Advanced Technology Payoffs for Future Small Propulsion Systems

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The objectives of the NASA/Army-sponsored Small Engine Component Technology (SECT) study were to identify high-payoff technologies for year-2000 small gas turbine applications and to formulate the required technology programs. The projected technologies were evaluated in terms of their influence on operating cost for the four candidate applications: rotorcraft, commuter, cruise missile, and auxiliary power unit (APU). This paper reviews the reference missions, engines, and aircraft, the year-2000 technology projections, cycle studies, advanced engine selections, and technology evaluations. Conventional simple cycles and heat-recovery cycles were both evaluated. The resulting direct operating costs (DOC) were nearly equal for simple and heat-recovery engines at low fuel prices ($1/gal). Heat-recovery engines clearly were advantageous at high fuel prices ($2/gal). System DOC improvements ranged from 6 to 11% for the rotorcraft and the commuter application. Reductions in engine DOC for the APU ranged from 37 to 47%. Missile cost per mile was reduced by nearly 80%, relative to today's rocket-powered system, and by 50% over a near-term turbojet propulsion system. The high-payoff technologies identified include ceramic materials for the rotorcraft, commuter, and APU engines and carbon-carbon (C-C) materials and boron slurry fuel for cruise missiles.

Introduction

OVER the past two decades, the performance of small gas turbine engines in the 250–1000 hp range has not kept pace with that of larger gas turbines. These performance differences can be attributed largely to the disproportionate share of research and development (R&D) resources devoted to large engine technologies, technologies generally not directly transferable to small engines. This results in an increasing performance disparity between large and small engines, which places an additional cost burden on the public (Fig. 1). Clearly, the challenge in future small gas turbines is to identify and advance the significant technologies required to approach the performance level of large engines.

In response to this challenge, the recently completed Small Engine Component Technology (SECT) program was charged with identifying the engine cycle, configuration, and component technology requirements for the substantial performance improvements desired in year-2000 small gas turbine engines. For the identified high-payoff technologies, technology plans were formulated to guide future research efforts. The Garrett Turbine Engine Company (GTEC) evaluated engines for four year-2000 applications: a rotorcraft, a commuter aircraft, a supersonic cruise missile, and an auxiliary power unit (APU).

This paper summarizes the SECT study and reviews the reference missions, engines, and aircraft, year-2000 technology projections, cycle study, advanced engine selections, and technology evaluations.

Reference Missions, Engines, and Aircraft

Projected year-2000 missions and aircraft were defined, as were current technology reference engines for each application. These reference aircraft/engine systems provide a benchmark from which improvements derived from the year-2000 engines can be measured. Finally, trade factors were generated with these reference systems relating changes in key engine parameters to aircraft operating costs.

Reference Missions

Representative reference missions that typify both military and civil applications were defined on the basis of recommendations by airframe manufacturers.

Rotorcraft: The reference mission was 130.4 n.mi. long and consisted of five cruise legs separated by 20 min of hover at each destination point. Total mission time was 2 h 19 min.

Commuter: A four-segment, 400-n.mi. mission was defined. Operational altitude was optimized at cruise to minimize mission time.

Cruise missile: The mission objectives for the supersonic tactical missile were tactical, defense suppression, and/or ship attack (collateral sea control). The reference mission consists of a low-altitude, high-speed dash to a target. The missile is launched at Mach 0.8, sea level, and immediately accelerates to a Mach 2.5, sea-level cruise condition. The missile range is calculated as the distance traveled when fuel is depleted.

APU: A survey of typical usage for airlines using a 150-passenger aircraft showed that existing APU's have three general operational requirements: main engine starting, on-ground electrical supply and air conditioning, and emergency in-flight operation. Typically, an APU operates one hour per aircraft flight hour. On this basis, a representative duty cycle, which consists of several conditions that represent each operational requirement, was defined.

Reference Engines

The reference engines were defined based on engines under development at GTEC. Performance and operating parameters of these engines were adjusted to represent 1985 component technology. For the cruise missile, the reference engine is based on a conceptualized GTEC turbojet engine of near-term (1989) component technology, due to the unavailability of a present engine with the necessary supersonic performance.

Rotorcraft: The reference engine is a two-spool design that uses an inlet particle separator (IPS) in front of a two-stage

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centrifugal compressor with a total pressure ratio of 13.5:1 and an inlet corrected flow of 6.7 lb/s. A reverse-flow annular combustor placed around a two-stage axial gas generator (GG) turbine resulted in a compact GG spool. Turbine rotor inlet temperature (TRIT) was set at 2100°F. Shaft power is provided by a two-stage axial power turbine. At sea-level static standard-day conditions, the engine was sized at 1000 shaft horsepower (shp) at the intermediate rated power (IRP) setting. Engine-specific fuel consumption (SFC), weight, diameter, length, and cost are representative of current technology.

Commuter: The commuter reference engine uses the same core technology as the rotorcraft application. To satisfy commuter requirements, the IPS was removed, and an offset propeller gearbox was added. The engine was sized for 1000 shp at sea level static but was matched at altitude for optimum cruise performance.

Cruise missile: The reference engine is a single-spool turbojet design that uses a mixed-flow plus axial-compressor system, which achieves an overall design pressure ratio of 6:1 and an inlet corrected airflow of 20 lb/s. The compressor is driven by a single-stage axial turbine with a TRIT of 2600°F. The engine had 1596 lb of thrust at sea-level static standard-day conditions.

APU: The reference engine is a single-spool design that uses a single-stage centrifugal core compressor with an overall pressure ratio of 5.44:1 and an inlet corrected airflow of 3.49 lb/s. On the same shaft, a single-stage centrifugal load compressor is used to supply up to 150 lb/min of air at 50 psia for airframe uses. A simultaneous 21-kVA electrical load is supplied from the gearbox. Driving the compressor system is a single-stage radial turbine with a TRIT of 1900°F. The use of a reverse-flow annular combustor resulted in a compact design. The APU was sized for 358 shp at the max power setting for sea-level static standard-day conditions.

Reference Aircraft

Reference aircraft were configured using the reference engines and by incorporating projected year-2000 airframe technologies into existing applications from the same size class. Major technology projections—including weight reductions in the airframe and associated subsystems, and aerodynamic improvements—were applied. Key improvements were derived from advancements in material technology, specifically the use of composites.

Rotorcraft: The selected helicopter (Fig. 2) has a takeoff gross weight (TOGW) of 9564 lb and carries a payload of 3676 lb. Fuselage length and width are 42.6 and 7.0 ft, respectively.

Commuter: The 19-passenger commuter (Fig. 3) has two pod-mounted engines and a TOGW of 13,080 lb.

Cruise missile: A fixed-volume supersonic tactical cruise missile was defined based on the packaging limitations of the current launch carriage (Fig. 4). The vehicle has an overall launch weight of 1500 lb.

APU: The APU is installed in the aft section of a 150-passenger commercial transport. Engine volume is typically not critical in this location.

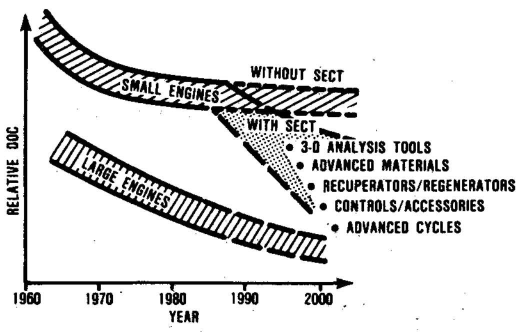


Fig. 1 Small engine gains have not kept pace with large engine gains.

Trade Factors

The Garrett Turbine Engine Company used aircraft DOC (cost per range for missile) as the primary system figure of merit. Aircraft DOC encompasses the acquisition, operation, and support costs of the airframe/engine system. Additionally, DOC is an effective figure of merit because it provides a common denominator for the evaluation of many dissimilar aspects of propulsion system costs.

Trade factors were generated from a detailed operating cost sensitivity analysis performed on the reference airframe/engine systems. These trade factors, which relate system costs to changes in engine/airframe interface parameters, were used as a means of screening a large number of candidate engines. Parameters evaluated include engine-specific fuel consumption (SFC), weight, diameter, length, engine acquisition, and maintenance costs. Maintenance aspects were addressed in detail on the selected year-2000 engines identified by this screening process. Both a low and high fuel price, $1 and $2/gal,

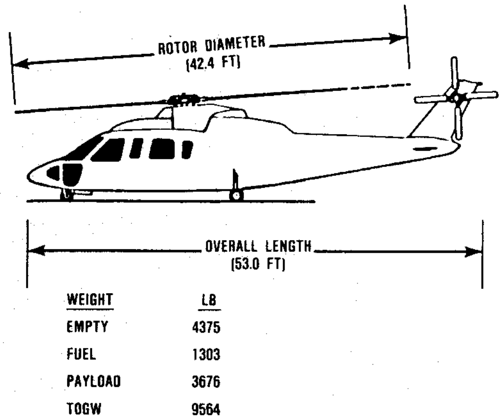


Fig. 2 Year-2000 reference rotorcraft.

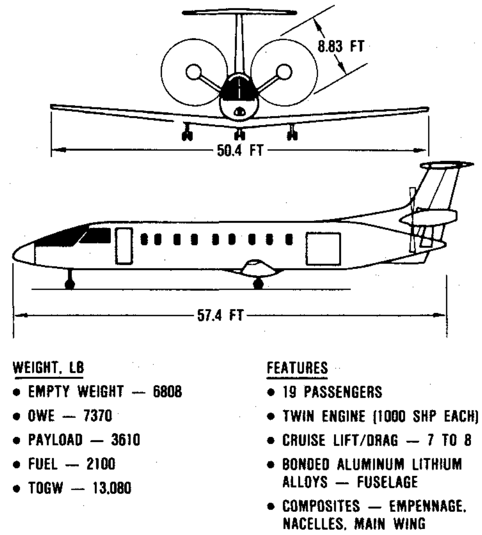


Fig. 3 Year-2000 reference commuter.

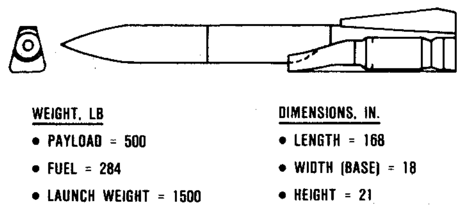


Fig. 4 Year-2000 reference cruise missile.

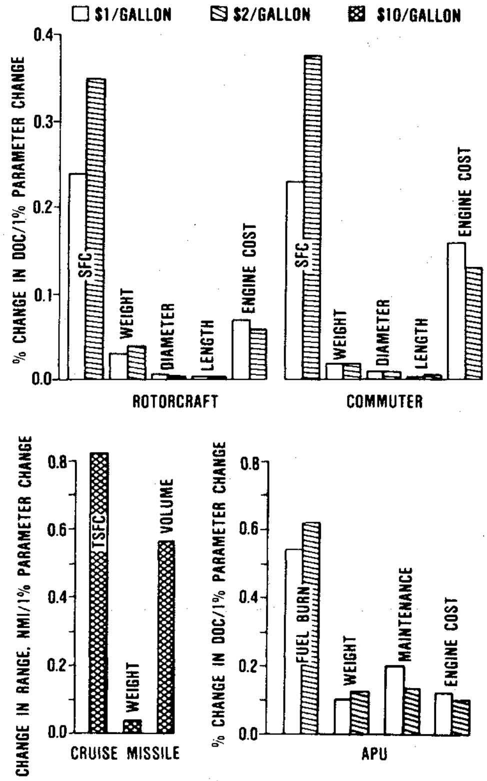


Fig. 5 Trade factors—sensitivity of selected engine parameters.

were selected to evaluate the impact of rising fuel cost. The price selected for the cruise missile was $10/gal.

The trade factors provide an indication of the importance of the various engine parameters. Engine SFC and cost were found to be the key drivers for the rotorcraft and commuter, as shown in Fig. 5. Thrust-specific fuel consumption (TSFC) and volume were of the greatest importance in minimizing cost/range for the cruise missile. The key DOC driver for the APU was SFC, although maintenance, cost, and weight each had a noticeable influence.

Year-2000 Technology Projections

The engine cycle studies were based on projected year-2000 component technologies. Inherent in these projections was the assumption that the technologies will be ready by the year 2000, given proper funding and support. Emphasis was placed on defining technologies that would significantly improve the performance of small gas turbines. These include technologies currently receiving some support, but not all at the level or direction of effort necessary to benefit small engines by the year 2000. These technologies influence the cycle study in terms of component efficiency levels, TRIT limits, and cooling flow requirements, as well as turbine stage count and hub speed limits.

The technologies evaluated were grouped into three major areas: materials, component aerodynamics, and heat recovery.

Materials

Materials, which traditionally have been the key drivers in improving gas turbine performance, are projected to play a key role in future advancements. Material improvements were identified for both the cold section (compressor, inlet, front structure) and the hot section (combustor, turbines, nozzle). Materials for cold-section components primarily allow reductions in engine weight and cost; materials for hot-section parts allow improved engine performance by permitting increased cycle temperature and component stress capabilities.

Table 1 Projected year-2000 cold-section materials

Material	Application	Benefit
High-temperature, PM aluminum alloy	Vanes, blades, rotors	Reduces cost, weight
Cast titanium alloy	Vanes, blades, rotors	Reduced cost
Ti_3Al	Vanes, blades rotors	Increased temperature
Polymeric composites	Gearboxes	Reduced weight
MMC	Shafts	Increased stiffness, strength/weight

Table 2 Projected year-2000 hot-section materials

Material	Application	Benefit
SSC	Vanes, blades	Temperature improvement (+100°F)[a]
Ni_3Al	Disks	Weight reduction
Ceramics	Vanes, blades, rotors, combustors, transition liners, recuperators	Temperature improvement (+800°F),[a] weight reduction
C-C	Vanes, blades, rotors, combustors, transitions liners, nozzles	Temperature improvement (+1500–2000°F)[a] weight reduction

[a]Relative to present metallic parts.

Five materials offer cost and/or weight advantages for the cold section (Table 1).

1) Powder-metallurgy (PM) aluminum can potentially reduce cost and weight relative to materials now used. By the year 2000, aluminum alloys will be able to withstand temperatures up to 850°F, which will allow the application of aluminum in engines with higher compressor discharge pressures and temperatures.

2) Cast titanium alloys (with the same strength as forged alloys) offer the possibility of a 20% cost reduction through the elimination of most machining operations.

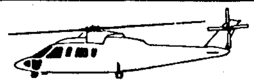
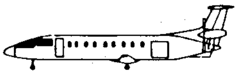
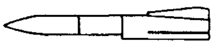
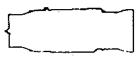
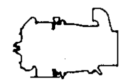
3) Titanium aluminides (Ti_3Al) offer the potential of increased temperature capabilities (up to 1500°F) for compressor vanes, blades, and rotors, allowing higher discharge pressures and temperatures.

4) Polymeric composites, which consist of fiber-reinforced resin (constituents yet to be identified), are predicted to reduce weight by as much as 30% relative to present aluminum gearboxes.

5) Metal-matrix composites (MMC) for shafting might be required for year-2000 turboshaft engines in this size class. With a 50% reduction in weight, combined with high-temperature strength and stiffness, MMC will be able to achieve the shaft critical-speed margins needed for the higher spool speeds and smaller bore sizes of future small engines.

Both metallics and nonmetallics were considered for the hot-section components (Table 2), specifically the turbine and combustor.

1) Super single crystal (SSC) for application in advanced metallic turbine blades and vanes is expected to increase the temperature capability of present single crystal (SC) materials by approximately 100°F. Super single crystal also will allow

APPLICATION	CYCLE OPTIONS	CONFIGURATION OPTIONS	CYCLE PARAMETERS
 ROTORCRAFT	 • SIMPLE • RECUPERATED*	• AXIAL-CENTRIFUGAL, 2-STAGE CENTRIFUGAL COMPRESSORS • METALLIC/CERAMIC TURBINES (AXIAL) • TURBINE STAGE COUNT • VARIABLE/FIXED LP TURBINES	• TRIT = 2200-3000F • PR = 16-26
 COMMUTER	 • RECUPERATED • REGENERATED • SIMPLE**	• AXIAL/CENTRIFUGAL, 2-STAGE CENTRIFUGAL, SINGLE-CENTRIFUGAL COMPRESSORS • METALLIC/CERAMIC/CARBON-CARBON TURBINES (AXIAL) • RECUPERATORS/REGENERATORS	• TRIT = 2200-3400F • PR = 4-12 • ϵ = 0.6-0.95 • $\Delta P/P$ = 6-10% • LEAKAGE = 4-10%
 CRUISE MISSILE	 • SIMPLE TURBOJET	• AXIAL, AXIAL-CENTRIFUGAL COMPRESSORS • CARBON-CARBON TURBINES (AXIAL) • THROUGH-FLOW COMBUSTOR • DIAMETER CONSTRAINT (≤14 IN)	• TRIT = 2600-3500F • PR = 6-14
 AUXILIARY POWER UNIT	 • SIMPLE • REGENERATED***	• AXIAL, RADIAL TURBINES • METALLIC/CERAMIC TURBINES • SINGLE/TWO-SPOOL • VARIABLE GEOMETRY • SINGLE/TWO-STAGE CENTRIFUGAL COMPRESSOR	• TRIT = 1900-2500F • PR = 4-10

*CYCLE SELECTED BASED ON COMMUTER STUDY
**CYCLE SELECTED BASED ON ROTORCRAFT STUDY
***BASED ON AGT101

Fig. 6 Configuration/cycle options.

higher stress and loading levels and could reduce cooling flow requirements at a given temperature in a cooled turbine.

2) Nickel aluminide (Ni_3Al) offers the potential of improved strength-to-weight ratio by reducing weight by approximately 15% relative to currently used Astrology and Waspaloy turbine disk materials. This leads to reduced turbine stage count and/or higher efficiency.

3) Ceramic components are envisioned for application in year-2000 engines. Ceramics have the potential for use in turbine vanes, blades, and rotors, combustors, transition liners, and heat exchangers. The increased temperature capability of ceramics will allow uncooled turbines to operate at increased inlet temperatures. Engine cycle temperatures up to 2600°F were projected for compatibility with an uncooled turbine. Significant weight savings also will be possible with ceramics. The low density of ceramics will reduce weight up to 60% on some components.

4) Carbon-carbon (C-C) composites have initial application in unmanned vehicles, specifically in turbine, combustor, and nozzle components. The high risk of C-C precludes its use in manned applications by the year 2000. Carbon-carbon consists of high-strength carbon fibers embedded in an amorphous carbon matrix, which maintains its strength characteristics up to 4000°F if adequately protected from oxidation. Carbon-carbon can allow uncooled turbines to operate at higher TRIT's, resulting in smaller and lighter engines. The reduced density of C-C can reduce weight by up to 70% on some components.

Component Aerodynamics

Improvements in component aerodynamic performance are foreseen. In conjunction with advancements in material technology, aerodynamic advancements for the year 2000 were projected for compressors, combustors, and turbines in terms of increased component efficiencies, reduced losses, and higher aerodynamic loading capabilities.

Compressor performance projections were made for four typical configurations: single-stage centrifugal, two-stage centrifugal, axial, and axial-centrifugal. Year-2000 efficiencies were projected to increase by 2–4 points (polytropic), depending on application, configuration, size, and pressure ratio. These improvements depend on development of three-dimensional viscous analytical codes and nonintrusive measurement techniques to support the analytical development. Additionally, reduced airfoil losses are assumed as a result of improved airfoil design and analysis methods.

Combustor performance improvements are expected in several areas. Combustor pattern factors for reverse-flow designs will be reduced to the 0.10–0.12 range from present values ranging from 0.15 to 0.20. Pattern factors for through-flow designs will be somewhat higher. The use of nonmetallics or advanced wall-cooling methods will be vital to meet pattern factor goals by providing additional dilution air. Furthermore, diffuser technology will be improved to maintain present pressure drop levels at increased inlet Mach numbers. Year-2000 combustors also will have higher heat-release rates, reduced size, and improved durability.

Alternate fuels (boron slurry) were also considered, specifically for the cruise missile application. Combustion changes, particularly in the nozzle configuration, will be necessary to accommodate this dense, high-energy fuel. Boron slurry has a fuel lower heating value approximately twice that of JP-10, which was used as the baseline fuel.

Gas generator turbine aerodynamic improvements were predicted to range from 2 to 3 points, relative to present levels, depending on application, configuration, flow, and loading. Performance improvements will result primarily from reduced rotor tip losses and minimized vane and blade interaction losses. Optimum matching of the vane exit and rotor inlet flowfields is expected to result in an efficiency improvement. Mechanical advances are required to minimize tip losses through reduced axial excursions. Furthermore, aerodynamic advances are expected to result in a 25% decrease in clearance sensitivity through casing and rotor tip treatments.

Power turbine efficiency improvements are expected to be similar in magnitude to the HP turbine. With shrouded blades, only small efficiency improvements will be possible by reducing clearance losses; however, improvements from vane and blade interaction are expected to be slightly higher, compared to the HP turbine.

Heat Recovery

Expected to play an increasingly important role in advanced propulsion engines, heat-recovery devices (recuperators and rotary regenerators) are used to recapture waste energy from the gas turbine exhaust. The recaptured heat energy is used to

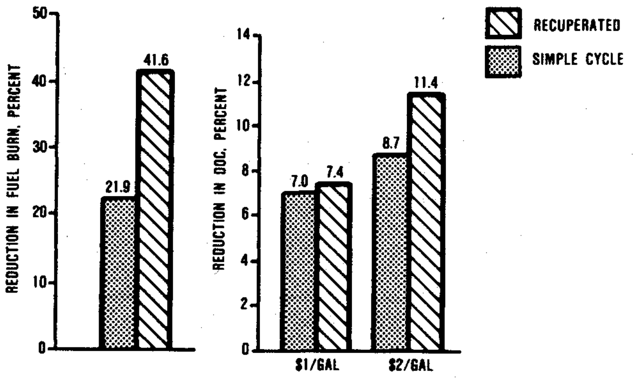


Fig. 7 **Rotorcraft mission analysis results.**

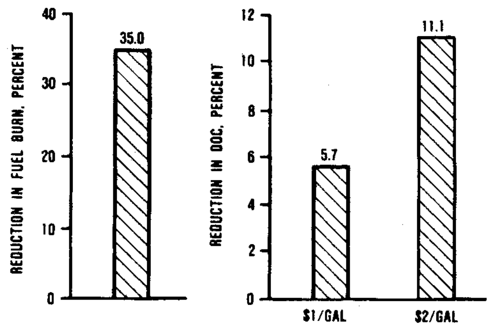


Fig. 8 **Commuter mission analysis results.**

preheat the combustor inlet air, thereby reducing the energy (or fuel flow) required to achieve the desired turbine inlet temperature. Of particular interest in this study was the counterflow ceramic plate-fin recuperator design. Improvements in heat-recovery (recuperator) technology are projected to be made in materials and processes, specifically in ceramics. As a result of these improvements in technology, cost and weight will be reduced and temperature capability will be increased, relative to today's heat-recovery engines.

Technology improvements for regenerators were based on GTEC experience with the AGT101 regenerated automotive engine sponsored by NASA and the Department of Energy (DOE).

Cycle Studies

The Garrett Turbine Engine Company parametrically examined a number of cycle and configuration options for the four applications (Fig. 6). For example, the rotorcraft studies evaluated both simple and recuperated cycles. Heat-recovery cycles, both recuperated and regenerated, as well as conventional simple cycles, were evaluated for the commuter application. Only simple-cycles, turbojets were considered feasible to meet the supersonic mission requirements of the cruise missile. Both simple and regenerated engines were evaluated for the APU.

Various cycle options and a number of component configurations were evaluated. Axial, axial-centrifugal, single-, and two-stage centrifugal compressors were evaluated and compared where appropriate. Of key importance was the comparison of several turbine airfoil materials: advanced metallics, ceramics, and C-C. Turbine materials were found to strongly affect TRIT and cooling flow levels which, in turn, have a dramatic influence on performance. The impact of turbine stage count, specifically the tradeoff among efficiency—including pressure ratio (PR) and TRIT capability—size, weight, and cost also was considered.

Both fixed boundary recuperator and rotary regenerator heat exchangers were considered, as were numerous design and material options. For example, ceramic and advanced metallic recuperators were compared in various configuration and packaging options.

Parametrically, the cycle studies assessed TRIT's ranging from 1900 to 3500°F, and PR's from 4:1 to 26:1. The heat-recovery cycles, additionally, examined heat-exchanger effectiveness (0.6–0.95) and pressure drop (6–10%). A leakage rate ranging from 6 to 10% was evaluted for the regenerated case.

Component efficiencies, aerodynamic loading, turbine cooling flows, and mechanical constraints were set to be consistent with the previously discussed year-2000 technologies.

Advanced Engine Selections

Numerous trends were exhibited from the cycle/configuration study in terms of performance, size, weight, and cost. The application of trade factors to screen the various options was found to be an effective approach, in view of these often diverging trends. Based on the figure of merit (DOC or cost/range) results, the originally large matrix of engines was reduced to six. These selected engines and their respective mission analysis results are discussed by application in the following paragraphs.

Rotorcraft

Both a conventional simple cycle and a recuperated engine were selected for the rotorcraft application.

Simple cycle: compressor—two-stage centrifugal (PR = 22:1); combustor—reverse flow annular, ceramic; HP turbine—single-stage axial, ceramic, uncooled, unshrouded (TRIT = 2600°F); and LP turbine—multistage axial, uncooled, ceramic. Recuperated cycle: compressor—single-stage centrifugal (PR = 10:1); combustor—reverse flow annular, ceramic; HP turbine—single-stage axial, ceramic, uncooled, unshrouded (TRIT = 2600°F); LP turbine—multistage axial, uncooled, ceramic, variable geometry stator; and recuperator—ceramic plate fin ($\epsilon = 0.8$, $\Delta P/P = 8\%$)

The mission analysis revealed significant reductions in fuel burn, 21.9 and 41.6%, for the simple and recuperated cycles, respectively (Fig. 7). As expected, the recuperated engine is larger and weighs more, relative to the simple cycle.

The selection of either a recuperated or a simple cycle is strongly dependent on fuel price. The recuperated and simple cycle have similar DOC's at $1/gal, approximately 7% lower than the reference engine. At the higher fuel price, the advantage clearly shifts toward recuperation: 11.4% reduction vs 8.7% for the simple cycle.

Commuter

Three cycle types were investigated during the preliminary screening process for the commuter application: recuperated, regenerated, and simple. The recuperated cycle had a definite DOC advantage at the high fuel price ($2/gal). At the low fuel price ($1/gal), both the recuperated and the conventional simple-cycle engine showed similar DOC improvements. Despite its SFC advantage, the regenerated engine's DOC was noticeably higher at both fuel prices. The unfavorable contributions of weight, size, and cost are enough to offset the SFC advantage for this application.

Based on the DOC results at the high fuel price, a recuperated engine essentially identical to that for the rotorcraft application was selected for the commuter. The only significant difference was in the LP turbine, where a fixed geometry stator replaces the variable stator used in the rotorcraft engine.

The mission performance is summarized in Fig. 8. As shown, the key improvement is a 35% reduction in fuel relative to the reference engine. With this fuel burn advantage, the recuperated engine achieves a reduction in DOC of 5.7 and 11.1%, respectively, at the low and high fuel price.

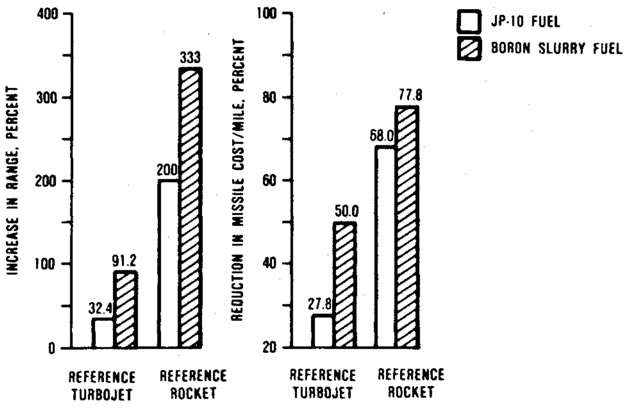


Fig. 9 Cruise missile mission analysis results.

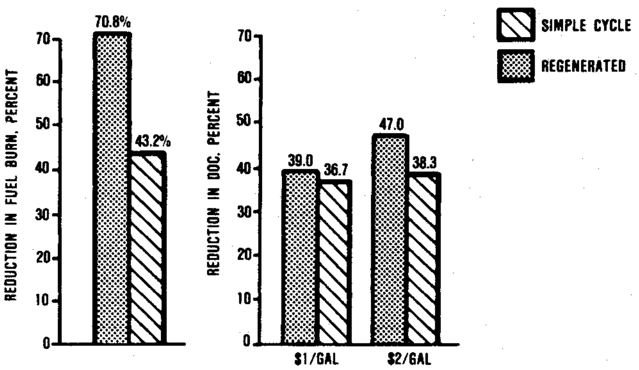


Fig. 10 APU mission analysis results.

Cruise Missile

For the cruise missile, a simple-cycle turbojet engine was selected. This configuration is described as follows: compressor—six-stage axial, PR = 12:1; combustor—annular through-flow, C-C; and HP turbine—single-stage axial, TRIT = 3500°F, uncooled, C-C.

Additional system technologies included in the engine are metal matrix composite shafts, high-temperature accessories, and high-temperature, minimally lubricated bearings.

The mission analysis results show a significant improvement in both missile range and missile cost/mile over the reference missile (Fig. 9). For comparison purposes, the approximate range and cost of a rocket-powered missile are also shown. The advanced missile achieves a 32 and 91% range increase using JP-10 and boron slurry fuels, respectively, relative to the reference turbojet. When compared to the rocket-powered missile, a 200 and 333% range increase is possible with JP-10 and boron slurry, respectively.

Missile cost/mile decreases of 27.8 and 50% for JP-10 and boron slurry, respectively, were shown relative to the reference turbojet. A 70–80% cost/mile reduction is achievable for JP-10 and boron slurry, when compared to the rocket-powered missile.

APU

Based on the DOC results, a simple-cycle engine and a regenerated cycle engine were selected. The DOC trends indicated an advantage for regeneration due to the strong sensitivity of DOC to SFC, particularly at high fuel prices. Additionally, radial turbines demonstrated a significant DOC advantage over axial turbines. The two selected configurations are described as follows: simple cycle: compressor—single-stage centrifugal (PR = 8.1); load compressor—single-stage centrifugal, IGV; HP turbine—single-stage radial, ceramic, uncooled (TRIT = 2500°F); and combustor—reverse-flow, ceramic. Regenerated cycle: compressor single stage centrifugal with inlet guide vane (IGV), (PR = 5.16:1); load compressor—single-stage centrifugal, IGV; turbine—single-stage radial, ceramic, uncooled (TRIT = 2500°F); combustor—single-can, ceramic; and regenerator—ceramic disk ($\epsilon = 0.94$, leakage = 3%).

As determined by the mission analysis, the advanced engines achieve fuel burn reductions of 43.2 and 70.8%, respectively, for the simple and regenerated cycles (Fig. 10). Despite the fuel burn advantage of the regenerated engine, however, the corresponding size, weight, and cost advantage of the simple cycle result in nearly equal DOC's at the low fuel price. At the high fuel price, however, the lower mission fuel requirements of the regenerated engine translate into a significant DOC advantage. Specifically, the regenerated cycle reduces engine DOC by 47% relative to the reference engine, compared to 38.3% for the simple cycle.

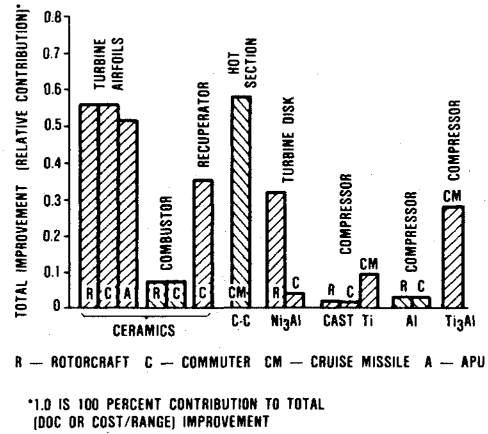


Fig. 11 Relative contribution of material technology.

Technology Evaluation

The selected engines each assume the availability of various year-2000 technologies. These technologies were isolated to determine the impact on the engines if one or more technologies were unavailable by the year 2000. The resulting values provide an indication of their relative importance.

Of the technologies quantitatively evaluated, hot-section materials were found to have the greatest influence on operating cost, as shown in Fig. 11. Ceramics contribute nearly 60% of the total DOC improvement for the rotorcraft, commuter, and APU applications. The use of ceramics in these engines influences performance, weight, size, and cost. Ceramics substantially improve performance (SFC) by allowing higher turbine inlet temperatures while minimizing cooling flows. Specific fuel consumption is particularly sensitive to turbine cooling flow.

A high TRIT not only improves cycle efficiency; it also increases engine-specific power, which results in reduced size and weight. Weight is further reduced by ceramics because of its lower material density. The cost of ceramics, compared to exotic high-temperature metals, is also lower.

Additionally, the use of ceramics in the combustor and recuperator contribute approximately 10 and 35%, respectively, to the overall reduction in operating costs. Ceramics reduced the cooling requirements in the combustor, thereby allowing more air to be used for dilution to control exit hot spots (higher TRIT's possible). In recuperators, ceramics also provide additional temperature capability; however, their greatest contribution comes from reducing the weight of this component. Recuperator weight can be reduced by approximately 50% with ceramics, compared to a metallic configuration.

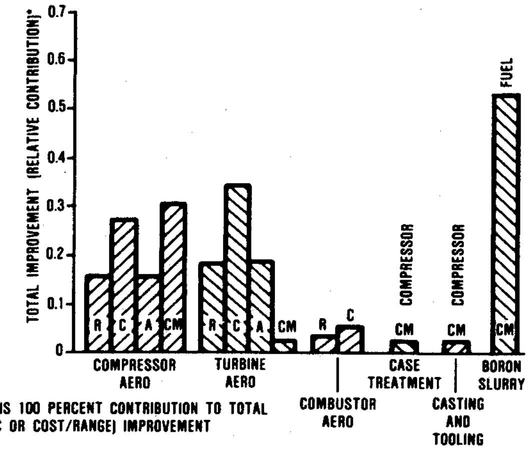


Fig. 12 Relative contribution from aerodynamic and combustion technologies.

The greatest single improvement from materials results from the use of C-C in the cruise missile hot section. Like ceramics, C-C is required in order to significantly improve engine performance, weight, size, and cost. Carbon-carbon allows for high-temperature, uncooled hot-section components (for increased specific thrust), which results in reduced engine size and weight. Carbon-carbon also has improved mechanical capabilities, allowing for increased shaft rotational speeds, which directly results in reduced compressor diameter and/or stage count.

Ni_3Al for turbine disks also was found to have a significant impact on DOC for the rotorcraft simple cycle. Without Ni_3Al turbine disks, the reduced hub speed capability reduces efficiencies and/or increases turbine stage count, thereby affecting performance, weight, size, and cost. Unlike the simple-cycle engines, Ni_3Al did not reduce operating costs for the recuperated engine. This is attributed to the much lower aerodynamic loading levels in the HP turbine. The lower acceptable blade and disk speeds associated with this lightly loaded turbine are within the capabilities of current materials.

Cold-section materials had a smaller influence on operating cost, with the exception of Ti_3Al for the cruise missile. For the compressor, Ti_3Al provided a significant unit cost improvement in the cruise missile application. Replacing Ti_3Al with a currently available material limits the achievable compressor discharge temperature. This results in greatly reduced cycle pressure ratio, therefore penalizing TSFC and reducing missile range.

Compressor and turbine efficiency improvements show significant operating cost improvements (Fig. 12). Specifically, relative improvements, ranging from 20 to 30%, are available from aerodynamic technologies in compressors and turbines. Combustor technologies that reduce pressure drop result in only small improvements in DOC. The improved efficiencies of these components not only influence fuel consumption directly; they also have a secondary effect on size and weight through increased specific power.

The use of slurry fuels was also addressed for the cruise missile application. As shown, approximately half the overall cost/range improvement for the missile can be attributed to boron slurry. The higher heating value per volume of boron greatly increases the range of this volume-limited application.

Conclusions

The SECT studies have identified a number of key technology areas for each of the four applications. Consistent with the past in the gas turbine industry, materials are expected to be the key drivers in improving performance for the year 2000. This is particularly true for small engines, where manufacturing limitations result in relatively greater cycle inefficiencies, and where the market is more sensitive to size, weight, and cost.

Hot-section materials such as ceramics and C-C will be vital to advanced engines by minimizing the penalties inherent in small gas turbines. These materials will allow higher TRIT's, which will reduce size and weight and will eliminate cooled airfoils, thereby reducing cost and improvement performance. Additional cost and weight savings will be realized by the elimination of exotic high-temperature metals. Although ceramics and C-C currently receive some funding, significantly more support and directed effort are required to address the special challenges related to small engine components and configurations.

Similar challenges also exist in other technology areas. Component performance will be improved by aerodynamic advancements through an increased understanding of losses and by improved analytical tools.

System technologies such as MMC shafts and high-temperature seals and bearings will be necessary to meet the mechanical requirements of year-2000 small engines.

Heat-recovery devices such as recuperators and regenerators are also expected to play an important role by the year 2000. Through the use of advanced materials (ceramics), heat-recovery engines will be competitive with more conventional simple cycles at lower fuel prices ($1/gal). They will show a definite advantage if fuel prices are higher ($2/gal).

The SECT studies have identified and outlined the support necessary to advance these high-payoff technologies for inclusion in year-2000 small gas turbines. Many of the long-lead-time technologies require immediate support to meet the year-2000 target date.

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