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# Comparisons of Four Alternative Powerplant Types for Future General Aviation Aircraft

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## ABSTRACT

Recently completed NASA-sponsored conceptual studies have culminated in the identification of promising new technologies for future spark ignition, diesel, rotary, and turbine engines. This paper reports the results of a NASA in-house preliminary assessment study that compares these four powerplant types in several general aviation applications. The evaluation consisted of installing each powerplant type in "rubberized" aircraft which are sized to accomplish fixed missions. The primary evaluation criteria include projected aircraft cost, total ownership cost, and mission fuel.

## INTRODUCTION

Four recent NASA-sponsored conceptual studies have identified several promising engine technologies applicable to the general aviation field. Advanced lightweight diesels (ref. 1), stratified-charge rotaries (ref. 2), inexpensive gas turbines (ref. 3-7), and spark-ignited reciprocating engines (ref. 8) were defined and then compared individually to current-technology reciprocating engines for several general aviation applications. Each study concluded that major improvements were possible. But because only a few applications were considered in each study, and the mission definitions varied from one study to the others, it is difficult to compare these alternative powerplant types with each other on a consistent basis. The results presented herein address that issue and are based principally on engine characteristics supplied by the competing engine companies. NASA assumptions were used only when required information was otherwise unavailable.

The results presented in this paper are preliminary in the sense that NASA has not yet attempted to resolve seemingly inconsistent or controversial assumptions, particularly in the level of technology advancement represented. The contractors assumed different levels of technology within engine types, thus, defining comparable technology and relative risk between engine types is further complicated. No attempt is made to define the inter-engine relative technology levels at this time. The results, then, represent only the first phase in a continuing assessment process. As time progresses, further definition of the improvements and risks involved in each engine type will require re-evaluation of the engine assumptions. In fact, this study was undertaken primarily to generate parametric sensitivity data to facilitate later modifications--either by NASA or others--under differing scenarios. Hence, at this stage, no conclusions are offered concerning the relative attractiveness of the competing engine types. Though overall trends are sometimes apparent, the engine ranking is subject to considerable shifting due to the preliminary nature of the engine performance, weight, and cost assumptions.

The engines were evaluated for eleven fixed-wing and two rotary-wing applications. This evaluation consisted of installing each engine type in a "rubberized" aircraft which is sized to accomplish each fixed mission. Three figures of merit were used to compare engine performance: aircraft acquisition cost, mission fuel, and five-year total ownership cost (TOC). TOC is based on 500 hr/year utilization and is defined in Table 1.

## SYMBOLS

| | |
|---|---|
| AC | acquisition cost, 1977 $ |
| BSFC (SFC) | brake specific fuel consumption, lb/HP-hr |
| $C_d$ | cooling drag, % aircraft drag |
| $C_e$ | engine cost, 1977 $/HP |
| $C_f$ | fuel cost, 1977 $/gal. |
| L/D | lift-to-drag ratio |
| MC | maintenance cost, $/flight-hr |
| OEM | original equipment manufacturer |
| TBO | time between overhaul, flight-hr |
| SHP | shaft horsepower, HP |
| SIR | spark ignited reciprocating engine |
| $W_e$ | engine weight, lb/HP |
| $W_f$ | mission fuel weight, lb |

## ANALYSIS

### Engine Technology Levels

Three terms will be used to differentiate different versions within each engine type: current, advanced and very advanced technology. Current technology is defined as circa 1980 production engines, except for the diesel and rotary where no aircraft production engines are available (prototypes were used instead). Since no relative technology level assessment has been completed between engine types, the terms advanced and very advanced technology define relative technology levels within particular engine types, but do not necessarily represent comparable technology levels between types. Aggressive research programs would be required to enable production versions of these engines by the early 1990's.

### Engine Design Assumptions

Spark-Ignited Reciprocating Engines - The engine design features for the Spark-Ignited Reciprocating (SIR) engine (ref. 8) are defined in figure 1. The current technology version serves as the baseline engine from which the improvements of all of the other engines are measured. This current technology engine is naturally aspirated below 10,000 foot cruise altitude and turbocharged above 10,000 foot. The advanced and very advanced versions are both turbocompounded. Since a turbocharger is necessary to achieve superior performance, no naturally-aspirated version was considered.

The current and advanced SIR engines use a homogeneous charge of aviation gasoline while the very advanced version uses a stratified-charge, which provides multifuel capability. This capability becomes increasingly important as aviation gasoline becomes scarcer and more expensive.

The cooling drag penalty for the current technology SIR was assumed to increase the aircraft drag by 10 percent. Reference 9 indicates cooling drag to be 5-20 percent of aircraft drag. A 50 percent reduction in SIR cooling drag is predicted in reference 10 due to better cooling techniques and better nacelle-cooling system integration. This 50 percent reduction was assumed for the advanced technology version, while a 65 percent reduction was assumed for the very advanced version relative to a current SIR.

Rotary Engines - The engine design features for future rotary engines (ref. 2) are shown in figure 2. The major emphasis of the rotary study was directed at an advanced technology version, though a lower-level effort did postulate a more advanced version, herein labeled very advanced. Both versions used a stratified-charged fuel injection system that provides multifuel capability. The advanced version is supercharged, while the very advanced version is pressure compounded. Both versions require a turbocharger to achieve high performance and both are liquid cooled. The advanced version is assumed to have 65 percent less cooling drag than a current SIR, while the very advanced version is assumed to have negligible cooling drag.

One of the design features of the very advanced rotary is the retracting apex seal. This retracting seal allows higher engine RPM without excessive seal wear. Higher RPM permits higher airflows and thus higher horsepower from the same size engine.

Diesel Engine - The engine design features for the lightweight diesel (ref. 1) are shown in figure 3. Both the advanced version and the very advanced version are two-stroke radial designs having the same cooling requirements as comparable technology SIR versions.

One of the unique design features of these diesels is the independent turbocharger loop. Along with the turbocharger compressor and turbine, a burner is also provided with the necessary ducting to allow the airflow to bypass the diesel and thereby permit the turbocharger to act as an independent auxiliary power unit. While this feature adds cost and complexity to the engine, it also offers some significant design improvements. This independent loop permits the turbocharger to provide auxiliary power while on the ground without the necessity of starting the entire powerplant. Many of the starting problems (hot, cold, and restart) associated with diesel engines are eliminated by first starting the turbocharger loop to preheat the air. Since high diesel compression ratios are normally required only for acceptable starting performance, the independent turbocharger loop allows the engine to be designed for much lower compression ratios. The lower compression ratio results in lower stresses and lighter recip-related component weights.

The turbocharger is a key component in the diesel design. It is required to operate well beyond current turbocharger capability. With the high turbocharger pressure ratio, the engine exhaust air does not contain sufficient energy to power the turbocharger above 17,000 foot cruise altitudes. To eliminate excessive thrust lapse at high altitudes it is necessary to burn fuel in the turbocharger loop to add additional energy to the turbine inlet air. A corresponding BSFC penalty was charged to the engine as shown in figure 4.

Turbine Engines - The engine design features for the inexpensive gas turbine are shown in figure 5. The turbine engines used in the present study are representative of those proposed by the General Aviation Turbine Engine (GATE) contractors (refs. 4-7). These studies addressed only one level of technology, herein termed advanced technology, with the major effort aimed at engine cost reduction, while still achieving some performance improvement. The turbine engine is assumed to take advantage of the 40 percent cost reduction projected for GATE low-cost manufacturing techniques with another 25 percent cost reduction predicted for large production rates (around 10,000 engines/year per manufacturer).

An additional cost reduction method considered in the GATE studies was the common-core engine family. The core engine has a single-stage, 9:1 pressure ratio centrifugal compressor driven by a single-stage radial turbine. As the horsepower requirements increase a single-stage axial compressor, a single-stage axial turbine as well as an identical set of gearbox components are added to obtain a 12:1 pressure ratio machine with about 70 percent higher horsepower.

Only one level of technology is presented for the turbine engine. Though a more advanced version can be configured, its relationship to the low-cost GATE theme is difficult to determine. An expensive turbine engine could be cost prohibitive in light general aviation airplanes.

## Installation Penalties

Engine installation penalties are shown in Table 2. The SIR and rotary engines are assumed to obtain the air conditioning and pressurization requirements from the turbocharger and no penalty was assessed to the engine. The diesel, with its high turbocharger design pressure ratio, did not have sufficient energy in the engine exhaust gas to supply the air conditioning and pressurization requirements for the entire flight regime, thus a 4 percent horsepower penalty was charged to the diesel. The turbine engine installation penalties are assessed differently from its positive displacement counterparts. While the power requirements for the alternator, fuel pump and oil pump are similar, the turboprop air conditioning and cabin pressurization requirements are not obtained from a turbocharger or as a horsepower penalty from the shaft. Instead, the turbine engine meets these requirements using compressor discharge air which causes significant BSFC penalties. This pressurization requirement need not take this form; instead, an auxiliary shaft-driven compressor or midstage bleed could be utilized to reduce the BSFC penalty markedly. However, it is assumed herein that compressor discharge bleed will be used to satisify the air conditioning and pressurization requirements (1 to 1½ lb/min/pass compressor discharged bleed was assumed).

## Engine Performance Assumptions

BSFC Assumptions - Projected cruise BSFC for each engine type, along with the corresponding percent improvement relative to their current technology versions are shown in figure 6, for 350 thermodynamic SHP at sea level static standard conditions. A 20 percent BSFC improvement over current state-of-the-art is projected for the advanced turboprop. This improvement is primarily due to improved component efficiencies and more efficient thermodynamic cycle (made possible by material improvements and lower cooling requirements). The BSFC for the advanced SIR is projected to improve 20 percent as a result of higher design brake mean effective pressure (BMEP), more efficient combustion, and turbocompounding. A further 5 percent BSFC improvement is projected for the very advanced version due to charge stratification. A 20 and 30 percent BSFC improvement is projected for the advanced and very advanced rotary engines. In the advanced version, this improvement is due to better combustion (stratified charge), higher BMEP and apex seal improvements. The BSFC improvements for the very advanced version are a result of the above with the additional advantage of pressure compounding. The advanced diesel's 8 percent improvement is a result of more efficient combustion and reduced friction losses, while the 20 percent improvement projected for the very advanced version is a result of the added benefits of higher BMEP and reduced cooling losses. The diesel BSFC accounts for fuel burned in the turbocharger loop at high altitudes. Below 17,000 feet this fuel burning is not necessary and the diesel BSFC is lower (figure 4). The assumed effects of engine size on BSFC are shown in figure 7 as a function of rated power (for turbine engines this is assumed to be identical to "thermodynamic horsepower", that is, maximum deliverable power without gearbox or any other limitations). All positive displacement engines are assumed to follow the same BSFC trends with horsepower. The turboprop BSFC is much more sensitive to size effects than positive displacement engines in this horsepower range due to limitations on end wall clearances and manufacturing tolerances, and the dominance of the boundry layer in the flow path. Turboprop BSFC is also dependent on speed and altitude. The turboprop BSFC curve is regressed through the BSFC points used in the study as calculated at each aircraft cruise condition (using a NASA in-house thermodynamic design point code which accounts for speed, altitude and size effects). The break in the turboprop curve at 300 horsepower is due to a change from a 9:1 overall pressure ratio below 300 horsepower to 12:1 above in accordance with the common core concept referred to earlier.

Engine Weight Assumptions - Engine installed specific weight comparisons are shown in figure 8. The already lightweight turboprop is predicted to improve a relatively modest 20 percent due mainly to reduced airflow (higher specific power) resulting from higher cycle temperatures. The use of higher compressor and turbine loadings which permit fewer stages also contributes to lower weight. The 17 and 30 percent projected weight reductions for the advanced and very advanced SIR are due to turbocompounding, higher BMEP and lighter materials (titanium parts). The 10 and 40 percent weight reduction predicted for the advanced and very advanced rotary engines, respectively, are the result of higher BMEP, turbosupercharging, higher RPM and pressure compounding. Composite materials are also being considered for the very advanced rotary. The large 35 and 45 percent weight reductions for the advanced and very advanced diesel are a result of turbosupercharging, higher RPM, lighter materials, higher BMEP and elimination of the scavenging blower.

Current technology turboprops have significantly lower specific weights than their positive displacement counterparts. However, with the large weight reductions projected for the rotary and diesel engines, the turboprop weight advantage is drastically reduced. The effect of engine size on specific weight is shown in figure 9. These curves are based on existing weight trends for all engine types except the diesel. The diesel sizing effects were supplied by the authors of reference 1.

Engine Cost Assumptions - Although engine original equipment manufacturer (OEM) cost estimates were provided to NASA by the contractors, they were essentially rough estimates based on controversial assumptions. To avoid the appearance of accuracy where none exists, none of their projected engine costs were utilized herein. Instead, as shown in figure 10, each engine was assumed to cost $40/SHP (above 250 SHP) except the naturally-aspirated current technology SIR which was set at $30/SHP. Higher costs were assumed for smaller engine sizes in conformance with existing cost trends. Interestingly, most of the contractors' estimates were in the neighborhood of $40/SHP including those for the turboprop (which represents a 65 percent decrease due to advanced manufacturing techniques and larger production rates). Different cost assumptions can be handled through the use of sensitivity coefficients presented in appendix A where examples are also provided.

Engine TBO and Maintenance Cost Assumptions - Time between overhaul (TBO) and engine maintenance cost assumptions are shown in figures 11 and 12, respectively. Since turbine engines have historically had longer TBO and lower maintenance cost than positive displacement engines, the majority of the GATE contractors did not specifically investigate possible improvements in these areas. The diesel contractor did investigate and project improvements in TBO and maintenance cost. The rotary contractor did not supply TBO and maintenance information (except for the TBO of the advanced version); NASA arbitrarily assumed it to have the same requirements as the diesel. Thus, when comparing the projected TBO and maintenance cost of the advanced turbine engines to the advanced diesel and rotary engines, the tubroprop advantage is significantly lower than comparing actual TBO and maintenance cost of current turbine engines to current positive displacement engines.

Several other engine assumptions are shown in Table 3. The diesel, rotary, and 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. Gas turbines are assumed to cruise at 2140$^{o}$F (typcial GATE value). Engines which do not have multifuel capability were assumed to use aviation gasoline at $1.10/gallon ($1977) while engines having multifuel capability were assumed to use Jet A fuel at $1.00/gallon. For the fixed wing missions, an 87 percent propeller efficiency was assumed with SIR and diesel engines, while slightly higher propeller efficiencies were assumed with rotary and turbine engines due to less engine vibration.

## Aircraft and Missions

A plot of design cruise altitude and speed for the 13 missions is given in figure 13. Each mission is assigned a number for labeling purposes. These missions are further defined in Table 4. Two groups of aircraft are presented: (1) Current--resembling today's aircraft and missions, but slightly better airframe technology, and (2) Futuristic--similar to Malcolm Harned's speculation (ref. 11) 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, full-span Fowler flaps, and higher cruise speeds and altitudes.

The current altitude limit shown in figure 13 is the approximate limit imposed on current positive displacement engines due to turbocharging capability. Projected improvements in turbocharging technology will raise this 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 positive displacement engines and (2) the lapse rate and cabin pressurization losses of the turboprop.

## RESULTS

Figures 14-16 present trend curves for the fixed-wing missions and are used to illustrate the major results. More specific information for each mission is presented along with sensitivity information in appendix A. These results were obtained using the General Aviation Synthesis Program (GASP) described in reference 12.

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 35-50 percent for the very advanced versions (figure 14). 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 the 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 7 and 9. Due to its lightness, the turboprop competes relatively well at 25,000 feet, but for the lower and slower missions (1, 2, 3, 5), it does not, because its efficiency drops for small sizes and power loading is low. Overall, the advanced positive-displacement 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 rotary 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). However, it is also judged to entail the most technological risk and is probably further into the future than other types.

The relative shift in the diesel's position between the 25,000 foot mission and the lower altitude missions stems from a necessity to burn supplementary fuel (figure 4) in the turbocharger loop above the 17,000 foot critical altitude to prevent a serious power lapse. Finally, it should be noted that the fuel savings are shown in terms of fuel weight rather than fuel cost. The actual cost savings are about 15 percent greater due to the fuel density and price advantage of Jet A and diesel fuel compared to aviation gasoline. The turboprop and diesel already utilize the lower grade fuels while the rotary and SIR types currently do not (both advanced rotary versions plus the very advanced SIR would too, but not the advanced SIR).

Aircraft acquisition cost reduction potential is shown in figure 15. Very little cost reduction potential is shown for the 10,000 foot cruise altitude missions because the higher engine cost necessary for the turbocharged advanced engine (a 25 percent cost reduction was assumed for the non-turbocharged SIR base) offsets the structural cost savings brought about by lower engine and fuel weights. The higher altitude missions, with a turbocharged base, show a substantial acquisition cost reduction for the advanced technology engines. This indicates that less expensive, naturally-aspirated versions of these engines might offer substantial cost reduction potential for the low altitude mission, provided large BSFC and engine weight penalties do not occur.

The turboprop suffers a downward shift in relative ranking going from the 10,000 to the 25,000 foot missions. This is a result of the turboprop lapse rate and pressurization requirements necessitating larger sea level horsepower. This higher horsepower requirement incurs both engine cost and weight penalties to the airplane.

Five-year Total Ownership Cost (TOC) reduction potential is shown in figure 16 Ten to 35 percent improvements are shown for the lower altitudes and 20-45 percent gains at the high altitudes. For this criterion, the turboprop's ranking improves considerably due to its low maintenance cost. While the spread in ranking is fairly broad, with the rotary still on top and the SIR at the bottom, the overall interpretation is that all of these alternatives offer substantial improvement potential and, therefore, all should be retained as competitive candidates.

The maximum rated horsepower forecasted for the 10,000, 16,000, and 25,000 foot cruise altitude missions are shown in figure 17. The range covered by these missions was 100-500 horsepower/engine. For the positive displacement engine, the very advanced rotary required the least horsepower due to its high cruise power rating (75 percent), zero cooling drag, light weight, and high propeller efficiency. The turboprop with zero cooling drag, lightest weight, and higher propeller efficiency would be expected to have the lower horsepower requirements. At the 10,000 foot cruise altitude mission, this is the case; however, at the higher altitudes, the turboprop lapse rate results in high sea level power ratings. Also note that as the cruise speed is increased at a given altitude, the turboprop relative horsepower is slightly reduced. This is due to forward velocity effects as well as a secondary effect from favorable engine sizing effects. Missions 7 and 11, which are not shown in this figure, have horsepower requirements between 450 and 1000 horsepower, with the turboprop requiring significantly more horsepower than its positive displacement counterparts.

The effect of the futuristic airframes, defined earlier, is to reduce the drag and power loading of the airplane. For a constant mission this somewhat lessens the importance of potential powerplant improvements. In this study, however, the futuristic airframes were combined with futuristic missions (having higher cruise altitudes and speeds). The higher cruise altitudes and high wing loadings produce higher L/D, thus decreasing the power loading, however, the higher cruise speeds increase the power loading. Thus the combination of futuristic aircraft and missions resulted in only minor differences in power loading and projected aircraft improvements.

Figure 18 shows the percent improvement in the three figures of merit for the two helicopter missions. The results are similar to the fixed-wing missions. The turboshaft fuel reduction potential is considerably lower than the other engine types, but the acquisition and maintenance cost advantages are sufficient to make it competitive to the other engine types on a vehicle acquisition cost or TOC basis.

## 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. However, it is felt that an opportunity may exist to substantially improve turbocharger technology and thereby permit operation at higher cruise altitudes. If so, then advanced positive displacement engines would have the advantage of avoiding the high power laspe suffered by turboprops, provided the complexity and penalties associated with high altitude turbochargers (yet to be determined) do not overshadow the laspe rate advantage. As altitude increases, lower atmospheric pressure requires higher turbocharger pressure ratios to achieve the same manifold air density, thus the same horsepower. The diesel and rotary, with their high pressure ratios required for turbosupercharging are more susceptible to having insufficient exhaust gas energy to power the turbocharger than the SIR. In fact, above 17,000 feet, the proposed diesel must supply supplementary energy by burning fuel in the turbocharger loop combustor. Therefore, the very advanced SIR was chosen to compare with the advanced turboprop to determine the effect of high altitudes on powerplant selection.

Another issue is the increasingly more difficult provision for cabin pressurization at higher altitudes. Piston engine advocates argue that this requirement penalizes the turboprop more than the piston engines since turbochargers can supply cabin air at negligible penalty. While this is true at low altitudes, it is not clear it will remain so at higher altitudes due to insufficient exhaust energy to power the turbocharger. Also, cabin pressurization for turboprops need not take the form of compressor discharge bleed; an auxiliary low-pressure shaft-driven compressor or midstage bleed could be used to reduce the turboprop penalty markedly. Nevertheless, it is assumed herein that compressor discharge bleed would be used to pressurize turboprop aircraft and that no penalty for pressurization would be incurred by the SIR.

The results of varying the cruise altitude with these assumptions are displayed in figure 19. 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. The solid SIR curve represents a SIR engine with an ideal turbocharger--one capable of providing 70 percent engine rated power regardless of altitude and without any weight or BSFC penalties. The projected 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). The dashed SIR curve represents a SIR engine using a turbocharger with a critical altitude of 21,000 feet. (The laspe rate above this critical altitude was provided by the contractor.) This 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 accompaning weight and cost penalties. As can be seen in the figure, the idealized SIR is about 10 percent better than the turboprop in terms of fuel and TOC and, about 25 percent better in terms of acquisition cost at 45,000 feet. The 21,000 foot critical altitude SIR is comparable to the turboprop in terms of fuel and TOC but has about a 20 percent advantage in acquisition cost. Up to about 35,000 feet, the turboprop is superior. At higher altitudes, the SIR may be better if very high critical altitudes can be successfully achieved without significant penalties.

## Sensitivity To Engine Parameters

The preceding comparisons were based on preliminary engine performance calculations which incorporated speculative technology levels, inconsistent assumptions between multiple contractors, etc. Hence, the specific comparisons between engine types are subject to modification as more credible engine data becomes available in the future. An extensive body of parametric variations is presented in appendix A so that the preceding results may be corrected for variations in BSFC, engine weight, O.E.M. engine cost, engine maintenance cost, cooling drag and fuel cost. To illustrate the relative importance of each engine assumption, graphical examples are given in figures 20-22, which show the effect of varying the BSFC, engine weight, O.E.M. engine cost and engine maintenance cost on projected TOC and mission fuel. These examples are for mission 10, a 6-place business twin. Figure 20 shows the effect that varying the engine BSFC has on TOC and mission fuel. Similarly, figure 21 shows the effect of varying engine weight. Both BSFC and engine weight can be predicted with reasonable accuracy. A 10 percent engine weight variation, for any one engine type, causes its projected improvements to shift only slightly with respect to the other engine types, while a 10 percent BSFC change causes significant shifting in the relative engine ranking. The nominal values assumed previously are denoted with symbols on each line.

The effects of variations in engine O.E.M. cost and engine maintenance cost on aircraft TOC is shown in figure 22. The maintenance cost shown here includes overhaul cost reserves. A 10 percent variation in engine O.E.M. cost for one engine type does not cause significant shifting in engine ranking while a 10 percent variation on maintenance cost will produce some relative shifting between engine types. Engine O.E.M. and maintenance costs for these advanced engines cannot be predicted with any degree of accuracy at this time.

Large variations in these parameters for any engine are possible and can cause significant shifting in relative engine ranking.

## Sensitivity to Mission Parameters

The effects of cruise speed, cruise range and aircraft utilization on projected aircraft improvements for mission 10 are shown in figures 23-25. In these figures, the very advanced technology versions of each positive displacement engine are compared with each other and with the advanced turboprop as well.

As cruise speed is increased, all engine types show increasing relative improvement in all three figures of merit (figure 23). Though actual fuel burned, acquisition cost and TOC worsen with speed for all advanced engine types, the current technology SIR engine, which they are compared against, worsens at a faster rate. As the speed increases the higher aircraft power loading offers the lighter, more efficient 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 appear at least comparable to all the very advanced positive displacement engines in all three figures of merit if the cruise speed were raised above 350 knots.

The effect of cruise range on the three figures of merit is shown in figure 24. All engine types produced slightly greater improvements as range increased, however, 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 improtant parameter in choosing an alternative powerplant.

The effect of aircraft utilization on TOC is shown in figure 25. Some shifting in relative ranking occurs below 500 hours/year utilization due to the effect of acquisition cost. Above 500 hours/year operating cost becomes more important and the utilization has little effect on the choice of an alternative powerplant.

## CONCLUDING REMARKS

This study has compared four proposed alternative engine types for future general aviation. Each of these engines offers substantial aircraft efficiency and economic improvements in terms of aircraft total ownership cost, acquisition cost and mission fuel. The rotary appears very promising due to its very low weight, BSFC and cooling drag. However, its advantages could easily be lost if it cannot achieve these goals--especially since differences in engine cost and technology risk were not taken into account. The diesel offers large advantages due to its good BSFC and relatively light weight, but the present design suffers large BSFC penalties at high altitudes. The turboprop, despite poor BSFC, is competitive due to its low weight, zero cooling drag, and low maintenance cost, especially for missions with high cruise speeds, but this competitiveness depends on meeting the forecasted large engine cost reductions. The SIR has similar performance to the diesel, but loses economic competitiveness due to its large maintenance cost. Maintenance cost forecasting is difficult, and projections may differ greatly from the actual cost. The presented sensitivity data permits comparison of engine types using different assumptions from the nominal ones used in this report and also permits evaluation of the benefit of incremental changes in engine parameters.

To compare these alternative powerplants globally involves considerations of many more characteristics than the three figures of merit presented herein. Engine vibration, emission, noise, reliability and other factors must all be taken into account. With the relative closeness of the projected improvements and the uncertainty of engine assumptions, it is premature to draw firm conclusions regarding the relative attractiveness of the alternative engines.

# APPENDIX A

## ENGINE PARAMETER SENSITIVITIES

One of the primary purposes of this study was to present sensitivity information to adjust the foregoing results for changes in the assumed engine characteristics. Sensitivity coefficients for total ownership cost, acquisition cost, and mission fuel with changes in cruise BSFC, installed engine specific weight, specific O.E.M. engine cost, fuel cost, and cooling drag are given in the bottom halves of Tables A1-A13. The base values of the three figures of merit as well as the assumed engine parameters are given in the top halves of the Tables.

To illustrate the use of this sensitivity data and as a check on its accuracy, consider the problem of estimating potential aircraft improvements due to <u>very</u> advanced technology given the improvements for advanced technology. To do this for mission 10, we note from Table A10 that the baseline improvements for the advanced SIR, for example, are:

| | |
|---|---|
| mission fuel, $W_f$ | - 30.6% |
| A/C acquisition cost, AC | - 7.8% |
| total ownership cost, TOC | - 19.8% |

These improvements stem from the following engine assumptions (Table 7):

| | | |
|---|---|---|
| specific fuel consumption, SFC | - 0.361 | lb/hp-hr |
| specific fuel weight, $W_e$ | - 1.42 | lb/hp |
| specific engine cost, $C_e$ | - 40.0 | \$/hp (OEM) |
| engine maintenance cost, MC | - 16.57 | \$/fl-hr |
| engine cooling drag, CD | - 5.0 | % |
| fuel cost, $C_f$ | - 1.1 | \$/gal |

For the <u>very</u> advanced SIR, the engine assumptions are (Table 7):

| | | | |
|---|---|---|---|
| SFC | - | .334 | lb/hp-hr |
| $W_e$ | - | 1.20 | lb/hp |
| $C_e$ | - | 40.0 | \$/hp (OEM) |
| MC | - | 15.56 | \$/fl-hr |
| CD | - | 3.5 | % |
| $C_f$ | - | 1.0 | \$/gal |

Using these values plus the sensitivity data in the lower portion of Table A10 yields the estimated aircraft improvements for a very advanced SIR:

$$\%\Delta W_f = \overline{\%\Delta W_f} + \frac{\partial W_f}{\partial SFC}\,(\overline{SFC} - SFC) + \frac{\partial W_f}{\partial W_e}\,(\overline{W_e} - W_e) + \frac{\partial W_f}{\partial CD}\,(\overline{CD} - CD)$$

$$= 30.6 + 214\,(.361 - .334) + 6.5\,(1.42 - 1.20) + 0.73\,(5.0 - 3.5)$$

$$= 38.9 \qquad \text{(Actual value is 39.2, from Table A14)}$$

$$\%\Delta AC = \overline{\%\Delta AC} + \frac{\partial AC}{\partial SFC}\,(\overline{SFC} - SFC) + \frac{\partial AC}{\partial W_e}\,(\overline{W_e} - W_e) + \frac{\partial AC}{\partial C_e}\,(\overline{C_e} - C_e) + \frac{\partial AC}{\partial CD}\,(\overline{CD} - CD)$$

$$= 7.8 + 29\,(.361 - .334) + 4.6\,(1.42 - 1.20) + 0.39\,(40.0 - 40.0) + 0.25\,(5.0 - 3.5)$$

$$= 10.0 \qquad \text{(Actual value is 10.8)}$$

$$\%\Delta TOC = \overline{\%\Delta TOC} + \frac{\partial TOC}{\partial SFC}\,(\overline{SFC} - SFC) + \frac{\partial TOC}{\partial W_e}\,(\overline{W_e} - W_e) + \frac{\partial TOC}{\partial C_e}\,(\overline{C_e} - C_e) + \frac{\partial TOC}{\partial MC}\,(\overline{MC} - MC)$$

$$+ \frac{\partial TOC}{\partial C_f}\,(\overline{C_f} - C_f) + \frac{\partial TOC}{\partial CD}\,(\overline{CD} - CD)$$

$$= 19.8 + 76\,(.361 - .334) + 5.21\,(1.42 - 1.20) + 0.33\,(40.0 - 40.0) + 0.82\,(16.57 - 15.56)$$

$$+ 107\,(.183 - .149) + 0.48\,(5.0 - 3.5)$$

$$= 28.2 \qquad \text{(Actual value is 26.1)}$$

In the above, bars over values denote baseline values and the cost of fuel is converted to a \$/lb basis by dividing by the fuel density (i.e., for AV gas, $C_f$ = 1.10/6.0 = 0.183 \$/lb and for Jet A, $C_f$ = 1.0/6.7 - 0.149 \$/lb).

Results for the SIR, diesel, and rotary are displayed in Table A14 and indicate good agreement between estimated and actual values.

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TABLE I. - TOTAL OWNERSHIP COST (TOC) ASSUMPTIONS

5 YEAR PERIOD OF OWNERSHIP

$$\boxed{\text{TOC = ACQUISITION COST + OPERATING COST + INTEREST-RESALE VALUE}}$$

WHERE:

Acquisition Cost is the total retail price of the aircraft

Operating Cost is based on 500 hr/yr utilization and includes fuel, oil, inspection and maintenance, overhaul reserve, insurance, storage and FAA tax

Interest is based on a 5 year loan with a 20% down payment and a 10% interest rate

Resale Value is assumed to be 70% of acquisition cost

TABLE 2. - ACCESSORY POWER REQUIREMENTS

| ENGINE TYPE | ALTERNATOR REQUIREMENTS | FUEL PUMP REQUIREMENTS | OIL PUMP REQUIREMENTS | A/C & PRESSURIZATION REQUIREMENTS |
|---|---|---|---|---|
| SIR | 3.7 HP | 1.4 HP | 0.5 HP | 0 |
| Rotary | 3.7 HP | 1.4 HP | 0.5 HP | 0 |
| Diesel | 5.0 HP | 3.5 HP | 0.5 HP | 10 HP |
| Turboprop | 5.0 HP for Single 8.0 HP for Twin | | | 1.0 - 1.5 lb/min/pass Compressor Discharge Air |

Note: Requirements are quoted for a complete aircraft and are based on a 350 horsepower design. For all engine types except the turboprop, these requirements are linearly scaled with engine size. The turboprop requirements are assumed fixed.

TABLE 3. - ENGINE ASSUMPTIONS

| ENGINE TYPE[a] | NOMINAL CRITICAL ALTITUDE FT | CRUISE POWER SETTING % POWER/RIT (°F) | OVERHAUL COST (b) | COOLING DRAG % A/C DRAG (AIRPLANES ONLY) | FUEL, TYPE/COST ($/GAL) | PROPELLER EFFICIENCY |
|---|---|---|---|---|---|---|
| S.I. Recip | | | | | | |
| Current (Baseline) | | | | | | |
| - Nat. Aspirated | 0 | 70 | 0.43 | 10 | AvGas/1.10 | 0.87 |
| Turbocharged | 18 000 | | | 10 | AvGas/1.10 | |
| Advanced | 21 000 | | | 5.0 | AvGas/1.10 | |
| Very Advanced | 21 000 | | | 3.5 | Jet A/1.00 | |
| Diesel | | | | | | |
| Advanced | 17 000 | 70 | 0.43 | 5.0 | Jet A/1.00 | 0.87 |
| Very Advanced | 17 000 | 70 | 0.43 | 3.5 | Jet A/1.00 | 0.87 |
| Rotary | | | | | | |
| Advanced | 20 000 | 75 | 0.43 | 3.5 | Jet A/1.00 | 0.88 |
| Very Advanced | 20 000 | 75 | 0.43 | 0 | Jet A/1.00 | 0.88 |
| Turbine Engines | | | | | | |
| Advanced | ----- | 2140[c] | 0.376 | 0 | Jet A/1.00 | 0.89 |

[a]All advanced positive displacement engines are turbocharged.

[b]Fraction of initial list price (O.E.M. cost + 0.6).

[c]Typical GATE rotor inlet temperature.

TABLE 4. - MISSION ASSUMPTIONS

| Mission | Airplane | Payload (Incl. Pilot), lb | AR | Altitude, Ft | Speed, Kts | Range, N. Miles | T.O.** Distance, 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* | 800 | 12 | 16000 | 160 | 800 | 1600 | 35 |
| 4 | Single 4-PL Utility* | 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* | 1200 | 12 | 40000 | 340 | 1600 | 2400 | 45 |
| 8 | Twin 4-PL Light* | 800 | 10 | 25000 | 300 | 1400 | 1600 | 45 |
| 9 | Twin 6-PL Medium | 1200 | 8 | 10000 | 230 | 1100 | 1700 | 30 |
| 10 | Twin 6-PL Business* | 1200 | 10 | 25000 | 270 | 1600 | 2200 | 50 |
| 11 | Twin 8-PL Executive* | 1600 | 10 | 45000 | 380 | 1700 | 2500 | 60 |
| 12 | Single 4-PL Helicopter | 800 | -- | 2000 | 110 | 300 | 6000*** | -- |
| 13 | Twin 6-PL Helicopter | 1200 | -- | 2000 | 130 | 500 | 10000*** | -- |

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

**Over a 35 Foot Obstacle
Fuselage Pressure Maintained at 8000 Ft. Alt.

***Hover Ceiling Out of Ground Effect

TABLE A1. - SENSITIVITY FOR MISSION 1, A 2-PLACE TRAINER

$W_L$ = 455 lb  H = 10000 ft  V = 110 kts  R = 500 N.M.  W/S = 10 lb/ft$^2$

| 1980 Recip | TOC* = $50000 | AC* = $24000 | $W_f$* = 190 lb | SHP* = 137 |
|---|---|---|---|---|

| | BENEFITS REL. TO 1980 RECIP. | | | | BASELINE ASSUMPTIONS | | | |
|---|---|---|---|---|---|---|---|---|
| | %ΔTOC | %ΔAC | %Δ$W_f$ | SHP | SFC | $W_e$ | Ce | MC |
| Adv. S.I. Recip | 8.9 | - 5.3 | 22.6 | 124 | .365 | 1.86 | 46.45 | 3.62 |
| Very Adv. S. I. Recip | 18.2 | 0.8 | 32.6 | 117 | .339 | 1.57 | 46.62 | 3.40 |
| Adv. Rotary | 18.3 | 4.4 | 24.7 | 107 | .386 | 1.50 | 46.57 | 3.07 |
| Very Adv. Rotary | 33.1 | 13.2 | 42.6 | 96 | .336 | 1.00 | 46.70 | 1.95 |
| Adv. Diesel | 17.6 | - 2.2 | 24.7 | 121 | .365 | 1.62 | 47.26 | 2.77 |
| Very Adv. Diesel | 26.0 | 2.6 | 37.9 | 115 | .326 | 1.45 | 47.60 | 2.31 |
| Adv. Turboprop | (SHP to small to model) | | | - | -- | -- | -- | -- |

SENSITIVITY COEFFICIENTS (% Δ PER Δ)

| | $\frac{\delta TOC}{\delta SFC}$ | $\frac{\delta TOC}{\delta W_e}$ | $\frac{\delta TOC}{\delta C_e}$ | $\frac{\delta TOC}{\delta MC}$ | $\frac{\delta TOC}{\delta C_f}$ | $\frac{\delta TOC}{\delta CD}$ | $\frac{\delta AC}{\delta SFC}$ | $\frac{\delta AC}{\delta W_e}$ | $\frac{\delta AC}{\delta C_e}$ | $\frac{\delta AC}{\delta CD}$ | $\frac{\delta W_f}{\delta SFC}$ | $\frac{\delta W_f}{\delta W_e}$ | $\frac{\delta W_f}{\delta CD}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S.I. | 98. | 8.4 | 0.47 | 5.0 | 148. | 0.53 | 41. | 11.3 | 0.90 | 0.60 | 236. | 7.1 | 0.77 |
| Rotary | 97. | 6.4 | 0.33 | 4.9 | 129. | 0.57 | 33. | 9.5 | 0.81 | 0.59 | 195. | 5.0 | 0.75 |
| Diesel | 89. | 7.1 | 0.35 | 4.9 | 137. | 0.60 | 37. | 10.8 | 0.87 | 0.60 | 214. | 4.2 | 0.70 |
| Turboprop | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |

TOC - Total Ownership Cost, $
AC - Acquisition Cost, $
Wf - Weight of Fuel, lb
Cf - Fuel Cost, $/lb
CD - Cooling Drag; %A/C Drag

SFC - Specific Fuel Consumption, lb/HP-Hr
We - Engine Weight, lb/HP
Ce - Engine Cost, $/HP
MC - Engine Maintenance Cost, $/Flight Hr

TABLE A2. - SENSITIVITY FOR MISSION 2, A 4-PLACE UTILITY

$W_L$ = 800 lb  H = 10000 ft  V = 130 kts  R = 600 N.M.  W/S = 20 lb/ft$^2$

| 1980 | Recip | TOC* = $76000 | AC* = $41000 | $W_f$* = 270 lb | SHP* = 200 |
|---|---|---|---|---|---|

| | BENEFITS REL. TO 1980 RECIP. | | | | BASELINE ASSUMPTIONS | | | |
|---|---|---|---|---|---|---|---|---|
| | %ΔTOC | %ΔAC | %Δ$W_f$ | SHP | SFC | $W_e$ | $C_e$ | MC |
| Adv. S.I. Recip | 6.9 | -5.1 | 20.4 | 185 | .363 | 1.59 | 43.23 | 5.44 |
| Very Adv. S. I. Recip | 14.2 | -1.6 | 28.9 | 178 | .337 | 1.35 | 43.52 | 5.23 |
| Adv. Rotary | 14.3 | 0.4 | 20.0 | 164 | .384 | 1.37 | 44.36 | 4.54 |
| Very Adv. Rotary | 26.3 | 5.9 | 35.6 | 152 | .334 | 0.914 | 44.88 | 3.01 |
| Adv. Diesel | 14.7 | -3.9 | 21.1 | 183 | .363 | 1.45 | 43.37 | 4.05 |
| Very Adv. Diesel | 21.1 | -1.1 | 31.9 | 177 | .324 | 1.31 | 43.60 | 3.46 |
| Adv. Turboprop | 23.2 | 3.1 | 7.4 | 140 | .525 | .798 | 45.53 | 1.92 |

SENSITIVITY COEFFICIENTS (% Δ PER Δ)

| | $\frac{\delta TOC}{\delta SFC}$ | $\frac{\delta TOC}{\delta W_e}$ | $\frac{\delta TOC}{\delta C_e}$ | $\frac{\delta TOC}{\delta MC}$ | $\frac{\delta TOC}{\delta C_f}$ | $\frac{\delta TOC}{\delta CD}$ | $\frac{\delta AC}{\delta SFC}$ | $\frac{\delta AC}{\delta W_e}$ | $\frac{\delta AC}{\delta C_e}$ | $\frac{\delta AC}{\delta CD}$ | $\frac{\delta W_f}{\delta SFC}$ | $\frac{\delta W_f}{\delta W_e}$ | $\frac{\delta W_f}{\delta CD}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S.I. | 82. | 5.8 | 0.45 | 3.3 | 144. | 0.60 | 23. | 7.7 | 0.78 | 0.43 | 233. | 5.8 | 0.87 |
| Rotary | 73. | 4.7 | 0.33 | 3.3 | 132. | 0.48 | 20. | 7.1 | 0.72 | 0.40 | 205. | 4.7 | 0.68 |
| Diesel | 77. | 5.0 | 0.34 | 3.3 | 137. | 0.50 | 31. | 7.1 | 0.77 | 0.40 | 218. | 5.5 | 0.77 |
| Turboprop | 66. | 5.1 | 0.29 | 3.3 | 172. | -- | 20. | 7.0 | 0.61 | -- | 206. | 7.6 | -- |

TOC - Total Ownership Cost, $
AC - Acquisition Cost, $
$W_f$ - Weight of Fuel, lb
$C_f$ - Fuel Cost, $/lb
CD - Cooling Drag; %A/C Drag

SFC - Specific Fuel Consumption, lb/HP-Hr
$W_e$ - Engine Weight, lb/HP
$C_e$ - Engine Cost, $/HP
MC - Engine Maintenance Cost, $/Flight Hr

TABLE A3. - SENSITIVITY FOR MISSION 3, A 4-PLACE UTILITY

$W_L$ = 800 lb    H = 16000 ft    V = 160 kts    R = 800 N.M.    W/S = 35 lb/ft$^2$

| 1980 | Recip | TOC* = \$85000 | AC* = \$44000 | $W_f$* = 323 lb | SHP* = 211 |
|---|---|---|---|---|---|

| | BENEFITS REL. TO 1980 RECIP. | | | | BASELINE ASSUMPTIONS | | | |
|---|---|---|---|---|---|---|---|---|
| | %ΔTOC | %ΔAC | %Δ$W_f$ | SHP | SFC | $W_e$ | $C_e$ | MC |
| Adv. S.I. Recip | 18.4 | 5.3 | 26.2 | 193 | .363 | 1.58 | 42.92 | 5.69 |
| Very Adv. S. I. Recip | 24.3 | 7.6 | 33.4 | 187 | .336 | 1.33 | 43.13 | 5.50 |
| Adv. Rotary | 24.5 | 9.2 | 25.6 | 173 | .384 | 1.36 | 43.89 | 4.75 |
| Very Adv. Rotary | 34.6 | 12.9 | 39.0 | 162 | .334 | .901 | 44.32 | 3.19 |
| Adv. Diesel | 25.3 | 5.9 | 26.9 | 192 | .363 | 1.44 | 42.94 | 4.23 |
| Very Adv. Diesel | 30.8 | 7.9 | 36.2 | 186 | .323 | 1.31 | 43.24 | 3.63 |
| Adv. Turboprop | 27.7 | 4.9 | 6.8 | 171 | .554 | .723 | 43.89 | 2.33 |

SENSITIVITY COEFFICIENTS (% Δ PER Δ)

| | $\frac{\delta TOC}{\delta SFC}$ | $\frac{\delta TOC}{\delta W_e}$ | $\frac{\delta TOC}{\delta C_e}$ | $\frac{\delta TOC}{\delta MC}$ | $\frac{\delta TOC}{\delta C_f}$ | $\frac{\delta TOC}{\delta CD}$ | $\frac{\delta AC}{\delta SFC}$ | $\frac{\delta AC}{\delta W_e}$ | $\frac{\delta AC}{\delta C_e}$ | $\frac{\delta AC}{\delta CD}$ | $\frac{\delta W_f}{\delta SFC}$ | $\frac{\delta W_f}{\delta W_e}$ | $\frac{\delta W_f}{\delta CD}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S.I. | 74. | 3.1 | 0.45 | 2.9 | 132. | 0.51 | 21. | 3.8 | 0.78 | 0.39 | 214. | 3.8 | 0.67 |
| Rotary | 67. | 2.2 | 0.33 | 2.9 | 123. | 0.42 | 18. | 3.3 | 0.72 | 0.37 | 194. | 3.7 | 0.64 |
| Diesel | 69. | 2.6 | 0.34 | 3.0 | 127. | 0.39 | 18. | 3.7 | 0.77 | 0.36 | 203. | 3.7 | 0.67 |
| Turboprop | 71. | 2.4 | 0.29 | 2.9 | 169. | -- | 31. | 3.4 | 0.61 | -- | 214. | 2.9 | -- |

TOC - Total Ownership Cost, \$
AC - Acquisition Cost, \$
$W_f$ - Weight of Fuel, lb
$C_f$ - Fuel Cost, \$/lb
CD - Cooling Drag; %A/C Drag

SFC - Specific Fuel Consumption, lb/HP-Hr
$W_e$ - Engine Weight, lb/HP
$C_e$ - Engine Cost, \$/HP
MC - Engine Maintenance Cost, \$/Flight Hr

TABLE A4. - SENSITIVITY FOR MISSION 4, 4-PLACE UTILITY

$W_L$ = 800 lb  H = 25000 ft  V = 210 kts  R = 1400 N.M.  W/S = 40 lb/ft$^2$

| 1980 | Recip | TOC* = $137000 | AC* = $70000 | $W_f$* = 723 lb | SHP* = 365 |
|---|---|---|---|---|---|

| | BENEFITS REL. TO 1980 RECIP. | | | | BASELINE ASSUMPTIONS | | | |
|---|---|---|---|---|---|---|---|---|
| | %ΔTOC | %ΔAC | %Δ$W_f$ | SHP | SFC | $W_e$ | $C_e$ | MC |
| Adv. S.I. Recip | 22.3 | 10.3 | 28.4 | 325 | .359 | 1.39 | 40.00 | 9.88 |
| Very Adv. S. I. Recip | 29.3 | 14.1 | 36.4 | 310 | .333 | 1.17 | 40.00 | 9.38 |
| Adv. Rotary | 30.4 | 15.5 | 27.9 | 289 | .380 | 1.18 | 40.00 | 7.54 |
| Very Adv. Rotary | 41.4 | 21.3 | 42.0 | 266 | .331 | .797 | 40.00 | 5.03 |
| Adv. Diesel | 30.2 | 11.5 | 27.1 | 322 | .370 | 1.22 | 40.00 | 6.85 |
| Very Adv. Diesel | 36.3 | 14.8 | 37.1 | 309 | .331 | 1.11 | 40.00 | 5.84 |
| Adv. Turboprop | 34.3 | 5.8 | 25.9 | 339 | .456 | .590 | 40.00 | 4.71 |

SENSITIVITY COEFFICIENTS (% Δ PER Δ)

| | $\frac{\delta TOC}{\delta SFC}$ | $\frac{\delta TOC}{\delta We}$ | $\frac{\delta TOC}{\delta C_e}$ | $\frac{\delta TOC}{\delta MC}$ | $\frac{\delta TOC}{\delta Cf}$ | $\frac{\delta TOC}{\delta CD}$ | $\frac{\delta AC}{\delta SFC}$ | $\frac{\delta AC}{\delta W_e}$ | $\frac{\delta AC}{\delta C_e}$ | $\frac{\delta AC}{\delta CD}$ | $\frac{\delta W_f}{\delta SFC}$ | $\frac{\delta W_f}{\delta W_e}$ | $\frac{\delta W_f}{\delta CD}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S.I. Recip | 91. | 4.8 | 0.45 | 1.8 | 136. | 0.67 | 44. | 6.5 | 0.83 | 0.58 | 212. | 4.3 | 0.73 |
| Rotary | 76. | 2.7 | 0.31 | 1.8 | 123. | 0.47 | 35. | 4.7 | 0.75 | 0.42 | 191. | 4.1 | 0.73 |
| Diesel | 85. | 3.8 | 0.34 | 1.8 | 129. | 0.55 | 42. | 5.4 | 0.80 | 0.52 | 208. | 3.8 | 0.73 |
| Turboprop | 74. | 6.1 | 0.39 | 1.8 | 143. | -- | 44. | 11.3 | 0.89 | -- | 192. | 6.1 | -- |

TOC - Total Ownership Cost, $
AC - Acquisition Cost, $
$W_f$ - Weight of Fuel, lb
$C_f$ - Fuel Cost, $/lb
CD - Cooling Drag; %A/C Drag

SFC - Specific Fuel Consumption, lb/HP-Hr
$W_e$ - Engine Weight, lb/HP
$C_e$ - Engine Cost, $/HP
MC - Engine Maintenance Cost, $/Flight Hr

TABLE A5. - SENSITIVITY FOR MISSION 5, A 6-PLACE UTILITY

$W_L$ = 1200 lb    H = 10000 ft    V = 180 kts    R = 600 N.M.    W/S = 25 lb/ft$^2$

| 1980 | Recip | TOC* = $136000 | AC* = $84000 | $W_f$* = 339 lb | SHP* = 342 |
|---|---|---|---|---|---|

| | BENEFITS REL. TO 1980 RECIP. | | | | BASELINE ASSUMPTIONS | | | |
|---|---|---|---|---|---|---|---|---|
| | %ΔTOC | %ΔAC | %Δ$W_f$ | SHP | SFC | $W_e$ | $C_e$ | MC |
| Adv. S.I. Recip | 8.2 | -2.4 | 21.2 | 312 | .360 | 1.40 | 40.00 | 9.44 |
| Very Adv. S. I. Recip | 16.0 | 1.6 | 30.7 | 297 | .333 | 1.18 | 40.00 | 8.93 |
| Adv. Rotary | 17.4 | 3.6 | 22.1 | 274 | .381 | 1.20 | 40.00 | 7.15 |
| Very Adv. Rotary | 29.0 | 9.3 | 38.1 | 250 | .331 | .808 | 40.00 | 4.73 |
| Adv. Diesel | 17.4 | -0.2 | 23.0 | 306 | .359 | 1.25 | 40.00 | 6.53 |
| Very Adv. Diesel | 23.6 | 2.5 | 33.9 | 294 | .320 | 1.13 | 40.00 | 5.56 |
| Adv. Turboprop | 26.2 | 7.4 | 12.7 | 231 | .496 | .608 | 40.99 | 3.11 |

SENSITIVITY COEFFICIENTS (% Δ PER Δ)

| | $\frac{\delta TOC}{\delta SFC}$ | $\frac{\delta TOC}{\delta W_e}$ | $\frac{\delta TOC}{\delta C_e}$ | $\frac{\delta TOC}{\delta MC}$ | $\frac{\delta TOC}{\delta C_f}$ | $\frac{\delta TOC}{\delta CD}$ | $\frac{\delta AC}{\delta SFC}$ | $\frac{\delta AC}{\delta W_e}$ | $\frac{\delta AC}{\delta C_e}$ | $\frac{\delta AC}{\delta CD}$ | $\frac{\delta W_f}{\delta SFC}$ | $\frac{\delta W_f}{\delta W_e}$ | $\frac{\delta W_f}{\delta CD}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S.I. Recip | 80. | 7.8 | 0.42 | 1.8 | 137. | 0.57 | 21. | 9.6 | 0.67 | 0.47 | 224. | 7.8 | 0.80 |
| Rotary | 70. | 6.1 | 0.31 | 1.8 | 124. | 0.47 | 17. | 7.5 | 0.60 | 0.31 | 200. | 5.4 | 0.80 |
| Diesel | 75. | 6.4 | 0.32 | 1.8 | 131. | 0.47 | 18. | 8.8 | 0.65 | 0.33 | 214. | 7.0 | 0.80 |
| Turboprop | 63. | 5.6 | 0.26 | 1.8 | 155. | -- | 36. | 8.0 | 0.52 | -- | 205. | 7.2 | -- |

TOC - Total Ownership Cost, $
AC - Acquisition Cost, $
$W_f$ - Weight of Fuel, lb
$C_f$ - Fuel Cost, $/lb
CD - Cooling Drag; %A/C Drag

SFC - Specific Fuel Consumption, lb/HP-Hr
$W_e$ - Engine Weight, lb/HP
$C_e$ - Engine Cost, $/HP
MC - Engine Maintenance Cost, $/Flight Hr

TABLE A6. - SENSITIVITY FOR MISSION 6, A 6-PLACE HI-PERFORMANCE

$W_L$ = 1200 lb H = 28000 ft V = 250 kts R = 1000 N.M. W/S = 35 lb/ft$^2$

| 1980 | Recip | TOC* = $248000 | AC* = $152000 | $W_f$* = 737 lb | SHP* = 579 |
|---|---|---|---|---|---|

| | BENEFITS REL. TO 1980 RECIP. | | | | BASELINE ASSUMPTIONS | | | |
|---|---|---|---|---|---|---|---|---|
| | %ΔTOC | %ΔAC | %Δ$W_f$ | SHP | SFC | $W_e$ | $C_e$ | MC |
| Adv. S.I. Recip | 24.3 | 12.8 | 32.3 | 493 | .354 | 1.39 | 40.00 | 15.90 |
| Very Adv. S. I. Recip | 32.2 | 18.2 | 41.5 | 462 | .328 | 1.16 | 40.00 | 14.76 |
| Adv. Rotary | 35.3 | 21.2 | 35.0 | 420 | .376 | 1.03 | 40.00 | 10.96 |
| Very Adv. Rotary | 45.7 | 27.5 | 49.1 | 378 | .328 | .926 | 40.00 | 7.15 |
| Adv. Diesel | 34.9 | 18.2 | 34.3 | 468 | .366 | 1.01 | 40.00 | 9.97 |
| Very Adv. Diesel | 40.5 | 21.3 | 44.0 | 446 | .327 | .704 | 40.00 | 8.44 |
| Adv. Turboprop | 38.6 | 15.6 | 33.4 | 495 | .526 | .549 | 40.00 | 7.20 |

SENSITIVITY COEFFICIENTS (% Δ PER Δ)

| | $\frac{\delta TOC}{\delta SFC}$ | $\frac{\delta TOC}{\delta W_e}$ | $\frac{\delta TOC}{\delta C_e}$ | $\frac{\delta TOC}{\delta MC}$ | $\frac{\delta TOC}{\delta C_f}$ | $\frac{\delta TOC}{\delta CD}$ | $\frac{\delta AC}{\delta SFC}$ | $\frac{\delta AC}{\delta W_e}$ | $\frac{\delta AC}{\delta C_e}$ | $\frac{\delta AC}{\delta CD}$ | $\frac{\delta W_f}{\delta SFC}$ | $\frac{\delta W_f}{\delta W_e}$ | $\frac{\delta W_f}{\delta CD}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S.I. Recip | 83. | 10.0 | 0.36 | 1.0 | 116. | 0.67 | 38. | 12.6 | 0.59 | 0.53 | 203. | 8.7 | 0.80 |
| Rotary | 67. | 6.8 | 0.25 | 1.0 | 101. | 0.45 | 29. | 9.5 | 0.51 | 0.41 | 173. | 6.1 | 0.65 |
| Diesel | 74. | 7.6 | 0.26 | 1.0 | 108. | 0.47 | 34. | 10.8 | 0.56 | 0.47 | 191 | 7.0 | 0.67 |
| Turboprop | 66. | 10.5 | 0.31 | 1.0 | 117. | -- | 34. | 16.7 | 0.61 | -- | 187. | 11.4 | -- |

TOC - Total Ownership Cost, $
AC - Acquisition Cost, $
$W_f$ - Weight of Fuel, lb
$C_f$ - Fuel Cost, $/lb
CD - Cooling Drag; %A/C Drag

SFC - Specific Fuel Consumption, lb/HP-Hr
We - Engine Weight, lb/HP
Ce - Engine Cost, $/HP
MC - Engine Maintenance Cost, $/Flight Hr

TABLE A7. - SENSITIVITY FOR MISSION 7*, A 6 PLACE HI-PERF

$W_L$ = 1400 lb  H = 40000 ft  V = 340 kts  R = 1600 N.M.  W/S = 45 lb/ft$^2$

ADVANCED TURBOPROP  TOC* = $188000  AC* = $168000  $W_f$* = 572 lb  SHP* = 827

| | BENEFITS REL. TO ADV. TP | | | SHP | BASELINE ASSUMPTIONS | | | |
|---|---|---|---|---|---|---|---|---|
| | % ΔTOC | % ΔAC | % $\Delta W_f$ | | SFC | $W_e$ | $C_e$ | MC |
| Very Advanced S.I. Recip With Idealized Turbocharger | 6.9 | 21.0 | 8.6 | 486 | 0.327 | 1.16 | 40.00 | 15.66 |
| Very Advanced S.I. Recip With 21 000 Ft Critical Turbocharger | 1.2 | 17.3 | 6.8 | 552 | 0.327 | 1.16 | 40.00 | 17.35 |
| Advanced Turboprop | 0 | 0 | 0 | 827 | 0.386 | 0.464 | 40.00 | 12.91 |

SENSITIVITY COEFFICIENTS (% Δ PER Δ)

| | $\frac{\delta TOC}{\delta SFC}$ | $\frac{\delta TOC}{\delta W_e}$ | $\frac{\delta TOC}{\delta C_e}$ | $\frac{\delta TOC}{\delta MC}$ | $\frac{\delta TOC}{\delta C_f}$ | $\frac{\delta TOC}{\delta CD}$ | $\frac{\delta AC}{\delta SFC}$ | $\frac{\delta AC}{\delta W_e}$ | $\frac{\delta AC}{\delta C_e}$ | $\frac{\delta AC}{\delta CD}$ | $\frac{\delta W_f}{\delta SFC}$ | $\frac{\delta W_f}{\delta W_e}$ | $\frac{\delta W_f}{\delta CD}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S.I. Recip** | 102 | 10.4 | 0.50 | 1.3 | 157 | 0.82 | 38 | 11.3 | 0.63 | 0.64 | 341 | 14.4 | 1.12 |
| Turboprop | 95 | 21.5 | 0.69 | 1.3 | 154 | ---- | 45 | 24.1 | 0.94 | ---- | 311 | 18.0 | ---- |

TOC - Total Ownership Cost, $
AC - Acquisition Cost, $
$W_f$ - Weight of Fuel, lb
$C_f$ - Fuel Cost, $/lb
CD - Cooling Drag; % A/C Drag

SFC - Specific Fuel Consumption, lb/HP-Hr
$W_e$ - Engine Weight, lb/HP
Ce - Engine Cost, $/HP
MC - Engine Maintenance Cost, $/Flight Hr

*Advanced Turboprop Baseline Engine.
**Based on Very Advanced S.I.R. with Idealized Turbocharger.

TABLE A8. - SENSITIVITY FOR MISSION 8, A 4-PLACE LIGHT TWIN

$W_L$ = 800 lb  H = 25000 ft  V = 300 kts  R = 1400 N.M.  W/S = 45 lb/ft$^2$

| | | | | | |
|---|---|---|---|---|---|
| 1980 | Recip | TOC* = $264000 | AC* = $179000 | $W_f$* = 896 lb | SHP* = 308 |

| | BENEFITS REL. TO 1980 RECIP. | | | | BASELINE ASSUMPTIONS | | | |
|---|---|---|---|---|---|---|---|---|
| | %$\Delta$TOC | %$\Delta$AC | %$\Delta W_f$ | SHP | SFC | $W_e$ | $C_e$ | MC |
| Adv. S.I. Recip | 22.8 | 10.5 | 31.6 | 265 | .361 | 1.44 | 40.00 | 15.68 |
| Very Adv. S. I. Recip | 29.9 | 14.4 | 40.0 | 250 | .335 | 1.21 | 40.00 | 14.68 |
| Adv. Rotary | 29.9 | 14.7 | 32.3 | 233 | .381 | 1.26 | 40.85 | 12.30 |
| Very Adv. Rotary | 40.6 | 20.3 | 47.1 | 209 | .333 | .849 | 40.00 | 8.06 |
| Adv. Diesel | 28.9 | 11.2 | 29.9 | 263 | .372 | 1.32 | 40.00 | 11.20 |
| Very Adv. Diesel | 35.1 | 14.6 | 40.5 | 249 | .333 | 1.20 | 40.00 | 9.42 |
| Adv. Turboprop | 33.2 | 8.8 | 26.7 | 261 | .459 | .601 | 40.00 | 7.05 |

SENSITIVITY COEFFICIENTS (% $\Delta$ PER $\Delta$)

| | $\frac{\delta TOC}{\delta SFC}$ | $\frac{\delta TOC}{\delta W_e}$ | $\frac{\delta TOC}{\delta C_e}$ | $\frac{\delta TOC}{\delta MC}$ | $\frac{\delta TOC}{\delta C_f}$ | $\frac{\delta TOC}{\delta CD}$ | $\frac{\delta AC}{\delta SFC}$ | $\frac{\delta AC}{\delta W_e}$ | $\frac{\delta AC}{\delta C_e}$ | $\frac{\delta AC}{\delta CD}$ | $\frac{\delta W_f}{\delta SFC}$ | $\frac{\delta W_f}{\delta W_e}$ | $\frac{\delta W_f}{\delta CD}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S.I. Recip | 83. | 7.0 | 0.38 | 0.93 | 117. | 0.54 | 35. | 7.8 | 0.53 | 0.34 | 203. | 5.7 | 0.74 |
| Rotary | 70. | 5.2 | 0.25 | 0.97 | 103. | 0.40 | 30. | 6.5 | 0.47 | 0.31 | 182. | 5.2 | 0.71 |
| Diesel | 75. | 5.7 | 0.27 | 0.96 | 109. | 0.42 | 35. | 8.0 | 0.51 | 0.34 | 200. | 7.4 | 0.71 |
| Turboprop | 74. | 7.6 | 0.32 | 0.97 | 129. | -- | 52. | 10.7 | 0.56 | -- | 207. | 8.4 | -- |

TOC - Total Ownership Cost, $
AC - Acquisition Cost, $
$W_f$ - Weight of Fuel, lb
$C_f$ - Fuel Cost, $/lb
CD - Cooling Drag; %A/C Drag

SFC - Specific Fuel Consumption, lb/HP-Hr
$W_e$ - Engine Weight, lb/HP
Ce - Engine Cost, $/HP
MC - Engine Maintenance Cost, $/Flight Hr

TABLE A9. - SENSITIVITY FOR MISSION 9, A 6-PLACE MEDIUM TWIN

$W_L$ = 1200 lb    H = 10000 ft    V = 230 kts    R = 1100 N.M.    W/S = 30 lb/ft$^2$

| 1980 | Recip | TOC* = $375000 | AC* = $253000 | $W_f$* = 1324 lb | SHP* = 493 |
|---|---|---|---|---|---|

| | BENEFITS REL. TO 1980 RECIP. %ΔTOC | %ΔAC | %Δ$W_f$ | SHP | BASELINE ASSUMPTIONS SFC | $W_e$ | $C_e$ | MC |
|---|---|---|---|---|---|---|---|---|
| Adv. S.I. Recip | 9.7 | - 1.1 | 23.6 | 450 | .356 | 1.38 | 40.00 | 28.64 |
| Very Adv. S. I. Recip | 19.3 | 4.7 | 34.7 | 419 | .329 | 1.16 | 40.00 | 26.45 |
| Adv. Rotary | 21.9 | 6.8 | 26.5 | 384 | .377 | 1.07 | 40.00 | 20.04 |
| Very Adv. Rotary | 34.6 | 13.8 | 43.6 | 345 | .329 | .726 | 40.00 | 13.05 |
| Adv. Diesel | 23.9 | 5.5 | 29.2 | 415 | .356 | 1.07 | 40.00 | 17.68 |
| Very Adv. Diesel | 30.8 | 9.3 | 40.7 | 393 | .317 | .991 | 40.00 | 14.86 |
| Adv. Turboprop | 36.1 | 15.0 | 27.7 | 282 | .455 | .627 | 40.00 | 7.67 |

SENSITIVITY COEFFICIENTS (% Δ PER Δ)

| | $\frac{\delta TOC}{\delta SFC}$ | $\frac{\delta TOC}{\delta W_e}$ | $\frac{\delta TOC}{\delta C_e}$ | $\frac{\delta TOC}{\delta MC}$ | $\frac{\delta TOC}{\delta C_f}$ | $\frac{\delta TOC}{\delta CD}$ | $\frac{\delta AC}{\delta SFC}$ | $\frac{\delta AC}{\delta W_e}$ | $\frac{\delta AC}{\delta C_e}$ | $\frac{\delta AC}{\delta CD}$ | $\frac{\delta W_f}{\delta SFC}$ | $\frac{\delta W_f}{\delta W_e}$ | $\frac{\delta W_f}{\delta CD}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S.I. Recip | 106. | 12.2 | 0.45 | 0.67 | 132. | 0.76 | 57. | 12.6 | 0.66 | 0.58 | 240. | 14.8 | 0.91 |
| Rotary | 89. | 9.7 | 0.34 | 0.67 | 115. | 0.57 | 47. | 11.7 | 0.59 | 0.51 | 211. | 11.0 | 0.79 |
| Diesel | 98. | 8.1 | 0.33 | 0.66 | 121. | 0.52 | 51. | 9.8 | 0.63 | 0.42 | 228. | 8.7 | 0.70 |
| Turboprop | 85. | 7.6 | 0.28 | 0.57 | 128. | -- | 82. | 10.2 | 0.53 | -- | 220. | 8.9 | -- |

TOC - Total Ownership Cost, $
AC - Acquisition Cost, $
Wf - Weight of Fuel, lb
Cf - Fuel Cost, $/lb
CD - Cooling Drag; %A/C Drag

SFC - Specific Fuel Consumption, lb/HP-Hr
We - Engine Weight, lb/HP
Ce - Engine Cost, $/HP
MC - Engine Maintenance Cost, $/Flight Hr

TABLE A10. - SENSITIVITY FOR MISSION 10, A 6-PLACE BUSINESS TWIN

$W_L$ = 1200 lb    H = 25000 ft    V = 270 kts    R = 1600 N.M.    W/S = 50 lb/ft$^2$

| | | | | | |
|---|---|---|---|---|---|
| 1980 | Recip | TOC* = $311000 | AC* = $233000 | $W_f$* = 1214 lb | SHP* = 323 |

| | BENEFITS REL. TO 1980 RECIP. | | | | BASELINE ASSUMPTIONS | | | |
|---|---|---|---|---|---|---|---|---|
| | %ΔTOC | %ΔAC | %Δ$W_f$ | SHP | SFC | $W_e$ | $C_e$ | MC |
| Adv. S.I. Recip | 19.8 | 7.8 | 30.6 | 278 | .361 | 1.42 | 40.00 | 16.57 |
| Very Adv. S. I. Recip | 26.1 | 10.8 | 39.2 | 263 | .334 | 1.20 | 40.00 | 15.56 |
| Adv. Rotary | 26.3 | 11.4 | 30.7 | 246 | .381 | 1.24 | 40.22 | 12.87 |
| Very Adv. Rotary | 35.6 | 15.4 | 45.6 | 221 | .332 | .839 | 41.51 | 8.48 |
| Adv. Diesel | 25.5 | 8.4 | 29.2 | 276 | .371 | 1.30 | 40.00 | 11.77 |
| Very Adv. Diesel | 30.9 | 11.4 | 39.7 | 262 | .332 | 1.18 | 40.00 | 9.92 |
| Adv. Turboprop | 28.0 | 6.1 | 23.1 | 289 | .471 | .601 | 40.00 | 7.89 |

SENSITIVITY COEFFICIENTS (% Δ PER Δ)

| | $\frac{\delta TOC}{\delta SFC}$ | $\frac{\delta TOC}{\delta W_e}$ | $\frac{\delta TOC}{\delta C_e}$ | $\frac{\delta TOC}{\delta MC}$ | $\frac{\delta TOC}{\delta C_f}$ | $\frac{\delta TOC}{\delta CD}$ | $\frac{\delta AC}{\delta SFC}$ | $\frac{\delta AC}{\delta W_e}$ | $\frac{\delta AC}{\delta C_e}$ | $\frac{\delta AC}{\delta CD}$ | $\frac{\delta W_f}{\delta SFC}$ | $\frac{\delta W_f}{\delta W_e}$ | $\frac{\delta W_f}{\delta CD}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S.I. Recip | 76. | 5.2 | 0.33 | 0.82 | 107. | 0.48 | 29. | 5.2 | 0.44 | 0.27 | 214. | 6.5 | 0.73 |
| Rotary | 64. | 4.0 | 0.23 | 0.81 | 96. | 0.37 | 24. | 4.6 | 0.39 | 0.25 | 188. | 5.3 | 0.62 |
| Diesel | 71. | 5.7 | 0.25 | 0.82 | 101. | 0.39 | 26. | 5.0 | 0.43 | 0.27 | 203. | 5.6 | 0.67 |
| Turboprop | 66. | 5.8 | 0.29 | 0.77 | 121. | -- | 29. | 7.5 | 0.48 | -- | 207 | 7.5 | -- |

TOC - Total Ownership Cost, $
AC - Acquisition Cost, $
$W_f$ - Weight of Fuel, lb
$C_f$ - Fuel Cost, $/lb
CD - Cooling Drag; %A/C Drag

SFC - Specific Fuel Consumption, lb/HP-Hr
$W_e$ - Engine Weight, lb/HP
$C_e$ - Engine Cost, $/HP
MC - Engine Maintenance Cost, $/Flight Hr

TABLE A11. - SENSITIVITY FOR MISSION 11*, A 8 PLACE EXECUTIVE

$W_L$ = 1800 lb    H = 45000 ft    V = 380 kts    R = 1700 N.M.    W/S = 60 lb/ft$^2$

| ADVANCED TURBOPROP | TOC* = $460000 | AC* = $471000 | $W_f$* = 1069 lb | SHP* = 973 |
|---|---|---|---|---|

| | BENEFITS REL. TO ADV. TP | | | SHP | BASELINE ASSUMPTIONS | | | |
|---|---|---|---|---|---|---|---|---|
| | % ΔTOC | % ΔAC | % $\Delta W_f$ | | SFC | $W_e$ | $C_e$ | MC |
| Very Advanced S.I. Recip With Idealized Turbocharger | 13.9 | 23.4 | 7.4 | 461 | 0.33 | 1.16 | 40.00 | 29.46 |
| Very Advanced S.I. Recip With 21 000 Ft Critical Turbocharger | 1.2 | 15.3 | -0.6 | 617 | 0.33 | 1.16 | 40.00 | 41.12 |
| Advanced Turboprop | 0 | 0 | 0 | 973 | 0.373 | 0.421 | 40.00 | 31.13 |

SENSITIVITY COEFFICIENTS (% Δ PER Δ)

| | $\frac{\delta TOC}{\delta SFC}$ | $\frac{\delta TOC}{\delta W_e}$ | $\frac{\delta TOC}{\delta C_e}$ | $\frac{\delta TOC}{\delta MC}$ | $\frac{\delta TOC}{\delta C_f}$ | $\frac{\delta TOC}{\delta CD}$ | $\frac{\delta AC}{\delta SFC}$ | $\frac{\delta AC}{\delta W_e}$ | $\frac{\delta AC}{\delta C_e}$ | $\frac{\delta AC}{\delta CD}$ | $\frac{\delta W_f}{\delta SFC}$ | $\frac{\delta W_f}{\delta W_e}$ | $\frac{\delta W_f}{\delta CD}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S.I. Recip** | 119 | 8.7 | 0.38 | 0.52 | 125 | 0.67 | 53 | 7.1 | 0.41 | 0.40 | 335 | 13.6 | 1.17 |
| | 104 | 28.9 | 0.66 | 0.52 | 122 | ---- | 47 | 29.9 | 0.85 | ---- | 306 | 27.6 | ---- |

TOC - Total Ownership Cost, $
AC - Acquisition Cost, $
$W_f$ - Weight of Fuel, lb
$C_f$ - Fuel Cost, $/lb
CD - Cooling Drag; % A/C Drag

SFC - Specific Fuel Consumption, lb/HP-Hr
$W_e$ - Engine Weight, lb/HP
$C_e$ - Engine Cost, $/HP
MC - Engine Maintenance Cost, $/Flight Hr

*Advanced Turboprop Baseline Engine.
**Based on Very Advanced S.I.R. with Idealized Turbocharger.

TABLE A12. - SENSITIVITY FOR MISSION 12, A 4-PLACE HELICOPTER

$W_L$ = 800 lb   H = 2000 ft   V = 100 kts   R = 300 N.M.   W/S = ---

| 1980 | Recip | TOC* = $213000 | AC* = $106000 | $W_f$* = 245 lb | SHP* = 354 |
|---|---|---|---|---|---|

| | BENEFITS REL. TO 1980 RECIP. | | | | BASELINE ASSUMPTIONS | | | |
|---|---|---|---|---|---|---|---|---|
| | %ΔTOC | %ΔAC | $\%\Delta W_f$ | SHP | SFC | $W_e$ | $C_e$ | MC |
| Adv. S.I. Recip | 6.9 | 1.8 | 16.6 | 348 | .359 | 1.42 | 40.00 | 10.67 |
| Very Adv. S. I. Recip | 13.6 | 4.2 | 24.8 | 338 | .332 | 1.20 | 40.00 | 10.33 |
| Adv. Rotary | 13.8 | 4.1 | 14.8 | 338 | .379 | 1.12 | 40.00 | 8.80 |
| Very Adv. Rotary | 22.2 | 7.9 | 29.2 | 322 | .329 | .745 | 40.00 | 6.10 |
| Adv. Diesel | 15.9 | 3.8 | 18.7 | 339 | .358 | 1.19 | 40.00 | 7.22 |
| Very Adv. Diesel | 20.0 | 5.5 | 29.2 | 333 | .319 | 1.07 | 40.00 | 6.29 |
| Adv. Turboshaft | 21.3 | 13.8 | -12.8 | 261 | .526 | .476 | 40.00 | 3.43 |

SENSITIVITY COEFFICIENTS (% Δ PER Δ)

| | $\frac{\delta TOC}{\delta SFC}$ | $\frac{\delta TOC}{\delta W_e}$ | $\frac{\delta TOC}{\delta C_e}$ | $\frac{\delta TOC}{\delta MC}$ | $\frac{\delta TOC}{\delta C_f}$ | $\frac{\delta TOC}{\delta CD}$ | $\frac{\delta AC}{\delta SFC}$ | $\frac{\delta AC}{\delta W_e}$ | $\frac{\delta AC}{\delta C_e}$ | $\frac{\delta AC}{\delta CD}$ | $\frac{\delta W_f}{\delta SFC}$ | $\frac{\delta W_f}{\delta W_e}$ | $\frac{\delta W_f}{\delta CD}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S.I. Recip | 51. | 9.5 | 0.50 | 1.17 | 92. | -- | 15.4 | 8.4 | 0.83 | -- | 236. | 8.3 | -- |
| Rotary | 47. | 8.0 | 0.41 | 1.17 | 85. | -- | 13.9 | 7.6 | 0.79 | -- | 224. | 7.8 | -- |
| Diesel | 49. | 8.2 | 0.43 | 1.17 | 88. | -- | 14.7 | 8.0 | 0.82 | -- | 233. | 6.3 | -- |
| Turboprop | 51. | 8.9 | 0.33 | 1.17 | 122. | -- | 18.6 | 8.6 | 0.64 | -- | 231. | 12.2 | -- |

TOC - Total Ownership Cost, $
AC - Acquisition Cost, $
$W_f$ - Weight of Fuel, lb
$C_f$ - Fuel Cost, $/lb
CD - Cooling Drag; %A/C Drag

SFC - Specific Fuel Consumption, lb/HP-Hr
$W_e$ - Engine Weight, lb/HP
Ce - Engine Cost, $/HP
MC - Engine Maintenance Cost, $/Flight Hr

TABLE A13. - SENSITIVITY FOR MISSION 13, A 6-PLACE TWIN HELICOPTER

$W_L$ = 1200 lb H = 2000 ft V = 130 kts R = 500 N.M. W/S = ---

| 1980 | Recip | TOC* = $503000 | AC* = $246000 | $W_f$* = 923 lb | SHP* = 398 |
|---|---|---|---|---|---|

| | BENEFITS REL. TO 1980 RECIP. | | | | BASELINE ASSUMPTIONS | | | |
|---|---|---|---|---|---|---|---|---|
| | %ΔTOC | %ΔAC | %Δ$W_f$ | SHP | SFC | $W_e$ | Ce | MC |
| Adv. S.I. Recip | 16.0 | 7.3 | 25.8 | 367 | .358 | 1.41 | 40.00 | 22.73 |
| Very Adv. S. I. Recip | 23.8 | 10.9 | 34.1 | 352 | .331 | 1.18 | 40.00 | 21.63 |
| Adv. Rotary | 23.3 | 10.4 | 24.7 | 353 | .378 | 1.10 | 40.00 | 18.44 |
| Very Adv. Rotary | 32.8 | 15.8 | 38.6 | 330 | .329 | .738 | 40.00 | 12.50 |
| Adv. Diesel | 25.5 | 10.2 | 28.5 | 358 | .357 | 1.17 | 40.00 | 15.10 |
| Very Adv. Diesel | 30.2 | 12.8 | 38.0 | 344 | .319 | 1.06 | 40.00 | 13.00 |
| Adv. Turboshaft | 27.8 | 14.5 | 7.1 | 328 | .486 | .488 | 40.00 | 8.87 |

SENSITIVITY COEFFICIENTS (% Δ PER Δ)

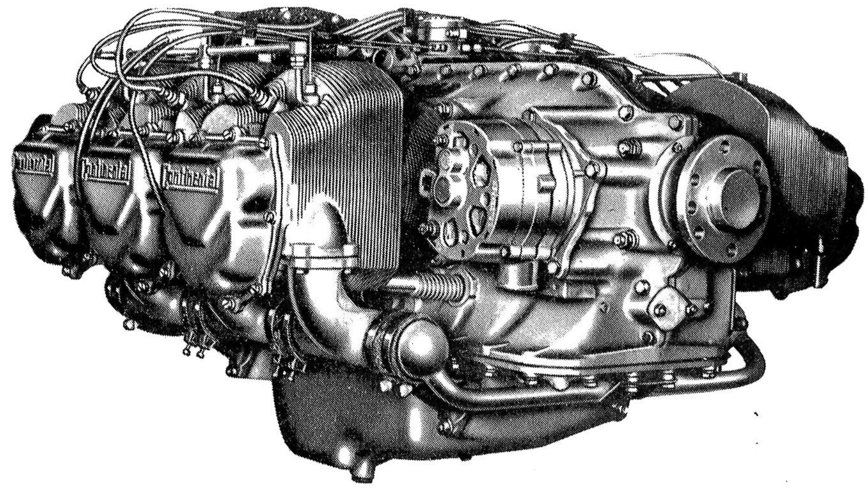
| | $\frac{\delta TOC}{\delta SFC}$ | $\frac{\delta TOC}{\delta W_e}$ | $\frac{\delta TOC}{\delta C_e}$ | $\frac{\delta TOC}{\delta MC}$ | $\frac{\delta TOC}{\delta C_f}$ | $\frac{\delta TOC}{\delta CD}$ | $\frac{\delta AC}{\delta SFC}$ | $\frac{\delta AC}{\delta W_e}$ | $\frac{\delta AC}{\delta C_e}$ | $\frac{\delta AC}{\delta CD}$ | $\frac{\delta W_f}{\delta SFC}$ | $\frac{\delta W_f}{\delta W_e}$ | $\frac{\delta W_f}{\delta CD}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S.I. Recip | 66. | 11.6 | 0.44 | 0.50 | 119. | -- | 32.1 | 11.0 | 0.75 | -- | 216. | 8.9 | -- |
| Rotary | 58. | 9.6 | 0.36 | 0.50 | 104. | -- | 28.3 | 9.8 | 0.71 | -- | 202. | 8.2 | -- |
| Diesel | 61. | 10.3 | 0.37 | 0.50 | 110. | -- | 29.7 | 10.5 | 0.73 | -- | 209. | 8.3 | -- |
| Turboprop | 69. | 14.1 | 0.35 | 0.50 | 166. | -- | 41.3 | 14.8 | 0.70 | -- | 218. | 15.7 | -- |

TOC - Total Ownership Cost, $
AC - Acquisition Cost, $
$W_f$ - Weight of Fuel, lb
$C_f$ - Fuel Cost, $/lb
CD - Cooling Drag; %A/C Drag

SFC - Specific Fuel Consumption, lb/HP-Hr
$W_e$ - Engine Weight, lb/HP
Ce - Engine Cost, $/HP
MC - Engine Maintenance Cost, $/Flight Hr

TABLE A14. - ESTIMATED AND ACTUAL VALUES OF MISSION 10 AIRCRAFT IMPROVEMENTS FOR VERY ADVANCED TECHNOLOGY ENGINES. ESTIMATES DERIVED FROM ADVANCED TECHNOLOGY BASELINE VALUES PLUS SENSITIVITY DATA OF TABLE A10

| | Estimated Value | Actual Value |
|---|---|---|
| S.I.R. % $\Delta$TOC | 28.2 | 26.1 |
| S.I.R. % $\Delta$AC | 10.0 | 10.8 |
| S.I.R. % $\Delta W_f$ | 38.9 | 39.2 |
| Diesel % $\Delta$TOC | 31.0 | 30.9 |
| Diesel % $\Delta$AC | 10.4 | 11.0 |
| Diesel % $\Delta W_f$ | 38.8 | 39.7 |
| Rotary % $\Delta$TOC | 35.6 | 35.6 |
| Rotary % $\Delta$AC | 14.9 | 15.4 |
| Rotary % $\Delta W_f$ | 44.2 | 45.6 |




Current Technology

- Nat. aspir. below 10 000 ft
- Turbocharged over 10 000 ft
- Homogeneous charge
- AvGAS
- Cooling drag - 10% of total A/C

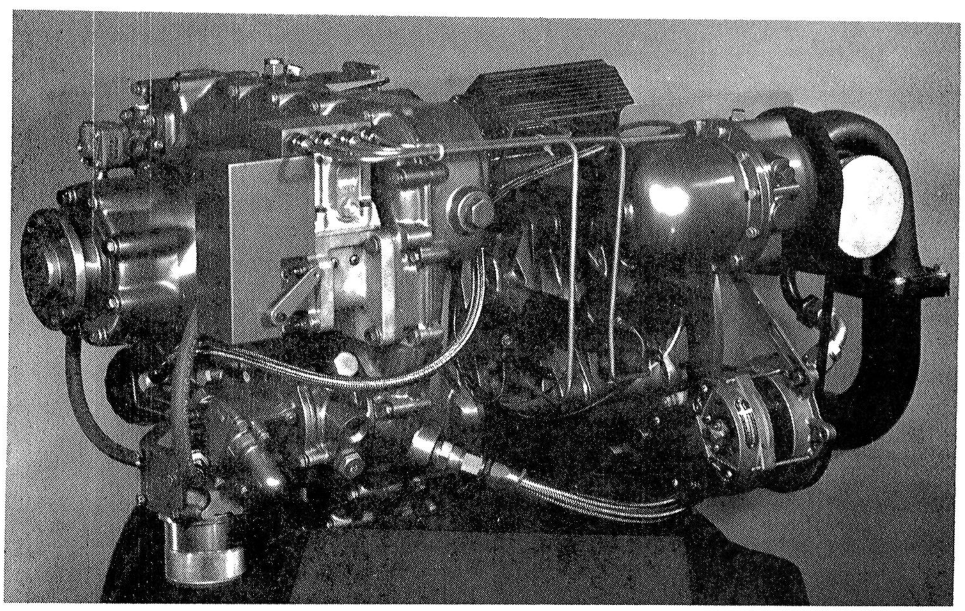
Advanced Technology

- Turbocompound - all altitudes
- Lean-burn
- Homogeneous charge
- AvGAS
- 50% cooling drag reduction

Very advanced technology

- Turbocompound - all altitudes
- Stratified charge
- Multifuel
- 65% cooling drag reduction

Figure 1. - Design features for spark-ignited reciprocating (SIR) engine. All designs presented are four-stroke with horizontally opposed cylinders.



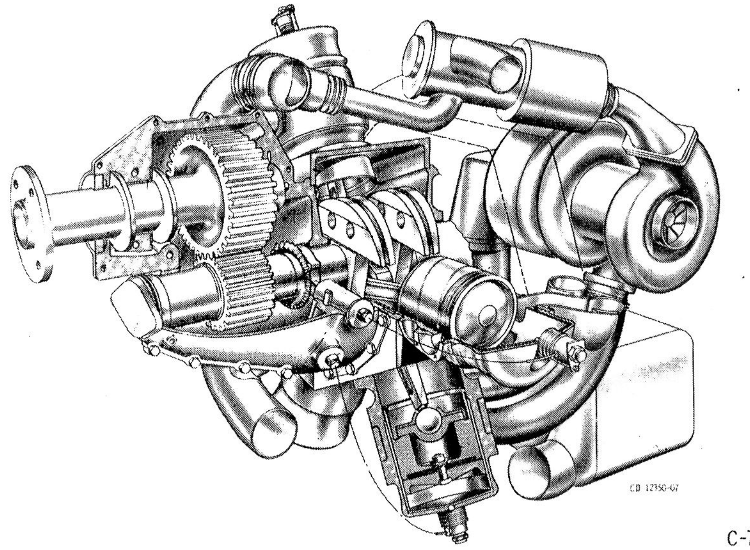
Advanced Technology

- Stratified charge
- Multifuel capability
- Turbocharged
- Liquid cooled (65% drag reduction)
- Conventional apex drag

Very Advanced Technology

- Stratified charge
- Multifuel capability
- VAT turbocharged/pressure compounded
- Liquid cooled (zero cooling drag)
- Retracting apex seals

Figure 2. - Design features for advanced rotary engines.



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Advanced Technology

- Radial design
- Two-stroke cycle
- Limited cooling (50% drag reduction)
- Turbocharged (7.25:1 P/P at 25 000 ft)
- Conventional combustor in T. C. loop
- Conventional lubrication

Very Advanced Technology

- Radial design
- Two-stroke cycle
- Limited cooling (65% drag reduction)
- Turbocharged (9:1 P/P at 25 000 ft)
- Catalytic combustor in T. C. loop
- Synthetic oil

Figure 3. - Design features for lightweight diesel engines.

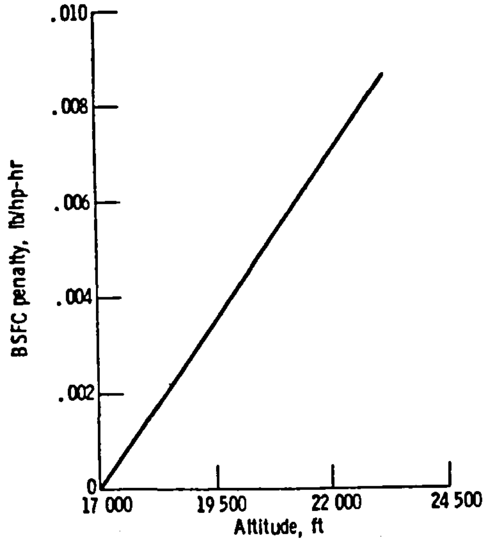



Figure 4. - Diesel BSFC penalty resulting from fuel burned in the turbocharger loop.

- LOW-COST GATE TECHNOLOGY (40% COST REDUCTION)
- COMMON CORE ENGINE FAMILY - E. G.:
  - 9:1 P/P (SHP < 300)
  - 12:1 P/P (SHP ≥ 300)
- TURBINE R.I.T. 2140° F (CRUISE)

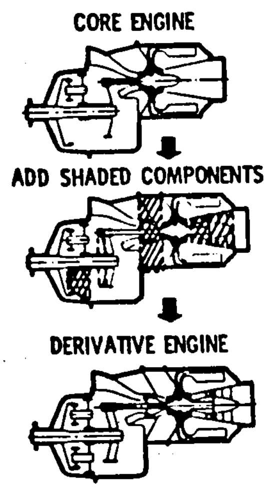



Figure 5. - Design features of advanced turbine engines.

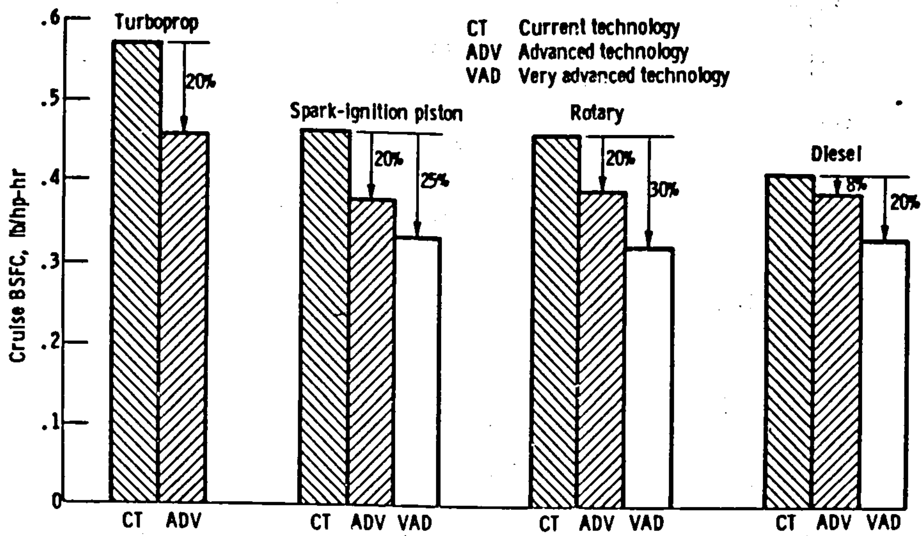



Figure 6. - Projected BSFC improvements for advanced engines at 350 maximum rated power. Flight conditions are 25 000 foot altitude and 250 knots and includes pressurization and auxiliary power penalties.

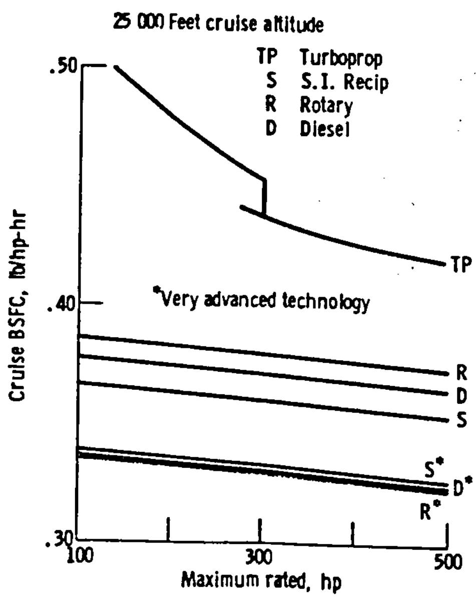



Figure 7. - BSFC size effects for the advanced engines.

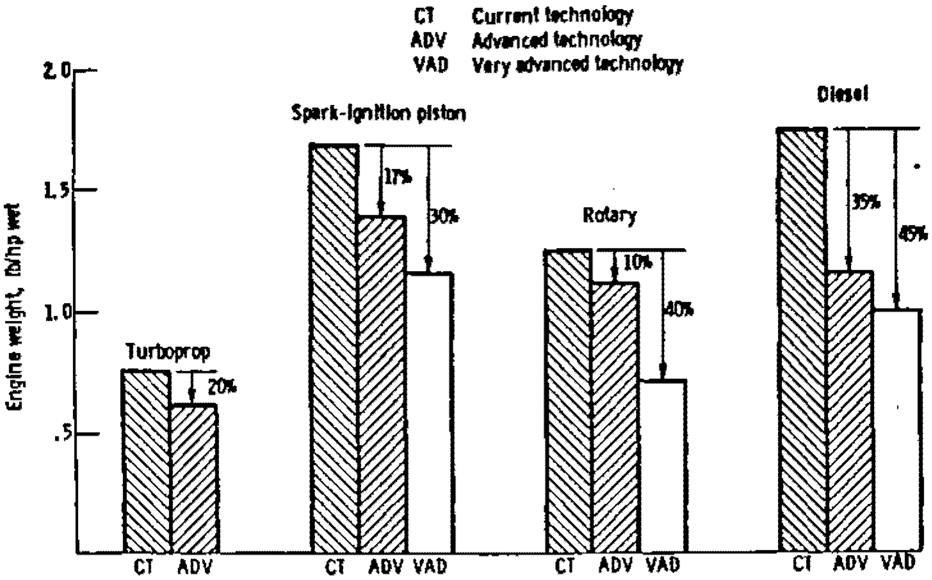



Figure 8. - Projected engine weight reduction for the advanced engines at 350 maximum rated power.

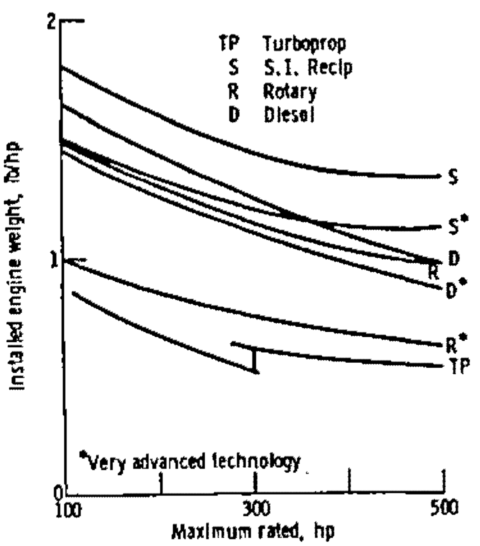



Figure 9. - Effect of size on engine weight for the advanced engines.

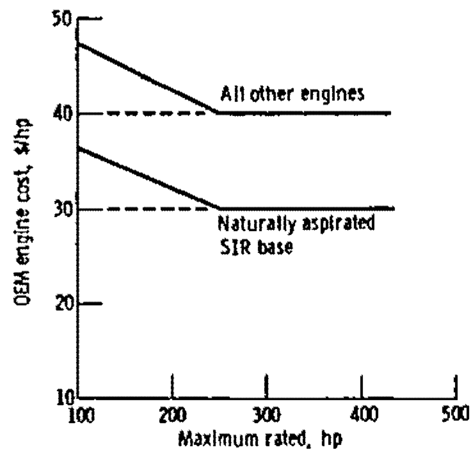



Figure 10. - Assumed engine cost (1977$).

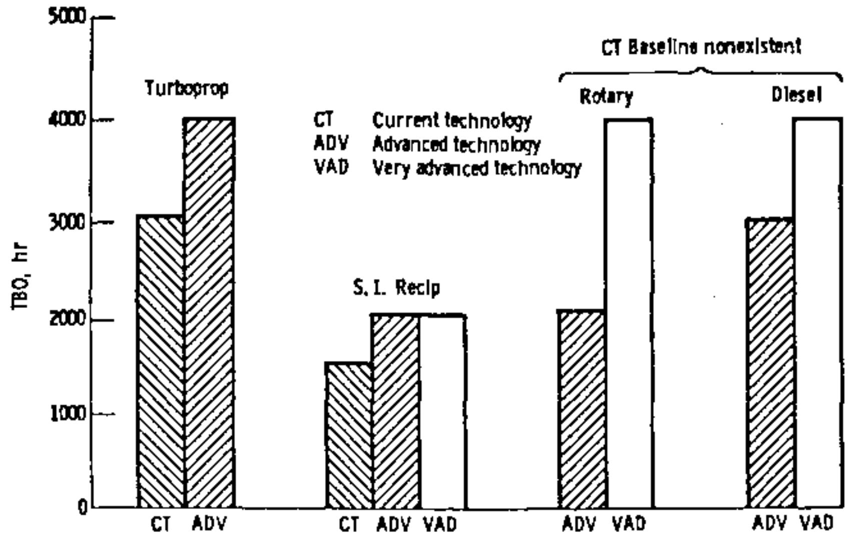



Figure 11. - Projected time between overhaul (TBO) for advanced engines at 350 maximum rated power.

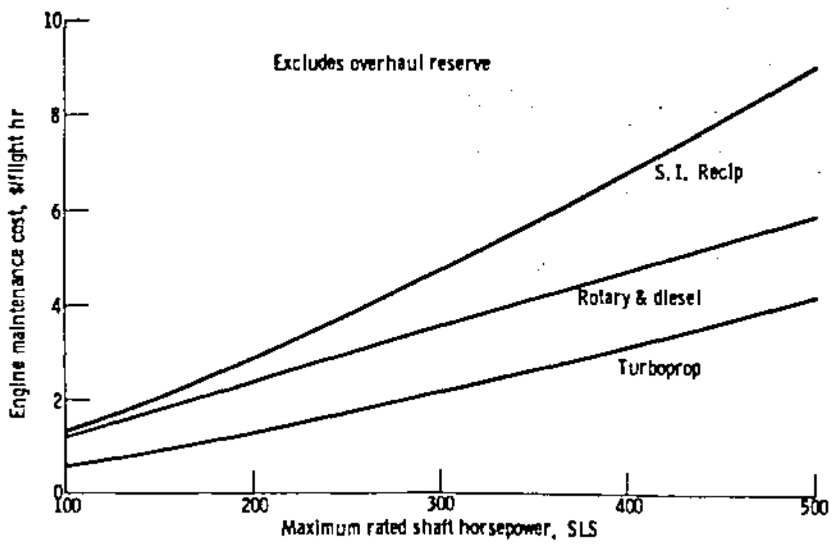



Figure 12. - Assumed engine maintenance cost.

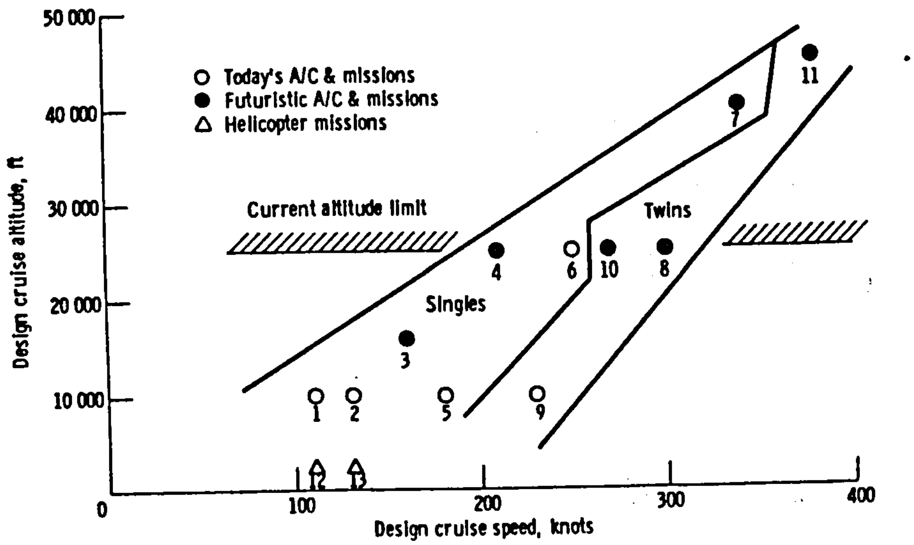



Figure 13. - Cruise speed and altitude spectrum considered.

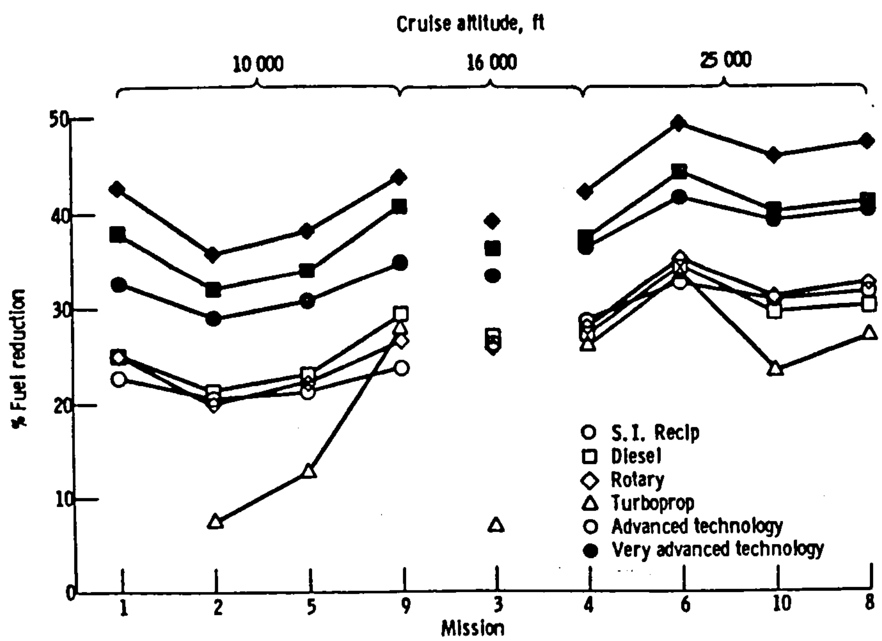



Figure 14. - Mission fuel reduction potential of advanced engines.

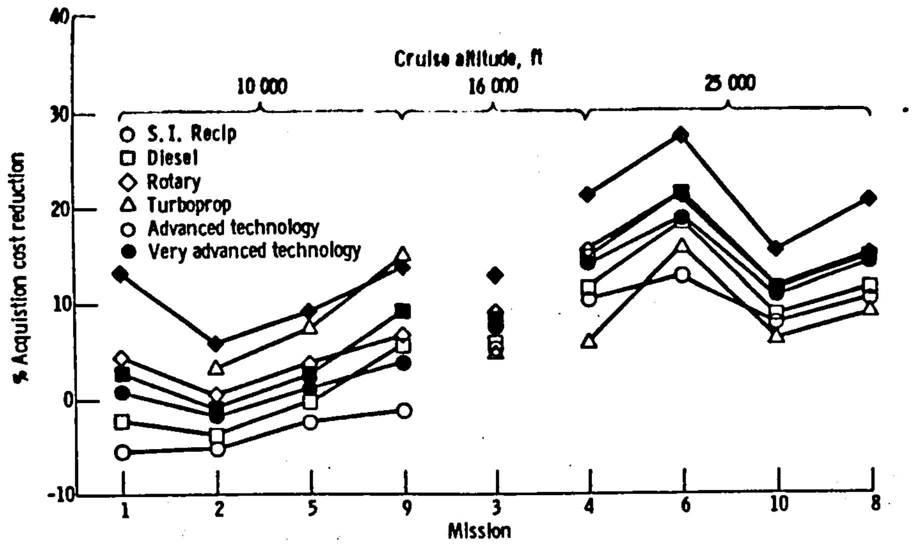



Figure 15. - Aircraft acquisition cost reduction potential for advanced engine.

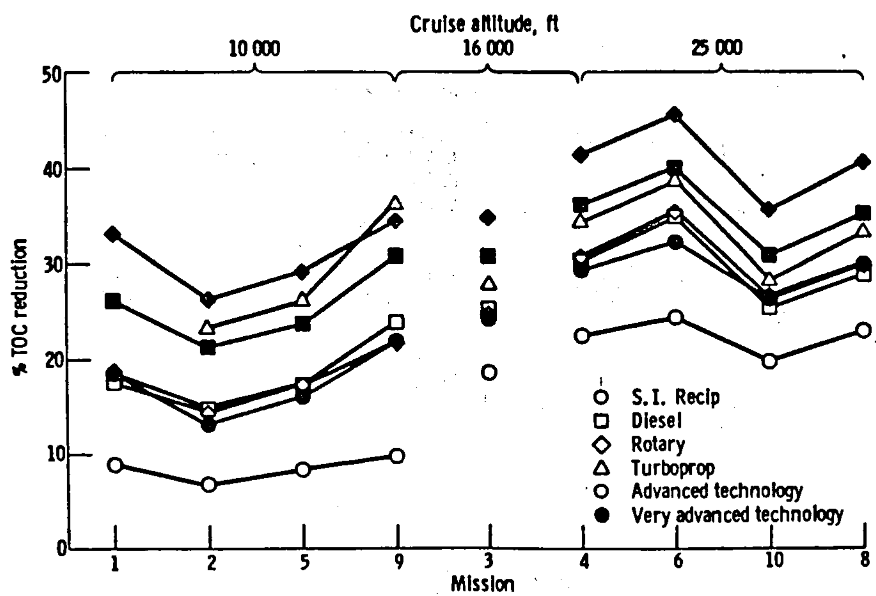



Figure 16. - Aircraft total ownership cost reduction potential for advanced engines.

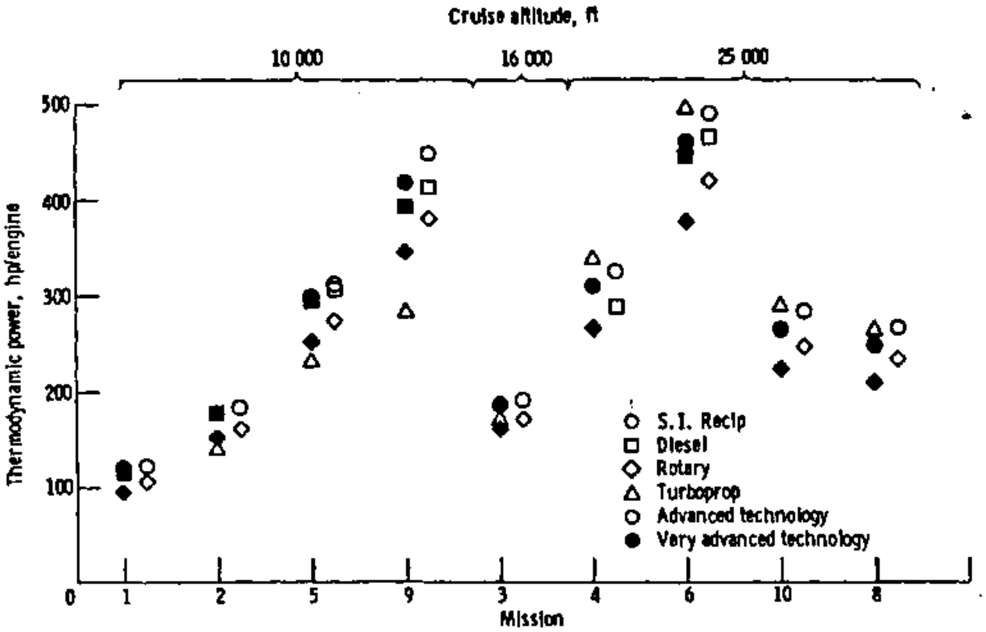
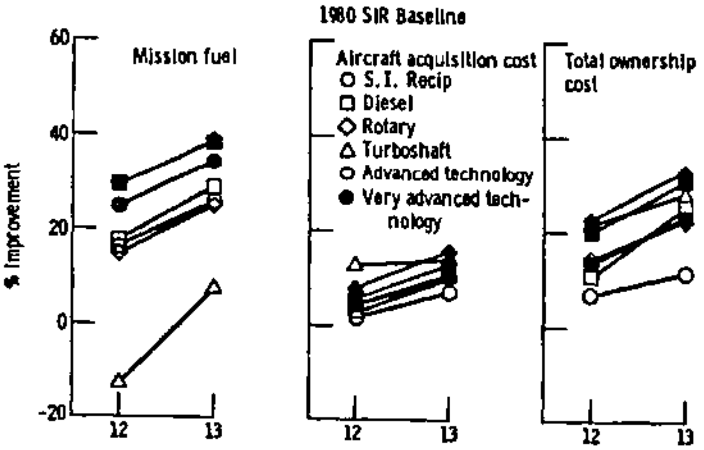



Figure 17. - Horsepower requirement of the advanced engines.

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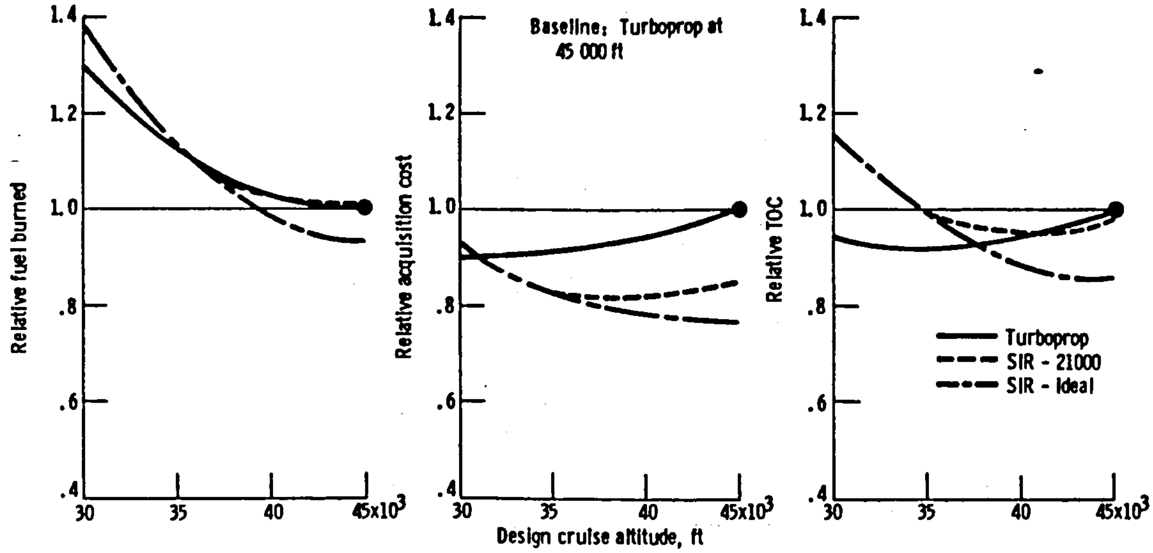


Figure 19. - Effect of high altitude on forecasted aircraft improvements. Mission 11 (8-place executive twin, 380 knots, 1700 n. m. ).

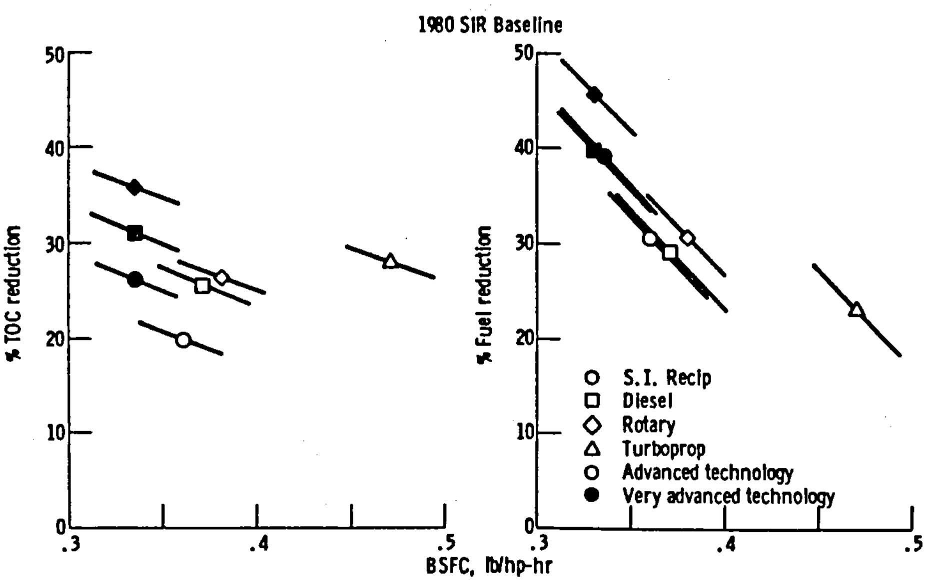


Figure 20. - Effect of varying engine BSFC on TOC and mission fuel. Mission 10 (6 place business twin).

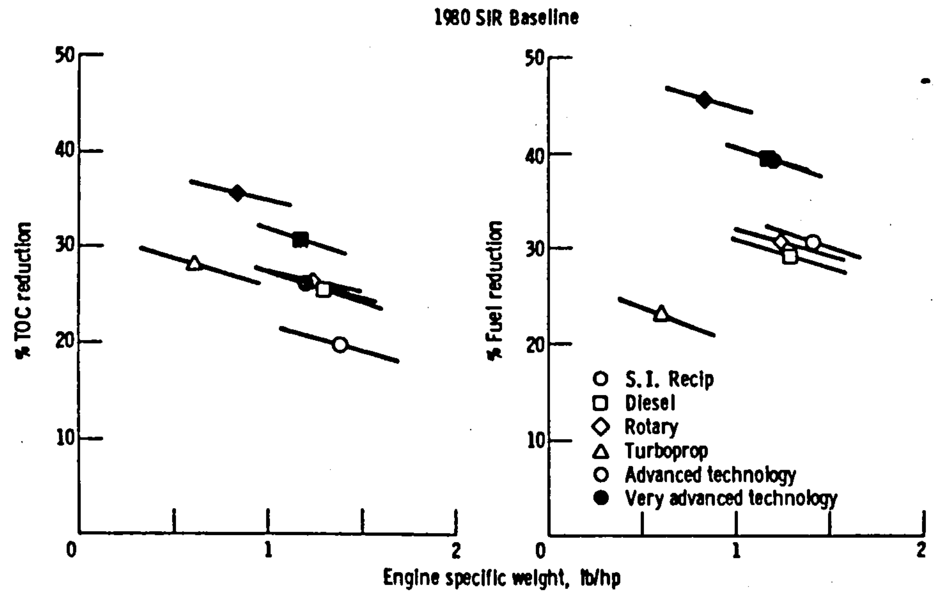


Figure 21. - Effect of varying engine installed specific weight on TOC and mission fuel reduction potential. Mission 10 (6 place business twin).

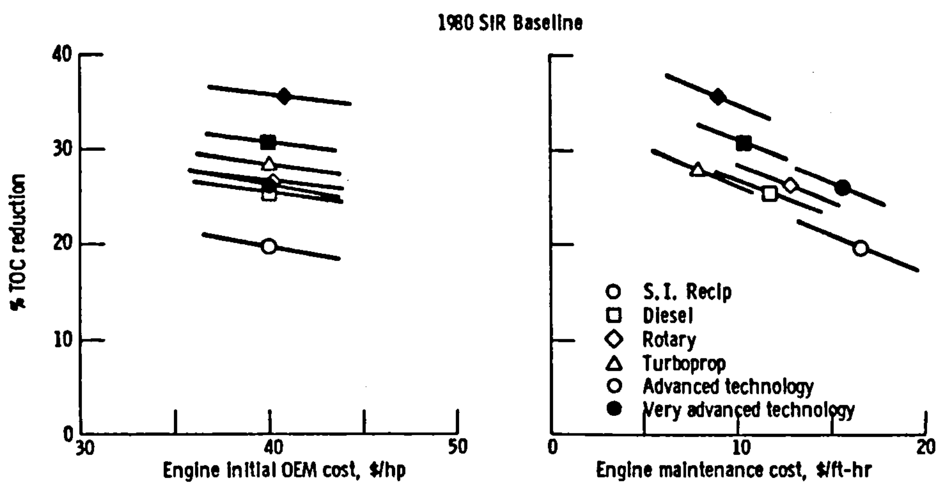


Figure 22. - Effect of varying engine OEM and maintenance cost on TOC. Mission 10 (6 place business twin).

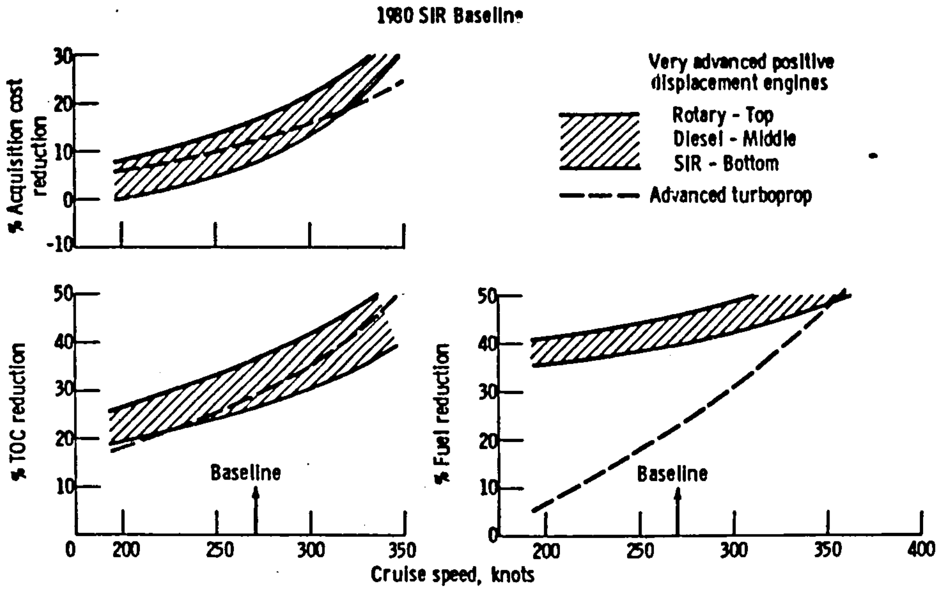


Figure 23. - Effect of cruise speed on forecasted aircraft improvements. Mission 10 (6 place business twin).

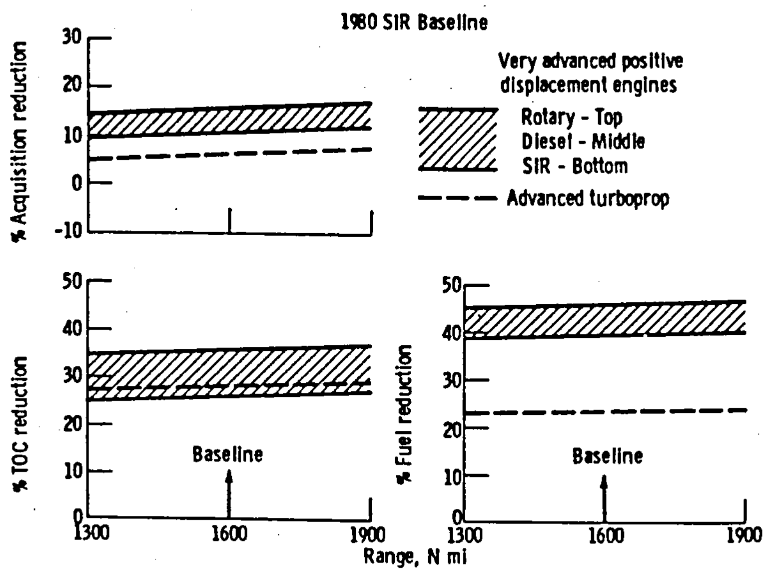


Figure 24. - Effect of range on forecasted aircraft improvements. Mission 10 (6 place business twin).

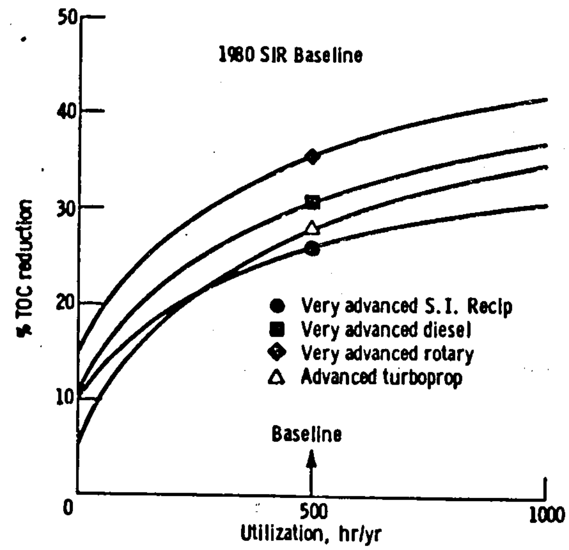


Figure 25. - Effect of aircraft utilization on aircraft improvements. Mission 10 (6 place business twin).

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16. Abstract

Recently completed NASA-sponsored conceptual studies have culminated in the identification of promising new technologies for future spark ignition, diesel, rotary, and turbine engines. This paper reports the results of a NASA in-house preliminary assessment study that compares these four powerplant types in several general aviation applications. The evaluation consisted of installing each powerplant type in "rubberized" aircraft which are sized to accomplish fixed missions. The primary evaluation criteria include projected aircraft cost, total ownership cost, and mission fuel.

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