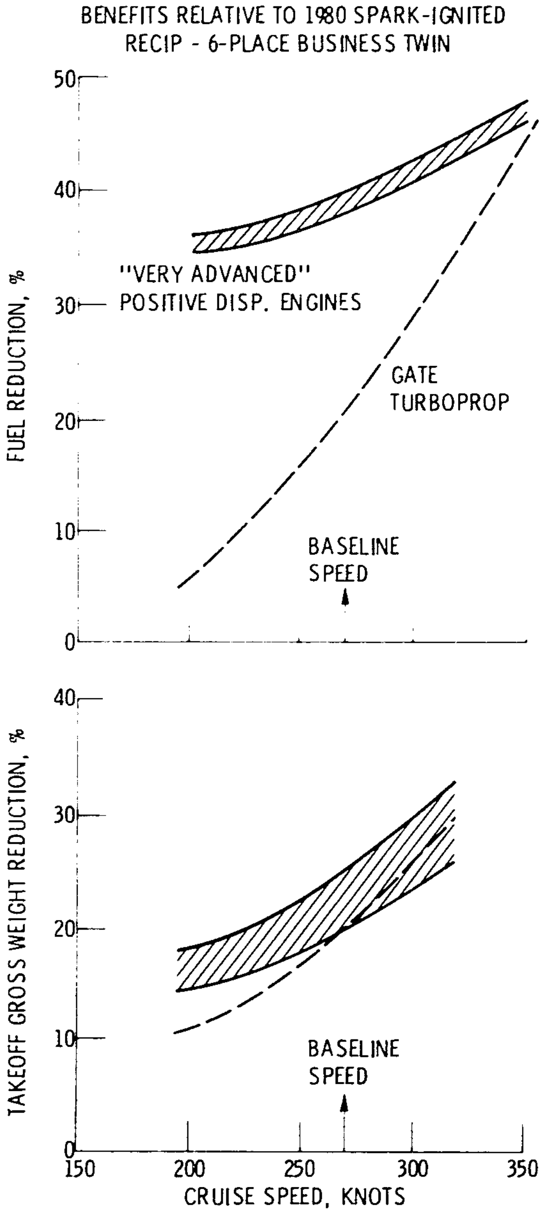

Figure 34. - Effect of cruise speed.

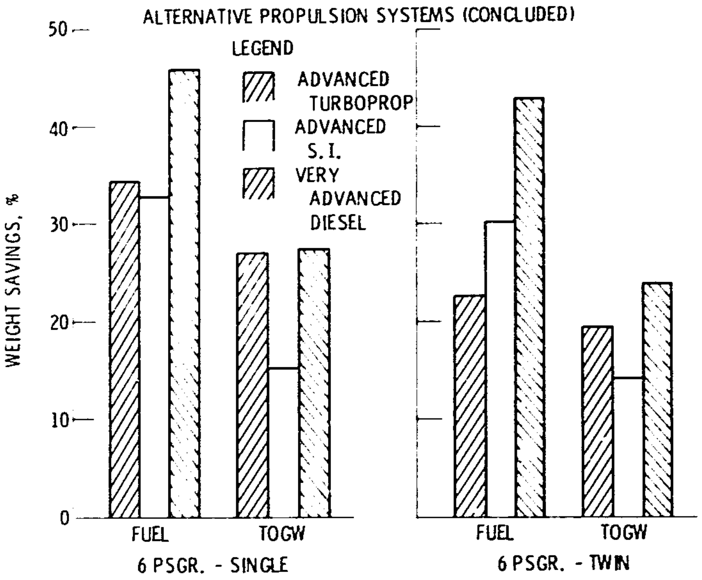

Figure 35. - Fuel and airplane weight savings with advanced turboprop and diesel powerplants in future G/A airplanes (25 000 cruise - 250 KT, 1000 - 1600 MI range).

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An Overview of General Aviation Propulsion Research Programs at NASA Lewis Research Center

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AN OVERVIEW OF GENERAL AVIATION PROPULSION
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SUMMARY

This paper presents a brief overview and technical highlights of general aviation (g/a) propulsion research efforts and studies which have been underway at NASA's Lewis Research Center (LeRC) for the past several years. The review covers near-term improvements for current-type piston engines, as well as studies and limited corroborative research on several advanced g/a engine concepts, including diesels, small turboprops and both piston and rotary stratified-charge engines. Also described is basic combustion research, cycle modeling and diagnostic instrumentation work that will be required to make the new engines a reality. The discussion emphasizes the most recently-completed studies and the basic underlying research work, which have not been reported previously.

FIGURE 1 ILLUSTRATES the major general aviation (g/a) industry needs and concerns as perceived by NASA. GAMA, in its July 6, 1979 position paper on g/a research needs[1]*, pointed out the first three items as being the industry's largest concerns. Safety has become an economic issue--product liability is becoming the largest single cost of doing business for many companies. Traffic control bears on the same issue as well as the general utility of the fleet. But, now more clearly than ever, energy efficiency is the long run survival issue. If this problem is not solved, the other issues will become moot.

Propulsion technology is the key area in which to attack this problem. The need for near term as well as long term technology follows from the inherent nature of the industry and fleet. In 1980, the 186,000 gasoline-burning piston engine airplanes comprised 93% of the fleet[2], an investment of about $10 billion. Their number is expected to reach 269,000 by 1990[2], then representing an investment of $30 billion or more.

These are long-lived airplanes--25 to 30 years and often more. Many of them could be converted into expensive "white elephants" if aviation gasoline (avgas) becomes unavailable or unreasonably expensive. One fairly common perception is that these airplanes must eventually be adapted to use a commodity fuel such as autogas, diesel or jet fuel. There is no other way known to assure fuel availability. GAMA went so far as to suggest retrofittable technology. The potential engine retrofit market is an order of magnitude larger than the annual Original Equipment Manufacturer's (OEM) market for new engines.

Based on relative BTU content and production costs per gallon, the kerosine/ diesel-type fuels also offer an inherent economic advantage of 20% or more over gasoline. This is significant because avgas prices are already approaching $2 per gallon in the U.S. and $4 to $5 per gallon in Europe. In many parts of Africa and the Middle East, avgas is not available at any price; and in other

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*Superscript numbers denote references listed at the end of the paper countries it is available only at a 5/1 to 10/1 price differential compared to locally produced kerosine/diesel fuel. Clearly, this situation could inhibit the development of a strong U.S. g/a export position in the emerging, potentially lucrative Third World markets.

NASA's overall priorities clearly reflect the industry's stated needs. The current program addresses energy efficiency directly, both by improving BSFC and other engine attributes, and through the capability to burn less-costly, readily-available future fuels. In what follows, work that relates primarily to improving current-production-type gasoline engines is presented in the "Piston Engine Technology" section. The section on "Combustion Diagnostics and Modeling" describes basic IC engine research efforts that underly both near-term engine improvements and futuristic alternative engines. Finally, the section on "Alternative Engines" presents the results of several recently completed design and comparative mission performance studies on the alternative engine types.

PISTON ENGINE TECHNOLOGY

The piston engine technology area includes some of the relatively near-term work that was formerly covered by the emissions reduction program. Figure 2 indicates the current status of the program. One of the year's highlights is the successful completion of the Teledyne-Continental Motors, Aircraft Products Division (TCM) near-term improvements contract, which will be discussed later in more detail. More recently initiated efforts include improved cooling and fuel injection technology programs, a high-altitude turbocharger study, and a workshop to be held on problems related to avgas.

COOLING - Cooling is a new area of endeavor. It is a very important one since many turbocharged installations now operate near detonation or cooling limits. This problem, which affects both safety and economy, could be greatly aggravated by efforts to fly higher via improved turbochargers. The overall effort is being handled as a joint program between the NASA Lewis and Langley Research Centers. This would eventually require augmented funding. The first phase, however, has been initiated with R&T base funds. TCM has been selected to do experimental heat-transfer work on a single-cylinder test rig; while NASA will use the TCM results to calibrate an existing, generalized heat transfer code called "SINDA". The resultant simulation will represent a generalized case of the air-cooled, valve-in-head cylinder's cooling and heat transfer characteristics, and will be available to the entire industry.

FUEL INJECTION - The fuel injection program was originally planned to consist of two parts. The completed Spectron contract effort produced quantitative characterizations of the performance (droplet size and velocity distribution, etc.) of eight injection nozzles, using laser-optic techniques[3]. It was intended that a parallel, in-house flow visualization program would photographically study the same set of nozzles via fiber optics and high-speed cameras. At this point, two of the eight nozzles have been studied. These were the standard TCM nozzles for the engine (TSIO-360) and a set of standard AVCO-Lycoming nozzles for a comparable engine. Both nozzles performed similarly, giving conspicuously poor atomization under high-flow power settings. A brief color film clip from this work is available. The project, however, is currently inactive.

TURBOCHARGING - The turbocharger study seeks to define a family of cost-effective high-altitude turbochargers which would meet the requirements of several of the improved near-term engines and more advanced candidates. Contract negotiations are underway now and award is anticipated in early 1981.

NEAR-TERM IMPROVEMENTS - As mentioned earlier, the early part of the IC engine program focused on near-term, relatively simple improvements which could be incorporated into current-production type engines without major disruption of facilities, manufacturing processes, etc. Under a recently-completed contract, TCM has evaluated four concepts which could be integrated neatly together into a new cylinder-head package. The new TCM head is illustrated in more detail in Figure 3. The four improvements evaluated by TCM[4] were timed fuel injection, variable spark timing, a thermal-barrier exhaust port liner and spot cooling via air injection in the exhaust valve area. These were engineered into a well-integrated new cylinder head and accessory package for their existing IO-520 engine, and tested both individually and in various combinations in an engine/ dynomometer rig. The final round of tests were made with a complete flightworthy engine, and the contract was extended to include an airplane flight test/ demonstration phase in early 1981. Besides the obvious economy/emissions benefits, there are other effects which make the new engine easier to live with than the old one. The timed fuel injection results in easier starting and a smoother idle. Engine vibration is noticeably reduced at ultra-lean cruise power settings. The exhaust port liners result in lower cylinder head temperatures, which means a larger detonation margin--a plus for safety. The reduced heat load into the cylinder head reduces cooling air requirements and this could be converted into reduced cooling drag. The exhaust valve metal temperatures are reduced about 200° F by the spot cooling air, which should improve durability in this sensitive area.

COMBUSTION DIAGNOSTICS AND MODELING

As previously mentioned, both the piston engine and alternative engine technology programs are supported by continuing efforts in the basic ICE combustion diagnostics and modeling area. Figure 4 indicates the general intent and the approach being followed. Briefly, the combustion research efforts include: (a) the development of both detailed and rapid/approximate computer cycle simulation models, (b) the experimental validation and refinement of the models, and (c) the continuing development/improvement of in-house test facilities, instrumentation and combustion-diagnostic capabilities.

DIAGNOSTIC INSTRUMENTATION - The development and use of unique, specialized engine diagnostic instrumentation has long been a specialty at LeRC. Figure 4 lists several recent items relevant to the IC engine field. The first three items are NASA research firsts and are now also being utilized by MTI, Chrysler, and TCM. The specific items targeted for completion in 1980 and 1981 will be discussed one by one in the following paragraphs.

Sample Analysis System - As Figure 5 suggests, this system consists of a fast-acting sample valve, installed in an engine and connected to a vacuum pump via a sensitive mass spectrometer. The valve opens and closes extremely rapidly, to withdraw a small sample of the cylinder's air/fuel or combustion-gas charge, over a period corresponding to a few crank-angle degrees. The sample flows through the mass spectrometer which produces electrical outputs corresponding to the concentration of each chemical species. An early sample valve is illustrated in Figure 6, mounted with the sampling tip protruding into the cylinder head of a Chevrolet V-8 engine. The tip can be moved back and forth axially so that space-resolved samples can be obtained along the line from the spark plug to the combustion chamber surface.

The design for this valve was furnished to NASA by General Motors Research (GMR). Subsequent development at LeRC, to resolve leakage and reliability problems, resulted in a significantly improved manufacturing process specification for the valve; the new specification has been furnished to GMR and other users of the valve.

Figure 7 illustrates a typical mass spectrometer output in a test that was designed to measure fuel/air ratio in the charge just after combustion. Here, the ordinate represents an output voltage proportional to the density of a given species, while the abcissa represents the mass number of the species. In the case shown, the first appreciable peak at the left is for mass No. 14, atomic nitrogen. The smaller peak at the far right is for mass No. 43, which is characteristic of gasoline-type fuels. By electronically ratioing these two signals, a measure directly proportional to fuel/air ratio is produced. By comparison with known calibration gas mixtures, it has been shown that the resultant real-time fuel/air output is substantially accurate as long as system vacuum is maintained in the range of 10^{-3} to 10^{-5} bar (hence, the importance of a leak-free sample valve).

Based on a year's experience with the GMR valve design, LeRC has designed, built and checked out an improved new valve, illustrated in Figure 8. This zero-leakage design features much faster actuation through the use of an unique, helically-wound solenoid actuator. Leakage tendencies and friction are minimized by the use of stiff, lightweight, close-coupled internal parts.

Stratified-Charge Test Facility - Figure 9 illustrates the recently completed stratified-charge single-cylinder test facility. The spark-ignited AVL test engine, the dynamometer, and basic instrumentation are now operational. Baseline performance mapping of the carbureted version shown should be complete in 1980. In early 1981, the new sample valve and a more sensitive mass spectrometer will be installed. During the first half of 1981, two advanced, high-compression, high-turbulence, homogeneous-charge configurations will be evaluated while components for the multifuel-capable, direct-injection, stratified-charge (DISC) system are being designed and fabricated. This system is intended to use Jet-A as the fuel of choice, but will retain the capability to use any grade of avgas as a back-up fuel, with no major degradation of maximum power, efficiency or durability for doing so.

The basic principle of operation is similar to the Texaco system, which recently provided excellent performance in United Parcel Service tests[5]. The Lewis system differs principally in having a higher (16/1) compression ratio, higher turbulence and in using multiple-pulsed rather than single-shot fuel injection. Initial tests using Jet A fuel are expected to commence in late 1981.

Rotary IMEP Instrumentation - It was previously indicated that a major target for 1980 was to adapt the LeRC-developed real time IMEP instrumentation[6] to the rotary (Wankel) engine configuration. This was not a trival extension, due to the unique structural arrangement of the Wankel engine, even though it operates on the familiar 4-stroke cycle. As can be seen from Figure 10, there is no one place on the fixed rotor housing from which a single pressure transducer can "see" the complete thermodynamic cycle of a single charge. Instead, it is necessary to mount four transducers at intervals around the housing, each of which sees a portion of a given charge's cycle. In previous rotary engine research, the resulting multitude of partial pressure-time traces were stored in digital data banks, for post-run processing by a main-frame computer to reconstruct the desired continuous traces. This is a costly, timeconsuming process which has impeded the progress of rotary engine research.

The new LeRC system, however, uses a unique digital circuit to electronically switch from one transducer to the next, thus following one charge in its path around the housing, and producing the desired continuous pressure-time trace in real time.[7]

Figure 11 illustrates the process. Beginning at the upper left, the first photo shows the raw pressure-time outputs from the 4 transducers. Proceeding clockwise, the second photo shows the continuous pressure-time trace constructed by the above-mentioned switching circuitry for one selected charge. In the third photo, this has been converted to a classical P-V diagram by further real-time digital computations which model the geometrical relationships of the rotor/trochoid system. The next photo (lower right) is an expansion of the lower part of the P-V diagram, showing the pumping loop in detail. Clearly visible is an adverse pressure pulse due to the opening of the exhaust port of the adjacent rotor. By using longer exhaust tubes to damp out this undesirable pulse, the power output and BSFC could have been improved by about 2% in the case shown. By using a tuned system which would convert the pressure pulse to a rarefaction, more significant improvements might be expected.

The contour integral of PdV around the diagram, divided by the total volume change, gives the indicated mean effective pressure (IMEP) which is a measure of the power output of the cycle. The fifth photo (lower left) shows 100 values of IMEP measured for consecutive cycles of the rotary engine under the indicated operating conditions. The small differences between consecutive IMEP values indicate smooth operation, despite the lean fuel/air equivalence ratio of 0.88.

The use of four transducers in sequence to determine a single P-V diagram presents an unique problem in the possibility for instrumental error. This is due to the fact that each transducer may have a somewhat different calibration curve and may be operating under different temperatures or other environmental conditions. Now it is possible, electronically, to calibrate each transducer to agree with the one before it, at each transition from one instrument to the next. Thus, a smooth curve can be constructed at transition 1-2, 2-3 and 3-4. The error remaining at the 4-1 transition is referred to as the closure error, and is a measure of the inherent accuracy or inaccuracy of the total system. The last photo (middle left) is an expansion of a small portion of the pumping loop. The closure error is represented by the discontinuity shown, approximately 2 psi compared to a peak pressure reading of about 300 psi. Based on this, it is felt that an accuracy of 1% or better is being achieved.

COMBUSTION RESEARCH AND MODELING

Hypergolic Fuel Injection/Ignition - The use of highly preheated fuel (over 800° F and above critical pressure) has come to be termed "hypergolic" fuel injection, i.e., the fuel ignites spontaneously when injected into air, with essentially zero ignition delay. This approach theoretically offers the advantages illustrated in Figure 12, which could result in significant improvements in engine performance.

This is a longer-range objective for which initial efforts are just recently getting underway. This concept is potentially applicable to any diesel or stratified-charge engine using piston/cylinder or rotary (Wankel) construction. The technical idea is that the fuel is preheated above its thermal decomposition temperature (about 800F) and injected at above the supercritical pressure in a diesel or DISC engine. This may greatly decrease the time usually required for droplet evaporation and for "pre-flame reactions," thus resulting in negligible ignition lag, with energy release rate then determined by fuel injection rate alone. This means that the P-V diagram can be tailored to meet specific requirements, by controlling the fuel injection rate. Several potential benefits result from this, as Figure 12 indicates. Although this subject is in its technical infancy, a theory developed by Eaton Research personnel* provides an analytical basis for these effects. An independent review of the theory, conducted by several major U.S. universities, indicates that the theory is correct as an initial approximation of a very complex "real" situation. It's predictions are consistent with the limited amount of applicable experimental data that is now available, some of which dates back to NACA aircraft diesel research in the 1930's[8]. In late 1980, a grant was awarded to the University of California-Berkely to study this phenomenon from a basic viewpoint, and a joint Army/NASA program leading to intensified efforts was under consideration.

Combustion & Cycle Models - The availability of a credible, generally-accepted combustion and cycle computer model would save untold hours and dollars of painstaking experimental effort. LeRC-sponsored efforts in this area fall into two distinct categories, as Figure 4 indicated: rapid, approximate codes for studies and trend analyses; and detailed, multi-dimensional codes for design purposes. (Due to their greater complexity and generally lower state of readiness for practical application, the latter category of codes is not included in the scope of this paper.)

Codes in the former category are often referred to as "zero-dimensional" codes because ordinary rather than partial differential equations are solved. These represent a conscious trade-off, sacrificing some degree of absolute accuracy and independence from empirical input data requirements for a

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*Private communication, L. Hoppie (Eaton) to E. Willis (NASA), April, 1980.

considerable gain in computing time. Among the several existent or developmental zero dimensional codes, the Lewis code is perhaps the most extensive and an early version of it[9] has been previously documented. It may be characterized as having variable fuel composition capability, extensive chemical kinetics during combustion and expansion, accurate modeling of inlet and exhaust flows, supercharging, turbulence effects on combustion, and a choice of three different heat transfer relations. Predictions from this code are presently being compared with engine experimental data from NASA and industry sources. The following results, from an in-house study on variable valve timing and "adiabatic" engine operation, will serve to illustrate the present capability of the Lewis code.

The fixed valve timing (duration, lift, overlap) of the typical IC engine is typically set to provide optimum performance at one selected power setting, e.g. cruise. It follows, then, that better performance could be obtained at other than the design power setting by varying the valve timing. Figures 13 and 14, which were generated by exercising the Lewis code, show the calculated effect of varying the $\underline{e}$xhaust-$\underline{v}$alve-$\underline{o}$pen (evo) event for both a standard (cooled) and a simulated "adiabatic" (uncooled) combustion chamber. For the case shown, the normal evo of 78° $\underline{b}$efore $\underline{b}$ottom $\underline{d}$ead $\underline{c}$enter (BBDC) was originally selected on the basis of cruise efficiency at about 75% power. In these illustrations, however, the engine is simulated to be operating at about 25% power, corresponding roughly to approach conditions.

In Figure 13, the $\underline{i}$ndicated $\underline{s}$pecific $\underline{f}$uel $\underline{c}$onsumption (ISFC) and thermal efficiency are plotted against evo angle for combustion chamber wall temperatures of 220° F (corresponding to normal, cooled operation) and 1000° F, simulating uncooled or adiabatic operation. As may be seen, both parameters improve substantially as the evo moves from the nominal 78° BBDC to about 30° BBDC. The improvement in ISFC of about 10% is in substantial agreement with previously published engine experimental data[10] for a similar case.

An explanation of these results is shown in Figure 14, where the predicted values of power lost to the coolant system and available power in the exhaust gases is plotted against evo angle for the two wall temperatures. As the exhaust valve opening angle is delayed, the power lost to the coolant system increases because more cylinder area is exposed to the hot post-combustion gas. For the case of the hot walls, this coolant power lost is greatly reduced as expected. However, as the evo event is delayed, the exhaust power decreases as the exhaust gas temperature decreases due to continued heat loss and work being done in the cylinder. At the late evo angles, the efficiency of expelling the charge decreases which increase residual gas concentration and pumping work. This causes the post combustion gas temperature to increase. Therefore, the net effects of power cost to the cooling system and power lost to the exhaust system establishes a minimum at about 30° BBDC. A final result shows, for the case of thermal barrier materials, that what was gained by decreasing the cooling loss went instead into added loss to the exhaust system. This implies that exhaust energy extraction mehods, such as turbo-compounding, are needed for a net gain if a thermally-insulated or adiabatic combustion chamber is used.

ALTERNATIVE ENGINES

The second engine-related work area, illustrated in Figure 15, relates to the longer term alternative engines. The overall objective is to achieve a state of technical readiness for an enhanced program by early FY82.

ENGINE STUDY PROGRESS TO DATE - NASA-sponsored studies have been conducted of four alternative engine types, including small, advanced turboprop engines, (known as General Aviation Turbine Engine or GATE), and three different types of advanced IC engines. Actually, four GATE turboprops configurations were studied. These reflected significant differences in structural arrangement, flowpath, materials and manufacturing methods, but all used the well-known, unregenerated Brayton thermodynamic cycle. Similarly, the three IC engine candidates are quite different in terms of their structural configurations, but all rely on the same hybrid-diesel thermodynamic cycle. Technically, this is best described as a low-compression, highly turbocharged, aided-ignition* diesel cycle. The GATE turboprop (Figure 16 shows one example) and diesel engine (Fig. 17) studies have been completed, final reports have been issued, and the results widely disseminated. Therefore, aside from noting that attractive results were obtained in each case, the present report will not dwell upon these completed studies[11-15]. Rather, attention is focussed upon the two stratified-charge engine studies. One, involving a piston engine concept not visually unlike current engines, has been completed and recently reported by TCM[16]. The most advanced version of this engine uses the hybrid-diesel, direct-injection stratified-charge (DISC) combustion system mentioned previously. The other study, of a rotary DISC engine, has recently been completed by Curtiss-Wright. An interim report[17] has been presented and the final report is expected in mid-1981.

Advanced Piston Engine - TCM's concept of an advanced, spark-ignited, air-cooled piston engine is shown in Figure 18. The most prominent external feature of this engine is the use of turbocompounding as well as turbocharging for maximum efficiency. The engine has been defined in two versions or levels of technology. The most desirable, "highly advanced" configuration would make use of the DISC combustion system previously referred to, together with many applications of lightweight, advanced materials to combine high

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*Spark plugs, glow plugs, preheated inlet air and preheated fuel can be equally effective as ignition aids. The use of spark plugs in particular leads to what is generally called a direct-injection stratified-charge (DISC) engine. The essential point, however, is that some extra energy has to be added for cold starting and for reliable ignition of low-cetane fuel such as gasoline. This is the key to multifuel capability in an IC engine.

efficiency, multifuel capability and relatively low weight. It is felt that this reflects the most advanced level of technology available for early-1990's introduction on a piston IC engine. The lower-risk, "advanced" version would be similar, but built of more conventional materials and with a high compression, high-turbulence gasoline combustion system in place of DISC. Both systems, however, would use the same basic combustion chamber configuration as illustrated in Figure 19.

The characteristic feature of this combustion chamber is the concentration of chamber volume into a narrow pocket or "bath tub" in the exhaust-valve area of the cylinder head. The inlet air-fuel charge is forced into this small region late in the compression stroke, thus acquiring a rapid swirling motion and a high degree of turbulence. The combination of high swirl and high turbulence with a relatively high compression ratio (about 12/1) enables this chamber to burn gasoline/air mixtures which normally would be too lean to ignite. In the DISC version, only the air charge is inducted through the intake valve, but it acquires the same high swirl velocities and turbulence as described above. Near the end of the compression stroke, the fuel charge is injected, diesel-fashion, directly into the swirling air mass. The fuel spray pattern is so arranged that at least one "fan" will fall adjacent to a spark plug, where an arc or timed spark ensures positive ignition. The combination of positive ignition with controlled-rate fuel injection is what makes the DISC-type engine independent of fuel octane or cetane characteristics. Many different fuels can be burned with reasonably good results, although details of the injection system (hole size, spray pattern, etc.) would, of course, be optimized for a fuel of choice.

Figure 20 provides a comparison of the leading specifications of a modern current production engine and the two versions of the advanced engines. The improvements in cruise BSFC and cruise altitude are especially valuable. Figure 21 illustrates typical results obtained by Beech Aircraft under subcontract to TCM, which indicates improvements of on the order of 40% in transportation efficiency (ton-miles/gallon) for the lower-technology gasoline engines, and over 65% for the higher-technology DISC multifuel engines.

Rotary Engine - Figure 22 illustrates the general configuration and specific performance of the rotary engine defined under the Curtiss-Wright study contract. As in the TCM study, both "advanced" and "highly advanced" versions are being considered. In this case, however, both versions use an adaptation of the DISC combustion system which provides a true multifuel capability.

In this system, the stationary injector/ignitor system establishes an essentially stationary flame front. The moving rotor then pushes the quiescent air mass through this front. The instantaneous fuel-injection flow rate is tailored so that it is proportional to the instantaneous local air mass flow across the front. Note that the air mass is spread around a long rotor circumference. This means that, at high powers, the fueling and combustion processes take place over a longer angular interval than is customary in DISC or diesel piston engines. This has several inherent implications. A negative aspect is that the late fueling/slow combustion may reduce the thermodynamic cycle efficiency, unless means can be found to speed up the combustion process. Otherwise, the rotary's basic fuel economy will remain 5-10% worse than that of an otherwise-similar piston engine. On the favorable side, however, the same phenomena result in higher exhaust-gas temperatures and energies. Hence, the potential benefits from exhaust-energy driven devices are larger for rotary than for piston engines. As applied to a conventional turbocharger system, this would result in higher altitude capability for a given level of technology, or equal altitude from simpler technology. Alternatively, the use of a properly designed turbocompounding system or a positive-work pumping loop (inlet P >> exhaust P) could decrease or eliminate the basic BSFC penalty.

Figures 23 and 24 illustrate the efforts of Cessna Aircraft, under subcontract to Curtiss-Wright, to optimize the installation of the "advanced-technology" rotary engine in a typical single-engine aircraft. The study airplane is a derivative of Cessna's current P210 model (top sketch); resized first to accept the baseline TSIO-550 engine, and then for the advanced RC 2-47 study engine. For the same range, payload and performance constraints, the airplane weight was reduced by 530 lbs out of 4330 lbs, a savings of about 12%. Figure 26, a carpet plot showing wing area and aspect ratio effects on gross weight, illustrates the treatment of constraints in this study. Constant minimum cruise speed and maximum stall speed contour lines are illustrated, with "acceptable" regions falling on the non-hatched sides of the curves. Thus, the airplane can be sized anywhere in the roughly triangular area shown. The final choice of aspect ratio = 8.0 and wing area = 150 ft^2 is then somewhat arbitrary, and the selected gross weight of 3800 lbs could have been sized at 3600 lbs or less by crowding the constraint margins.

COMPARING THE ALTERNATE ENGINES - As a logical follow-on to the engine studies described or referred to above, two independent application studies have been initiated to compare the performance and economic benefits of the four candidate engines in typical g/a airplanes and missions. One of these, conducted in-house at LeRC[18], involved an approximate analysis of a broad range of airplanes and missions. The other is being handled via ongoing contracts to Beech and Cessna, and will take a much more detailed look at two selected airplane/ mission combinations. Since the Beech and Cessna results were not available at the manuscript deadline, this section will present only a brief summary of the LeRC in-house study.

Powerplant Characteristics - The GATE turboprop studies and the three IC engine studies were conducted under separate NASA programs and involved some significant differences in objectives and technical emphasis. The GATE studies primarily emphasized reduced manufacturing cost, even at some small penalty in efficiency, since this area is seen as a major impediment to the more widespread adoption of small turbines. For similar reasons, the IC engine studies emphasized weight and TBO improvements, generally concluding that their direct manufacturing costs should be on the same order as those of current piston engines. In addition, the IC engine studies addressed two distinctly different levels of technology where GATE addressed only one. The most desired IC engine technology level was defined, as in the GATE efforts, as being "...the most advanced level of technology consistent with commercial introduction in the early 1990's..." However, a lower-risk or fallback level was also defined for the IC candidates, which might be more appropriate to an austere funding environment.

These factors, together with the differences of technological optimism, future funding expectations and other subjective judgments inherent whenever studies are carried out by several different contractors, mean that the comparisons to follow are not necessarily the most consistent. In particular, the issues of relative cost and relative risk between different engine concepts are admittedly subjective and controversial at this time. Readers desiring to alter the basic engine input assumptions may do so by using published sensitivity information[18], which contains a more complete review of these comparisons.

In the following several figures, results pertaining to the most-desired (Ca. 1992) and reduced-risk IC engine technologies will be denoted by the adjectives "very advanced" and "advanced," respectively. The single level of turboprop technology that has been considered is denoted simply as "GATE".

Figure 25 collectively shows the cruise BSFC's of this group of engines at 25,000 ft. altitude, as a function of maximum sea-level rated horsepower. The advanced IC engines are 15-20% more efficient than today's piston engines while the very advanced versions are 20-25% better. The GATE turboprop efficiency is much more sensitive to engine size effects which precludes its competitiveness at low power ratings. Below 300 SHP the turboprop utilizes a 9:1 pressure ratio core, but above 300 SHP an extra compressor (and turbine) stage is added to raise the pressure ratio to 12:1 with a corresponding efficiency improvement.

The forecasted weight improvements are shown in Figure 26 on an installed engine basis (e.g., including gearing, accessories, oil, coolant, etc.) for 350 SHP size engines. Considerable improvement potential is indicated for all types but particularly so for the very advanced diesel (1.0 lb/hp) and rotary (0.8 lb/hp). The weight reductions are due to the use of lighter materials, higher BMEP and RPM levels, turbosupercharging, and low parts counts. Such light weights in combination with superior BSFC's offer very stiff competition for the normally ultra-lightweight turboprop (0.6 lb/hp).

Several other engine assumptions are shown in Figure 27. The diesel, rotary and spark-ignited recip (SIR) engines have nominal critical altitudes of 17,000, 20,000, and 21,000 feet respectively. The diesel and the SIR are assumed to cruise at 70 percent maximum rated power, while the rotary cruises at 75 percent power. The turboprop was assumed to cruise at 2140^{0} F turbine rotor inlet temperature which is equivalent to about 80 percent of the maximum available power at any given altitude and flight speed. At 25,000 feet altitude, the turboprop cruise power ranged from 54 to 60 percent of the sea level maximum power, depending on flight speed. Engines which do not have multifuel capability were assumed to use aviation gasoline at $1.10/gallon while engines having multifuel capability were assumed to use Jet A fuel at $1.00/gallon (1979 economics).

Mission Analysis - In order to put the combination of projected engine improvements in efficiency, weight, and costs into perspective, a series of 13 missions was defined and a scaled version of each powerplant was hypothetically installed in an appropriately scaled aircraft to accomplish each mission. These missions are defined in Figures 28 and 29. Both single and twin engine airplanes as well as two helicopter applications were investigated. Two groups of aircraft are presented: (1) current--resembling today's aircraft and missions, but slightly better airframe technology, and (2) futuristic--with 15 percent reduction in aircraft empty weight, 15 percent reduction in aircraft zero-lift drag, engines submerged in the fuselage, higher wing loading and aspect ratios, fullspan Fowler flaps, and higher cruise speeds and altitudes.

The current altitude limit shown in Figure 28 is the approximate limit imposed on current IC engines due to turbocharging capability. Projected improvements in turbocharging technology will raise the limit. The high altitude missions 7 and 11 were included specifically to investigate possible shifts in ranking due to (1) the critical altitude assumptions for the IC engines and (2) the lapse rate and cabin pressurization losses of the turboprop.

Figure 30 shows the fuel savings improvement relative to a current technology piston engine. These results were obtained using the General Aviation Synthesis Program (GASP) mentioned in reference 18. The missions in these figures are grouped in order of increasing cruise altitude and, within each altitude group, in order of increasing cruise speed. The projected fuel savings for the 25,000 foot altitude missions are 25-35 percent for the advanced technology versions and 35-45 percent for the very advanced versions. About 5 percent lower fuel savings occur for the 10,000 foot altitude missions. This is a consequence of selecting a naturally-aspirated SIR (with its 7 percent better BSFC) for the lower altitude baseline but a turbocharged SIR for the higher altitudes while assuming that all future engines would require a turbocharger to meet engine weight and BSFC projections, even at low altitudes.

Except for the turboprop, not much sensitivity is shown in the results to mission definition. This reflects the moderate differences in BSFC and engine weight among engine types as displayed in Figures 25 and 26. Due to its light weight, the turboprop competes relatively well at 25,000 feet, but for the lower and slower missions (1, 2, 3, 5) it does not, because efficiency drops for small sizes and aircraft power loading is low. Overall, the advanced IC engines compete so closely with each other that no clear-cut ranking is apparent. Even for the very advanced versions, which show more spread, the differences displayed could easily shift with differing (but equally plausible) assumptions. The very advanced diesel is shown to be the most fuel efficient type due to its low weight, low BSFC, zero cooling drag, and high cruise power rating (75 percent).

The fuel savings shown are in terms of fuel weight rather than fuel cost. The actual cost savings are about 20 percent greater due to the fuel density and price advantage of Jet A and diesel fuel compared to aviation gasoline. Turboprop and diesel engines already utilize the lower grade fuels while the current and advanced SIR types do not. Both the advanced and very advanced rotary engines and the very advanced SIR would also use Jet A or diesel as the fuel of choice. The stratified-charge/diesel engines have an additional fuel flexibility advantage in that avgas can be used as an alternative fuel, in areas where Jet A or diesel fuel is not available.

Aircraft takeoff gross weight reductions relative to current piston engines are displayed in Figure 31 for the very advanced positive displacement engines plus the GATE turboprop. For clarity, improvements for the "advanced" IC engines are not shown, but are about 50 percent less than for the "very advanced" IC engines seen in the figure, and without shifts in relative ranking. Again, the high altitude missions lead to greater improvement potential (20-31 percent) than for the low altitude missions (10-28 percent). For the gross weight criterion, the rotary engine shows about a 5 percentage point greater gain than the diesel, which in turn is only a percentage point or so better than the SI recip. However, the most significant difference in looking at gross weight rather than fuel burned is the large upward shift in ranking of the turboprop.

Improvements in empty weight (not shown) parallel those of gross weight but are 5-9 percentage points greater. The only shift in relative ranking occurs for the turboprop airplane, which gains 1-4 percentage points relative to the IC engine cases due to its low engine weight. To the degree that aircraft price is proportional to empty weight and total ownership is proportional to gross weight, these results reflect corresponding benefits in aircraft economics. In the case of the turboprop, however, major engine cost reductions also need to be accomplished. (This, in fact, is a major objective of the proposed GATE program.) Assuming powerplant cost parity, 5-year total cost of ownership benefits were calculated as shown in Figure 32. Regions of cost improvement are displayed rather than specific data due to the controversial cost assumptions among different engine types. The main point is that economic benefits of as much as 30-45 percent are possible with very advanced technology engines flying high altitude missions, and even 10-20 percent gains are possible for lower technology engines at low altitudes. The overall interpretation is that all of these alternatives offer substantial improvement potential and, therefore, all should be retained as competitive candidates. Similar results for the helicopter missions were previously reported[18].

High Altitude Missions - Cruising altitudes as high as 30,000 to 45,000 feet have been suggested for some future general aviation airplanes. While this is a controversial issue, missions 7 and 11 were, nevertheless, included to explore the ramifications of such extreme altitudes on powerplant selection. Current production turbocharged SIR engines are not normally capable of flying these high altitude missions due to turbocharger limitations and cooling problems. However, it is felt that an opportunity may exist to substantially improve turbocharger and cooling technologies, and thereby permit operation at higher cruise altitudes. If so, then advanced IC engines would have the advantage of avoiding the high power lapse suffered by turboprops, provided the complexity and penalties associated with high altitude turbochargers (yet to be determined) do not overshadow the lapse rate advantage. The very advanced SIR was arbitrarily chosen to compare with the GATE turboprop to determine the effect of high altitudes on powerplant selection.

The results of varying the cruise altitude with these assumptions are displayed in Figure 33. These results are for mission 11, an 8-place executive twin with a nominal 45,000 foot cruise altitude. Similar results were obtained for mission 7, a 6-place high performance single. With an ideal turbocharger--one capable of providing 70 percent engine rated power regardless of altitude and without any weight or BSFC penalties--the SIR airplane performance improves continuously with higher cruise altitude, reflecting better aircraft L/D (wing loading was not optimized for maximum L/D as altitude varied). If the turbocharger has a critical altitude of 21,000 feet, the SIR engine is able to provide 70 percent power to about 35,000 feet, and then decreases to 56 percent at 45,000 feet.

The turboprop powered airplane performance is not only affected by improving L/D, but also by the turboprop power lapse and cabin pressurization penalty. The power lapse must be offset by an increase in engine size--the improving BSFC associated with the larger engine is offset by the accompanying weight penalties. As can be seen in the figure, the idealized SIR is about 10 percent better than the turboprop in terms of fuel and about 3 percent better in terms of airplane gross weight at 45,000 feet. The 21,000 foot critical altitude SIR is equal to the turboprop in terms of fuel but has a 6 percent advantage in airplane gross weight. At high altitudes, the SIR may be better than the turboprop if very high critical altitudes can be successfully achieved without significant penalties.

Effect of Cruise Speed - As cruise speed is increased, all of the advanced engine types show increasing improvement relative to 1980 SI piston engines. Figure 34 shows an example case with a baseline speed of 270 knots (mission 10, Fig. 29). Though actual fuel burned and gross weight worsen with speed for all advanced engine types, the current technology SIR engine worsens at a faster rate. As the speed increases, the higher aircraft power loading offers the lighter engines more potential for improvement. The turboprop, with the lowest specific weight, favorable performance scaling trends, and forward velocity effects has a significantly larger rate of improvement than the other engine types. In this particular case, the turboprop-powered aircraft would be as fuel efficient as any of the very advanced IC engines if the cruise speed were raised above 350 knots.

The effect of cruise range was also investigated but no significant shift in engine ranking occurred over a wide band of cruise range. Hence, for the short missions flown by general aviation, range is not an important parameter in choosing an alternative powerplant.

Mission Analysis Summary Remarks - Each of the new engines offers substantial aircaft efficiency and economic improvements in terms of aircraft gross weight and mission fuel. To compare these alternative powerplants globally involves considerations of many more characteristics than the figures of merit presented herein. Engine price, maintenance, vibration, emissions, noise, reliability, technical risk and other factors must all be taken into account in a more consistent fashion. With the relative closeness of the projected improvements, it is now premature to draw firm conclusions regarding the relative attractiveness of the alternative engines.

CONCLUDING REMARKS

In conclusion, very satisfying technical progress has been reported relative to potential near-term improvements for current-production type engines. The original objectives have been met already, and it is felt that other ongoing NASA-sponsored programs in cooling and turbocharging, coupled with industry's in-house efforts, will yield significant further gains. With the completion of these efforts in 1981 and 1982, the emphasis of future NASA IC engine research will begin to focus more heavily on the longer-term, higher-technology type of engines. These are generally of the diesel or stratified-charge variety. It was also reported that major progress has been made in developing the combustion-research, computer cycle modeling and diagnostic instrumentation capabilities that must underly these advanced engine undertakings.

All of the engine studies have progressed to the point where very attractive performance, weight, TBO, and cost numbers have been generated. It should be recalled that the three IC engines were defined in both "very advanced" and lower-risk ("advanced") versions, in order to provide a wider range of options to the industry. The difference between these engines is more a question of intensity of effort than of timing, with the lower-risk engines being more appropriate for an austere funding environment. As previously shown, the most advanced engine versions typically lead to a 25% lighter airplane and a 40% (by weight) reduction in mission fuel. Since kerosine is used rather than avgas, the fuel savings is closer to 50% in terms of gallons of finished fuel, 52-54% in terms of crude oil refinery input, and probably 55% or more in terms of 1981 dollars. These savings together with extended TBO times and other attributes should result in excellent economics for the final product.

As previously mentioned, the in-house comparative studies are complete[18] and the Beech and Cessna contracts are well underway. We should thus have a good sorting-out of the four future g/a engine concepts, relative to one another and to a representative current-production engine, by the middle of 1981. In conclusion, it is perhaps appropriate to take a final look at how the comparisons stand today. For brevity, consider just three of the advanced alternative engines--a representative GATE turboprop, the "advanced" gasoline engine, and the "very advanced" version of the lightweight diesel. The turboprop is of interest due to its inherent advantages of minimum noise, vibration and weight, and its good potential for long TBO's. On the other hand, it is less efficient than the others and its viability depends upon substantial cost reductions--always a risky proposition. The advanced gasoline engine is one which is believed to be developable with fairly routine efforts and could be viewed either as a testbed for the corresponding highly advanced technology engine or as a potential product in its own right. This is believed to be the lowest-risk engine within the scope of the recent studies. Although heavier than the others, it is reasonably efficient. Being similar to its manufacturer's current products, cost projections in this case are generally credible. Unfortunately, this engine's viability depends upon indefinitely-continued supplies of avgas, whose long-term availability and cost are somewhat in doubt. The very advanced diesel and stratified-charge engines depend upon larger technological steps (in such areas as turbocharging, combustion-chamber insulation and lubrication) than could be expected in the normal course of events. They are, nevertheless, the most fuel-efficient engines identified in the studies reviewed herein.

The three above-mentioned engines are representative of the three main classes of technology encompassed in the recent studies. The results to follow should, therefore, be interpreted broadly, i.e., among technology classes, but not between individual engines or manufacturers. The bargraphs in Figure 35 represent airplane and mission fuel weight savings compared to airplanes powered by a baseline, 1980-technology spark-ignition engine. Two airplanes are shown, both 6-passenger, pressurized, retractable models capable of cruising at 25,000 ft. and 250 kt or more. The single has a design range of 1000 n. mi. while the long-range twin can go 1600 n. mi. These results were generated via in-house LeRC calculations; however, the airplanes/missions chosen are fairly representative of those being considered in the Beech and Cessna contracts.

The results show that all 3 engines give attractive savings in airplane size and fuel usage. In terms of airplane size, the results are fairly close in that the difference between any two is smaller than the overall benefit produced by any one. The turboprop and the diesel would use the same commodity-type fuel--Jet A or its eventual broad-spec. successor. The fuel savings shown are in terms of weight, but are actually considerably larger in terms of gallons or dollars, considering the kerosine/avgas density and price ratios. In terms of fuel usage, the very advanced IC engine has a large edge over the others. This should be no surprise, since even WW II-vintage aircraft diesels[19] provided cruise BSFC's approaching those reported here. What the recent studies accomplished, in effect, was to show that a judicious combination of modern design and advanced technology can reduce the weight of these otherwise-attractive powerplants to very competitive values. As a result, it now appears that, despite years of neglect, the lightweight diesel and stratified-charge IC engines will emerge as the most efficient g/a engines of the future.

REFERENCES

1. "General Aviation and Energy - R&D Needs for the 1980's," General Aviation Manufacturing Association Position Paper, July 6, 1979.

2. "FAA Aviation Forecasts; Fiscal Years 1980-1991," Federal Aviation Administration, FAA-AVP-79-9, September 1979.

3. W. D. Bachalo and M. J. Houser, "Requirements for Fuel Injector Characterization Studies," (Spectron Development Labs., Inc., Costa Mesa, CA, NASA CR-165200.

4. B. J. Rezy, K. J. Stuckas, J. R. Tucker, and J. E. Meyers, "Concepts for Reducing Exhaust Emissions and Fuel Consumption of the Aircraft Piston Engine," SAE Paper 790605, April 1979.

5. J. M. Lewis and W. T. Tierney, "United Parcel Service Applies Texaco Stratified Charge Engine Technology to Power Parcel Delivery Vans - Progress Report," SAE Paper 801429, November 1980.

6. W. J. Rice and A. G. Birchenough, "Modular Instrumentation System for Real-Time Measurements and Control on Reciprocating Engines," NASA TP-1757, November 1980.

7. H. J. Schock, W. J. Rice, and P. R. Meng, "Experimental Analysis of IMEP in a Rotary Combustion Engine," proposed paper to be presented at the 1981 SAE International Congress and Exposition, Detroit, MI, February 23-27, 1981, also proposed NASA TM.

8. H. C. Gerrish and B. E. Ayer, "Influence of Fuel-Oil Temperature on the Combustion in a Prechamber Compression-Ignition Engine," NACA TN-565, April 1936.

9. F. J. Zeleznik and B. J. McBride, "Modeling the Complete Otto Cycle-Preliminary Version," SAE 770223, February 1977.

10. R. N. Moffett, "Exhaust Emission Reduction for Intermittent Combustion Aircraft Engines," Avco Lycoming Div., Williamsport, PA, October 1979. NASA CR-159757, October 1979.

11. A. P. Brouwers, "A 150 and 300 kW Lightweight Diesel Aircraft Engine Design Study," NASA CR-3260, April 1980. "Design Study: A 186 kW Lightweight Diesel Aircraft Engine," NASA CR-3261, April 1980.

12. C. F. Baerst and D. G. Furst, "General Aviation Turbine Engine (GATE) Study," AiResearch Manufacturing Co., of Arizona, Phoenix, AZ, AIRESEARCH-21-2997, February 1979. NASA CR-159482, February 1979.

13. J. C. Gill, F. R. Short, D. V. Staton, B. A. Zolezzi, C. E. Curry, M. J. Orelup, J. M. Vaught, and J. M. Humphrey, "Study of an Advanced General Aviation Turbine Engine (GATE)," Detroit Diesel Allison, Indianapolis, IN, DDA-EDR-9528, April 1979. NASA CR-159558, April 1979.

14. R. Smith and E. H. Benstein, "Advanced General Aviation Turbine Engine (GATE) Study," Teledyne CAE, Toledo, OH, CAE-1600, June 1979. NASA CR-159624, June 1979.

15. E. J. Lays and G. L. Murray, "Advanced General Aviation Turbine Engine (GATE) Concepts," Williams Research Corp., Walled Lake, MI, WRC-78-113-15, June 1979. NASA CR-159603, June 1979.

16. K. J. Stuckas, "Advanced Spark-Ignition Aircraft Piston Engine Design Study," Teledyne Continental Motors, Mobile, AL, NASA CR-165162, November 1980.

17. C. Jones and M. Berkowitz, "Multifuel Rotary Aircraft Engine," AIAA Paper 80-1237, June 1980.

18. T. J. Wickenheiser, G. Knip, R. M. Plencner, and W. C. Strack, "Comparisons of Four Alternative Powerplant Types for Future General Aviation Aircraft," NASA TM-81584, October 1980.

19. P. H. Wilkinson, "Aircraft Diesels," New York, NY, Pitman Publishing Corporation, 1940.

o IMPROVED SAFETY (PRODUCT LIABILITY)

o IMPROVED AIR TRAFFIC CONTROL

o IMPROVED ENERGY EFFICIENCY (<u>SURVIVAL ISSUE</u>)

o PROPULSION TECHNOLOGY A KEY AREA - SPECIFIC NEEDS

- REDUCED FUEL CONSUMPTION, WEIGHT & DRAG
- MULTIFUEL CAPABILITY (AVGAS & JET/DIESEL)
- BETTER RELIABILITY, DURABILITY, MAINTAINABILITY, FEWER FAILURE MODES
- NEAR TERM & LONG TERM TECHNOLOGY

Figure 1. - General Aviation Industry - needs/concerns.

o NEAR TERM IMPROVEMENTS -- TEST ENGINE INTEGRATING THE 4 MODS MET THE EMISSION STANDARDS AND DEMONSTRATED 10-11% IMPROVEMENT IN HIGH-PERFORMANCE CRUISE FUEL ECONOMY, 30% IMPROVEMENT OVER LTO CYCLE, FLIGHT DEMO PLANNED FY 81

o COOLING -- TCM CONTRACT UNDERWAY, CSD MANPOWER COMMITTED

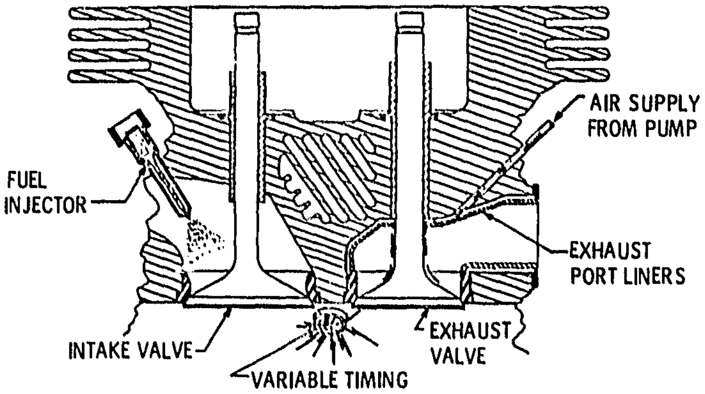
o FUEL INJECTION -- TECHNICAL EFFORT COMPLETE ON SPECTRON SPRAY CHARACTERIZATION CONTRACT.

-- IN-HOUSE FLOW VISUALIZATION FACILITY OPERATIONAL, INITIAL RESULTS GENERATED.

o ADV. TURBOCHARGER -- STUDY CONTRACT BEING NEGOTIATED

o AVGAS WORKSHOP -- PLANS FIRMED UP FOR FEBRUARY 3, 4, & 5, 1981

Figure 2. - Piston engine technology - status summary.



EMISSIONS	PRODUCTION ENG.	MODIFIED ENG.
CO% EPA STD.	182	20
HC% EPA STD.	127	1
NOx% EPA STD.	10	78
30% FUEL SAVINGS ON LTO CYCLE 10% FUEL SAVINGS IN 75% POWER CRUISE MODE		

Figure 3. - Concept integration.

OBJECTIVE: DEVELOP COMBUSTION DIAGNOSTIC CAPABILITIES AND PREDICTIVE COMBUSTION/CYCLE PERFORMANCE MODELS FOR SCIENTIFIC I.C.E. DESIGN

APPROACH:

- o COMPUTER MODELING OF I.C.E. COMBUSTION AND FLOW PROCESSES
  - RAPID APPROXIMATE CODES FOR STUDY
  - DETAILED MULTIDIMENSIONAL CODE FOR DESIGN
- o EXPERIMENTAL VALIDATION/REFINEMENT OF ABOVE
- o DEVELOPMENT AND UPGRADING OF FACILITIES AND INSTRUMENTATION
- o COMBUSTION DIAGNOSTIC INSTRUMENTATION
  - REAL TIME IMEP, MASS FRACTION BURNED
  - IONIZATION PROBES
  - SAMPLING VALVE/MASS SPECTROSCOPY
  - LASER DOPPLER VELOCIMETRY (LDV)
  - LASER/INFRARED SPECTROSCOPY

Figure 4. - Combustion diagnostics and modeling.

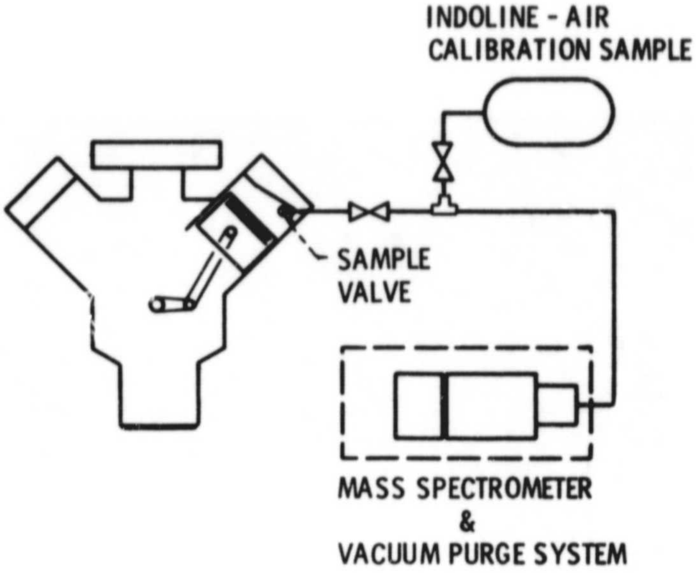


Figure 5. - Sample analysis system.

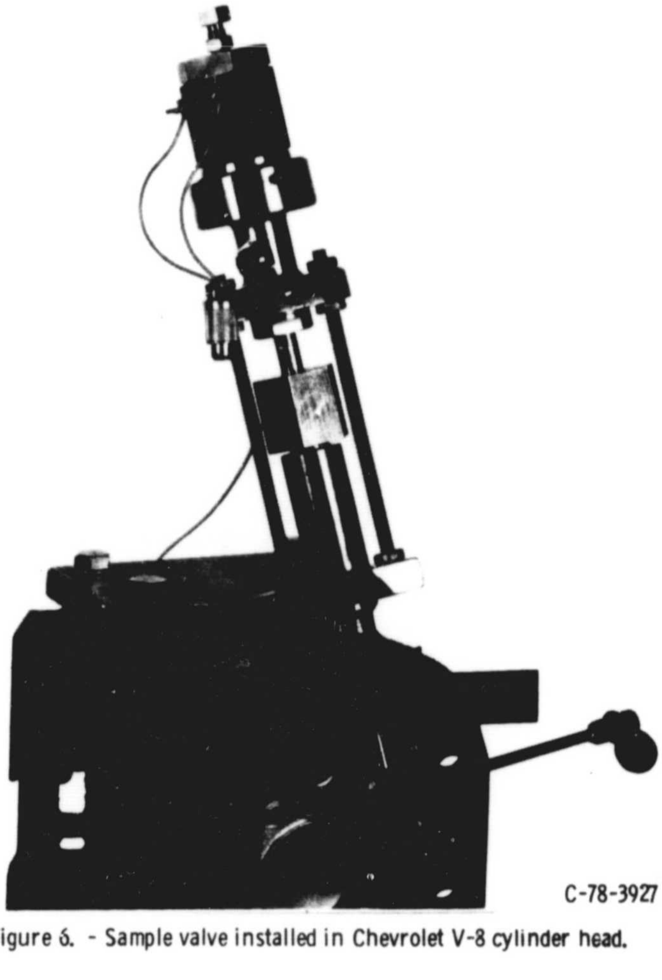


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Figure 6. - Sample valve installed in Chevrolet V-8 cylinder head.

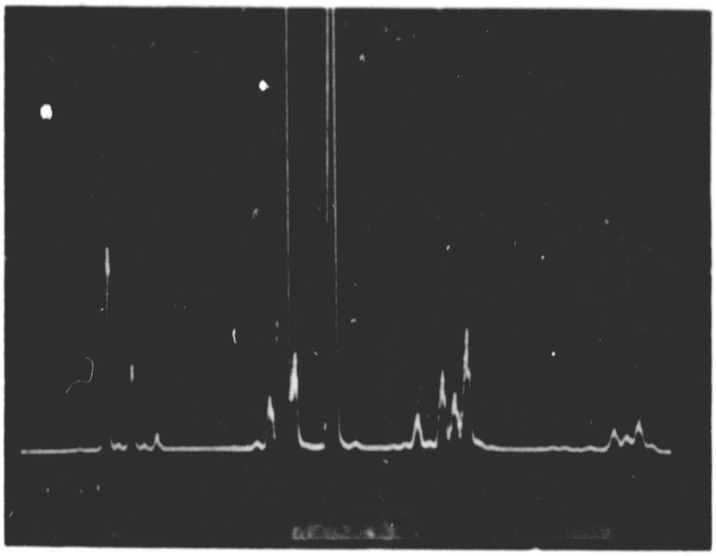


Figure 7. - Typical output of mass spectrometer.

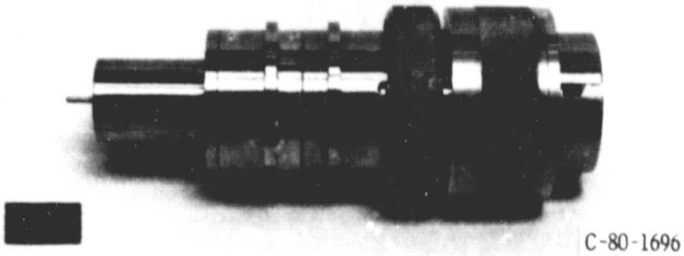


Figure 8. - NASA sampling valve.

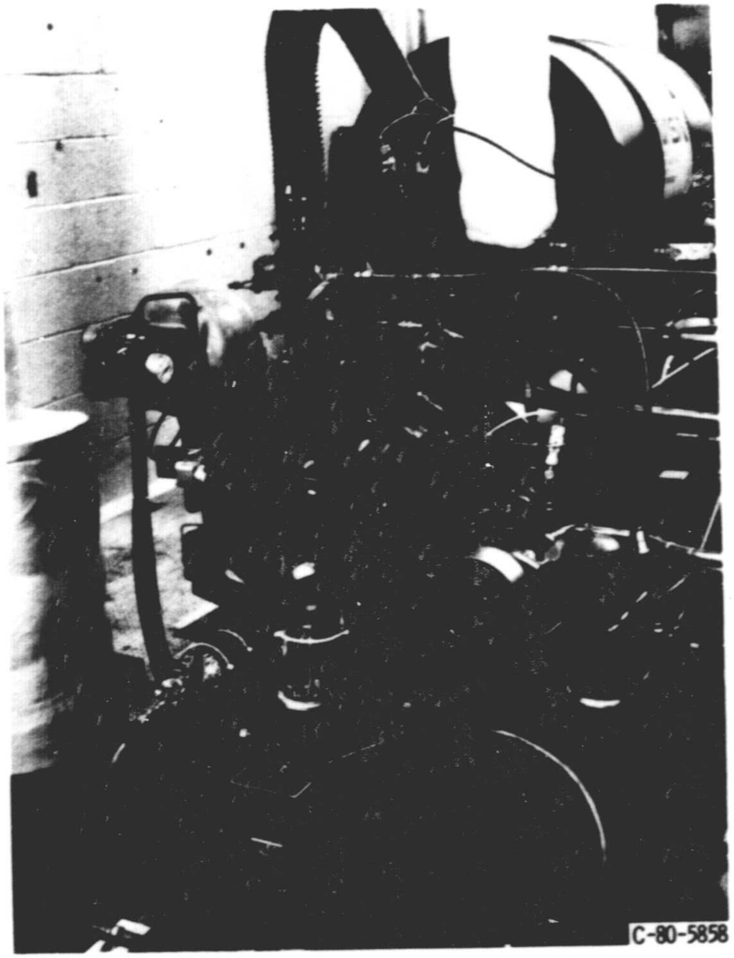


Figure 9. - Single cylinder, stratified charge test rig.

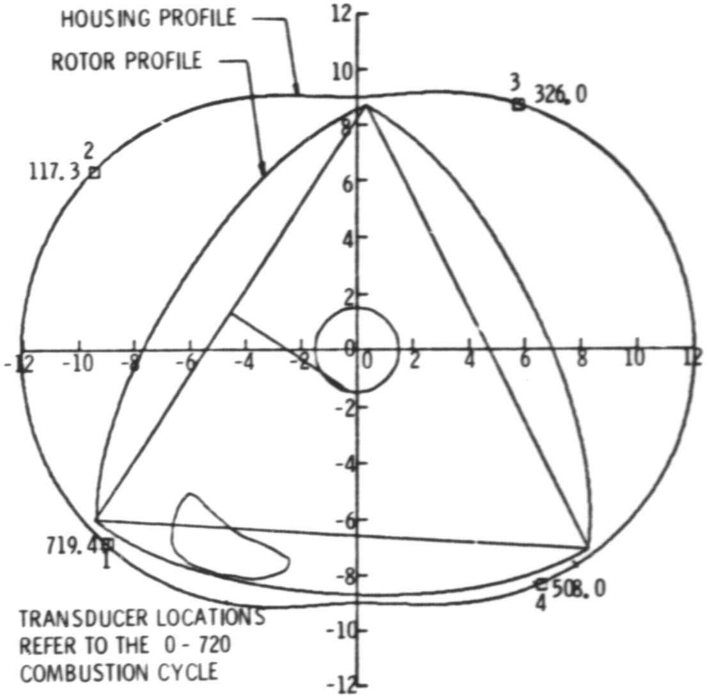


Figure 10. - Transducer locations.

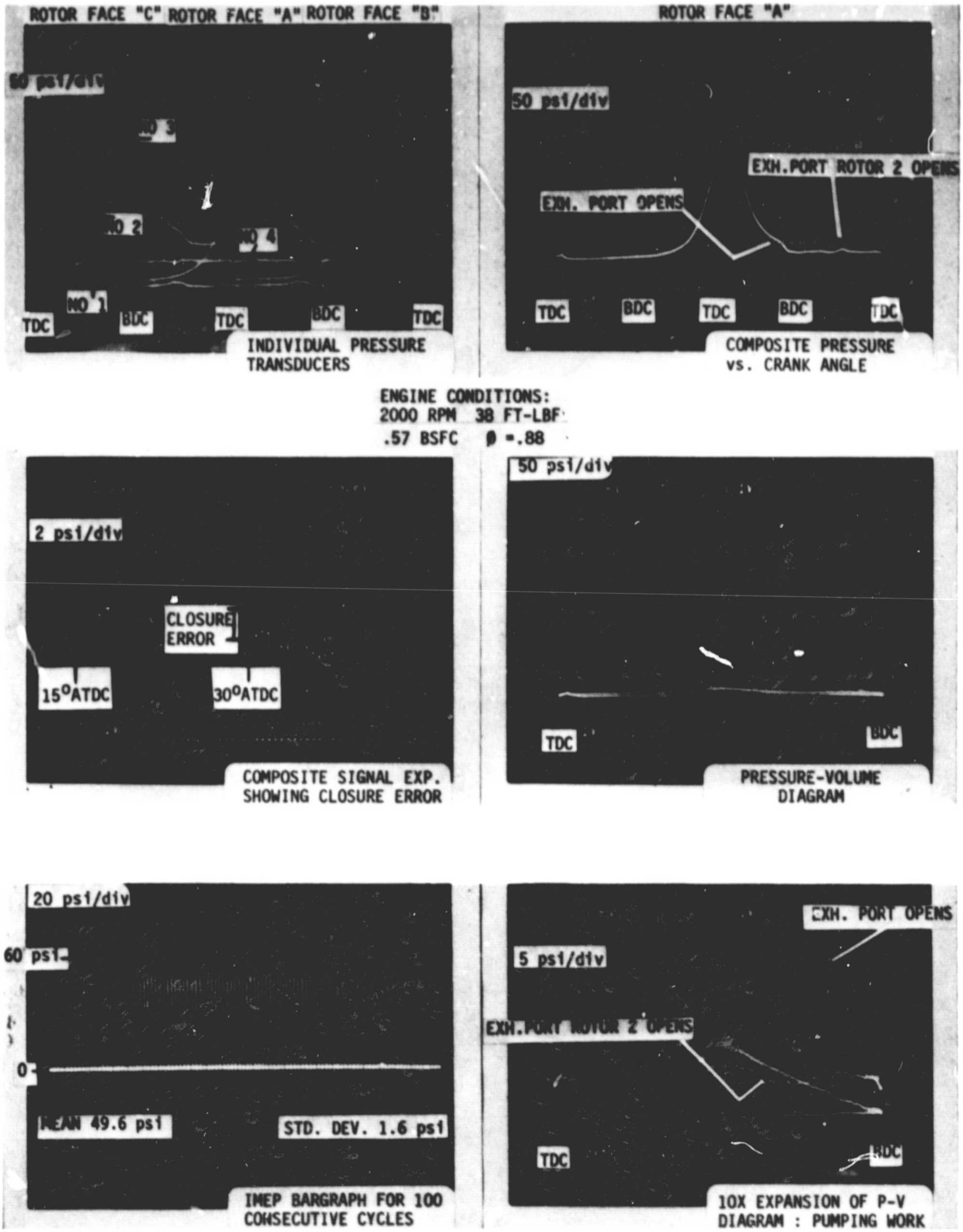


Figure 11. - Rotary engine IMEP data.

CONCEPT: FUEL IS PREHEATED TO ABOVE ITS THERMAL DECOMPOSITION TEMP AND INJECTED AT SUPERCRITICAL PRESSURE

THIS RESULTS IN NEGLIGIBLE IGNITION LAG

BENEFITS:
- o CAN TAILOR P-V DIAGRAM
- o REDUCED P MAX
- o NO DIESEL KNOCK
- o MULTIFUEL CAPABILITY
- o INCREASED POWER
- o IMPROVED EFFICIENCY
- o NO COMBUSTION CHAMBER DEPOSITS
- o NO HI-TENSION IGNITION
- o SYNERGISTIC WITH ADIABATIC OPERATION
- o APPLICABLE TO ALL ENGINES

STATUS:
- o APPROXIMATE THEORY RECEIVED POSITIVE EVALUATION
- o CONSISTENT WITH LIMITED EXPERIMENTAL DATA AVAILABLE
- o ARMY/NASA JOINT PROGRAM UNDER CONSIDERATION
  - \- ARMY: ENGINE EXPT'S (SINGLE & MULTI CYL.)
  - \- NASA: BASIC COMBUSTION (UNIV. GRANTS)

Figure 12. - Hypergolic fuel injection/ignition.

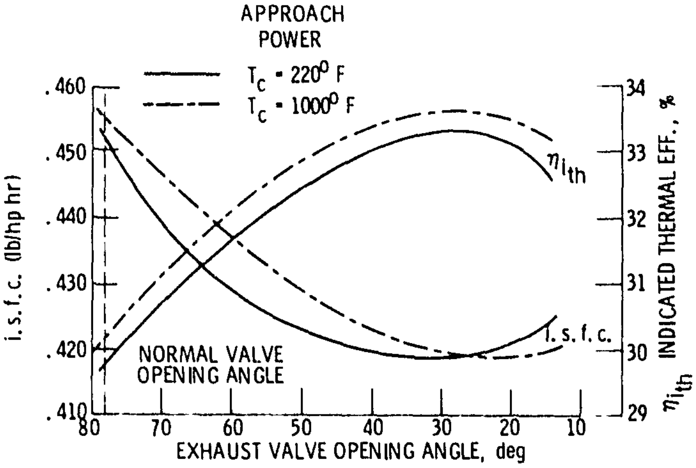


Figure 13. - i.s.f.c. and indicated thermal efficiency, $\eta_{i_{th}}$ versus exhaust valve open angle.

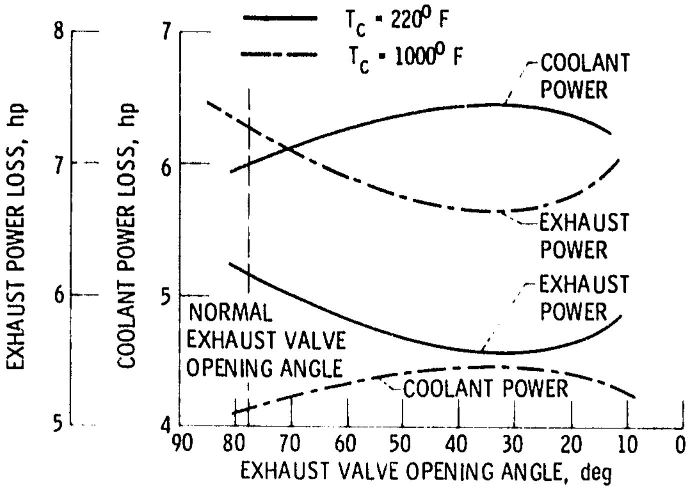
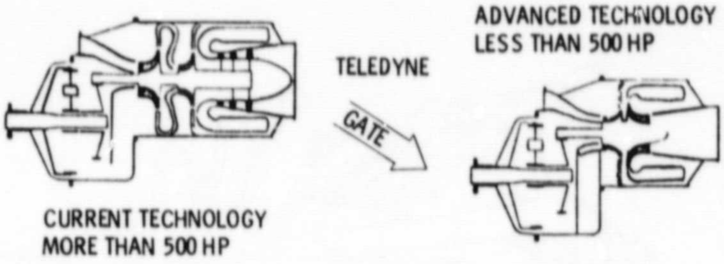


Figure 14. - Coolant power and exhaust power loss, hp versus exhaust valve open angle.

OBJECTIVE: ESTABLISH THE TECHNOLOGY BASE FOR ADVANCED IC ENGINES WHICH HAVE 30% - 50% REDUCED FUEL CONSUMPTION, LOW EMISSIONS, AND BROAD-SPEC. FUEL CAPABILITY

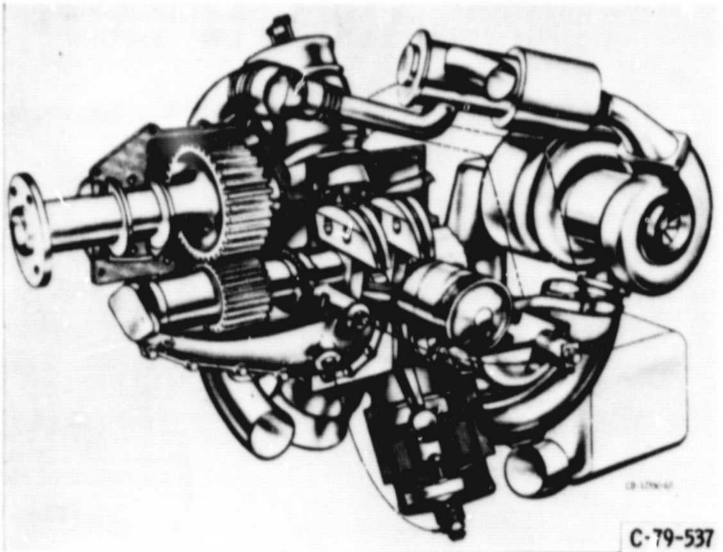
TARGETS:
- o (1980) COMPLETE ALTERNATIVE ENGINE DESIGN STUDIES AND AIRPLANE/MISSION EVALUATIONS AND DEFINE TECHNOLOGY NEEDS
- o (1981) SELECT ONE OR MORE CANDIDATE(S) FOR 1982 AUGMENTED PROGRAMS
- o (CONTINUING) SUPPORTING TECHNOLOGY INVESTIGATIONS
- o (1982) INITIATE AUGMENTED ENGINE TECHNOLOGY ENABLEMENT PROGRAMS

Figure 15. - Alternative propulsion systems.



	ENGINE COST SAVINGS	
2 CENTRIFUGAL COMPRESSORS	10%	1 CENTRIF. COMPRESSOR
3 AXIAL TURBINES	16%	1 RADIAL TURBINE
HYDROMECHANICAL CONTROLS	12%	ELECTRONIC CONTROL
ATOMIZING COMBUSTOR	2%	VAPORIZING PLATE COMB.
8-1/2 PR/1900° F CYCLE	9%	9.0 PR/2250° F CYCLE
	49%	

Figure 16. - Advanced technology investment reduces engine price.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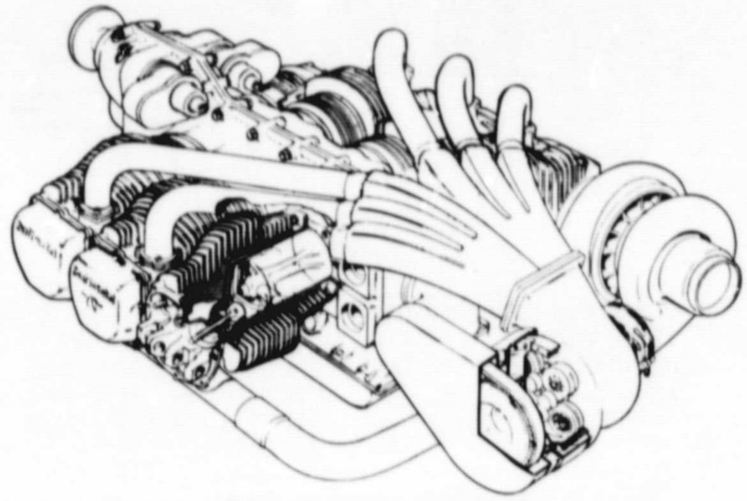
	ADVANCED VERSION	NEARER-TERM VERSION	
CRUISE BSFC	0.32	0.37	LBS/BHP-HR
SPECIFIC WEIGHT	1.02	1.14	LBS/TOHP

Figure 17. - Lightweight diesel aircraft engine study.



	ADVANCED VERSION	NEARER-TERM VERSION	
CRUISE BSFC	0.33	0.36	LBS/BHP-HR
SPECIFIC WEIGHT	1.16	1.39	LBS/TOHP

Figure 18. - Artist's conception of high risk technology engine.

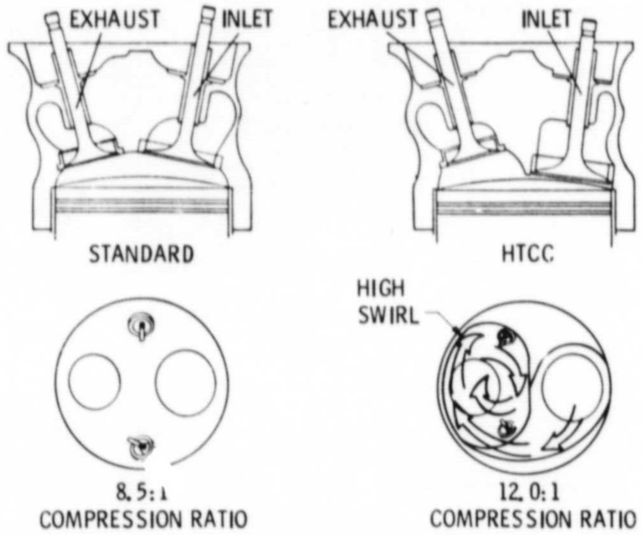


Figure 19. - High compression ratio/lean burn combustion chamber.

	CURRENT TECHNOLOGY TSIO-550	PERCENT IMPROVEMENT	MODERATE-RISK TECHNOLOGY GTSIO-420	PERCENT IMPROVEMENT	HIGH-RISK TECHNOLOGY GTSIO-420/SC
CONFIGURATION ENGINE DISPLACEMENT	6-Cylinder/Horiz. Opposed 550 Cubic Inches	—	6-Cylinder/Horiz. Opposed 420 Cubic Inches	—	6-Cylinder/Horiz. Opposed 420 Cubic Inches
MAXIMUM RATED POWER/SPEED	350 Bhp/2,800 rpm	—	350 Bhp/3,200 rpm	—	350 Bhp/3,200 rpm
BRAKE SPECIFIC FUEL CONSUMPTION AT MAXIMUM CRUISE POWER (250 Bhp)	0.448 lb/Bhp-hr	20%	0.358 lb/Bhp-hr	26%	0.331 lb/Bhp-hr
SERVICE CEILING	25,000 ft	40%	35,000 ft	40%	35,000 ft
INSTALLED ENGINE WEIGHT	585 lb	17%	485 lb	31%	405 lb
TYPE OF FUEL	100 Octane	—	100 Octane	—	Jet A
TIME BETWEEN OVERHAUL	1,400 hr	43%	2,000 hr	43%	2,000 hr
EXHAUST ENERGY RECOVERY SYSTEM	Turbocharging	—	Turbocharging Turbocompounding	—	Turbocharging Turbocompounding
EXHAUST POWER UNRECOVERED AT MAXIMUM CRUISE POWER	319 hp	33%	214 hp	51%	156 hp

Figure 20. - Engine specification comparison.

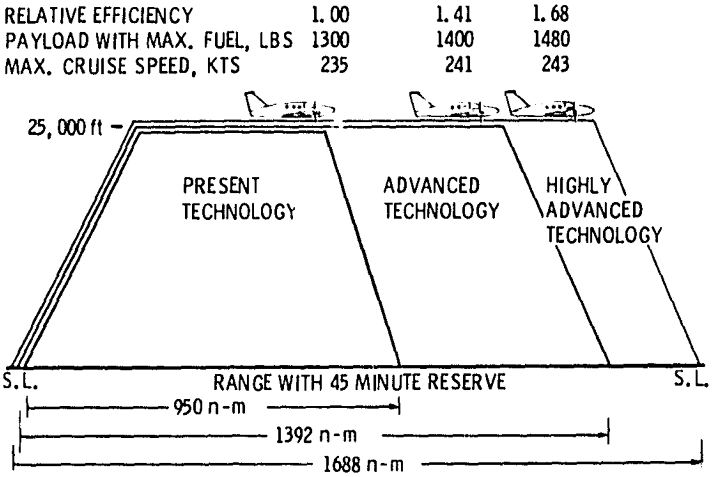
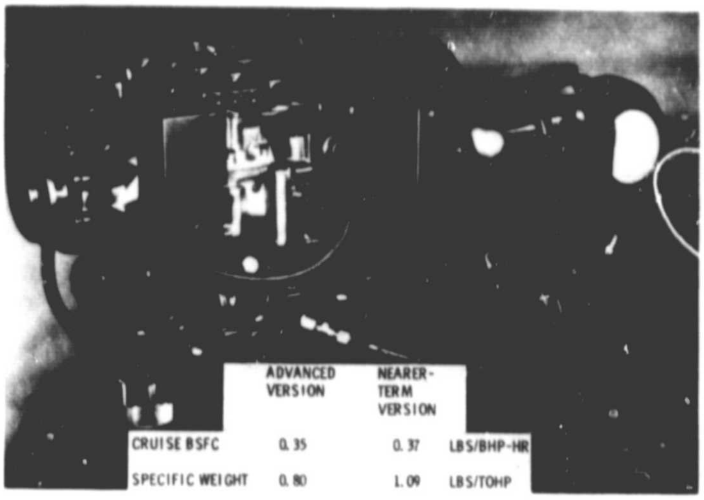


Figure 21. - Advanced technology twin-engine airplane.



	ADVANCED VERSION	NEARER-TERM VERSION	
CRUISE BSFC	0.35	0.37	LBS/BHP-HR
SPECIFIC WEIGHT	0.80	1.09	LBS/TOHP

Figure 22. - Multifuel rotary engine study.

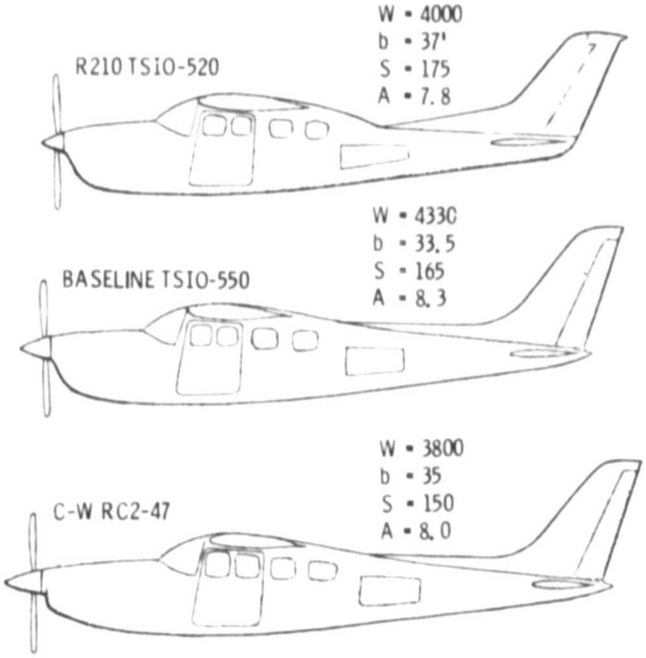


Figure 23. - Airplane/engine comparisons.

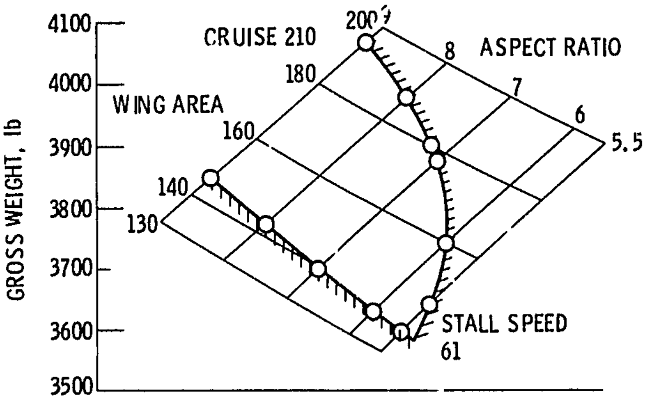


Figure 24. - Airplane sizing with Curtiss-Wright single engine RC2-47. Takeoff and climb performance exceeds constraint values for all design points.

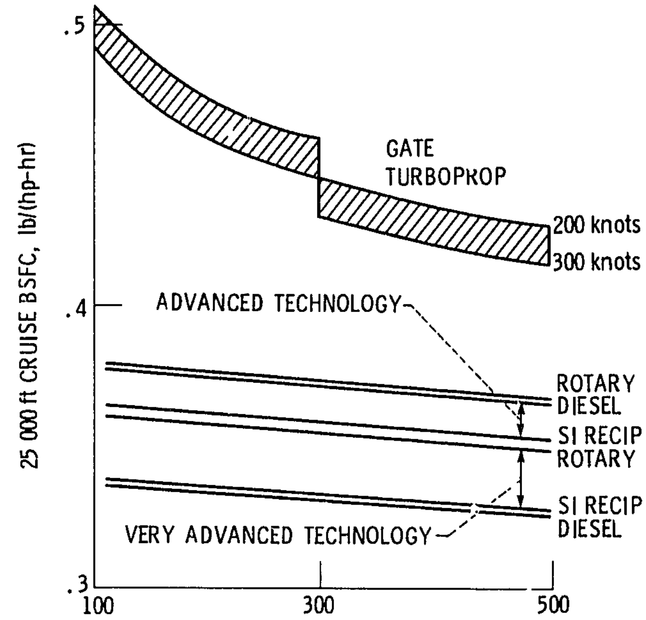


Figure 25. - Efficiency predictions.

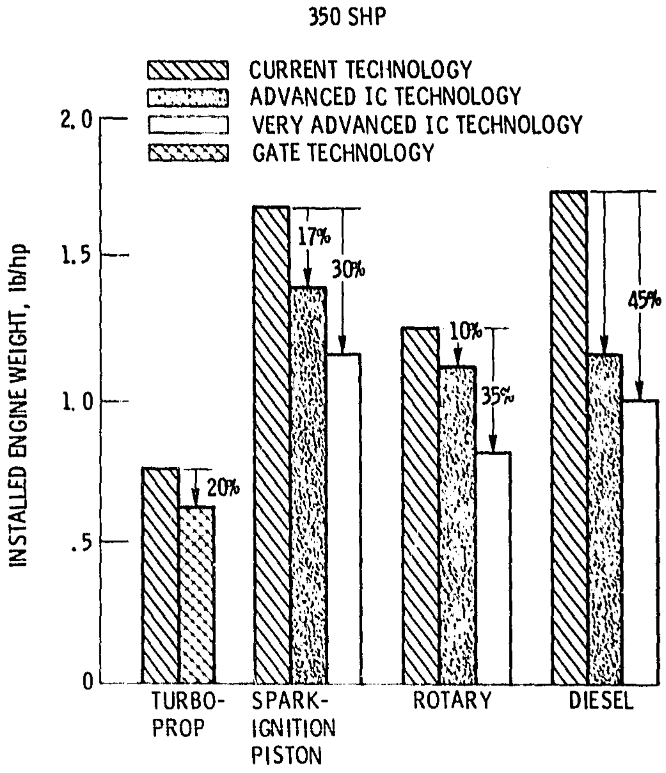


Figure 26. - Predicted engine weight reduction.

ENGINE TYPE (a)	NOMINAL CRITICAL ALTITUDE, FT	CRUISE POWER / MAX. POWER (c)	COOLING DRAG / AIRPLANE DRAG	FUEL	PROPELLER EFFICIENCY @ CRUISE	ALTERNATOR, HP (b)	FUEL PUMP, HP (b)	OIL. PUMP, HP (b)	AIRCRAFT PRESSURI-ZATION REQ'TS
S.I. Recip									
Current (Baseline)									
Nat. Aspirated	0	0.70	0.10	Avgas @	.87	3.7	1.4	0.5	0
Turbocharged	18000		0.10	$1.10/gal					
Advanced	21000		0.05	↓					
Very Advanced	↓		0.035	Jet A @ $1.00/gal		↓	↓		↓
Diesel									
Advanced	17000		0.05			5.0	3.5		10 HP
Very Advanced	↓	↓	0.035		↓	↓	↓		↓
Rotary									
Advanced	20000	0.75	0.035		.88	3.7	1.4		0
Very Advanced	↓	↓	0		↓	↓	↓	↓	↓
Turbine Engines									
GATE	---	0.54 - 0.60	0	↓	.89	Single, 5.0; Twin, 8.0			1.0-1.5 lb/min/PAX Air (Comp)

(a) All Advanced Positive Displacement Engines are Turbocharged

(b) Quoted on per aircraft basis assuming 350 SHP engines, but actually scaled with engine size (except unscaled turboprop req'ts)

(c) Cruise at 25000 feet. Turboprop values for 210 - 270 knots

Figure 27. - Engine assumptions.

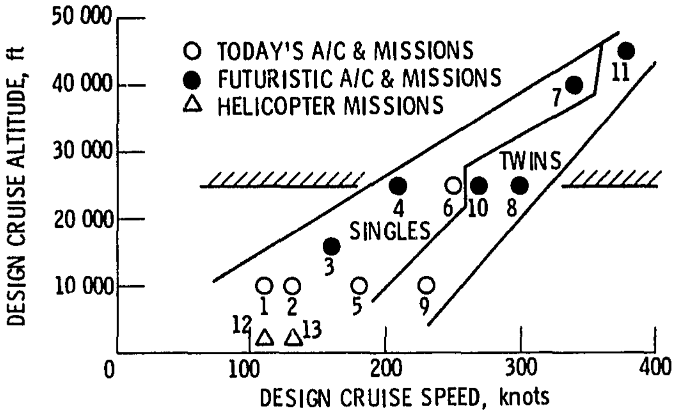


Figure 28. - Missions.

MISSION	AIRPLANE	DESIGN PAYLOAD, LB	AR	DESIGN ALTITUDE, FT	DESIGN SPEED, KN	DESIGN RANGE, NM	FIELD LENGTH, FT	W/S lb/ft^2
1	Single 2-PL Trainer	455	8	10000	110	500	1100	10
2	Single 4-PL Utility	800	8	10000	130	600	1600	20
3	Single 4-PL Utility (a)	800	12	16000	160	800	1600	35
4	Single 4-PL Utility (a)	800	12	25000	210	1400	1600	40
5	Single 6-PL Utility	1200	8	10000	180	600	1800	25
6	Single 6-PL Hi-Perf	1200	8	25000	250	1000	2200	35
7	Single 6-PL Hi-Perf (a)	1200	12	40000	340	1600	2400	45
8	Twin 4-PL Light (a)	800	10	25000	300	1400	1600	45
9	Twin 6-PL Medium	1200	8	10000	230	1100	1700	30
10	Twin 6-PL Business (a)	1200	10	25000	270	1600	2200	50
11	Twin 8-PL Executive (a)	1600	10	45000	380	1700	2500	60
12	Single 4-PL Helicopter	800	--	2000	110	300	6000 (b)	--
13	Twin 6-PL Helicopter	1200	--	2000	130	500	10000 (b)	--

(a) Futuristic Aircraft & Missions:
Empty Weight Reduced by 15%
Zero Lift Drag Reduced by 15%
Engines Located Inside Fuselage
Full Span Fowler Flaps

(b) Hover Ceiling Out of Ground Effect

Figure 29. - Mission definitions.

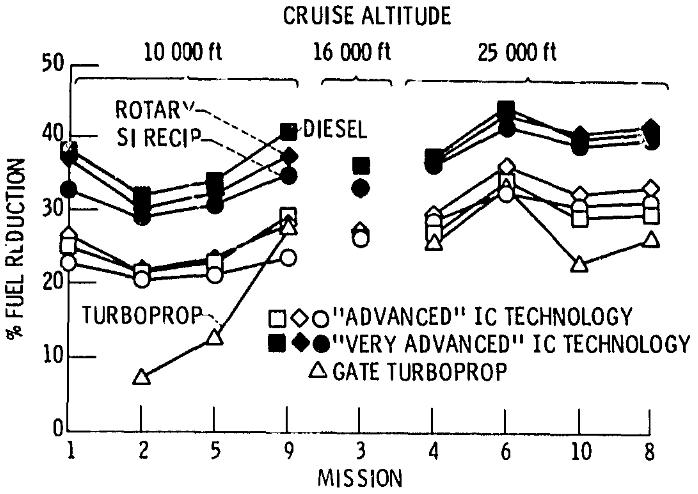


Figure 30. - Mission fuel reduction relative to 1980 S. I. Recip.

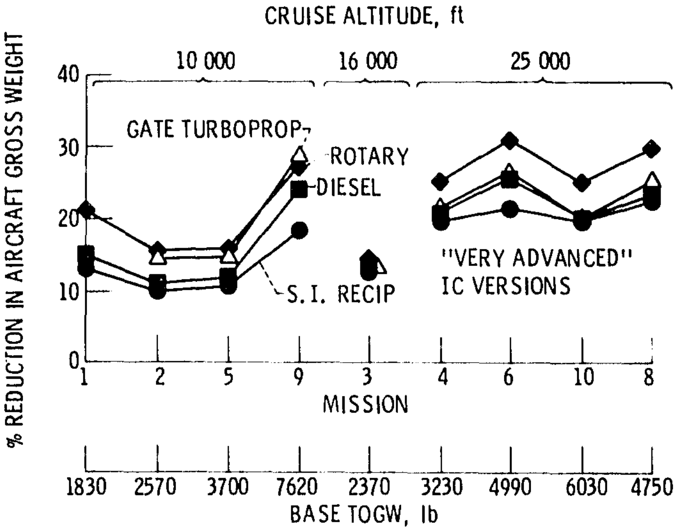


Figure 31. - Aircraft takeoff gross weight reduction relative to 1980 S. I. Recip.

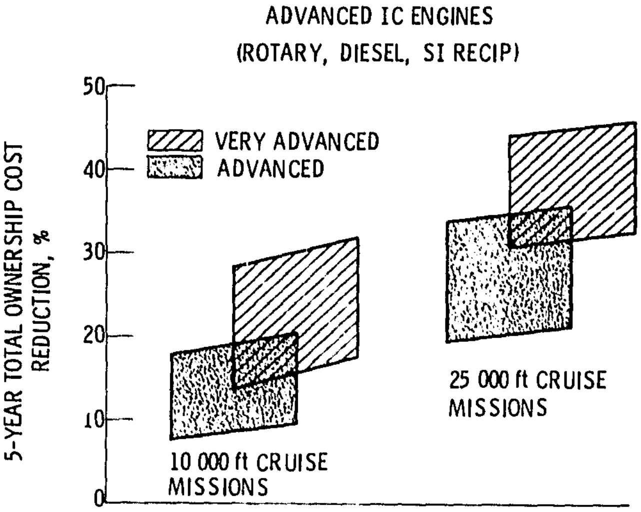


Figure 32. - Aircraft total ownership cost reduction relative to 1980 S.I. Recip.

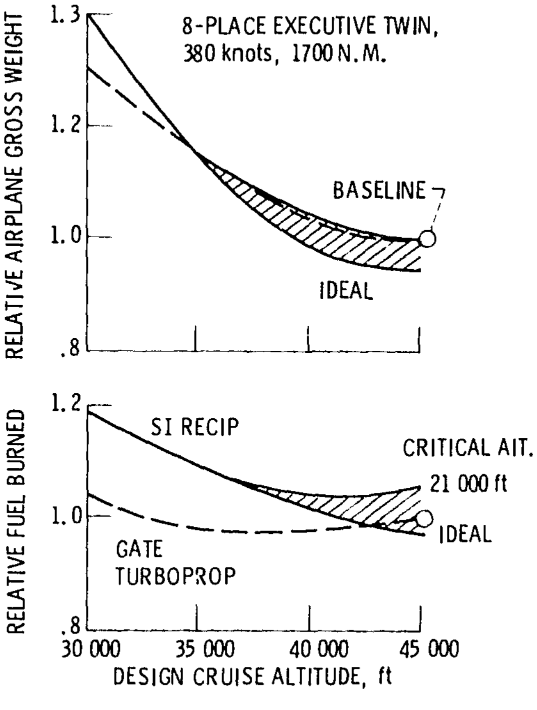


Figure 33. - Effect of design cruise altitude.

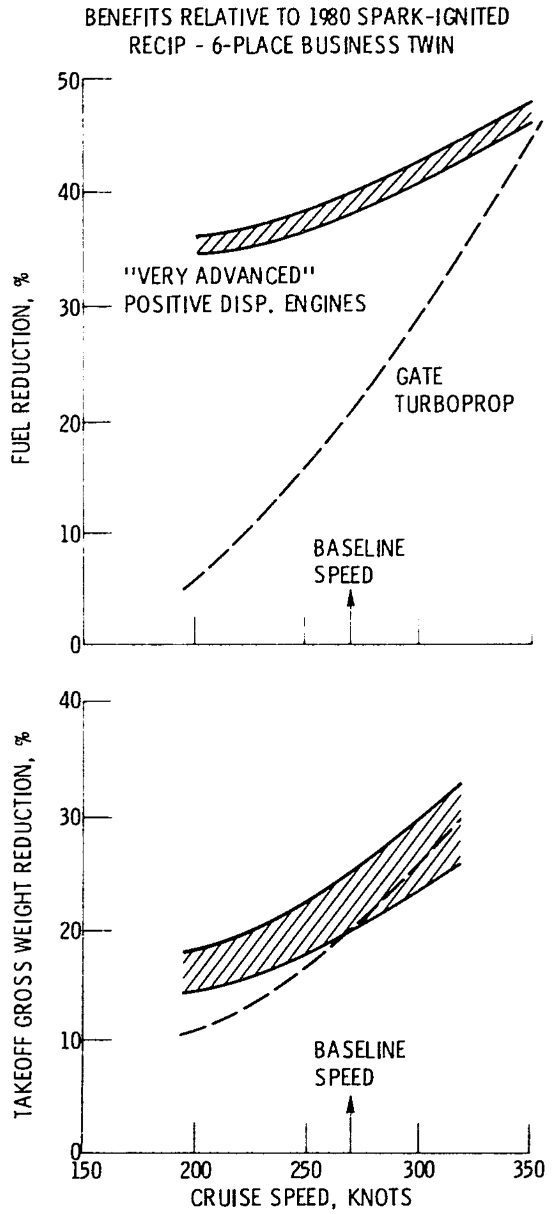


Figure 34. - Effect of cruise speed.

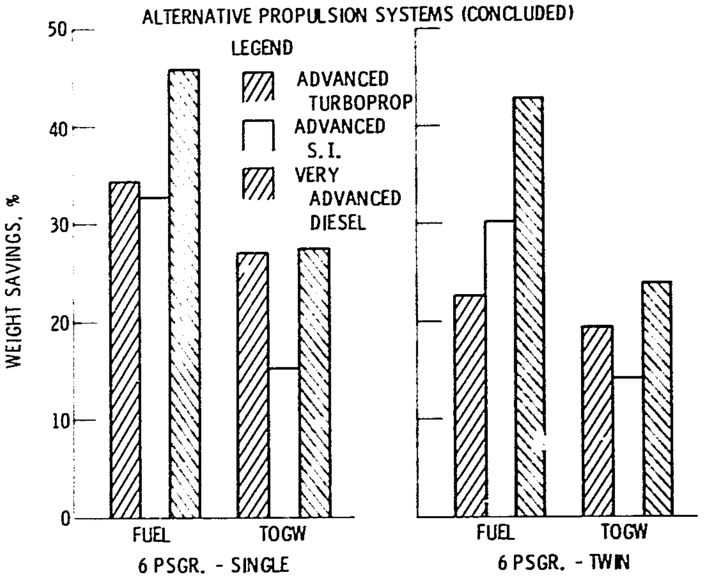


Figure 35. - Fuel and airplane weight savings with advanced turboprop and diesel powerplants in future G/A airplanes (25 000 cruise - 250 KT, 1000 - 1600 MI range).