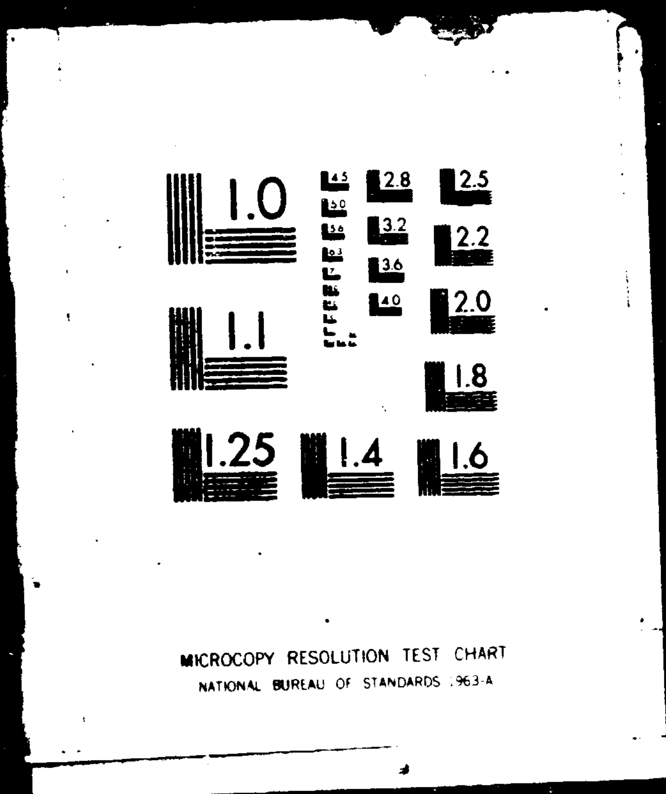
OF 2

N81 - 3963 INCLA



NASA CR-165162

NASA

ADVANCED TECHNOLOGY SPARK-IGNITION AIRCRAFT PISTON ENGINE DESIGN STUDY

(NASA-CR-165162) ADVANCED TECHNOLOGY SPARK-IGNITION AIRCRAFT PISTON ENGINE DESIGN STUDY Final Report (Teledyne Continental Motors, Mobile, Ala.) 127 p HC A07/MF A01 CSCL 21G G3/07

N81-13963

Unclas 29539

FINAL REPORT

BY KENNETH J. STUCKAS

TELEDYNE CONTINENTAL MOTORS
Aircraft Products Division

PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA LEWIS RESEARCH CENTER
CLEVELAND, OHIO 44135
CONTRACT NAS3-21272

1. Report No. NASA CR-165162	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle: Advanced Technology Spark-Ignition Aircraft Piston Engine Design Study		5. Report Date: November 1980
		6. Performing Organization Code
7. Author(s): Kenneth J. Stuckas		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address: Teledyne Continental Motors, Aircraft Products Division, P.O. Box 90, Mobile, Alabama 36601		11. Contract or Grant No. NAS3-21272
		13. Type of Report and Period Covered: Contractor Final Report
12. Sponsoring Agency Name and Address: National Aeronautics and Space Administration, Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes: Project Manager, Michael Skorobatckyi, NASA-Lewis Research Center, Cleveland, Ohio		

16. Abstract

The Advanced Technology, Spark-Ignition, Aircraft Piston Engine Design Study was conducted to determine the improvements that could be made by taking advantage of the new technology that could reasonably be expected to be made available for an engine intended for production by January 1, 1990. Two engines were proposed to account for levels of technology considered to be moderate risk and high risk. The *Moderate Risk Technology Engine* is a homogeneous charge engine operating on avgas and offers a 40% improvement in transportation efficiency over present designs. The *High Risk Technology Engine*, with a stratified charge combustion system using kerosene-based jet fuel, projects a 65% improvement in transportation efficiency.

Technology enablement program plans are proposed herein to set a timetable for the successful integration of each item of required advanced technology into the engine design.

17. Key Words (Suggested by Author(s)): Aircraft Piston Engine; Spark-Ignition Engine; General Aviation; Turbocompounding; Stratified Charge; Aviation Fuels; Propulsion		18. Distribution Statement	
19. Security Classif. (of this report): Unclassified	20. Security Classif. (of this page): Unclassified	21. No. of Pages	22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22161

FOREWORD

The work described herein was conducted by Teledyne Continental Motors, Aircraft Products Division, Mobile, Alabama, under Contract NAS3-21272. The following engineers from the Advanced Engineering Group contributed to the literature survey, analysis, and the Task I effort: Mr. J. Ronald Tucker - Combustion Systems, Turbocharging, and Turbocompounding; Mr. J. E. Meyers - Materials and Manufacturing; Mr. Samuel N. Crane - Configuration, Cooling and Coordination of the Beech Subcontract Work in Task III.

Subcontract work on Task III - Engine/Airframe Integration, was done at Beech Aircraft Corporation under the direction of Mr. Roger L. Benefiel, Group Engineer, Advanced Product Planning - R&D.

Consultants used during the engine design and performance studies of Task II were Mr. Paul J. Louzecky of Troy, Michigan, and Mr. Harold V. Wiknich of Cape Coral, Florida.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Concluded)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Concluded)

LIST OF TABLES

LIST OF TABLES (Concluded)

SECTION 1.0

SUMMARY

This design study was conducted to determine the benefits that could be realized by incorporating advanced technology items into a newly designed spark-ignition aircraft piston engine intended for production in the latter part of this decade.

The study resulted in the design and specification of two such engines. The first, called the *Moderate Risk Technology Engine*, is a design that could result from a moderate investment of both time and money, and whose associated level of technological risk is minimal. The second, called the *High Risk Technology Engine*, incorporates a greater degree of technological risk to achieve a much more efficient powerplant whose design reflects consideration of longer term applicability to the general aviation market.

While the *High Risk Technology Engine* is the main focus of this study, the *Moderate Risk Technology Engine* can be considered the minimum acceptable representation of an advanced technology design. These two engines bracket the levels of technology that could reasonably be expected to be made available for an engine that would be in production by December 31, 1989.

The critical item of advanced technology that needs to be developed to make the *High Risk Technology Engine* a commercial success is the stratified-charge combustion system. The principal obstacles to improved efficiency that now exist for the spark-ignition, homogeneous-charge engine using aviation gasoline are the detonation limit on increasing compression ratio and the octane number limitation of the fuel. Through high-pressure direct-injection of commercial jet fuel and spark-ignition of the resulting charge, improved efficiency can be realized.

Performance studies based on the installation of the *High Risk Technology Engine* in a current technology general aviation airframe show that the transportation efficiency of the airplane could increase by as much as 68%. The possibilities are even more attractive when consideration is given to the installation of the engine in a newly designed high technology airframe with improved aerodynamic efficiency.

A program plan has been formulated that is aimed at bringing the required technology to the point where it can be incorporated into an experimental demonstrator engine early in 1986, with the first production engines available for production airplanes by January 1, 1990.

Spinoff of items produced during the technology enablement programs are expected to have applicability to the existing product line to improve the efficiency of the piston-engine-powered general aviation fleet even before the introduction of the totally new advanced- achnology engine in 1990.

SECTION 2.0

INTRODUCTION

Contract NAS3-21272, "Advanced Technology Spark-Ignition Aircraft Piston Engine Design Study," provides for a study of advanced technology items that may reasonably be expected to be available for the design of an advanced technology spark-ignition aircraft piston engine for the late 1980 time period.

Task I was intended as a predesign phase during which a literature survey was conducted to establish a technology base from which advanced technology items could be chosen for the actual design, in Task II, of an engine capable of cruising flight at an altitude of 7,620 m (25,000 ft) with a minimum propeller shaft output of 186 kW (250 hp). In Task III, the simulated integration of the advanced-technology engine in both single- and multi-engine airplanes shows comparative advantages over the baseline engine representative of the current state of the art.

In Task IV, the new technology items are identified and discussed. Also, the extent to which the development needs of these emerging technology items are met by ongoing programs in Government and industry are addressed. Development schedules have been prepared to show a recommended timetable and plan of action that would result in bringing the expected new technology to the point of commercial production by December 31, 1989. Table I is a list of specific program goals by task.

During Task I, it became evident that there were two distinct engine designs possible for the advanced engine. The first, based on currently developing homogeneous-charge combustion systems, presented a somewhat conservative approach in terms of risk. The second, based on stratified-charge combustion, seemed a more formidable task in its application to a turbocharged aircraft piston engine. These two combustion systems were carried along through the study and are named *Moderate Risk Technology Engine* and *High Risk Technology Engine*, respectively.

In addition to stratified-charge combustion, the *High Risk Technology Engine* proposes the extensive use of advanced materials such as titanium; carbon-, graphite-, or boron-reinforced plastics; and ceramics that carry an additional risk in terms of cost and durability.

The *High Risk Technology Engine* is the main focus of this study, whereas the *Moderate Risk Technology Engine* can be considered a minimum acceptable representation of an advanced technology design. These two engines bracket the levels of technology that could reasonably be expected to be made available for an engine that would be in production by December 21, 1989.

The recommendations of Task IV are aimed specifically at developing the technology needed for the high risk technology design. Should any of the technology items not be available, then alternative technologies specified in the moderate risk technology design would be substituted.

SECTION 3.0

ADVANCED TECHNOLOGY SURVEY AND DESIGN CANDIDATE EVALUATION

3.1 Introduction

The search for a wide-ranging advanced technology base for this study covered areas that might otherwise have been discarded in short-term design improvement programs. The attempt here has been to identify rapidly developing technological areas, or areas in which purposeful, directed effort could result in significant improvements that would allow the beneficial use of this expected advanced technology in the design of future general aviation aircraft piston engines.

Anticipating the state of the art has its pitfalls, of course. A failure in the timely development of a critical item or the lack of availability of such an item at some time in the future could reduce a carefully planned effort to one of only academic interest. Also, unpredictable political, social, and economic forces have a great deal to do with the success of an attempt to design a product for a future marketplace. Textbooks and historical technical references abound with such ideas that were, at the time of their conception, thought to be "too advanced for their time." In all likelihood, however, some of these ideas were created to fill a perceived future need in an unknown political, social, and economic climate that never came about. As time went on, these ideas continued to surface from decade to decade in hope that the time would be ripe.

To avoid this problem, a great degree of flexibility was used in this attempt to predict what could reasonably be expected to be made available for an aircraft piston engine designed for the late 1980s and beyond. The result is a plan of alternatives in the event that the most critical items are not, or cannot be, developed in time for the certification of a preproduction prototype engine. This plan allows for the eventual adaptation of such items in the future as their development reaches the point where incorporation into the design is a possibility.

When considering the application of advanced technology items to the aircraft piston engine, it is convenient to break down the different groups, as in Table II. In some cases, it is not possible to make a choice of a "best concept" in one group without knowing what the "best concept" is an another group. In some cases, this interrelationship among items in different groups also provides for an automatic choice of an item in one group when an item in another group is selected. To avoid the problems involved in this situation, Table II identifies the hierarchical order by which decisions must be made. This table is not in perfect order because some of the items in a major group are not as important as others, but it shows that the most important topics are combustion systems and fuels. They are important not only because of the dependency of all other group topics upon them, but also because they will decide how fuel-efficient the engine will ultimately be. The decision groups will be discussed in the order of importance shown in Table II.

3.2 Fuel

3.2.1 The Spark-Ignition Internal Combustion Engine and Its Fuel

Historically, the abundance of a particular energy source has determined the nature of devices that are used to convert the available form of energy to a useful purpose. It is appropriate, then, that the discussion of an advanced, spark-ignition aircraft piston engine should begin with the subject of fuel.

The petroleum industry grew from the discovery of oil in Titusville, Pennsylvania, in 1859.(1)* During the early years of the industry, before the automobile, the main product from crude oil refining was kerosene, and gasoline was considered a useless (and hazardous) by-product, often being dumped into the nearest waterway. By 1890 the oil business had grown to the extent that the Sherman Anti-Trust Act was passed, dividing Standard Oil into 34 separate companies, the largest of which was Standard Oil of New Jersey (now Exxon).(2)

The invention of the first successful four-stroke cycle internal combustion engine in 1876 by Nicolaus Otto led the proliferation of this type of engine throughout the industrial nations of Europe and in the United States, and it can probably be said with a great deal of accuracy that the spark-ignition piston engine owed its successful beginnings in the U.S. to an abundance of gasoline.

Early automobile engines in the pre-1905 era used this volatile fuel that was a product of straight distillation of crude oil. With a compression ratio of 4:1 or less to avoid detonation, these engines started well and had good cold-weather performance because of the volatility of these early gasolines.(3)

Between 1907 and 1916, demand for gasoline increased fivefold. To meet this greater demand, the yield of gasoline was increased by the new process of thermal cracking, which converted other straight distillation products such as kerosene, gas oil, and residuals. This process, however, produced a gasoline with a broader boiling point range. The end point had increased from 93°C to 182°C (200°F to 360°F) by 1916, causing cold starting problems. These problems were alleviated somewhat by intake manifold heating and the invention of the electric starter.(3)

*Numbers in parentheses designate references at the end of this report.

The concept of anti-knock* properties of fuels was only vaguely recognized, and the poor quality, about 50 octane, kept compression ratios down to the 4-to-1 level. There was, however, research under way to solve the problem of knock-limited compression ratios. Two distinct paths of research involving the relationship of knock to fuel, and to combustion chamber design, led to the discovery that the addition of small amounts of tetraethyl lead (TEL) to gasoline (T. Midgley), or proper combustion chamber design (H. R. Ricardo), would allow the use of higher compression ratios without knock, which improved the fuel economy of the engine. By 1923, TEL as a gasoline additive was commercially available in the U.S.(4)

From that time on, the oil industry and the automotive industry grew rapidly and interdependently. Today, in the U.S., production of spark-ignition piston engines has reached about 10 million units per year - most for the automotive industry. In the past 120 years, the oil industry has pumped 150 billion barrels of oil out of the ground in the U.S.(5), with estimated 1979 production consuming about 3.47 billion barrels of domestic oil and 3.83 billion barrels of imported oil. The demand for motor gasoline alone in 1979 is estimated to be 2.75 billion barrels of oil equivalent (BOE).**(6)

3.2.2 The Energy Situation

Figure 1 shows estimated 1979 U.S. energy use broken down by source, product, and transportation mode. The total 1979 U.S. energy demand is estimated to be 14.78 billion BOE. Of this amount, half will be derived from crude oil. The largest single product of crude oil is motor gasoline, which will comprise about 37.7% of oil production.(6) In the transportation sector, which uses half of the total products produced from crude oil, motor gasoline accounts for 73.3% of all transportation fuels, and aviation fuels, about 11.0%.(7) General aviation accounts for the use of only 7.6% (including manufacturing) of all aviation fuel. Thus, the aviation fuels used by general aviation amount to about 0.2% of the estimated 1979 total U.S. energy consumption, as shown in Figure 2. Aviation gasoline, in particular, will comprise less than 0.7% of all gasoline produced.

The current domestic energy situation is tied strongly to the history of Federal Government regulation and support of the oil industry. Table III gives a brief historical summary of legislation affecting the relationship between oil price and oil supply.

*The definition of "knock" as used here is the audible result of self-ignition of pre-flame-front end gases during the combustion process.

**5.86 GJ (5.55 million Btu) = 1 barrel of oil (159 liters or 42 gal), which gives an average lower heating value of 42 MJ/kg (18,100 Btu/lbm).

Although there are many conflicting views of what the future will hold with regard to the specific energy supply from now until the turn of the century, the following gener l predictions seem to be prevalent in the literature: (7) through (12)

- The requirements for energy in the U.S. are projected to increase, but at a rate of about half of the historic rate.
- U.S. energy demand as a percent of total world energy demand will continue to decline.
- U.S. imports of oil and natural gas will continue to increase at least through 1990.
- Transportation will continue to be almost entirely dependent on oil through 1990, although demand growth will be slower than the historic rate because of increased fuel efficiency of new cars.
- Coal, oil shale, and nuclear energy are projected to have the greatest potential for growth in reducing U.S. dependence on imported gas and oil.
- Hydro, geothermal, and solar energy will supply between 3 and 6% of U.S. energy needs by 1990. Hydro and geothermal power have little growth potential because of limited site availability.
- There will be no drastic changes in the demand for various sources of energy. There may be spot shortages in supply, and politically motivated shortages in supply of imported oil and gas will be short term and will be handled by rationing and domestic inventory drawdowns.

Many energy outlook studies have been made based on both optimistic and pessimistic prediction models that attempt to bracket a probable future energy situation. From these studies, it seems clear that while there is no immediate "oil crisis" the real crisis lies in the problem of the lead-time required to develop alternate energy sources into profitable use.

The rate of energy consumption has always been tied to economic growth. Recently, the President's Council on Environmental Quality undertook a study, "to investigate the potential for achieving lower energy growth in the United States and the implications of this low energy growth for the economy, the environment and government policy."(13) One might conclude that this study reflects the Administration's view of the potential for satisfying all the conflicting needs that arise when the traditional ties are broken between increased real Gross National Product and energy demand growth. The conclusion of this study is that it is possible for the U.S.

to prosper, "on much less energy than has been commonly supposed." One study cited by this report suggests that, "a major slowdown in demand growth can be achieved simultaneously with significant economic growth by substituting technological sophistication for energy consumption." This study also found that the demand for energy in the year 2010 could be about the same as today's level, while providing a higher level of amenities, even with a population increase of 35%.

In surveying the literature, one cannot help but be overwhelmed by the enormity of worldwide energy production and consumption. Such complex interrelationships exist that even the most sophisticated mathematical model can deal only with isolated segments of the effect of any energy-related change to entire worldwide systems. From all of these studies, however, comes a clear picture of what the future must be. A shift in emphasis must take place toward energy resources that are more vast than the relatively minute quantities of petroleum and natural gas that exist. It is estimated that about 1,624 billion barrels of oil remain as the world's ultimate petroleum supply. At the current world rate of consumption, that amounts to only a 60- to 70-yr supply. At a growth rate of 3% per yr, only a 38-yr supply exists.(14) (The oil exporting nations, such as Saudi Arabia, are interested in controlling the rate of depletion of their finite resource, while establishing an industrial economy that is not totally dependent on the sale of crude oil. So, it is unlikely that all of the available petroleum will ever be consumed by exportation.)

In comparison, U.S. ultimate coal, uranium, and oil shale reserves are estimated to amount to 33-times as much as the world's ultimate petroleum supply.(14)

In summary, there is not an energy shortage, but rather an impending crude oil shortage. With the certainty of decreasing availability of petroleum-based fuels, plans must be made to shift toward the use of alternate energy sources in those areas that are the most economically, environmentally, and practically susceptible to such a change.

3.2.3 Analysis of Possible Future Fuel Sources for the Spark-Ignition Internal Combustion Aircraft Piston Engine

The following discussion is based on a list of candidate fuels that will be discussed individually with reference to Table IV, which compiles significant fuel properties for comparison purposes. One of the columns in Table IV lists the mass of each fuel plus its tank, equivalent to 227 liters (60 gal) of 100LL avgas in energy content. This, of course, assumes that equivalent brake thermal efficiency can be attained for each fuel in the engine for which it is intended. A departure from the reasonableness of this assumption occurs when consideration is given to the efficiency of the entire aircraft. A fuel that occupies a large volume or is high in mass per unit energy content may affect overall aircraft efficiency. This possibility forms one important basis in considering each fuel for aircraft use.

3.2.3.1 Hydrogen

Hydrogen as a fuel for internal combustion engines has been a favorite proposed alternate fuel for some time. Combustion of hydrogen with air produces water vapor and some oxides of nitrogen. Its energy content per unit mass (120,824 kJ/kg, or 51,980 Btu/lbm) is over 2.5 times greater than most liquid hydrocarbon fuels (see Table IV). Part of the fascination with hydrogen relates to its abundance. It is the third most abundant atom to be found in the Earth's crust (atmosphere, oceans, and 16 km of solid material), and while rarely found in the free state, it can be produced easily (if not cheaply) by electrolysis of water.

Hydrogen, however, cannot be considered a primary energy resource, but rather must be regarded as an energy carrier. Like electricity, another primary energy resource is required to produce it. The technical feasibility of using hydrogen as a fuel is in its ability to replace other gaseous and liquid hydrocarbon fuels in many applications.

In the near term, the use of hydrogen would rarely prove the most economical alternative in either monetary or basic energy resource terms for the remainder of this century. The massive investments in the production, distribution, and storage of today's fuels pose a very significant barrier to a rapid voluntary conversion to a hydrogen economy.(15)

The main sources for obtaining large quantitites of hydrogen are coal and water. For the various processes for producing hydrogen from coal, the basic common reaction is

$$C + H_2O \rightarrow CO + H_2$$

although the exact process is more complex. The economical electrolysis of water depends to a great extent on the cost of electricity used in the process:

$$2H_2O \rightarrow 2H_2 + O_2 .$$

A great deal of promise for this method was expected to result from the widespread availability of electricity from nuclear power in the near term with supplemental production from solar converters in the more distant future. Also, thermochemical processes with the net effect of the electrolysis reaction have been studied.

Studies have shown that hydrogen produced by electrolysis would cost 1.77 times as much as that produced from coal gasification (16), and hydrogen from coal would cost 3.83 times as much as Jet A fuel made from oil shale.(17)

Recent studies have also shown that liquid hydrogen (LH_2) may have interesting possibilities for large, long-range supersonic jet aircraft.

Flight profiles for these aircraft and the improved ratio of fuel weight to tank mass because of their large size make hydrogen an attractive fuel. Table IV shows that for all three storage methods considered for hydrogen, the tank plus fuel mass equivalent to 227 liters (60 gal) of 100LL avgas presents a severe payload penalty to the small aircraft. At best, liquid hydrogen in a cryogenic storage tank would reduce the payload by 112 kg (248 lb). Also, since liquid hydrogen would most probably have to be stored in the fuselage, a penalty would be paid for the additional 0.807 m^3 (28.5 ft^3) of storage space. The current practice of storing fuel in the wings of aircraft reduces aircraft empty mass by allowing the internal wing structure to serve as a fuel tank and the fuel load in the wings reduces structural mass by helping to reduce bending moments within the wing and loads at the wing attachment points. We may clearly eliminate the use of hydrogen gas in its compressed state for similar reasons and also include the risk of tank failure.

While metal hydride storage can contain more hydrogen per unit volume than normal high-pressure or cryogenic techniques, and its safety features seem to be favorable, the tankage mass is beyond reason for aircraft. The fact that 1 ft^3 of a finely divided metal can absorb 25.5 m^3 (900 ft^3) of hydrogen gas without an appreciable increase in volume seems attractive until it is realized that the storage tank must be filled with the finely divided metal. Even the light complex hydrides such as $LiAlH_x$, $LiBH_x$, $MgAlH_x$, and Mg_2NiH_x (on which the weight in Table IV is based) do not improve the situation. The fact is that the entire payload of most light aircraft would be consumed by enough metal hydride stored hydrogen to equal 227 liters (60 gal) of avgas.

3.2.3.2 Alcohol

Derived from the hydrocarbons methane (CH_4) and ethane (C_2H_6), methanol (CH_3OH) and ethanol (C_2H_5OH) are monohydric alcohols (containing only one OH per molecule). The hydroxyl radical (OH) has the property of bestowing waterlike properties on what were originally volatile but inert hydrocarbons.

Current U.S. production of methanol amounts to less than 0.1% of all of the energy consumed by the U.S. The greatest quantity of production methanol comes from the catalytic hydrogenation of carbon monoxide:

$$2H_2 + CO \rightarrow CH_3\ OH\ .$$

The source of the carbon monoxide and hydrogen is currently synthesis gas that is manufactured from natural gas. However, synthesis gas can also be produced from coal in the manner similar to that discussed earlier in the production of hydrogen from coal.

The use of alcohols as internal combustion engine fuels in the U.S. is limited primarily to use as a gasoline extender in the mixture called "gasohol." The recently passed National Energy Act provides for the exemption of gasohol containing "at least 10% alcohol produced from agricultural products or waste from the 4 cents per gallon Federal Excise Tas." Alcohol produced from coal, oil, or natural gas is ineligible for the tax exemption.(18)

The oil import problem is so critical for Brazil, which imports 80% of its crude oil, that now between 5 and 10% alcohol is mixed with Brazilian gasoline, and consideration is being given to raising this percentage to 25 or 30% to further reduce oil imports.(19)

It is estimated that less than 2% of the land area in Brazil could produce enough fuel to replace its imported petroleum (the U.S. Consumes 20 times as much oil as Brazil). Brazil's eventual use of ethanol by itself as a transportation fuel seems certain because of the following conditions:

- The internal combustion engine can readily be converted to use ethanol efficiently.
- The climate of Brazil is excellent for sugarcane and casava growing, from which ethanol can be produced.
- The sugarcane and casava industries in Brazil are a well-established part of the economy.
- Brazilian government supports and encourages the production and use of ethanol as a transportation fuel.
- Brazil's economically recoverable coal and oil reserves are insufficient to reduce its dependence on imports.
- The availability of cheap agricultural labor improves the economics of the use of agricultural products for ethanol production.
- Arable, readily accessible land in Brazil is estimated to be in excess of 405,000 km^2 (100 million acres).

Brazil's situation is unique in that it promises to make it the first developing country without large oil and coal resources to achieve energy self-sufficiency.(20)

In the U.S., however, the situation is quite different. The availability of large reserves of coal and oil shale make the production of ethanol from biomass an uneconomical prospect.

The production of methanol from coal is estimated to be only three-fourths as efficient as the conversion of coal to gasoline (Figure 3). In other words, producing methanol as a fuel from coal would deplete coal reserves a third faster than coal-derived gasoline. Also, methanol has some problems in practical use as an aviation fuel. Its low energy content when compared with gasoline means reduced range or decreased payload. A tank of methanol equivalent to 227 liters (60 gal) of 100LL avgas imposes a 181 kg (400 lb) mass penalty (Table IV).

The use of methanol as an extender for avgas similar to automotive gasohol would have a problem of phase separation if the mixture contacts water. Also, its motor octane number of 92, while quite adequate for automobile engine use, would degrade the minimum octane requirement (100) for the majority of modern aircraft piston engines. The expected trend toward increased compression ratios in aircraft piston engines for high thermal efficiency would preclude the use of any blending constituent that would reduce octane number.

3.2.3.3 Petroleum and Syncrude-Based Fuels

The remainder of the fuels shown in Table IV fall into the category of petroleum and syncrude-based fuels. That is, they can be most economically and efficiently derived from the refining of crude oil, or syncrude made from coal, oil shale, or tar sands.

A summary of the conclusion of an EPA-sponsored study by Exxon Research and Engineering Company (16) indicates that the most likely direction for alternative fuels for the 1982 - 2000 time frame is the supplement of petroleum fractions by blending with coal and oil-shale-derived components.

The report predicts that initial production of petroleum-type fuels from coal and oil shale is likely by 1981. Also, the production of these fuels will not be limited by the size of domestic and oil shale resources, but eventually by water availability and environmental and ecological considerations. The report goes on to say that coal and oil shale fuels have the potential for becoming a major factor in contributing to automotive fuel supplies by the year 2000. While the initial cost of synthetic fuels may be high, the costs of these fuels are expected to decline on a constant dollar basis, reflecting new and improved technology. As the more economically producible synthetic fuels are depleted, costs will rise again. As other forms of energy, such as nuclear power, displace liquid fuels from nontransportation uses, then these liquid fuels can be released for transportation needs.

This report seems to indicate a need for a priority system that will define the allocation of portable fuels to the various transportation modes on the basis of economic, environmental, and technological flexibility (e.g., the previous discussion indicated it will be more feasible for supersonic transport aircraft to use liquid hydrogen as a fuel than for small general aviation aircraft).

The fuels we will be discussing here can all be obtained from what can be regarded as the near-future U.S. transportation system energy source - hydrocarbon fuels derived from petroleum, coal, and oil shale. The specific fuels will all be produced from a refining process similar to that which exists today.

To understand the specific needs of an advanced spark-ignition aircraft piston engine, it is useful to take a brief look at the process by which today's hydrocarbon fuels are produced. Figure 4 shows a schematic that is representative of a modern petroleum refining process and the products that are produced.

Crude oil (and syncrude) consists of a range of hydrocarbons from the simplest CH_4 (methane) to very heavy molecules containing over 20 atoms of carbon per molecule. The specific characteristics of crude oils vary considerably.(21)

Generally, crude oils contain 84 to 88% carbon and 11.5 to 14.5% hydrogen, with small percentages of impurities such as water, sulphur, oxygen, and nitrogen.

The refining of crude oil begins with fractional distillation that separates the distilled products into groups or fractions according to boiling point ranges. The products may be broadly classified, in order of decreasing volatility, into gases, light distillates, middle distillates, and residue.(22)

While the operational processes of a modern refinery are extremely complex, the fundamental processes that are applied to the products produced after fractional distillation amount to a molecular reorganization to achieve more of the desired end-product mix.

The molecular reorganization or conversion processes that are commonly used are:

- <u>Cracking</u> (22) (16)
  - <u>Thermal Cracking</u> - a process used during the early days of refining in which high pressures (up to 2448 kPa) and high temperatures (482°C) are used to break carbon-to-carbon bonds in high molecular weight fractions. Because insufficient hydrogen atoms are present to attach to the broken carbon bonds, "unsaturated" compounds such as ethylene (C_2H_4) and acetylene (C_2H_2) are formed.
  - <u>Catalytic Cracking</u> - the most important source of high-grade gasoline and petrochemicals. The use of a finely divided catalyst (alumina + silica) increases the rate of cracking reactions while improving the quality of gasoline blending stock.

- *Hydrocracking* - involves the use of hydrogen under pressure with a catalyst to produce lower molecular weight molecules.

• *Reforming* (22) (16)

  - *Thermal Reforming* - a process not used much today, it has the purpose of achieving molecular rearrangements rather than conversion to lower molecular weight molecules.

  - *Catalytic Reforming* - uses a catalyst (such as platinum) and hydrogen to increase octane of naphtha fractions for use as a blending component for gasoline. Hydrogen is produced as a by-product.

• *Upgrading* (16)

  Upgrading is any process that improves the quality of a product relative to the feedstock. Desulfurization and reduction of viscosity (visbreaking) are upgrading processes that improve product quality.

All of these processes, including distillation, are considered to be potentially applicable to the refining of synthetic crudes derived from coal or oil shale.(17)

Table V shows the estimated average yield from a barrel of crude oil. While the average yield of gasoline was 44.4%, gasoline production can change to suit the refinery end-product mix requirements. Very efficient and modern hydrocrackers can produce as much as 67% gasoline from a barrel of oil, if given the appropriate crude oil with which to work. The maximum percentage of gasoline that can be produced by any refinery is a strong function of the type of crude oil used.

The amount of gasoline produced in a refinery is to the detriment of the production of heavier fuels. Also, specifications (including boiling point range) restrict the production of more of a given fuel, but in relaxing those specifications fuel quality suffers.

An advanced spark-ignition aircraft piston engine would most certainly have a high compression ratio compared to today's engines. The limit on compression ratio in a normal homogeneous-charge, spark-ignition piston engine is the fuel octane number. In a multifuel engine, the object is to design a combustion system that is insensitive to either octane or cetane number.

The most important question to answer when considering what fuel an advanced engine should use, if conservation of total crude oil is the ultimate goal, is "What single fuel from a barrel of oil will reduce total refinery/vehicle energy consumption?"

Figure 5 shows the distillation characteristics of a variety of products derived from crude oil by refining. Also shown are methanol and ethanol, which, because of their monomolecular content, are single boiling-point fuels. As an example, Figure 5 shows that aviation gasoline has a narrower distillation range (66 to 171°C) than premium motor gasoline (32 to 213°C) and that JP-4, a naphtha-type jet fuel used primarily by the military, has a very wide distillation range (60 to 243°C) compared to Jet A (Kerojet) fuel (179 to 254°C), which is used as commercial jet fuel.

Two studies of the Vehicle-Fuel-Refinery (VFR) as a system have shown that a broad-range distillate fuel (38 to 343°C) used in a direct-injection stratified-charge (DISC) engine would provide superior VFR economy over other fuels.(23) (24)

Such a fuel might be called "diesoline" because it covers the entire distillation range from gasoline to No. 2 diesel fuel. The use of this fuel would require a specialized combustion system with multifuel capability such as the Texaco TCCS system. The economics of the VFR system study is indicative that refinery yield is an important consideration in crude oil resource conservation. The yield of a broad-specification fuel may reduce refinery energy consumption per unit of product energy content.

The automotive industry could be adaptable to such a change. The primary fuel for the domestic auto system is gasoline. Diesel fuel is available in retail quantities to support the expansion of the U.S. diesel-powered automobile market. A manufacturer could produce a direct-injection stratified-charge engine that would run on either fuel at the consumer's option (fuel price or availability) and the DISC auto population could expand sufficiently to allow production and distribution of a broad-specification fuel. The largest apparent roadblock to the realization of this hypothetical outlook would probably be the stringency of automotive exhaust emission standards.

The use of diesoline in a DISC, spark-ignition aircraft piston engine would depend on its widespread production by U.S. refineries and an additional distribution network to supply the fuel to airports throughout the country. Current projections of the introduction of automotive DISC engines do not hold much promise of a broad-range fuel being marketed commercially within the time period being considered for the advanced aircraft piston engine. Exhaust emission constraints on the first several generations of DISC automotive engines will cause them to be designed to operate on currently available fuels.

Form many years, and especially recently, proposals have been made to allow the use of automotive gasoline (mogas) in aircraft piston engines. While an advanced engine and airframe system could certainly be designed to use automotive gasolines, some serious problems would have to be overcome. These problems could be solved, but the resulting engine would not be capable of the efficiencies attainable on the higher octane 100LL avgas that exists today. Premium, leaded mogas, which is being phased out in favor of unleaded mogas, has a motor octane number of about 90.(25) Unleaded regular mogas has a motor octane rating of only 84 and has been shown to have a negative impact on the VFR system.(24) In addition, the supply of mogas at airports would require separate tank provisions since its use is not compatible with the existing aircraft piston engine fleet.

Consideration given to the use of a wide-cut (broader-specification) avgas would necessarily require an investigation into VFR economy. Considering the total impact on VFR economy of the relatively small percentage of avgas produced in the U.S., a strong case cannot be made on behalf of crude oil conservation. However, the objection of separate tanks at airports for this fuel could be overcome, unlike the case with the use of mogas. If a wide-cut avgas could be produced that would be compatible with the existing aircraft fleet, the possibility exists that it would be a good candidate for an advanced spark-ignition aircraft piston engine.

The use of so-called "heavy fuels" in the advanced engine poses problems similar to those stated previously. Diesel fuel, while widely available, would require additional tanks to be installed at many of the over 14,000 airports available for use by general aviation aircraft. The economic incentive for such a task is decisively unfavorable for the small numbers of aircraft that would exist. The same argument can be applied to the JP-4, JP-5, and JP-6 fuels, which are primarily used in military jet aircraft.

A circumstance does exist, however, that would permit consideration of commercial Jet A fuel in an advanced DISC aircraft piston engine. Before business jets became a significant factor in general aviation, most full-service airports carried at least two types of aviation gasoline. The lower octane 80/87 served most existing general aviation aircraft piston engines, whereas a higher octane gasoline was used for commercial aircraft. The two-tank system remained and the second, higher octane, fuel is now 100/130 low lead (or 100LL). The 100LL fuel was intended to be a universal fuel for aircraft piston engines during the gradual phaseout of 80/87. All current production aircraft piston engines are designed to operate satisfactorily on 100LL avgas, and supplies of 80/87 will continue to decrease as the population of older engines dwindles and the premium price of 80/87 avgas increases over that of 100LL.

It would be easy to draw a parallel to the current availability of diesel fuel for diesel-powered cars, to the availability of Jet A fuel for an advanced spark-ignition aircraft piston engine. Although jet fuel is produced in larger quantities than avgas, it is not as widely available. The situation is similar to the availability of diesel fuel for diesel-powered automobiles. As an example, of all the public airports in the State of California, only 71% have aviation fuels for retail sale. Of those airports that have fuel, only 25% have Jet A fuel available. If this statistic is typical of the entire U.S., then only 18% of all airports would be capable of providing for the fuel needs of aircraft using Jet A fuel. This inconvenience would require more careful flight planning.

Another advantage of a stratified-charge combustion system for an advanced aircraft piston engine is that the broader tolerance of the engine-to-fuel characteristics would be an advantage, should the specifications for jet fuel be modified in the future to accommodate the use of refinery feedstocks or blending stocks derived from oil shale or coal syncrudes. Current aircraft piston engines have exhibited much more sensitivity to changes in fuel specifications, as was seen in the attempt to develop a universal aviation gasoline (100LL) to replace existing 80/87 and 100/130.

Table IV shows that the mass penalty of Jet A fuel compared to 227 liters (60 gal) of avgas would be negligible, provided the efficiencies of the engines using these fuels is the same. An engine (probably direct-injection, stratified-charge) designed to use Jet A fuel would be more capable of adapting to an adjustment in VFR economy by broadening the specifications of the fuel than current homogeneous-charge, avgas-fueled aircraft piston engines.

The price controls on Jet A fuel and avgas have recently been removed, which should provide the economic incentive for production, eliminating spot shortages that had been predicted had the price controls not been removed.(26)

Current U.S. production of commercial-grade jet fuel amounts to slightly less than 7% of barrel of oil. Free-world production of jet fuel is from 4 to 5%. The potential yield of jet fuel by straight distillation is nearly 12% if it becomes economically attractive to do so.

Thus, increased production of commercial jet fuel is possible without increasing total crude oil demand if the use of alternate energy sources can be provided for other current crude oil users, notably stationary powerplants. There appears to be no ready substitute for fueling aircraft with anything but petroleum-derived products in the foreseeable future, and the assurance of adequate supplies of these fuels for aviation depends heavily on the development of alternate energy sources, especially nuclear power and coal.

3.2.4 Summary - Fuel

There are two reasonable fuel choices for an advanced spark-ignition aircraft piston engine: 1) a wide-cut aviation gasoline with an octane rating not less than the current 100LL and 2) Jet A or Kerojet fuel.

The development of an advanced, high-compression-ratio, lean-burn combustion system would allow an improvement in efficiency using 100LL, or a wide-cut, 100 octane fuel.

Development of a direct-injection stratified-charge type of engine would permit the use of widely available commercial jet fuel or a wider-cut version of this fuel that could be developed to improve the VFR system efficiency in conserving crude oil resources.

The high-compression-ratio, lean-burn system is an area of developing technology that could be ready for introduction by the late 1980s.

A direct-injection stratified-charge engine using Jet A fuel would require more intense development to be ready for introduction by the late 1980s.

While it appears that the total use of Jet A fuel would be the ultimate goal, a nearer term solution with less risk and more immediate results is the development of a more fuel-efficient engine that could use a wide-cut avgas compatible with the current piston engine fleet.

The specific advanced technology items identifiable are as follows:

- Determine the limits of a wide-cut avgas compatible with the current aircraft piston engine fleet that could be used in an advanced engine. Maximum VFR efficiency would be the goal for the advanced engine, within the constraints imposed by existing engines.

- As a long-range goal, develop a combustion system compatible with the use of commercial jet fuel, with the idea of eventually displacing the need for aviation gasoline. The combustion system should have a demonstrably higher VFR efficiency and the capability of using a broader range of fuels.

3.3 Combustion Systems

3.3.1 Introduction

Once the matter of fuel availability is decided, the choice of combustion system can be determined. In Section 3.2, the relationship between fuels and combustion systems was briefly described. The principal limitation to improved fuel economy for the homogeneous-charge engine was identified as knock-limited compression ratio, and the two methods of overcoming this limitation were identified as 1) fuel octane number modification by using additives and 2) combustion chamber design.

In the aircraft piston engine industry, fuel economy has always been a major consideration in engine design. The motivating force for fuel economy in the aircraft piston engine was traditionally one of increased utility. For every extra liter of fuel carried on board, the useful payload had to be reduced by 0.72 kg - the mass of a liter of fuel. Any deviations from operation at best economy fuel-air mixtures were dictated by the desire for maximum power for takeoff and by temperature limitations on engine materials. As a result, the aircraft piston engine has been among the most fuel-efficient, spark-ignition engines in the world. Now, with the fuel accounting for an ever-increasing portion of the direct operating costs associated with aircraft ownership, fuel economy has become even more important.

3.3.2 Homogeneous Charge Engines

Improving the fuel efficiency of this class of engine by increasing compression ratios is limited in two ways. First, increasing the fuel octane rating above its current level of 100 PN* by using additives is limited by the lead tolerance of the existing piston engine fleet. Unfortunately, no known additive exists that could economically increase the performance number of aviation gasolines without adverse environmental or engine durability effects. Second, while increased octane rating can be refined into a fuel, current 100LL avgas is considered to be at the limit now. The improvement in efficiency of an advanced, homogeneous-charge engine gained by increasing compression ratio to take advantage of increased octane rating refined into the fuel would be offset by increased energy use at the refinery needed to make such a fuel. Again, the importance of looking at VFR efficiency asserts itself.

At an average motor octane number of 84, current unleaded mogas is also considered to be at the point of diminishing returns in VFR efficiency. However, environmental concerns for lead emissions and the effects of lead poisoning of catalytic converters have been determined to outweigh the improvements in VFR efficiency, which are possible with TEL and increased compression ratio.

Combustion chamber design as a means of increasing knock-limited power has not received as much attention in recent years as has the effect of combustion chamber design on exhaust emissions. Compression ratios of automobile engines had been gradually reduced during the early 1970s to control emissions of oxides of nitrogen and hydrocarbons at the expense of fuel economy. Lower peak firing pressures and temperatures during combustion helped to reduce NO_x, and higher exhaust gas temperatures because of lower expansion ratios increased the oxidation of HC.

Recent developments have shown that additional limited economy improvements are possible with combustion chamber redesign, provided exhaust emissions are not a factor. Figure 6 shows a comparison between a standard hemispherical combustion chamber used on today's engines and a high turbulence combustion chamber (HTCC).

*PN - Performance Number. Above 100 octane number (100% isooctane), the anti-knock rating is called "performance number" and is indicative of the increase in knock-limited power obtainable compared to 100 PN gasoline.

With a given fuel, the HTCC extends the knock-limited compression ratio over a standard combustion chamber. With variable ignition timing to retard the spark during detonation-prone operating modes, the HTCC has been demonstrated to be capable of operating at 12:1 CR compared to 8.5:1 for the standard chamber with fixed timing. Operation of the engine at 12:1 CR has been demonstrated to give an improvement in cruise fuel economy of more than 7%.

The higher, knock-limited compression ratio of the HTCC is due to the faster rate of combustion at the high rates of swirl and turbulence. The compact combustion chamber increases swirl velocity near top center of the compression stroke because of its smaller diameter (smaller than the cylinder bore) through conservation of angular momentum. This high swirl and turbulence is thought to reduce the residence time of the preflame front charge as more of the mixture becomes more quickly involved in combustion.

The HTCC was chosen for the *Moderate Risk Technology Engine* as being representative of the best available solution to improvement of the homogeneous-charge combustion system operating on existing aviation gasoline.

These limitations on efficiency improvement of the homogeneous-charge, spark-ignition internal combustion engine have led to a search for combustion systems that are insensitive to octane number.

3.3.3 Stratified-Charge Engines

While the term stratified-charge covers a broad range of combustion system designs, most have in common the attempted solution to several problems of the homogeneous-charge engine:

- Elimination of end gas or reduction of end gas residence time to eliminate knock.
- Stratify the fuel-air mixture to obtain a locally able mixture even at extremely lean overall fuel-air ratios.
- Reduce pumping losses by controlling power by variations in fuel-air ratio rather than by throttling.

Of the many forms of charge stratification, the one chosen for the *High Risk Technology Engine* is an open chamber type with high-pressure, direct fuel injection. The concept of charge stratification is not new, having been described by Nicolaus Otto as early as 1877 and having been reduced to practice in the early part of this century. The commercial application of charge stratification, however, has only recently begun.

The most notable example of an open-chamber, direct-injected stratified-charge combustion system is the Texaco Controlled-Combustion System (TCCS). Its application is being directed toward automotive use to take advantage of its ability to operate at high compression ratios for good fuel economy, while at the same time run at overall lean fuel-air ratios for low exhaust emissions. The stratification of the charge provides a combustible mixture that is spark-ignited. The combination of high-pressure, direct fuel injection and spark ignition have the effect of making this form of charge stratification insensitive to both octane and cetane rating of the fuel. For this reason, this type of engine has been called a "semi-diesel." It combines some characteristics of both spark-ignition gasoline fueled engines and the compression-ignition diesels.

As can be expected, an attempt to combine the best features of two systems often involves including some of the disadvantages of both. This type of engine usually exhibits some degree of multiple fuel use capability, which can be considered a synergistic result of combining the two types of combustion systems. However, some of the disadvantages of the diesel remain. Because of the direct injection, the stratified-charge engine, like the diesel, is incapable of full air utilization. Compared to the homogeneous-charge engine where maximum power dictates a fuel-air ratio of about 0.076, direct injected engines are normally limited to a fuel-air ratio of 0.055 to 0.060, beyond which incomplete combustion causes soot formation because of poor mixing of fuel and air in the combustion chamber. The result can be a 20 to 30% reduction in brake output for a given displacement. Using a middle distillate fuel, the stratified-charge engine is capable of better air utilization than the diesel by delaying ignition to some point after the start of injection. The power loss can be reduced to nearly 15%. As with the diesel, stratified-charge engines exhibit a sensitivity to maladjustment of injection timing and duration, and the relationship between injection and spark-ignition must be closely controlled and must vary with load and speed. Also, the cost of the fuel injection systems are quite high compared to low-pressure fuel injection or carburetion.

In considering the use of charge stratification for an advanced aircraft piston engine, priorities differ radically from those of the automotive application. These priorities are based on differing constraints and operational requirements. The aircraft piston engine operates at high indicated mean-effective pressures during cruise compared to relatively low road load conditions for automotive applications. Maximum power is frequently used in an airplane, and high power-to-weight ratios consistent with durability at high power is required.

The case for developing a stratified-charge combustion system for an advanced spark-ignition aircraft piston engine remains a convincing one. The risk associated with the successful development of a commercial product suitable for use in general aviation aircraft, however, remains high. The history of development of stratified-charge combustion systems is rife with painfully slow development programs yielding modest gains in the direction of merely adequate performance. Because of many large gaps in the body of knowledge concerning combustion in piston engines in general, and stratified engines in particular, these engine development programs have tended toward iterative cut-and-try methods without a solid foundation of input from theoretical models. More often, the theoretical models are "fine-tuned" using data from engine development programs and are of little help in pointing the way to any substantial improvement.

The quantification of fuel atomization, fuel vaporization, turbulent diffusion, chemical kinetics, and heat and momentum transfer in multidimensional combustion models, although proceeding at a rapid pace, cannot be expected to be brought to the point of making a significant impact in predicting the design of the *High Risk Technology Engine* combustion system being proposed here. In the 3.5 yr set aside for applied research of the stratified-charge combustion system, a great deal of reliance on the experience of good design practice proven by other stratified-charge engines will be required. The synthesis of a combustion model coupled with the hardware program is suggested, provided the model can be capable of making a positive contribution to the combustion system design rather than running the engine for the sake of improving the combustion model.

Experience has shown that one of the major problems faced in the design of a stratified-charge engine is the compromise in performance dictated by fixed geometries. To some extent, this problem will be lessened for an aircraft engine, which operates most of the time at constant speed and load within a narrow power range and without the burden of exhaust emission constraints. The operation of the engine at off-design points need only be adequate, provided the design points such as full power and cruise give the expected results.

In an open chamber, high-pressure fuel injection design, the fixed geometries of concern are: nozzle type, nozzle location and penetration depth, spray pattern (determined by nozzle hole size and location and number of holes), spark plug type, spark plug location and penetration, combustion chamber geometry, intake port geometry, piston clearance in the squish zone, compression ratio (expansion ratio), piston crown geometry, and materials used for the piston and cylinder head. While an infinite number of combinations and permutations exist, the experience of the many stratified-charge engine development programs that are ongoing will serve to reduce the choices to a more manageable level. The use of fractional factorial testing as a development tool will help to further minimize the choices in optimizing the design that will initially be based on the existing HTCC combustion chamber design (Figure 6).

3.4 Turbocompounding and Turbocharging

It has long been recognized that there are benefits to be derived from a compound engine. Not only can power be derived from expansion in the working cylinder of an internal combustion engine, but also from a second thermodynamic machine using waste exhaust gas energy. In a sense, all turbocharged engines are compound engines as well. Exhaust gas energy is used to drive a Brayton cycle engine (turbocharger) that has the potential of increasing the specific output of the engine. Also, in the aircraft application, the turbocharger allows the engine to operate at a constant power from sea level to high altitudes.

In a naturally aspirated engine, depending on operating condition, anywhere from 30 to 50% of the energy of the fuel is lost in the exhaust process. By turbocharging, part of that energy can be recovered to improve specific output of the engine, but its effect on fuel economy may be detrimental. For a homogeneous-charge engine, a limit must be placed on peak cylinder pressures to avoid detonation. When turbocharging this type of engine where the intention is to improve specific output, the compression ratio is reduced to maintain peak combustion pressures below some limiting value. Reducing compression ratio reduces expansion ratio, and for the same peak pressure level as the naturally aspirated version, it reduces indicated thermal efficiency as well. An additional negative effect of turbocharging is the fact that, not only is the geometric expansion ratio reduced but also the higher pressures in the exhaust system tend to reduce the expansion pressure ratio, which further reduces fuel economy.

In turbocharging a direct-injected, stratified-charge engine, however, there is no octane requirement and peak combustion pressures are limited only by structural strength considerations and, especially for aircraft engines, a reasonable power-to-weight ratio. Beyond a certain level, increasing the peak pressure will only serve to increase engine weight without a significant gain in fuel economy. The high risk technology stratified-charge engine has a compression ratio of 12:1 while limiting peak combustion pressures to 10,340 kPa (1500 psia).

An expansion turbine is not the most efficient means of extracting waste exhaust gas energy. There are other thermodynamic machines (bottoming cycles) that offer greater efficiencies but with a severe penalty in weight, size, and cost. The turbine is well-suited for operation with large quantities of gases at low pressure, and its cost, weight, and specific performance counteract its lower efficiency.

Were it not for the desirability of maintaining constant power from sea level to high altitudes and the need for cabin pressurization in an airplane, the turbine work output would be put to better use by mechanically gearing it back into the output shaft of the engine. The engine would then produce more power on a given amount of air and fuel. The benefits of turbocompounding are more directly related to fuel economy, where turbocharging, as it is used in current aircraft piston engines, relates more to operational requirements.

To optimize the system for fuel economy, the turbocompounding power turbine has been placed ahead of the turbocharger turbine to put the recovery of exhaust pulse energy to the most efficient use. The turbocharger turbine uses the remaining exhaust energy as a means of driving the compressor (Figure 7).

Figures 8, 9, and 10 show a detailed power balance, starting with the equivalent fuel power required to produce 186 shaft kW (250 hp) for each of three engines. The TSIO-550 engine (Figure 8) represents current technology with a brake thermal efficiency of 30.49% (BSFC = 271 g/kW-hr) at 7620 m (25,000 ft) cruise altitude.

The *Moderate Risk Technology Engine* (Figure 9) requires 20% less fuel input for 186 kW and has a 38% brake thermal efficiency (BSFC = 28 g/kW-hr).

The *High Risk Technology Engine* (Figure 10) has a further 8% reduction in fuel input required over the *Moderate Risk Technology Engine* design and has a brake thermal efficiency of 41.39% (BSFC = 201 g/kW-hr).

As the basic power section becomes more efficient, there is less exhaust gas energy available. For example, the *High Risk Technology Engine* has only 63% of the exhaust gas energy available as the current technology engine. Yet it produces 71% as much power through turbocharging and turbocompounding. The result of improving the efficiency of the piston engi power section is the requirement for greatly improved turbocharger and turbocompound power turbine efficiency.

The need for great efficiency of these components is also due to the rating of this engine beyond the minimum requirement of 186 kW (250 bhp) cruise at 7620 m (25,000 ft). The engine is designed to produce 261 kW (350 bhp) from sea level to 7620 m and a minimum of 149 kW (200 bhp) at 10,668 m (35,000 ft). Operation at 10,668 m means that more cabin bleed air will need to be supplied by the compressor. Also, rating the engine at 216 kW at 7620 m means that a larger engine is required than one designed to operate at a maximum of 186 kW. Designing the engine for 261 kW but limiting maximum cruise power to 186 kW (71% of maximum power) permits a built-in conservatism in design that extends engine life and also allows cruise power levels to fall into a band of engine operation where best economy occurs.

To achieve a successful turbocharging/turbocompounding system for the *High Risk Technology Engine*, a great improvement will be necessary over current turbomachinery. The table below compares the compressor performance of three turbochargers. The first, an older model has a design point pressure ratio of 2.77 at a speed of 70,700 RPM and an adiabatic efficiency of 55%. The second, representing a recent turbocharger, has a pressure ratio of 3.70 at 99,200 RPM with a 55% efficiency. The third shows the compressor requirements, which will enble the *High Risk Technology Engine* to operate at 7620 m and 261 kW and 10,668 m at 149 kW on the exhaust gas energy available downstream of the turbocompounding power turbine.

TURBOCHARGER COMPRESSOR

DESIGN POINT PERFORMANCE

	OBSOLETE DESIGN	CURRENT DESIGN	HIGH RISK TECHNOLOGY REQUIREMENTS	
	6858 m (22,500 ft)	7620 m (25,000 ft)	7620 m/261 kW (25,000 ft/350 bhp)	10,668 m/149 kW 35,000 ft/200 bhp
Pressure Ratio	2.77	3.70	4.0	5.2
Adiabatic Efficiency, %	55	55	78	78
Compressor Speed, RPM	70,700	99,200	100,000+	100,000+

Because the *High Risk Technology Engine* is turbocompounded, in order to meet the light weight proposed for this engine design, the turbocharger will have to be made lighter than current designs and the entire turbocompounding power turbine and speed reduction system should be kept at a power-to-weight ratio of greater than 1 hp/lb at the design cruise point (7620 m). At this operating point, where the engine shaft horsepower is 186 kW, the turbocompounding turbine is contributing 14.9 kW (20 bhp) to the brake output of the engine (Figure 10) and should weigh 9 kg (20 lb), including its reduction drive.

Two emerging areas of technology can be combined to achieve the required design criteria for the turbocharger and turbocompounding system - ceramics and the Nasvytis traction drive. Ceramics are proposed for both the turbocharger and turbocompounding system turbines and Nasvytis traction drive to speed reduction of the turbocompounding power turbine to crankshaft speed.

The application of ceramics is covered in Subsection 3.8.

The Nasvytis traction drive is proposed as a lightweight, low-cost means of reducing the 100,000-plus RPM of the power turbine down to engine crankshaft speed. The drive, shown in Figure 11, consists of a single-stage, planetary roller system with two rows of stepped planet rollers. The fixed ratio system provides traction for the rollers in proportion to the transmitted torque using a roller-ramp loading scheme. This provides for extended life by lowering the Herzian contact stresses at the roller interfaces to only that value required to transmit the torque delivered through the unit at any given level. Other traction drives are preloaded to the level required to carry maximum torque plus some design margin, and the preload remains on the rollers even when the unit is delivering low torque. Thus, the Nasvytis traction drive has eliminated one of the principal reasons for the poor durability of traction drives.

A Nasvytis traction drive designed to transmit 30 hp at an input speed of 95,000 RPM has been tested at NASA Lewis Research Center. It weighs 9 lb. These units are projected to be manufactured more cheaply than gear reduction drives because of their simplicity and higher tolerance to dimensional variability. Also, for high reduction ratios where a number of gears would be required, the traction drive has comparable drive efficiency (95%).

Research now under way and future programs planned in industry and Government are expected to bring both ceramic technology and the Nasvytis traction drive to a level of commercial application in time for design of the prototype *High Risk Technology Engine* (January 1, 1984).

In particular, the "Automotive Propulsion Research and Development Act of 1978" has as its aim the establishment of a comprehensive program to ensure the development of advanced automotive propulsion systems within the shortest practical time consistent with appropriate R&D techniques. A part of the overall program administered by the Department of Energy (DOE) has as its goals improvements in transmissions and drive trains and high-temperature ceramic components for engines. Also, through the Heat Engine Development Program managed by the Office of Transportation Programs of DOE, intense development of ceramics for advanced automotive gas turbines is now under way.

3.5 Engine Operational Systems

The engine operational systems are systems that directly relate to engine combustion, e.g., fuel delivery and ignition systems:

- Low-Pressure Fuel Injection
- High-Pressure Fuel Injection
- Electronic Fuel Control
- Electronic Air Control
- Electronic Ignition Control.

3.5.1 Low-Pressure Fuel Injection

Most modern aircraft piston engines use either single-point or multipoint, low-pressure fuel injection systems. The remainder are carbureted.

The existing types of low-pressure fuel injection systems now used in aircraft piston engines are different in terms of the degree to which they offer automatic air density compensation. The simplest of these is the TCM continuous flow system, which injects fuel into the intake manifold upstream of each intake valve (multipoint) in proportion to throttle position and engine speed for naturally aspirated engines. For turbocharged engines, an additional compensating device is added to respond to changes in compressor discharge pressure.

The homogeneous-charge *Moderate Risk Technology Engine* will use a continuous flow system similar to that just described for turbocharged engines, as shown schematically in Figure 12.

3.5.2 High-Pressure Fuel Injection

The stratified-charge *High Risk Technology Engine* will require a high-pressure fuel injection system similar to that used in diesel applications. In the case of idealized stratified-charge combustion, the fuel is injected near top center on the compression stroke and a spark ignites the mixture to establish a relatively stable and stationary burning zone. As the combustion products are carried downstream in the direction of the air swirl, air is being swept into the fuel spray upstream of the burning zone. The swirl velocity in the combustion chamber is thus a critical parameter in maintaining a nearly stationary flame front.

Since the burning zone is rich of stoichiometric, flame speed should remain high even at part load so that with sufficiently low injection duration (less than 30-deg of crank angle rotation), a close approximation to constant volume combustion can be maintained.

A great deal of development work will be required to match injector design to the HTCC combustion chamber characteristics.

3.5.3 Electronic Fuel Control

Electronic fuel control for both the homogeneous-charge engine and the stratified-charge engine provides the advantage of tailoring fuel delivery requirements more closely with engine operation without the complexity of hydromechanical systems. Of course, there must be a mechanical system for fundamental control in the event of failure of the electronics.

Controlling or modulating the fuel flow supplied by a mechanical fuel delivery system using electronics gives an inherent failsafe capability while still employing all of the benefits of electronic fuel control strategies. The electronic logic unit is allowed to modulate fuel flow only within the boundaries of satisfactory engine operation. Failure of the electronics or electrical system would permit the mechanical fuel supply system to operate in a normal manner.

Figure 13, shows a schematic of such a system applied to the TCM continuous flow fuel injection system. In parallel with the variable orifice fuel pump bypass (Figure 12), an additional variable orifice is used that is controlled by a microcomputer in response to various input signals.

The greatest cost of adding an electronic fuel controller would be the cost of the transducers. The automotive industry represents the largest near-term growth market for the electronics industry, so it is very likely that inexpensive transducers and clever control strategies will be developed to reduce the overall cost of this area of advancing technology. The widespread use of electronics in the automotive industry guarantees that a solid technology base will be established on which the design of electronics for an advanced spark-ignition aircraft piston engine can be based.

For the high-pressure fuel injection system, electronic control of the start of injection and injection duration as a function of measured engine operating parameters would provide the precision and flexibility needed to maintain optimum control of the charge stratification concept.

3.5.4 Electronic Air Control

For lean combustion systems, an alternative to electronic fuel control has been proposed. Normal spark-ignition engines supply fuel in response to change in air flow (throttle position). Stivender (27) has proposed an alternate control scheme based on an engine air control (EAC) principle. The proposed system involves operator control of fuel flow and a response provided by the electronic system that controls airflow. For lean mixture combustion systems, the EAC strategy is said to give improved engine response and stability while minimizing actuator requirements and undesirable control interactions. Further exploration into this area of advanced technology will be considered for application to the *High Risk Technology Engine* design.

3.5.5 Electronic Ignition Control

The design of an ignition system for an advanced aircraft piston engine must take into consideration the type of combustion system being used. For current aircraft piston engines, dual high-tension magnetos are used. It is a simple, reliable system that is compact and does not require a battery. Figure 14 shows a schematic of a six-cylinder aircraft piston engine magneto ignition system. Two independently driven magnetos supply spark current to each set of two spark plugs in each cylinder. Failure of one magneto still permits the engine to operate, although some loss in maximum power is suffered. The two spark plugs in each cylinder fire simultaneously and ignition timing is fixed at a value that will allow maximum power at full throttle while avoiding detonation. Normally a 10 to 15% margin in fuel flow is provided rich of the fuel flow at which the engine would detonate while running at maximum allowable cylinder head temperature and 38°F (100°F) induction air temperature.

Because the magneto has fixed running timing, two problems must be solved. An impulse coupling on the magneto drive shaft solves the problem of insufficient magneto speed during engine cranking. During cranking, the magneto is restrained from turning, while winding up a spring, until the engine comes to a position near top center on the compression stroke. At that time, the rotor is suddenly released and rotates at a high instantaneous angular velocity, resulting in a higher electromotive force to produce a spark of sufficient intensity. This system also provides a retarded spark for better engine-starting by using a separate set of breaker points at the low engine cranking speed.

Recent work done by Bendix (28) has shown that breakerless magnetos can go a long way toward improving maintenance requirements and timing shift because of breaker point and cam follower wear, contamination, and corrosion. This principle has been successfully demonstrated in automotive battery-powered ignition systems. An additional benefit to a breakerless ignition system is that it is more easily adaptable to interfacing with electronic ignition timing control.

For current naturally aspirated aircraft piston engine combustion systems, there appears to be little benefit for variable ignition timing. This is because minimum advance for best torque (MBT) timing at the fuel-air ratios during cruise is very close to the current ignition timing setting.

For the *Moderate Risk Technology Engine*, a stepped timing ignition timing system could be used to overcome the problem of running retarded timing in cruise to avoid detonation at the high power settings with fixed ignition timing. A breakerless magneto could be designed to run at advanced timing in cruise and retarded timing at higher powers. The step shift in timing could be keyed to manifold pressure. High-pressure, direct cylinder injection will require ignition timing that can be precisely controlled in its relationship to injection timing. For these reasons, a continuously variable timing ignition system will be required for the *High Risk Technology Engine*.

An improved ignition system would have to be developed that would provide longer service life, automatic spark advance capability, low radio frequency interference (RFI), improved altitude performance, and reduced weight. The system would have to be independent of the aircraft electrical system and be compatible with the microcomputer-controlled engine fuel control system.

3.6 Configuration

The history of development of the internal combustion engine encompasses a multitude of cylinder arrangements and drive mechanisms. Only a few configurations have survived in general service. Four configurations for the advanced-technology, spark-ignition aircraft engine are discussed in this section. These are horizontally opposed, V, radial, and a swashplate drive barrel configuration (Figures 15 and 16). Among the criteria to be discussed in choosing a configuration are frontal area, weight, balance and vibration, cooling, maintenance accessibility, producibility, and cost.

3.6.1 Horizontally Opposed

Air-cooled, horizontally-opposed-cylinder, four-stroke cycle engines currently dominate the general aviation light aircraft category. This arrangement results in a short, compact, lightweight engine with easily accessible cylinder assemblies. The horizontally opposed configuration (HOC) might be classed as a 180 deg V, except that it requires a separate crank for each cylinder, which is particularly well-suited to air cooling. The individual cranks require a relatively wide cylinder spacing, which provides space for cooling fins between cylinders. Since aircraft drag is directly proportional to frontal area, this is an important consideration in engine design. The HOC results in one of the lowest frontal areas for a given engine displacement of any conventional crank/connecting rod design.

For a given engine power and cylinder arrangement, the number of cylinders to be used depends primarily on weight, frontal area, vibration, and cost. For equal displacements, the more cylinders used the smaller the frontal area will be.

Weight and vibration characteristics tend to favor use of many small cylinders. Since power tends to be proportional to piston area while weight is proportional to displacement, small cylinders tend to exhibit high power-to-weight ratios. However, small cylinders result in lower thermal efficiencies because of their higher surface-area-to-volume ratio. Numerous cylinders result in more evenly spaced power pulses and a more balanced crank arrangement. As the number of cylinders increases, the length of the crankshaft increases because of the separate throws, but the number of main support bearings also increases. The net result is that the crankshaft weight-per-unit power decreases with the increasing number of cylinders.

Cost favors a few large cylinders because labor costs per unit exceed the material costs. These factors limit the choice of the number of cylinders to 4, 6, or 8. The various crank throw arrangements using separate throws result in zero primary and secondary shaking forces without the use of counterweights. Four- and six-cylinder HOCs result in unbalanced yawing moments. An eight-cylinder HOC with uniform firing pulses has a primary unbalanced moment. The simultaneous firing of two cylinders allows a crank arrangement for an eight-cylinder HOC with no unbalance. However, torsional oscillations would be a problem.

3.6.2 V Configuration

The V configuration offers the advantage of running two connecting rods per crank throw, resulting in a shorter, stiffer, lower weight crankshaft. For V angles of 90 deg or greater, the arrangement is suitable for either air or liquid cooling. However, an air-cooled V cannot be made as short as a liquid cooled V because of the spacing required for intercylinder cooling. The V engine can be designed with the V either upright or inverted. The inverted V is attractive for cylinder accessibility and increasing the propeller shaft ground clearance, but it would require a dry sump lubricating system. Frontal area for the V configuration is nearly the same as for an opposed arrangement.

For comparison of the frontal areas of different configurations, a frontal area index (FAI) was defined based on assigning a value of 1 to the six-cylinder HOC. This index is based on geometric considerations of height and width for engines of equal displacement, bore-stroke ratio, and similar connecting rods: FAI = (Engine Width × Height)/(Six-Cylinder HOC Width × Height). For the 120-deg V-6, FAI = 1.11, whereas a 90-deg V-8 has an FAI = 1.04. The FAI is representative of the frontal area of a rectangular enclosure. A V engine would be better fitted with a more triangular shaped cowl. Thus, the actual frontal area for a V would be the same or lower than for the HOC.

An eight-cylinder, 90-deg V with a counterweighted antisymmetric crankshaft represents an ideally balanced engine; all primary and secondary shaking forces and rocking motions are zero. The 120-deg V-6 has balanced primary and secondary shaking forces, but it exhibits primary and secondary rocking moments.

3.6.3 Radial

The air-cooled, four-stroke cycle radial engine was once the predominant aircraft engine configuration, especially for the large military aircraft. The four-stroke-cycle radials require an odd number of cylinders per row for even firing intervals and may be single- or multi-row configurations. Each row has one master rod connected to the crankshaft, with the other connecting rods hinged to the master. The radial arrangement results in the lowest weight-per-unit displacement of any configuration because the material in the crankshaft and crankcase is at a minimum for a given number of cylinders. However, the radial configuration features a large frontal area (Five-Cylinder FAI = 2.00, Seven-Cylinder FAI = 1.66). Cooling drag on the air-cooled radials was high because the required cowling shape was not conducive to dynamic pressure recovery. Balancing of the single-row radial is accomplished by counterweights on the master rod, which negates the primary shaking force and leaves only second-order unbalance. Double-row radials with 180-deg crank spacing produce unbalanced primary and secondary moments. The radial arrangement requires a dry sump lubricating system.

3.6.4 Barrel/Swashplate

The barrel configuration consists of reciprocating pistons parallel to the drive shaft (Figure 16). The swashplate drive mechanism features an inclined disc rigidly attached to the rotating shaft. Application of the tilting-pad thrust bearing to the swashplate drive has made it a possible competitor to the widely used crank and connecting rod mechanism. Mechanical efficiencies of 90% have been reported for swashplate drives. A current application of the swashplate drive concept is in automotive air-conditioning compressors. The barrel/swashplate configuration is attractive for aircraft application because of its overall compactness, low frontal area (Five-Cylinder Bundle FAI = 0.59), and perfect dynamic balance.

Perfect dynamic balance can be achieved because the reciprocating pistons move with simple harmonic motion. The common center of mass of the pistons remains fixed at the center of the mechanism for all speeds. The summation of the forces caused by piston accelerations is zero. Since opposing piston forces do not act along the centerline, there is an inertial couple present. This inertial couple can be balanced by the mass of the swashplate because it produces an inertial moment in the opposite direction because of the inclination of its principal axis of mass moment of inertia to the axis of rotation. By suitably matching the relative masses of the pistons and the swashplate, perfect dynamic balance is obtained.(29)

The compactness of the barrel arrangement necessitates liquid cooling. To take full advantage of the available space in a barrel configuration, a minimum of five cylinders per bundle is desirable. Also, each cylinder should use opposed pistons acting on a common slider. This results in a 10-cylinder engine that is extremely compact for its displacement. Unfortunately, production costs are likely to be prohibitive. The number of separate cylinders, pistons, and valves will increase the price because production cost for these items is labor rather than material intensive. Also, the cost of new tooling for such a radically different design could probably not be justified for a low-volume market such as general aviation.

3.6.5 Summary

Only one of the configurations that was considered looked promising compared to the air-cooled, horizontally opposed, six-cylinder design, which was ultimately chosen; this 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 and the swashplate design was eliminated because of its cost.

3.7 Cooling

Any internal combustion engine requires cooling because of structural and lubrication limitations. Extremely low heat transfer rates would require the surfaces in contact with the combustion gases to be near the mean working gas temperature. Since maximum combustion temperatures are of the order of 2760°C (5000°F), developing an internal combustion engine requiring near zero cooling would be extremely difficult, if not impossible. Lubricating conditions currently limit the maximum allowable surface temperatures. When the oil film temperature exceeds about 204°C (400°F) for petroleum-based oils, lubricating conditions deteriorate rapidly, resulting in increased wear or possibly seizure of the contact surfaces. Conventional materials used in cylinders, pistons, and cylinder heads limit maximum temperatures to about 316°C (600°F). Beyond this temperature, the strength of conventional metal alloys decreases rapidly.

Depending on the specific engine design and operating conditions, 15 to 35% of the heat energy available from the fuel is lost to cooling. This heat transfer to the coolant is a definite loss since no useful work can be obtained from it and part of the engine power is used in its removal, either directly running fans or pumps, or indirectly through vehicular motion. Reducing the amount of heat transferred to the coolant increases the thermal efficiency of the engine. Decreasing the parasitic power required for cooling improves the installation efficiency. The result is an increase in vehicular fuel economy.

The atmosphere serves as the heat sink to which all waste heat of an aircraft engine is transferred. This is true whether air is used directly to cool the engine (air-cooled) or an intermediate fluid is used to transfer the heat from the engine to the air by means of a heat exchanger (liquid-cooled). The general types of cooling systems that were considered for the advanced-technology spark-ignition aircraft piston engine are:

- Direct Air Cooling
- Liquid Cooling
- Air/Liquid Cooling (Combination).

Cooling subsystems to be considered for use with any of the above systems include thermal barriers, such as liners or coatings, and air-flow augmentors such as fans or exhaust ejectors.

Some of the important criteria to consider in comparing aircraft engine cooling systems are cooling drag power, system weight, reliability, maintenance, and cost.

3.7.1 Air Cooling

The fundamental advantage of air cooling over liquid cooling is the inherent simplicity and reliability of the system. Since heat transfer occurs by direct convection from the cylinder, there is nothing to fail; no maintenance required or parts to replace.

The temperature difference between the cylinder and cooling air is much greater for an air-cooled engine (~200°C) than is the corresponding temperature difference between the heat exchanger of a liquid-cooled engine and the cooling air (~83°C). This higher operating temperature differential for the heat transfer process results in several beneficial effects. An air-cooled engine incurs lower heat losses than an equal-displacement, liquid-cooled engine because of the lower temperature difference between combustion gases and the cylinder. This results in better indicated specific fuel consumption. Because of the higher temperature gradient, less surface area and cooling airflow is required for heat transfer for air-cooled cylinders than for the radiator of a liquid-cooled engine. Hot weather penalizes a liquid-cooled installation more than an air-cooled engine. For example, a 22°C (40°F) increase in cooling air temperature reduces the heat transfer temperature gradient of a liquid-cooled installation about 27% (83 to 61°C). The same change for an air-cooled engine reduces the thermal difference by only 11% (200 to 178°C). Likewise, an air-cooled aircraft engine benefits more from reduced ambient temperatures at altitude than does a liquid-cooled engine.

The cylinder of an air-cooled engine warms up more rapidly because it is surrounded by a smaller quantity of material. This has a favorable influence on the wear of cylinders. Maximum wear occurs immediately after starting when the cylinder walls are cold and lubrication is inadequate. Corrosion develops when combustion products condense on cold cylinder walls and attack the bearing surface. This critical period is considerably shortened in an air-cooled engine, resulting in reduced cylinder wear compared to a liquid-cooled engine.

The higher mean cylinder temperature of an air-cooled engine prevents excessive buildup of carbon deposits on the surfaces surrounding the combustion chamber. These deposits reduce volumetric efficiency and can induce preignition because of local hot spots. Lack of carbon buildup contributes to the sustained performance of air-cooled engines.

The air-cooled engine design requires a unit cylinder construction that can advantageously be combined into engine units with varying number of cylinders. Since most of the component parts that are subject to wear are identical for all engines, a smaller stock of spare parts is required. Unit cylinder construction allows rapid and less expensive repairs. A damaged cylinder can be individually dismantled and replaced. Similar damage to a liquid-cooled engine without separate cylinders would require replacement of the entire engine block or crankcase.

In designing an air-cooled engine installation, there are no limitations on engine position because of the danger of vapor pockets forming and interrupting coolant circulation. Installing or removing an air-cooled engine from an aircraft is easier than for a liquid-cooled engine since there are no coolant hoses and no radiator.

Although there are significant advantages to air-cooled engines, there are shortcomings. The external surface area of a cylinder places a limitation on the effective fin area that can be used. This limits the heat transfer that can be dissipated at a given airflow rate. Liquid-cooled installations are not so limited, provided a larger heat exchanger and coolant circulating pump can be installed. However, in current air-cooled aircraft engines, available fin area has not been a critical problem. Absence of a water jacket surrounding the cylinders means that air-cooled engines are noisier. Cylinder temperature variations cause clearance variations because of differential thermal expansion. Special attention must be paid to piston and ring clearances. Valve clearance is controlled through the use of hydraulic tappets. The necessity of a separate oil cooler might be considered a disadvantage. Cooling of the oil is important for high specific output engines. Water-cooled engines cool the oil by extending the water jacket the entire length of the cylinder, with the resulting undesirable fuel and combustion product condensation on the cylinder walls.(30)

3.7.2 Liquid Cooling

The utility of liquid cooling lies with the flexibility of a remotely mounted heat exchanger whose size and location are independent of cylinder size or spacing. With no cooling airflow limitations on cylinder spacing or orientation, the liquid-cooled engine can be made more compact than an air-cooled engine can be made more compact than an air-cooled engine. However, the total installation, including the radiator, may not be any smaller. Optimum sized radiators can be used in installations with different power or altitude ratings, whereas a family of air-cooled engines is limited to the finning on the basic unit cylinder. If the radiator is sized to handle the full-power heat rejection under climb conditions at best power fuel flows, then the fuel consumption will be lower than for an air-cooled engine, which usually requires rich fuel settings for cooling at takeoff. A properly designed liquid-coolant jacket produces a more uniform cylinder temperature distribution, which means lower thermal stresses. Local hot spots in the combustion chamber of a liquid-cooled engine produce nucleate boiling of the coolant if the temperature is high enough. The latent heat of vaporization of the coolant is used to achieve the high heat flux. Liquid cooling usually results in lower combustion chamber and exhaust valve temperatures that can reduce detonation tendencies.

Although liquid cooling has some advantages, especially for closely spaced cylinders and high heat flux, it also has some serious drawbacks. These are principally in the area of system complexity, reliability, and required maintenance. A liquid-cooled engine requires a coolant circulating pump, a radiator, hoses, and a thermostat. Furthermore, an aircraft engine liquid cooling system must be pressurized to prevent coolant boiling at altitude and a header tank will be required to prevent coolant loss resulting from thermal expansion at high coolant temperatures. Pressurized coolant systems require a safety valve in the radiator cap. The most commonly used coolant is water, which has a high specific heat, mixed with ethylene-glycol as an anti-freeze to lower the freezing temperature. Statistical data indicates that 20% of all automotive engine failures involve the water cooling system. This is not surprising considering the various equipment problems that can occur. Sealing of joints in a pressurized radiator is difficult. Water pump seals tend to leak with age. Hoses connecting the engine must be flexible and this presents a leakage risk. In addition, hoses must be periodically replaced to prevent splitting caused by aging. Scale deposits in the radiator adversely affect heat transfer and use of cleaning agents tends to expose minute fissures causing leaks. Failure of the control thermostat is another potential problem. Thus, a liquid-cooled aircraft engine will require more maintenance to meet aviation safety standards than its air-cooled equivalent.

Other disadvantages of liquid-cooled engines include increased cylinder wear caused by condensation corrosion and poor lubrication following a cold start and a larger reduction in system cooling capacity in hot weather. The maximum operating temperature of the radiator of a liquid-cooled engine is limited by the boiling point of the coolant. Since the heat exchanger temperature cannot be increased to offset the reduced thermal gradient in hot weather, the radiator surface area must be sized for the worst condition. The higher temperature of air-cooled cylinders results in easier hot weather cooling and relatively better performance at cooler temperatures and higher altitudes.

Unless a liquid-cooled engine can produce significant savings in weight, cost, or cooling drag, the reliability and maintenance requirements obviously favor air cooling.

3.7.3 Cooling Power Comparison

A generalized comparison of the cooling power required for an air-cooled versus a liquid-cooled engine installation is difficult because of the large number of variables involved. The cooling airflow in an aircraft is produced by virtue of the forward motion of the vehicle. The flow limitation for a finned cylinder or a radiator is the pressure drop, which cannot exceed the dynamic pressure recovered by the ducting system. Therefore, any comparisons should be made at constant pressure drop. Since the radiator must operate at a lower thermal gradient, it will require more surface area than the finned cylinders. Using a water-ethylene glycol mixture as the coolant limits the heat exchanger temperature to about 104°C (220°F), whereas air-cooled cylinder temperatures average about 221°C (430°F). When equal film heat transfer coefficients are assumed, the radiator surface area would have to be 2.4 times the cylinder finning area.

A comparison of cooling power between a 224 kW (300 hp), air-cooled aircraft piston engine at sea level and an equivalent liquid-cooled engine showed the cooling power required by the liquid-cooled engine to be 30% higher. The coolant-pump power accounted for most of this excess. Compared to total cooling drag power for the engine installation, which includes inlet and outlet losses, the cooling power for the engine alone is small, so that the total power losses associated with cooling either air- or liquid-cooled engines is nearly the same. Considering reliability and maintenance of a liquid-cooled engine, the conclusion is that air cooling is the best choice for the configuration chosen - the horizontally opposed, six-cylinder engine.

3.8 Materials

The use of advanced materials was considered from the standpoint of weight reduction and increased durability. Table VI compares three engines where the weight of each is divided among the materials it contains. The first engine is a TSIO-550 engine representing the current level of technology.

It contains 3.6 kg (8 lb) of miscellaneous materials such as plastic, rubber, and copper 151 kg (332 lb) of steel and 111 kg (245 lb) of aluminum, for a total weight of 265 kg (585 lb). The *Moderate Risk Technology Engine* contains only 115 kg (253 lb) of steel and 98 kg (215 lb) of aluminum, whereas 4.5 kg (10 lb) of advanced materials have been added for a total weight of 220 kg (485 lb), which is a weight reduction of 17% over the current 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*, there are only 36 kg (80 lb) of steel, primarily in the crankshaft, reduction gears, cylinders, and exhaust valves. The use of aluminum has been reduced somewhat, and a total of 54 kg (119 lb) of advanced materials are used for an engine weight of 184 kg (405 lb), a 31% improvement over the current engine. In this engine, the greatest part of the advanced material weight is titanium, with a small amount of reinforced plastic and ceramics.

3.8.1 Titanium

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 is that it is not usually found in great quantity in any one location, but is relatively 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. An advancement in titanium production and metallurgy would permit an overall saving 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.

Researchers view powder metallurgy as one of the most promising means of reducing the cost of titanium products. At the recent International Titanium Conference in Japan, research papers reported that by compacting titanium powder into near final shape by hot isostatic pressing (HIPing), large cost savings were possible over the conventional practices of forging and machining. The powder is produced directly from titanium sponge, which bypasses the expensive, scrap-intensive process ordinarily used to convert sponge into mill products such as bar, sheet, or plate.

Also, U.S. researchers are working on the production of ultra-stiff metal matrices consisting of titanium reinforced with silicon carbide fibers.

The cost of titanium has dropped steadily on a volumetric basis compared to equal volumes of steel and aluminum. In the mid 1950s, titanium cost 110 times as much as steel and 35 times as much as aluminum. Projected costs per unit volume in 1980 show that titanium will cost only 10 to 15 times as much as either steel or aluminum, and powdered metallurgy technology should reduce that relative cost considerably as the cost of energy increases.

The use of titanium in an advanced-technology engine need not be limited to structural applications, but it can also be used in intake valves and valve springs, as well as in connecting rods, nuts, and bolts.

3.8.2 Reinforced Plastics

Although there are many forms of reinforced plastics available today, the highest performance combinations are matrices of graphite and epoxy. Although epoxy has a rather low elastic modulus (6.9×10^6 kPa), some forms of carbon fiber have a modulus exceeding that of steel (483×10^6 kPa). The combination of graphite and epoxy can have a modulus close to that of steel while weighing only one-fourth as much.

Many parts require a material with superior stiffness properties in only one or two modes of flexure. Reinforced plastics can reduce the weight of such parts by orienting the fibers in the proper direction to take the load. A longitudinal member with only bending moments applied would have the fibers placed longitudinally if no requirement for torsional rigidity existed for the part. Basically, fiber orientation in a well-designed part will always be in the direction of the principal stress.

Chopped fibers can be mixed with thermoplastic materials for injection molding to produce parts with omnidirectional properties, although their strength would be reduced accordingly.

Because of the low volume involved in the manufacture of general aviation piston engines, graphite-reinforced plastic (GRP) parts may be rather costly to produce compared to the weight savings achieved. The items that could be produced from GRP are not of sufficient weight to effect a large percentage saving in overall engine weight. Items considered for fabrication from GRP are: pushrods, rocker arms, accessory brackets, and control rods.

3.8.3 Ceramics

The application of ceramics to expansion turbines in place of ductile superalloy metals has been studied for many years. The principal difficulty lies in the fact that ceramics fail catastrophically because of their inherent brittleness, whereas ductile metals yield when they are overstressed. The direct substitution of ceramics for metals has met with limited success in the past in application where extremes of mechanical, thermal, and impact stresses are found. The driving force for ceramics in turbomachinery is their high-temperature capability, light weight, low cost, and that no rare metals of strategic importance are required. Ceramics exhibit excellent corrosion and erosion resistance. The proposed TCM *High Risk Technology Engine* offers a promising candidate for application of ceramics to rotating turbomachinery components. The high expansion ratio of the stratified-charge combustion system has lower exhaust gas temperatures so the ceramic material will not be operating against the limits of creep (1200°C) and strength (1400°C) required by turbine engine applications. Also, the catastrophic failure of a turbocharger or turbo-compounding power turbine, if proper containment is provided, would not necessarily result in engine failure. The engine would still be capable of operation in a naturally aspirated mode at lower altitudes. A radial inflow turbine wheel made from single-phase alpha silicon carbide by a process developed by the Carborundum Company might weigh only 50% of an existing superalloy wheel and would not exhibit any loss in strength at a temperature as high as 1650°C. This weight reduction could mean a turbo-charger weighing only 75% of current designs if containment requirements are found to be less stringent with ceramics. About 60% of the total weight of a typical turbocharger is in the turbine housing, which is designed for containment should the turbine impeller fail.

Figure 17 shows an alpha silicon carbide turbine wheel manufactured on an experimental basis by the Carborundum Company for a Volkswagen automotive application. Also shown is a scroll housing made of the ceramic material that was used to demonstrate the complexity of parts that can be made. The scroll housing was intended for automotive turbine engine hot section application. The turbine wheel has been run cold in a vacuum at up to 120,000 RPM and has also been operated in an automotive turbocharger.

Other applications for ceramics are in the Nasvytis Traction Drive (see Section 3.4), valve train tappets, pushrod ends, and piston wrist pins. The superior coefficient of friction of lubricated ceramic surfaces running against steel may provide some reduction in engine friction losses.

3.8.4 Summary

The application of new materials to existing aircraft piston engines by the process of substitution, as has been done in the past, is rather limited. With the design of an all-new engine, advanced-technology materials such as titanium, reinforced plastics, and ceramics can be integrated into a complete compatible package where best use of their properties can be made. Weight savings in one part can usually be propagated throughout the entire engine design and weight saved in the engine can reduce the entire airframe structure weight. The resultant payback is an improvement in the utility of the aircraft by allowing it to carry more payload or more fuel (increased range) or to fly at faster cruise speeds on the same amount of fuel.

3.9 Manufacturing

In 1979, Teledyne Continental Motors (TCM) manufactured about 8300 new engines for the original equipment manufacturer (OEM) market, 400 new engines for aftermarket sales as replacements for engines in existing air-frames, and 2100 factory rebuilt engines for the aftermarket.

On the average, each of the 10,800 engines produced required 65 to 75 man-hours of labor. About 60% of the people involved directly in manufacture of the engines perform manual tasks and the remainder operate machine tools, from drill presses to numerically controlled (NC) tape machines. At the 1979 rate, TCM produced an average of about 44 engines each 8-hr working day.

By comparison, the highly automated production plants of the U.S. automotive industry produce about 10 million engines annually.

A recent Delphi forecast sponsored by the Society of Manufacturing Engineers has distilled the opinions of 105 manufacturing experts in the U.S., Great Britain, and Japan to predict the adoption of computer-aided manufacturing (CAM) over the next 20 yr.

The results of the study showed that by 1990, 25% of all small factories will use some kind of CAM and by 1995, 20% of small batch manufacturers will use robots for automatic assembly.

As a result of this predicted trend, it seems inevitable that an advanced, spark-ignition aircraft piston engine intended for production in the early part of the next decade could more profitably be manufactured using a greater degree of automation.

In fact, the trend in the industry is in that direction with the greater use of NC machines in production and computer-controlled production test cells that run the engines through their initial green run and performance qualification tests.

3.10 Engine Auxiliary Systems

The auxiliary systems are those that do not directly relate to engine function but are nevertheless required as a part of an engine installed in an airframe.

3.10.1 Single-Lever Control

In today's air traffic control system, the increasing burden placed on the pilot has demanded a higher level of pilot proficiency, increasing the need for improved aircraft systems that ease pilot workload.

In the past 5 yr, total pilot certificates increased by 24%, while pilots holding instrument ratings increased by almost 30%. Forecasts by the Federal Aviation Administration (FAA) predicted that over the next 10 yr, total pilot certificates are expected to increase by 22%, while the number of pilots with instrument ratings will increase by 53% to take advantage of full use of the U.S. airspace system. Recently proposed rulemaking by the FAA, which has the effect of excluding visual flight rules traffic from flying into certain airspace, may further increase the growth rate of instrument-rated pilots.

The demand for improved systems to ease pilot workload has largely been made through improved avionics. Also, little attention has been paid to improving pilot-to-engine interface, which remains very much as it has always been in the three-level engine/propeller control system.

Recent cooperation between Beech Aircraft, Woodward Governor, and TCM has led to the development of a so-called "single-lever control" which, using a servomechanical system, provides the pilot with control of engine throttle, propeller RPM, and fuel mixture ratio through the use of a single lever. Rather than having the choice of a variety of propeller RPM/manifold pressure combinations, the single-lever control has a mechanical linkage connecting the propeller governor and throttle with an override to allow propeller governor cycling as part of the preflight engine check procedure. A mixture control override lever also exists with detents to allow the pilot to select "MANUAL RICH," "AUTOMATIC," "MANUAL LEAN," and "IDLE CUT-OFF" positions.

To activate the system, the pilot sets the mixture control lever to the "AUTOMATIC" detent and selects an engine speed compatible with the power level he desires. The system automatically regulates manifold pressure and fuel flow, maintaining constant manifold pressure up to critical altitude (wide open throttle) for the naturally aspirated engine, while attempting to maintain constant fuel-air ratio at higher altitudes.

The system has been compared to the automatic transmission in an automobile in terms of reducing workload. The comparison is an apt one, but the time when there is a heavy cockpit workload is much more intense and of longer duration than would ever be encountered by the driver of a car.

With the rapid growth of electronics, a logical extension of the Woodward system would be an electronic control that would integrate all the engine/propeller control functions into a single-lever package. The task of controlling the propeller governor, manifold pressure, and fuel flow with a servoelectrical system that, in turn, is controlled by a microcomputer is technically a fairly straightforward idea.

The idea of combining all engine control functions into a common package seems technologically desirable. The success of such a system would depend on the ability to design a failsoft system that would rely either on a mechanical backup or be redundant in design. The ultimate system would be able to control the engine to an optimum schedule of propeller RPM, manifold pressure, fuel flow, and ignition timing, which would maximize performance fuel economy to the greatest extent.

Such a system would seem to have a positive effect on aircraft safety, while product liability implications of an unpredetermined failure mode would remain a serious concern. An electronic assembly containing a relatively modest count of 100 parts, each 99.9% reliable, would suffer an in-use failure rate of nearly 10%. This is clearly an undesirable situation for an aircraft control system, even if provisions are made for a failsafe or failsoft backup.

Lacking a high level of reliability, an electronic system could be designed that would diagnose problems within itself and switch to alternate circuitry until repair could be done on the primary circuit. This method of failsafe operation seems to be a promising trend, which can rely on the enormous capacity available with modern large-scale integrated circuits.

The cost burden of the concept of electronic engine/propeller control would be mainly in the transducers, which are required to supply signals for the system. However, the rapid development of low-cost, reliable transducers is expected as a result of automotive electronic research.

3.10.2 Electric Power Generation

While engine operation does not depend on the aircraft electrical system, the engine is required to drive an alternator that supplies power for the aircraft. The engine electrical system consists of a 12- or 24-V supply that provides power for items such as the starter motor, external and internal lights, gages, electrically operated flaps and landing gear, fuel boost pump, wing de-ice system, plus all the required avionics. Usually, provisions are made for excluding the alternator from the system with a manual switch, and in case of battery failure the electrical system will operate adequately on the alternator alone. Electronic systems are protected by isolating them on a separate bus bar so that they can be protected form harmful transient voltage excursions.

A typical aircraft alternator is similar to its automotive counterpart. The rotor magnets are energized by the battery during the startup period and then in operation are self-energized by rectified dc output of the alternator. Should the battery not supply sufficient power on startup, the alternator will not function because there will not be enough magnetic field strength in the rotor to produce output to sustain operation.

Recent improvements have included small permanent magnets in between the electromagnetic pole pieces, which are capable of producing enough alternator output at low starting speeds to energize the alternator until a stable operating speed is reached.

An area of advanced technology in alternator development that may prove valuable from the weight standpoint is the high-speed alternator. Current aircraft alternators weigh about 8 kg (18 lb) and operate at speeds below 8,000 RPM. High-speed, brushless alternators, developed primarily for military aircraft applications weigh only 4 kg (9 lb) while turning at 15,000 RPM. Current alternators are gear-driven at about three times engine speed, so provisions for driving a high-speed alternator at six times engine speed would not incur any additional weight penalty. In addition, the brushless feature would improve alternator reliability. The only problem area in adopting this technology to the aircraft piston engine is cost. Indications are that the automotive industry is working to improve the cost factor, much of which can be reduced by high-volume production.

A recent patent assigned to Simmonds Precision (No. 4,027,229 - May 31, 1977) has led to the development of a permanent magnet alternator (PMA) that can be regulated. The rotor section consists of a hub, soft iron wedges, and samarium/cobalt (33%/67%) permanent magnets to form a multi-pole rotor. The self-regulation is achieved by a metallic sleeve that trims the alternator output to the load, greatly reducing the need for external regulation. The brushless feature and high-speed operation made it a small, lightweight design with excellent reliability. Major efforts at cost reduction includes the development of high-power permanent magnets made of less expensive materials than cobalt and samarium, which are able to maintain magnetic properties with time and temperature.

The combination of a starter motor/generator is attractive from the standpoint of weight and size reduction. The concept involves the use of one dc electric motor to start the engine, which is subsequently used as a generator. One problem with this idea is that a variable or two-speed drive would be required as the torque and that speed requirements for a starter motor require a large gear reduction (25 to 55:1), whereas a generator does not require as much reduction to the crankshaft (3 to 6:1). Compound epicyclic gearing could provide the high reduction for starting while giving a lower reduction for running by means of a centrifugal switch operating a magnetic clutch. No such system is known to exist in a form available for aircraft piston engine use.

Starter-generators are a common practice for turbojet and turboprop engines, however, since starting speed and generating speed requirements are in an overlapping range. Also, in the starting mode, at low speed, the high starting torque characteristic is provided by an extra series field winding supplied for this purpose. These combined units, however, cost up to 10 times the cost of separate starter and alternator units derived from automotive designs and provide little weight advantage.

3.10.3 Engine-Driven Air Conditioning

Engine-driven air conditioning is an optional feature on many twin-engine cabin airplanes. Its function is mainly used for passenger comfort on the ground and at low altitudes. At higher cruising altitudes, air conditioning is not required because of the lower temperature air available for cabin pressurization and ventilation.

The air conditioning units currently used are similar to the freon systems used in automobiles. While these systems are low in cost and are efficient, the ROVAC-type of system might be explored as a possible alternative. The ROVAC system uses a rotary vane compressor to compress air, which then flows through an air-to-air heat exchanger and is expanded in the opposite side of the rotary compressor to recover some of the energy used in compression. This system is said to be lighter in weight while providing immediate cooling capability, which would seem to be advantageous for aircraft applications.

3.11 Lubricants

The reliability of the modern aircraft piston engines depends greatly on the quality of the fuels and lubricants it uses. Lubricants for the aircraft piston engine are specially formulated to meet the needs of this class of engine.

The lubricating oils used in aircraft piston engines must be capable of doing many tasks:

- Lubrication — Reduce resistance to relative motion between two surfaces:
  - Boundary Lubrication - Partial surface-to-surface contact
  - Fluid Film Lubrication - No surface-to-surface contact
- Cooling — Removal of heat from various engine parts:
  - Cooling of bearings and gears during the lubrication process
  - Cooling of pistons and cylinder walls
- Actuation — Used as a hydraulic fluid for actuation:
  - Propeller governor uses oil to control propeller speed
  - Oil used to control turbocharger wastegate valve for control of induction air absolute pressure.

These oils are mineral-based, ashless dispersant oils with viscosity grades ranging from SAE 30 to SAE 50. The new multiviscosity oils recently approved (SAE 15W-50, SAE 20W-50) contain viscosity improving additives (e.g., butadiene-styrene copolymer), which, when mixed with an SAE 15 or SAE 20 base oil stock, raises the high-temperature viscosity (100°C) to that of an SAE 50 oil. This additive is highly resistant to permanent shear loss of viscosity and is contained in the first multiviscosity grade oil approved for all-weather use in modern aircraft piston engines.

Figure 18 shows roughly the effect a viscosity index improver has on SAE 20 base stock to convert it to an SAE 20W-50 oil. The use of multigrade oil means that the same oil can be used from hot to cold weather with improved cold cranking, while maintaining sufficient viscosity at high temperatures.

While paraffin-base lubricating oils have viscosity that is independent of shear rate (Newtonian), the polymer-thickened oils behave in a different manner in that they exhibit a distinct non-Newtonian behavior called pseudoplasticity. Specifically, the apparent viscosity decreases with increasing shear rate. This temporary shear loss is an important consideration in the use of multiviscosity grade oils.

Although multiviscosity grade oils have been used for years in automobiles, the higher temperatures and loads in aircraft piston engines and the requirement for an ashless oil have led to the need for a special formulation for aircraft piston engines. The development of these oils is expected to continue with more manufacturers submitting oils for certification.

Normal engine maintenance procedures require oil and filter changes at 50-hr intervals, or if a full flow filter is used, a filter change at 50 hr and oil change at 100 hr. Also, oil analysis is a common practice to help detect incipient engine damage.

Synthetic lubricants have been used for many years in turbine engines and automatic transmissions. More recently, they have been marketed commercially for use in automobile engines. They provide high-temperature stability and low pour point, and their lower viscosity reduces engine friction. Current synthetics with viscosity in the SAE 10W-40 range are unsuitable for aircraft piston engine use except perhaps during cold weather operation.

There have been claims that synthetics can reduce engine fuel consumption, but counter-claims say that a reduced viscosity mineral-based oil will do the same. Extended oil drain intervals are also claimed for synthetics, but the fact remains that for aircraft piston engines an extended oil drain period is not desirable because of the more rigid maintenance requirements. The synthetic oils still contain suspended particles from combustion blowby gases, and the additive package (detergents, dispersants, rust inhibitors, oxidation inhibitors, antifoaming agents) can still become depleted.

Ester-base synthetics can be obtained from agricultural products, a renewable source, but process energy required to produce them is double that for a mineral-based oil.

Conventional mineral-base, straight-grade oil and the new multigrade oils will be adequate for an advanced, spark-ignition aircraft piston engine design. No distinct advantage is recognized with synthetic lubricants for aircraft piston engine use, and no area of developing technology appears that would replace mineral-base oil technology.

SECTION 4.0

ENGINE DESIGN

4.1 Design Specification Goals

At the outset of the contract, certain specifications were set as goals for the design phase. They are listed below:

- Two engines will be designed to meet the requirements for nominal 149 and 298 kW (200 and 400 hp) ratings with geometric scaling factors to allow each engine to be scaled over a range of $\pm 25\%$ in power.

- Engine performance and efficiency improvement targets were specified as follows:

  - BSFC less than 231 g/kW-hr (0.38 lbm/hp-hr) at 75% cruise power

  - Specific weight less than 0.61 kg/kW (1.0 lbm/hp)

  - Cooling airflow times pressure drop factor reduced by 50%

- The engine should be capable of operating on one or more alternative fuels other than 100 octane avgas.

- The exhaust emissions must be below the 1980 EPA Standards.

- Engine direct manufacturing costs should be comparable to or less than current spark-ignition aircraft piston engines.

- Overall life-cycle costs and maintenance should be lower than for current aircraft engines.

During the study, some of these goals were modified to reflect new information or a more consistent approach among the other competing engine designs (diesel and rotary).

It was decided that one common power specification be set for all of the engines. One engine design was selected instead of two. It must be capable of continuous operation in cruise at 186 kW (250 hp) at an altitude of 7620 m (25,000 ft).

Also, no consideration was given to analytically predicting exhaust emissions because the 1980 EPA Standards were cancelled for aircraft piston engines. The carbon monoxide emissions could have been predicted fairly easily, and for the *High Risk Technology Engine*, they would have been well below the standard because of the stratified-charge combustion system. Likewise, hydrocarbon emissions would be low for this engine because of lean operation. In all likelihood, emissions of oxides of nitrogen would have also been within the standards for the *High Risk Technology Engine* but the *Moderate Risk Technology Engine*, because of its homogeneous-charge combustion system, would have exceeded the NO_x standards.

The specific weight goal of 0.61 kg/kW (1.0 lbm/hp) cannot be met with any reasonable, cost-effective technologies. The *High Risk Technology Engine* approaches this goal with a specific weight of 0.71 kg/kW (1.16 lbm/hp). The tradeoff is really a balance among weight, cost, fuel economy, and engine life. Fuel economy being the important factor, a high-speed engine as a means to reduce specific weight was precluded because of disproportionately increased friction. A high-speed engine would have also tended to increase the wear rate and reduce the life of critical engine parts.

The goal of cooling drag reduction was met for the *High Risk Technology Engine*. The cooling drag was reduced by 52% compared to a competitive current technology engine (see Section 5.0, "Engine/Airframe Integration").

The multifuel capability requirement is addressed to some extent by the stratified-charge combustion system of the *High Risk Technology Engine*. The degree to which it will be capable of operating successfully on gasoline as well as distillate fuels is, of course, unknown. In theory, the lack of octane or cetane requirement for the spark-ignition, high-pressure direct injection would permit operation on a wide variety of fuels. Practical problems, however, may preclude operation on fuels other than the commercial kerosene-base jet fuel for which the engine would be designed. Variations in lubricity, viscosity, density, and volatility of various fuels alter the injection characteristics and affect fuel pump wear.

As far as the manufacturing cost criteria goes, it would be difficult to offset the investment in new machine tools with a more efficient manufacturing and assembly of the engines for the very low volume of parts produced annually by the industry.

Life-cycle cost (LCC) for the advanced-technology engines can, however, be improved to offset an increase in the initial price because of higher manufacturing costs and certification costs. The components contributing to reduced LCC are fuel economy, time between overhaul (TBO), overhaul cost, aircraft use rate, inspection, and maintenance. During the design phase, these components were kept in mind with major emphasis on the driving factors of fuel economy and TBO. The LCC of the engine by itself may not be indicative of overall LCC of the airplane. There are other driving factors in LCC that are independent of engine design such as hangar rental, insurance, and airframe LCC. The LCC discussion appears in Section 5.0, "Engine/Airframe Integration." Briefly, single-engine airplanes using the

Moderate Risk Technology Engine and *High Risk Technology Engine* had a 3.16% and 6.21% increase in acquisition cost, respectively, over a baseline current-technology airplane. Their direct operating costs (DOC) per hour were 11% and 15% lower. The LCC then could be lower for the advanced engines, depending on use, especially when considering the increasing price of fuel.

4.2 Engine Sizing

Although the requirement set forth at the beginning of the contract was for an engine that would produce at least 186 kW (250 hp) at 7620 m (25,000 ft), it is common practice to design the engine to produce at least one-third more power than its maximum cruise power rating. The tradeoff is to gain takeoff and climb performance as well as improved fuel economy and increased engine life at the expense of engine size and weight. As such, the maximum power was rather arbitrarily selected as 261 kW (350 hp). The maximum engine speed was kept at a level slightly below that of current technology geared engines (3200 RPM versus 3400 RPM). This allowed a fairly compact design without sacrificing fuel economy because of friction at higher engine rotational speeds.

The engine displacement turned out to be 6.88 liters (420 in^3) as the result of a rather complex iterative procedure. Limits on peak cylinder pressure were set at 8274 kPa (1200 psia) for the *Moderate Risk Technology Engine* and 10,342 kPa (1500 psia) for the *High Risk Technology Engine*. The bore-to-stroke ratio for both engines was chosen to be 1.25 as a compromise among the desired low mean piston speed (friction), low cylinder heat loss, high air swirl rate, and compact combustion chamber.

A large-bore, short-stroke engine reduces engine width and mean piston speed for a given displacement and RPM. Reduced mean piston speed reduces friction, which helps reduce brake specific fuel consumption (BSFC). The large bore, however, increases indicated specific fuel consumption because of higher heat losses and increased combustion duration. To minimize BSFC then, an optimum bore-to-stroke ratio must be selected such that the increasing ISFC is offset by decreasing friction specific fuel consumption (FSFC):

$$BSFC = ISFC - FSFC.$$

In the conventional spark-ignition aircraft piston engine, a somewhat higher bore-to-stroke ratio can be accommodated because the increased combustion duration is somewhat compensated by the two spark plugs in each combustion chamber that fire simultaneously, resulting in reduced combustion duration.

The bore-to-stroke ratios for modern aircraft piston engines range from 1.25 to 1.35 compared to automotive engines, which range from 0.8 to 1.3.

The compression ratio for both engine designs was set at 12:1 as a nominal value for calculating the engine's maximum pressures. In actual practice the compression ratios will be adjusted slightly from this value to ensure operation at or below these peak pressure values.

4.3 Engine Power Balance

The result of the complex iterative procedure used to arrive at engine size and performance can be capsulized in the form of a power balance. Starting with the equivalent power input in terms of fuel to each of the engines, a thermodynamic accounting has been made of the flow of power to the various losses within the engine in order for it to produce a brake output of 186 kW at 7620 m in cruise. This was done for the two advanced engines as well as for a current-technology engine, which is used as a baseline. Figure 19 shows the distribution of power among the three categories of consumption: brake output, exhaust losses, and cooling losses, for each of the three engines. The quantity of equivalent fuel input power was reduced by 20% and 26%, respectively, for the *Moderate Risk Technology Engine* and *High Risk Technology Engine* over the current-technology engine.

Figures 8, 9, and 10 show detailed power flow diagrams for each of the three engines.

The current-technology, TSIO-550, engine is turbocharged and, for 186 kW (250 hp) shaft output, has an equivalent of 292 kW (391 hp) available in the exhaust, of which only 25 kW (34 hp), or 8.7%, is recovered as power to the turbocharger compressor. The *Moderate Risk Technology Engine* has only 219 kW (294 hp) available in the exhaust but recovers 20 kW (27 hp), or 9.2%, through turbocharging and turbocompounding. Likewise, the *High Risk Technology Engine* recovers 18 kW (24 hp) of the 182 kW (245 hp) available in the exhaust.

4.4 Special Features

The engine design contains many special design features, some of which are not considered advanced technology but rather crossover technology - that is, existing technology from other areas that had not been applied to aircraft piston engines before. Figure 20 shows cross sectional views of the *High Risk Technology Engine*, where some of these features can be seen.

Because of the high-peak firing pressures (10,342 kPa) in the *High Risk Technology Engine* a unisteel cylinder is used. It is a fabricated assembly made by welding the cylinder barrel, combustion chamber dome, and exhaust port into a single unit and then casting the aluminum fin section around it. This unisteel design eliminates the weakness of an aluminum head screwed onto a steel barrel and also helps to retard heat transfer to the head and exhaust port. The unisteel design gives a more rigid construction so that the exhaust valve operation is not hampered by large thermal distortions between the valve seat and valve guide. Also, in combination with the unisteel design, Inconel exhaust port liners are included to help further decrease heat transfer to the cylinder head region, retaining as much energy as possible in the exhaust gases for use in turbocompounding.

The high thermal and mechanical loading of the aluminum piston dome will require better cooling of the underside of the piston. Normal practice is to provide a steady stream of oil from a tube in the crankcase fed from an oil gallery. The steady stream of oil is aimed at the underside of the piston, providing a rather irregular cooling pattern. The use of a so-called cocktail shaker on the underside of the piston provides more positive cooling. Oil is fed through passages inside the connecting rod (Figure 20) to a cavity formed between the cocktail shaker and the underside of the piston. The oil is splashed back and forth by the motion of the piston (as in a cocktail shaker) and the excess spills over the edges of the cocktail shaker and returns to the sump by way of the inside of the piston skirt and lower cylinder barrel.

The piston ring package was especially designed for this engine by Koppers Company. The three-ring design is intended for reduced friction, reduced oil consumption, and lower combustion gas blowby. One unique feature of this design is a "fire ring" at the top corner of the piston (Figure 21). The ring material is ductile iron with a plasma-coated molybdenum face operating in a iron ring groove that has been cast into the aluminum piston.

The intermediate ring is also plasma-coated and was designed to survive marginal lubrication periods. It also assists in oil control when the piston approaches bottom dead center.

The lower ring is the oil control ring, which is vented to the underside of the piston and backed by a spring to maintain uniform pressure.

The engine lubricant plays an important part in maintaining proper engine temperatures. In this design (Figure 20), additional cooling is provided to the exhaust valve seat by circulating oil in a torroidal passage behind the seat.

Normally, the heat rejected to the engine oil of a high-output engine is of such high magnitude that a separate oil cooler must be used to cool the oil. Although it is not shown in detail, the scheme used for cooling the oil for the advanced engines is to design the oil sump to serve as an oil cooler as well, avoiding the need for a separate oil cooler. The sump would be designed with finned passages, which would be cooled externally by ram air. Internally mounted thermostatic switches would maintain oil temperature at the desired level for a given operating condition (approximately 77°C).

The Nasvytis traction drive, which reduces the speed of the turbocompounding turbine, is coupled with a power transfer system and clutch, which transfers power back into the engine crankshaft when excess power is available. The output of the traction drive is connected to the clutch assembly by a toothed belt similar to that used to drive the overhead camshaft in automotive engines. The toothed belt will help reduce the transmission of torsional vibrations and will operate quieter than a chain or gear drive, while at the same time providing an additional speed reduction.

Torsional vibrations caused by the forces of the firing pulses of each of the six cylinders through the crankshaft to the engine output reduction drive and finally to the propeller must be dealt with to avoid high stress in the crankshaft and propeller. The predominant harmonic is a third-order excitation resulting directly from engine firing pulses for the six-cylinder engine. In a geared engine, which runs at higher speed than a direct-drive engine, the natural torsional vibration frequency of the drive system would be near the third-order forcing function of the firing pulses, causing large amplitude flexing of the system with correspondingly high stresses. The stresses are reduced by placing along the crankshaft three pairs of pendulum weights tuned to attenuate third-order torsional vibrations (Figure 22), adding a viscous damper at the rear of the crankshaft and using a flexible quill shaft to reduce the system stiffness. The pendulum weight pairs are not needed for engine balance. They are placed opposite each other so that they balance each other out, and so the additional weight they add to the crankshaft is not a necessity if another method can be found to reduce torsional vibration amplitudes.

A method used on the Tiara 6-285 series of engines is incorporated in the advanced engine designs. It is called a Vibratory Torque Control (VTC) unit. It eliminates the need for pendulum vibration absorbers by hydraulically causing the drive system to exhibit two distinct degrees of torsional rigidity, depending on engine speed. At low speed, the VTC unit locks up to make the system torsionally rigid, and at a higher speed, it becomes more flexible, driving through the quill shaft (Figure 22). As a result, the crankshaft using a VTC unit weighs less than half that using pendulum vibration absorbers.

4.5 Advanced Engine Specifications

Table VII shows a comparison among the specifications of the three engines: current-technology, TSIO-550; *Moderate Risk Technology*, GTSIO-420; and *High Risk Technology*, GTSIO-420/SC.

An indication of the improvement in efficiency gained over the current-technology engine is in the exhaust power unrecovered at maximum cruise power. Table VII shows a 33% reduction in this value for the *Moderate Risk Technology Engine*, and, for the *High Risk Technology Engine*, the unrecovered power rejected in the exhaust is reduced by half.

Figure 23 shows an artist's conception of the *High Risk Technology Engine*.

SECTION 5.0

ENGINE/AIRFRAME INTEGRATION

5.1 Introduction

This project resulted from an agreement by Beech to evaluate two advanced piston engine concepts developed by TCM. The evaluation objective was to determine the effects of the two new engines on overall airplane performance when compared to airplanes using current-technology engines. To accomplish this, two airframes, one single engine and one twin engine, were synthesized. Performance and cost calculations were made for each, using all three engines. Since the airplanes were otherwise identical, differences in performance and cost were attributed to the engines.

The two advanced engines, termed *Moderate Risk Technology Engine* and *High Risk Technology Engine*, are both six-cylinder, horizontally opposed, geared, turbocharged, turbocompounded, spark-ignition, fuel injection units of 6.88 liters (420 in^3). Both are rated at 260 kW (350 hp) using gasoline in the *Moderate Risk Technology Engine* and jet fuel in the *High Risk Technology Engine*. The engines are alike exernally but the more advanced engine is lighter in weight and has lower fuel consumption. TCM furnished details on these engines and a current-technology engine with the same power to use in the comparison baseline.

Beech synthesized two airframes for the study, both pressurized, for operational altitudes compatible with the turbocharged engines. The single-engine and twin-engine airframes are six-place designs, the latter with more cabin room for a lavatory and baggage. With these airplanes and engines, performance, cost, and noise estimates were made and compared. Sketches were made of the engine installations and the airplanes to check compatibility.

The results of the project indicate that very considerable savings in fuel could result from the use of advanced engines of this type. Airplane acquisition costs would be up somewhat but overall operational costs would be significantly reduced. No outstanding problems with noise, installation, or airplane configuration were indicated by the study.

5.2 Airplane Performance

A series of iterative calculations were used to establish the baseine airframe configurations used in this study. Data used to start the process can be grouped into three types: 1) desired mission profile parameters, including range, speed, payload, and field lengths; 2) airplane characteristics, including drag parameters, weight parameters, and field length parameters; and 3) engine characteristics, including weight, power, and fuel consumption. The objective of this process is to produce specific airplane characteristics, including drag, wing area, power required, and weights that match the chosen input parameters and mission profile. The iteration method was calibrated by a series of trial calculations, beginning with characteristics of known single- and twin-engine airplanes.

The calibrated calculation method was used with data for the current-technology engine and desired mission profiles to obtain the characteristics and performance of airplanes using that engine. These results were used as a baseline for comparison with the performance of the same airplanes using the two advanced engines, all cruising at 7620 m (25,000 ft).

Performance for the airplanes using the *Moderate Risk Technology Engine* and *High Risk Technology Engine* was established next. These engines had lower weight, fuel consumption, and cooling drag. With these changes, advanced-engine airplane performance was calculated with a straightforward series of equations. Performance was calculated at 7620 m (25,000 ft) for comparison with the baseline airplanes and also at 9144 m (30,000 ft) and 10,668 m (35,000 ft) to get an indication of high-altitude results with the advanced engines. Significant improvements in airplane efficiency are indicated with the advanced-engine technology.

With the method calibrated, the current-technology engine data in Table VII and the desired mission profiles for cruising at 7620 m (25,000 ft) were used to calculate the single- and twin-engine current-technology airplane data shown in the left column in Tables VIII and IX. These tables show mission profiles, airplane characteristics, and airplane performance. The baseline airplane data is used as a basis for comparison with data generated for the same airplanes with advanced engines, as described in the next section.

The *Moderate Risk Technology Engine* and *High Risk Technology Engine* airplanes differed from the baseline configurations only in engine installation. Takeoff weights, engine powers, cruise altitudes, field lengths, and wing areas from the baseline configurations were held constant. The other mission profile values of range, speed, and payload were increased as a result of the advanced-engine's lower drag, weight, and fuel consumption. Advanced engine data was taken from Tables VII and X. The reductions in installed engine weight resulted in increased useful load. Since large increases in range were indicated for the airplanes with advanced engines, the arbitrary decision was made to divide the increase in useful load equally between fuel and payload. This still left substantial range increases for the advanced-engine airplanes and illustrates another advantage for them, that of increased payload.

After the project was well under way, NASA requested that cruise at 10,668 m (35,000 ft) be investigated. Performance figures for the airplanes using the two advanced engines cruising at 9144 m (30,000 ft) and 10,688 m (35,000 ft) were obtained in the same way at 7620 m (25,000 ft) figures using the high-altitude engine data in Table X. The results are shown in Tables VIII and IX. The only difference was that average rates of climb at 8382 m (27,500 ft) and 9144 m (30,000 ft) and 10,668 m (35,000 ft). [1] Cruise speed, range, and reserve calculations were made at 9144 m (30,000 ft) and 10,668 m (35,000 ft) using the same methods used for 7620 m (25,000 ft) performance.

Range at 9144 m (30,000 ft) for both the *Moderate and High Risk Technology* singles is higher than 10,668 m (35,000 ft). The models for the airframes used in this study were based on current-technology airplanes, so apparent performance improvements would be due to the engines. Airplanes of this type are designed to have a maximum cruise altitude of about 7620 m (25,000 ft). The decrease in cruise speed going from 7620 m (25,000 ft) to 10,668 m (35,000 ft) shows that service ceiling is being approached. Even for the twin, the small range improvement is probably not worth increased mission time. Different baseline airframe designs should be used if cruise at these high altitudes to save fuel is a primary objective.

Current certification requirements for single- and twin-engine airplanes result in single designs that have a lower rate of climb than a twin using the same engines at a given altitude. Maximum range for turbocharged airplanes can generally be expected to increase to some altitude where the rate of climb drops low enough to cause the total range to begin decreasing because of the amount of fuel used in climb. This has apparently happened in the altitude range of this study for the single-engine airplane. The altitude for this effect would be higher for the twin with its higher rate of climb. Considerably more detailed engine and airframe data would have to be developed to investigate this situation in more detail. In any case, the margin of range increase with the advanced engines in this study is great enough to conclude that these engines offer a considerable increase in efficiency.

Comparative performance advantages that would be realized with these advanced engines are indicated by the percentage performance differences shown in Tables VIII and IX. These percentages relate both the *Moderate and High Risk Technology Engine* columns to the current technology column. The increases in useful load are significant but the increases in range or fuel efficiency are extremely high. The prospect of reducing fuel consumption by percentages of this order should make these new engine concepts well worth developing. Figures 24 and 25 show a summary of the single- and twin-engine performance for all three engines - current, moderate risk, and high risk technology.

For the particular mission profile of maximum range at maximum cruise at an altitude of 7620 m (25,000 ft), a number called "relative efficiency" has been calcualted to quantify the improvement over a current-technology

[1] The use of average climb rates was checked with a more extensive climb performance method and found to be reasonable for purposes of this project.

design. The number is normalized to unity for the current-technology single- and twin-engine airplanes and the relative efficiency numbers for the *Moderate and High Risk Technology Engines* are ratios that indicate a percent improvement in transportation efficiency over current technology.

The transportation efficiency (TE) numbers from which these normalized values were calculated are based on the simple definition that the highest efficiency means transporting the largest payload over the greatest distance using the least amount of energy:

$$TE = \frac{\text{Payload} \times \text{Range (with 45 min reserve fuel)}}{\text{Mass of Fuel Consumed}} \left[\frac{\text{kg-km}}{\text{kg}} \left(\frac{\text{ton-n.mi.}}{\text{lbm}} \right) \right].$$

The TE number is not a constant for a given airplane, but it depends on the mission profile, in the case of Figures 24 and 25, maximum range at 71.4% power cruise and 7620 m (25,000 ft) cruise altitude.

These TE numbers provide a useful means of comparison among similar airplanes, although no weighting factors are used to indicate the value of time saved during a trip. Of two airplanes having the same TE value, the one that flies faster would obviously be more valuable by some degree. Figure 24 shows that the *Moderate and High Risk Technology Engines* give a 39 and 63%, respectively, better TE when installed in the single-engine airplane. For the twin-engine airplane, the corresonding improvements in TE are 41 and 68%, respectively.

Another less rigorous comparison can be made by calculating passenger-distance per unit mass of fuel. Both the single- and the twin-engine airplanes proposed here are six-place, including the pilot. The current-technology, single-engine airplane has a payload with full fuel of 554 kg (1200 lbm), which means it could carry a per-passenger load of 91 kg (200 lbm). It would have a passenger efficiency of 39 passenger-km/kg of fuel (9.6 passenger-n.mi./lb of fuel) compared to the *High Risk Technology*, single-engine powered airplane of 59 passenger-km/kg of fuel (14.5 passenger-n.mi./lb of fuel). This factor makes the *High Risk Technology Engine* version appear to be only 1.5 times as efficient compared to the relative efficiency of 1.63-times as calculated by the TE method.

5.3 Aircraft Noise Estimates

Aircraft noise estimates were based on the criteria in FAR 36. This calls for a noise measurement when the airplane flies over the measuring station at an altitude of 305 m (1000 ft) using full power and maximum speed. This measured noise is then corrected by a term calculated according to a formula given in FAR 36. The correction favors high initial rates of climb.

Maximum power flyover speeds were calculated with the method already described using appropriate cruise drag figures, including changes caused by cooling drag differences and 85% propeller efficiency. Flyover noise figures were calculated using a modified method based on empirical data developed by Hamilton-Standard.

Climb speed, total distance to climb to a 15-m and (50-ft) altitude, and rate of climb for use in calculating correction factors were based on the corresponding calculations used in determining airplane mission performance. Climb propeller efficiencies of 75% and reasonable ratios of liftoff to stall speeds were assumed. Corrected flyover noise estimates for the baseline engine at 2800 RPM and the two advanced engines at 2400 RPM are shown by the upper figures in Table XI. In all cases, the propellers were sized to maintain 85% cruise efficiency. This combined with small differences in flyover speed, climb speed, and drag resulted in the indicated variation in propeller diameters. These preliminary estimates indicate that 2400 RPM is the maximum that could be used for the advanced engines to just meet the maximum corrected noise value of 80 dB(A) currently allowed by FAR 36.

Noise estimates for the most advanced engine at 2200 and 2000 RPM were also made. A propeller diameter of 2.4 m (95 in.) was used in all of these estimates. This is nearly the maximum practical propeller diameter for airplane configurations of the type considered in this study. Smaller diameters could probably be used and cruise efficiency maintained, but climb performance could be expected to be lower. A more extensive propeller optimization would be needed to further investigate lower propeller speed. These results indicate that an RPM lower that 2400 is desirable for engines of this power in these applications to provide a comfortable margin on current noise limits.

5.4 Engine Installation

Since the *Moderate* and *High Risk Technology Engines* are essentially identical externally, the following comments and installatin sketches shown in Figures 26 and 27 apply to both. Engine features initially taken into consideration for the installation sketches included the aft-mounted accessories and turbines, the location of the propeller speed reduction gear case with the extended shaft, and the updraft cooling. The fairly high extended propeller shaft suggested a tapered forward nacelle faired into the propeller spinner with the extended shaft and the updraft cooling. These features were used on both the single and the twin. A bed-type mount was used to leave the back of the engine clear for accessories. The mount would be steel to meet FAA fireproofing requirements. This applies to both the single and the twin; in the former case, the bed mount ties to the keel to transfer nose gear loads and allow a relatively lightweight combination structure for both keel and mount.

The two cooling air inlets supply air to a common plenum below the cylinders. Cooling air for all purposes is supplied from the plenum. After flowing up around the cylinders, cooling air is discharged through top exists in the twin nacelle. On the single, this air must be routed down the back of the engine compartment to a bottom exit. This avoids the possibility of oil vapor impinging on the windshield. Intercooler air is routed to these exits. Oil cooling is accomplished by fins on the engine oil sump. A shroud around the sump takes air from the plenum past the fins and to the exit.

A flush induction air inlet, separate from the cooling air is used. This provides cool induction air and avoids the possibility of bleed air contamination from the area adjacent to the engine itself.

5.5 Cost Estimates

The cost estimates for this study, as noted in the summary, were made in two parts: acquisition costs and operating costs. Beech used internal data and methods to estimate airframe construction costs and added markups for a total selling price estimate. Operating costs were based on a survey of actual costs being encountered by users of Beech airplanes. Details of both cost estimates are given with numerical data and results in Tables XII, XIII, and XIV.

The method used in estimating acquisition costs is based on airframe weight, historical data, and learning curve theory. Six sets of estimates were made, as described in this section: single- and twin-engine airplanes using the three study engines. The main items in an estimate of the selling price of an airplane are shown in Figure 29. The cost to the factory in building the airplane is the sum of material, labor, and amortized development costs. Factory and dealer markups or profits are added to the factory costs. Since most airplanes are delivered with options in addition to standard equipment, this amount is added to produce the unit selling price, or acquisition cost.

Airframe weights for the single- and twin-engine airplanes were estimated from the airplane empty weights produced by the airplane synthesis calculations, engine weights from the TCM data, and Beech estimating methods. These weights were used, as described below, in calculating airframe labor and amortized development costs.

As shown in Figure 28, material costs are grouped into four categories. Engine costs were supplied by TCM. Equipment and standard avionics costs were estimated by Beech using current data for airplanes in the classes considered for this study. Current material costs for airframes of the types considered in the study were used to estimate dollar-per-pound figures for the study airframes. These figures multiplied by the airframe weights derived from the synthesis process provided airframe costs. The sum of engine, equipment, standard avionics, and airframe costs is the total material cost.

Labor costs were obtained by multiplying man-hours required to produce each pound of airframe weight by the cost of each hour of labor. Experience has shown that when the number of hours required to produce a given airframe is plotted against the cumulative number of airframes produced, a curve of the form $y = C/X^n$ results where

- y - hours to produce a given unit
- c - number of hours required to produce the first unit
- X - cumulative number of units produced
- n - exponent representing the "slope" of the curve.

Slope is the fraction of hours required to produce a doubled number of airframes, such as the second referred to the first of the 1000th referred to the 500th. An 80% slope means that the second or 100th unit required 80% of the hours for the first or 500th, respectively. Appropriate historical data of this type was used to choose a cumulative number of units produced for costing purposes and corresponding hours per pound figures for the airplanes in this study. Current labor rates were used to estimate labor cost per hour. The product of these estimates and the airframe weights provided estimated labor cost.

Historical data was also used with considerations of current trends to estimate development cost-per-pound numbers for the study airplanes. This number multiplied by the airframe weight and divided by the cumulative number of units chosen from the learning curve data provided amortized development costs.

The sum of total material cost, labor cost, and amortized develoment cost is the total factory cost. Typical manufacturers' and dealers' profits were then calculated and added to the total factory cost. A final increment was added for typical optional equipment and avionics selections to obtain representative dealer's price tag figures. The same sets of reasonably realistic assumptions were used throughout, so the results should be adequate for obtaining an idea of the difference in retail prices resulting from the engines in this study. Acquisition price percentage changes from the baseline configurations to the configurations with advanced engines are shown on the cost summaries for single and twin-engine airplanes (Tables XIII and XIV). The maximum cost increase, about 7%, for the more advanced twin, is quite reasonable when combined with the 16% reduction in operating cost for the same airplane.

Operating cost estimates in this study are based on two sources: engine costs supplied by TCM and data taken from operating cost surveys made by Beech. The engine cost factors contributing to airplane operating costs are listed in Table XII. Depreciation is not included. The survey data consisted of recent averages of actual nationwide operating costs for airplanes similar to those in this study. Since the survey was made in late 1979 when fuel costs in particular were rapidly trending upward, that aspect of this study should be considered in relative rather than absolute terms. Cost summaries for the single- and twin-engine airplanes are shown in Tables XIII and XIV in the form of percentage changes relative to values calculated for the baseline airplanes using the current-technology engine. The first item is acquisition cost, which was explained in the previous section. The remaining items are operating costs per hour, which are explained in sequence in the following paragraphs, beginning with fuel. Note that an 800-hr operation per year was assumed for the single-engine airplane and 1000 hr for the twin.

Fuel costs per hour were calculated from cruise fuel consumption, cruise power, fuel cost, and fuel density. Oil costs per hour were calculated similarly from oil consumption rates, oil cost, and oil density:

$$\text{Fuel Cost Per Hour} = \frac{(\text{Cruise SFC})(\text{Cruise Power})(\text{Fuel Cost})}{(\text{Fuel Density})}$$

$$\text{Oil Cost Per Hour} = \frac{(\text{Oil Consumption})(\text{Oil Cost})}{(\text{Oil Density})} .$$

Inspection maintenance costs for the single-engine airplane were estimated indirectly. Since the single- and twin-engine airframes are similar and similarly equipped, the following method was used to estimate inspection and maintenance costs for a pressurized single-type airframe. "I&M" is inspection and maintenance for the airframe; "ENG" is engine; and "Pres. Sing." is pressurized single engine airframe. The 58P and 58TC are current pressurized and unpressurized twin-engine airplanes. The A36TC is a current unpressurized single-engine airplane. The ratio of the difference in engine and airframe I&M cost for an unpressurized airplane was established using 58P, 58TC, and TCM current-engine I&M cost data:

$$\text{Ratio} = \frac{(\text{58P I\&M} - \text{2XENG I\&M}) - (\text{58TC I\&M} - \text{2XENG I\&M})}{(\text{58TC I\&M} - \text{2XENG I\&M})} .$$

Ratio was then used to get an engine and airframe I&M cost for a pressurized single, starting with A36TC data:

$$\text{Ratio} = \frac{(\text{Pres. Sing. I\&M} - \text{ENG I\&M}) - (\text{A36TC I\&M} - \text{ENG I\&M})}{(\text{A36TC I\&M} - \text{ENG I\&M})} .$$

Solve for Pres. Sing. I&M:

Pres. Sing. I&M - Current Engine I&M = Pres. Sing. Airframe I&M.

Airframe inspection and maintenance costs for the twin-engine airframe were based directly on the survey results:

(Duke, 58P average I&M) - (2 times Current ENG I&M) = Twin airframe I&M.

Engine inspection and maintenance costs are TCM-supplied values. Corresponding propeller costs are taken from the survey data.

Engine exchange costs were calculated by dividing the total cost by the time between overhauls, both values supplied by TCM.

Hangar rental figures were taken from the survey results for similar airplanes. An increment was added to account for storage costs when the airplane was away from its base. Both the single and the twin values were calculated with the method shown using appropriate survey figures:

$$\text{Hanger Rental} = \frac{\text{Rent/Year + \$/Hour Storage Away from Base (Hours/Year)}}{\text{Hours/Year}} .$$

Insurance costs were estimated by using survey results to calculate the annual insurance cost per $1000 of selling price for similar airplanes. This was multiplied by the estimated acquisition costs of the study airplanes to get annual insurance cost estimates. Costs for the pressurized single-engine airplanes were estimated with a ratio method similar to that explained earlier for the airframe inspection and maintenance costs. Insurance cost per year per $1000 of selling price is denoted by $/K. For the single-engine airplane, the following method was used:

$$\frac{\text{58TC \$/K - 58P \$/K}}{\text{58TC S/K}} = \text{Ratio}$$

$$\frac{\text{A36TC \$/K - Pres. Sing. \$/K}}{\text{A36TC RK}} = \text{Ratio}$$

Solve for Pres. Sing. $/K:

$$\text{Ins./Year} = \frac{\text{(Selling Price/1000) \$/K}}{\text{Hours/Year}} .$$

Survey numbers were used more directly to estimate the twin-engine airplane values:

$$\text{Ins./Year} = \frac{\text{(Selling Price/1000) \$/K}}{\text{Hours/Year}} .$$

The notable advantage of the advanced engines on Tables XIII and XIV is the marked decrease in fuel consumption. Fuel costs for the most advanced engine are dramatically lower because of the combination of lower consumption and lower per-gallon cost. This would be an increasing advantage as fuel costs continue to rise. Total operating costs are reduced by a lower proportion when all factors are summed up. The percentage decreases in direct operating cost could be calculated on a per-mile basis because of the higher cruise speed of the advanced-engine airplanes. The exact figures would depend on block speeds that were not estimated in the scope of this study.

5.6 Airplane Three-View Sketches

Airplane sketches for the single- and twin-engine configuration concepts are shown in Figures 29 and 30. As noted in the engine installation discussion, the two advanced engines are nearly identical externally, so these three views represent airplanes with either one. The synthesis program provided basic wing areas and a tail area ratios. The engine installation layouts provided nose and nacelle shape information. The payload and fuel load figures from the synthesis process and the mission concepts were used with the other data to make these representative sketches of the airplane concepts evolved in this study. The engine concepts go well with these conventional airplane concepts; no airframe configuration problems are foreseen with engines of this type.

SECTION 6.0

TECHNOLOGY ENABLEMENT PLAN

6.1 Introduction

In Task IV, a timetable is offered with a recommended plan of action that would result in bringing the expected new technology to the point of commercial production by December 31, 1989. The technology enablement portion is suggested to be a joint Government/industry program with the actual engine prototype development programs through production to be accomplished by industry.

The *High Risk Technology Engine* is the main focus of this study, whereas the *Moderate Risk Technology Engine* can be considered a minimum acceptable representation of an advanced-technology design. These two engines bracket the range of technology that could reasonably be expected to be made available for an engine that would be in production by the beginning of the next decade.

The recommendations of Task IV are aimed specifically at acquiring that technology needed for the *High Risk Technology Engine* design. Should any of the technology items not be available, then alternative techologies specified in the *Moderate Risk Technology Engine* design would be substituted.

6.2 New Technology Program Schedules

Table XV shows the overall program plan necessary for introduction of the *High Risk Technology Engine* into the marketplace by January 1, 1990.

A preliminary engine definition completed in mid 1980 (the results of this contract work) followed by the suggested technology programs, some of which are now under way, would result in a precise engine definition by December 31, 1984. A first experimental engine containing all of the elements of advanced technology would be ready by the beginning of 1986, followed by a certification and production decision early in 1988. The remainder of the time would involve FAA engine and airworthiness certification and, finally, production. The critical technology items that are needed are shown in Table XVI: stratified-charge combustion system, electronically controlled ignition, improved turbocharger, turbocompounding system, and electronic engine controls. This work covers the period from the beginning of 1981 until mid 1984.

Tables XVII through XXI are detailed program plans for each of the five critical advanced-technology programs. Each of the five programs is independent of one another initially during rig tests and is integrated for propeller stand and dynamometer testing after proven satisfactory in design. The single-cylinder tests for the stratified-charge combustion system (Table XVII) will provide the design basis for multicylinder engine configuration testing using an existing six-cylinder, turbocharge engine with modified cylinder assemblies. This work not only provides the basis for the final integrated advanced design, but also explores the potential for conversion of existing turbocharged engines to charge stratification should that strategy appear attractive in the future. During Task 6 of the stratified-charge combustion system program, a second design is used approaching more closely the desired integrated engine design.

At this point, the second design is integrated with its electronic ignition system (Task 4, Table XVIII; the advanced turbocharger, which has already been flight-tested; the turbocompounding system (Task 6, Table XX); and the electronic, single-lever power control system (Task 5, Table XXI). The integrated system is then ready for propeller stand and dynamometer testing during the second half of 1983, preceding actual flight tests in 1984.

SECTION 7.0

CONCLUSIONS AND RECOMMENDATIONS

With the decentralization of American business and the deregulation of the commercial air carriers, general aviation has become an increasingly important segment of our national transportation system serving all of the country's 14,000 airports compared to only 350 airports available to the airlines. Over 92% of the active aircraft in the general aviation fleet are now powered by spark-ignition aircraft piston engines fueled by aviation gasoline.

Rapidly advancing areas of new technology, fuel shortages, increasing fuel cost, and demands for increased safety have led to a reconsideration of the suitability of current engine designs to meet the needs of the decades beyond the year 1990.

This study has shown that a reasonable plan of action, not without some technical and financial risk, could result in a new generation of spark-ignition aircraft piston engines that would be suitable to accommodate the need for a vastly improved powerplant to better serve general aviation beyond 1990. A conservative analysis based on the installation of such an engine in current state-of-the-art airframes yields transportation efficiency improvements of over 60% compared to existing single- and twin-engine airplane designs.

Successfully adopting the stratified-charge concept would allow this new family of engines to use liquid hydrocarbon fuels, which are more abundant and more efficient from an overall VFR viewpoint than the aviation gasolines used today.

The integration of electronic engine control has a positive effect not only on fuel efficiency but also on safety of flight, by reducing the amount of interaction between pilot and engine, thereby reducing pilot workload.

The concepts suggested in this study and the programs outlined for the realization of their successful development are deemed worthy of a firm and timely commitment by both the industry and Government to meet the changing needs of general aviation propulsion in the years to come.

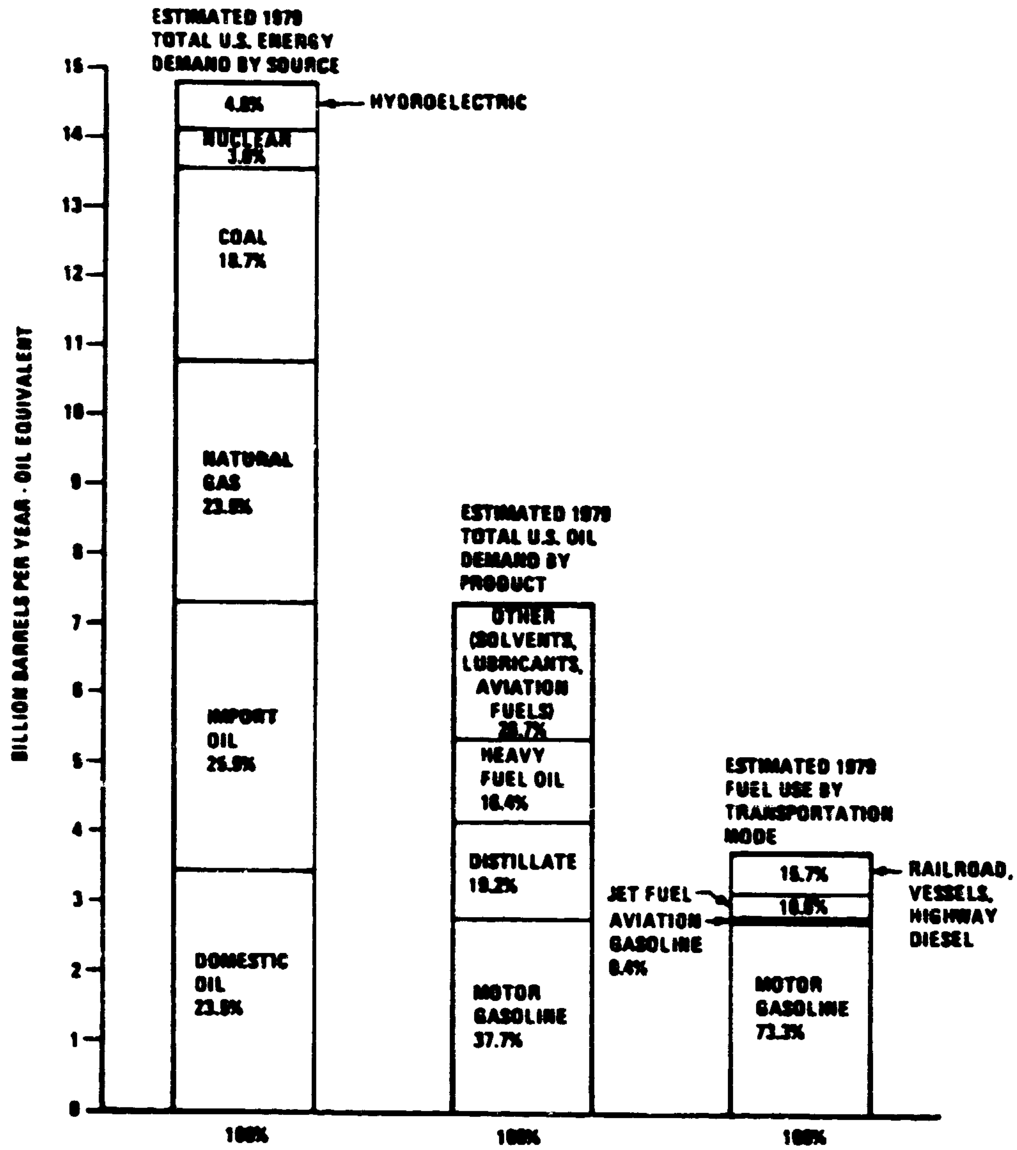


Figure 1. Estimated 1979 U.S. Energy Use.

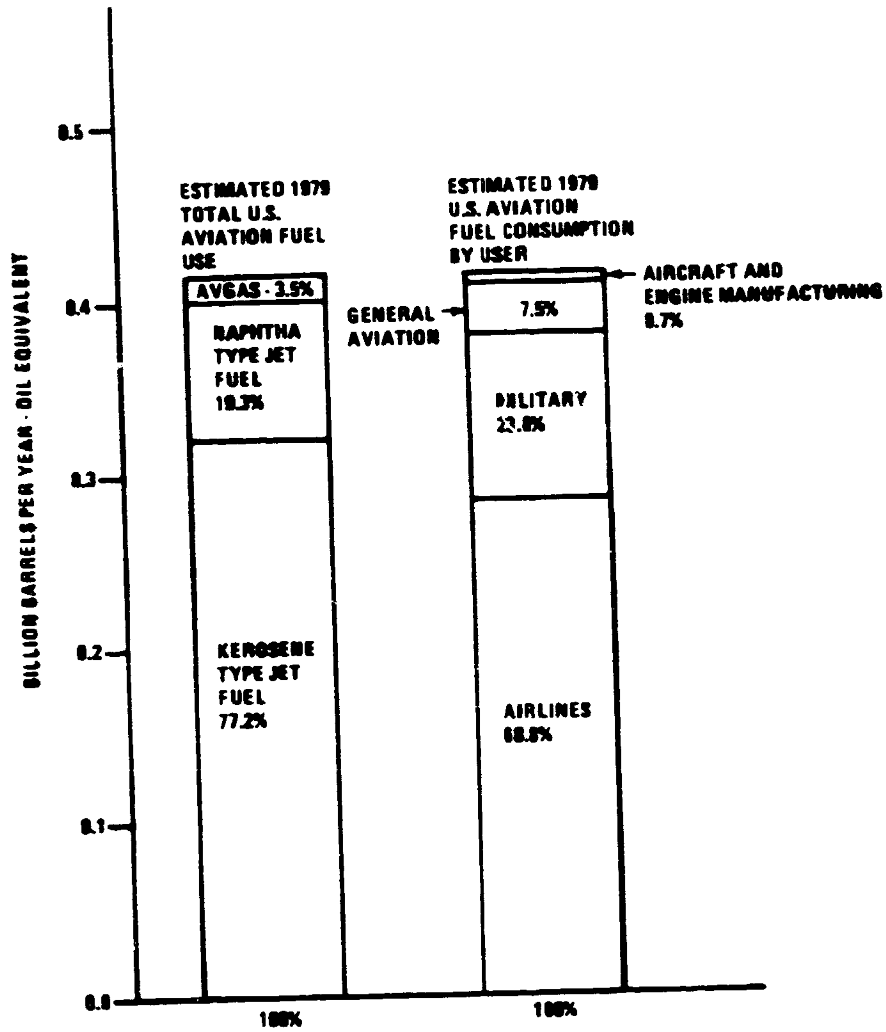


Figure 2. Estimated 1979 U.S. Aviation Fuel Use.

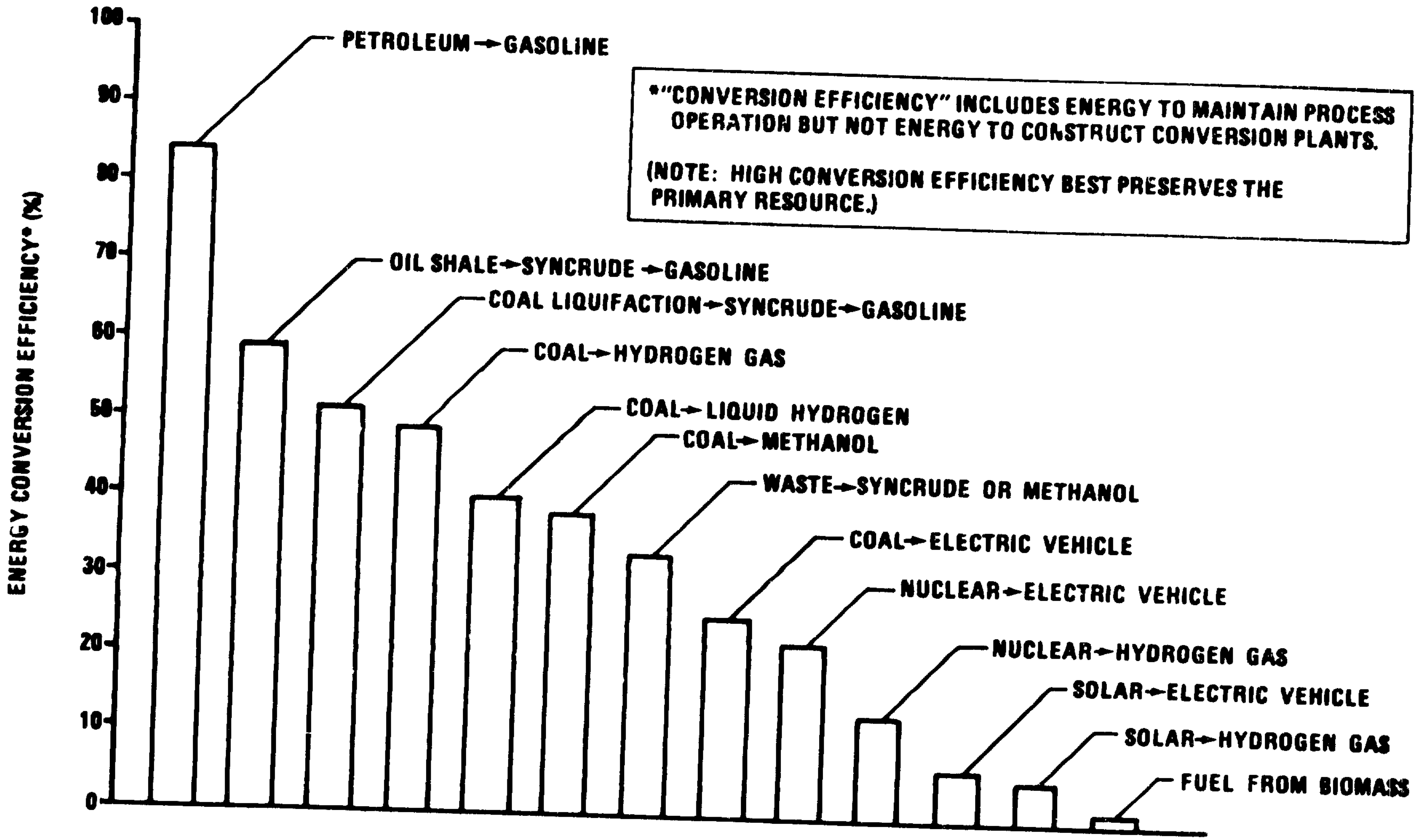


Figure 3. Estimated Conversion Efficiencies of Internal Combustion Fuels from Primary Resources.

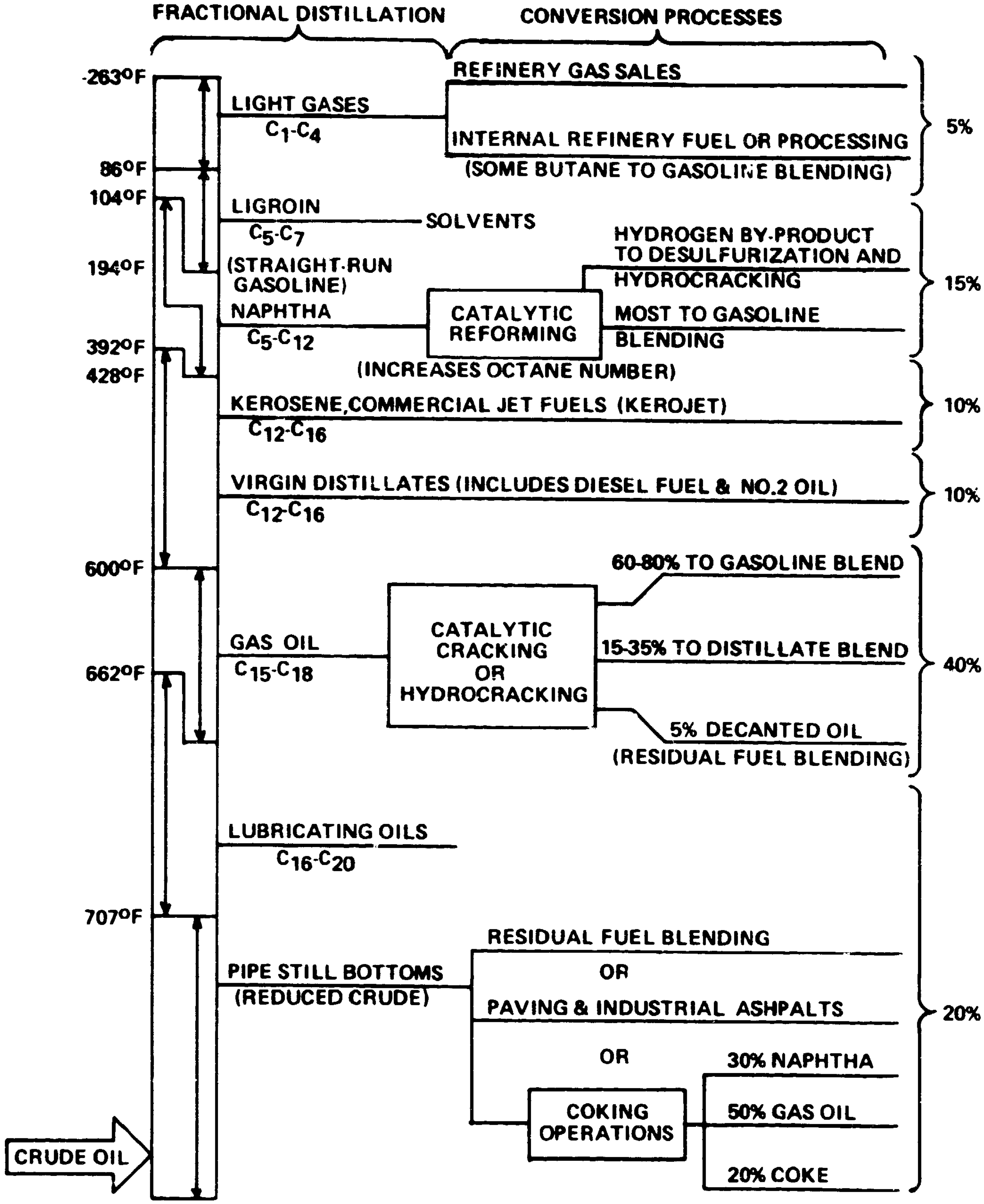


Figure 4. Crude Oil Refining Schematic.

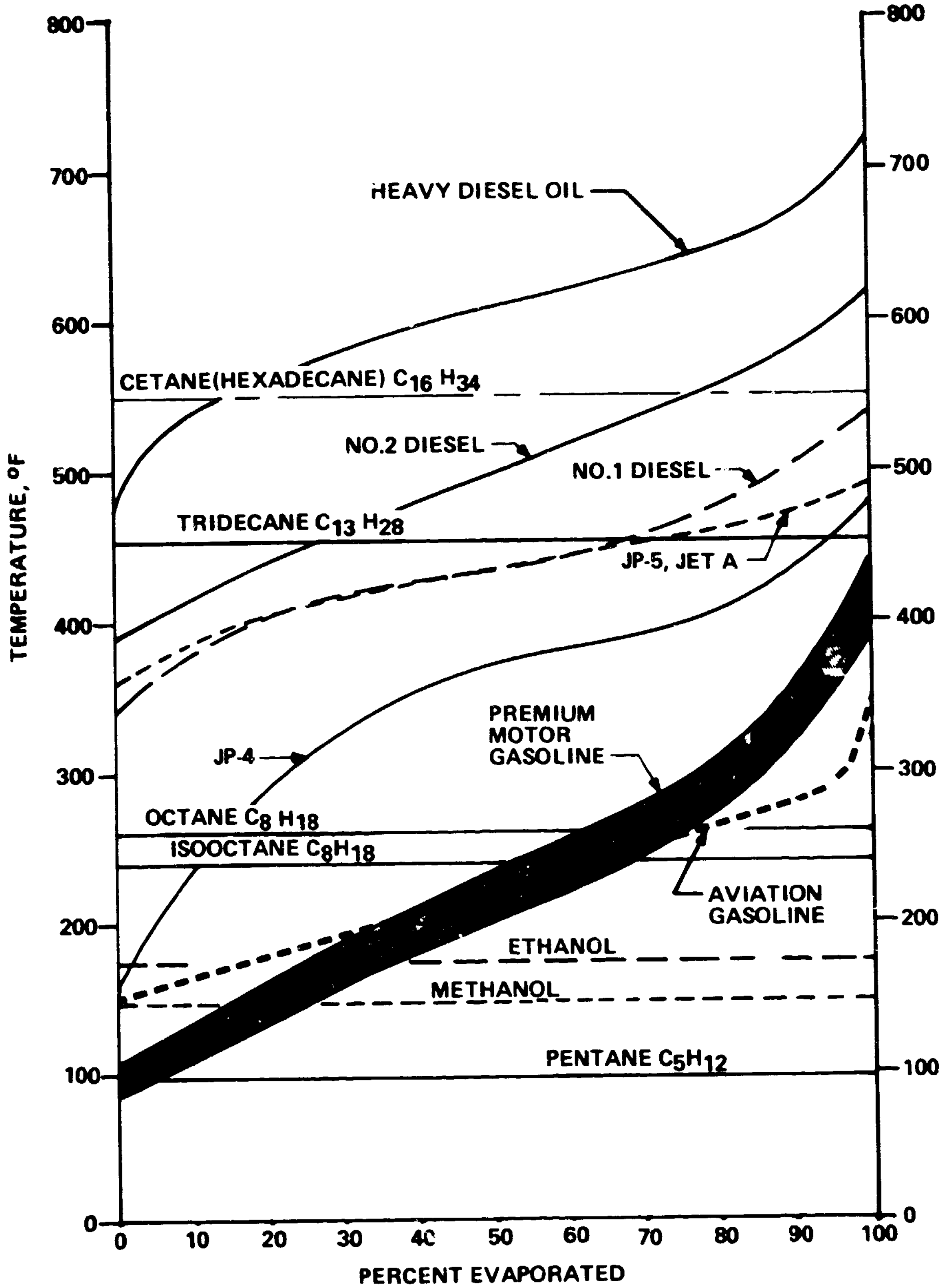


Figure 5. Distillation Characteristics of Fuels.

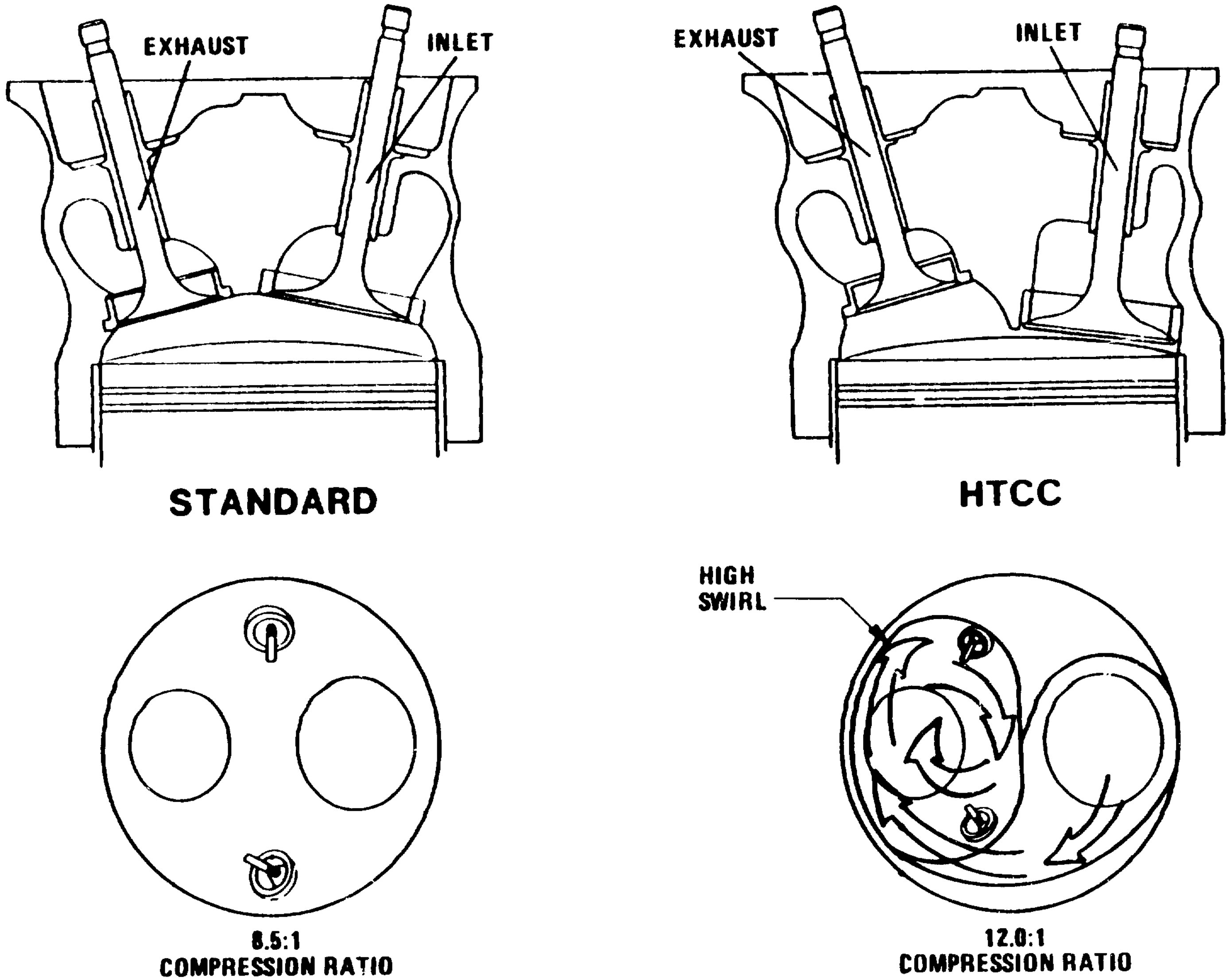
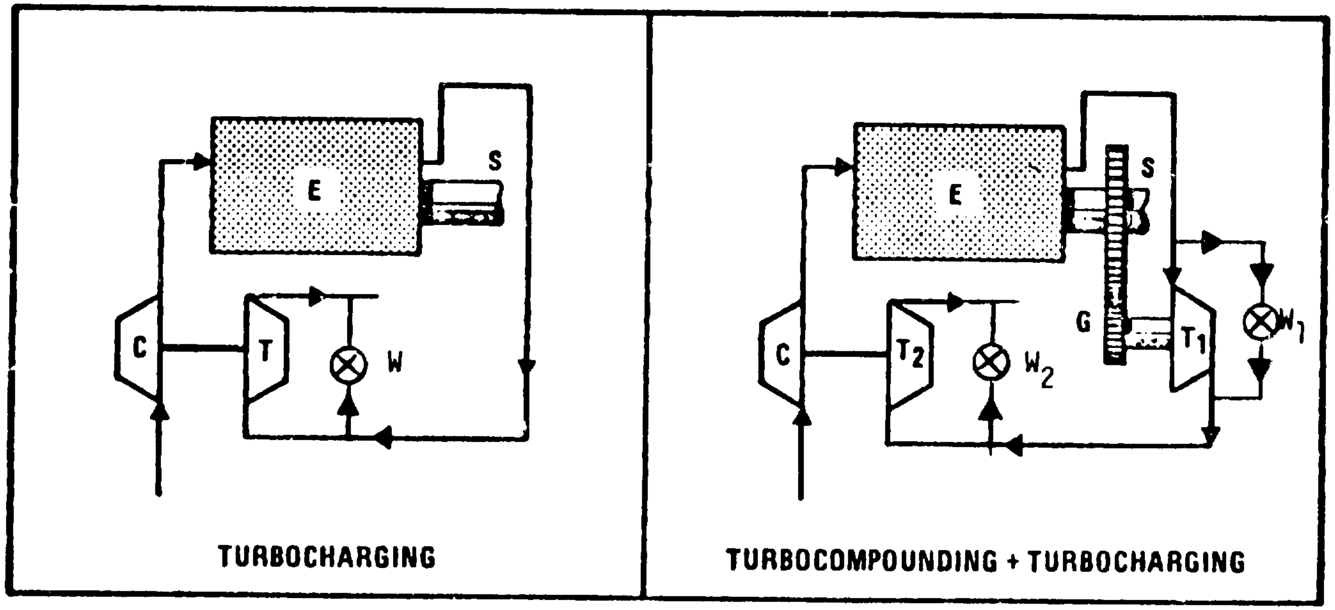


Figure 6. Comparison Between Standard Hemispherical and High Turbulence Combustion Chambers.



E - engine
S - propeller shaft
T, T_2 - turbocharger turbines
W, W_1, W_2 - waste gates

C - turbocharger compressor
T_1 - turbocompounding power turbine
G - speed reduction drive

Figure 7. Schematic Comparison Between a Normal Turbocharged Engine and a Turbocompounded Engine.

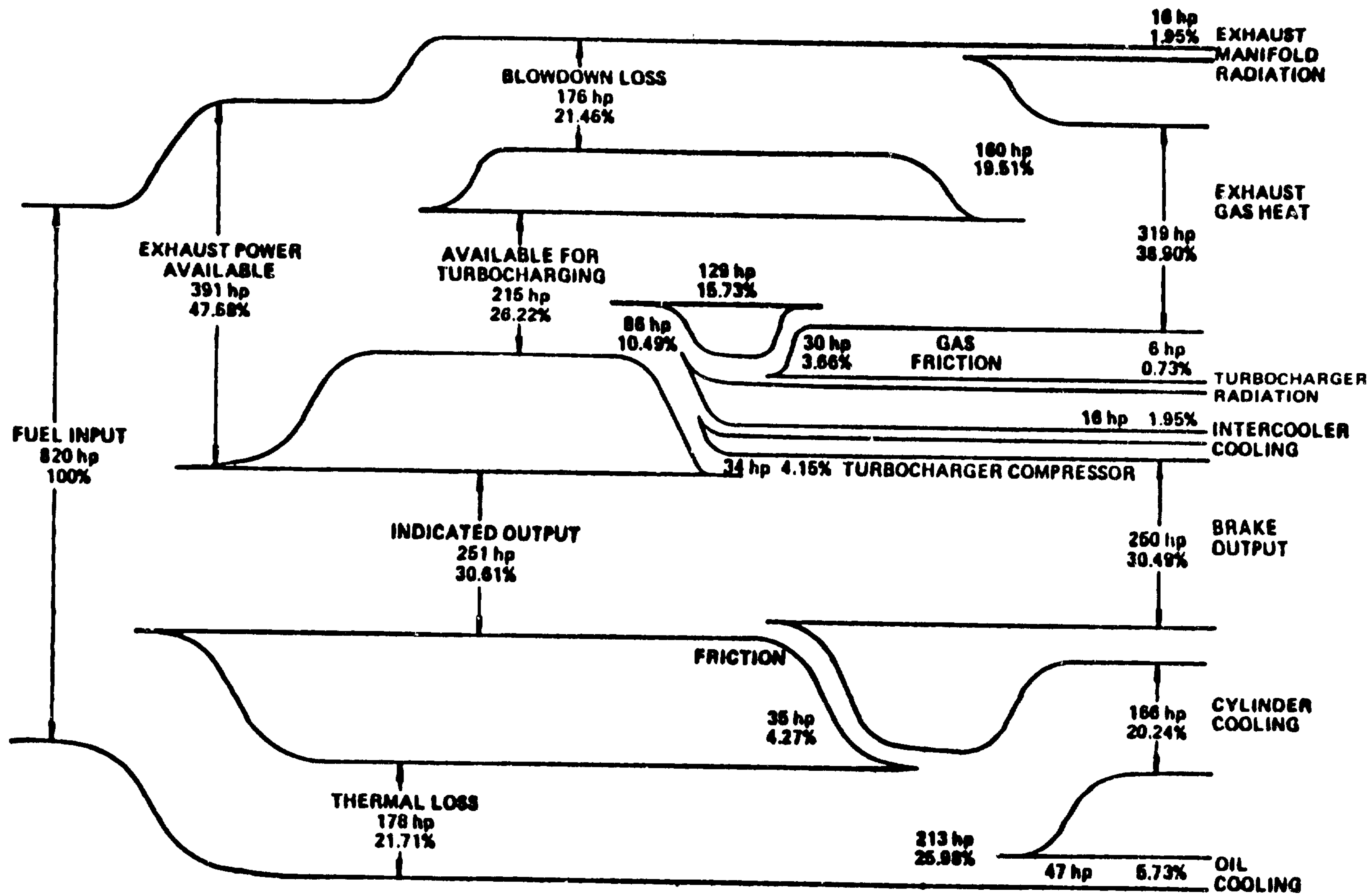


Figure 8. Current Technology Engine Power Balance, TSIO-550, Maximum Cruise at 25,000 ft.

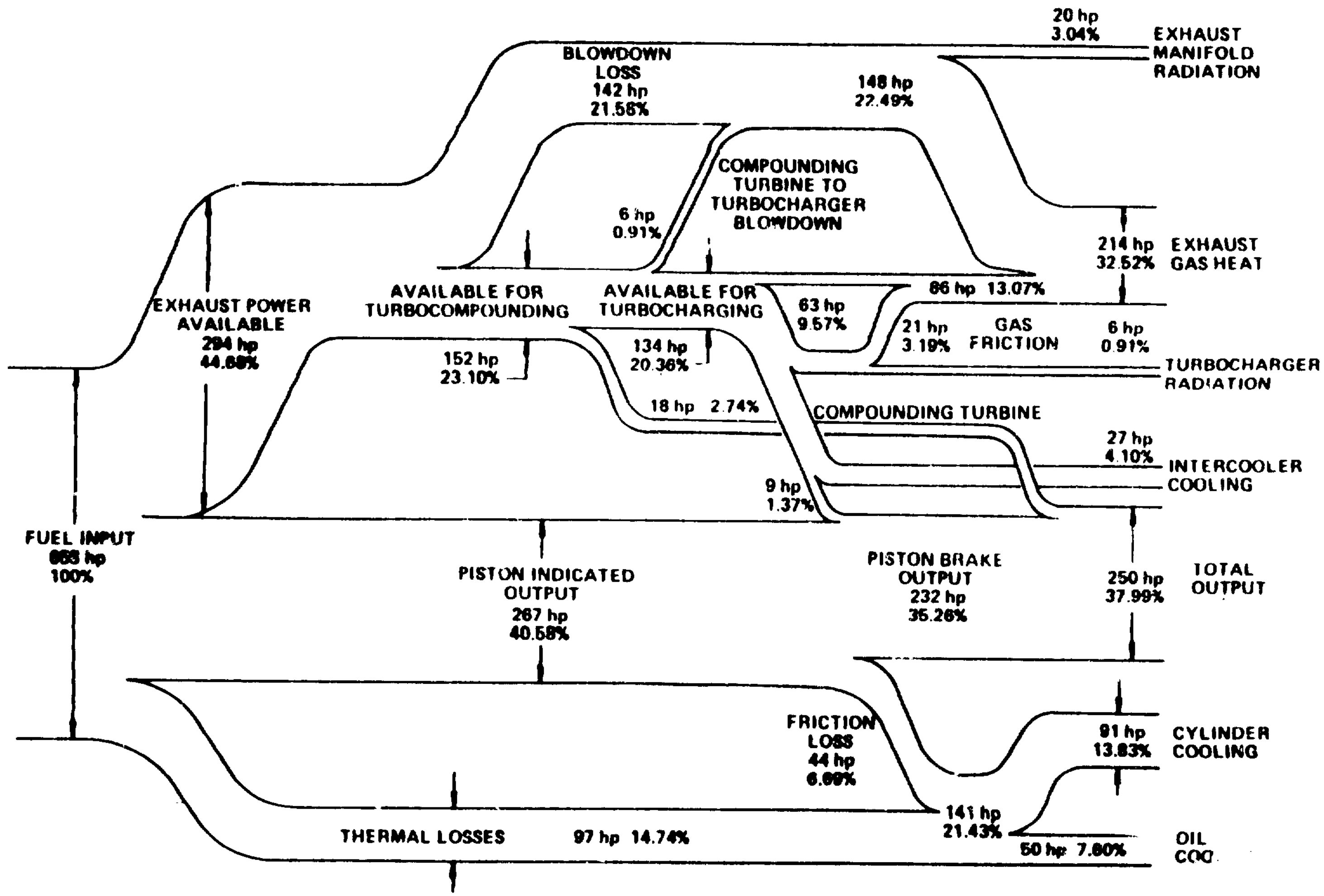


Figure 9. Moderate Risk Technology Engine Power Balance, GTSIO-420, Maximum Cruise at 25,000 ft.

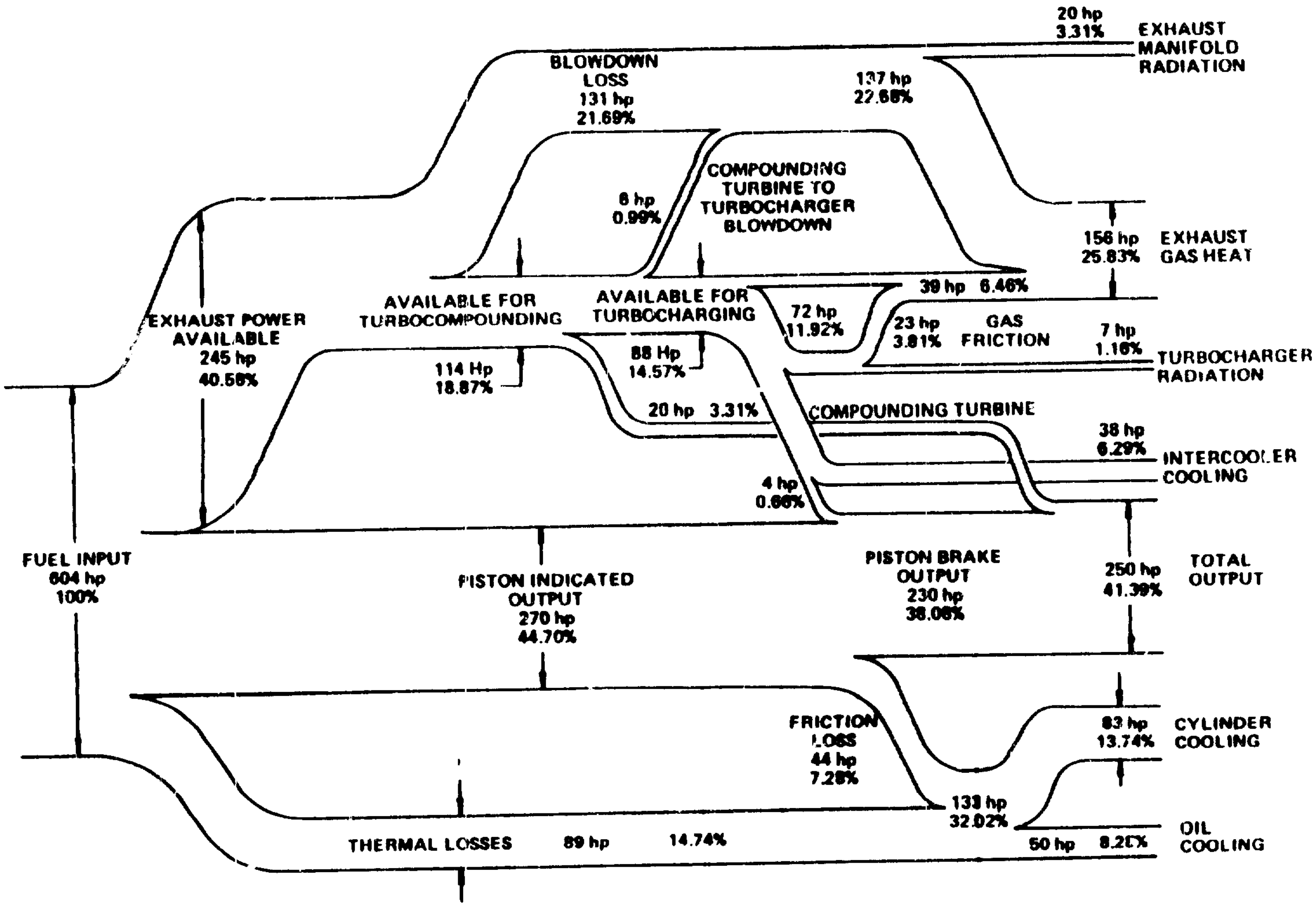


Figure 10. High Risk Technology Engine Power Balance, GTSIO-420/SC, Maximum Cruise at 25,000 ft.

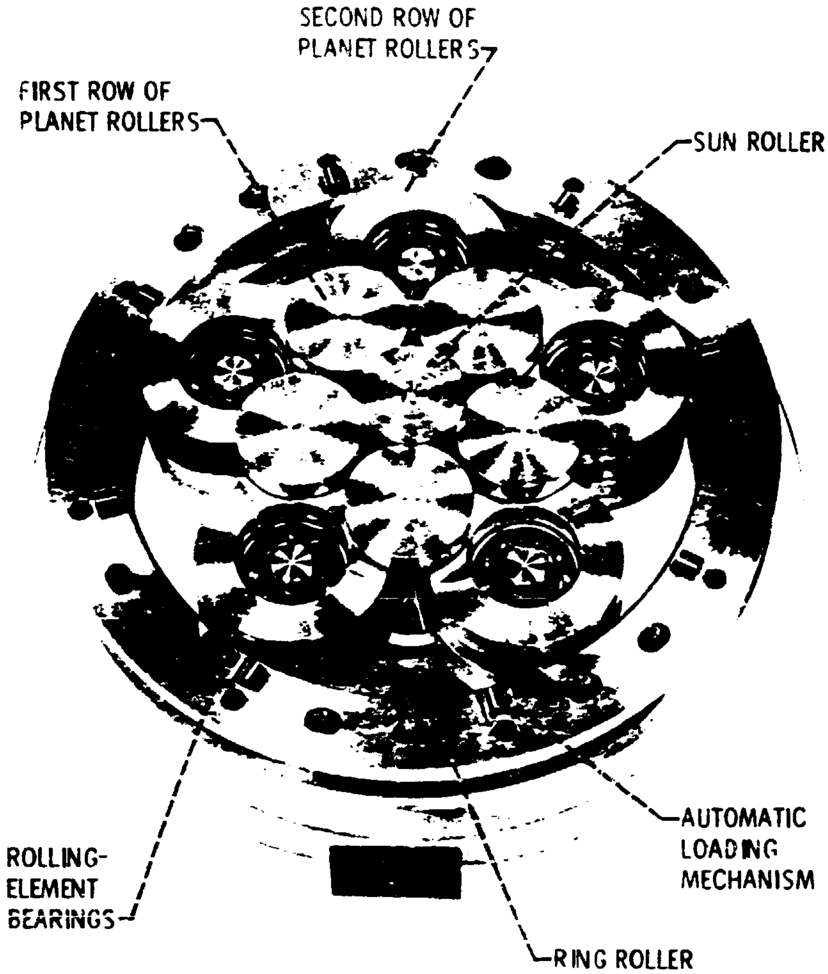


Figure 11. Basic Geometry of a Nasvytis Multiroller Traction Drive.

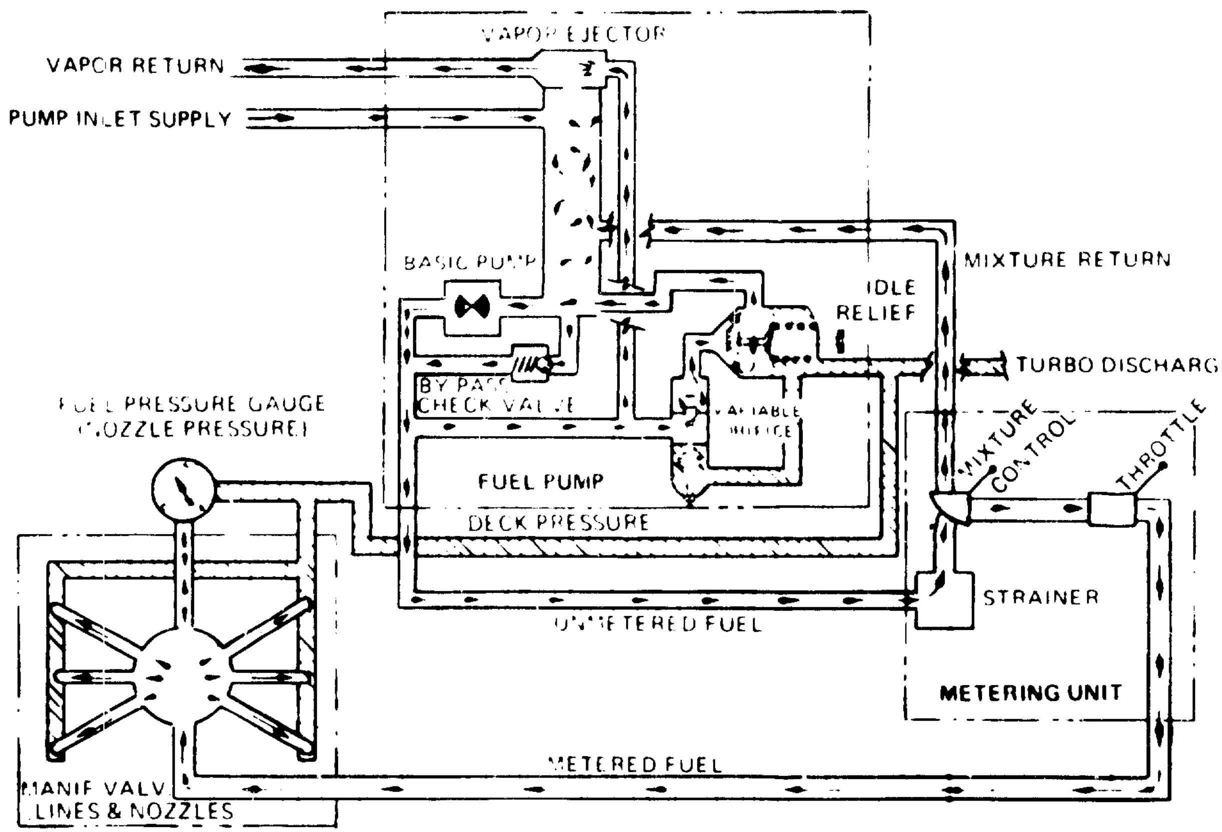


Figure 12. TCM Continuous Flow, Multipoint Fuel Injection System Schematic.

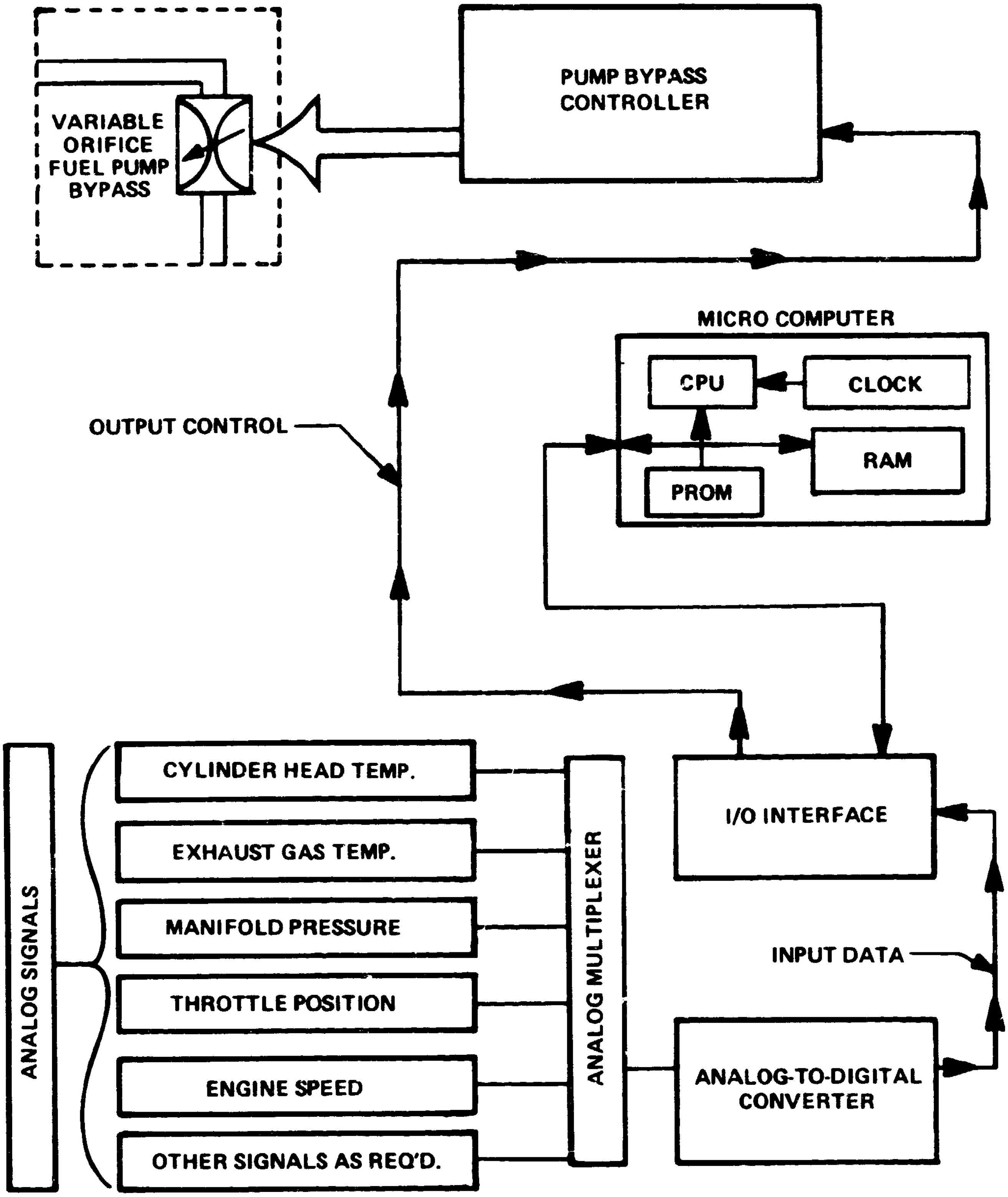
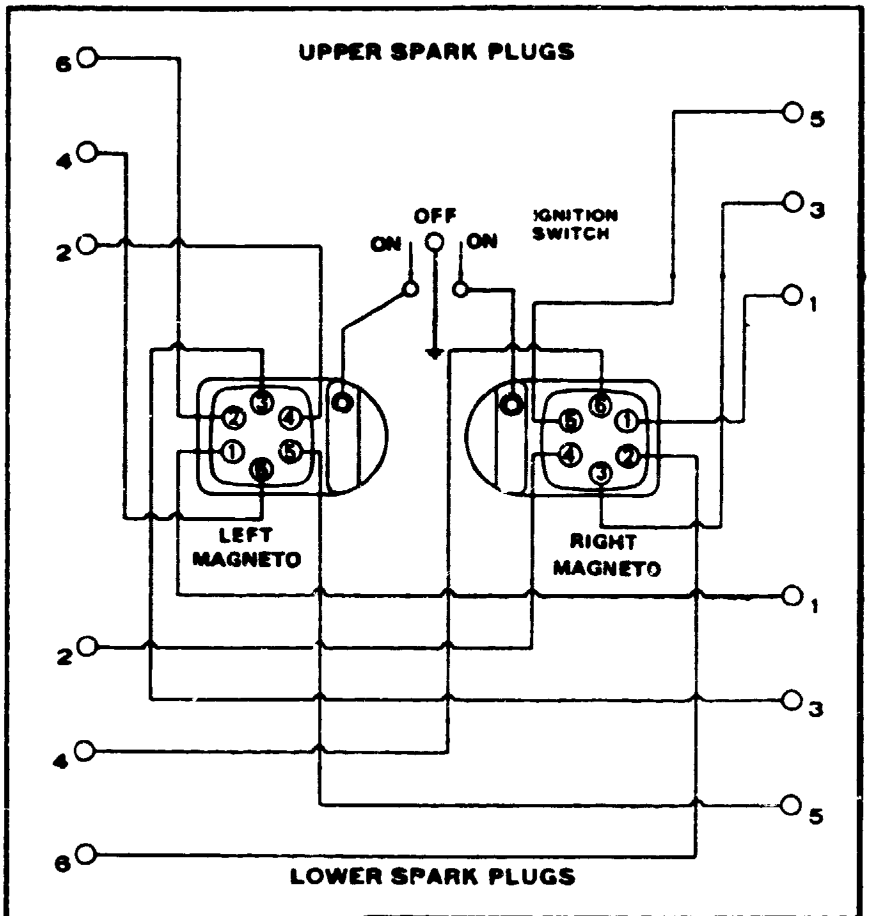


Figure 13. Schematic of Possible Electronic Fuel Control System as Applied to the TCM Continuous Flow Fuel Injection System.



ENGINE FIRING ORDER	1	6	3	2	5	4
MAGNETO FIRING ORDER	1	2	3	4	5	6

Figure 14. Magneto Ignition System Schematic for Six-Cylinder Aircraft Piston Engine.

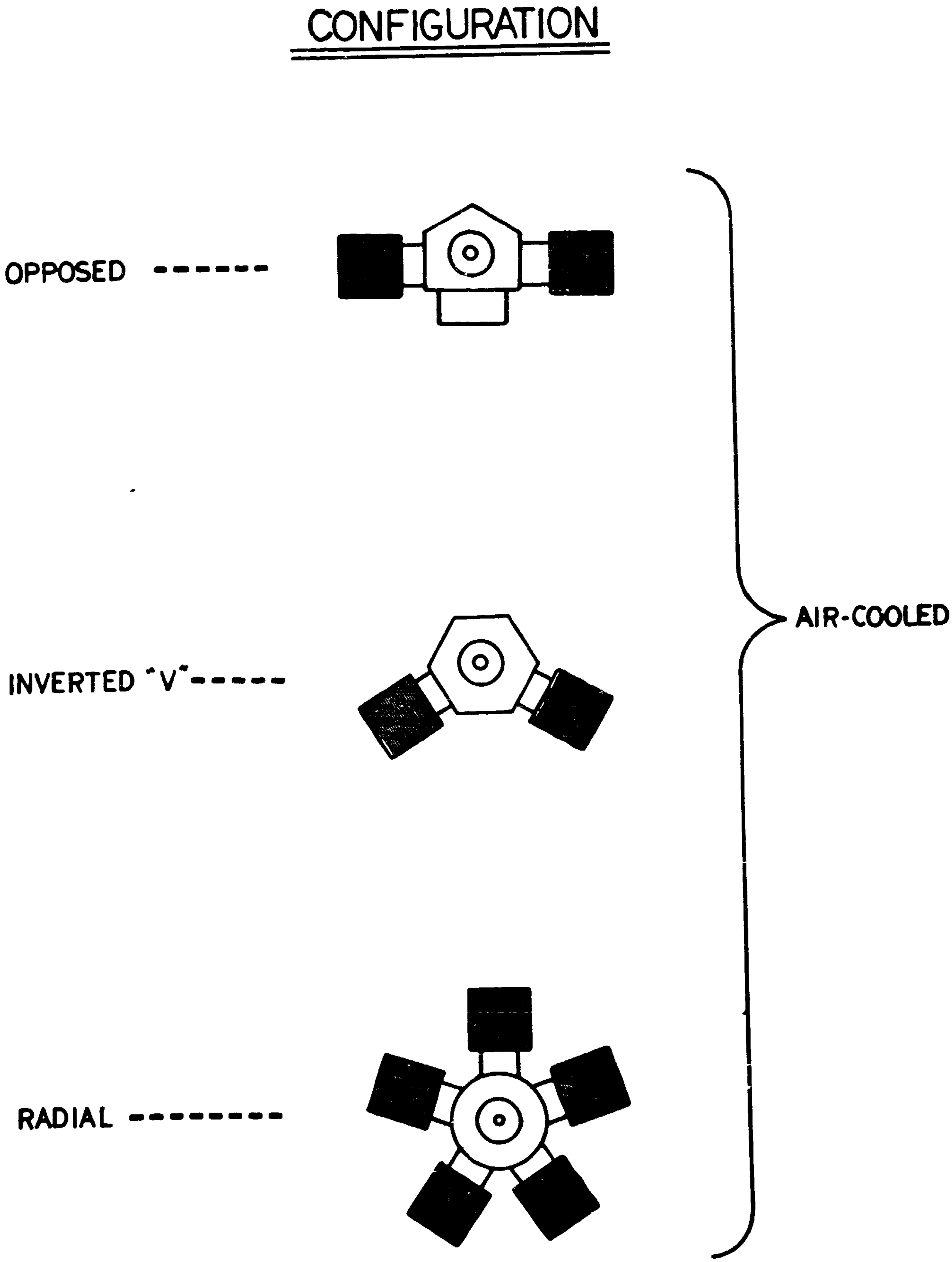
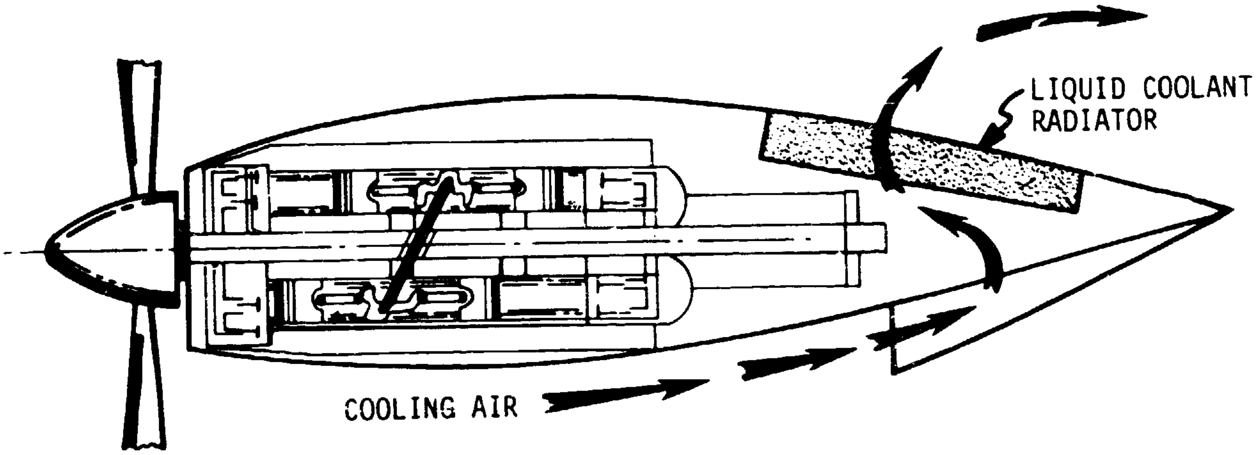
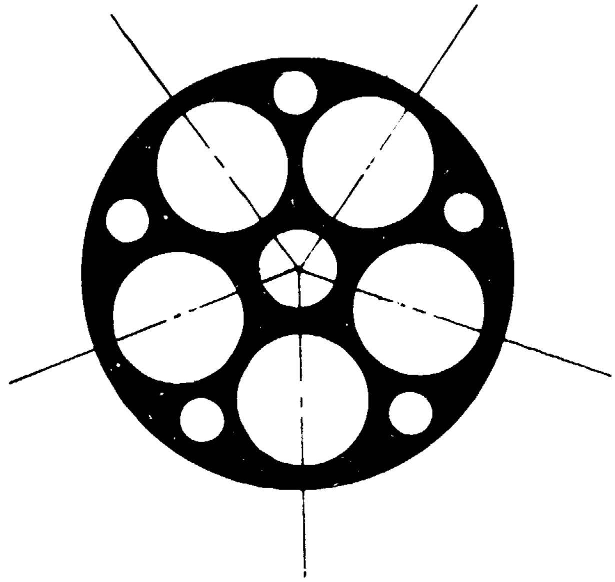


Figure 15. Air-Cooled, Horizontally Opposed, Inverted "V," and Radial Configurations.



SIDE VIEW OF ENGINE INSTALLATION



FRONT VIEW CROSS SECTION OF CYLINDER HOUSING

Figure 16. Liquid-Cooled, 10-Cylinder Swashplate Configuration.

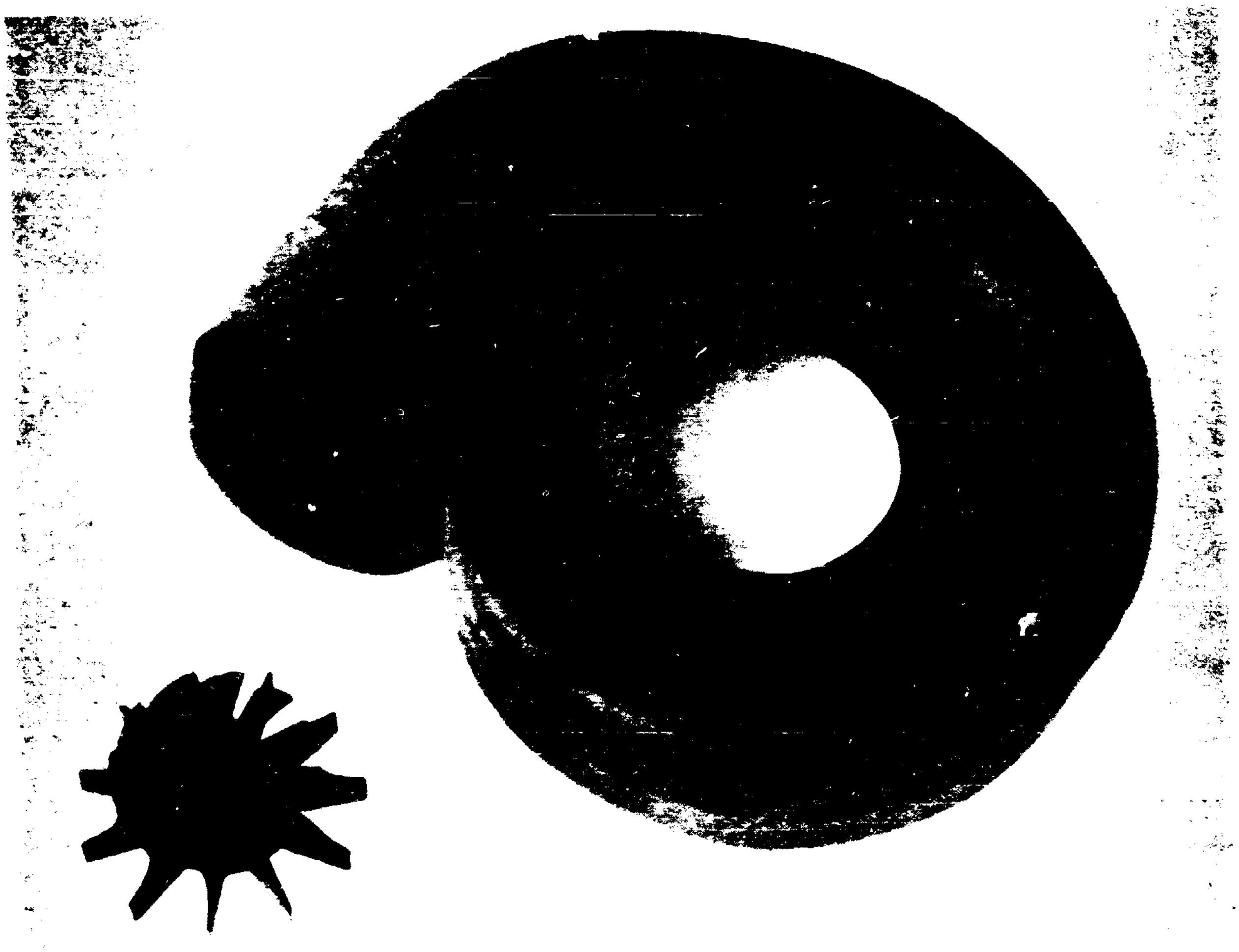


Figure 17. Alpha Silicon Carbide Turbine Wheel and Scroll Housing.

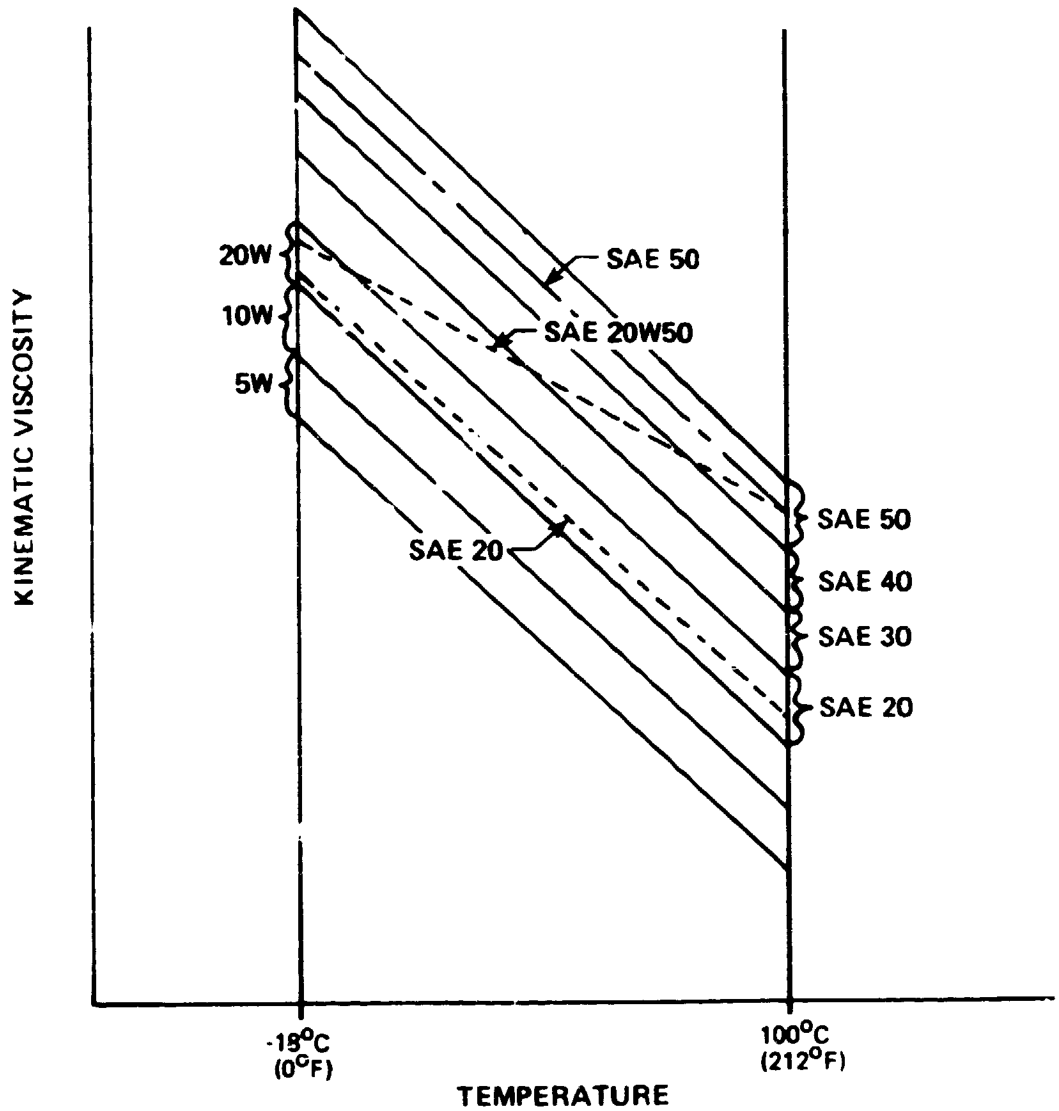


Figure 18. Viscosity Variation of Engine Lubricants with Temperature.

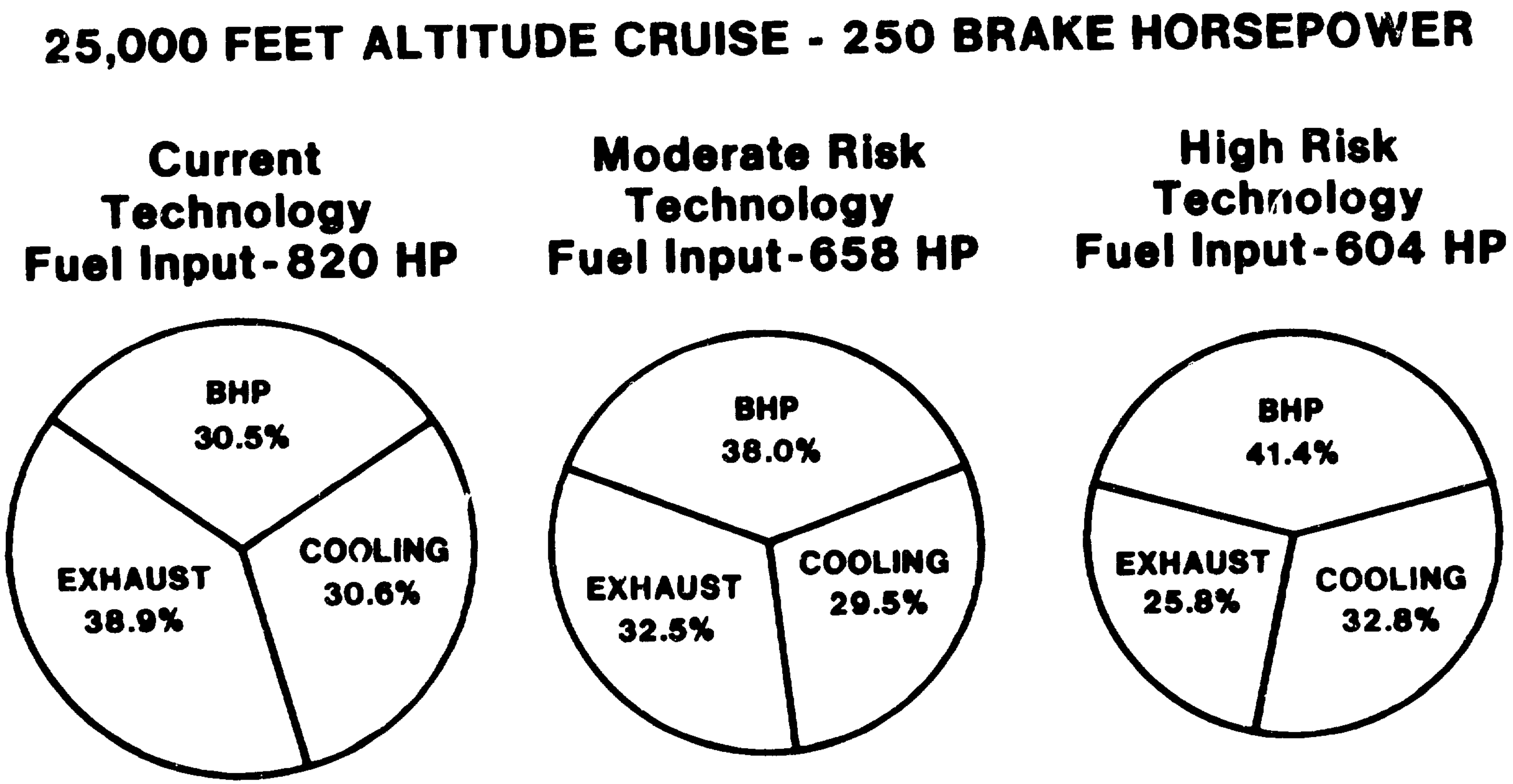


Figure 19. Power Balance Comparison.

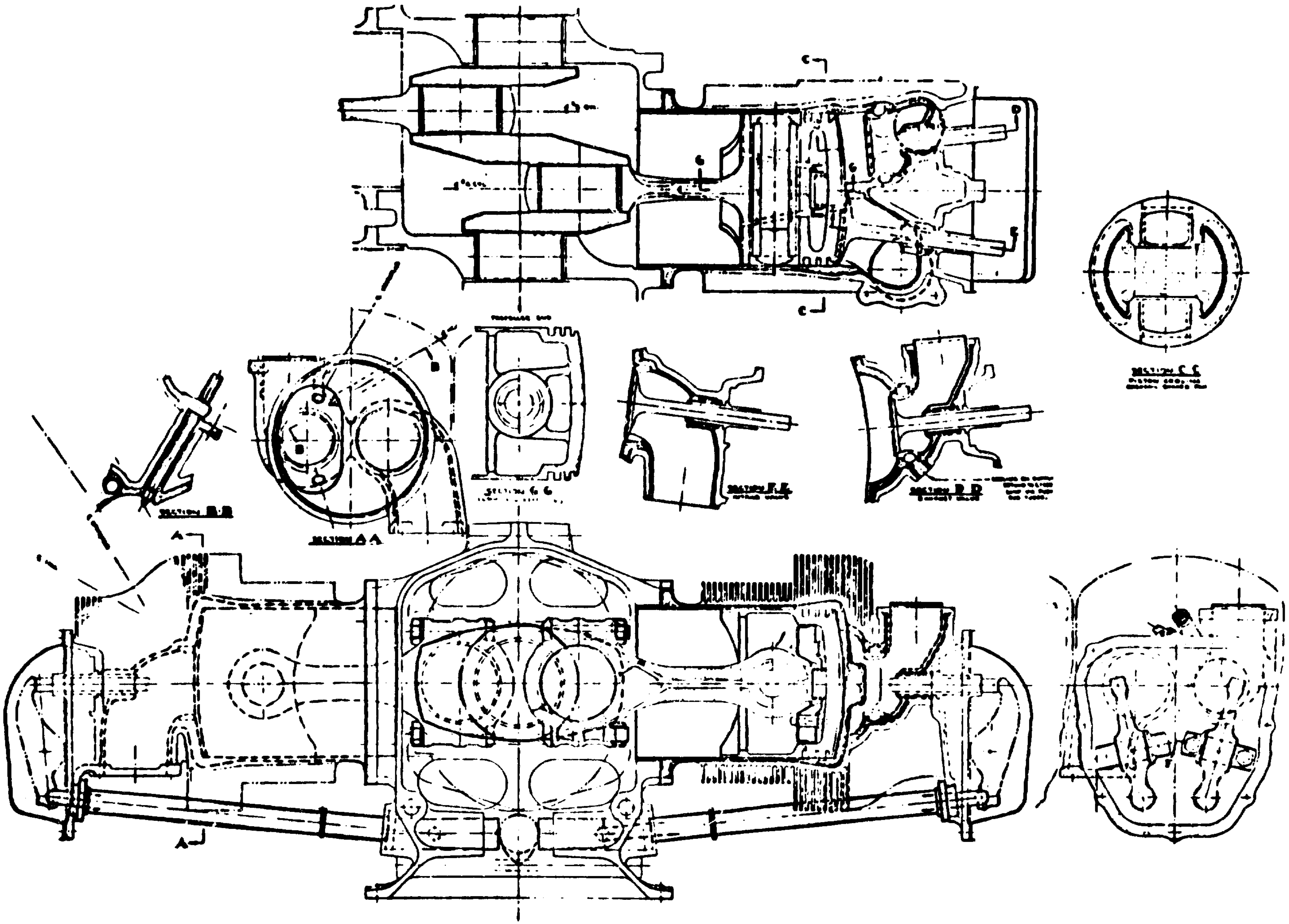


Figure 20. Cross Sectional Views of the High Risk Technology Engine.

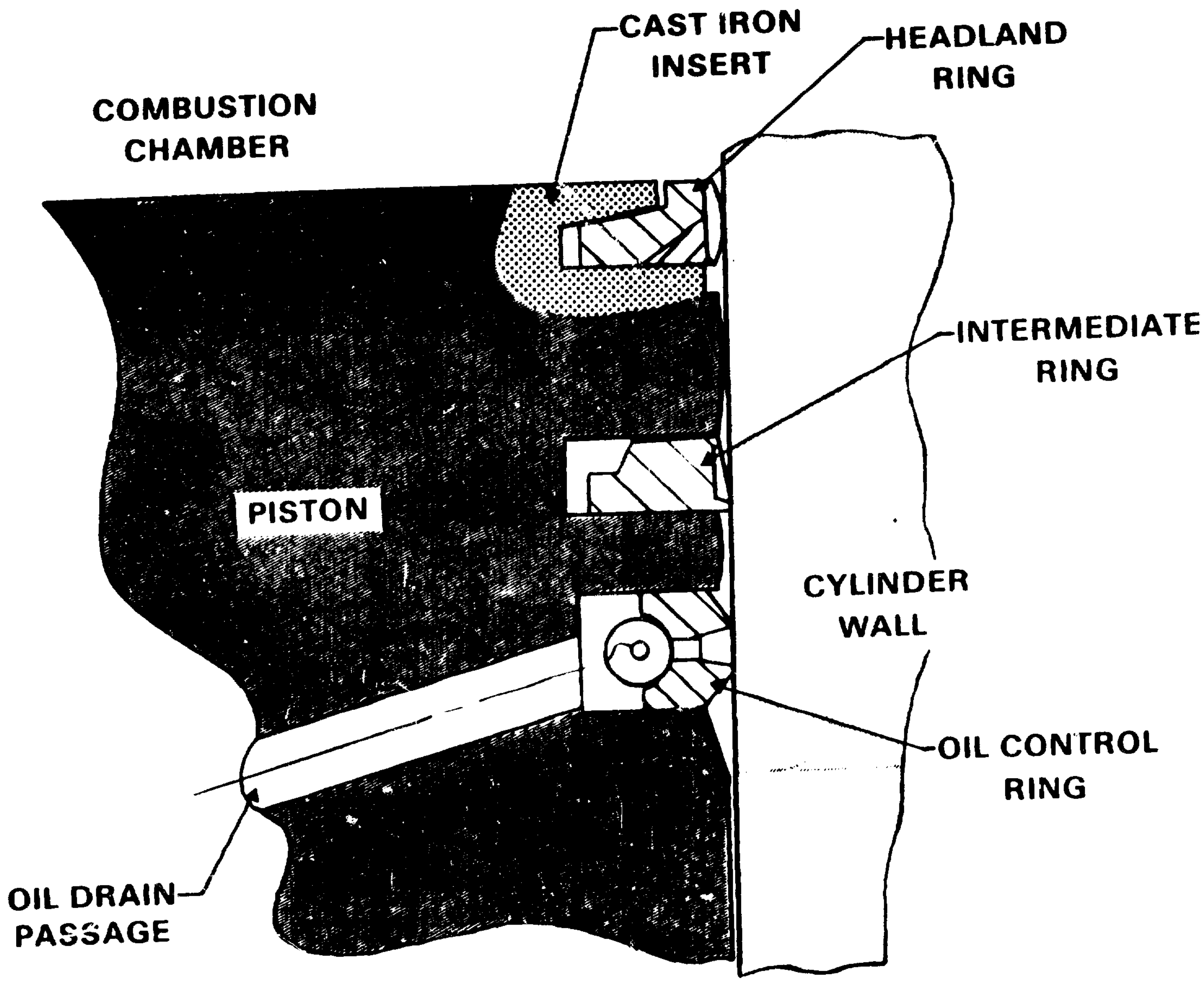


Figure 21. Koppers Company Piston Ring Package Design.

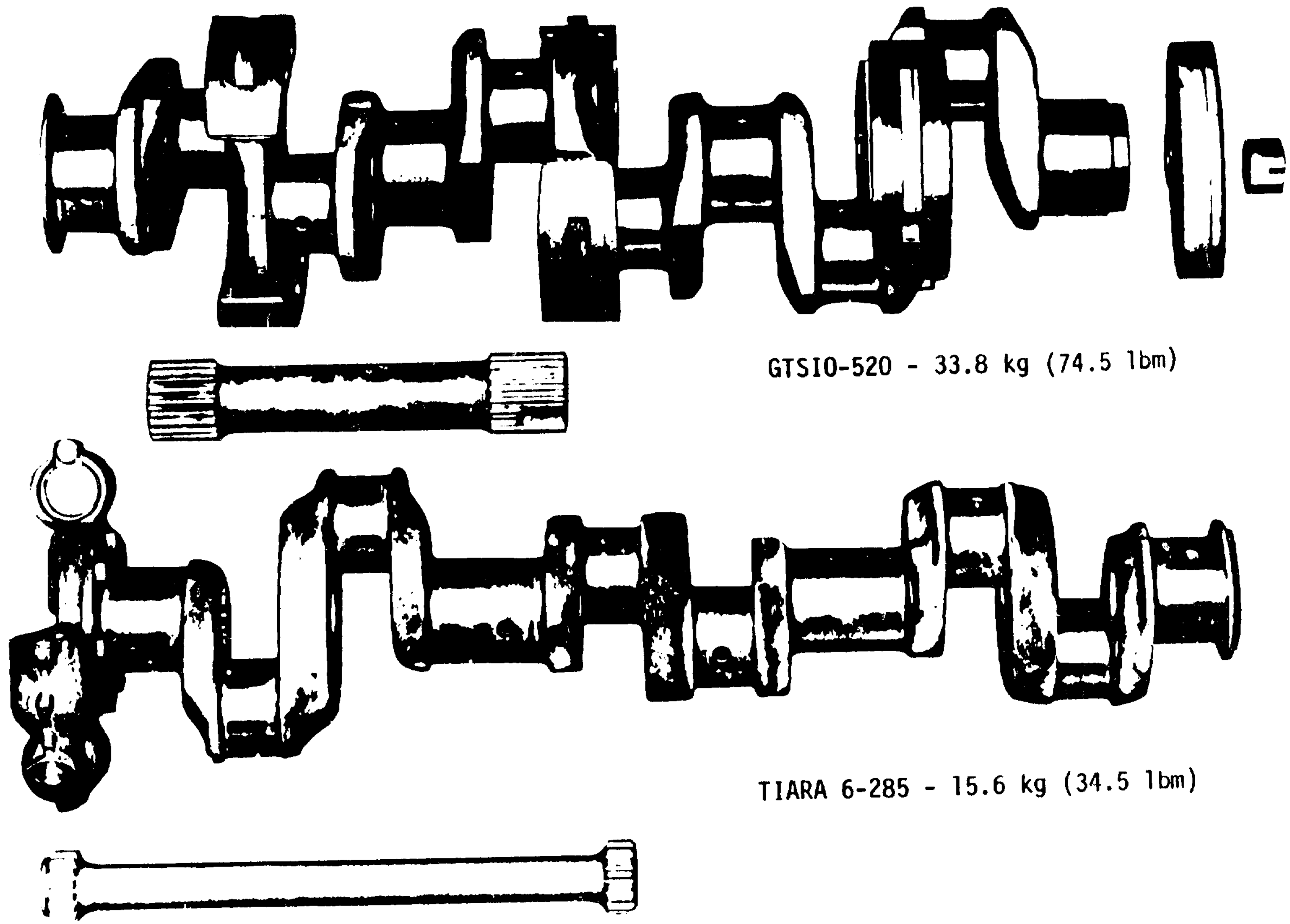


Figure 22. Comparison of GTSIO-520 Crankshaft with Tiara 6-285 Crankshaft.

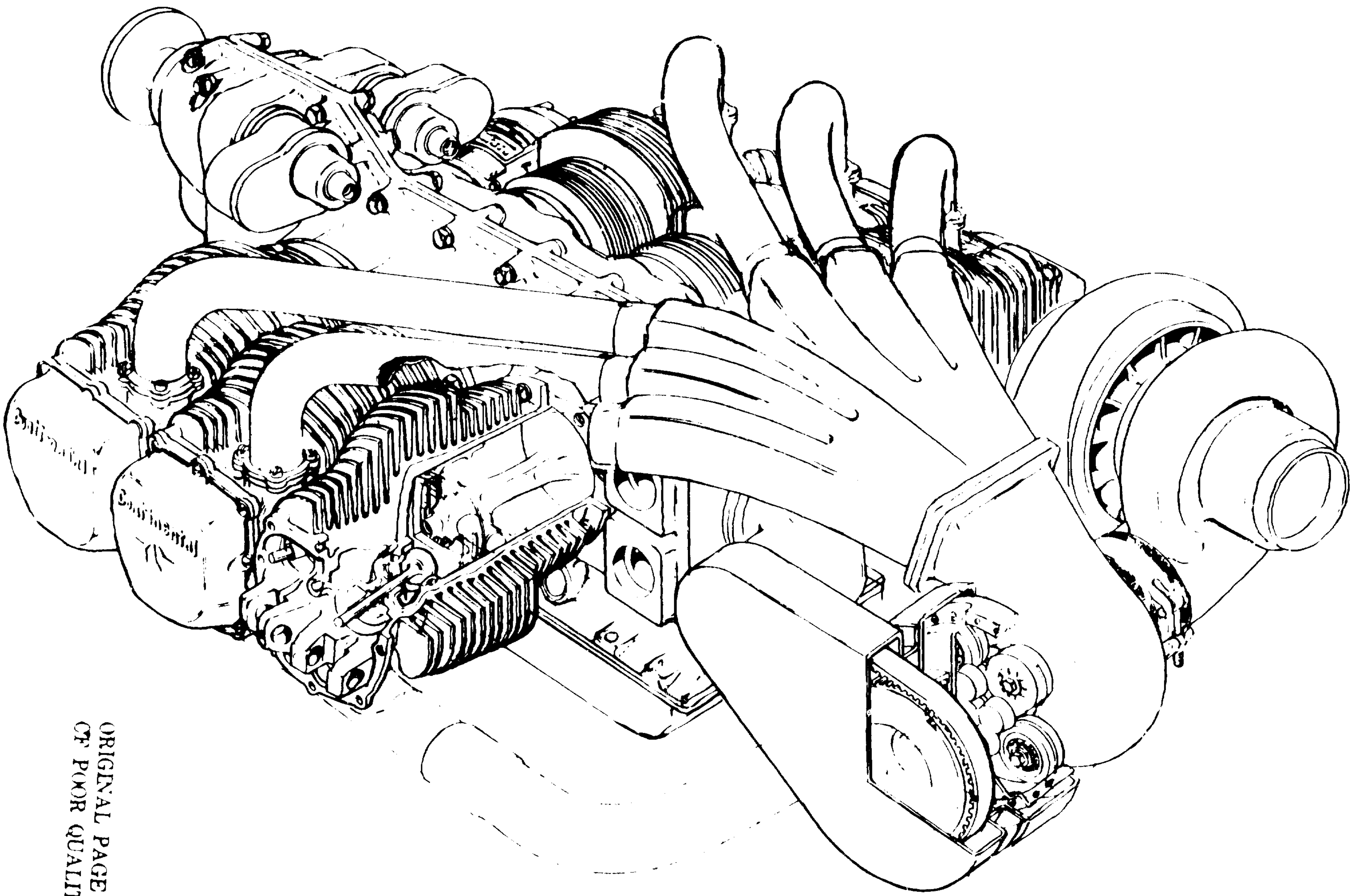
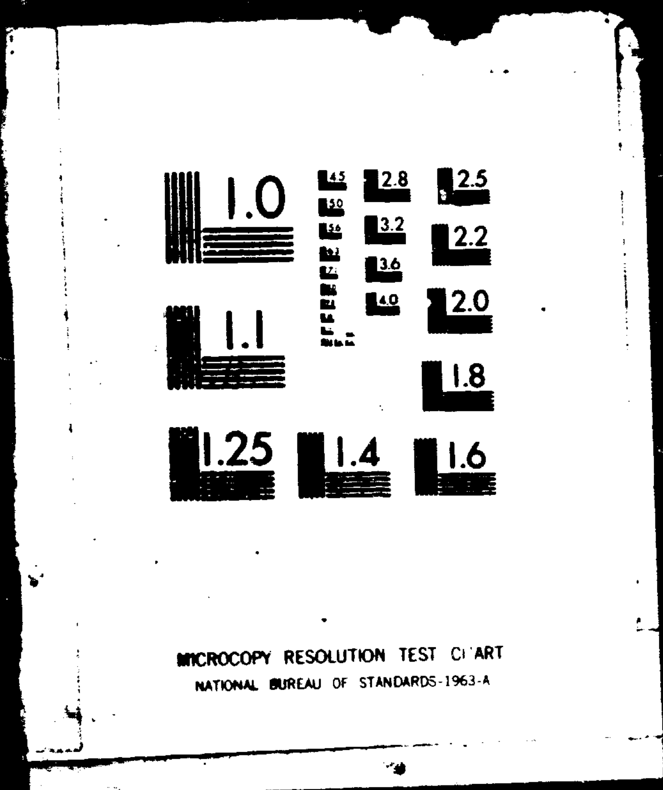


Figure 23. Artist's Conception of High Risk Technology Engine.

ORIGINAL PAGE IS
OF POOR QUALITY

2 OF 2

N81-3963



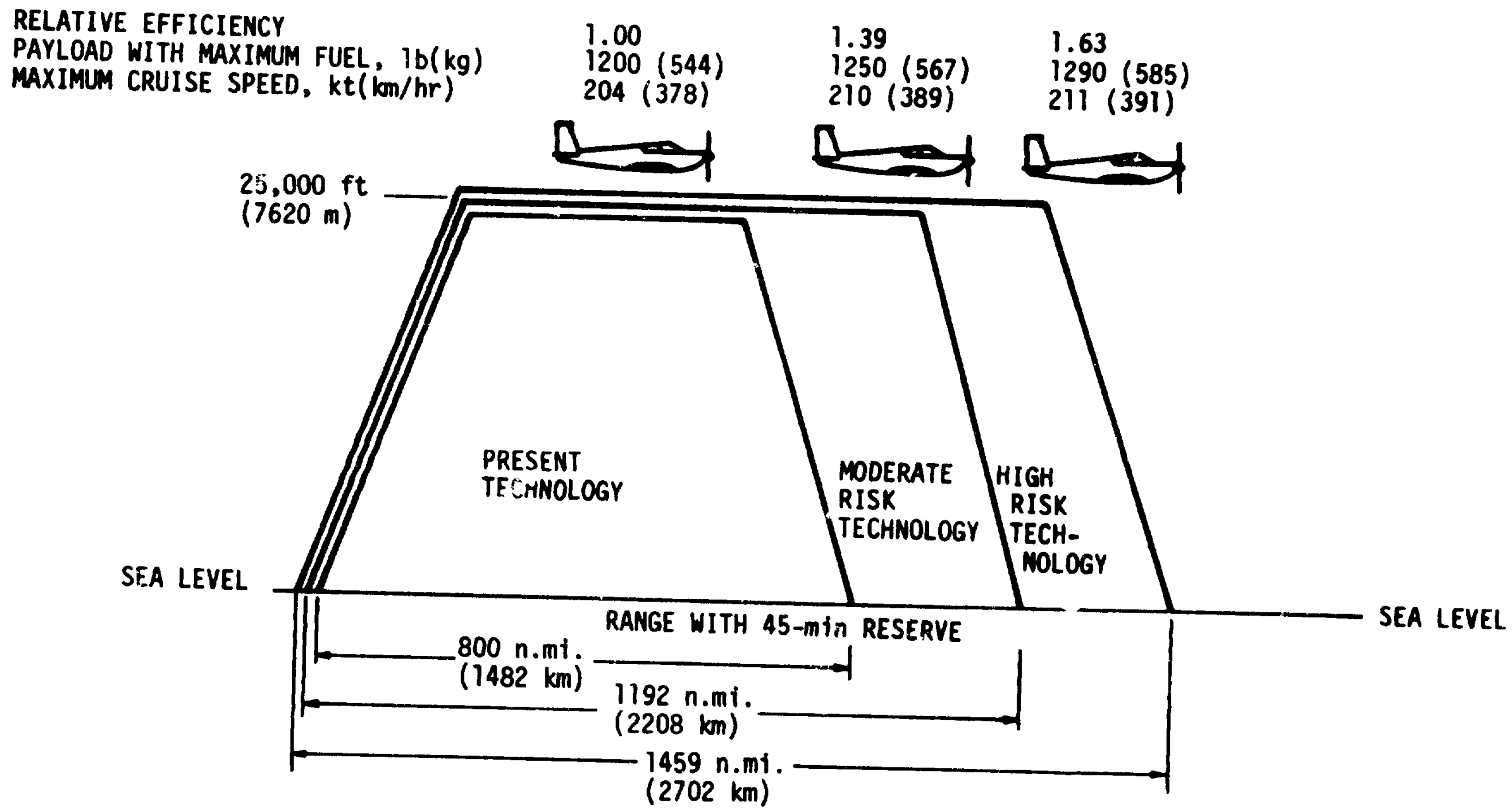


Figure 24. Comparison of Single-Engine Airplane Performance with Current Moderate Risk and High Risk Technology Engines.

C-2

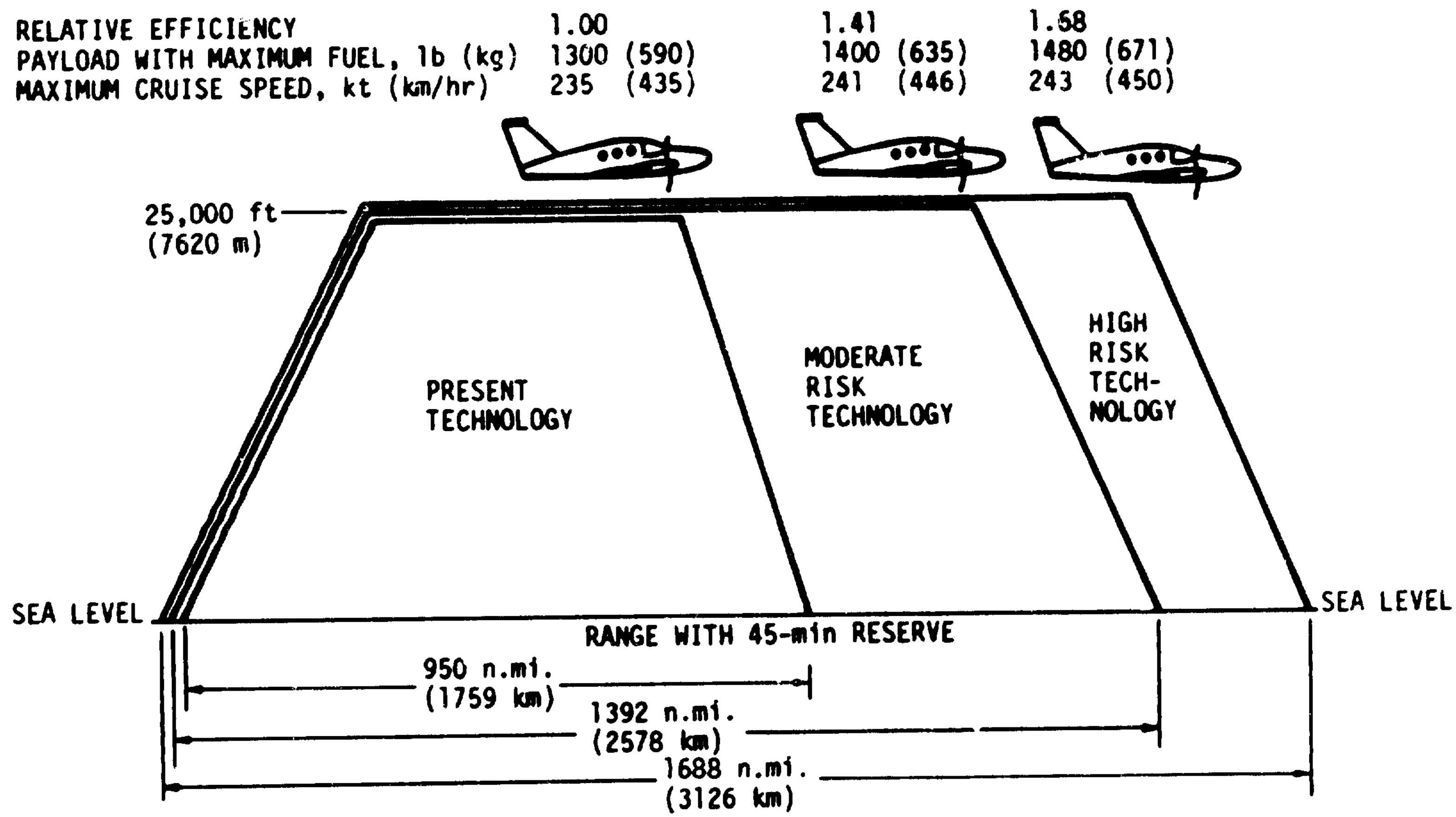


Figure 25. Comparison of Twin-Engine Airplane Performance with Current Moderate Risk and High Risk Technology Engines.

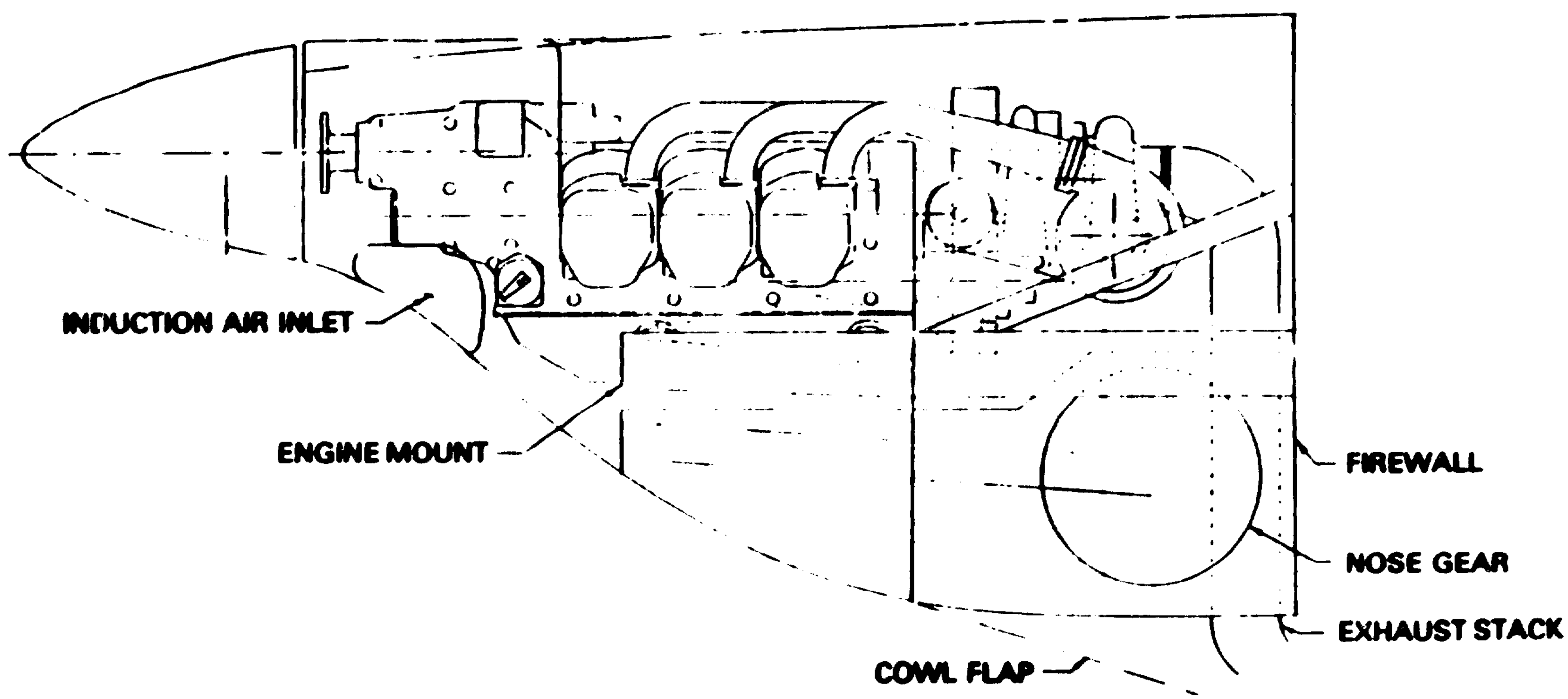


Figure 26. Engine/Airframe Integration -- Single-Engine Installation.

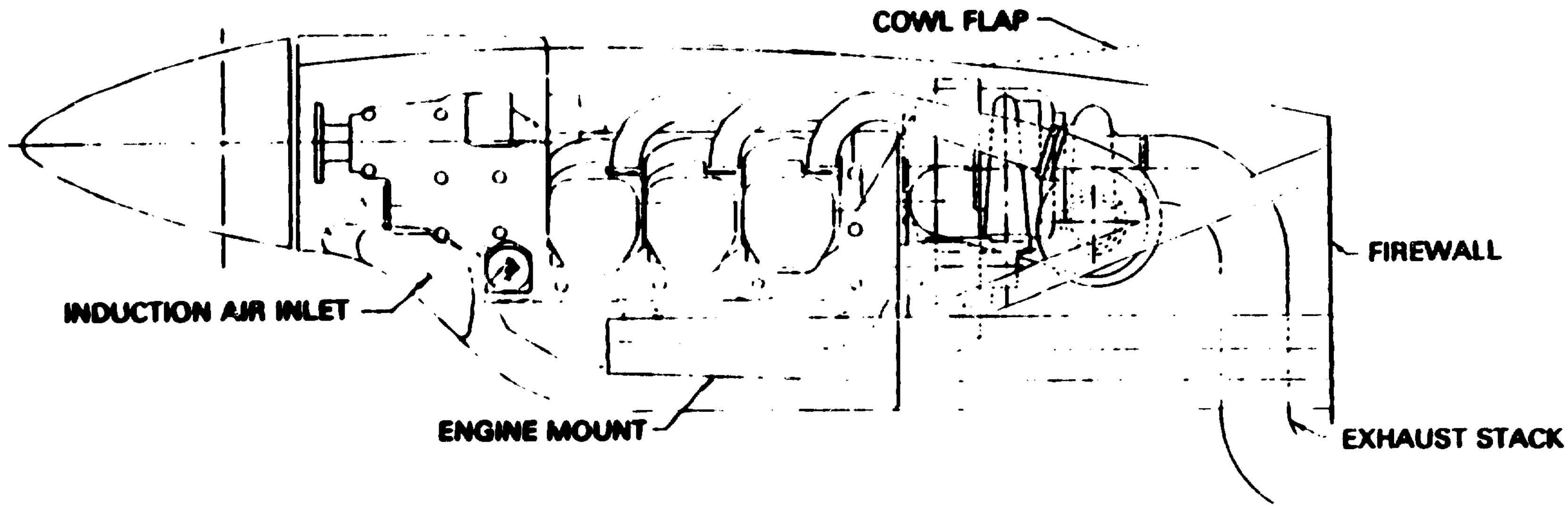


Figure 27. Engine/Airframe Integration -- Twin-Engine Installation.

MATERIAL

ENGINES

EQUIPMENT

STANDARD AVIONICS

AIRFRAME, $/lb × lb

TOTAL MATERIAL COST

LABOR

$\frac{hr}{lb} \times lb \times \frac{\$}{hr}$ LABOR COST

DEVELOPMENT

$\frac{\$}{lb} \times lb$ / NUMBER OF UNITS AMORTIZED DEVELOPMENT COST

TOTAL COST

FACTORY MARKUP

DEALER MARKUP

OPTIONS

UNIT SELLING PRICE

OR ACQUISITION COST

Figure 28. Factors Used in Determining Unit Selling Price.

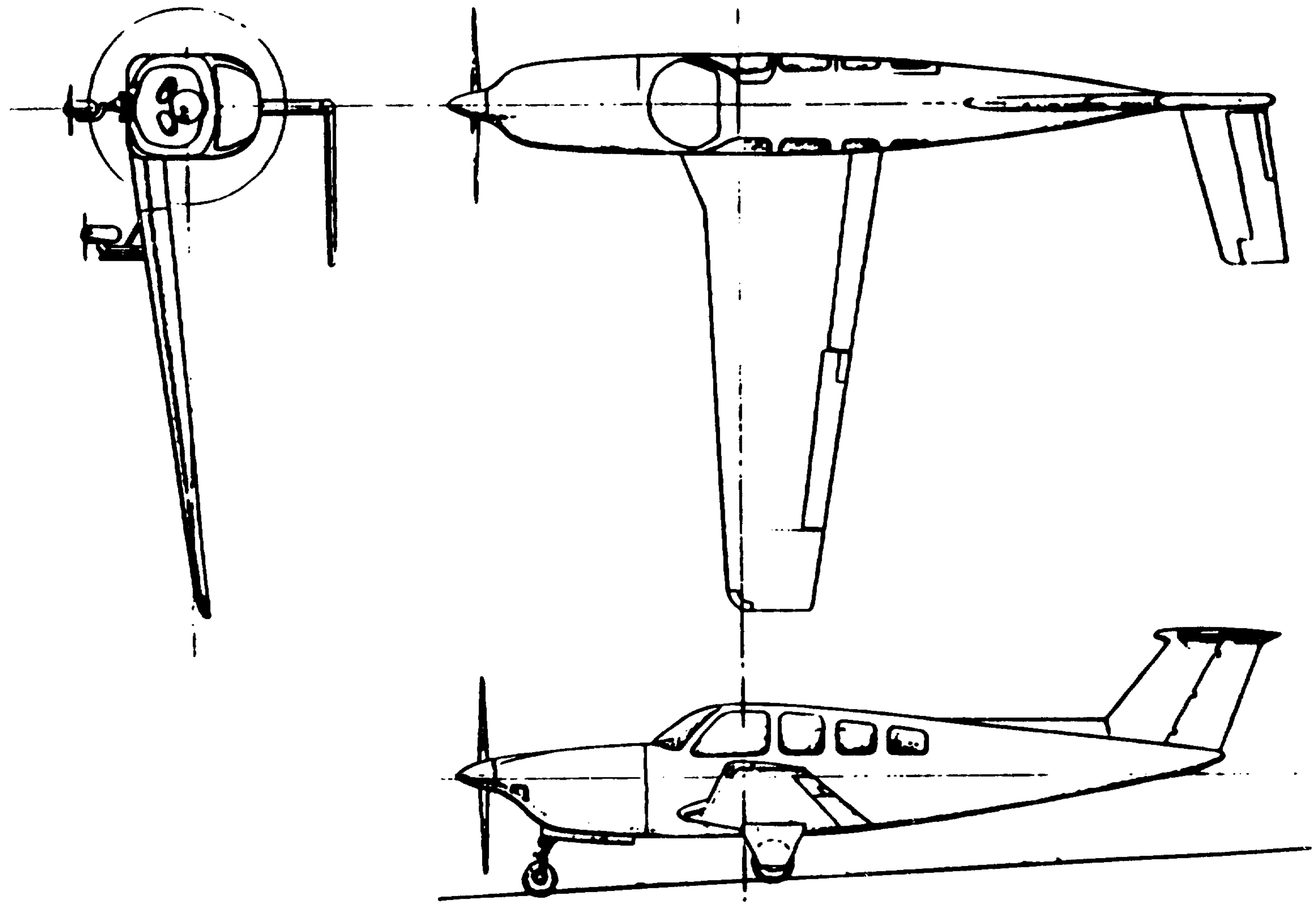


Figure 29. Single-Engine Airplane, Three-View Sketch.

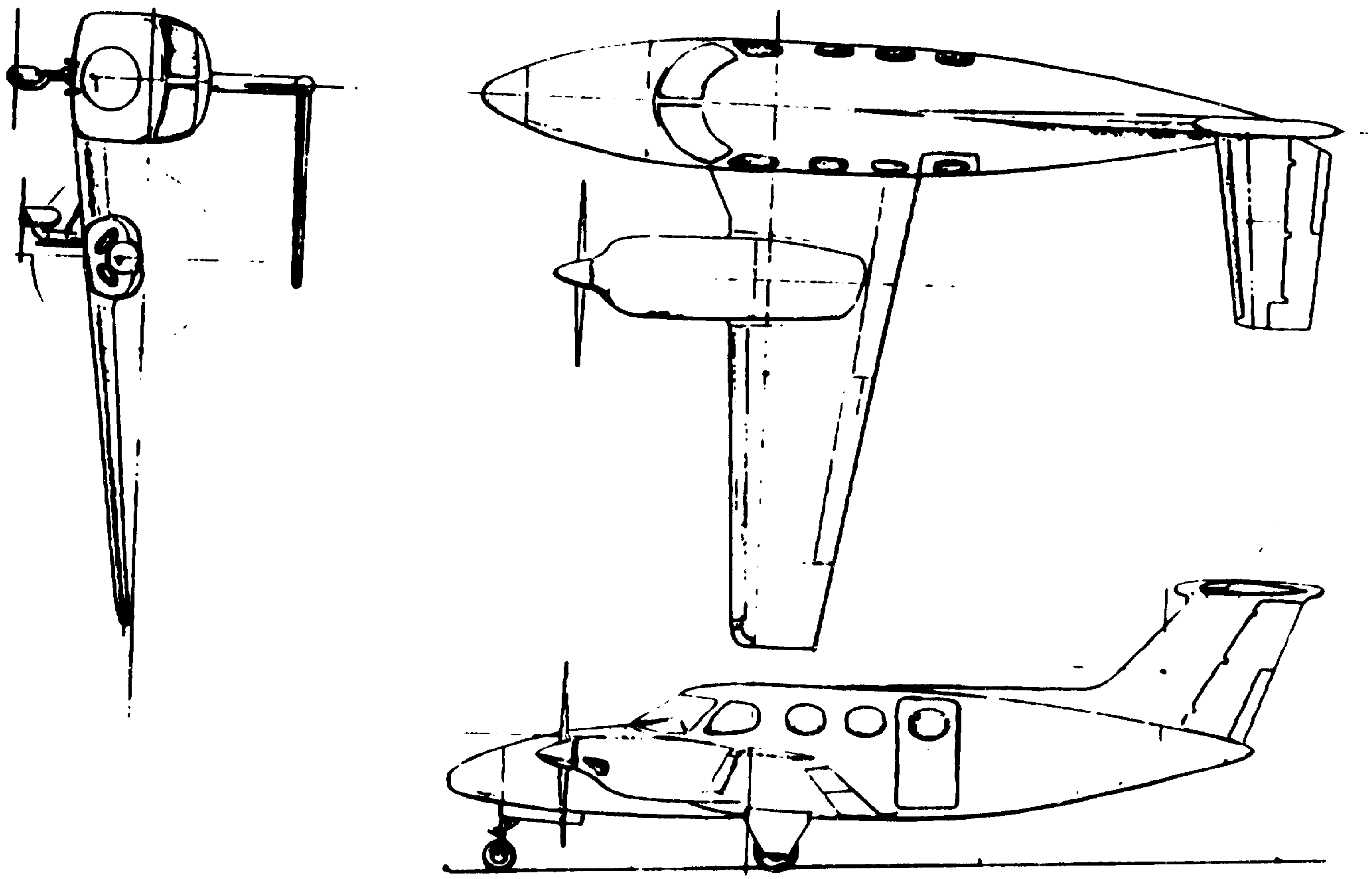


Figure 30. Twin-Engine Airplane, Three-View Sketch.

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE I. ADVANCED ENGINE DESIGN PROGRAM OUTLINE

TASK I – TECHNOLOGY ANALYSIS AND DESIGN CANDIDATE EVALUATION

- DEFINE EXPECTED TECHNOLOGY BASE FOR AN ENGINE DESIGNED FOR THE LATE 1[illegible] TIME PERIOD
- EVALUATE CANDIDATE ITEMS AND CHOOSE MOST LIKELY ADVANCED TECHNOLOGY
- RECOMMEND NEW TECHNOLOGY PROGRAMS

TASK II – ENGINE CONCEPTUAL DESIGN

- DESIGN CANDIDATE ENGINES
- CALCULATE ENGINE GEOMETRIC AND PERFORMANCE PARAMETERS

TASK III – ENGINE/AIRFRAME DESIGN INTEGRATION

- PERFORMANCE ANALYSIS OF ADVANCED ENGINE/ADVANCED AIRFRAME COMBINATION
- PAPER STUDY COMPARISON OF PERFORMANCE IMPROVEMENT COMPARED TO PRESENT STATE-OF-THE-ART

TASK IV – NEW TECHNOLOGY PROGRAM RECOMMENDATIONS

- IDENTIFY NEW TECHNOLOGY ITEMS WITH MOST SIGNIFICANT PAYOFF
- DISCUSS EXTENT TO WHICH NEEDS ARE MET BY ONGOING NEW TECHNOLOGY PROGRAMS
- PREPARE DEVELOPMENT SCHEDULE REQUIRED TO BRING EXPECTED NEW TECHNOLOGY TO THE POINT OF COMMERCIAL PRODUCTION

TABLE II. ADVANCED TECHNOLOGY BASE HIERARCHICAL STRUCTURE

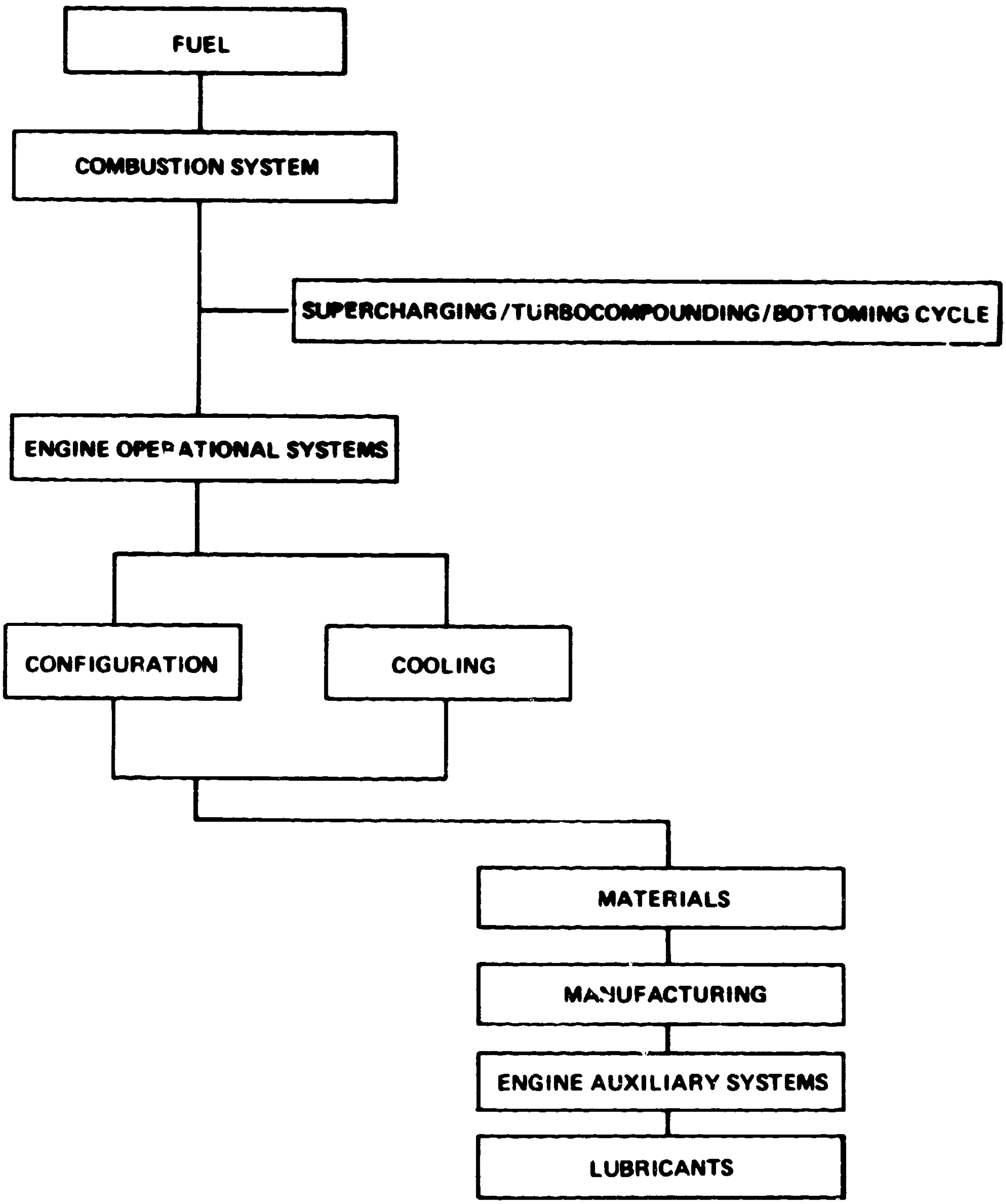


TABLE III. GOVERNMENT LEGISLATION PERTAINING TO OIL INDUSTRY

1926	OIL DEPLETION ALLOWANCE - A 22% flat-rate deduction that applies to both domestic and foreign oil wells. (2)
1931	DEMAND PRORATIONING - The oil boom caused excess oil on the market, which drove the price down to 10¢ per barrel. Demand prorationing limits the production of oil to that quantity which can be sold at a profitable price. (2)
Post-1945	FOREIGN TAX CREDITS - Relating to the Persian Gulf discoveries after World War II, the foreign tax credit allows oil companies to subtract foreign taxes (royalties) in total from their U.S. tax bill. (2)
1959	IMPORT QUOTAS - Foreign oil was cheaper by about $1.50 per barrel. Import quotas reduced the amount of imported oil. It became more economically feasible to build new refineries abroad where there was no import quota. The result was a shortage of U.S. refining capacity. (2)
1971	FEDERAL PRICE CONTROLS (2)
1975	ENERGY POLICY AND CONSERVATION ACT - Phased decontrol of oil price controls and mandatory energy efficiency standards. (8)
1975	REVISED OIL DEPLETION ALLOWANCE - The Oil Depletion Allowance ended in 1975 for all but independent oil companies and leaseholders.
1978	NATIONAL ENERGY ACT - A five-segment plan that deals with reduction of energy use and promotes the use of alternate energy sources. The purpose of the plan is to reduce U.S. dependence on foreign oil. (8)
1979	CRUDE OIL DEREGULATION - Deregulation of crude oil with "windfall profits" taxed at 70 to 90%. About 15% of windfall profit taxes collected by the Federal Government to go toward research and development of alternate sources of energy. (6)
1980	ALTERNATE FUEL RESEARCH AND DEVELOPMENT - Initial $200 million awarded by Department of Energy for feasibility studies and co-op agreements for coal liquefaction, gasification, alcohol and other biomass fuels, coal-oil mixture, and municipal waste.

TABLE IV. COMPARISON OF TANKAGE PROPERTIES OF FUELS

	CHEMICAL COMPOSITION	STORAGE PRESSURE kPa	(psig)	STORAGE TEMPERATURE °C	(°F)	DENSITY kg/ℓ	(lbm/gal)	(LHV) ENERGY DENSITY kJ/kg	(Btu/lbm)	kJ/L	(Btu/gal)	AMOUNT EQUIVALENT TO 227 liters (60 gal) AVGAS liters	(gal)	kg	(lbm)	FUEL + TANK kg	(lbm)	MOTOR OCTANE (CETANE) (Minimum)
100LL AVGAS	C_4-C_{10}	0	(0)	15.5	(60)	0.70	(5.85)	43,540	(18,720)	30,524	(109,512)	227	(60.00)	159	(351.0)	173	(381.0)	100
UNLEADED PREMIUM	C_4-C_{10}	0	(0)	15.5	(60)	0.70	(5.86)	44,377	(19,080)	31,165	(111,809)	222	(58.77)	156	(344.4)	170	(374.4)	92
METHANE GAS	CH_4	13,790	(2,000)	15.5	(60)	0.11	(0.948)	50,006	(21,500)	5,679	(20,376)	1,221	(322.50)	139	(305.7)	382	(841.2)	105
LIQUID PROPANE	C_3H_8	690	(100)	15.5	(60)	0.51	(4.25)	46,284	(19,900)	23,582	(84,605)	294	(77.66)	150	(330.1)	177	(390.1)	97
METHANOL	CH_3OH	0	(0)	15.5	(60)	0.80	(6.64)	20,095	(8,640)	16,002	(57,411)	433	(114.45)	345	(759.9)	358	(788.9)	90
ETHANOL	C_2H_5OH	0	(0)	15.5	(60)	0.79	(6.63)	26,863	(11,550)	21,350	(76,597)	325	(85.78)	258	(568.7)	272	(598.7)	89
LIQUID HYDROGEN	H_2	0	(0)	-253	(-423)	0.71	(0.592)	120,897	(51,980)	8,571	(30,751)	809	(213.68)	57	(126.5)	285	(629.0)	-
HYDROGEN GAS	H_2	13,790	(2,000)	15.5	(60)	0.01	(0.089)	120,897	(51,980)	1,291	(4,633)	5,368	(1,418.24)	57	(126.2)	472	(1,040.0)	-
METAL HYDRIDE HYDROGEN	$Mg_2Ni \cdot H_x$	0	(0)	15.5	(60)	1.77	(14.75)	10,117	(4,350)	17,[illegible]4	(64,163)	388	(102.41)	685	(1,510.5)	800	(1,763.0)	
JET A (KEROJET)	C_{10}-C_{15}	0	(0)	15.5	(60)	0.81	(6.75)	42,795	(18,400)	34,618	(124,200)	200	(52.90)	162	(357.1)	176	(387.1)	(40)
JP-4 (NAPHTHA BASE)	C_6-C_{14}	0	(0)	15.5	(60)	0.77	(6.46)	42,795	(18,400)	33,131	(118,864)	209	(55.28)	162	(357.1)	176	(387.1)	-
JP-5	C_{10}-C_{18}	0	(0)	15.5	(60)	0.82	(6.82)	42,563	(18,300)	34,787	(124,800)	199	(52.66)	163	(359.1)	176	(387.1)	(40)
JP-6		0	(0)	15.5	(60)	0.81	(6.80)	42,795	(18,400)	34,875	(125,120)	199	(52.52)	162	(357.1)	176	(387.1)	-
DIESEL FUEL 1-D	C_{10}-C_{26}	0	(0)	15.5	(60)	0.90	(7.47)	43,903	(18,876)	39,301	(141,000)	176	(46.60)	158	(348.1)	172	(378.1)	(40)
DIESOLINE	C_5-C_{26}	0	(0)	15.5	(60)	0.84	(7.00)	42,563	(18,300)	36,235	(130,000)	191	(50.54)	160	(353.8)	174	(383.8)	-

TABLE V. ESTIMATED AVERAGE 1976 YIELD FROM A BARREL OF CRUDE OIL

PRODUCT	% YIELD
GASOLINE	44.4
DISTILLATE FUEL OIL	21.3
RESIDUAL FUEL OIL	10.0
JET FUEL	6.6
STILL GAS	3.6
PETROCHEMICAL FEEDSTOCKS	3.2
ASPHALT	2.7
COKE	2.5
LIQUIFIED GASES	2.4
LUBRICANTS	1.3
KEROSENE	1.1
SPECIAL NAPHTHAS	0.7
ETHANE (INCLUDING ETHYLENE)	0.1
WAX	0.1
	100.0

SOURCE: Percentage Yield, U.S. Bureau of Mines

TABLE VI. ADVANCED MATERIALS FOR ENGINE WEIGHT REDUCTION

	MISCELLANEOUS MATERIALS kg	(lb)	STEEL kg	(lb)	ALUMINUM kg	(lb)	ADVANCED MATERIALS* kg	(lb)	TOTAL ENGINE WEIGHT kg	(lb)	PERCENT (%) WEIGHT REDUCTION
CURRENT 350 hp TSIO-550 ENGINE	3.6	(8)	151	(332)	111	(245)	-	-	265	(585)	0
MODERATE RISK TECHNOLOGY ENGINE	3.2	(7)	115	(253)	98	(215)	4.5	(10)	220	(485)	17
HIGH RISK TECHNOLOGY ENGINE	2.7	(6)	36	(80)	91	(200)	54	(119)	184	(405)	31

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

TABLE VII. ADVANCED ENGINE SPECIFICATIONS

	CURRENT TECHNOLOGY TSIO-550	PERCENT DIFFERENCE FROM CURRENT TECHNOLOGY	MODERATE RISK TECHNOLOGY GTSIO-420	PERCENT DIFFERENCE FROM CURRENT TECHNOLOGY	HIGH RISK TECHNOLOGY GTSIO-420/SC
CONFIGURATION	SIX-CYLINDER HORIZONTALLY OPPOSED	-	SIX-CYLINDER HORIZONTALLY OPPOSED	-	SIX-CYLINDER HORIZONTALLY OPPOSED
ENGINE DISPLACEMENT liters (in^3)	9.0 (550)	-24%	6.9 (420)	-24%	6.9 (420)
MAXIMUM RATED BRAKE* POWER/ENGINE SPEED kW (hp)/RPM	261 (350)/2800	-	261 (350)/3200	-	261 (350)/3200
MAXIMUM PROPELLER RPM	2800	-14%	2400	-14%	2400
MAXIMUM CRUISE BRAKE POWER/PROPELLER SPEED kW (hp)/RPM	186 (250)/2300	-	186 (250)/2150	-	186 (250)/2150
MAXIMUM CRUISE BSFC kg FUEL/kW-hr (lbm FUEL/hp-hr)	0.271 (0.446)	-20%	0.218/(0.358)	-26%	0.201/(0.331)
INSTALLED ENGINE** WEIGHT, kg (lbm)	265 (585)	-17%	220 (485)	-31%	184 (405)
FUEL TYPE	100 OCTANE	-	100 OCTANE	-	JET A
TIME BETWEEN OVERHAUL, hr	1400	+43%	2000	+43%	2000
EXHAUST ENERGY RECOVERY SYSTEM	TURBOCHARGING	-	TURBOCHARGING TURBOCOMPOUNDING	-	TURBOCHARGING TURBOCOMPOUNDING
EXHAUST POWER UNRECOVERED AT MAXIMUM CRUISE POWER kW (hp)	238 (319)	-33%	160 (214)	-51%	116 (156)

*ALL POWER AND SFC VALUES ARE BASED ON ACTUAL PROPELLER SHAFT OUTPUT, TAKING ACCESSORY AND CABIN PRESSURIZATION LOSSES INTO ACCOUNT.

**WEIGHT INCLUDES ALL ACCESSORIES AND LUBRICANT, BUT NO PROPELLER

TABLE VIII. SINGLE-ENGINE AIRPLANE SPECIFICATIONS

	CURRENT TECHNOLOGY ENGINE TSIO-550	PERCENT DIFFERENCE FROM CURRENT TECHNOLOGY	MODERATE RISK TECHNOLOGY ENGINE GTSIO-420 (HOMOGENEOUS CHARGE)	PERCENT DIFFERENCE FROM CURRENT TECHNOLOGY	HIGH RISK TECHNOLOGY ENGINE GTSIO-420/SC (STRATIFIED CHARGE)
RATED SHAFT POWER, kW (hp)	261 (350)		261 (350)		261 (350)
TAKEOFF WEIGHT, kg (lb)	1935 (4267)		1935 (4267)		1935 (4267)
EMPTY WEIGHT, kg (lb)	1143 (2520)	-4%	1098 (2420)	-7%	1061 (2340)
FUEL WEIGHT, kg (lb)	248 (547)	+9%	271 (597)	+16%	289 (637)
PAYLOAD, kg (lb)	544 (1200)	+4%	567 (1250)	+8%	585 (1290)
USEFUL LOAD, kg (lb)	792 (1747)	+6%	838 (1847)	+10%	874 (1927)
71.4% POWER, 7620 m (25,000 ft)					
CRUISE SPEED, km/hr (kt)	378 (204)	+3%	389 (210)	+3%	391 (211)
RANGE, km (n.mi.)	1482 (800)	+49%	2208 (1192)	+82%	2702 (1459)
64.3% POWER, 9144 m (30,000 ft)					
CRUISE SPEED, km/hr (kt)			378 (204)		382 (206)
RANGE, km (n.mi.)			2282 (1232)		2839 (1533)
57.1% POWER, 10,668 m (35,000 ft)					
CRUISE SPEED, km/hr (kt)			343 (185)		348 (188)
RANGE, km (n.mi.)			2193 (1184)		2808 (1516)
TAKEOFF DISTANCE, m (ft)	658 (2160)		658 (2160)		658 (2160)
LANDING DISTANCE, m (ft)	482 (1580)		482 (1580)		482 (1580)
WING AREA, m^2 (ft^2)	17 (186)		17 (186)		17 (186)
STALL SPEED, km/hr (kt)	107 (58)		107 (58)		107 (58)

TABLE IX. TWIN-ENGINE AIRPLANE SPECIFICATIONS

	CURRENT TECHNOLOGY ENGINE TSIO-550	PERCENT DIFFERENCE FROM CURRENT TECHNOLOGY	MODERATE RISK TECHNOLOGY ENGINE GTSIO-420 (HOMOGENEOUS CHARGE)	PERCENT DIFFERENCE FROM CURRENT TECHNOLOGY	HIGH RISK TECHNOLOGY ENGINE GTSIO-420/SC (STRATIFIED CHARGE)
RATED SHAFT POWER, kW (hp)	261 (350)		261 (350)		261 (350)
TAKEOFF WEIGHT, kg (lb)	3050 (6723)		3050 (6723)		3050 (6723)
EMPTY WEIGHT, kg (lb)	1969 (4340)	-5%	1878 (4140)	-8%	1805 (3980)
FUEL WEIGHT, kg (lb)	491 (1083)	+9%	537 (1183)	+17%	573 (1263)
PAYLOAD, kg (lb)	590 (1300)	+8%	635 (1400)	+14%	671 (1480)
71.4% POWER, 7620 m (25,000 ft)					
CRUISE SPEED, km/hr (kt)	435 (235)	+3%	446 (241)	+3%	450 (243)
RANGE, km (n.mi.)	1759 (950)	+47%	2578 (1392)	+78%	3126 (1688)
64.3% POWER, 9144 m (30,000 ft)					
CRUISE SPEED, km/hr (kt)			439 (237)		443 (239)
RANGE, km (n.mi.)			2724 (1471)		3324 (1795)
57.1% POWER, 10,668 m (35,000 ft)					
CRUISE SPEED, km/hr (kt)			413 (223)		419 (226)
RANGE, km (n.mi.)			2754 (1487)		3432 (1853)
TAKEOFF DISTANCE, m (ft)	753 (2470)		753 (2470)		753 (2470)
LANDING DISTANCE, m (ft)	716 (2350)		716 (2350)		716 (2350)
WING AREA, m^2 (ft^2)	18 (190)		18 (190)		18 (190)
STALL SPEED, km/hr (kt)	139 (75)		139 (75)		139 (75)

TABLE X. HIGH-ALTITUDE ENGINE SPECIFICATIONS

	MODERATE RISK TECHNOLOGY ENGINE GTSIO-420 (HOMOGENEOUS CHARGE)	HIGH RISK TECHNOLOGY ENGINE GTSIO-420/SC (STRATIFIED CHARGE)
AVERAGE MAXIMUM CONTINUOUS POWER		
7620 m (25,000 ft) TO 9144 m (30,000 ft), kW (hp)	239 (321)	239 (321)
7620 m (25,000 ft) TO 10,668 m (35,000 ft), kW (hp)	221 (296)	221 (296)
SFC AT MAXIMUM CONTINUOUS POWER		
7620 m (25,000 ft) TO 9144 m (30,000 ft), kg FUEL/kW-hr (lb FUEL/hp-hr)	0.319 (0.524)	0.219 (0.360)
7620 m (25,000 ft) TO 10,668 m (35,000 ft), kg FUEL/kW-hr (lb FUEL/hp-hr)	0.342 (0.562)	0.235 (0.386)
*MAXIMUM CRUISE POWER AT 9144 m (30,000 ft), kW (hp)	168 (225)	168 (225)
AT 10,668 m (35,000 ft), kW (hp)	149 (200)	149 (200)
CRUISE SFC AT 9144 m (30,000 ft), kg FUEL/kW-hr (lb FUEL/hp-hr)	0.220 (0.362)	0.204 (0.336)
AT 10,668 m (35,000 ft) kg FUEL/kW-hr (lb FUEL/hp-hr)	0.222 (0.365)	0.207 (0.340)
COOLING DRAG, EQUIVALENT FRONTAL AREA (f, BASED ON WING AREA), m^2 (ft^2)		
MAXIMUM CRUISE, COWL FLAPS CLOSED, AT 9144 m (30,000 ft) SINGLE	0.025 (0.264)	0.021 (0.222)
TWIN	0.020 (0.210)	0.016 (0.177)
AT 10,668 m (35,000 ft) SINGLE	0.026 (0.281)	0.022 (0.236)
TWIN	0.021 (0.223)	0.017 (0.188)
MAXIMUM CLIMB, COWL FLAPS OPEN, AT 7620 m (25,000 ft) TO 10,668 m (35,000 ft) SINGLE	0.023 (0.246)	0.019 (0.209)
TWIN	0.021 (0.225)	0.018 (0.191)

*ALL POWER AND SFC VALUES ARE BASED ON ACTUAL PROPELLER SHAFT OUTPUT, TAKING ACCESSORY AND CABIN PRESSURIZATION LOSSES INTO ACCOUNT.

TABLE XI. AIRPLANE FLYOVER NOISE ESTIMATES

261 kW (350 hp)

ENGINE	AIRPLANE	FLYOVER SPEED (KTAS)	km/hr	MAXIMUM CRUISE RPM	PROPELLER DIAMETER m	(in.)	CORRECTED FLYOVER* NOISE ESTIMATE [dB(A)]
TSIO-550	SINGLE	190	352	2800	2.3	(92)	91.6
	TWIN	216	400	2800	2.0	(78)	84.2
GTSIO-420	SINGLE	194	359	2400	2.2	(88)	79.8
	TWIN	220	407	2400	2.0	(80)	77.4
GTSIO-420/SC	SINGLE	195	361	2400	2.3	(90)	80.8
	TWIN	221	409	2400	2.1	(82)	78.1
	SINGLE	195	361	2200	2.4	(95)	78.3
	TWIN	221	409	2200	2.4	(95)	78.3
	SINGLE	195	361	2000	2.4	(95)	74.0
	TWIN	221	409	2000	2.4	(95)	74.8

*THE MAXIMUM VALUE CURRENTLY ALLOWED BY FAR 36 IS 80 dB(A).

NOTE: 305 m (1000 ft) STANDARD DAY CONDITIONS WITH 85% PROPELLER EFFICIENCY.

TABLE XII. ENGINE COST FACTORS

	CURRENT	MODERATE RISK	HI
CRUISE, kW (hp)	186 (250)	186 (250)	186
CRUISE SFC, 7620 m (25,000 ft) kg FUEL/hp-hr (lb FUEL/hp hr)	0.271 (0.446)	0.218 (0.358)	0.20
FUEL DENSITY, kg/ℓ (lb/gal)	0.70 (5.85)	0.70 (5.85)	0.70
FUEL COST, \$/ℓ (\$/gal)	0.33 (1.25)	0.33 (1.25)	0.27
OIL CONSUMPTION, kg/hr (lbm/hr)	0.34 (0.75)	0.23 (0.50)	0.23
OIL DENSITY, kg/ℓ (lb/gal)	0.89 (7.4)	0.89 (7.4)	0.89
OIL COST, \$/ℓ (\$/gal)	1.22 (4.60)	1.22 (4.60)	1.22
ENGINE MAINTENANCE ALLOWANCE, \$/hr	6.31	5.65	6.84
TIME BETWEEN OVERHAULS, hr	1400	2000	2000
ENGINE EXCHANGE COST	BASE	128%	155%
NEW ENGINE PRICE	BASE	128%	155%
BEECH COST	BASE	128%	155%

TABLE XIII. COST SUMMARY -- SINGLE-ENGINE AIRPLANE

USE: 800 HOURS/YEAR

PERCENTAGES INDICATE CHANGES FROM BASELINE AIRPLANE VALUES.

	MODERATE RISK (%)	HIGH RISK (%)
ACQUISITION COST	+ 3.16	+ 6.21
FUEL	-20	-48
OIL	-34	-34
INSPECTION AND MAINTENANCE		
AIRFRAME	0	0
ENGINES	-10	+ 8
PROPELLERS	0	0
ENGINE EXCHANGE	-10	+ 9
HANGAR RENTAL	0	0
INSURANCE	+ 3	+ 6
TOTAL DOC/HOUR	-11	-15

TABLE XIV. COST SUMMARY -- TWIN-ENGINE AIRPLANE

USE: 1,000 HOURS/YEAR

PERCENTAGES INDICATE CHANGES FROM BASELINE AIRPLANE VALUES.

	MODERATE RISK (%)	HIGH RISK (%)
ACQUISITION COST	+ 3.63%	+ 7.12%
FUEL	-20	-48
OIL	-33	-33
INSPECTION AND MAINTENANCE		
AIRFRAME	0	0
ENGINES	-10	+ 8
PROPELLERS	0	0
ENGINE EXCHANGE	-10	+ 9
HANGAR RENTAL	0	0
INSURANCE	+ 4	+ 7
TOTAL DOC/HOUR	-12	-16

TABLE XV. ADVANCED TECHNOLOGY SPARK-IGNITION AIRCRAFT PISTON ENGINE PROGRAM PLAN

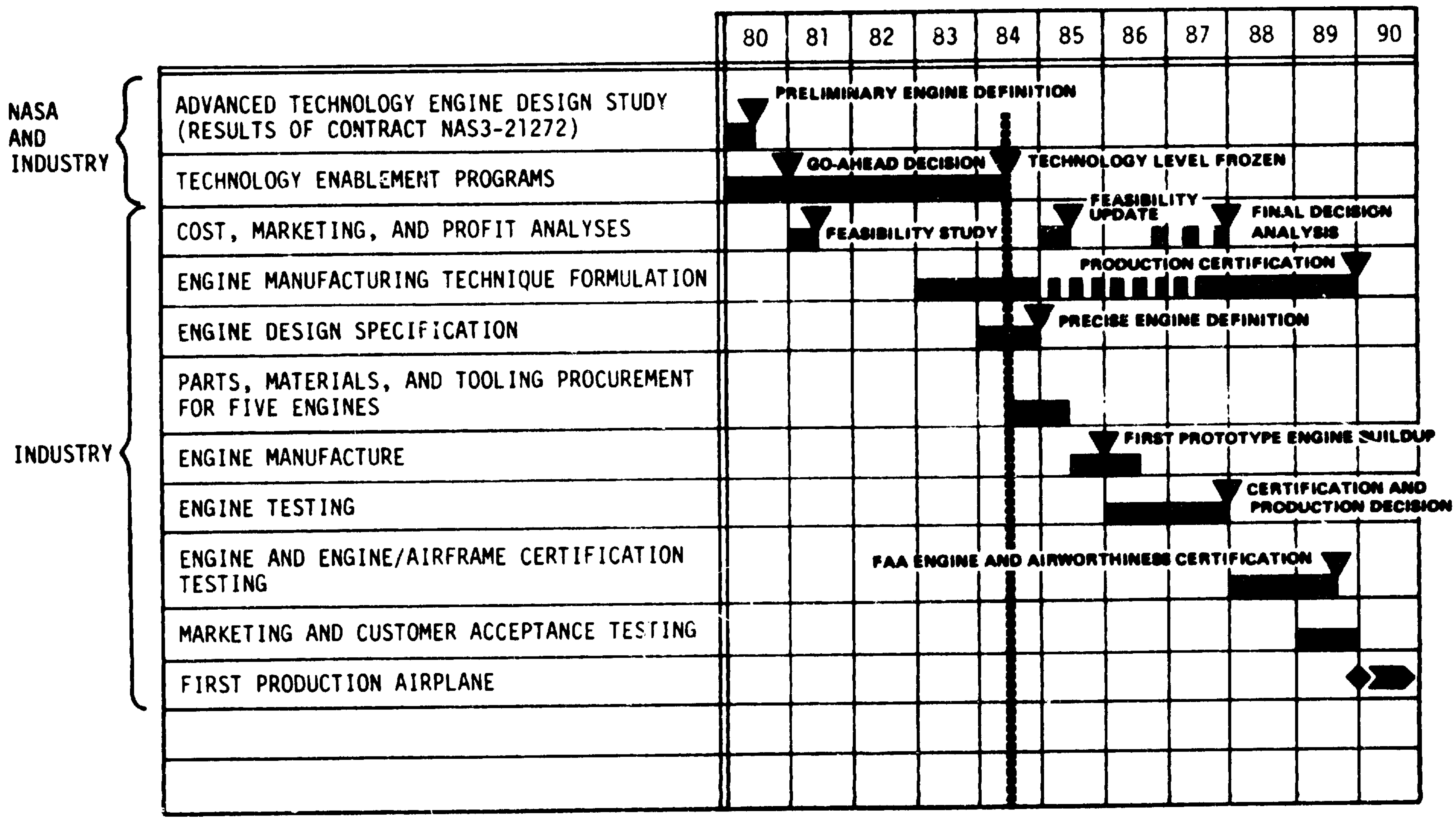


TABLE XVI. ADVANCED TECHNOLOGY SPARK-IGNITION AIRCRAFT PISTON ENGINE TECHNOLOGY ENABLEMENT PROGRAM PLAN

		1980	1981	1982	1983	1984
NASA AND INDUSTRY	TECHNOLOGY ENABLEMENT PROGRAMS					
	STRATIFIED-CHARGE COMBUSTION SYSTEM					
	ELECTRONICALLY CONTROLLED IGNITION SYSTEM FOR STRATIFIED-CHARGE ENGINE					
	HIGH-EFFICIENCY, HIGH-PRESSURE-RATIO, LIGHTWEIGHT TURBOCHARGER					
	TURBOCOMPOUNDING POWER TURBINE REDUCTION DRIVE, CLUTCH, AND CONTROL SYSTEM					
	ELECTRONIC ENGINE CONTROL (SINGLE-LEVER POWER CONTROL)					

TABLE XVII. OPEN CHAMBER, SPARK-IGNITION STRATIFIED CHARGE COMBUSTION SYSTEM PROGRAM

		1980	1981	1982	1983	1984
STRATIFIED-CHARGE COMBUSTION SYSTEM PROGRAM						
TASK 1	LITERATURE SURVEY ON STATE OF THE ART OF OPEN-CHAMBER, SPARK-IGNITION, STRATIFIED-CHARGE ENGINES	(MONTHS)	3			
TASK 2	COMBUSTION SYSTEM DESIGN STUDY FOR SINGLE-CYLINDER TESTING		3			
TASK 3	PROCUREMENT AND BUILDUP OF SINGLE-CYLINDER TEST ENGINE		4			
TASK 4	TESTING OF SINGLE-CYLINDER STRATIFIED-CHARGE ENGINE			12		
TASK 5	MULTICYLINDER ENGINE DESIGN BASED ON CONVENTIONAL, TURBOCHARGED ENGINE			3		
TASK 6	PROCUREMENT AND BUILDUP OF MULTICYLINCER STRATIFIED-CHARGE EXPERIMENTAL ENGINE FOR PROOF-OF-CONCEPT TESTING				5	
TASK 7	DYNAMOMETER AND PROPELLER STAND TESTING OF MULTICYLINDER STRATIFIED-CHARGE EXPERIMENTAL ENGINE				6	
TASK 8	FLIGHT TESTING OF EXPERIMENTAL TESTING					7

TABLE XVIII. ELECTRONIC IGNITION SYSTEM PROGRAM

		1980	1981	1982	1983	1984
ELECTRONIC IGNITION SYSTEM PROGRAM						
TASK 1	DESIGN OF BREADBOARD UNIT WITH MANUALLY VARIABLE TIMING, DURATION, AND SPARK ENERGY FOR SINGLE-CYLINDER ENGINE TESTING	(MONTHS)	3			
TASK 2	PROCUREMENT AND BUILDUP OF BREADBOARD DESIGN		4			
TASK 3	TESTING ON SINGLE-CYLINDER ENGINE TO DETERMINE REQUIRED IGNITION SYSTEM PARAMETERS			12		
TASK 4	DESIGN OF MULTICYLINDER IGNITION SYSTEM AND SOFTWARE PROGRAM				8	
TASK 5	DYNAMOMETER AND PROPELLER STAND TESTING OF ELECTRONIC IGNITION SYSTEM ON MULTICYLINDER STRATIFIED-CHARGE ENGINE				6	
TASK 6	DESIGN AND MANUFACTURE OF EXPERIMENTAL FLIGHT TEST IGNITION SYSTEM				3	
TASK 7	FLIGHT TESTING					7

TABLE XIX. ADVANCED TURBOCHARGER PROGRAM

		1980	1981	1982	1983	1984
ADVANCED TURBOCHARGER PROGRAM						
TASK 1	TURBOCHARGER DESIGN STUDY - MATERIALS, AERODYNAMICS, ENGINE MATCHING, BEARINGS, AND FRAME SIZING	(MONTHS)	6			
TASK 2	PROCUREMENT AND RIG TESTING OF COMPRESSOR IMPELLER, BEARINGS AND SINGLE-PHASE, ALPHA SILICON-CARBIDE TURBINE WHEEL		9			
TASK 3	EXPERIMENTAL TURBOCHARGER DESIGN			3		
TASK 4	PROCUREMENT AND BUILDUP OF EXPERIMENTAL TURBOCHARGER DESIGN(S)			3		
TASK 5	COMBUSTION RIG TESTING, SPIN PIT CONTAINMENT TESTING			3		
TASK 6	ENGINE DYNAMOMETER, PROPELLER STAND, AND FLIGHT TEST				6	

TABLE XX. TURBOCOMPOUNDING SYSTEM PROGRAM

		1980	1981	1982	1983	1984
TURBOCOMPOUNDING SYSTEM PROGRAM						
TASK 1	DESIGN OF TURBOCOMPOUNDING SYSTEM - TURBINE WHEEL, HOUSING, BEARINGS, TRACTION DRIVE, CLUTCH	(MONTHS)	3			
TASK 2	DESIGN OF ELECTRONIC CONTROL SYSTEM AND LOGIC FLOW DIAGRAM		6			
TASK 3	PROCUREMENT OF EXPERIMENTAL HARDWARE AND BUILDUP OF RIG TEST SYSTEM		9			
TASK 4	RIG TESTING OF EXPERIMENTAL SYSTEM			12		
TASK 5	FINAL DESIGN FOR ENGINE TESTING				3	
TASK 6	PROCUREMENT OF SYSTEM HARDWARE AND BUILDUP				6	
TASK 7	ENGINE DYNAMOMETER AND PROPELLER STAND TESTS WITH ADVANCED TURBOCHARGER					6
TASK 8	FLIGHT TESTING					3

TABLE XXI. ELECTRONIC, SINGLE-LEVER, POWER CONTROL SYSTEM PROGRAM

		1980	1981	1982	1983	1984
ELECTRONIC, SINGLE-LEVER, POWER CONTROL SYSTEM PROGRAM						
TASK 1	DESIGN OF SYSTEM CONTROL STRATEGY	(MONTHS)	9			
TASK 2	DESIGN OF EXPERIMENTAL SYSTEM HARDWARE AND BUILDUP		6			
TASK 3	PROCUREMENT OF EXPERIMENTAL SYSTEM HARDWARE AND BUILDUP			6		
TASK 4	RIG TESTING OF SYSTEM			3		
TASK 5	EXPERIMENTAL SYSTEM PROPELLER STAND ENGINE TEST				6	
TASK 6	EXPERIMENTAL SYSTEM FLIGHT TEST				12	

REFERENCES

(1) Obert, E. F., "Internal Combustion Engines and Air Pollution," Intext Education Publishers, 1973, p. 1.

(2) ABC-TV Special Program on the "Oil Crisis," March 20, 1973.

(3) Cummins, C. L., Jr., "Early IC and Automotive Engines," SAE Paper 760604, 1976.

(4) Hempson, J. G. G., "The Automobile Engine - 1920-1950," SAE Paper 760605, 1976.

(5) Reasoner, H., "Reasoner Report," ABC-TV Program, February 16, 1974.

(6) Starbird, E., "Presentation to the Energy Committee of the General Aviation Manufacturers Association," Exxon Company, U.S.A., June 6, 1978.

(7) "Energy Data Reports," Office of Energy Data and Interpretation, Energy Information Administration, U.S. Department of Energy, 1978.

(8) "The National Energy Act -- An Analysis," General Aviation Manufacturers Association, November 1, 1978.

(9) World Energy Outlook," Exxon Corporation, April 1978.

(10) "The National Energy Outlook - 1980-1990," Shell Oil Company, July 1978.

(11) "Energy Outlook 1978-1990," Exxon Corporation, May 1978.

(12) "Projections of Energy Supply and Demand and Their Impacts," U.S. Department of Energy, Energy Information Administration, Annual Report to Congress, Volume II, 1977.

(13) "The Good News About Energy," Executive Office of the President, Council on Environmental Quality, 1979.

(14) Bidwell, J. B., "GM Research Looks at Alternative Fuels," Automotive Engineering, Vol. 86, No. 11, November 1978.

(15) "Alternate Portable Fuels for Internal Combustion Engines," An Assessment by Alternate Fuels Committee of the Engine Manufacturers Association, SAE Paper 790426, 1979.

(16) "Feasibility Study of Alternative Fuels for Automotive Transportation," Exxon Research And Engineering Company, NTIS Report PB-235 582, Vol. II, June 1974.

REFERENCES (Concluded)

(17) Cart, E. N., Jr., et al., "Alternate Energy Sources for Non-Highway Transportation," DOT Contract EC-77-C-05-5438, Progress Report for Tasks 3, 5, and 6, December 15, 1978.

(18) "The National Energy Act," Office of Public Affairs, Department of Energy, 1978.

(19) Mazzone, J. S., "Brazil's '76 Export and Gas Problems," Automotive Industries, January 15, 1976.

(20) "Alcohol: A Brazilian Answer to the Energy Crisis," Science, Volume 195, February 11, 1977.

(21) Marks' Standard Handbook for Mechanical Engineers," Seventh Edition, p. 7-21, McGraw-Hill.

(22) "The Petroleum Handbook," Fifth Edition, p. 78 ff, Shell International Petroleum Company Ltd., 1966.

(23) Tierney, W. T., Wilson, R. F., "Adequate Future Transportation Demands Vehicle-Fuel-Refinery System Optimization Today," 19th Meeting of the American Petroleum Institute, January 29, 1976.

(24) Tierney, W. T., Johnson, E. M., Crawford, N. R., "Energy Conservation/ Optimization of the Vehicle-Fuel-Refinery System," SAE Paper 750673, 1975.

(25) Shelton, E. M., "Motor Gasolines, Summer 1978," U.S. Department of Energy, Technical Information Center, BETC/PPS-79/1, February 1979.

(26) "A Texaco Position Paper: The Outlook for Aviation Turbine Fuel," October 1977.

(27) Stivender, D. L., "Engine Air Control - Basis of a Vehicular Systems Control Hierarchy," SAE Paper 780346, 1978.

(28) Cerny, R. S., Wycallis, J. J., "Dual Breakerless Aircraft Magneto," SAE Paper 790606, 1979.

(29) Maki, E. R., and DeHart, A. O., "A New Look at Swash-Plate Drive Mechanisms," SAE Paper No. 710829, 1971.

(30) Mackerle, Julius, Air-Cooled Automotive Engines, London, U. K., Charles Griffin & Company Ltd., 1972, Chapter 1.

END

DATE

FILMED

FEB 9 1981