THE SPARK-IGNITION AIRCRAFT PISTON ENGINE OF THE FUTURE*

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SUMMARY

A study is underway to define and apply those areas of advanced technology appropriate to the design of a spark-ignition aircraft piston engine for the late 1980 time period. Results of the study, so far, show that significant improvements in fuel economy, weight and size, safety, reliability, durability and performance may be achieved with high degree of success, predicated on the continued development of advances in combustion systems, electronics, materials and control systems.

INTRODUCTION

The modern aircraft piston engine has represented the best compromise among fuel economy, weight, size, cost, ease of maintenance, durability and versatility. The evolution of the aircraft piston engine over the past 50 years has included the incorporation of appropriate new technology on a systematic basis, minimizing exposure to risk as this technology became well established and proven in lower risk military and automotive applications. As a result, the product which has evolved from this process has a demonstrated reputation of safety and reliability. Today, the spark-ignition aircraft piston engine serves as a prime mover for 93% of the nearly 200,000 active aircraft in the general aviation fleet.

In recent years, the reality of rising fuel prices coupled with the possibility of reduced fuel availability has added impetus to the search for items of advanced technology which, when incorporated in a newly designed aircraft piston engine, will continue to preserve the increasing utility of this segment of our U. S. transportation system.

ADVANCED ENGINE CHRONOLOGY

Table 1, shows a chronology of events which we know from experience must be accomplished before an aircraft piston engine of a totally new design

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can enter the marketplace.

In generating this schedule, we started at December 31, 1989 and worked backwards allowing time for Marketing and Customer Acceptance Testing, Engine and Airframe Certification Testing, Prototype Engine Build-up and Testing and Parts and Materials Procurement for the Prototype. At this point, we arrive at the time when the level of technology to be included in the engine must be frozen. This leads to a somewhat discouraging revelation. Our advanced technology engine of the late 1980's will reflect a level of technology that is five and a half years old! If we begin to develop the technology that we see emerging as of January 1, 1980, then we have about four and a half years to develop it to the point where it can be realistically included in our advanced technology engine.

TECHNOLOGY CATEGORIZATION

As part of our study we took all those areas of advanced technology we deemed appropriate to an advanced spark-ignition aircraft piston engine, and put them into categories which we ranked, from top to bottom, in order of importance or dependence, as shown in Figure 1.

Our study covered the topics of fuels; combustion systems; various means for extracting additional power from waste exhaust gases - supercharging, turbocompounding and bottoming cycles; engine operational systems such as fuel injection ignition and engine governing systems; configuration and cooling - shown here on the same level because of their interwining relationship (some engines because of their configuration require liquid cooling); materials, from the standpoint of weight reduction and increased durability; manufacturing; engine auxiliary systems - such as air conditioning and electrical power generation and, finally, lubricants.

FUELS

The most important decision we had to make, and in many ways the most difficult, was the determination of fuel availability. We did a very thorough literature survey covering the past, present and future of the energy industry. We looked at not only the technical aspects of development of primary energy resources, but also the economic, social and political trends which might affect our choice of a future fuel.

Considering the fact that the U.S. has the energy equivalent of 33 times as much oil shale, coal and uranium as there is crude oil in the entire world, we came to the conclusion that petroleum-based fuels would be around for a long time to come to meet the needs of transportation. The assumption being, of course, that these needs will be met by the satisfactory development of the technology necessary to efficiently produce synthetic crude oil from our oil shale and coal resources within economic and environmental constraints, and that non-transportation needs will be met by continued conservation measures and development of alternative non-petroleum fuels.

This study showed that there were two identifiable prospects for fuel for our advanced engine. First, for the near term, the continued use of 100LL avgas is indicated, which dictates the use of a homogeneous charge combustion system similar to that which is used today, and second, for the far term, we see the desirability of moving away from this highly specialized aviation gasoline, which comprises less than one percent of all the gasoline produced in the country today. For the far term, our choice of fuel is kerosene-based commercial jet fuel, which suggests the use of a stratified charge combustion system (Table 2).

A parallel can be drawn between the use of jet fuel in an advanced, spark-ignition aircraft piston engine and the increased production of diesel engine powered cars. One of the biggest problems associated with the introduction of a powerplant designed to operate on an alternate fuel is the availability of that fuel to the consumer. As in the case of the diesel-powered car where diesel fuel is widely available because of the existing distribution system for long haul trucking, jet fuel is becoming more widely available due to the increased use of jet-powered business and commuter airplanes.

The availability of two fuels suggested that our study should address the possibility of two advanced engines rather than one. The two engines we have chosen we will call moderate risk technology and high risk technology engines. Both engines are similar, except the moderate risk technology engine is designed to use 100LL avgas in a homogeneous charge combustion system and the high risk technology engine with a stratified charge combustion system will use jet fuel.

COMBUSTION SYSTEM

Once the matter of fuel availability was decided, then the choice of combustion systems could be determined. Shown in Figure 2, on the left, is a standard combustion chamber used on nearly all aircraft piston engines. The combustion chamber volume is hemispherical in shape, with one intake valve, one exhaust valve and two spark plugs per cylinder. On the right is the combustion chamber we are proposing for both the moderate risk and high risk technology engines. In the case of the moderate risk technology engine, the combustion system will use a low pressure fuel injection system where gasoline is injected in the intake manifold just upstream of the intake valve. The high risk technology stratified charge system will inject jet fuel at high pressure directly into the combustion chamber just before the piston reaches top dead center.

This combustion chamber we have called the HTCC, or high turbulence combustion chamber. Through the use of swirl and high turbulence, it permits the combustion of lean mixtures of fuel and air at high compression ratios without the detonation which limits the compression ratio of the standard engine. With the HTCC combustion chamber, we have recently demonstrated the detonation-free operation of a homogeneous charge, 6-cylinder engine at a compression ratio of 12:1 compared to a compression ratio of 8.5:1 for a standard engine. This increase in compression ratio had the effect of improving fuel economy at cruise powers by 7 percent.

TURBOCOMPOUNDING

Among the various means of extracting power from the waste exhaust gases of an internal combustion engine are turbocharging and turbocompounding. In an aircraft piston engine, turbocharging serves two purposes. First, it is a means of extracting greater power from a given engine displacement, and second it is possible to maintain that power from sea level to high altitudes. Turbocharging is a common practice in the aircraft piston engine industry. In 1979, about 65% of all aircraft engines manufactured by Teledyne Continental Motors will be turbocharged.

For our advanced engines we are proposing the use of turbocompounding in addition to turbocharging. The schematic in Figure 3, shows one method of employing turbocompounding. The exhaust gases leave the engine, "E", and pass first through a power turbine T_1, which transmits power back into the engine crankshaft through a speed reduction unit. The exhaust gases then carry their remaining energy to a turbocharger. The advantages of turbocompounding are that it is possible to extract one horsepower for every pound of weight added, and the combination of turbocharging plus turbocompounding is more efficient than turbocharging alone.

Although turbocompounding is not a novel idea in its application to aircraft piston engines, turbocompounding does consititute advanced technology of the basis that we will be attempting to apply it to an engine of only 350 horsepower, compared to the 3000 horsepower of the Wright engine and the Napier Nomad of the post- World War II era.

ENGINE OPERATIONAL SYSTEMS

We see for the future a significant impact on our industry by the work that is now going on in the field of automotive electronics. There is no doubt that the auto industry represents the greatest potential for far term growth for the electronics industry. Partly responsible for this growth is the development of inexpensive and reliable signal transducers and the development of sophisticated electronic control system strategies.

For both the moderate risk and high risk technology engines we see the adaptation of all engine operational systems to electronic control. This means that the present three levers now in use to control engine speed, manifold pressure and fuel flow will be combined into a single lever by which the pilot controls power. The trick is to be able to accomplish this task so that the systems exhibit fail-soft behavior. This means that a mechanical backup system will be required.

In view of the increasing complexity of our air traffic control system and the increasing amount of single-pilot IFR flying, the extent to which we can reduce pilot workload impinges directly on safety of flight. Table 3 lists those operational systems which will be converted to electronic control and the benefits derived from each.

CONFIGURATION AND COOLING

We examined many different engine configurations and reduced our choices to the three shown in Figure 4. As far as cooling is concerned, our conclusions for these three configurations and an engine of 350 horsepower, was that liquid cooling provides no distinct advantage in either weight or cost over air cooling. In fact, when considering the added systems required for liquid cooling, a certain additional risk is involved. Since all engines are ultimately air-cooled, and because of the low temperature differentials present with liquid cooling, the placement of a radiator large enough to remove the rejected heat would pose a problem in the already compact design of an airplane for which this size engine is intended.

Only one of these configurations looked promising compared to the horizontally-opposed, six-cylinder design we ultimately chose, and that was the inverted V-8. The V-8 engine would be more vibration-free than the horizontally-opposed six, but from a cost and maintainability standpoint, six-cylinders are preferable. The radial design was rejected because of its large frontal area.

ADVANCED MATERIALS

The use of advanced materials was considered from the standpoint of weight reduction and increased durability. Table 4 compares three engines where the weight of each is divided up among the materials it contains. The first engine is a TSIO-550 engine representing the present level of technology. It contains 8 lbs. of miscellaneous materials such as plastic, rubber and copper, 332 lbs. of steel, and 245 lbs. of aluminum, for a total weight of 585 lbs. Our moderate risk technology engine contains only 253 lbs. of steel and 215 lbs. of aluminum while we have added 10 lbs. of advanced materials for a total weight of 485 lbs., which is a weight reduction of 17% over the present engine. The reduction in use of steel and aluminum in this engine is brought about primarily by the more judicious use of these materials.

In the high risk technology engine we are using only 80 lbs. of steel, primarily in the crankshaft, reduction gears, cylinders and exhaust valves. The use of aluminum has been reduced somewhat and a total of 119 lbs. of advanced materials are used for an engine weight of 405 lbs., a 31% improvement over the present day engine. In this engine the greatest part of the advanced material weight is titanium, with a small amount of reinforced plastic and ceramics.

Titanium is one of the most abundant metals to be found on earth. While titanium is not a rare metal, it is very costly to produce. The problem being that it is not usually found in great quantity in any one spot, but it's pretty much evenly distributed over the earth. Another problem is that it takes 13 times as much energy to produce a pound of titanium from ore as it does to make a pound of steel. What we are counting on here is an advancement in titanium production and metallurgy which would permit an overall savings in energy consumption to be realized. The question is whether the fuel saved by reducing the weight of the engine by 31% will be overcome by the energy used to produce the titanium in the first place.

ENGINE SPECIFICATION

Many of the details of the design study have been omitted for the sake of brevity, but Table 5 shows comparison of some of the specifications of the three engines we have discussed. All three are six-cylinder, horizontally-opposed. The current technology engine has a displacement of 550 cubic inches, with 420 cubic inches for the moderate and high risk technology designs. All three are rated at 350 BHP and can cruise at 25,000 feet at 250 BHP. At this cruise power the brake specific fuel consumptions are .446, .358 and .331, respectively. The service ceilings of our advanced engines are increased to 35,000 feet compared to 25,000 feet for the present engine.

We've already discussed the installed weight and type of fuel.

The TBO, or time between overhaul, for our current technology engine is 1400 hours, which we have increased to 2000 hours for the advanced engine.

To get an idea of the fuel economy improvements which were made, compare the power wasted in the exhaust of the three engines. The current technology engine dumps the equivalent of 319 HP out the exhaust at maximum cruise power. For the moderate risk technology engine this loss has been reduced by 33% to 214 HP, and by 51% to only 156 HP for the high risk technology engine.

IMPROVED AIRPLANE PERFORMANCE

Well, what does all this buy us? It's not enough to consider only the improvements in the engine. We must look at the bottom line. That is, what benefits do we see when the engine is installed in an airplane?

We are not quite finished with this part of our study. But here are some preliminary results based on the installation of the three engines in a current technology single-engine airframe.

What we've done here in Figure 5 is to simulate the installation of all three engines in an identical airframe designed for a chosen arbitrary mission profile for the high risk technology engine. We chose a range of 1000 nautical miles with 45 minutes fuel in reserve, a cruise altitude of 25,000 feet at 250 horsepower which corresponds to maximum cruise power for all three engines. The resulting calculations show that the present technology engine would have a range of only 518 nautical miles and the moderate risk technology engine, 814 nautical miles.

A relative efficiency was calculated for all three cases based on the payload each airplane could carry, multiplied by its speed and divided by its fuel consumption. The efficiency factor was then normalized to the value of 1.00 for the present technology engine. Based on this factor, the relative efficiency of the moderate risk technology engine was increased by 32% and that of the high risk technology engine by 49%. Of course, these factors will change depending upon the mission profile selected.

A similar analysis was done for the case of a twin-engine airplane (Figure 6), with similar results. In this case the mission profile was set at 1300 nautical miles for the high risk technology twin. The results show normalized relative efficiencies of 1.00, 1.37 and 1.57, respectively.

ENGINE DESIGN FEATURES

Figure 7 shows the top, side and rear external views of an advanced engine, pointing out some of the important features. Both the moderate risk and high risk technology engines will appear substantially the same, externally.

Compared to present engines, the gear-driven propeller shaft has been extended somewhat to accommodate a more streamlined cowling. The exhaust system is designed for good pulse recovery to enhance the power recovery of the turbocompounding power turbine. The speed reduction system from the power turbine to the crankshaft is a Nasvytis traction drive which was chosen over a gear reduction drive because of its potential for damping torsional vibrations and its lighter weight. The engine also includes an integral oil sump/oil cooler to save weight and volume.

In order to achieve a compact design, the exhaust system is on top of the engine rather than on the bottom. Because of this, the engine is designed for updraft cooling, instead of the usual downdraft method. This, in conjunction with an advanced airframe design and well-designed baffling will permit the design of a more efficient ram air pressure rise recovery plenum.

CONCLUSIONS

While this study has not been completed, we have identified several items which require development in the next four and a half years in order for the proposed engines to become a reality by the end of the next decade, as outlined in Table 6.

The critical development items we have identified include; stratified charge HTCC combustion system and a compatible advanced ignition system; an improved efficiency, high pressure ratio, lightweight turbocharger; a reduction drive system for the turbocompounding power turbine; electronic control strategies appropriate to a turbocompounded aircraft piston engine, and a method to improve engine cooling and reduce cooling drag.

Other items of a non-critical nature which have been identified include the reduction of engine friction, the low cost production of titanium, the development of lightweight accessories and improved heat exchangers for oil cooling and induction air intercooling.

ADVANCED SPARK-IGNITION AIRCRAFT PISTON ENGINE TECHNOLOGY BASE CHRONOLOGY (OPTIMISTIC)

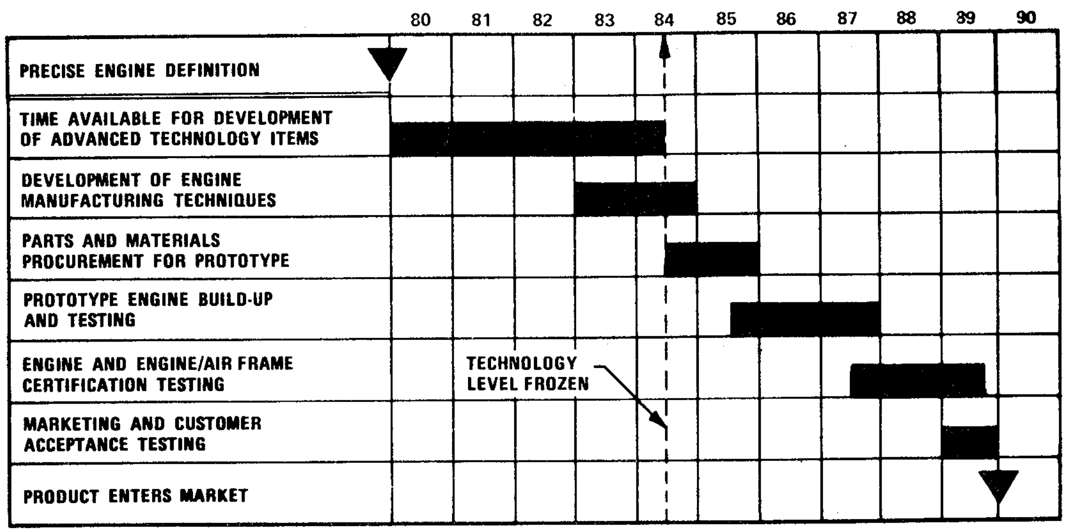

TABLE 1

FUELS FOR ADVANCED SPARK-IGNITION AIRCRAFT PISTON ENGINE

NEAR TERM

- 100 LL AVGAS OR WIDE-CUT VERSION (HOMOGENEOUS CHARGE COMBUSTION)

FAR TERM

- KEROSENE BASE COMMERCIAL JET FUEL (JET A) (STRATIFIED CHARGE COMBUSTION)

TABLE 2

ENGINE OPERATIONAL SYSTEMS

MODERATE RISK
(HOMOGENEOUS CHARGE)

- ELECTRONIC FUEL CONTROL
  - ▲ ELIMINATES MANUAL MIXTURE CONTROL
  - ▲ REDUCES PILOT WORKLOAD
  - ▲ PROVIDES OPTIMUM FUEL ECONOMY
  - ▲ PREVENTS ENGINE DAMAGE DUE TO IMPROPER MIXTURE CONTROL TECHNIQUES
- ELECTRONIC SINGLE-LEVER POWER CONTROL
  - ▲ ELIMINATES SEPARATE THROTTLE (RACK) AND PROP CONTROLS
  - ▲ REDUCES PILOT WORKLOAD
  - ▲ PROVIDES OPTIMUM ENGINE SPEEDS AND THROTTLE (RACK) SETTINGS

HIGH RISK
(STRATIFIED CHARGE)

- ELECTRONIC AIR CONTROL
  - ▲ PROVIDES AIR THROTTLING FOR OPTIMUM FUEL ECONOMY
- ELECTRONIC IGNITION
  - ▲ COUPLES IGNITION TIMING WITH FUEL INJECTION FOR OPTIMUM COMBUSTION
- ELECTRONIC SINGLE-LEVER POWER CONTROL (SAME AS MODERATE RISK)

TABLE 3

ADVANCED MATERIALS FOR ENGINE WEIGHT REDUCTION

	MISCELLANEOUS MATERIALS (lb)	STEEL (lb)	ALUMINUM (lb)	ADVANCED MATERIALS* (lb)	TOTAL ENGINE WEIGHT (lb)	PERCENT (%) WEIGHT REDUCTION
PRESENT 350 hp TSIO-550 ENGINE	8	332	245	---	585	0
MODERATE RISK TECHNOLOGY ENGINE	7	253	215	10	485	17
HIGH RISK TECHNOLOGY ENGINE	6	80	200	119	405	31

*TITANIUM, CARBON/GRAPHITE/BORON REINFORCED PLASTICS, CERAMICS

TABLE 4

ENGINE SPECIFICATION COMPARISON

	CURRENT TECHNOLOGY TSIO-550	PERCENT IMPROVEMENT	MODERATE-RISK TECHNOLOGY GTSIO-420	PERCENT IMPROVEMENT	HIGH-RISK TECHNOLOGY GTSIO-420/SC
CONFIGURATION ENGINE DISPLACEMENT	6-Cylinder/Horiz. Opposed 550 Cubic Inches	---	6-Cylinder/Horiz. Opposed 420 Cubic Inches	---	6-Cylinder/Horiz. Opposed 420 Cubic Inches
MAXIMUM RATED POWER/SPEED	350 Bhp/2,800 rpm	---	350 Bhp/3,200 rpm	---	350 Bhp/3,200 rpm
BRAKE SPECIFIC FUEL CONSUMPTION AT MAXIMUM CRUISE POWER (250 Bhp)	0.446 lb/Bhp-hr	20%	0.358 lb/Bhp-hr	26%	0.331 lb/Bhp-hr
SERVICE CEILING	25,000 ft	40%	35,000 ft	40%	35,000 ft
INSTALLED ENGINE WEIGHT	585 lb	17%	485 lb	31%	405 lb
TYPE OF FUEL	100 Octane	---	100 Octane	---	Jet A
TIME BETWEEN OVERHAUL	1,400 hr	43%	2,000 hr	43%	2,000 hr
EXHAUST ENERGY RECOVERY SYSTEM	Turbocharging	---	Turbocharging Turbocompounding	---	Turbocharging Turbocompounding
EXHAUST POWER UNRECOVERED AT MAXIMUM CRUISE POWER	95 hp	41%	56 hp	87%	12 hp

TABLE 5

ADVANCED SPARK-IGNITION AIRCRAFT PISTON DESIGN STUDY
TECHNOLOGY PROGRAM RECOMMENDATIONS

Critical Development Items

- STRATIFIED CHARGE HTCC COMBUSTION SYSTEM
- ADVANCED IGNITION SYSTEM
- IMPROVED EFFICIENCY, HIGH PRESSURE RATIO LIGHT-WEIGHT TURBOCHARGER
- REDUCTION DRIVE SYSTEM AND CLUTCH FOR TURBO COMPOUNDING TURBINE
- ELECTRONIC CONTROL STRATEGIES APPROPRIATE TO TURBOCOUMPOUNDED AIRCRAFT PISTON ENGINES
- IMPROVED ENGINE COOLING AND COOLING DRAG REDUCTION

Non-Critical Development Items

- REDUCED ENGINE FRICTION
- LOW COST PRODUCTION OF TITANIUM
- LIGHTWEIGHT ACCESSORIES
- IMPROVED HEAT EXCHANGERS

TABLE 6

ADVANCED TECHNOLOGY CATEGORIES HIERARCHICAL STRUCTURE

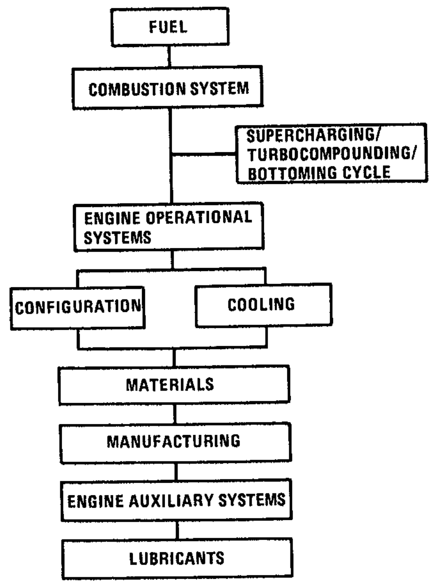

FIGURE 1

HIGH COMPRESSION RATIO/LEAN BURN COMBUSTION CHAMBER

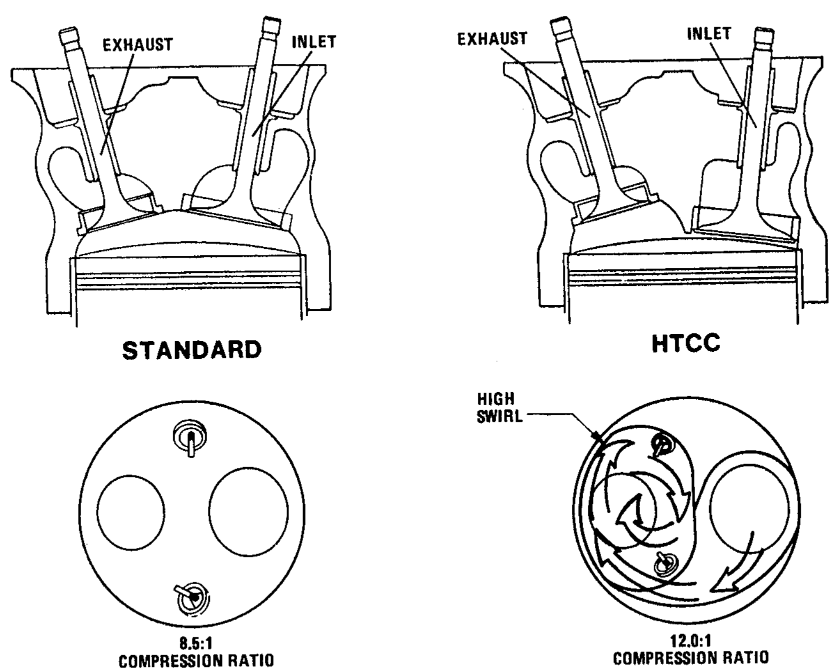

FIGURE 2

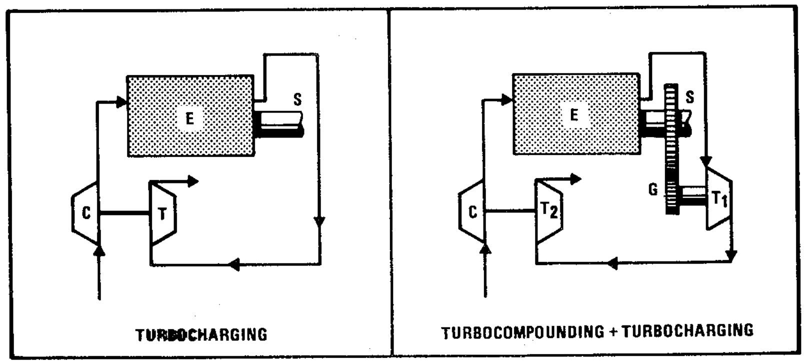

FIGURE 3

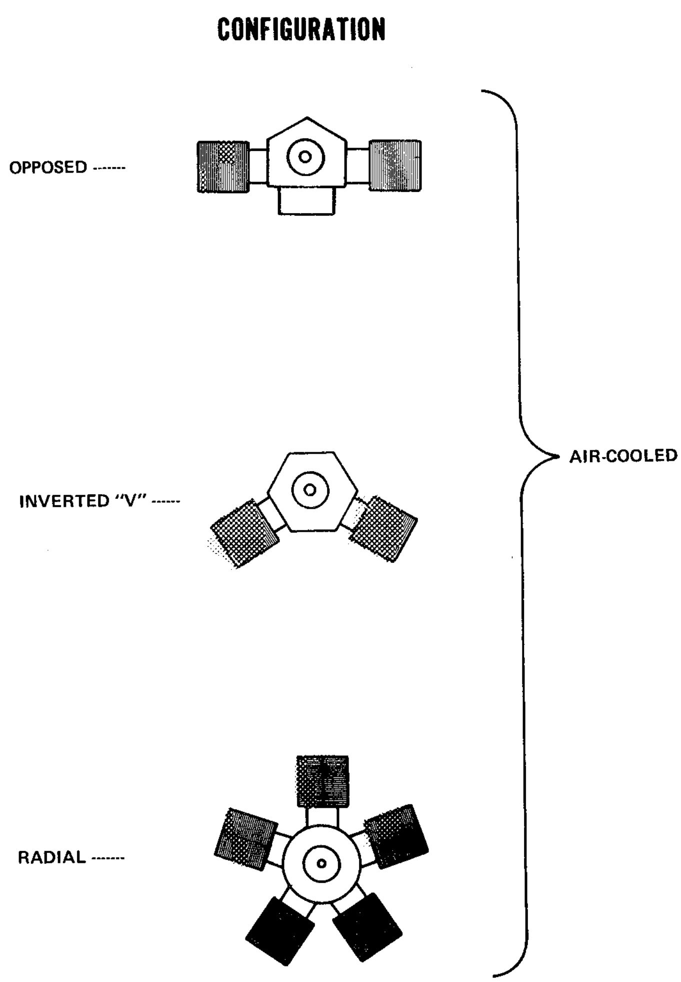

FIGURE 4

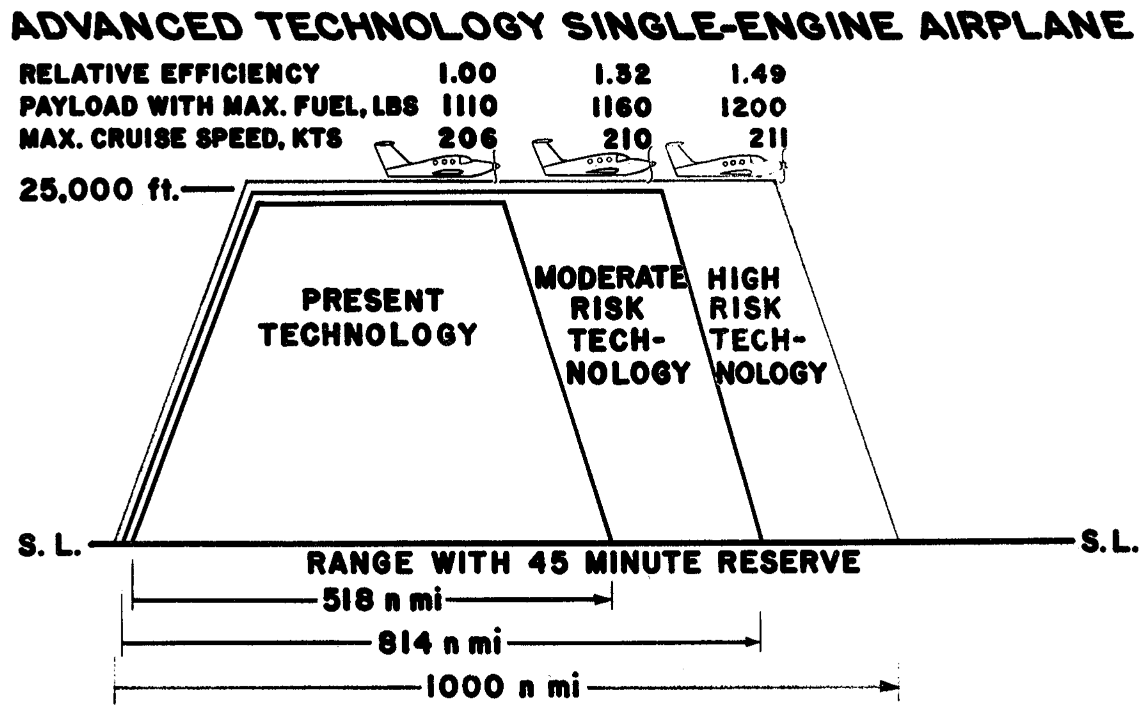

FIGURE 5

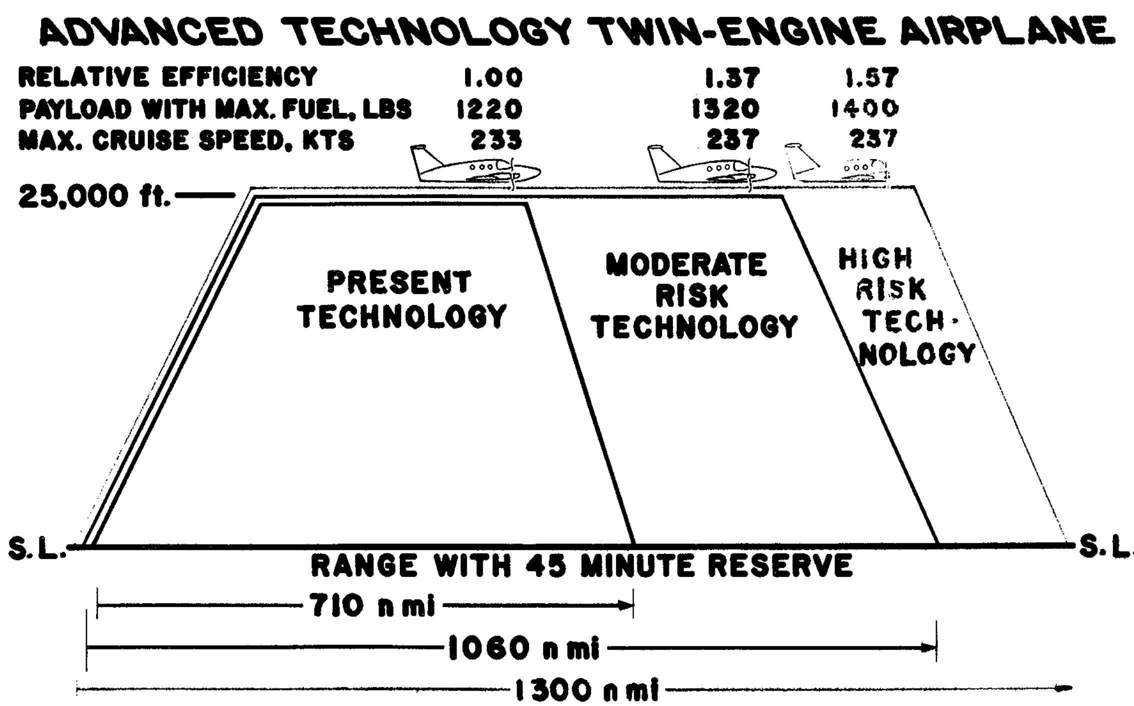

FIGURE 6

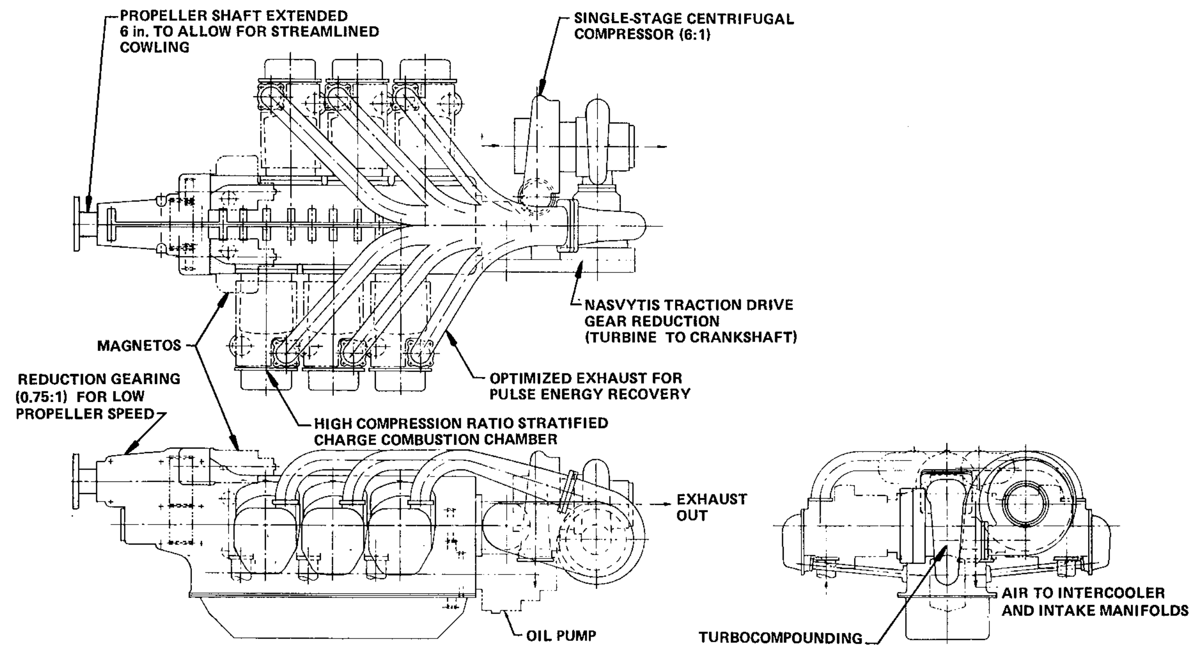
PROPELLER SHAFT EXTENDED
6 in. TO ALLOW FOR STREAMLINED
COWLING
SINGLE-STAGE CENTRIFUGAL
COMPRESSOR (6:1)
NASVYTIS TRACTION DRIVE
GEAR REDUCTION
(TURBINE TO CRANKSHAFT)
MAGNETOS
REDUCTION GEARING
(0.75:1) FOR LOW
PROPELLER SPEED
OPTIMIZED EXHAUST FOR
PULSE ENERGY RECOVERY
HIGH COMPRESSION RATIO STRATIFIED
CHARGE COMBUSTION CHAMBER
EXHAUST
OUT
AIR TO INTERCOOLER
AND INTAKE MANIFOLDS
OIL PUMP
TURBOCOMPOUNDING

FIGURE 7