due to much higher peak cylinder combustion pressures - over 2000 PSI as compared to 1100 PSI. In addition, it is not uncommon for a Diesel engine to require a 40-60 PSIA manifold pressure (15-20 PSIA for turbocharged spark ignition) which impacts compressor pressure ratio requirements with a resulting substantial increase in turbomachinery size and weight. Reduced exhaust gas temperature at low power presents additional challenges for the Diesel engine.

PROPULSION SYSTEM CONCEPT

Reflecting the above assessments, it is concluded that the turbocharged liquid cooled spark ignition engine is currently the most attractive candidate for powering a high altitude long endurance aircraft. The most successful application of this strategy to date is the propulsion system selected to power the twin engine Boeing Condor which recently set several world altitude and endurance records. The Condor, a very large experimental autonomous HALE air vehicle with a 200 ft wingspan, established an altitude first for piston powered aircraft by reaching an altitude of 66,980 feet above sea level (2). An endurance record of 58 hours, 11 minutes was also achieved.

The Condor powerplant is a Teledyne developed series turbocharged Voyager 300 liquid cooled engine with a rating of 175 BHP at 2800 RPM. Each engine drives a three bladed, variable pitch, 16 foot diameter propeller through a two speed reduction gearbox (2). The Voyager 300 is a six cylinder 300 cubic inch displacement engine utilizing an advanced design high turbulence combustion chamber with 11.4 compression ratio (7). The engine is capable of providing specific fuel consumption values well below .375 lbs/BHP/hr across a broad operating range and has demonstrated a .355 lbs/BHP/hr cruise capability at 90 BHP/1700 RPM. The turbocharger system consists of two stages, a high pressure (HP) unit and a low pressure (LP) unit, operating in series with both intercooling and aftercooling as illustrated in the schematic of Figure 7.

Turbocharger system controls consist of a single exhaust wastegate valve positioned upstream of the HP turbine with a single air bypass connecting HP compressor discharge to HP turbine inlet. The turbomachinery is capable of providing a total compressor pressure ratio of over 20:1.



POWER, BHP (RATED)	175
DISPLACEMENT CU. IN.	300
NO. OF CYLINDERS	6
CORE ENGINE WT., LBS.	320
BORE, IN.	4.06
STROKE, IN.	3.88
RATED RPM	2800
COMPRESSION RATIO	11.4:1
INLET MAN. PRESS., PSIA	14.7
FUEL/AIR RATIO (LEAN)	.055
BSFC, LBS./BHP/HR. (LEAN)	.360
BSAC, LBS./BHP/HR.	6.0
BRAKE MEAN EFF. PRESS., PSI	165
HP TURBO. WT., LB.	30
LP TURBO. WT., LB.	60

Fig. 7 - Schematic of Turbocharger System

Analysis of advanced turbocompounded (inclusion of an exhaust gas driven power turbine) versions of the Voyager 300 type engine indicate the potential for achieving specific fuel consumption levels near .290 lbs/BHP/hr. Continued interest in HALE air vehicles is likely to precipitate further research into powerplant technology improvements. Hybrid engines (part turbine, part piston) offer the potential for substantial gains in thermal efficiency. At HALE altitudes of 60,000-70,000 feet, the predicted thermal efficiency improvement is as high as 25-40% due to the higher expansion ratios available at those altitudes.

TURBOCHARGER SYSTEM

The turbomachinery required for the previously described propulsion system supplies the proper inlet manifold pressure to the engine in order to maintain sea level power at altitude. The engine can be flat rated from sea level to an altitude of 100,000 feet, providing adequate inlet air manifold pressure is maintained. The exhaust gas driven turbocharger system for a typical HALE application may consist of two or three units operating in a series arrangement. Figure 7 is a schematic of a two stage series turbocharger system. The charge air is intercooled between compressor stages and downstream of the HP compressor. The intercooler reduces compression work while the aftercooler limits intake manifold air temperature. An exhaust gas wastegate is used to control turbocharger speed. The charge air bypass valve bypasses air from the compressor discharge to the turbine inlet for surge margin control. Other control strategies are possible such as variable area diffusers and nozzles.

The number of stages required is dependent upon the total compressor pressure ratio which is influenced by three primary factors: ambient pressure, inlet manifold pressure, and system pressure losses which include heat exchanger and duct losses. Table 2 illustrates the effect of altitude on the compressor pressure ratio for a Voyager 550 type engine system, with an air vehicle mach number of .4.

TABLE 2 - Effect of Altitude on Compressor Pressure Ratio

Engine horsepower	350	350	350	350	350
Altitude, thousand of feet	0	20	60	70	100
Ambient temperature, °F	59	-12	-69	-67	-53
Ambient pressure, in HgA	29.92	13.75	2.12	1.31	.32
Inlet manifold pressure, in HgA	38.0	38.0	38.0	38.0	38.0
Pressure drop, (# of Hx)*(% loss)	---	1x5	2x5	2x5	3x5
Total compressor pressure ratio	1.2	2.7	18.2	29.5	125
Number of turbochargers	1	1	2	2	3
Compressor stage pressure ratio	1.2	2.7	4.27	5.43	5.0

Each column in Table 2 represents a design point for the altitude shown. Figure 8 graphically depicts the effect of altitude on the total compressor pressure ratio. As altitude increases, the ambient pressure decreases significantly until at 100,000 feet a total compressor pressure ratio of 125:1 is required. If each compressor stage has the same pressure ratio at design speed, a pressure of 5:1 is required for each of the three stages.

State-of-the-art pressure ratio for single stage centrifugal compressors is approximately 10:1. At this upper limit for a single stage, the specific speed is usually low in order to minimize inducer tip relative mach number. As the pressure ratio increases the specific speed or swallowing capacity typically decreases. As the inducer tip relative mach number exceeds 1.3, losses can become unacceptable. Maintaining a balance between pressure ratio (i.e. tip diameter), specific speed, and inducer tip relative mach number is crucial to optimizing efficiency, size and weight. Minimizing compressor wheel tip diameter reduces weight since

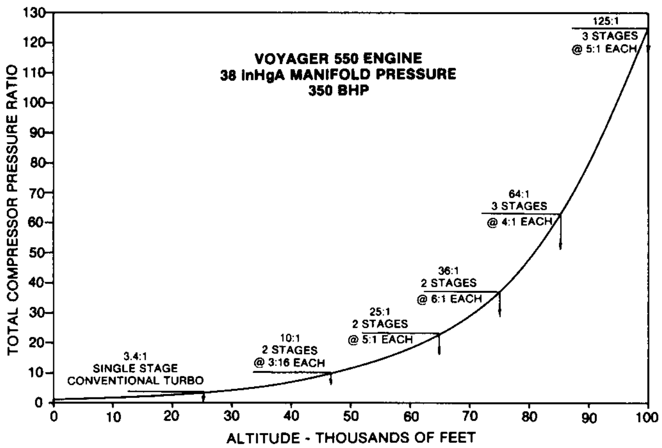


Fig. 8 - Total Compressor Pressure Ratio

weight is proportional to approximately the square of the tip diameter. Both the HP and LP turbochargers have been optimized for operation at the low Reynolds numbers experienced with HALE operation.

Typical compressor pressure ratios for ground vehicle applications range from 2.5 to 3.5:1. Adaptation of commercially available turbochargers is considered practical for operation only at altitudes less than 35,000 feet. Mechanical efficiencies are low due to sleeve type bearing systems. Compressor and turbine efficiencies are less than optimum because diffuser and nozzle vanes are not utilized. For flight above 35,000 feet, an on-purpose design is required. Lightweight and efficient on-purpose turbochargers for aircraft can be provided incorporating state-of-the-art gas turbine technology to improve performance and reduce weight (1).

Table 3 presents the effect of altitude on compressor corrected flow. For an engine flat rated at 350 BHP the compressor corrected flow rises with increased altitude even though the actual engine flow does not change. The effect on compressor size is substantial with increased altitude. Between 70,000 and 100,000 feet altitude a mixed flow or axial compressor becomes a better design choice in order to minimize size and weight.

TABLE 3 - Effect of Altitude on Corrected Flow

Engine BHP	350	350	350	350	350
Altitude, thousands of ft.	0	20	60	70	100
Engine air flow, lbs/sec	.58	.58	.58	.58	.58
Ambient temperature, °F	59	-12	-69	-67	-53
Ambient pressure, in HgA	29.92	13.75	2.12	1.31	.32
Compressor corrected flow, lbs/sec	.58	1.1	6.5	10.5	43.6

CONDOR TURBOCHARGERS

Examples of on-purpose turbochargers designed specifically for use on HALE aircraft are the Condor HP and LP turbochargers. The LP turbocharger is shown in Figure 9. The HP turbocharger (1), identical in design concept, is an example of a very high pressure ratio unit. Table 4 lists design parameters for the HP and LP turbochargers. The goals of high component efficiencies and light weight are reflected in these values. The compressor map for the LP unit is shown in Figure 10. Figure 11 depicts the machined titanium HP and aluminum LP compressor rotors.

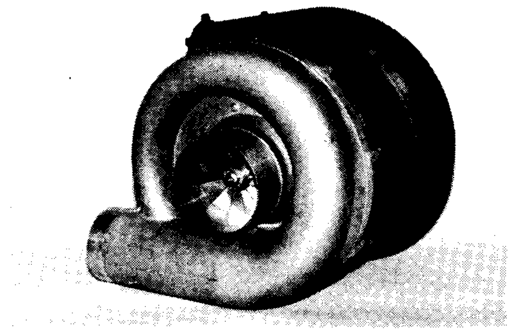


Fig. 9 - LP Turbocharger

TABLE 4 - Turbocharger Design Parameters

	HP Turbocharger	LP Turbocharger
Compressor Corrected Flow, lbs./min.	90	290
Specific Speed, Nss (Balje definition)	90	140
Compressor Corrected Speed, RPM	85890	56000
Compressor Pressure Ratio	5.7	4.0
Peak Compressor Adiabatic Efficiency, %	78	78
Compressor Tip Diameter, inches	5.0	7.0
Rated Turbine Inlet Temperature, °F	1650	1650
Flight Configured Weight, lbs.	30	60
Peak Turbine Adiabatic Efficiency, %	85	87
Weight, lbs.	30	60

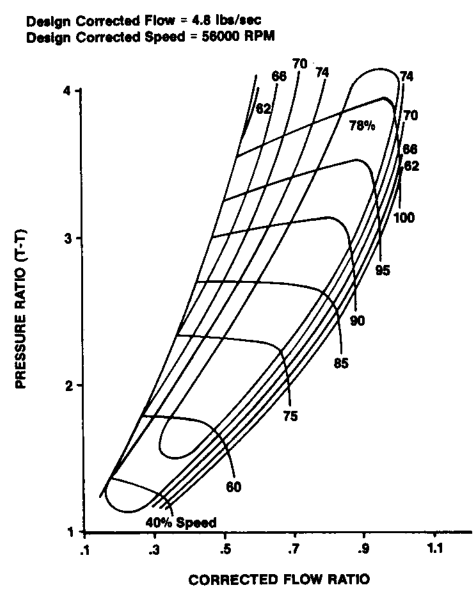


Fig. 10 - LP Compressor Performance

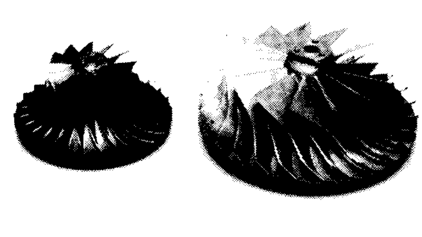


Fig. 11 - HP and LP Compressor Rotors

Figure 12 illustrates the cross section of the LP turbocharger. The HP and LP units share a common bearing system design strategy and application of the latest gas turbine technology. Lightweight, thin walled castings were used extensively. Compressor diffuser vanes are machined in the compressor housing. Turbine nozzle vanes are cast in the turbine housing.

Both turbochargers feature aluminum bearing housings to minimize weight. The turbine backplate was designed with convolutions to minimize heat transfer to the aluminum bearing housing and ball bearings. Angular contact ball bearings are used to reduce mechanical losses. Ball bearings can reduce mechanical losses up to 90% as compared to automotive sleeve type bearings (1).

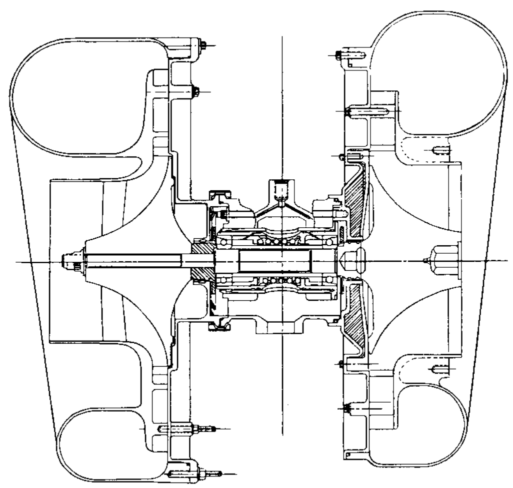


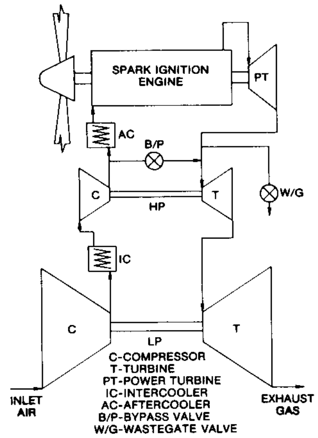
Fig. 12 - LP Turbocharger Cross Section

TURBOCOMPOUNDING

Turbocompounding is an extension of the principle of turbocharging. Excess energy remains in the exhaust gases of a spark ignition engine, even when using exhaust gas driven turbochargers. Turbocompounding recovers additional exhaust gas energy which can be converted to shaft horsepower by using a power turbine mechanically coupled into the engine output shaft. Some of the most efficient internal combustion engines to date were turbocompounded such as the Napier Nomad (5) and the Wright turbocompound radial (6). The Napier Nomad was capable of a BSFC of 0.345 lbs/BHP/hr. For ground operation, the Caterpillar 3406 diesel was recently turbocompounded with the BSFC improving from 0.321 to 0.304 lbs/BHP/hr (8).

The above turbocompounded engines were either ground engines or aircraft engines flying below an altitude of 35,000 feet. As altitude is further increased, the gains in horsepower and thermal efficiency increase due to the higher expansion ratios available at HALE altitudes. The technology necessary to take advantage of turbocompounding requires extensive use of gas turbine technology in the areas of aerodynamics and materials. Figure 13 provides a schematic of a turbocompound engine system with a power turbine positioned in series with a two stage turbocharger system. The power turbine can be located just aft of the engine, between the two turbocharger turbines, or aft of both turbocharger turbines.

For a given altitude and exhaust manifold pressure (which defines the available expansion ratio), the level of turbocompounding is dependent primarily on the component or overall efficiency and the turbine inlet temperature. Turbocharger and



POWER, BHP (RATED)	350
DISPLACEMENT, CU. IN.	550
NO. OF CYLINDERS	6
CORE ENGINE WT., LBS.	450
BORE, IN.	5.25
STROKE, IN.	4.25
RATED RPM	2700
COMPRESSION RATIO	8.5:1
INLET MAN. PRESS. PSIA	18.7
FUEL/AIR RATIO (LEAN)	.060
BSFC, LBS./BHP/HR. (LEAN)	.380
BSAC, LBS./BHP/HR.	6.0
BRAKE MEAN EFF. PRESS., PSI	186
TOTAL SHAFT HORSEPOWER	462
TOTAL BSFC, LBS./BHP/HR.	.288
TOTAL BSAC, LBS./BHP/HR.	4.55
POWER TURBINE HP	112

Fig. 13 - Schematic of Turbocompound System

power turbine efficiencies can be evaluated using Brayton cycle calculations. The overall efficiency, ETAO, is defined as follows:

$$ETAO = ETAC * ETAT * ETAM \quad (1)$$

where ETAC = Compressor adiabatic efficiency
ETAT = Turbine adiabatic efficiency
ETAM = Mechanical efficiency

defining Percent Thermal Efficiency Gain as PTEG, and Total Shaft HP as TSHP:

$$PTEG = PTHP/EBHP \quad (2)$$
$$TSHP = EBHP + PTHP \quad (3)$$

where PTHP = Power Turbine HP
EBHP = Engine BHP

the Total BSFC (TBSFC) can be calculated:

$$TBSFC = BSFC * (EBHP / (EBHP + PTHP)) \quad (4)$$
$$= BSFC * (EBHP / TSHP) \quad (5)$$

Figures 14 and 15 present the effect of turbine inlet temperature (TIT) on PTEG. Both curves assume an engine brake specific air consumption of 6.0 lbs/BHP/hr. and a best power fuel-to-air ratio of 0.072. As the overall efficiency, ETAO, increases from 0.55 to 0.75, the benefit of turbocompounding also increases. Analysis indicates turbocompounding improves with altitude to nearly 75,000 feet.

Figures 16 and 17 illustrate the effect of TIT on PTEG at overall efficiencies of 0.60 and 0.70 respectively. At an overall efficiency of 0.70 and a TIT of 1650°F, a PTEG of nearly 32% at 70,000 feet is possible. Component efficiencies capable of producing an overall efficiency of 0.70 are possible even with low Reynolds numbers. A four stroke spark ignition engine with a well insulated exhaust system can yield a TIT well in excess of 1650°F. Table 5 presents predicted performance gains possible at 70,000 feet with a Voyager 550 type engine.

TABLE 5

Engine BHP, (Rated)	350
Engine BSFC, lbs/BHP/hr.	0.380
TIT, °F	1650
Engine BSAC, lbs/BHP/hr.	6.0
Overall Efficiency, ETAO	0.70
Percent Thermal Efficiency Gain, PTEG %	32
Power Turbine Horsepower, PTHP	112
Total Shaft Horsepower	462
Total BSFC, lbs/BHP/hr.	0.288
Total BSAC, lbs/BHP/hr.	4.55
System Thermal Efficiency, %	48.5

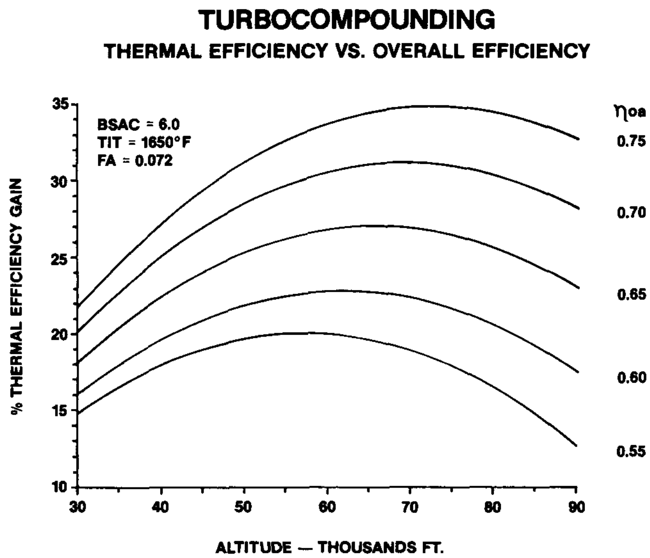


Fig. 14 - Turbocompound of Performance @ TIT = 1650°F

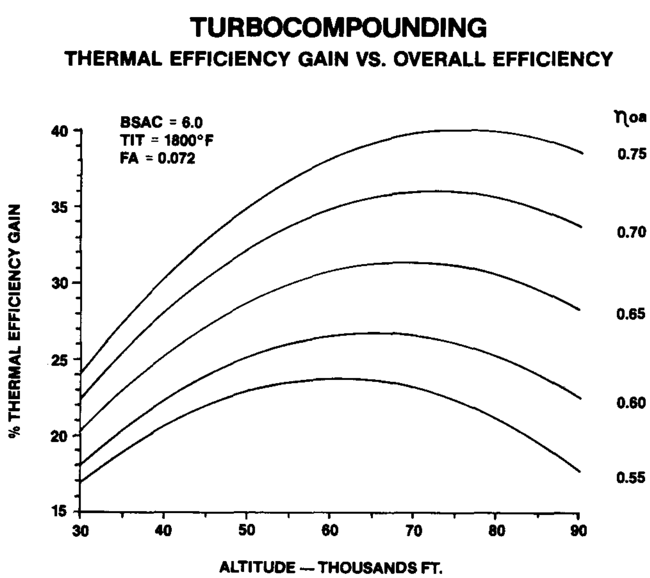


Fig. 15 - Turbocompound Performance @ TIT = 1800°F

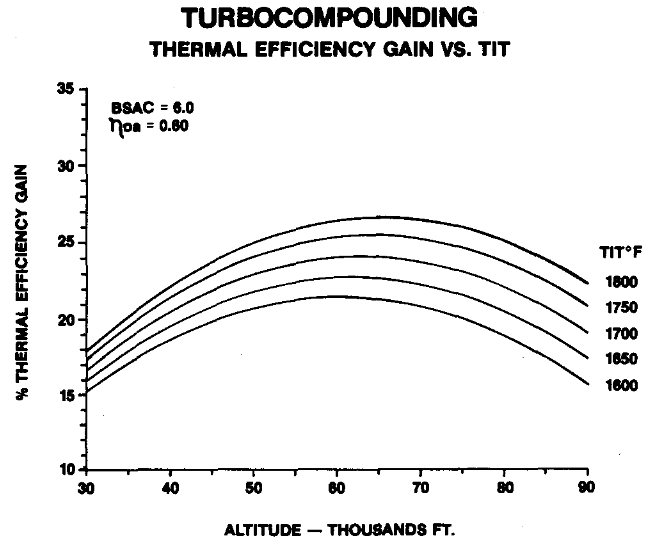


Fig. 16 - Turbocompound Performance @ ETAO = .60

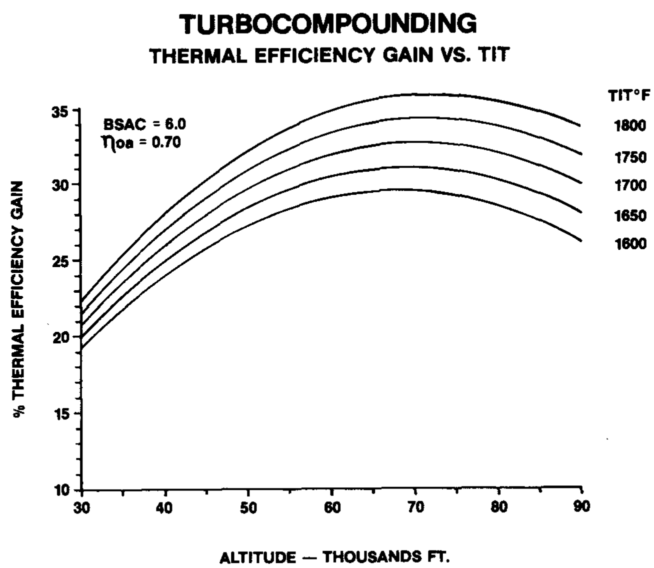


Fig. 17 - Turbocompound Performance @ ETAO = .70

The thermal efficiency of the above turbocompounded system is 48.5%. Means of increasing the turbine inlet temperature to further increase power turbine horsepower and thermal efficiency are currently being explored. A turbocompounded spark ignition engine offers one of the most efficient strategies available for HALE propulsion.

SUMMARY

A liquid cooled turbocharged spark ignition propulsion system is currently the best choice for a HALE air vehicle based on an overall assessment of BSFC, BSAC, heat losses and low power modulation as compared to other engine cycles. Fuel efficiency and reliability of the spark ignition liquid cooled engine have been proven with world records established in the Voyager and Condor aircraft. Light weight efficient turbochargers can allow an engine system to operate efficiently at very high altitudes up to 100,000 feet. Well designed turbochargers combined with high turbine inlet temperatures permit the use of a power turbine to extract excess energy available in the exhaust at high altitude. A HALE turbocompounded, liquid cooled, spark ignition engine can approach a thermal efficiency of 50% with a BSAC below 5.0 lbs/BHP/hr.

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