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(NASA-TM-82869) DEVELOPMENT POTENTIAL OF  
INTERMITTENT COMBUSTION (I.C.) AIRCRAFT  
ENGINES FOR COMMUTER TRANSPORT APPLICATIONS  
(NASA) 31 p HC A03/MF A01 CSCI 21E

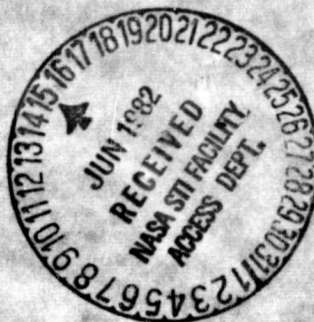
N82-26297

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G3/07 28026

# Development Potential of Intermittent Combustion (I.C.) Aircraft Engines for Commuter Transport Applications

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Prepared for the  
Commuter Airlines and Operations Meeting  
sponsored by the Society of Automotive Engineers  
Savannah, Georgia, May 23-24, 1982

**NASA**

DEVELOPMENT POTENTIAL OF INTERMITTENT COMBUSTION (I.C.)  
AIRCRAFT ENGINES FOR COMMUTER TRANSPORT APPLICATIONS

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ABSTRACT

This paper presents a brief update on general aviation (g/a) and commuter aircraft propulsion research efforts and studies which have been underway at NASA's Lewis Research Center (LeRC) for several years. The review covers studies and limited corroborative research on several advanced I.C. engine concepts, emphasizing lightweight diesels and rotary stratified-charge engines.

Using available information, the current state-of-the-art is first evaluated for lightweight, aircraft-suitable versions of each engine. This information together with available study and experimental results is used to project the engine characteristics that can be expected on "near-term" and "long-term" time horizons. The key enabling technology requirements are identified for each engine on the "long-term" time horizon.

EXPERTS WITHIN THE PETROLEUM AND RELATED INDUSTRIES have long pointed out that oil is a non-renewable resource and that an irreconcilable divergence must eventually occur between worldwide supply and demand(1)\*. Figure 1 illustrates one scenario, under which the ultimate divergence might occur as early as 1982, if several major producers were to limit their annual production. The recent problems in the Middle East region have merely hastened a process that was already inevitable.

This situation may affect different consumers in different ways. Small users, such as general aviation, may arguably be the earliest and hardest hit because they cannot command a large market share alone. While Figure 2 may be an overdramatization of the pressures resulting from a chronic shortage, every owner and operator of general aviation and commuter airplanes knows that aviation fuel costs have increased drastically in recent years. Many feel that this is, or will soon become, the largest single cost of doing business. In addition, operators of the smaller recip-powered airplanes have discovered that aviation gasoline or "avgas" is sometimes

hard to find. If this is already a problem in North America, it is a calamity in some other areas which are largely dependent on imported fuel supplies; and where any available allotments must be distributed by primitive, inefficient and often unreliable means.

Against this background, the present paper reviews the results of several recent studies and experimental activities which were intended to assess the performance potential and key technology requirements of advanced I.C. alternatives to the current crop of turbines and air-cooled gasoline reciprocating engines. In a recent NASA Workshop on "Aviation Gasolines and Future Alternatives" (see Appendix), it was concluded that kerosine-type jet fuel or "Jet-A" will remain in good supply for a relatively long time because there is already a large commercial market and a large-scale, efficient worldwide distribution network for it. On that basis, it was further concluded that any all-new small aircraft engine - whether of the turbine or I.C. variety - should burn this fuel as the fuel of choice. These considerations established the basic directions for the efforts to be described below.

Other sources of information include NASA in-house activities and NASA-sponsored contract/grant efforts. Primary emphasis is placed on one rotary (Wankel) and one recip engine concept. Either could employ a highly turbocharged, hybrid stratified-charge/diesel combustion cycle to obtain a multifuel capability, with jet kerosine the primary fuel of choice.

The current state-of-the-art is first evaluated for lightweight, aircraft-suitable versions of each engine. This information together with available study and experimental results is used to project the engine characteristics that can be expected on "near-term" and "long-term" time horizons. The key enabling technology requirements are identified for each engine on the "long-term" horizon.

\*Numbers in parentheses designate  
References at end of paper

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## DISCUSSION

As previously indicated, the NASA programs related to aircraft I.C. engines have been underway for several years. Figure 3 indicates the status of these efforts at the close of 1981. Most of the originally-planned, near-term oriented work has been completed. Coupled with present funding constraints, this now results in a strong program emphasis on longer-term alternative I.C. engines and technologies. These engines and technologies -- as they might be applied to commuter-type airplanes -- comprise the major thrust of this paper. Nevertheless, since this relatively new area of effort derives entirely from the previous and ongoing programs related to smaller G/A engines, it seems appropriate to begin with a short update on those programs.

STATE-OF-THE-ART AND NEAR-TERM IMPROVEMENTS - Figure 4 illustrates a typical current G/A engine of the type that NASA's near-term efforts were concerned with. Due to the great multiplicity of sizes, models, prices, applications and design vintages represented by this illustration, it is rather difficult to define a single set of numbers as the current state-of-the-art. Although exceptions doubtless exist, the following ranges are believed to be fairly representative for as-installed and as-used comparative purposes.

Table 1

### Conventional I.C. Engine State-of-Art

Specific Weight (LBS/T.O.HP)	Cruise BSFC 75% power	(LBS-BHP-HR) 55% power
1) 1.75	0.48	0.42
2) 1.50	0.55	0.46

- 1) Normally Aspirated Models
- 2) Turbocharged Models

As the illustration suggests, there are some potential near-term improvements to these values as well as some longer term possibilities that will be discussed later. How might these nearer-term improvements be accomplished? Figure 5 briefly illustrates one program that has been completed. A contract effort with Teledyne-Continental Motors, Aircraft Products Division (TCM) evaluated four related improvements(2), namely: 1) timed fuel injection with improved atomization; 2) variable spark timing; 3) a thermal-barrier (insulative) liner inside of the exhaust port; and 4) air injection to spot-cool the exhaust valve. Concurrently, NASA in-house research was conducted on the effects of ambient air temperature and humidity(3), exhaust port air injection(4), fuel injection parameters(5,6) and the development of advanced diagnostic instrumentation(7).

The resulting improvements, compared to the original normally aspirated engine operated "by the book", are shown in the box at the bottom of the figure. It should be noted that the original purpose of these activities was just to reduce emissions as much as possible. The four concepts selected were believed to offer maximum cost-effective improvements in that direction. The first three lines indicate the three gaseous emission levels recorded for the baseline and modified engines over the "7-Mode" cycle, expressed as percentages of the proposed (but later withdrawn) EPA standards. Clearly, the original engine would have been in some trouble. It is equally clear that the proposed modifications resulted in drastic reductions in CO and HC, without excessive NO<sub>x</sub> production.

When it was learned that the emission standards would be withdrawn, the above-mentioned activities were all redirected so that the remaining efforts could be applied to improving fuel economy. The previously-selected engine modifications were then readjusted to produce best BSFC, yielding the results shown in the two bottom lines. (The emissions corresponding to minimum BSFC were then somewhat higher than shown above.) In the landing-takeoff (LTO) mode, the combination of cooler cylinder head temperatures (due to the exhaust-port liners) plus more precise fuel metering enabled the engine to operate leaner than usual at full power. The 30% fuel savings over the LTO cycle is, of course, relative to a full-rich baseline, but is probably representative of what would be seen in a training environment.

The savings at cruise conditions are more controversial. It is well known that small airplanes give their best MPG figures at about 55% power, not 75%, and at such reduced power settings little, if any, savings were noted. On the other hand, when there are business schedules to be kept, it can be argued that cruising at less than the maximum continuous rating (75% power, usually) may result in an unproductive waste of valuable time. The NASA sponsored activities were oriented toward the latter type of utilization. Also, the savings of 10% are relative to the original baseline engine (the same one that produced the emissions readings shown) when operated "by the book" at factory-nominal settings. This we believe is a fair comparison, assuming that a state-of-the-art electronic controller would be used to implement the improvements shown (or other modifications for the same purpose) in a flight environment.

In the course of work, however, it was found that the majority of the cruise improvement shown was due to the density-compensating feature of the particular fuel



injection system selected for the test program. This system employed a constant 180° crank-angle fuel-injection pulse, which, when synchronized with intake-valve opening, resulted in nearly homogeneous air/fuel inlet mixture flows. As a result, the interesting axial-charge-stratification effects recently noted by G.M. researchers(8) in a short-pulse, late-injection test rig would not be expected in this case. Because of these circumstances, it was possible in the present work to get nearly as much benefit by manually leaning the original fuel injection system -- at least in the dynamometer-laboratory environment. Ergo, one might assume that a sufficiently skilled pilot could be trained to provide the same function in flight. While this is indeed a technical possibility and well within the skill range of a typical test pilot, one must question whether such practices will ever become routine in the everyday world of business flying.

Upon the conclusion of the above-mentioned dynamometer testing, the modified engine was installed in a Cessna 210 (Figure 6) and tested in flight during early 1981. In brief, it was found that the power levels and fuel schedules established on the dynamometer could be maintained in the flight environment. Cylinder-head temperatures were significantly reduced in the exhaust-port regions and it was estimated that total heat rejection to the cooling air was reduced by 10 to 11%(3).

Based on the foregoing, it is concluded that relatively simple modifications such as shown above (or simplified, cost-effective variants thereof) can produce on the order of 10% to 30% fuel savings in a realistic flight environment. (It should be recognized that the precise magnitude of savings to be expected will vary with application, and is highly dependent on the baseline chosen for comparison.) It is also felt that an electronic control system may be needed to translate dynamometer-demonstrated improvements to a routine flight environment. Despite these qualifications, it is felt that the above would constitute a substantial step forward for G/A. Since the modifications discussed primarily involve accessory systems rather than basic engine structure, no significant technical impediment is foreseen to the near-term commercial introduction of such technology.

Further improvements may require greater efforts insofar as the basic engine structure is affected -- e.g., by increased peak firing pressures. For instance, the current (1982 model XJ-S) Jaguar V-12 automobile features a high-compression, high-turbulence combustion chamber (HTCC) which is known in Europe as the May "Fireball" system after its Swiss inventor. Significant improvements in both performance and

gasoline mileage have been observed(9), compared to the otherwise-similar 1981 model.

The technical principle involved is shown in Figure 7, which illustrates both a standard hemi chamber and one version of the HTCC. In the latter, a bathtub-shaped recess is cut into the firedeck in the exhaust-valve area. A specially-shaped passage leading from the intake-valve area to a corner of the bathtub produces an extremely strong air swirl motion, as illustrated, when the piston nears top dead center. This motion, combined with the HTCC's typically high compression ratio (11.5:1 in the Jaguar V-12), results in high flame speeds. In effect, it becomes possible to ignite and burn mixtures which otherwise would be too lean to support stable combustion. The rapid burn and high initial compression of the HTCC result in increased peak firing pressures. These first result in a substantial -- e.g., 10% -- improvement in fuel economy as has been demonstrated by the model XJ-S Jaguar V-12 automobiles. For aircraft-type engines, this would mean cruise BSFC's in the neighborhood of 0.36 lbs/BHP-hr. On the other hand, the increased peak pressures impose greater loads on the bottom-end components, so that these may need to be strengthened or -- in extreme cases -- completely redesigned. Nevertheless, the major part of the development of the HTCC Jaguar V-12 engine, from single cylinder test rigs through L-6 and V-12 prototypes, apparently occurred within a period of about five years(9).

Therefore, it is believed that judicious combinations of the above-mentioned technologies (or their functional equivalents) can be found which will result in aircraft-engine cruise BSFC's in the 0.36 to 0.40 lbs/BHP-hr range with specific weights substantially the same as shown before in Table 1. For typical G/A type engines (horizontally-opposed, air-cooled, etc.), no major technical impediment is foreseen which would prevent such improved engines from being available on a fairly near-term basis -- say roughly five years.

In the higher-horsepower categories, the prospect for near term improved aircraft I.C. engines is less encouraging, because at this writing (April 1982) there are no modern, certified, current-production examples to improve upon. An exception may well occur in the 500-800 HP range, where modern automotive liquid-cooled aluminum V-block engine technology could be applied to a high-performing V-8, or even an engine family having many common internal components and including V-6, V-8, V-10 and V-12 examples. (The latter might resemble a scaled-up Jaguar V-12.) Such technology is highly developed, both domestically and abroad. Aircraft engines derived from such origins could benefit of

course from the same technology approaches as described above. It is believed that with HTCC technology and turbocharging, such engines could be rated at near 1 lb/T.O.hp and could provide cruise BSFC's in the neighborhood of 0.36 lbs/BHP-hr.

On the other hand, given the present avgas situation worldwide, some may question the wisdom of bringing "another" gasoline aircraft engine to market in this particular era. This issue can be finally settled only by the interplay of technical, business and marketing factors. In any case, the development and certification of any all-new aircraft engine is a major financial and technical undertaking in even the simplest of cases. In view of this, it is recommended that, if any such engine is to be developed, consideration be given to providing it with the capability to burn spark-ignitable fuels other than gasoline; such as, liquified petroleum gases (LPG) or alcohols. On the longer-term horizon, the next section will discuss means by which engines of this general type could be set up to burn jet-kerosine or broad-spec. jet type fuels.

**LONGER TERM DEVELOPMENTS** - The remainder of this discussion will pertain to engine concepts and technologies for which the road to commercial introduction is much less straightforward, and will emphasize developments that might be expected in the 800-HP and above categories.

**NASA AVGAS WORKSHOP** - In February of 1981, a workshop on "Aviation Gasolines and Future Alternatives" was convened at the NASA Lewis Research Center. The purpose was to review the dimensions of the avgas problem and, hopefully, to agree on technical approaches and strategies to minimize its ill effects. The major conclusions are presented in Figure 8; and the Appendix presents the Chairman's Summation of the 3-day proceedings. For the purposes of the present discussion, the significant point is that nearly 100 high-level attendees, reflecting a representative cross-section of the entire business flying and G/A community, concluded that any all-new business or G/A aircraft engine should be designed to use jet kerosine as its fuel of choice. This was not meant to preclude or discourage specific groups from pursuing alternative approaches that they consider more useful for their own specialized needs. It was rather intended as a statement that public funds would be most appropriately directed towards mainstream developments for the greatest good of the total G/A and commuter aircraft community.

**ALTERNATIVE G/A ENGINE STUDIES** - According to the above philosophy, NASA's studies and other I.C. engine-related efforts have been focused sharply on a class of engine concepts which can burn jet kerosine and similar fuels with high efficiency. With the completion of the near-

term work described above, this has now (early 1982) proceeded to the exclusion of further aircraft gasoline engine research.

Although no proposals were received to study rubber-band-powered airplanes (Figure 9), the NASA contract studies identified a group of engines which, while hopefully more realistic than the cartoon illustrated here, did encompass a diversity of novel concepts and technological features. As Figure 10 illustrates, the group included an advanced air cooled spark-ignition engine of more-or-less conventional configuration, analyzed by TCM-Aircraft Products Division(10); a remarkably compact 2-stroke radial-piston diesel engine, analyzed by Teledyne-General Products Division(11); and a lightweight liquid-cooled, stratified-charge rotary engine, analyzed by Curtiss-Wright(12).

The "bottom-line" numbers, i.e., specific weight and cruise BSFC, that pertain to each engine are also indicated. Using these results and related data, airplane/mission evaluation studies of each engine in representative airplane/mission scenarios were conducted in-house by NASA(13), and under contract by Beach Aircraft(14) and Cessna Aircraft(15). Since these G/A results have been previously presented(16), and another presentation in this session is to cover corresponding but more recent results for larger engines, the present discussion is limited to a very brief summation.

It suffices here to say that all of the I.C. candidates recorded very creditable performance, in comparison with both a modern current-production baseline gasoline engine and a hypothetical, highly advanced but unregenerated small turboprop. Figure 11 illustrates a typical outcome, in terms of mission fuel and aircraft weight savings, which reflects the majority of the cases studied. The rotary and the diesel, which were very close and provided the best overall performance in all categories, produced especially dramatic fuel weight savings -- about 43% in the case illustrated. It should be noted that these engines and the turboprop used jet kerosine while the baseline used avgas. Considering the differences in energy content, density and cost between jet kerosine and avgas, the savings shown for the kerosine-burners should be extended by another 10% to 15% to obtain a more realistic measure of the economic benefits. The aircraft weight savings of about 25% are also quite attractive.

The third engine illustrated is a reduced-risk, gasoline-burning version of the horizontally-opposed spark engine. This is similar technologically to the possibilities discussed under the Near-Term section, but additionally assumes an all-new engine structure for the sake of lower weight. While the results from this engine



are not unattractive -- especially in view of the greater confidence with which its development could be undertaken -- the reservations previously expressed about an all-new gasoline-burning engine apply in this case as well.

The rotary engine emerged as the overall top choice from these studies, with the diesel a strong second. Performance wise, the rotary had only a small edge; installation-related advantages and predicted passenger-comfort levels (based on low vibration) were viewed as significant positive factors in the overall rotary evaluation, which only the turboprop could match. Figure 12 illustrates the rotary twin installation concept developed by Cessna for a small (6 passenger) high performance business twin. Aesthetically at least, the slim, clean lines speak for themselves.

COMMUTER ENGINE STUDIES - Figure 13 shows the spectrum of different engine types considered in recent and ongoing NASA studies of advanced commuter aircraft propulsion systems. Of particular interest here are two near the bottom, the rotary and the diesel, both labelled "Adiabatic, Turbocompound". This nomenclature (often abbreviated to "ATC") will be used hereafter to indicate that the most desirable versions of these engines both use insulative combustion-chamber components, e.g., ceramics, to block most of the heat transfer that would otherwise go to the coolant; and that a compounding turbine or equivalent technique is used to recover a portion of the thermal energy thus saved into useful crankshaft work. Figure 14 illustrates the thermodynamic principle in terms of a highly simplified, classical P-V diagram. Since heat-transfer is a time-dependent phenomenon, the total savings resulting from blocking it off only accumulate gradually with time; thus, they appear mostly at the end of the normal cycle. Therefore, a compounding turbine or equivalent must be added at the bottom of the cycle, as shown, to recover any major fraction of this energy.

Although little publicized, promising work on automotive-type adiabatic diesel engines has been underway for some time. Under the sponsorship of the U.S. Army's Tank-Automotive Command (TACOM), the Cummins Diesel Engine company has been performing adiabatic diesel R&D since the early 1970's and very substantial progress has been made(17). Although specific details are best left to Cummins and its sponsors, it can now be disclosed that the resulting technology is currently under test on the highways. An Army truck equipped with an adiabatic conversion of a current 6-cylinder Cummins diesel was in fact displayed and demonstrated at the February 1982 SAE Congress and Exposition in Detroit, Michigan. Figure 15 is a snapshot of that truck, taken on the morning of

2/26/82 outside of Cobo Hall. Notable was the complete absence of radiator, fan, water pump and tank, expansion tank, water hoses, fan belt and pulleys and related paraphernalia. The hood had no air openings and there was no water in the engine. The ceramic cylinder liners, piston crowns, firedeck and other internal insulated components were able to contain the high temperature combustion gases, block off most of the heat transfer to the now-empty cooling jackets, and direct the very hot exhaust gases to a turbocharger and compounding turbine. This engine's experimental minimum BSFC has been consistently determined to be about 0.285 lbs/BHP-hr. Recent reports(18) indicate that Kyoto Ceramics, Ltd. and Isuzu, in Japan, are also moving rapidly in this direction.

While this truck diesel is too large and heavy for an airplane, there is apparently little to prevent the new technology from being incorporated into lightweight engine structures such as have been previously illustrated. The breakthrough has now been made. It should be remembered that the same company that developed this truck engine had previously (in the 1950's) successfully developed a lightweight, high performance diesel for Indianapolis racing. At the above mentioned SAE meeting, it was observed that the combination of adiabatic I.C. engine technology with lightweight structure and design philosophy would result in a very desirable Army helicopter engine(19).

STRATIFIED-CHARGE ROTARY COMBUSTION TECHNOLOGY - During the same time period, significant advances have also occurred in the rotary engine field. Toyo Kogyo, Ltd. appears to have overcome the early rotary automobile-engine difficulties with the introduction in 1979 of the highly successful RX-7 sports model. The Curtiss-Wright Corp., Rotary Engine Facility, has, under U.S. Navy/Marine Corps. sponsorship, developed a large stratified-charge multi-fuel rotary marine engine.(20) This 5-year program began in 1977 after C-W had succeeded in demonstrating, at smaller scale, the key ingredients of the unique stratified-charge combustion system which provides this engine with its multi-fuel capability and flexible, generally efficient operational characteristics. Figure 16 illustrates the major features of this system. Two fuel injectors, denoted as "pilot" and "main", are located in the "wasp-waist" region of the trochoid housing near the top-center position. The pilot injector sprays in a small amount of fuel over a high-energy multiple-discharge spark plug, thus establishing an ignition "torch", which continuously ignites the main fuel charge as it is injected. The motion of the rotor in the trochoidal housing is such that the air motion in the injector region always proceeds in the



downstream or "leading" direction, as illustrated. Thus, by tailoring the main injector flow to the instantaneous airflow rate past the injector station, a stationary flame front is established under the "wasp-waist". The rotor merely pushes the air through the flame front by virtue of its inherent motion and geometry. The ignition torch is energetic enough to immediately ignite any fuel that can be pumped through a diesel-type injection system. Therefore, the stratified-charge rotary engine can burn any clean liquid fuel whose vapor-pressure and freezing point characteristics are consistent with the operating environment.

The previously-mentioned marine rotary engine is being developed in a 350 CID per rotor basic capacity. Two-rotor and four-rotor, normally-aspirated versions are under consideration for various applications. The four rotor version is illustrated in Figure 17. This particular version consists essentially of two twin-rotor engines joined end-to-end, so it is by no means an optimum design from the viewpoint of minimum weight or package volume. Nevertheless, this 1400 CID engine fits into a 2-1/2' x 3' x 5' box, weighs under 1900 lbs and -- without turbocharging -- develops 1500 hp at only 3600 RPM. It is believed (based on C-W and in-house NASA calculations) that this power output could be more than doubled by turbocharging plus a moderate increase in rotational speed. A four rotor engine of this type could very possibly develop 3500 to 4000 hp or more, without weighing in excess of 2000 lbs.

Of more immediate interest, however, is the twin-rotor version which is essentially half of the engine shown. Currently nearing the end of a five-year development and pre-production testing program, this engine is now (early 1982) undergoing NATO Qualification Testing for use in Marine Corps. assault boats. In mid-1981, C-W conducted a brief study on the growth potential of this engine with the results indicated in the next chart (Figure 18). The leading characteristics of the existing baseline engine are summarized in the left-hand column. The next column shows the results expected by applying the less ambitious of the two levels of advanced technology covered in the previously mentioned NASA G/A engine study. The next two columns indicate the results from applying the more ambitious, "highly-advanced" level. Although based on a non-aviation prototype, we suspect that such engines would command a certain degree of interest if they were commercially available today. To obtain any such engine, the technical risks that must be assumed -- implied in the technology items listed at the bottom of the chart and which will be discussed later in detail -- are no greater and no less than those of the G/A rotary engine. Here, everything is just bigger.

Taken together, the previously discussed NASA G/A engine studies, Cummins' adiabatic diesel truck engine results, and the C-W work on stratified-charge rotary engines were viewed as indicating exceptionally good technical prospects for aircraft diesel and rotary engines in larger horsepower categories. Therefore, during 1981, NASA sponsored additional studies of aircraft diesel and rotary engines in the 800 HP to 2400 HP class. The results are discussed in the next several sections, and then compared with each other and with what may be expected from a comparably-advanced gas turbine.

**DIESEL COMMUTER ENGINE STUDY** - Under contract to NASA, Teledyne-General Products has completed a study(21) on the 800-2400 HP class of lightweight aircraft engines. Although retaining many key features found in the previously-mentioned G/A engines, these larger engines ultimately involved higher speeds, higher loadings and adiabatic/ceramic combustion chamber technology of the type Cummins has described.

Figure 19 indicates the leading features of these engines. In essence, they combine the lightweight two-stroke radial design philosophy of the G/A designs with Cummins-type adiabatic componentry. The expected advantages of this combination are as indicated. The insulated combustion chamber in particular greatly reduces (and may even eliminate) the coolant-system heat load, which should correspondingly reduce the cooling drag and provide more energy to the turbocharger and compounding turbine. This high speed, high pressure cycle of course demands the generation of substantial technology advancements, particularly the four items listed at the bottom of the chart.

Given this technology, the resulting commuter aircraft engine has the appearance and general arrangement portrayed in Figure 20. It is a 90° X-8, two-stroke, piston ported adiabatic turbocompound high speed engine. Developing 2000 HP, this engine -- including turbomachinery -- would fit into a 2-1/2' x 3' x 5' box, making it as compact as the large rotary engine illustrated before. Depending on whether or not advanced, lightweight composite structural materials are extensively employed, the engine is projected to weigh 1350 to 1550 lbs(14) in the "minimum runnable engine" configuration. Other details are itemized in the next chart, Figure 21. Notable is the fact that the 15,000 ft cruising BSFC of 0.30 lbs/bhp-hr appears somewhat conservative when compared to what has already been demonstrated (0.285 lbs/bhp-hr) in the Army/Cummins program. This is because friction is a more major factor in this very high speed and high output engine. Evidently, the aircraft diesel previously shown in Figure 20 is no larger than the Cummins' truck diesel and probably no

heavier. Yet it develops ten times the power, nearly equal BSFC, and all that on a fulltime, 100% duty-cycle basis. Although the technical risks involved are substantial, this is clearly a goal worth shooting for.

**ROTARY COMMUTER ENGINE STUDIES** - In parallel with the foregoing, studies were also conducted on stratified-charge rotary engines in the same power range. Under contract to NASA, C-W conducted one study(22) which involved a direct extension of the previous G/A studies to the larger sizes of interest here. The only difference was that turbocompounding was allowed as an option. However, the significant operating parameters such as peak pressures, sliding velocities, materials and material temperatures were not increased. This resulted in engine definitions based on conventional cooling; while including many advanced mechanical technologies, these engines have neither the benefits nor the technical risks associated with adiabatic ceramic componentry.

In addition to the above, a brief, parallel and previously unreported in-house NASA study was conducted to assess the potential benefits of adding adiabatic uncooled operation to the C-W engine definitions. It was estimated that, by adding ceramic or other insulative trochoid liners and rotor/end housing faces and deleting the conventional cooling system, the power recovered in the compounding turbine could be increased by an amount equivalent to 10% to 15% of engine total shaft power output. Owing to the large technical uncertainties related to this totally unprecedented engine concept, the lower value was assumed to be representative. The structural weight added for ceramic/insulative components was approximately offset by eliminating the conventional coolant system entirely. Thus, finally, the NASA first approximation to an adiabatic turbocompounded rotary engine amounted to improving the C-W specific weights and cruise BSFC's by 10% apiece. As the next section will indicate, subsequent comparative performance studies disclosed that the conventionally cooled rotary is not competitive with a highly advanced turboprop for commuter applications. Therefore, in the remainder of this section, attention will focus primarily on the adiabatic/turbocompound or ATC version of the rotary engine study. The next several figures should be viewed as a composite of C-W and NASA in-house results.

Figure 22 lists leading features. In any definition, the engine retains all of the known desirable features inherent to rotary engines, with greatly extended durability a realistic possibility via the use of retractable or reduced-contact-force apex seals. As in the diesel case, the use of insulated (possibly ceramic) combustion

chamber components results in zero or minimal coolant heat rejection and cooling drag and more energy to the compounding turbine. Also, as in the diesel case, the high speed, high pressure cycle demands considerable technology advancements, although with uncertainties higher than before due to the unprecedented nature of this engine.

Assuming that the technology can be made available, the corresponding engines would appear as indicated in Figure 23. General arrangement, major dimensions, weight and fuel consumption are indicated on the chart for the two power extremes covered in the study. Compared to the diesel previously illustrated, this is a long, cigar-shaped package. Figure 24 lists some of the relevant details for the 2000 HP version, which can be directly compared to the previously illustrated diesel engine. In terms of envelope, the diesel required a 2-1/2' x 3' x 5' box, as may be recalled, while the rotary will fit into a 2' diameter x 8' long cylinder. Engine weights are comparable, between the conventionally-cooled rotary and the diesel that used conventional structural materials; and also between the ATC rotary and the diesel version that made extensive use of structural composites. BSFC's are comparable if one accepts the ATC cycle as the appropriate definition of the rotary. One very significant difference, however, may escape notice when one compares the Figure 24 and 21 engine details. This is the fact that the rotary is rated to cruise at a nominal 75% of maximum takeoff power where the diesel was rated to cruise continuously at 100% of its maximum power. This has obvious implications for those applications where the engine is sized by cruise-power requirements. Aside from this, and problematical differences in technological risk/credibility, the two engines appear at this time to be "too close to call."

**COMPARATIVE EVALUATION** - As previously mentioned, the above engine definitions have been used for inputs to airplane/mis-sion evaluation studies(16) (NASA in-house) in which the present diesel and rotary engines were compared to each other and to a comparably-advanced turboprop engine definition. The results of this study, which is still at a very preliminary stage compared to the G/A studies, will be described in detail elsewhere in this session. For completeness, however, Figure 25 presents a typical comparison for a 30-passenger, Mach 0.6, 20,000 ft mission with a 2400 N.M. design range. Engine, fuel, airplane, payload and cost-related parameters are compared in the three columns for turboprop, diesel and rotary powerplants, respectively. It is first noted that both the diesel and the rotary are sized considerably smaller than the turboprop because of the latter's considerably-



worse power lapse rate from sea level up to the 20,000 ft cruise altitude where engine sizing occurred. Also, the previously mentioned fact that the diesel can cruise at full power while the rotary was cut back to 75%, results in the rotary engine being 1/3 larger than the diesel, with a correspondingly larger base engine weight and corresponding weight differences reflected throughout the airplane. Bearing this important difference in mind, the subsequent data show that the diesel and rotary engines, to varying degrees, are both substantially heavier than the turboprop but consume considerably less fuel. All three airplanes turn out to be about the same size. At the all-important bottom line, it may be seen that both the rotary and diesel engined airplanes are at least competitive with the turboprop. The diesel shows a definite edge over the rotary, due almost entirely to its more aggressive rating philosophy.

In summing up the illustrated chart, the main message is both the diesel and the rotary give competitive overall performance, but are simply more economical than the turboprop. The savings recur and cumulate, trip after trip, throughout the life of the engine. While many elements of the D.O.C. equations are argumentative at this point in the studies, one conclusion stands out loud and clear: These engines use less fuel. In an era of true fuel scarcity -- which would be entirely different from today's high-fuel-price scenario -- they could well make the difference between continuing operations or not.

#### TECHNOLOGY REQUIREMENTS AND FUTURE SOURCES

As was mentioned in passing, both the diesel and the rotary require four major new technology items to be completely successful. The first four bullets in both Figures 26 and 27 indicate the requirements. As also indicated, contract single-cylinder/single-rotor test programs and supplementary in-house NASA efforts are already underway or planned to address these items.

Despite the varied applications, the two lists are more similar than different. The new engines both require advancements in the tribology area -- i.e., low-friction, low-wear sealing elements and lubes to survive in a high speed, hot, high-pressure environment. For the rotary engine in particular, there is a major need for apex seals which achieve either reduced contact force or a controlled-clearance liftoff condition at high speeds -- perhaps by using a combination of aerodynamic and inertial forces.

Both require at least partially insulated combustion chamber componentry to approach the benefits of the ATC cycle. For the diesel, a fairly straightforward

extension of the present Cummins approach may suffice. For the rotary, however, there exists no precedent at all, even though the basic intent is the same. This is another area where a major new innovative approach would be welcomed.

Both engines also require very fast fuel injection and stratified-charge combustion systems. This is a substantial problem, despite the progress reported in other areas, because both require cyclic combustion rates four to six times higher than state-of-the-art truck diesels. In the basic stratified charge combustion concept, illustrated in Figure 28, fuel is injected, across an ignition source, tangentially into a rapidly-swirling air mass. (It may be recalled that the rotary engine accomplishes the same effect by virtue of its inherent geometry.) With immediate ignition assured by a positive ignition source, the fuel then proceeds to burn smoothly at a rate controlled by the fuel injection. There is then no "ignition-delay" period and no question of knocking or detonation; these engines have no cetane or octane requirements. While a spark plug is often used as the ignition source, other means may eventually prove to be more desirable. These could include glow plugs, catalyst strips, or even the very hot internal surfaces of an adiabatic engine.

The ultimate limit for rapid heterogeneous combustion is expected to occur<sup>(23)</sup> when the fuel as well as the air and combustion chamber surfaces is heated to a highly combustible temperature. This eliminates the physical part of the ignition lag process (droplet evaporation) so that the combustion rate is then controlled by mixing processes. This results in several potential benefits as illustrated in Figure 29. As also indicated, both the Army and NASA have taken a substantial interest in this concept and have initiated experimental efforts to evaluate basic feasibility aspects and fundamental theoretical aspects.

Finally, it may be recalled that both engines ultimately required advanced turbochargers and compounding concepts. The compounding system was not considered cost effective for the G/A class of engines but is a unique requirement of the present larger engines. The classical approach of using a compounding turbine plus a reduction-gear drive to the crankshaft is straightforward and results in efficient energy recovery. On the other hand, it adds weight, cost and historically-based concerns about reliability. An alternative approach is available however for four-stroke cycle engines. This is the "pressure" or "pneumatic" compounding concept in which a "super turbocharger" concentrates any available excess exhaust energy into the form of higher compressor-discharge pressures. With high component efficien-



cies it should be possible to run the compressor discharge pressure substantially higher than the turbine inlet pressure. In the IC engine, this condition is reflected by a positive-work contribution to the indicated P-V diagram, between the exhaust and intake strokes, as shown in Figure 30. The specific example shown is from recent NASA in-house testing of a four-stroke diesel test engine. In the case shown, the over-pressure of about 20 psig was clearly seen in the lower loop of the diagram, and added directly to both the net IMEP and BMEP. There was no effect on friction and, with constant fueling, there was but little increase in peak firing pressure. Therefore, the 20 psi-wide positive pumping loop shown contributed improvements of over 10% to both power output and specific fuel consumption rate, with minimal implications regarding engine weight. In this series of tests, the minimum observed BSFC of the AVL model 521 diesel test engine declined from 0.34 to 0.31 lbs/bhp-hr when 20 to 25 psig of positive pressure compounding was applied.

Such laboratory feats might be duplicated by applying the best of known rotating-machinery technologies to a conventional-looking turbocharger. What is needed is simply very high component efficiencies in a mass-producible form. The significance of this approach is that it could open a mass market as opposed to the very limited appeal of the G/A and commuter engine market. That is, a very efficient new turbocharger could be applied, via pressure compounding, to the benefit of many existing and current-production four-stroke diesel engines, without changing their maximum internal loads or stress levels. A development of this nature is one of the most straightforward ways that can now be foreseen by which the present, low-cost G/A turbocharger scenario might be extended to a higher-technology environment.

#### CONCLUDING REMARKS

To briefly sum up, the preceding discussions have reviewed the present state-of-the-art in aircraft IC engine technology and have projected a series of modest but highly "do-able" improvements for the near-term time horizon. Although economic difficulties may prove to be an inhibiting factor, no technical reason is apparent why previously-described advances such as the NASA/TCM improvement package and the May/Jaguar HTCC combustion system -- perhaps modified to accept LPG or alcohol fuels -- could not be made available in a timely manner.

Looking farther into the future, a brief review and update on the NASA G/A engine studies identified the rotary and diesel engines as perhaps the likeliest among several very attractive candidates.

Despite the mundane and prosaic applications typical of IC engines in general, it should be kept in mind that these two engines are in fact examples of highly advanced aerospace technology. Although relatively simple in execution, each represents a truly sophisticated answer to a formidably complicated set of technical, economic and other requirements. Each has its own set of problems and technology needs which are such that concerted major efforts will be required from all concerned, to get from "here" to "there." This could take ten years or longer under present circumstances.

In the higher-power range, the results of the ongoing Army/Cummins program on adiabatic truck diesels and the Navy/USMC/Curtiss-Wright program on stratified charge marine rotary engines were reviewed as a background and prelude to the NASA commuter engine study discussed later. In both areas, major accomplishments have been posted recently. The adiabatic diesel truck engine has broken the "magic" 0.30 BSFC barrier for the first time by a highway vehicle, both in a laboratory environment and in over-the-road tests. From a historical viewpoint, we believe that this may come to be viewed as a breakthrough comparable to the first four-minute mile. While others unquestionably will eventually improve on it, this is indeed the beginning of an era.

Meanwhile, no less of an accomplishment has been posted by the Navy/USMC/C-W rotary engine activity. The combination of known stratified-charge combustion techniques with the unique geometry and air-motion characteristics inherent to the rotary has resulted not only in a broad-range multi-fuel capability, but also in very respectable efficiency levels from an engine type which -- despite other advantages -- was previously best known for its heavy fuel consumption. A technical turn-around of this magnitude (20% BSFC improvement in one step) can scarcely be ignored; it has to be another major milestone.

These results add substantial amounts of technical credibility to the NASA studies on commuter IC engines. In view of the aerospace industry's long tradition of technological leadership, it could perhaps be regretted that these significant innovations had to be pioneered elsewhere. At this point, however, the mere fact that so much has been accomplished with relatively modest investments is a compelling argument for continuing and intensifying the efforts along these lines. The NASA studies which were described show that judicious combinations of adiabatic combustion-chamber technology, stratified charge combustion technology, and advanced tribology with lightweight IC engine design and structural philosophy can result in highly competitive future engines. Installed in commuter-type

airplanes, these result in size and performance levels about the same as would be expected from an advanced turboprop -- but they use considerably less fuel. (An independent study reached the same conclusion for Army helicopters.) This simple fact provides the strongest of possible motivations in an era when fuel is already expensive and true scarcity looms on the distant horizon.

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#### APPENDIX

#### TECHNICAL WORKSHOP ON AVIATION GASOLINES AND FUTURE ALTERNATIVES

National Aeronautics and Space  
Administration  
Lewis Research Center

February 3, 4, and 5, 1981

#### CHAIRMAN'S SUMMATION

by John B. Olcott

After two days of presentations and discussions pertaining to the impact of fuel on the technology of propulsion for

Willis



general aviation, the attendees of NASA's Technical Workshop on Aviation Gasolines and Future Alternatives, held February 3, 4, and 5, 1981, made several observations, conclusions and recommendations.

## OBSERVATIONS

A workshop on fuels and their impact on the development of general aviation powerplants was an appropriate undertaking for NASA. The occasion provided an excellent opportunity to hear and debate the positions of knowledgeable representatives from the producers of petroleum products, aircraft and engine manufacturers, aircraft fixed base operators, users of general aviation and members of the research community. In addition to providing NASA with recommendations for meaningful research pertaining to propulsion, the workshop served a valuable informational function due to the different perspectives that members of the aviation community brought to the forum. A constructive cross fertilization of ideas resulted from the program.

Members of the workshop observed that general aviation provides essential functions for business throughout the United States and the world. Business travelers who need to move rapidly between smaller cities or who must travel to several cities during the same day find that airline service frequently is not available or is inappropriately scheduled to satisfy their requirements. With the continuing rise in fuel prices and the advent of airline deregulation, the major air carriers have concentrated their schedules between city pairs that are separated by long distances and are sufficiently large to generate high load factors. Such flights yield the highest profits for the airlines. Commuter airlines have not completely filled the gap in service. Consequently, general aviation has become an integral part of the nation's transportation system, and its importance will increase as the airlines continue to react to the rising costs of fuel and labor.

In addition to being a time-efficient form of transportation, general aviation also is fuel-efficient. If the same travel capability that now is available with small general aviation equipment were provided by airlines, using current airline equipment, more fuel would be consumed.

Another important factor is the role general aviation products play in the U.S. balance of payments. The U.S. sells more products throughout the world's general aviation community than does any other nation, and we enjoy the number one position in exports of general aviation goods. But this U.S. dominance is being challenged. Only by offering products that embody the most advanced technology and offer the most desired features, such as

high fuel efficiency, low life cycle costs and high reliability, will the U.S. maintain its leadership in world markets.

The optimum powerplant for general aviation aircraft is one that provides desirable performance while using a readily available fuel and operating for the lowest possible cost per mile.

Participants at the workshop concurred that the most readily available aviation fuel for the next 30 years will be a product that meets the specification of ASTM D1655 or its future derivatives. That consensus is based upon the extensive use of such turbine fuel by the world's major airlines, thereby being readily available at major airports. The turbine fuel that airlines normally use is more easily refined and distributed than is aviation gasoline. Also, considering the long term sources of aviation fuel, attendees noted that turbine fuel can be synthesized from shale with good efficiency.

The workshop participants agreed in general that the availability of aviation gasoline during the next 20 to 30 years will be constrained by marketing and distribution considerations rather than by refining capability. In markets where there is a strong demand for aviation gasoline, it will be available. But at outlying airports where flying activity is sparse or the normal consumption of fuel is low, petroleum dealers are finding the distribution of aviation gasoline to be uneconomical. Therefore, shortages or lack of availability may be prevalent at smaller airports in the future.

Furthermore, the availability of aviation gasoline has been limited or interrupted in several foreign countries, due mainly but not exclusively to the problems that have occurred within Iran.

While the majority of the workshop participants felt that the fuel needs of general aviation would be met adequately with aviation gasoline and airline-type turbine fuel, a minority group felt that flying in remote areas would be seriously hindered unless the use of automotive gasoline in aircraft was approved. Consequently, they wanted NASA to pursue a research program that would develop technical information relevant to the safe use of automotive gasoline in present and future aircraft reciprocating powerplants and fuel systems. Parts of that program would include identifying the limits for using automotive gasoline, examining the effects of aromatic variability on elastomers and possibly developing portable, easy to use devices for measuring the properties of gasoline.

The majority of the workshop attendees were against the aviation use of automotive gasoline because of the possible problems associated with the wide variation in its properties relative to the needs of general aviation.



## CONCLUSIONS

1. Although there appears to be many questions concerning the use of automotive gas in aircraft, the majority of the workshop attendees did not feel that NASA is the appropriate agency to generate relevant information in this area since work to be done is of an applications nature and the results would differ according to the specific engine and aircraft considered. The majority of the workshop attendees felt that the tradeoff between potential problems, such as the variability of automotive gas and the specter of product liability, when compared with the possible rewards of approving the use of such fuel in aircraft did not provide sufficient incentive to commit NASA's or another Federal agency's funds to a research program. However, the attendees did not wish to preclude the use of private funds for such investigations if some manufacturer or user desired to seek approval for using automotive gas in aircraft.

2. There is no advantage to the manufacturer, distributor or consumer in changing the characteristics of aviation gasoline in a manner that would require recertification of existing engines.

3. The composition of the general aviation fleet will be dominated by gasoline-fueled reciprocating engines for the next 30 years, with significant numbers of such aircraft remaining in use well beyond that period of time.

4. A need exists to enhance the capabilities of gasoline-fueled reciprocating engines, particularly in the area of altitude performance, fuel consumption, noise, cooling, reliability, weight, size and ease of operation.

5. A need exists to develop simplified and more convenient methods of testing aviation fuels.

6. The fuels to be used for researching and developing future general aviation engines should match the specifications for aircraft gas turbine fuels, which means ASTM D1655 or its derivatives. The suitability of such a fuel should be established by parametric studies of pertinent fuel properties. However, the fuel ultimately should be identical to the fuel used by large commercial gas turbine engines for aircraft.

7. A need exists for an intermittent combustion engine that is optimized to operate with the type of turbine fuel that is in most widespread use by the airlines. It would be desirable if such engines could also operate on aviation gasoline. While such an engine might be classified as possessing a multi-fuel capability, that feature is of secondary importance and should not be allowed to compromise the design. Also, the engine should have a form factor that allows it to be easily retrofittable

to aircraft powered by gasoline-fueled reciprocating engines, and it should possess better specific fuel consumption, lower life cycle costs and less weight per horsepower than existing intermittent combustion engines.

8. Although the workshop concentrated on intermittent combustion powerplants, NASA should continue to pursue the objectives of its General Aviation Turbine Engine Program since turbines have their own place in the general aviation market.

## RECOMMENDATIONS

1. That NASA not undertake research that is intended to modify the properties of aviation gasoline.

2. That NASA consider a research program that would lead to the development of simplified and convenient methods for testing aviation fuels, with specific emphasis on the measurement of the rich rating.

3. That NASA proceed with and accelerate its proposed Piston Engine Technology ("PET") Program since the results of that effort will benefit existing gasoline-fueled engines as well as future intermittent combustion engines whether they are of the compression or spark ignition type and use reciprocating or rotary combustion techniques. The attendees emphasized that the results of "PET" would have an immediate application, would benefit engine types that will be operating for the next 30 or more years and are needed now.

4. That NASA proceed with a research program that will result in the enabling technologies needed to develop a general aviation powerplant that runs efficiently on the type of turbine fuel that is in most widespread use by the airlines. The engine, which is described in Conclusion 6, could use either compression or spark ignition and either reciprocating or rotary combustion. Furthermore, except for the form factor, it might be a gas turbine although the recommended effort should lead to powerplants that are cost competitive with gasoline-fueled engines, which might preclude a turbine design. The recommended engine should be designed around the most plentiful airline fuel although the ability to run on more than one type of fuel is desirable. Otherwise, the recommended research program possesses the objectives of NASA's proposed General Aviation Multi-fuel Engine ("GAME") Program.

5. That NASA initiate the recommended programs as quickly as possible so that the results of the "PET" effort will be available within the next few years and that an intermittent combustion engine optimized for airline-type turbine fuel can be developed by the general aviation industry for use in the early 1990s.

6. That NASA recognize the very long lead times associated with developing alternatives to fossil-based fuels and establish an exploratory program to examine the use of non-fossil fuels for general aviation.

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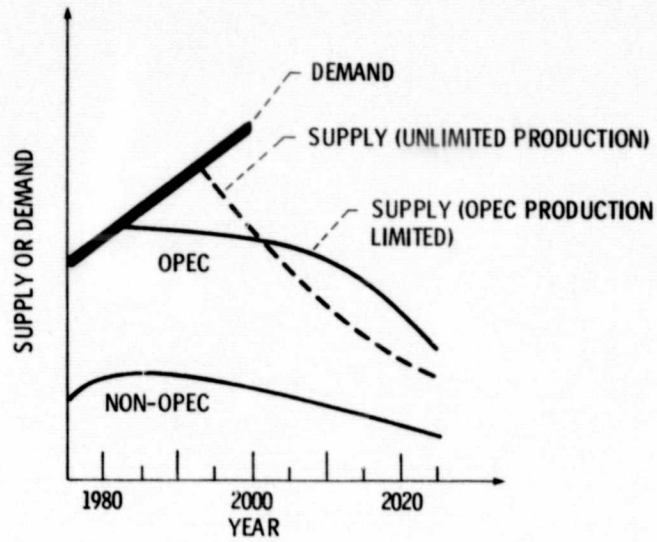


Figure 1. - The chronic oil shortage may begin as early as 1982.

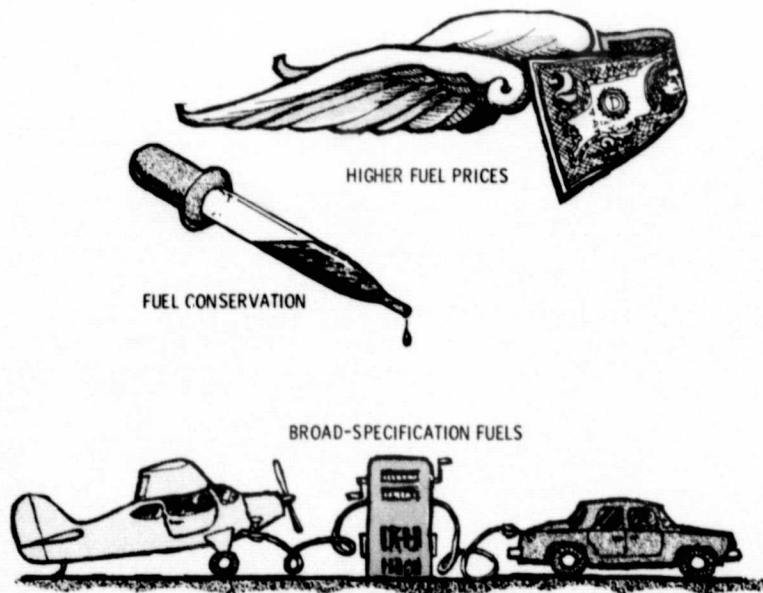


Figure 2. - Pressures resulting from an oil shortage.



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- o NEAR TERM WORK COMPLETED
- o ROTARY AND DIESEL ENGINES LOOK GOOD FOR G/A
- o FY 82 FUNDING CONSTRAINTS FORCE CONCENTRATION OF EFFORT
- o ROTARY AND DIESEL ENGINES SELECTED FOR LEWIS TECHNOLOGY PROGRAM
- o TWO-STROKE CYCLE DIESEL EFFORT FOR G/A TO BE CONTINUED AS BACKUP
- o HIGH POWER (2000 HP) DIESEL ENGINE FOR TRANSPORT A/C LOOKS GOOD ESPECIALLY FOR LONGER RANGE

Figure 3. - Program status - end of 1981.

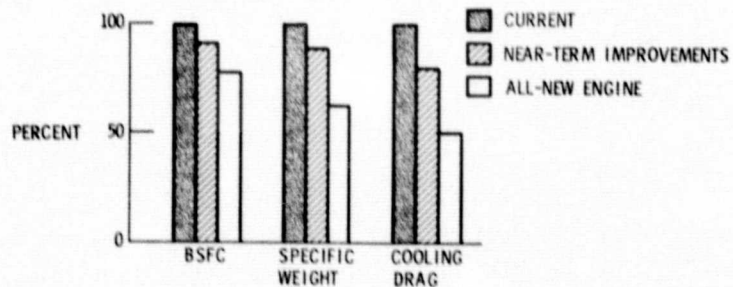
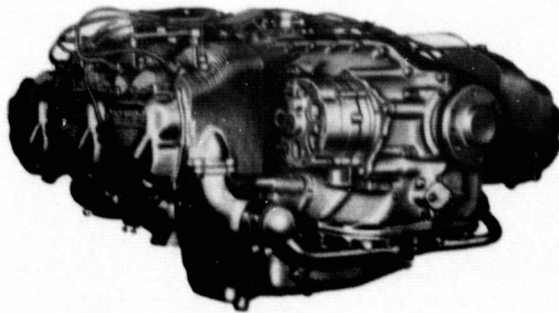
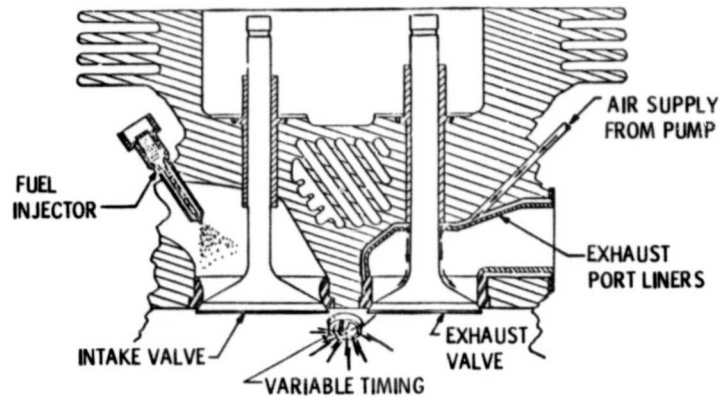


Figure 4. - Aircraft piston engine potential for improvement.

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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 5. - Concept integration.



Figure 6. - Engine installation.



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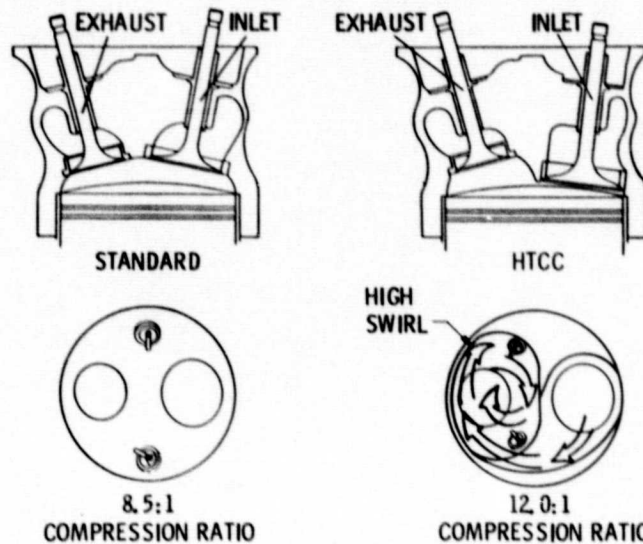


Figure 7. - High compression ratio/lean burn combustion chamber.

- o JET KEROSENE IS FUEL OF CHOICE FOR ANY ALL-NEW G/A ENGINE FOR AT LEAST THE NEXT 30 YEARS
- o CONVENTIONAL-TYPE RECIPS WILL REMAIN NUMERICALLY PROMINENT OVER THE SAME PERIOD, IN SUFFICIENT NUMBERS TO WARRANT THE PURSUIT OF ADVANCED AVGAS/RECIP COMBUSTION TECHNOLOGY
- o JET KEROSENE WILL EVOLVE TOWARD BROADER SPECS. AVGAS SPEC. WILL CHANGE LITTLE IF AT ALL
- o ESTABLISH THE BASIC THRUSTS OF G/A-RELATED ENGINE RESEARCH FOR YEARS TO COME

Figure 8. - Lewis workshop on "Aviation gasolines and future alternatives" (LeRC, February 3, 4, and 5, 1981).

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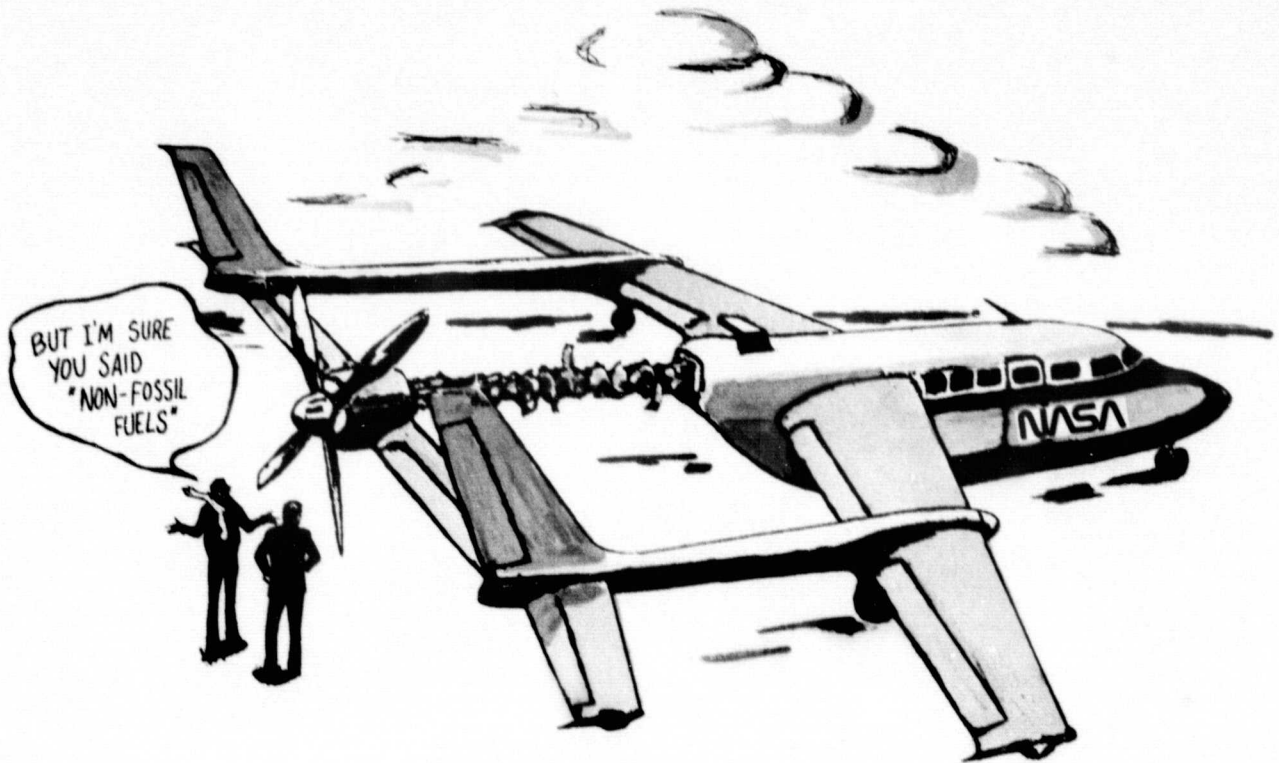
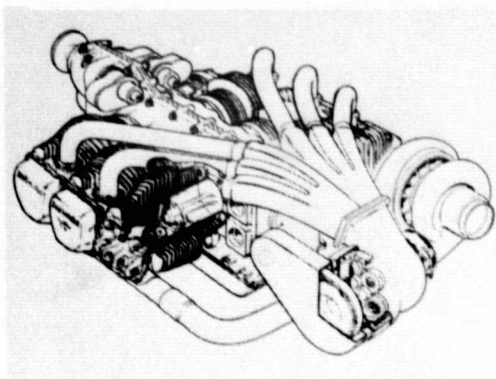


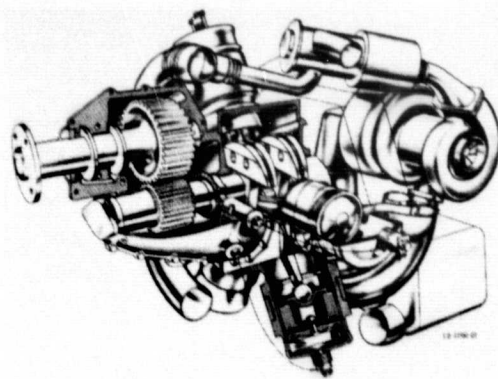
Figure 9. - Alternative propulsion systems.

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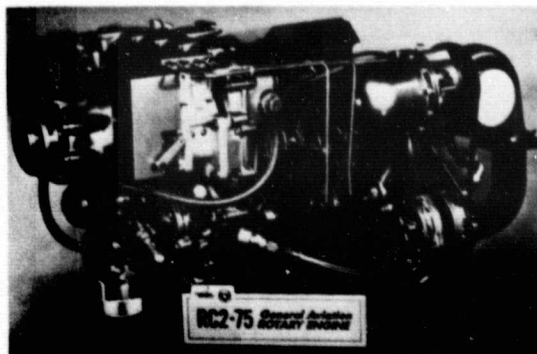
SPARK IGNITION RECIPROCATING ENGINE

SFC = 0.33 lb/hp-hr  
SP. wt. = 1.16 lb/hp  
\*TURBOCOMPOUNDED



LIGHTWEIGHT DIESEL ENGINE

SFC = 0.32 lb/hp-hr  
SP. wt. = 1.02 lb/hp



ROTARY ENGINE

SFC = 0.35 lb/hp-hr  
SP. wt. = 0.80 lb/hp

Figure 10. - Advanced technology general aviation engines.



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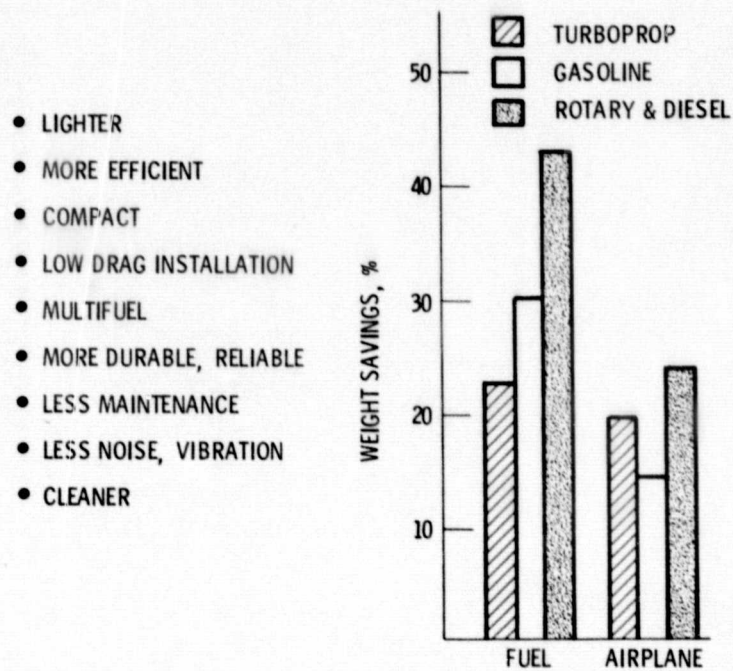


Figure 11. - Advanced propulsion system benefits.

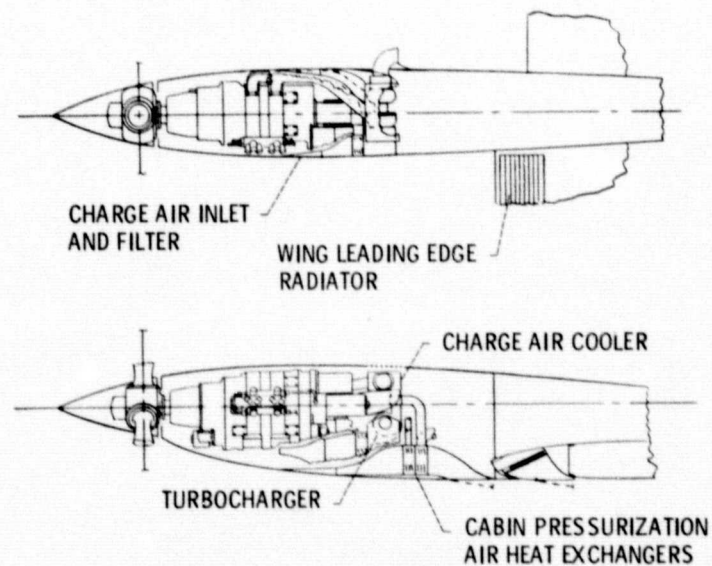


Figure 12. - Rotary engine installation.

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5000 FT, 125 KTS, 4000 HP

TYPE	CRUISE BSFC	CRUISE WE/HP
TURBOFAN	0.60	--
TURBOPROP	0.36	0.25
REGENERATIVE TP	0.34	0.34
ROTARY/TP COMPOUND	0.32	0.31
CERAMIC REGENERATED INTERCOOLED TP	0.30	0.33
ROTARY - ADIA. TURBOCOMPOUNDED	0.30	0.83
DIESEL - ADIA. TURBOCOMPOUNDED	0.30	0.53
NUCLEAR	0.00	6.50

Figure 13. - Candidate engine types.

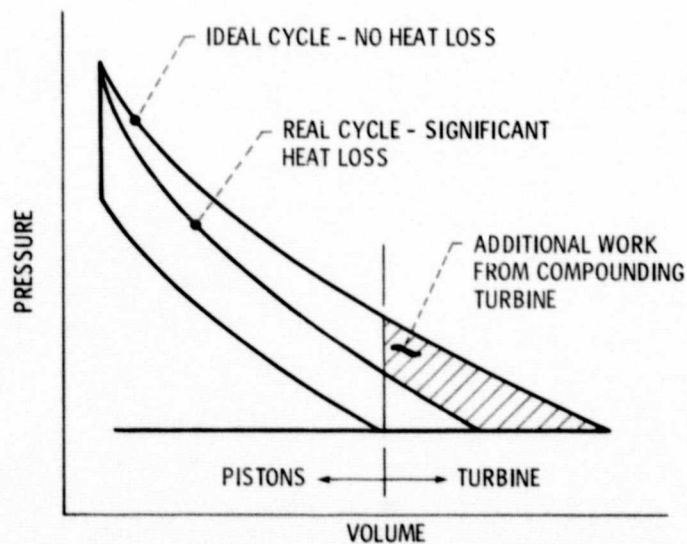


Figure 14. - Adiabatic - turbocompound cycle (ATC) concept.

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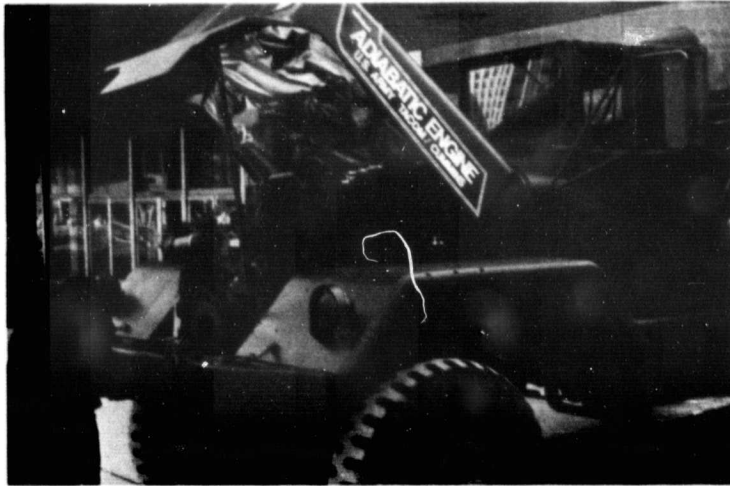


Figure 15. - Adiabatic (uncooled) diesel truck.



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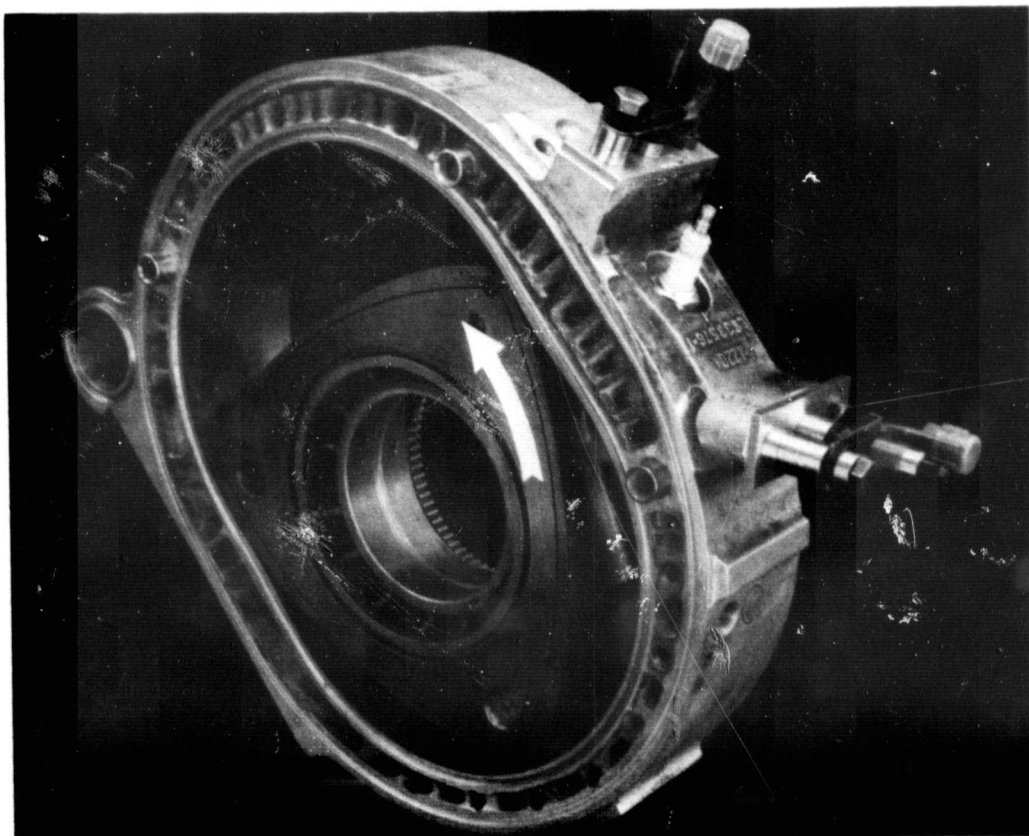
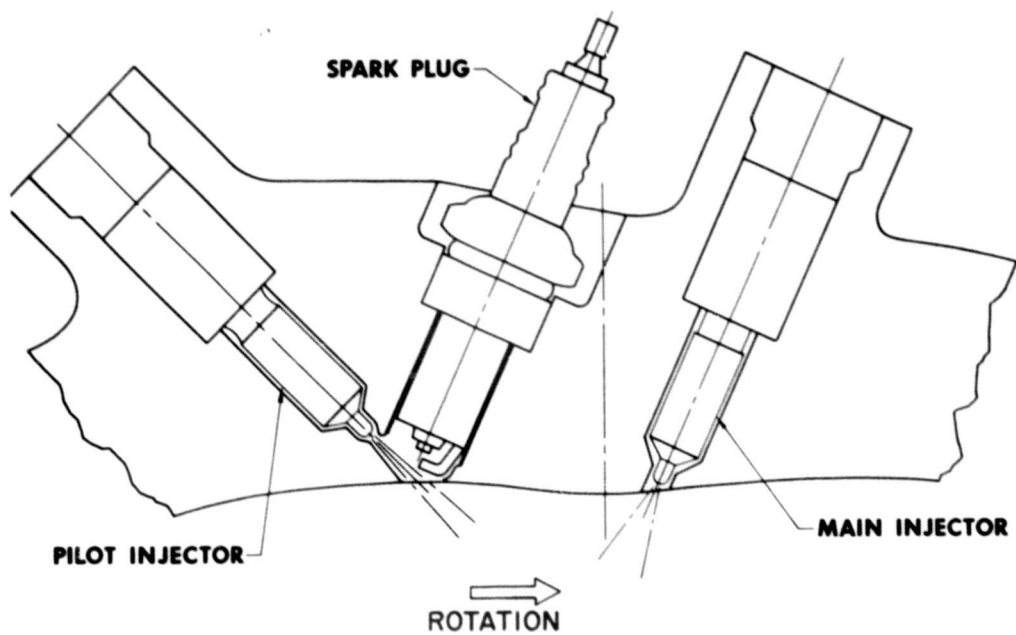


Figure 16. - Rotary stratified-charge concept.

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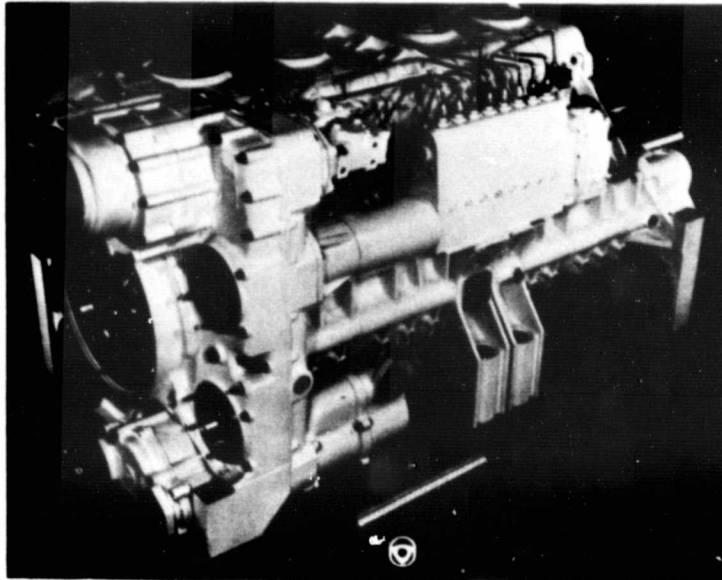


Figure 17. - 1500 hp rotary marine engine.

	750 BHP	ADVANCED* 1440 BHP	HIGHLY ADVANCED* 1780 BHP	HIGHLY ADVANCED (BSFC FAVORED) 1300 HP
MAX. RPM	3600	4300	4800	3600
MAX. BMEP	117	187	208	202
BSFC @ MAX. HP	.40	.40	.375	.35
MIN. BSFC @ 50% POWER	.39	.37	.35	.34
MULTI-FUEL	YES	YES	YES	YES
WEIGHT** (DRY) - LBS.	1106	1285	1150	1011
SPECIFIC WEIGHT - LBS/HP	1.61	0.89	0.65	0.78

\*ADVANCED: INCREASED IMEP AND RPM  
HIGH STRENGTH, HIGH TEMPERATURE ALUMINUM ALLOY CASTINGS  
LIGHTWEIGHT ROTOR  
EXHAUST PORT THERMAL LINER AND ROTOR INSULATION FOR REDUCED HEAT REJECTION  
IMPROVED APEX SEALS/TROCHOID COATINGS  
REDUCED FRICTION

\*HIGHLY ADVANCED: SAME AS ADVANCED PLUS:  
WEIGHT REDUCTION THROUGH ADVANCED MATERIALS  
VARIABLE AREA TURBOCHARGER  
FURTHER INCREASES IMEP, RPM, AND REDUCTIONS IN FRICTION

\*\*ENGINE ONLY

Figure 18. - Turbocharged SCRC2-350 growth potential.

- o TWO STROKE, RADIAL-PISTON, ADIABATIC TURBOCOMPOUND (ATC) DIESEL CYCLE
  - LOWER WEIGHT
  - COMPACT DESIGN
  - LOW FUEL CONSUMPTION
  - INHERENT BALANCE
  - LOWER PARTS COUNT
- o INSULATED COMBUSTION CHAMBER (PARTIAL ADIABATIC)
  - REDUCED COOLING HEAT LOAD
  - REDUCED COOLING DRAG
  - MORE EXHAUST ENERGY TO TURBOCHARGER/TURBOCOMPOUND
- o HIGH SPEED, HIGH PRESSURE CYCLE DEMANDS ADVANCED COMBUSTION, THERMAL AND MECHANICAL TECHNOLOGIES
  - INSULATED COMBUSTION CHAMBER COMPONENTS
  - HIGH SPEED, HIGH PRESSURE FUEL INJECTION
  - HIGH PERFORMANCE TURBOCHARGER/TURBOCOMPOUND SYSTEM
  - ADVANCED PISTON RINGS AND LUBES

RELIABILITY

Figure 19. - Diesel commuter study engine - leading features.

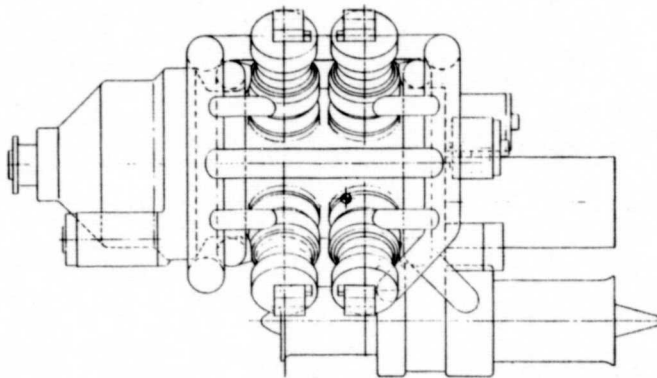


Figure 20. - Commuter diesel, 2000 hp configuration.

NUMBER OF CYLINDERS	8
CYCLE	2 S.C.
CONFIGURATION	RADIAL/COMPOUNDED
BORE x STROKE	4.80 x 5.34 IN.
DISPLACEMENT	773 IN <sup>3</sup>
EFFECTIVE C.R.	9:1
ENGINE SPEED	4000 RPM
HP (FLAT RATED CONTINUOUS)	2000 RPM
BMEP	230 PSI
PISTON SPEED	3557 RPM
SPECIFIC POWER	2.33 HP/IN <sup>3</sup>
SPECIFIC WEIGHT	.65 TO .75
BSFC @ 15,000 FT.	0.30
TURBO PR	8:1

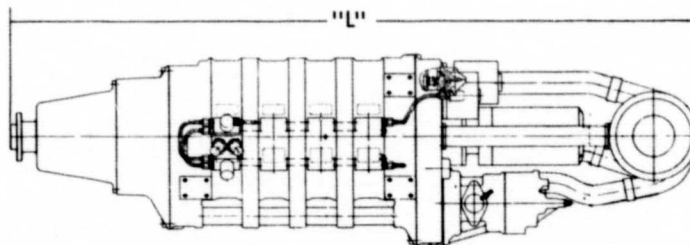
Figure 21. - 2000 hp ATC diesel engine characteristics.



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- o FOUR-STROKE, ROTARY (WANKEL) STRATIFIED-CHARGE, ADIABATIC-TURBOCOMPOUND (ATC) CYCLE
  - LIGHTWEIGHT
  - COMPACT, LOW FRONTAL AREA
  - LOW FUEL CONSUMPTION
  - MULTIFUEL CAPABILITY
  - INHERENT BALANCE--ALL ORDERS
  - MINIMAL TORQUE PULSATIONS
  - EASILY SCALED
  - LOW PARTS COUNT--RELIABILITY
  - EXTENDED DURABILITY POTENTIAL (RETRACTABLE SEALS)
- o INSULATED COMBUSTION CHAMBER (PARTIAL ADIABATIC)
  - REDUCED COOLING HEAT LOAD
  - ZERO OR MINIMAL COOLING DRAG
  - MORE EXHAUST ENERGY TO TURBOCHARGER/TURBOCOMPOUND
- o HIGH SPEED, HIGH PRESSURE CYCLE AND EXTREME DURABILITY DEMAND ADVANCED COMBUSTION, THERMAL AND MECHANICAL TECHNOLOGIES
  - ADVANCED (E.G., RETRACTABLE) APEX SEALS--THE KEY TO ALL ELSE
  - HIGH TEMPERATURE COOLING/INSULATED ROTORS AND HOUSINGS
  - HIGH SPEED, HIGH BMEP STRATIFIED-CHARGE COMBUSTION SYSTEM
  - HIGH PERFORMANCE TURBOCHARGER/TURBOCOMPOUND SYSTEM

Figure 22. - Rotary-combustion commuter study engine - leading features.



T. O. HP*	"L"	DIA.	WEIGHT	BSFC @ CRUISE*
800/(880)	67	21	510	0.33/(0.30)
2500/(2750)	110	25	1780	0.33/(0.30)
	(inches)	(inches)	(lb)	(lb/bhp-hr)

\*CONVENTIONAL COOLING/(ATC CYCLE)

Figure 23. - Rotary combustion commuter aircraft engine.

	<u>CONVENTIONAL-COOLED</u>	<u>ADIABATIC (ATC)</u>
NUMBER OF ROTORS	6	6
CYCLE	4 S.C.	4 S.C.
CONFIGURATION	WANKEL/COMPOUND	WANKEL/COMPOUND
DISPLACEMENT	522 IN <sup>3</sup>	480 IN <sup>3</sup>
EFFECTIVE C.R.	8:1	8:1
ENGINE SPEED	6680 RPM	6900 RPM
HP (TAKEOFF)	2000 HP	2000 HP
BMEP	210 PSI	210 PSI
APEX SPEED (AVE)	6314 FPM	6314 FPM
SPECIFIC POWER	3.83 HP/IN <sup>3</sup>	4.16 HP/IN <sup>3</sup>
SPECIFIC WEIGHT	.75 LB/BHP	.65 LB/BHP
BSFC @ 15,000 FT.	0.33 LB/BHP-HR	0.31 LB/BHP-HR
TURBO PR	4:1	6:1

Figure 24. - 2000 hp rotary engine characteristics - two versions.

MACH 0.30, 20,000 FT, 2400 N.M.

	<u>ADVANCED TURBOPROP</u>	<u>ATC DIESEL</u>	<u>ATC ROTARY</u>
ESHP (1)	4550	3265	4068
ENGINE WEIGHT (2)	1638	--	4481
GEARBOX WEIGHT (2)	766	--	577
ENG + G.B. WGT (2)	2404	3410	5058
ENG + G.B. WGT/ESHP	0.28	0.53	0.62
PROP WEIGHT (2)	1000	964	1028
FUEL WEIGHT	14975	12366	13344
CRUISE BSFC	.346	.304	.300
A/C EMPTY WEIGHT	26620	26950	30250
PAYLOAD WEIGHT	6000	6000	6000
TOW, LB	48660	46570	50850
AIRFRAME COST	4.14M	4.04M	4.31M
ENGINE COST (1)	.569M	.408M	.508M
PROPELLER COST (1)	20100	19700	20500
AIRCRAFT COST	5.31M	4.90M	5.38M
ENG MAINT \$/FLT HR	121	99	114
REL. DOC	1.0	.82	.95

Figure 25. - 30 PAX commuter comparison.

- o HIGH-SPEED, HIGH BMEP FUEL INJECTION SYSTEM
- o "ADIABATIC" COMBUSTION CHAMBER COMPONENTS
- o ADVANCED PISTON RINGS/LUBES
- o ADVANCED TURBOCHARGER AND COMPOUNDING TURBINE
- o SINGLE-CYL., 2-STROKE TEST ENGINE  
- RUNNING @ TELEDYNE GENERAL PRODUCTS DIVISION
- o PARALLEL IN-HOUSE EFFORT BEGINNING FY 83

Figure 26. - Diesel engine-specific technology.

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- o ADVANCED SEALING GRIDS/LUBES
- o THERMAL BARRIER COMBUSTION CHAMBER COMPONENTS
  - CERAMIC COATINGS
  - COMPOSITE STRUCTURES
- o HIGH-SPEED, HIGH BMEP STRATIFIED-CHARGE COMBUSTION SYSTEM
- o ADVANCED TURBOCHARGERS AND COMPOUNDING CONCEPTS
- o HIGH-SPEED, HIGH BMEP ROTARY TEST ENGINE
  - CONTRACT WITH CURTISS-WRIGHT, \$3M, FY 82-85
  - SINGLE ROTOR, 32-47 CU. IN/ROTOR
- o PARALLEL IN-HOUSE EFFORTS

Figure 27. - Rotary engine-specific technology.



Figure 28. - Direct-injection stratified-charge.



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

THIS RESULTS IN REDUCED IGNITION LAG

BENEFITS:

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

STATUS:

- o THEORY CONSISTENT WITH LIMITED EXPERIMENTAL DATA AVAILABLE
- o ARMY/NASA COORDINATED PROGRAM UNDERWAY
  - ARMY: ENGINE EXPT'S (SINGLE CYL., EATON RESEARCH)
  - NASA: BASIC COMBUSTION (UNIV. OF CA GRANT)
- o CURRENT PLANS RECEIVED POSITIVE RESPONSE @ 2/23/82 REVIEW MEETING
- o NEXT MEETING: SEPT. 1982

Figure 29. - Preheated fuel injection - "hypergolic combustion".

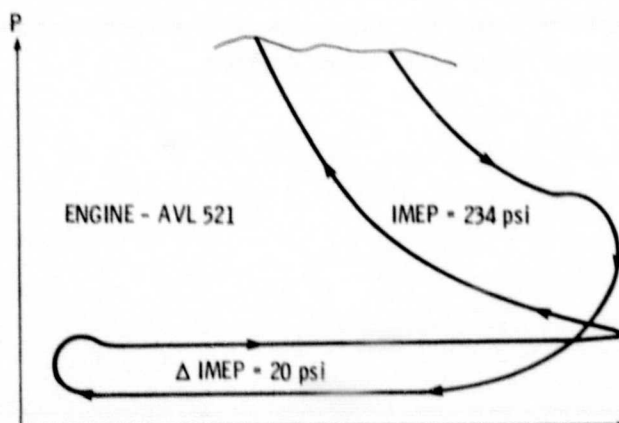


Figure 30. - Pressure compounding concept.