NASA/CR—2003-212519

Small Engine Technology Investigation

Brent B. Gregory
GE Aircraft Engines, Lynn, Massachusetts

August 2003

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Prepared under Contract NAS3–CR–26617, Task Order 47

National Aeronautics and
Space Administration

Glenn Research Center

August 2003

Document History

This research was originally published internally as AST21, in January 27, 1998.

Note that at the time of research, the NASA Lewis Research Center was undergoing a name change to the NASA John H. Glenn Research Center at Lewis Field. Both names may appear in this report.

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1.0 SUMMARY

The Regional Aircraft Propulsion Technology (RAPT) Investigation is a segment of the NASA Advanced Subsonic Technology (AST) initiative being worked under contract NASA CR-26617 - Task Order #47. The AST initiative was undertaken by NASA working closely with industry to improve engine and vehicle performance and to lower direct operating costs (DOC). The Regional Engine Investigation concentrates on engines used in regional applications with the intent of identifying technology for development for subsequent introduction into future designs.

1.1 PROGRAM SCHEDULE

The Regional Aircraft Propulsion Technology (RAPT) Program is divided into nine tasks. These tasks are described as follows: Task 1, establish the overall goals of the effort, Task 2, define the performance baseline for the two regional study aircraft, Task 3, define the figure of merit, Task 4, establish the baseline performance and performance sensitivities, Task 5, identify the component technologies and estimate the benefits and development costs for the technologies, Task 6, translate the component improvements into their impact on the aircraft economics and evaluate the figure of merit for the various candidate technologies, Task 7, rank the technologies, Task 8, deleted, and Task 9, provide NASA with analysis data. The program schedule illustrated in Figure 1-1 was established at the beginning of the program.

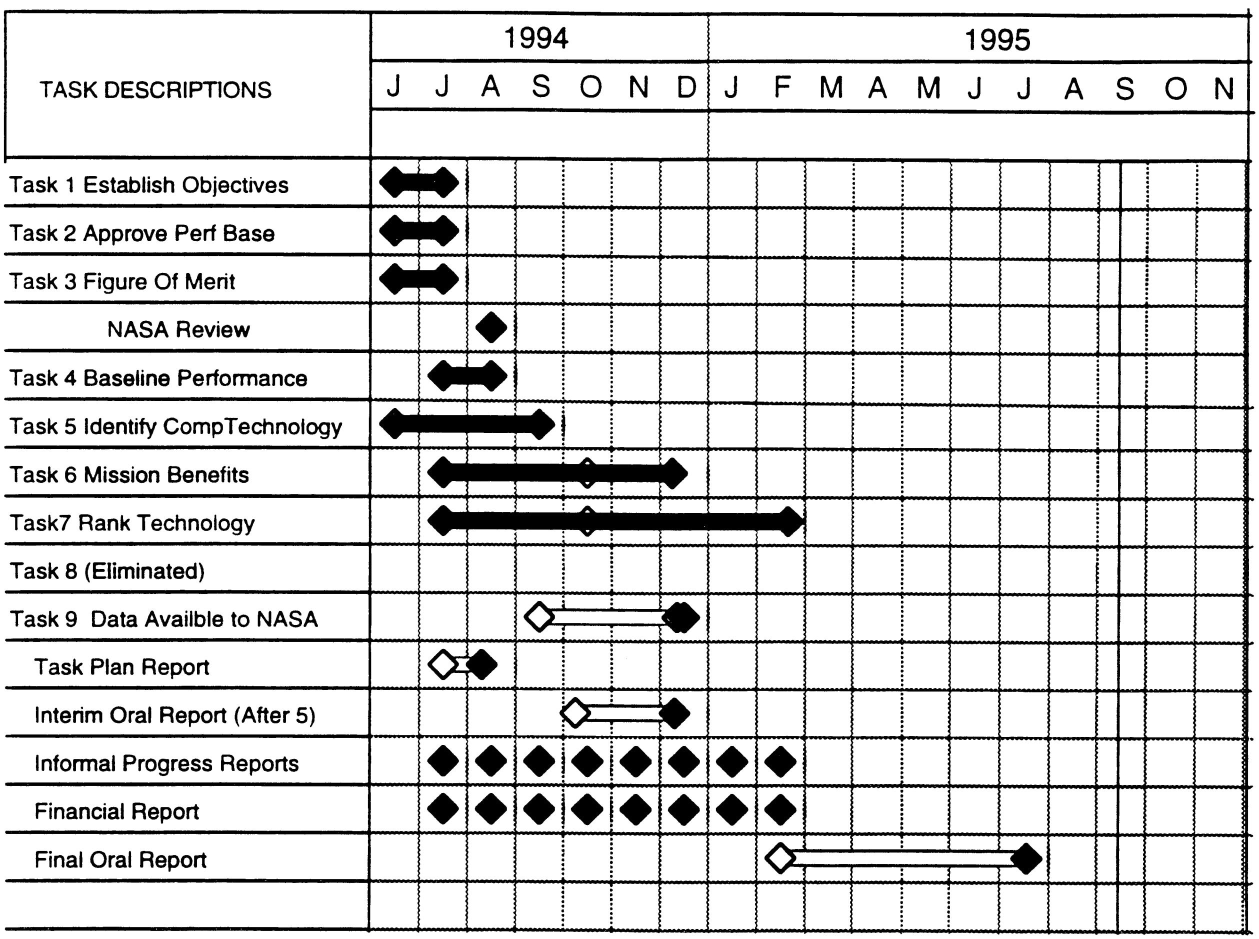


Figure 1-1. Program Schedule For Regional Aircraft Propulsion Technology Investigation.

1.2 OBJECTIVES AND SCOPE OF THE WORK

The primary objective of the Regional Aircraft Propulsion Technology study task was to identify key, enabling jet engine component technologies for improved economic benefits to the airlines, primarily for commercial, regional subsonic aircraft. The study goal is to identify those key technologies required for advanced regional engines for the year 2005 entry-into-service (EIS) and to identify near term technology developments which may be incorporated into existing or new engine designs entering service prior and up to the year 2005 (regional engines are defined as engines 5,000 shaft horsepower or less for turboshaft engines, and 20,000 pounds of thrust or less for turbofan engines).

The regional gas turbine engine design requires very separate technical solutions from those applied to large engines. The most significant differences derive from distinct operational requirements and restrictive engine size. Typical small engine missions, which are low cruise altitudes and short block or cyclic times, greatly influence the architecture of small engine design. The size issue is characterized by the high density mechanical design requirements which challenge the classical concepts of the engine scaleability and generic producibility relationships.

Therefore, the technologies evaluated reflect the regional engine requirements and the regional airline economics which differ from the longer range airline economics and the large engine requirements.

1.3 OVERVIEW OF RESULTS OBTAINED FROM THE STUDIES

The studies involved two regional applications, the CF34 turbofan engine installed on the Canadair Regional Jet (RJ) and the CT7-9B turboprop engine installed on the Saab SF340B aircraft. The results consist of comparisons of technologies recommended for consideration by a team of specialists from the engineering sections working these two product lines and various other engine programs within the small engine department. The recommendations are based on current and future technical requirements, production needs, and customer needs.

The results of the comparative studies show that the largest impact on airline economics requires considering technology improvements that would enable the aircraft to increase the revenue potential, such as added seats, in addition to reducing the direct operating costs. This is largely a result of the fact that fuel costs and overall engine costs contribute about 28% to the turboprop regional aircraft DOC, and for the turbofan, the engine related expenses are approximately 36% of the overall DOC. For comparison the larger aircraft with longer range missions (3,000 NM), the engine related costs, which include the fuel burn, are more like 55% of the total direct operating costs. Therefore, for this study the overall economic benefits include evaluating increased revenue potential (added seats), in addition to the direct operating costs. Thus the total economic picture was considered in assessing the technologies.

The study indicated that improvements in the direct operating costs, which are more easily quantified, are driven strongly by sell price, specific fuel consumption (sfc), and maintenance cost and represent less than half of the airline operating economics. Airline revenue is also another significant contributor that should be considered.

Increased utilization and increased passenger capacity are two ways to achieve increased revenue and are strongly influenced by power and SFC, and often site specific. Combining both direct operating costs and the potential for increasing revenue completes the economic picture and allows for a complete evaluation of the technologies being assessed.

The evaluation and comparison of the various technology categories was based on a factor of merit (FOM) involving the economic benefits, the probability of success and the development costs. The FOM indicated the relative payback for the development cost to be expended.

1.4 PRINCIPAL CONCLUSIONS REACHED

During the course of the program, a preliminary ranking indicated that the three technology groupings that would give the best payback were: A) an aircraft engine integrated controls system development program, B) a 3-D turbine aero design and test development program and C) a high pressure turbine clearance control and performance retention program. The final ranking has supported the initial results.

A Factor Of Merit (FOM) based on sfc was calculated for the initial comparative look at ranking. The FOM ranking for turboprop performance benefits is based on the percent improvement in sfc times the probability of achievement divided by the development evaluation costs associated with that technology item. Table 1-1 shows the performance ranking and the units are reported in percent sfc improvement per million dollars development cost.

Table 1-1. Performance Ranking.

Turboprop Technology Item	% Delta sfc/$M
Controls And Accessories	0.351
Integrated 3-D Turbine Aero Design	0.267
HPT Turbine Clearance Control	0.084
Compressor Performance Improvement	0.129
Extended Capability Impeller	0.118
Turbine Leakage And Cooling Air	0.104
Mechanical Systems	0.086
Materials	0.054
Design/Manufacturing LCC Reductions	0.044
Exhaust Systems Design	0.040
Engine Starting Systems	0.014
Inlet System Design For turboprops	0.012

A comparison of the estimated development costs and the sfc improvement potential associated with the investment in the technology for the turboprop technology illustrated in Table 1-1 is illustrated in Figure 1-2. The plot shows that in order to achieve a larger economic benefit, a larger development cost will be required. However, from the plot in Figure 1-2, it can be seen that there is a spread and that by selecting the projects on the lower side of the band, more economic benefit for each dollar spent in development can be achieved. This band or spread is related to the slope of the curve which corresponds to the performance ranking illustrated in Table 1-1 where each data point is from the turboprop sfc ranking in that table. An improvement in SFC reduces DOC by requiring less fuel for a specific mission. The improvement in range which is another benefit of improved SFC does not impact DOC.

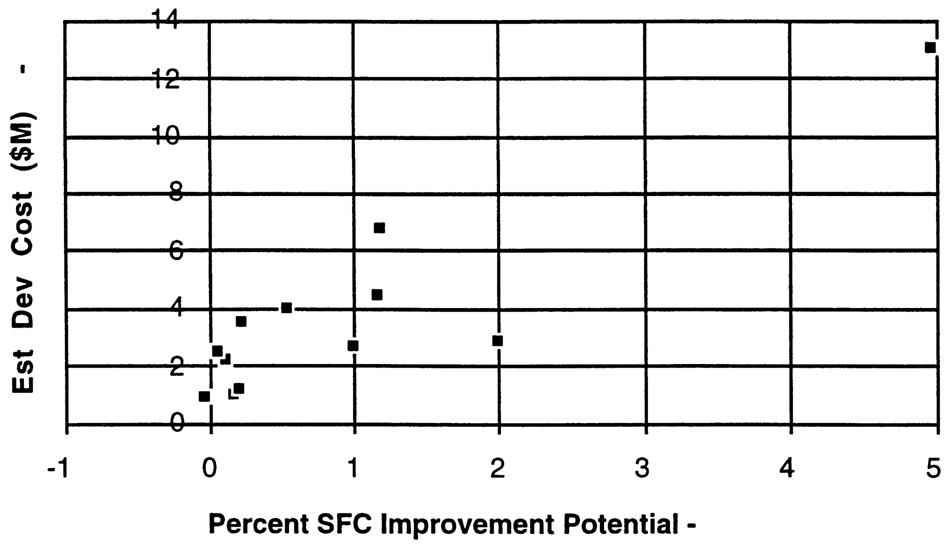


Figure 1-2. Estimated Development Cost ($M) Versus SFC.

2.0 INTRODUCTION

This introduction to the Regional Aircraft Propulsion Technology (RAPT) investigation program describes the background, and gives the definition of the engines and processes used for the technology assessments. This program is in support of the NASA Advanced Subsonic Technology (AST) Initiative that is being worked with industry to define technology requirements of advanced engines and to identify engine technology to improve engine efficiency and lower operating costs to the airlines.

2.1 BACKGROUND THAT PRECEDED AND LED TO THIS WORK

NASA began the AST Initiative to improve both the engine and vehicle performances and lower the airlines' direct operating costs (DOC). In this initiative, NASA is working closely with the aircraft industry using engines and technology being certified today as the baseline. The general program goals include reducing engine fuel burned and reducing the direct operating costs to the airlines. The program is divided into two categories: large engines with (3000 NM)long range applications, and small engines in regional applications. The engines used in regional applications are defined as less than 20,000 pounds of thrust for turbofan engines and 5,000 shp or less for turboprop engines. The missions and cruise legs for the regional applications are substantially shorter than for the large engines. Turboprop applications are represented by a 200 NM cruise sector and turbofans by a 600 NM cruise sector.

2.2 RECOGNITION OF SIMILAR WORK

NASA and GEAE have a traditional relationship of cooperation in both large and regional engine research, resulting in substantial technical progress in the propulsion field. The Lynn family of engines covers a broad spectrum of turboshaft and turboprop engines up to 5,000 shp and turbofan engines with future potential of up to 20,000 pounds of thrust.

Many of the engines evolved directly from government sponsored demonstrators into commercial and military applications. Examples are shown in Table 2-1, such as the commercial turboprop (CT7) and the high bypass turbofan (CFE738). The more recent JTAGG demonstrator will follow the same course. Maintaining pace with the expected growth in the commercial small engine market, this process of improvement will continue using the results from such programs as the Advanced Subsonic Technology Program (AST), Internal Research and Development (IR&D), and the Integrated High Performance Turbine Engine Technology Program (IHPTET).

Table 2-1. Regional Engines.

Configuration	Model	Today	Future
Turboprop/Turboshaft	T700/CT7	2,000 shp	3,000 shp
Turboprop	GLC38	5,000 shp	6,000 shp
Turbofan	CFE738	5,600 lb	7,000 lb
Turbofan	CF34	8,700 lb	13,000 lb
Turboprop/Turboshaft	CM42		3,000 shp class

2.3 THE SCOPE OF CURRENT WORK

The present task of the RAPT investigation is to identify technology for regional applications, to determine their economic benefits, and to rank them for the best payback for the investment required to develop the technology. A determination as to the highest ranking technology categories will be made.

2.4 RELEVANCE OF THE MATERIAL REPORTED TO THE GENERAL FIELD

The effort/tasks in this program are distinct from the large engine technology in that they address the needs and development necessary to carry the small commercial engine development into the 21st century. Increasing pressure ratio cycles require more precise control of mechanical parameters to avoid increase parasitic losses due to the high operating pressures. These high operating pressures can result in increased internal and external leakage, which are disproportionately large to the engine cycles due to the small size.

Also for the axicentrifugal compressor configuration, the impeller is driven to higher thermal gradients and life considerations at the high operating pressure ratio must be addressed. However, the ranking procedure used in this program does not result in a high ranking factor for this parameter. None the less, the development of increased life impellers is critical for future small engines. Improved impeller capability is being addressed with development of a dual titanium alloy material system in other programs.

The size and power of the regional engines are "boxed" in and the primary technologies needed for this size of engines is the need for obtaining more power (increase the specific power) in the same size package and improved fuel consumption.

2.5 PURPOSE OF THIS EFFORT

This initiative was undertaken to prepare and develop technologies for applications of regional airline equipment that will be entering into revenue service in the time frame of the year 2005.

2.6 THE PROCEDURE USED

The procedure used to analyze the technologies is as follows: a figure of merit was defined that combines the economic benefits to the airline with engine technology and development costs of launching the new technology:

$$\text{e.g., Ranking Factor} = \frac{\text{Present Worth x Probability of Success}}{\text{Total Costs}}$$

Current aircraft performance data was used for the SF340B (turboprop) and for the Canadair Regional Jet (turbofan) for this study. Sensitivities to engine efficiencies, weight, and cost were determined by analyzing each aircraft mission and determining fuel burned and aircraft DOC. For these two baseline engines, the contribution of each component improvement and changes within each of the technology categories that affect the overall airline economics were determined.

Identification of small engine technologies which had good prospects for improving small engine economics were defined by a team established from each of the engineering system groups supporting the small regional engines. The individual component improvements were translated into their impact on the aircraft economics using the sensitivities developed for each of the two applications. The figure of merit was then used for evaluation and ranking of the candidate technology groupings.

2.6.1 Technical Approach

The technical approach to this program was to define the following:

- The most promising concepts employing advanced component technology for a near term propulsion system with a technology availability date of 2005. Also, to define a far term system with an availability date of 2005 EIS if the market conditions dictate the need.
- The benefits of introducing emergent technologies into current product lines.
- The achievable cost effective levels of direct operating costs and fuel burn savings.
- The relative benefits of emergent technology using an evaluation process which considers value to current fleet economics, probability of success and costs to develop and implement.

2.6.2 Baseline Engines

GEAE is in a unique position having both small turboprop and turbofan engines recently introduced into the commercial regional market. These two types of regional airline applications listed below make good candidates for this study program and both have been selected for evaluation on this study:

A) The CF34-3A1 turbofan engine started revenue service in the Canadair RJ in November 1992.

B) The turboprop base engine is the CT7-9B engine. This engine currently powers the SAAB SF340B aircraft.

2.6.3 Aircraft And Missions

The two aircraft being used in this evaluation are the Canadair RJ and the SAAB SF340B. The Canadair RJ is a 50 passenger regional jet based on the successful Canadair Challenger CL601 business jet. This aircraft and engine have the distinction of being the quietest twin engine jet in revenue service. Growth versions of this aircraft are envisioned that will require significant increases in thrust. A representative flight profile for this application is described in Table 2-2.

Table 2-2. Canadair RJ With CF34-3A1 (600 NM Cruise Sector, ISA).

Mission Leg	Comment
Start-up and Taxi	Time and fuel allowance for 4 minutes at Ground Idle, 0.1 Mach, SL
Takeoff	Time and fuel allowance for 1 minute at Takeoff rated thrust, 0.2 Mach, SL
Climb	Climb to the climb ceiling, Max Cruise Mach
Cruise	Cruise at the climb ceiling, Max Cruise Mach
Descend	Descend to sea level, Mach =0.7
Approach	Time and fuel allowance for 2 minutes at 0.3 Mach, SL
Landing and Taxi	Time and allowance for 3 minutes at Ground Idle, SL
Reserve	Fuel required for 100 NM diversion plus 45 minutes holding

The SAAB SF340B is a 34 passenger aircraft that entered revenue service in 1990. This aircraft is considered by many to be the quintessential regional turboprop aircraft. As with the RJ, a high speed growth variant of this aircraft is envisioned that will require a significant increase in shaft horse power. Again, as with the RJ, the engine to power this growth aircraft shall have good fuel burn, low cost, low noise and shall be easy to maintain. A representative flight profile for this turboprop application is described in Table 2-3.

Table 2-3. SAAB SF340B With CT7-9B (200 NM Cruise Sector, ISA).

Mission Leg	Comment
Start-up and Taxi	Time and fuel allowance for 4 minutes at Ground Idle, 0.1 Mach, SL
Takeoff	Time and fuel allowance for 1 minute at Takeoff power, 0.2 Mach, SL
Climb	Climb at Max climb rated power to optimum cruise altitude
Cruise	Cruise at 15K altitude at maximum cruise speed
Descend	Descend to sea level
Approach	Time and fuel allowance for 2 minutes at 0.3 Mach, SL
Landing and Taxi	Time and fuel allowance for 3 minutes at Ground Idle, SL
Reserve	Fuel required for 100 NM diversion plus 45 minutes holding

3.0 TECHNOLOGY IDENTIFICATION

Emergent technologies for small gas turbine engines utilized in regional airline applications are needed for aircraft growth versions of the two regional aircraft selected for evaluation in this program. The growth versions will require significant thrust increases and they must be accomplished with good fuel burn and other favorable economic factors.

The identification of the technologies needed should reflect the needs of the customer, the technical requirements and the productions needs. In order to obtain input and identify those technologies, a team of specialists was created that represented each of the current and mature regional size products manufactured by GEAE in Lynn, Massachusetts. These specialists identified the technology needs of current production engines future needs. See Figure 3-1 for a schematic of the team and process.

3.1 PROCESS

An evaluation team was set up with specialists from each of the product systems engineering sections in order to obtain direct input of technical and customer needs for each product line. Technology evaluation and system analyses were conducted to define the following:

1. The most promising concepts employing advanced component technology for a near term propulsion system with a technology availability date of 2005
2. The benefits of introducing the emergent technologies into current product lines
3. The achievable effects of those technologies
4. The relative benefits of the emergent technology using as an evaluation process which considers value to current fleet economics, probability of success and costs to implement

Various study cases were established to evaluate the technology impact for current and near term application. Table 3-1 shows the study cases considered.

Table 3-1. Study Cases For RAPT Program.

Source	Baseline		Task Study	
	Engine	Aircraft	Engine	Aircraft
Initial Task	CT7-9 CF34-3A1	SF340 Canadair-RJ	CT7-9 Plus CF34-3A Plus	SF340 Canadair-RJ
GEAE Added Study CF34-3A1	CT7-9 Canadair-RJ	SF340 CF34-3A Plus	CT7-9 Plus Next	Next Generation Generation
Growth engines	CT7-9 CF34-3A1	SF340 Canadair-RJ	CT7-11, 2005 CF34-8C, 2005	Derivative Derivative

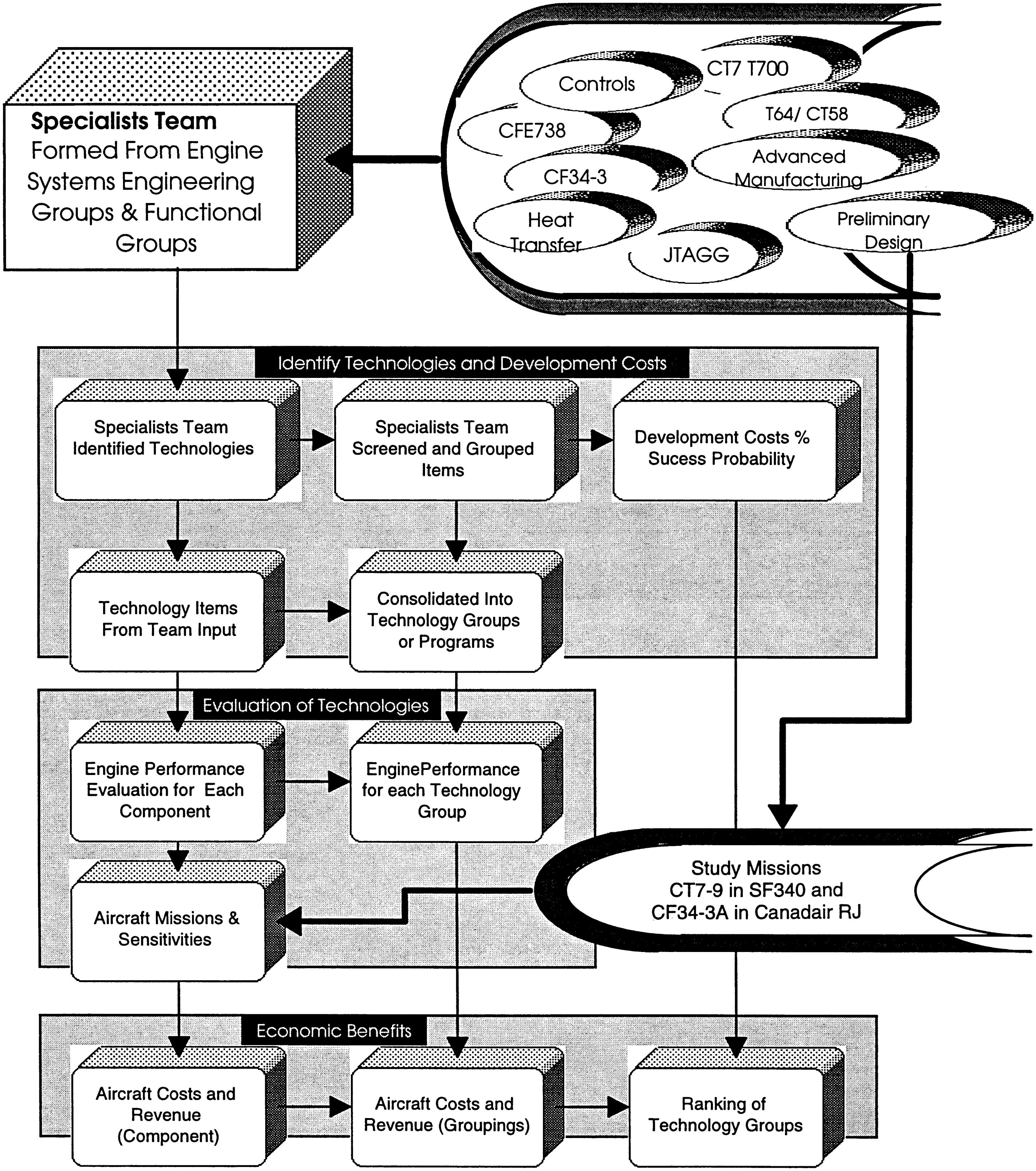


Figure 3-1. Technology Team of Specialists for Study and Ranking.

The technology items recommended for consideration by the team of specialists numbered 117. These reflected items needed for growth and both customer concerns and production concerns. The number of items were considered too numerous to compare and rank individually. Many of the items were related either in function or by virtue of being in the same component of the engine. The team met and screened the items and grouped them into categories in order to more easily evaluate them. The end result was twelve groupings of technology categories to study and review.

3.2 LISTING OF ITEMS

The candidate list of items recommended by the team is listed in Appendix A. These items are the direct input before being consolidated into the various technology groupings.

3.3 CONSOLIDATION OF ITEMS

The team members screened and grouped the technology items into the categories as listed in Appendix B. Included in the listing is the economic benefit and the estimated rough order of magnitude (ROM) development cost.

3.4 COSTS AND ECONOMIC BENEFITS

The development costs of each of the technology items have been estimated as the development costs to design, analyze, and/or test the concept on an engine or rig. The economic benefits are the performance improvements or other economic factors for the items. The costs and economic benefits of the items are shown in Appendix B.

4.0 ENGINE CYCLES

GEAE is in the position of having extensive experience in small engine technology and an understanding of the critical mission needs from applications such as the CF34 Canadair Regional Jet and the CT7 SAAB Turboprop. The CF34 turbofan began service in the 50 passenger Canadair Regional Jet in November of 1992 and has the distinction of being the quietest engine in revenue service. The turboprop CT7 powers the 34 passenger SF340B, began revenue service in 1990 and is considered as the quintessence of turboprop aircraft. These two engines have been selected as the baseline engines for this technology evaluation. Both of these two engines will need power upgrades with better fuel efficiencies to satisfy future operational requirements, as illustrated in Figure 4-1 (CF34 Turbofan Development) and Figure 4-2 (CT7 Turboprop and Turboshaft Development).

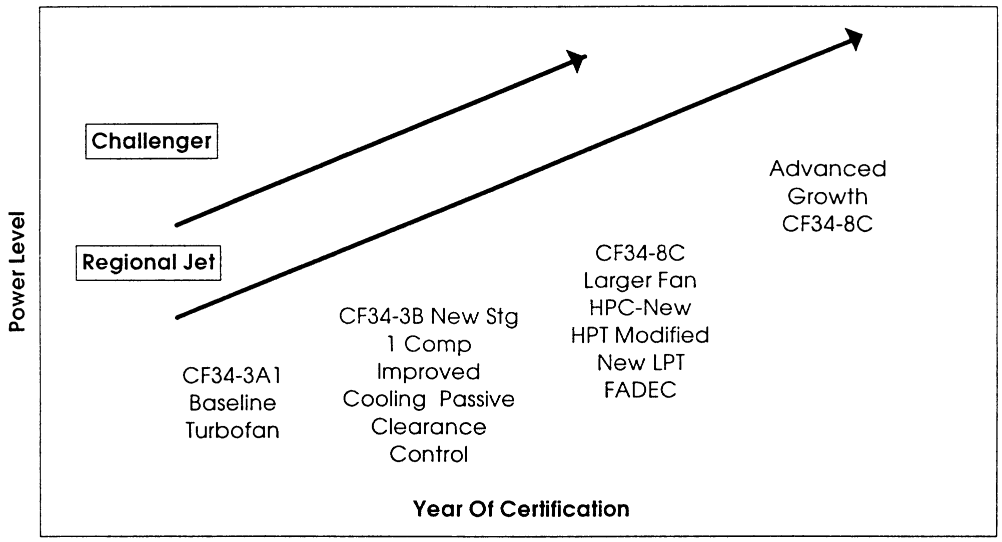


Figure 4-1. CF34 Turbofan Development.

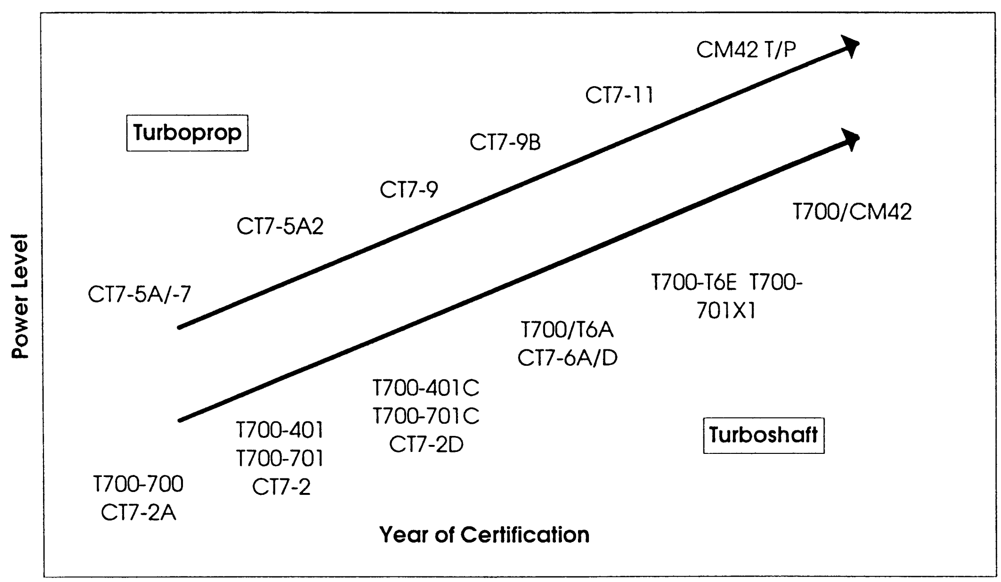


Figure 4-2. CT7 Turboprop And Turboshaft Development.

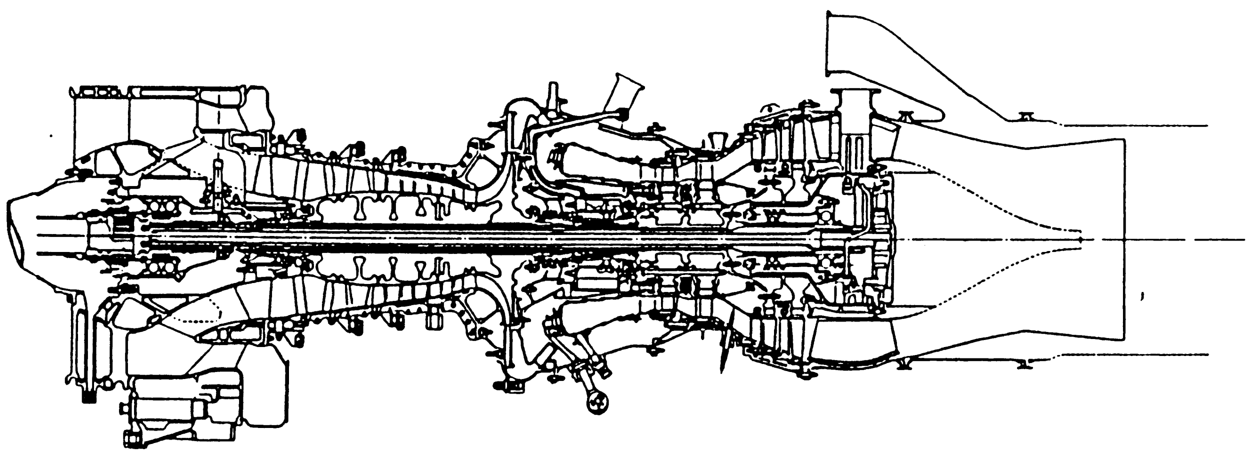
4.1 TURBOPROP BASELINE CYCLE AND ENGINE DESCRIPTION

The CT7-9B is a turboprop engine in commercial service that was derived from the T700 turboshaft military engine. It is an 18 to 1 pressure ratio engine cycle with an inlet airflow of approximately 11 pounds per second, and is in the 1,800 shp class powering the SAAB SF340B, the CASA CN-235, and the LET L610 aircraft.

4.1.1 Engine Description

The CT7 turboprop engine is a prop configuration driven by turbomachinery consisting of an axial-centrifugal compressor, a centrifugal diffuser, an annular combustor, a cooled gas generator turbine (high pressure turbine), an uncooled power turbine and an axial inlet particle separator (see Figure 4-3). The axial centrifugal compressor consists of five axial stages and a single stage centrifugal. The gas generator turbine is a two-stage air-cooled high-pressure turbine and the power turbine is a two-stage turbine. The exhaust frame is a deswirl vane configuration with multiple ejectors. The first ejector is configured to pull nacelle air through the power turbine impingement baffle for cooling the power turbine casing. A second ejector is configured to pull in air through the axial inlet particle separator. The inlet particle separator is integral to the engine and is in place for Foreign Object Damage (FOD) protection. The third ejector provides bay cooling.

1800 SHP Class



- W2R = 11.0 pps
- Compressor P/P = 18.0
- 100% Power Turbine Speed = 22,000 rpm

Figure 4-3. The Baseline CT7-9B Turboprop Engine.

4.1.2 Cycle Characteristics

The CT7-9B is in the 1800 shp class with an inlet airflow of 11 pounds per second (pps) and an overall compressor ratio of approximately 18. The CT7-9B engine performance, which has been used as the baseline for the technology studies for the turboprop engine, is quoted at Sea Level Static Takeoff (SLS) and at Maximum Cruise (25K/240 kt/ ISA). Figure 4-4 compares the cycle pressure ratio to other engines.

CT7s Operate At Competitive Cycle Pressure Ratios.

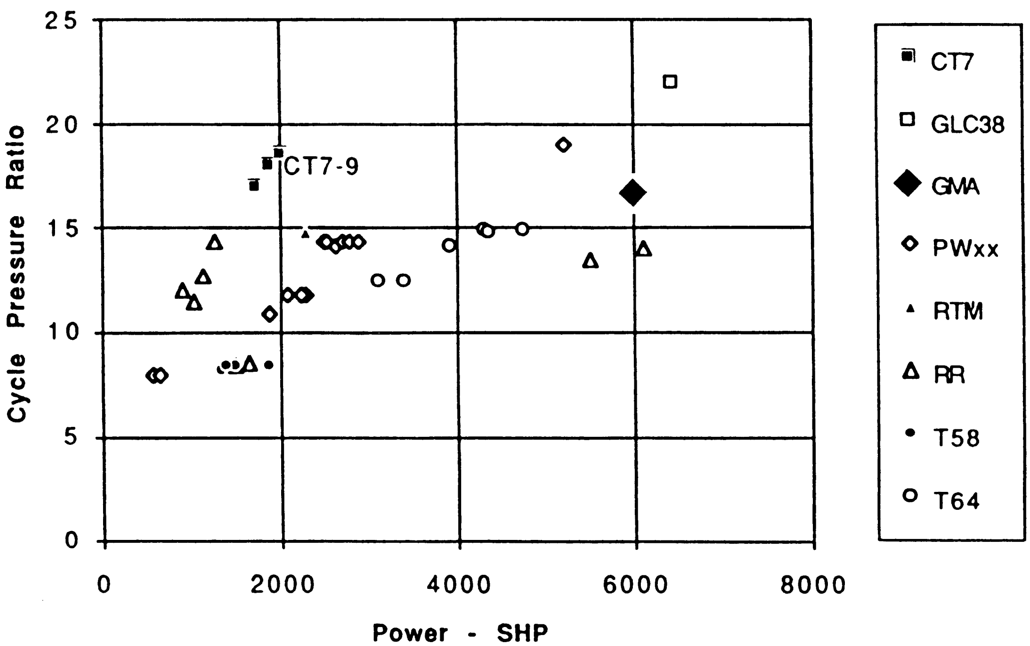


Figure 4-4. CT7-9 Cycle Pressure Ratio Compared With Other Engines.

4.1.3 Performance Benefits Of Technologies

The performance benefits listed and ranked in Paragraph 1.3 were analyzed for this engine cycle with the following assumptions :

- The engine configuration is fixed, however, the turbine nozzle flow functions were modified to maintain stall margin.
- Performance derivatives were generated at a constant turbine rotor inlet temperature (T41) to calculate overall benefits in terms of power and sfc.
- Performance effects of individual technology items were evaluated at typical cruise conditions and the impact was extrapolated across the mission envelope for the mission evaluation effects reported in the next sections.

The performance benefits for the various components are tabulated in Table 4-1.

4.1.4 Projected Cycle For 2005

At the Interim Oral Presentation at NASA Lewis (December 12,1994), GEAE was asked to expand the evaluation of the performance benefits of the technologies identified and evaluated for current product applications to future advanced engines that would be entered into service by the year 2005.
A full study and evaluation of the 2005 engines were originally proposed in Task #8 as a baseline to study a far term propulsion systems, but that task was agreed to be deleted by both NASA and GEAE for program costs reduction. The NASA/GEAE agreement was to do technology ranking on the most current applications, which are the Canadair RJ powered by the CF34-3A1,which entered into revenue service in 1992, and the SAAB 340 a 34 passenger regional turboprop.

Table 4-1. Turboprop Performance Benefits For Component Assessments.

25K/240 kt/ISA - Max Cruise

Component	Technology Improvement	%ΔESFC	%ΔESHP
Inlet ΔP/P	-0.002	-0.1%	+0.3%
Compressor η	+1.3 pt	-1.1	+1.9
Compressor P/P	+0.5%	-0.1	+0.0
HP Turbine η	+3.1 pt	-3.2	+3.4
Interturbine Duct ΔP/P	-0.004	-0.2	+0.0
Power Turbine η	+1.4 pt	-1.5	+1.6
Exhaust Duct ΔP/P	-2.2%	-1.2	+1.2
Cooling Air %W2	-3.6%	-1.2	+5.4

In response to this discussion, benefits for these future applications were evaluated by the way of cycle derivatives and it was determined that the benefits are similar or slightly better than the benefits available to current product engines.

The cycle used for the advanced engine evaluation was the CT7-11 which is currently under development at GEAE in Lynn, Massachusetts. Incorporation of the technology items into this engine could be accomplished in the time frame of 2005.

The turbofan engine cycle was presented at the NASA Lewis Interim Oral Presentation in December 1994 and the CT7-11 engine cycle is presented in this report for information. The improvements in the CT7-11 over the current product (CT7-9B) include a new axial Inlet Particle Separator (IPS), a new compressor design (axial flowpath flared, incorporation of centrifugal impeller aerodynamics, and a total new aero flowpath), a flared power turbine (same inlet area, opened up exit area, new blading), and optimized exhaust area for takeoff and cruise performance. The CT7-11 probable engine configuration is illustrated in Figure 4-5.

The technology improvements evaluated for the CT7-9B were also evaluated for the advanced cycle, which, with the improvements could be ready for entry into service by the year 2005. The performance benefits were equal to or better than the improvements that could be achieved on the current CT7-9B product. The results are tabulated in Table 4-2.

4.2 TURBOFAN BASELINE CYCLE AND ENGINE DESCRIPTION

The CF34 turbofan engine commercial service was derived from the military TF34 turbofan engine. It is a 19-to-1 pressure ratio engine cycle with the inlet airflow of approximately 317 pounds per second.

Advanced CT7-11 Turboprop Engine Updated With Technology Improvements

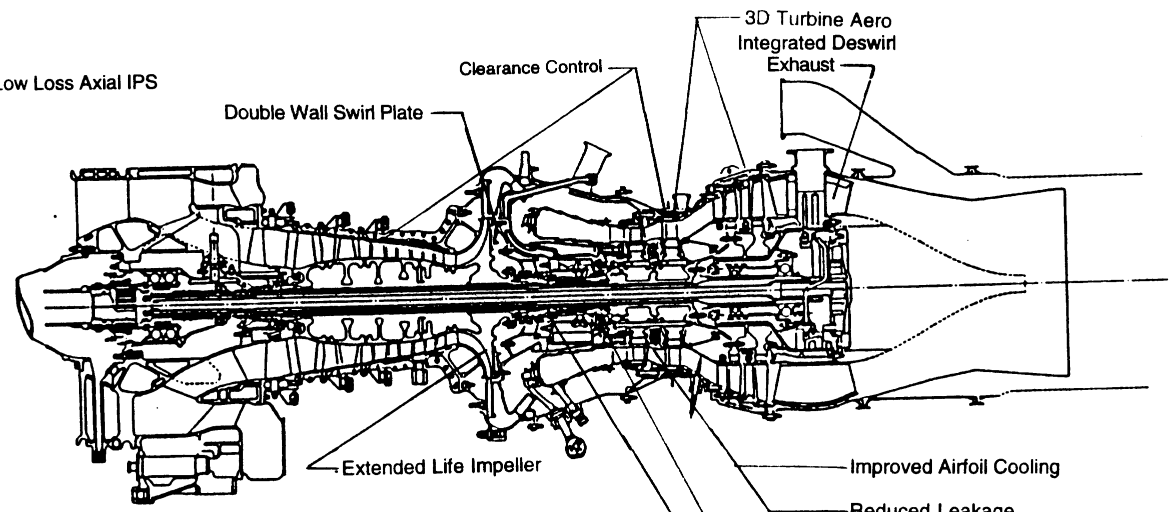


Figure 4-5. The CT7-11 With Technology Improvements.

Table 4-2. Turboprop Performance Benefits for Component Assessments. CT7-9B Versus CT7-11 25K/240 kt/ISA - Max Cruise (Constant T41)

Component	Technology Improvement	CT7-9B Baseline %ΔESFC	CT7-9B Baseline %ΔESHP	CT7-11 Advanced %ΔESFC	CT7-11 Advanced %ΔESHP
Inlet ΔP/P	-0.002	-0.1	+0.3	-0.1	+0.3
Compressor η	+1.3 pt	-1.1	+1.9	-1.3	+2.1
Compressor P/P	+0.5%	-0.1	+0.0	-0.1	+0.0
HP Turbine η	+3.1 pt	-3.2	+3.4	-3.9	+4.0
Interturbine Duct ΔP/P	-0.004	-0.2	+0.2	-0.2	+0.2
Power Turbine η	+1.4 pt	-1.5	+1.6	-1.5	+1.5
Exhaust Duct ΔP/P	-2.2%	-1,2	+1.2	-1.2	+1.3
Cooling Air %W2	-3.6%	-1.2	+5.4	-2.0	+6.2

4.2.1 Engine Description

The CF34-3A1 is a high bypass turbofan engine consisting of a high bypass single stage fan, an axial flow 14 stage compressor with variable stages, an annular combustor, a two stage cooled high pressure turbine, a four stage uncooled low pressure turbine and a fixed convergent exhaust nozzle, as illustrated in Figure 4-6.

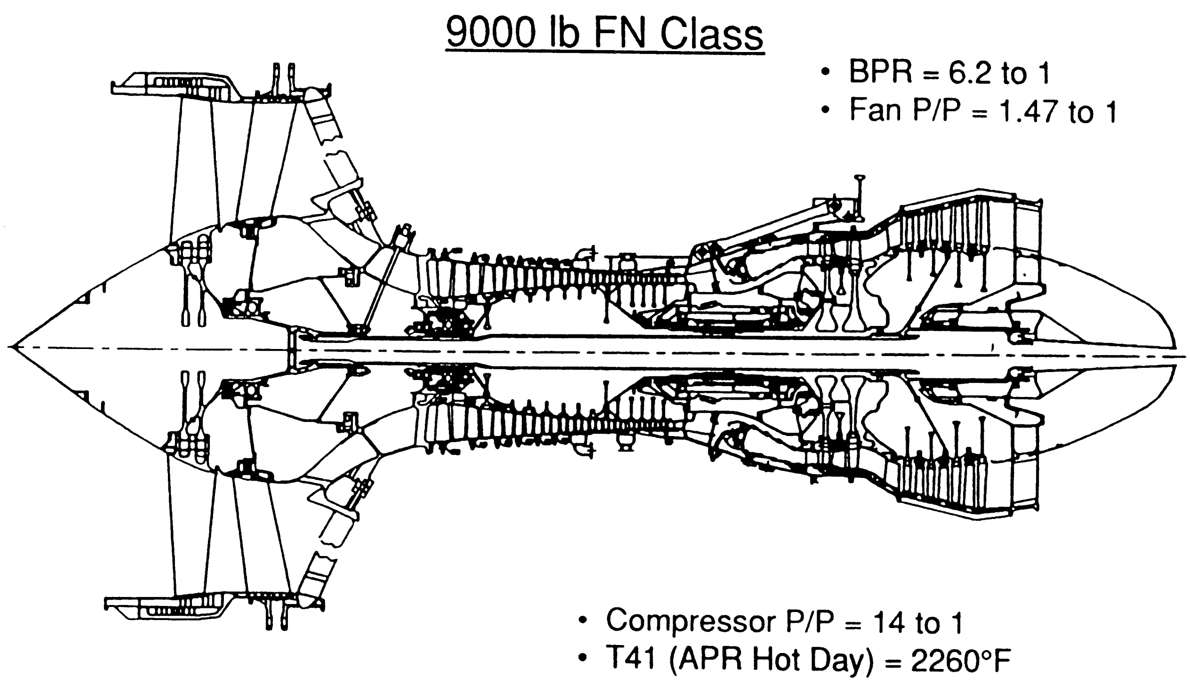


Figure 4-6. The Baseline CF34-3A1 Turbofan.

4.2.2 Cycle Characteristics

The CF34-3A1 is in the 9000 pound thrust class with an inlet airflow of 317 pounds per second (pps), a bypass ratio (BPR) of 6.2 to 1, and an overall cycle pressure ratio of approximately 19 to 1. The baseline engine performance, which will be used as the baseline for the technology studies for the turbofan engine, is quoted at sea level static takeoff (SLS) and at Maximum Cruise (35K/0.8 MN/ ISA).

4.2.3 Performance Benefits Of Technologies

The performance benefits for the component assessments were analyzed for the turbofan engine cycle with the following assumptions:

a) The engine configuration is fixed, however, the turbine nozzle flow functions were modified to maintain stall margin.

b) Performance derivatives were generated at a constant turbine rotor inlet temperature (T41) to calculate overall benefits in terms of change in thrust and sfc.

c) Performance effects of individual technology items were evaluated at typical cruise conditions and the impact was extrapolated across the mission envelope for the mission evaluation effects reported in the next sections.

The performance benefits for the various components which would result from the technology programs for the current CF34-3A1 product engine are tabulated in Table 4-3.

Table 4-3. Turbofan Performance Benefit Results For Components.
35K/0.8 MN/ISA+18^{O}F - Max Cruise

Component	Technology Improvement	%ΔESFC	%ΔFN
Compressor η	+1.1 pt	-0.5	+1.2
Compressor P/P	+0.3%	-0.0	+0.0
HP Turbine η	+2.2 pt	-1.3	+1.3
Fan Turbine η	+1.5 pt	-0.9	+0.9
Cooling Air %W22	-3.1%	-0.3	+3.8

4.2.4 Projected Cycle For 2005

At the Interim Oral Presentation at NASA Lewis (December 12,1994), GEAE was asked to expand the evaluation of the performance benefits of the technologies identified and evaluated for current product applications to future advanced engines that would be entered into service by the year 2005. The benefits for these future applications have been evaluated and are similar or slightly better than available to current product engines. The slightly higher benefit is due to the higher pressure ratio cycle.

The turbofan engine cycle was presented to NASA Lewis at the Interim Oral Presentation in December 1994 and is presented in this report for information. The improvements in the CF34-8C1 over the current product (CF34-3A1) include a new larger fan; a new compressor design scaled from the F414 plus a zero stage and two new aft stages; a new, low pressure turbine; and an optimized exhaust area for takeoff and cruise performance.

The technology improvements evaluated for both the baseline CF34-3A1 and for the advanced cycle are tabulated in Table 4-4 and the probable engine configuration is illustrated in Figure 4-7.

Table 4-4. Turbofan Performance Benefits For Component Assessments.
35K/0.8 MN/ISA +10°C Max Cruise (Constant T41)

Component	Technology Improvement	CF34-3A1 Baseline %ΔESFC	CF34-3A1 Baseline %ΔESHP	CF34-8C1 Advanced %ΔESFC	CF34-8C1 Advanced %ΔESHP
Compressor η	+1.1 pt	-0.5	+1.2	-0.6	+1.4
Compressor P/P	+0.3%	-0.0	+0.0	-0.0	+0.0
HP Turbine η	+2.2 pt	-1.3	+1.3	-1.3	+1.5
LP Turbine η	+1.5 pt	-0.9	+0.9	-1.0	+1.1
Cooling Air %W2	-3.1%	-0.3	+3.8	-0.4	+4.2

Advanced CF34-8C1 Turbofan Engine
Updated With Technology Improvements

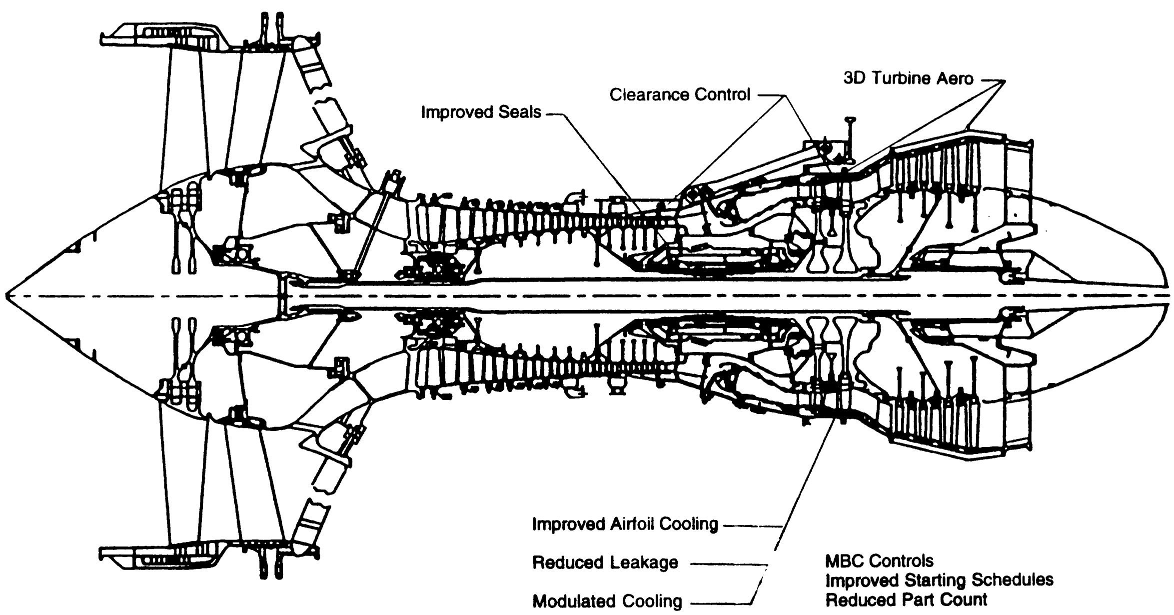


Figure 4-7. The CF34-8C With Technology Improvements.

4.2.5 Advanced Growth Turbofan Engine Cycle

For this study, NASA asked what type of engine cycle would be projected for applications out into the future. In response to that inquiry, an advanced turbofan engine cycle was prepared and presented at the Interim Oral Presentation in December, 1994. The engine cycle is based on assessments of future propulsion requirements. The cycle is consistent with the GEAE multi-generation product development plan for the CF34 series of engines. This advanced cycle reflects a realistic class of engines for entry into service in the years ranging as early as the year 2005 to 2020 depending on how the market requirements develop. It basically is a follow on derivative of the CF34-8C1. The CF34-8C1 is the advanced version of the CF34-8C that is currently in development at GEAE for certification by the year

1999. This engine cycle is shown in Table 4-5. Overall cycle pressure ratio for this family of engines is illustrated in Figure 4-8.

Table 4-5. Projected Advanced Turbofan Engine Cycle For EIS 2010-2020.
(Needs Demonstrated Technologies)

Component	Advanced Growth 18K Lb FN Class ~2005 EIS
Fan Diameter (in.)	53
Booster Stages	3
Fan Tip P/P	1.75
O/A Booster P/P	3.00
SLS/+27°F APR	
FN (pounds)	18300
T41 (°F)	2550
XN25 (RPM)	18010
T3 (°F)	1150
P3 (psia)	500
WCL (% W22)	13.0
Cycle P/P	34.0
37K/0.8MN/ISA Max Cru	
FN (pounds)	3750
SFC	0.639
T41 (°F)	2190

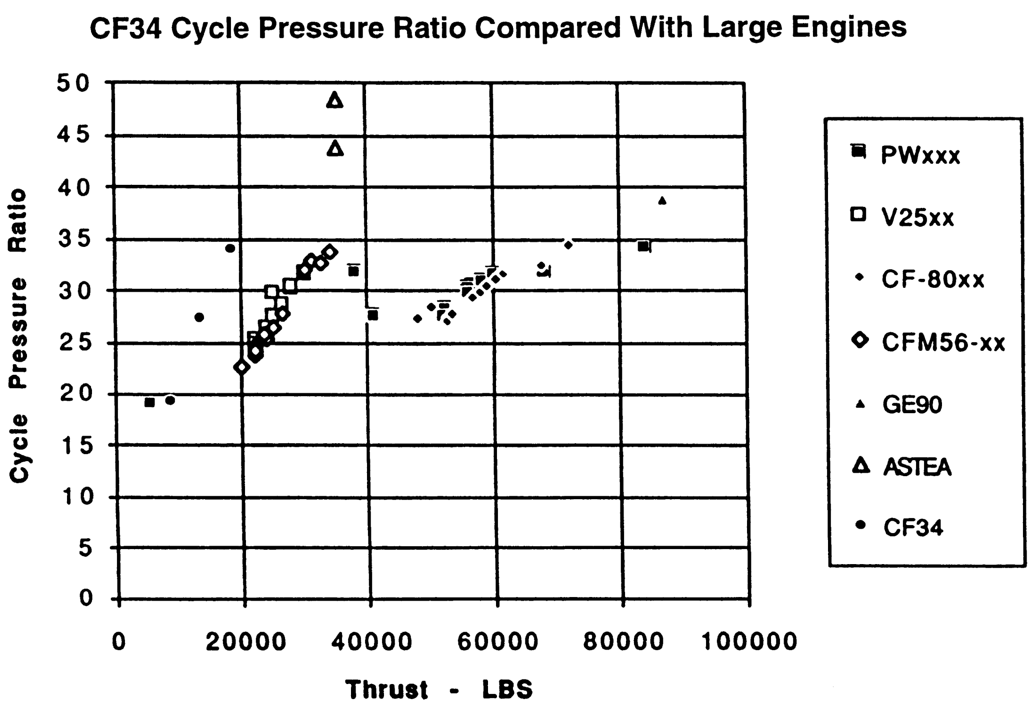


Figure 4-8. Comparison of CF34 Family Cycle Pressure Ratios.

5.0 AIRCRAFT/MISSION/ECONOMIC FACTORS

The figures of merit for commercial aircraft are driven by the market place, i.e., worldwide airline requirements. Predictions and forecasts are continually being made for traffic growth and replacement needs of airlines for the future. These needs are categorized by capacity (number of seats) and range requirements. As the market requirements for passenger comfort and cargo hauling capability increases, so does the cost to build the aircraft and the cash operating costs; so the market segment must be analyzed to see that the demand will produce the revenue to cover costs. Constraints such as noise and emissions, which are not driven by economics, but by regulations, need to be considered, as well as airline-perceived performance requirements such as field length, approach speeds, initial cruise altitude and block times per trip.

In the regional engine community, projections of the future airline requirements indicate that steady growth is expected in the turbofan and turboprop regional aircraft such as the S340 and the Canadair Regional Jet (RJ) illustrated in Figure 5-1. It is forecasted that regional airlines will add nearly 5000 new aircraft over the next twenty years. New high performance turboprops and turbofans are expected to meet the demand of faster and more efficient aircraft.

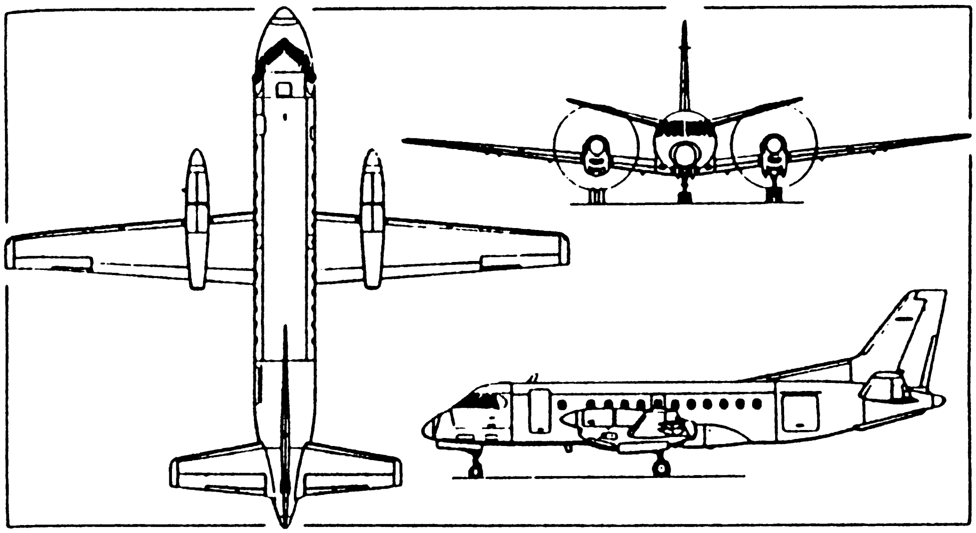
The business projections indicate that the regional and commuter aircraft trend is to higher installed power for reduced block time, and more passenger seats (more passengers per trip with increased revenue) resulting in lower DOC. These trends guide GEAE business planning and have resulted in the multi generation product plan for the CF34 and the CT7 families of engines. Projections of future needs demonstrate the importance of participating in AST activities in order to be able to apply and insert results of the RAPT program directly into real application opportunities.

The life cycle direct operating costs (DOC), i.e., net present value of ownership cost plus cash operating costs per mile and per seat-mile, is commonly used as a figure of merit for competing aircraft. Typically, cash operating costs include fuel, flight crew, maintenance, and insurance. The market price for new or derivative aircraft was also estimated or calculated to evaluate improvements to the DOC of derivative aircraft within the market segment. The GEAE multi generation product plan closely follows GEAE projections of the regional future aircraft.

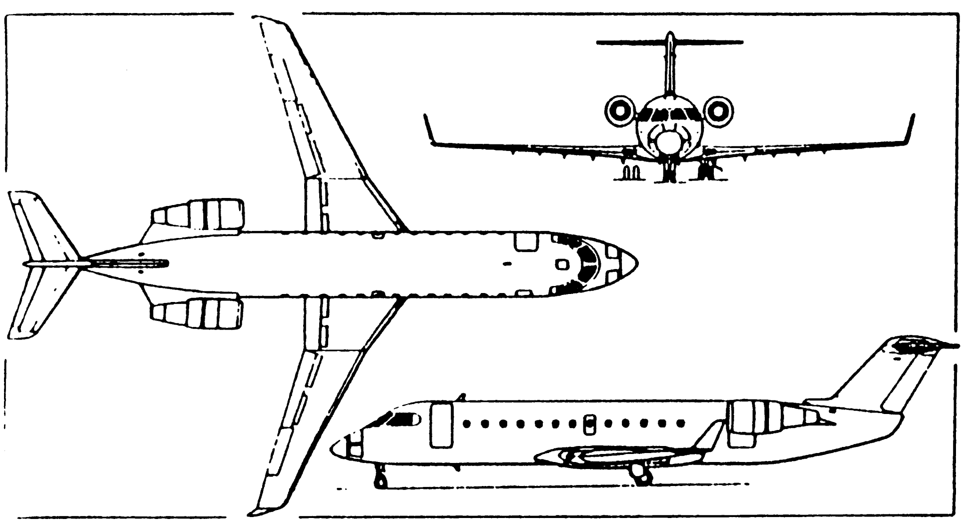
The primary objectives of the RAPT technology studies are to identify key technology needs and preliminary concepts for advanced engine configurations entering revenue service in 2005. The two baseline applications for these studies were the current leading technology GEAE small engines which entered revenue service around 1990 to 1993. These referenced engines, both the turbofan and the turboprop, were analyzed through selected regional/commuter missions for the turbofan and the turboprop applications as identified in Figure 5-2, These unique small engine mission definitions which are summarized in Figure 5-2, are typically at low cruise altitudes and short cycle times which significantly influence small engine designs. Advanced technology concepts were evaluated using the GEAE design methodology, including mission analyses, to established figures of merit for each technology group studied. The resulting effects on direct operating costs are compared with longer transport missions in Figure 5-3.

5.1 TURBOFAN APPLICATION

The CF34-3A1 turbofan engine started revenue service in the Canadair Regional Jet (RJ) in November 1992. The RJ is a commercial regional jet aircraft based on the successful CL601 business jet. This aircraft and engine has the distinction of being the quietest twin engine jet in revenue service. A growth version of this aircraft that requires significant increases in thrust and the derivative CF34



SAAB S-340B with CT7-9



Canadair RJ with CF34-3A1

Figure 5-1. Aircraft Platforms For Regional Aircraft Propulsion Technology Evaluation

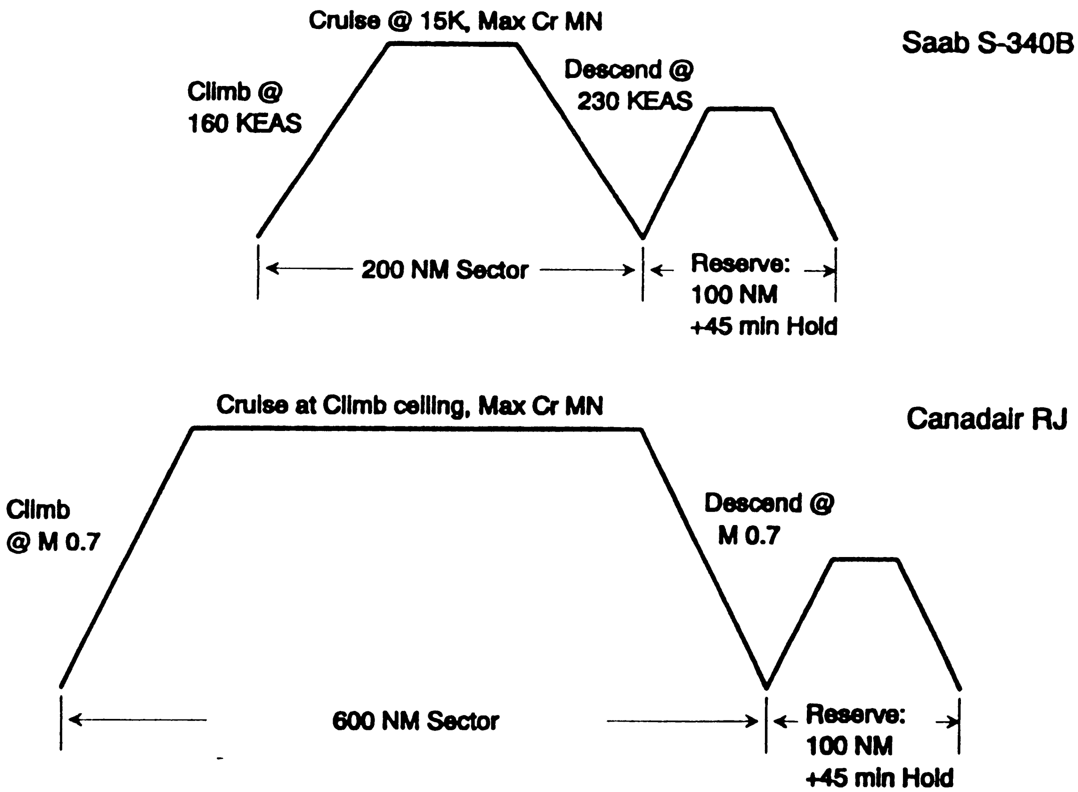


Figure 5-2. Mission Profiles For Technology Evaluation.

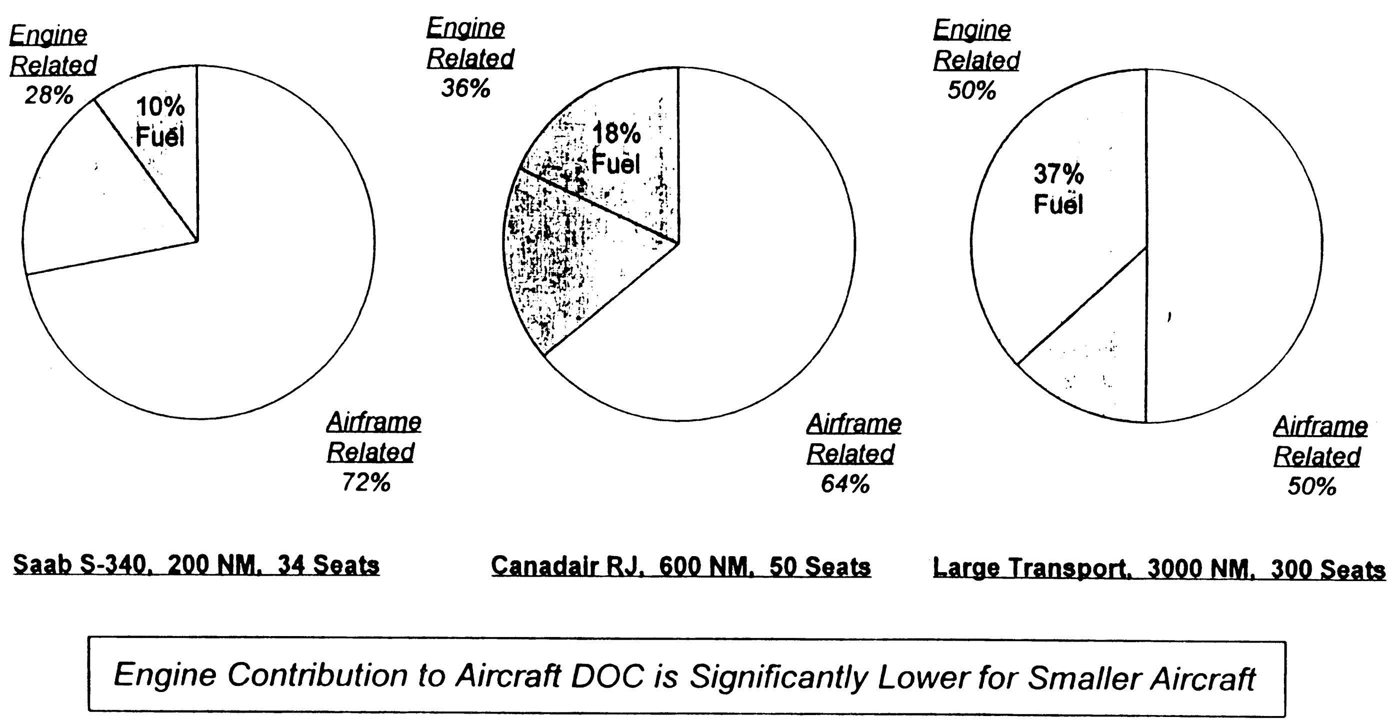


Figure 5-3. Regional Versus Transport Direct Operating Costs (DOC) Comparison.

engine are currently in the design phase. GEAE is developing the engine to power the growth aircraft which must have good fuel burn, low cost, low noise and be easy to maintain. The cycle for this engine is being modified taking into account all of the desired characteristics of the next generation engines.

The future 2005 turbofan regional engine is projected to be a CF34 derivative in the 15 to 16,000 pound thrust range. A full study and evaluation of this engine or a slightly larger thrust engine was originally proposed in Task #8 as a baseline to study a far term propulsion system, but that task was agreed to be deleted by both NASA and GEAE for program costs reduction. The NASA/GEAE agreement was to do technology ranking on the most current application, which is the Canadair RJ powered by the CF34-3A1. This aircraft entered into revenue service in 1992.

Engine cycle studies for turbofan engines in the CF34 family have shown that the technology improvements evaluated for the CF34-3A1 (baseline study engine cycle) which powers the commercial Canadair Regional Jet are directly applicable to the Canadair Business Jet engine CF34-3B and to the growth regional jet engine, the CF34-8C now in development for entry into service in 1999 on the Canadair RJX. The future derivative engine applies the technologies to the CF34-8C in order to provide a path to successfully transition the technologies to a product that fits into the business projections of the size engine needed for the regional aircraft anticipated for the year 2005.

5.1.1 Turbofan Aircraft Description

The baseline, or reference, engine for this study, the CF34-3A1, is currently in service on the Canadair Regional Jet. It is also in service on the business jet , the Challenger CL-601. The Regional Jet is a 50 passenger aircraft with a design takeoff weight of 51,000 pounds. This aircraft is manufactured by the Canadair Group, Bombardier, Inc., Montreal, Quebec, Canada.

"The US launch Customer for the Canadair regional jet was Comair in 1992. Since that introduction Comair increased the number to twenty RJ's in its fleet of 85 aircraft along with a 30% increase in traffic from the previous year. It is anticipated that at least ten aircraft will be delivered in 1995. The RJ's 50-seat capacity and 10-hour-a-day utilization rate are increasing Comair's productivity which is reflected in declining unit costs. The RJ's seat-mile costs are drawing close to 8 cents. The RJ factor caused Comair's overall fleet seat-mile cost to drop to 14.7 cents in a six month period ending September 1994, down from 17.1 cents during the previous similar six month period in 1993." (AW&ST Dec. 12/19, 1994)

Comair operates as a Delta Connection Carrier and is one of the regional carriers that is experiencing significant growth. GEAE is positioning itself to be ready for the growth in regional carriers by developing the next generation engine for the next generation Canadair RJX. This aircraft will be powered by the CF34 derivative, the CF34-8C which is projected to be needed to meet the growth expected by the regional carriers. Technologies identified will be available for product insertion to the growth version of the CF34-8C and in the revenue service arena by the year 2005.

5.1.2 Turbofan Mission/Flight Profile

The CF34-3A1 in this application is designed for a mission of 1800 nautical miles (NM) at a Mach Number of 0.74 at 35,000 feet altitude; however, the typical aircraft usage is not consistent with the design mission. Therefore, a more typical mission is used to evaluate the DOC characteristics. It is a 600 NM mission at maximum cruise. The representative or typical flight profile, or mission, for this reference (baseline) turbofan is as follows:

Canadair RJ w/CF34-3A1 - 600 NM sector, ISA

Start-up and Taxi	Time and allowance for 4 minutes at ground idle, 0.1Mach, SL
Takeoff	Time and allowance for 1 minute at takeoff rated thrust 0.2 Mach
Climb	Climb at max climb thrust to optimum cruise altitude
Cruise	Cruise at optimum altitude and long range cruise speed
Descend	Descend to sea level
Approach	Time and allowance for 2 minutes at 0.3Mach, SL
Landing and Taxi	Time and allowance for 3 minutes at ground idle, SL
Reserve	Fuel required for 100NM diversion plus 45 minutes holding

5.1.3 Economic Factors

Operating costs and capacity trends for the turbofan applications are shown in Figure 5-4. This figure illustrates that the trends are towards increasing passenger capacity which improves the direct operating costs per available seat mile (ASM). It should be noted that the ranking procedure used in this study was based on current aircraft applications. It is anticipated that larger aircraft will represent the future regional product needs. However, this ranking procedure is a good way to evaluate the merits of the various technology groupings which were identified for evaluation. Therefore, since the future growth aircraft will have more seats and also higher cruise speeds, it is important to identify increased thrust for minimal or small increases in engine size. (Most of the growth aircraft will probably include trends such as increased capacity to be achieved through aircraft modifications rather than a total new aircraft. For example, insertion of sections in the fuselage for increased passenger capacity is one technique that may be used.)

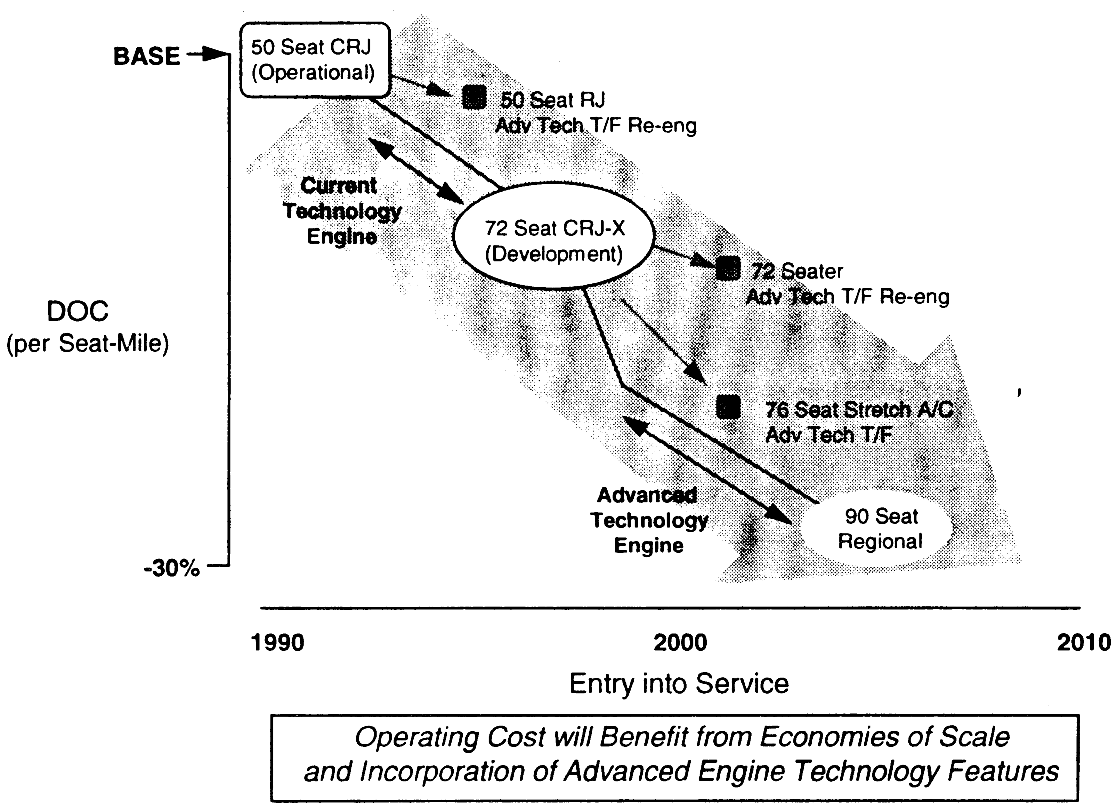


Figure 5-4. Turbofan Operating Costs And Capacity Trends.

The engine contribution to the aircraft direct operating costs (DOC) in the turbofan application is 36% with only 18% of the DOC affected by the fuel costs. This is illustrated in Figure 5-5 along with the other engine related costs. This low contribution of the fuel costs makes it difficult to influence the overall DOC by sfc improvements alone. In fact a one percent improvement in engine sfc for the Canadair application would result in approximately 0.12% improvement in DOC as illustrated in Figure 5-6 along with various other illustrated parameters.

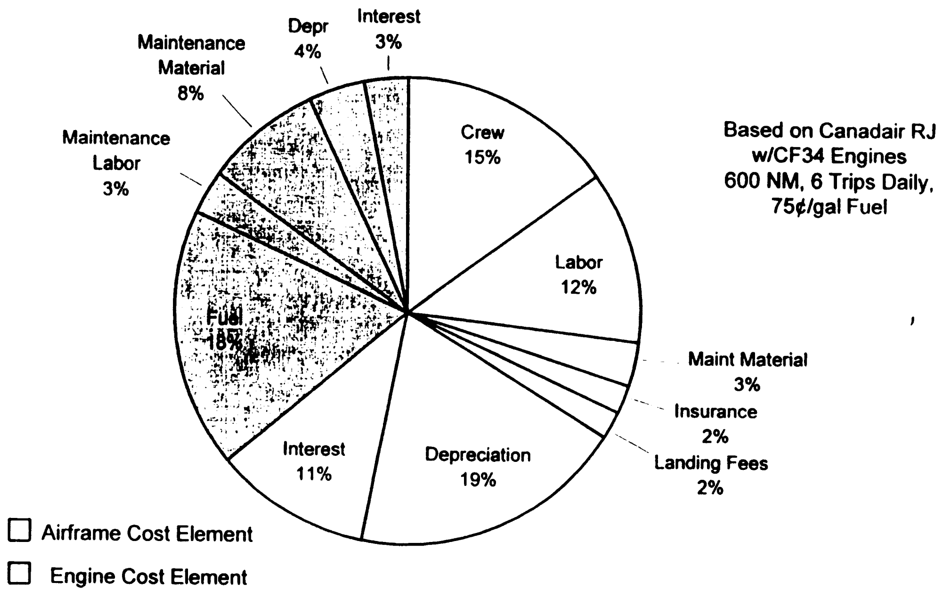


Figure 5-5. DOC Breakdown for T/F Regional Aircraft.

DOC Evaluation For T/F Technology Ranking
Relative Influence Of Engine Parameters On Aircraft DOC

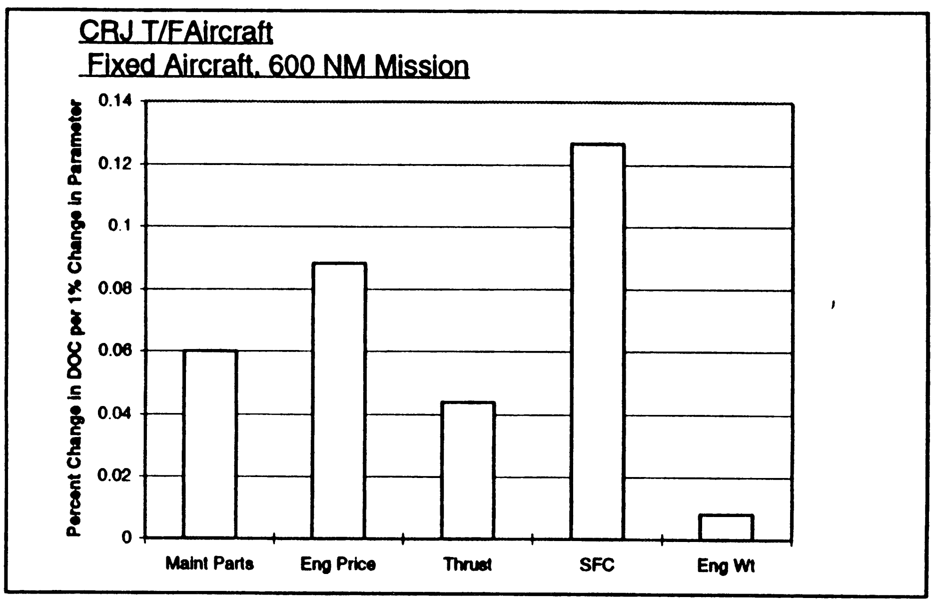


Figure 5-6. Effect of Regional Engine Technology On Present Day T/F Aircraft.

However, a significant improvement in DOC can be achieved when the aircraft capacity can be increased (perhaps with a plug to increase the length and add a seat row of passengers) when a higher thrust level can be made available in the engine. Figure 5-7 illustrates this effect. For example, referring to the Figure 5-7, if a five percent increase in thrust could be made available to support an aircraft modification including the increase size and weight to add one seat row, a five percent reduction in DOC could be achieved!

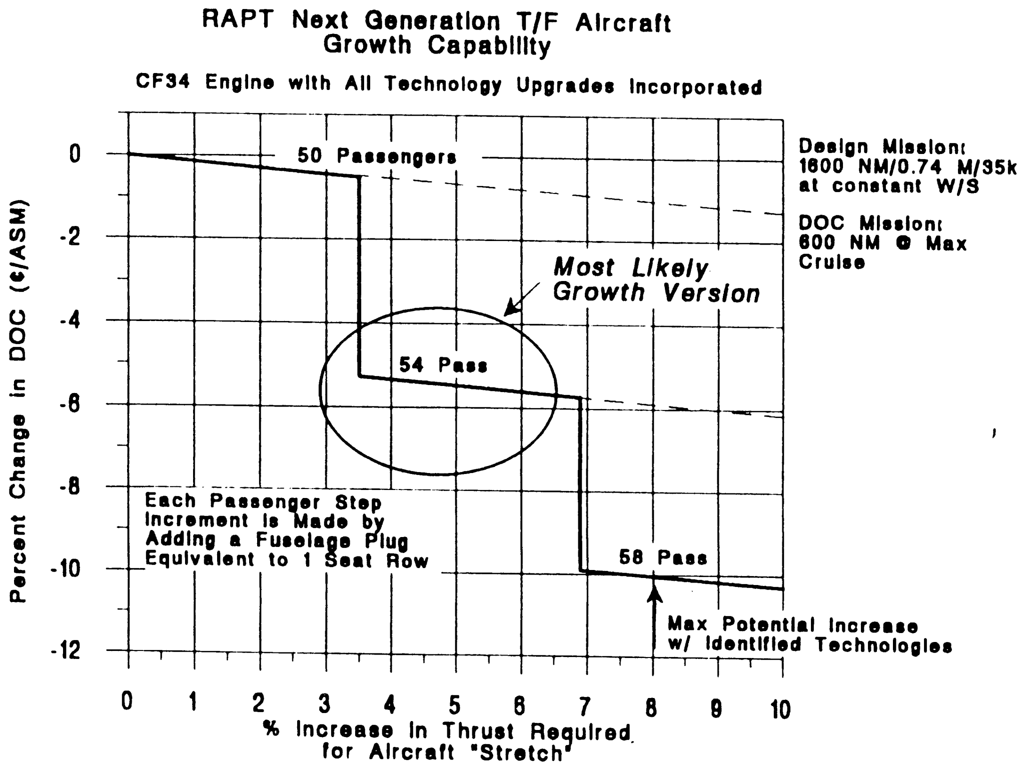


Figure 5-7. Effects of Thrust Increases on Next Generation T/F Aircraft DOC.

5.1.4 Technology Benefits

The total potential turbofan engine improvements were evaluated and are illustrated in the chart in Figure 5-8. The for example the improvements available in HPT efficiency improvements were able to provide 0.291% improvements in DOC. The summation of all the technology improvements were able to provide 1.3% improvements in DOC. The engine was basically evaluated at constant turbine inlet temperature, which did allow a thrust increase. Note that this analysis was for a fixed aircraft and did not take full advantage of the thrust increase potential to improve direct operating costs. The intent was to use these figures for ranking the technologies.

5.2 TURBOPROP APPLICATION

The turboprop base engine is the CT7-9B engine. This engine currently powers the Saab S340B aircraft. The S340B is a 34 passenger aircraft that entered revenues service in 1990. The T700/CT7 family has maintained its pre-eminence in the market place through continual infusion of the latest technological advancements, proven on one or more of GEAE aircraft engines' other advanced engines programs. This approach has assured that the T700/CT7 family remains the most advanced turboshaft/turboprop engine today and well into the future.

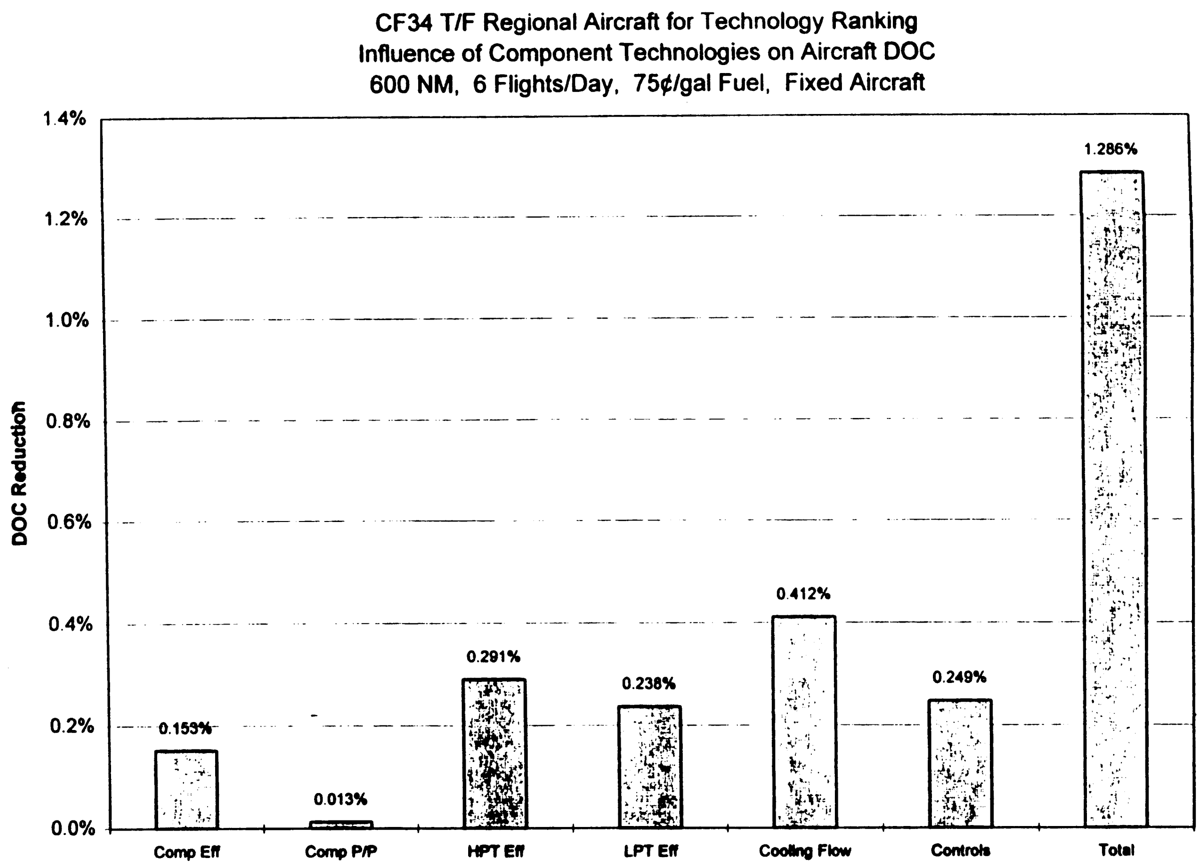


Figure 5-8. Influence of RAPT Technologies on Turbofan Aircraft DOC.

As with the Regional Jet (RJ), a high speed growth variant of turboprop powered aircraft is envisioned that will require a significant increase in shaft horsepower (SHP). In support of this projection GEAE has evaluated growth derivative engines.

These T700 growth engines will serve as the key building block for a family of higher powered T700/CT7 turboshaft and turboprop engines for next generation military and civil rotary-wing and fixed wing aircraft.

Again as with the RJ, the engine to power this growth aircraft is in the design phase and must offer good fuel burn, low cost, low noise and must be easy to maintain. The turboprop engine cycle is being continually modified as aircraft customers better define their needs for the future

5.2.1 Turboprop Aircraft Description

The CT7-9B is currently in revenue service on the Saab 340, manufactured by Saab-Scania and used primarily as a commuter airliner. This aircraft was used for this study. It carries a crew of two and 34 passengers. The aircraft has a wing span of 70.3 feet and a length of 64.8 feet. The empty weight is 17,000 pounds and the gross weight is 27,000 pounds.

5.2.2 Turboprop Mission/Flight Profile

The CT7-9B engine in this application is capable of flying the design mission of 560 nautical miles (NM) at 275 knots air speed at 25,000 feet altitude; however, the aircraft usage is not typical of this design mission and characteristically flies shorter segments. Therefore, a more typical mission is used to evaluate the DOC characteristics. It is a 200 NM mission at maximum cruise. The representative or typical flight profile, or mission, for this reference (baseline) turboprop is as follows:

Saab S-340 w/CT7-9B - 200 NM sector, ISA

Start-up and Taxi	Time and allowance for 4 minutes at ground idle, 0.1Mach, SL
Takeoff	Time and allowance for 1 minute at takeoff power 0.2 Mach
Climb	Climb at max climb rated power to optimum cruise altitude
Cruise	Cruise at optimum altitude* and long range cruise speed
Descend	Descend to sea level
Approach	Time and allowance for 2 minutes at 0.3Mach, SL
Landing and Taxi	Time and allowance for 3 minutes at ground idle, SL
Reserve	Fuel required for 100NM diversion plus 45 minutes holding

* Altitude limited by requirements to fly at least one-third of sector length in cruise leg

5.2.3 Economic Factors

Operating costs and capacity trends for the turboprop applications are similar to those for the turbofan which was shown in Figure 5-4. That figure illustrates that the trends are towards increasing passenger size which improves the direct operating costs per available seat mile (ASM). However, The turboprop application will probably not experience as much increase in passenger capacity as will the turbofan.

The engine contribution to the aircraft direct operating costs (DOC) in the turboprop application is 17% with only 10% of the DOC affected by the fuel costs. This is illustrated in Figure 5-9 along with the other engine related costs. This low contribution of the fuel costs makes it difficult to influence the overall DOC by sfc improvements alone. In fact a one percent improvement in engine sfc for the Saab S340 application would result in approximately .088% improvement in DOC as illustrated in Figure 5-10 along with various other parameters.

However, a significant improvement in DOC can be achieved when the aircraft capacity can be increased (perhaps with a plug to increase the length and add a seat row of passengers) when more power can be made available in the engine. Figure 5-11 illustrates this effect. For example, referring to the figure, if a seven percent increase in shaft horsepower could be made available to support an aircraft modification to add two seat rows, a thirteen percent reduction in DOC could be achieved.

5.2.4 Technology Benefits

The total potential turboprop engine improvements were evaluated and are illustrated in the chart in Figure 5-12. For example the improvements available in HPT efficiency improvements were able to provide 0.5% improvements in DOC. The summation of all the technology improvements were able to provide slightly over 2% improvements in DOC. The engine was basically evaluated at constant turbine inlet temperature, which did allow a power increase. However, this analysis was for a fixed aircraft and did not take full advantage of the power increase potential to improve direct operating costs. The intent was to use these figures for ranking the technologies, which is discussed in the following section.

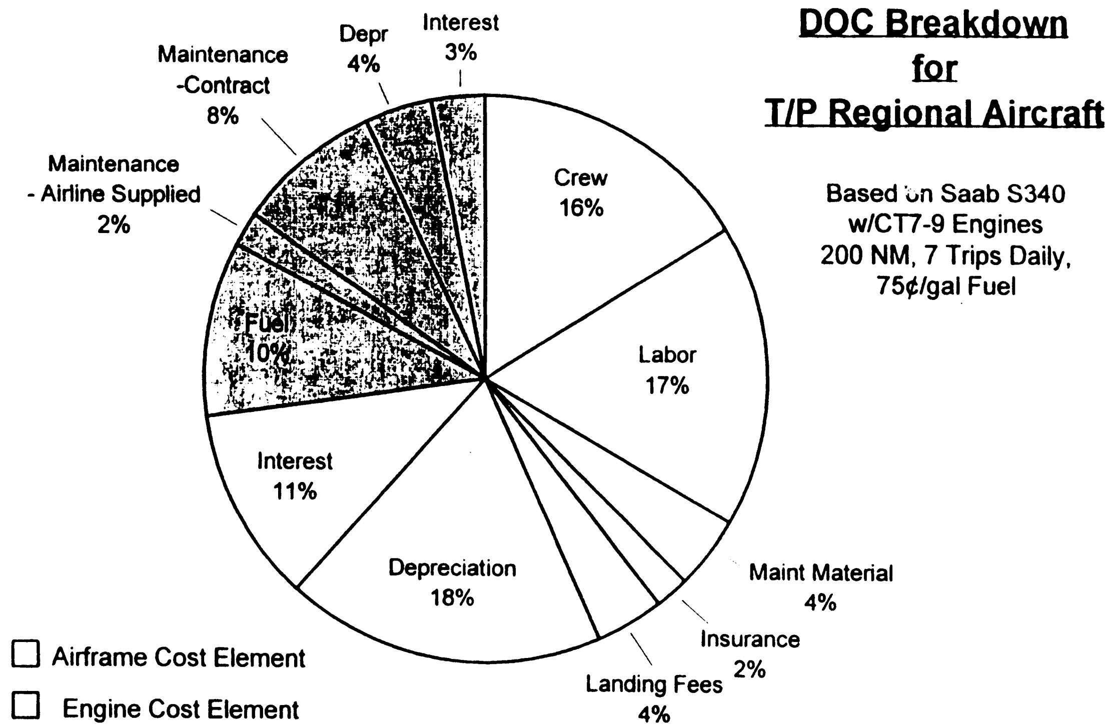


Figure 5-9. DOC Breakdown for T/P Commuter Aircraft.

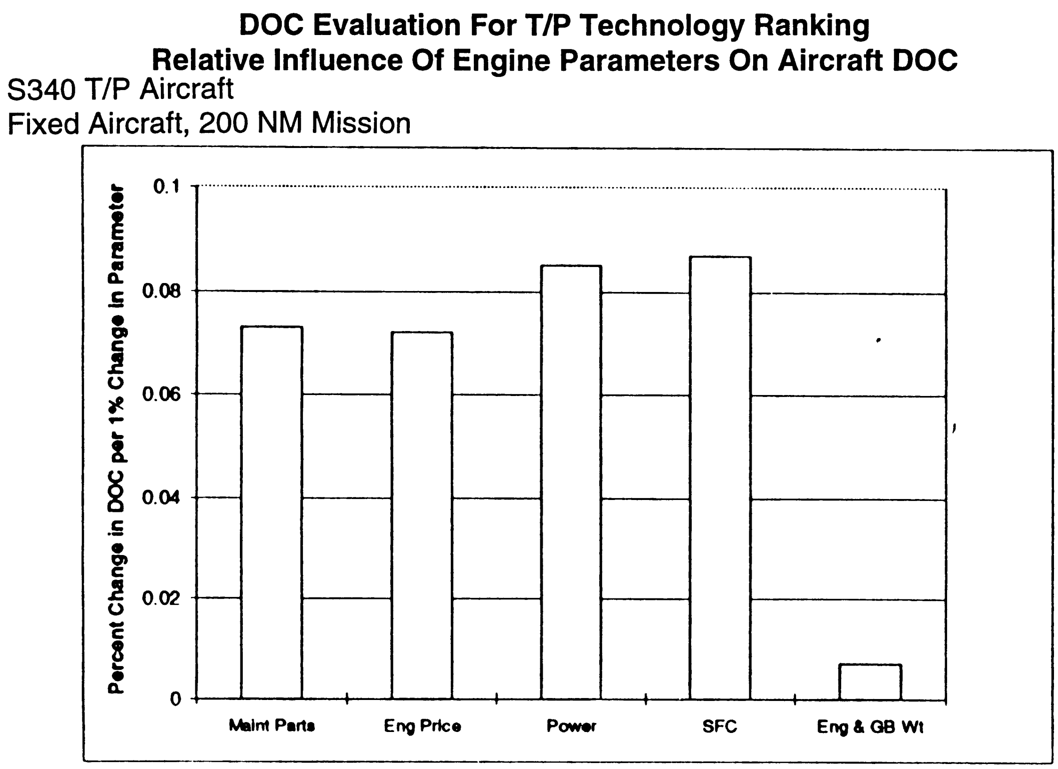


Figure 5-10. Influence Of 1% Change In Parameters On T/P Aircraft DOC.

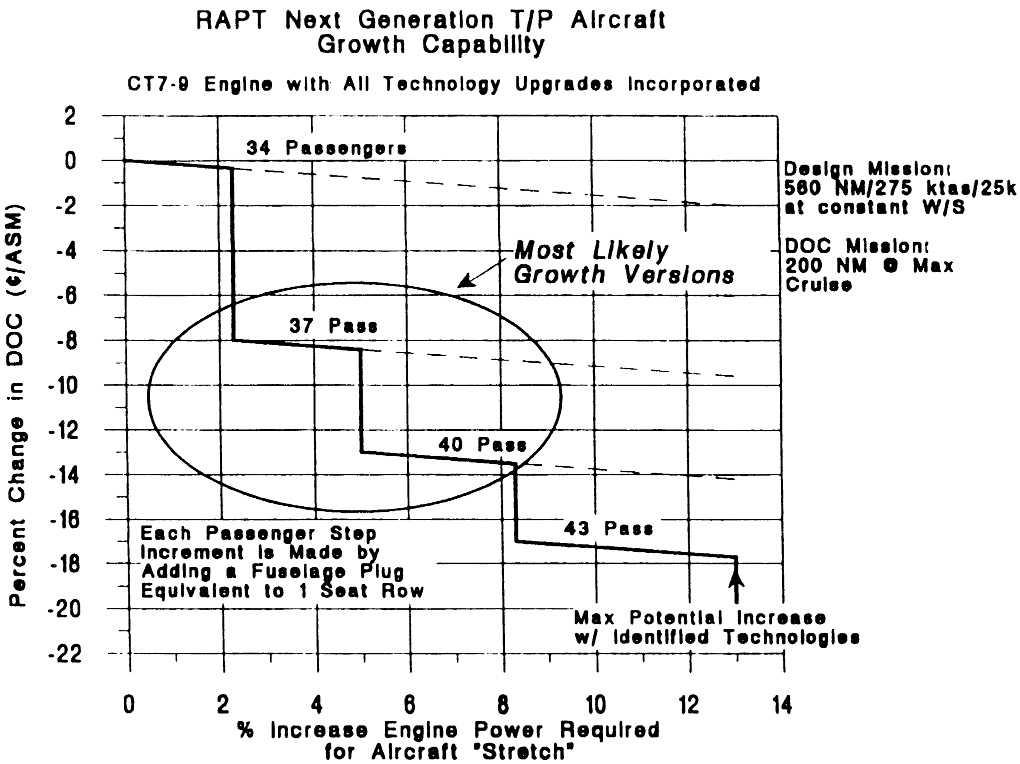


Figure 5-11. Effects Of Thrust Increases On Next Generation T/P Aircraft.

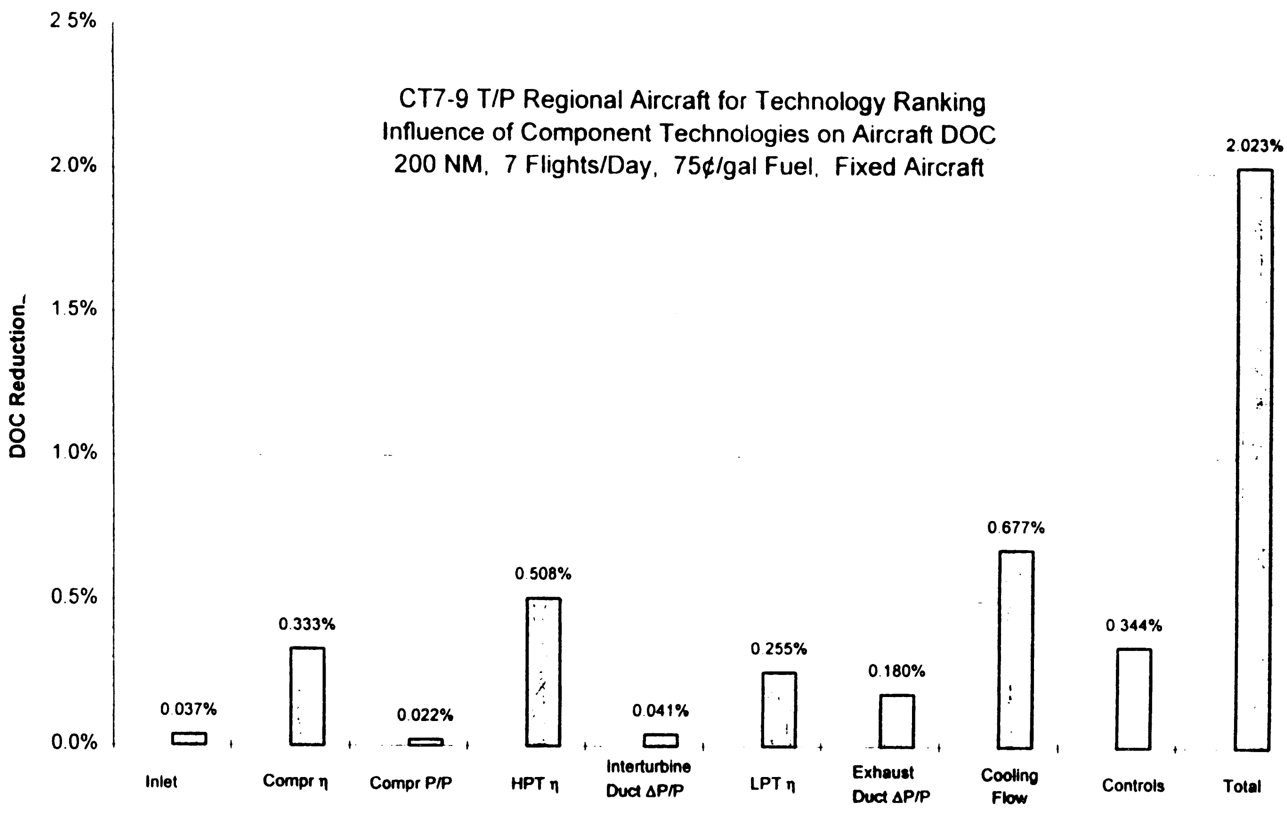


Figure 5-12. Influence of RAPT Technologies On T/P Aircraft DOC.

6.0 RANKING PROCEDURE

The ranking procedure was formulated in order to evaluate the best payback for the investment or development dollar spent for each of the technology groupings. It is basically the procedure used to rank the technologies in the assessment for the large engines in the NASA AST Program. The process involved the identification of rewarding technologies and determining the prospective economic benefits.

The identification of the technologies reflected the needs of the customer, the technical requirements and the production needs. In order to obtain input and identify those technologies, a team of specialists was created that represented each of the current and mature regional size products manufactured by GEAE in Lynn, Massachusetts. These specialists identified the technology needs of current production engines future needs. The evaluation team considered and set in place a process to define and evaluate the following:

1. The most promising concepts employing advanced component technology for a near term propulsion system with a technology availability date of 2005
2. The benefits of introducing the emergent technologies into current product lines
3. The achievable effects of those technologies
4. The relative benefits of the emergent technology using as an evaluation process which considers value to current fleet economics, probability of success and costs to implement

The procedure used is illustrated in Figure 6-1 and involved the team of specialists, a systems analysis (for engine cycle performance) and aircraft mission and operating cost analysis. The study task to identify technologies for commercial regional subsonic aircraft started with 117 technology items. These items were screened and consolidated into 12 groupings by the team members.

After identifying the 117 technologies, the next step was to develop regional aircraft mission and sensitivities, then convert the technology influences into aircraft costs and revenue. This analysis was conducted on a component level for each of the components of the engines. Then the sensitivities were used to evaluate the airline benefits for the various groupings which represent the technology programs that can be conducted.

Also, the probability of success was established for each technology grouping for use in the ranking. The development costs are an important ingredient in the assessment and an estimate of the development costs of the proposed technologies was used for the comparison.

From this information, a ranking factor was devised. The ranking factor, or factor of merit (FOM) consists of multiplying the value to the airline of the technology, times the probability of success in implementing the improvement, all divided by the development costs, as illustrated in the following equation:

FOM = (Value to Airline X Probability of Success) / (Development Cost)

The 12 technology groupings are: a) Inlet System Design for Turboprops, b) Extended Capability Impeller, c) Compressor Performance Improvement, d) Integrated 3-D Turbine Aero Design, e) Turbine Leakage and Cooling Air, f) HPT Turbine Clearance Control, g) Manufacturing LCC Reductions, h) Mechanical Systems, i) Exhaust Systems Design, j) Engine Starting Systems, k) Materials, and l) Controls and Accessories. These groupings along with the economic benefits and the estimated development costs are listed in Appendix B.

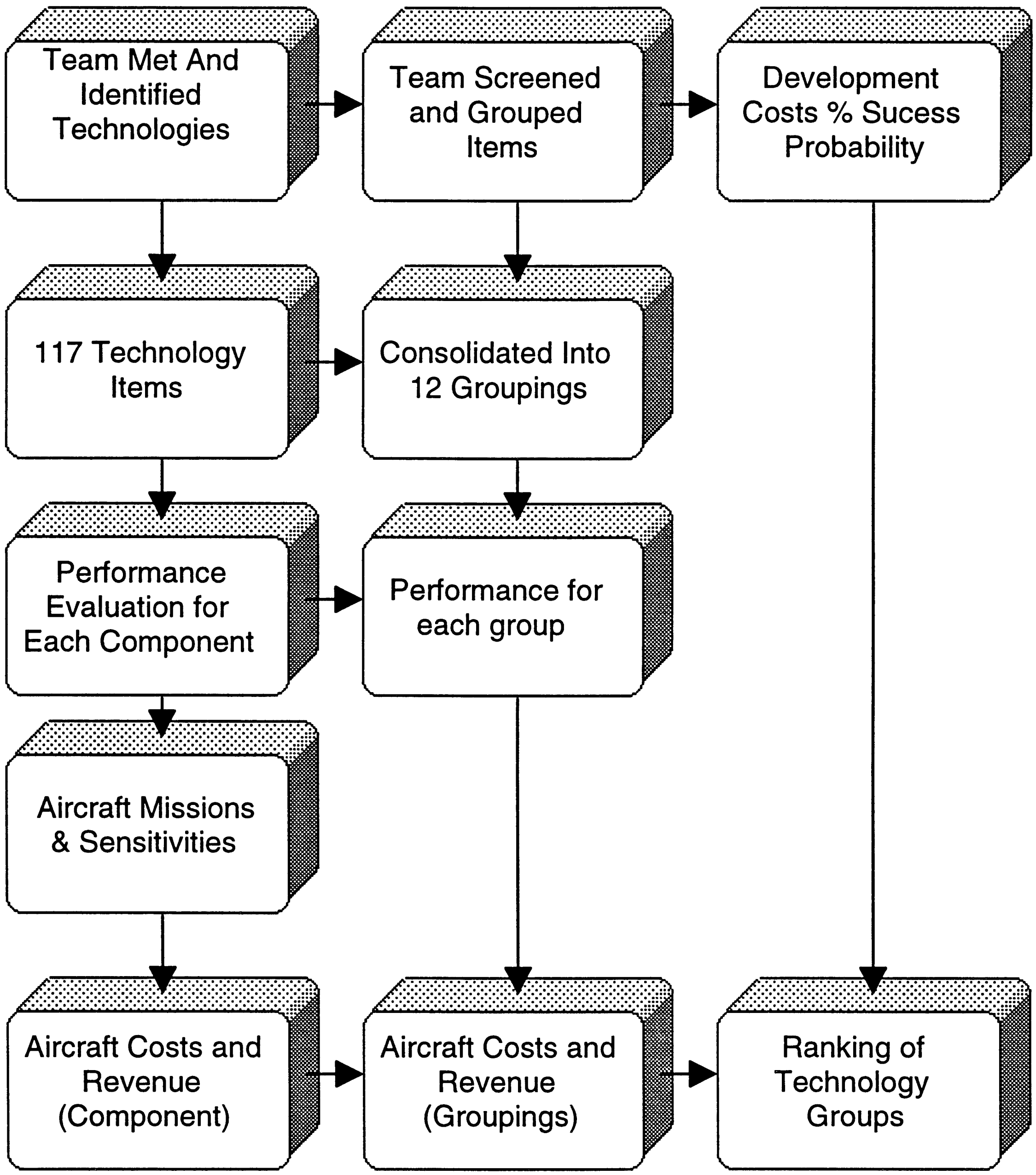


Figure 6-1. The Ranking Procedure Of The Technology Groupings.

7.0 RANKING OF TECHNOLOGY GROUPINGS

The analysis conducted and reported in Section 5 provided derivatives for the economic benefits identified for the various engine components as related to the airline economics. The economic benefit could then be consolidated into the various technology groupings defined by the team. The technology groupings may overlap engine components, therefore the derivatives have been used for the groupings rather then the engine component benefits which may include technology items from more than one group.

For example in Table 4-1, the potential improvement in turbine efficiency is 3.1 points. This value is based on all of the technology items identified by the team of specialists. These include items from the following groupings listed in Appendix B: D) Integrated 3-d turbine aero design, E) Reductions in turbine leakage/cooling & improved durability, F) Close tolerance HPT turbine clearance control, and K) Materials study/evaluation items & goals. The airline economic derivatives described in Section 5 were used to evaluate and rank each of the groupings described in Appendix B:

A) Inlet system design for turboprop
B) Extended impeller capability for increasing cycle speeds
C) Compressor performance improvement
D) Integrated 3-d turbine aero design
E) Reductions in turbine leakage/cooling & improved durability
F) Close tolerance HPT turbine clearance control
G) Design/manufacturing LCC reductions
H) Mechanical systems/seals (Rotor Thrust Control, Leakage, Bearing Life)
I) Exhaust systems designs (T/P)
J) Engine starting systems
K) Materials study/evaluation items & goals.
L) Controls and accessories

The technology groupings provide the technology programs that are defined in this study and the rankings for them provide a selection criteria for the best return on the development investment.

7.1 TURBOPROP

The turboprop ranking is based on the baseline mission for the 34 passenger SAAB-S340B with the CT7-9 engine. The baseline mission for this engine has a 200 NM sector as illustrated in Figure 5-2 with more specific details in Table 2-3. The influence derivatives as reported in Figure 5-8 were used to assess the potential benefits for each of the groupings from Appendix and then these were ranked to obtain the best return. Each of the groupings represent a technology program.

Data for the ranking of the turboprop application is tabulated in Table 7-1 and is further illustrated in three figures. Figure 7-1 shows the ranking of the twelve technology groups based on the improvement on direct operating costs for the regional airline application. Figure 7-2 shows this data along with the development costs for each the technologies. Figure 7-3 then shows the ranking based on the most favorable benefit per dollar invested.

Based on DOC and FOM comparisons, two technology groupings show the best technology to address for the turboprop applications: the clearance control improvement and the control system development.

Table 7-1. Turboprop Ranking.

Turboprop Technology Item	DOC % of Costs	Probability of Success	Developmer Cost $ Mil	FOM %DOC/$Mil
F) HPT TURBINE CLEARANCE CONTROL	-0.707	0.50	2.7	-0.131
L) CONTROLS AND ACCESSORIES	-0.791	0.60	4.4	-0.108
I) EXHAUST SYSTEMS DESIGNS	-0.200	0.50	2.2	-0.045
D) INTEGRATED 3-D TURBINE AERO	-0.769	0.70	12.0	-0.045
E) TURBINE LEAKAGE/COOLING AIR	-0.486	0.60	6.8	-0.043
C) COMPRESSOR PERFORMANCE	-0.333	0.50	4.5	-0.037
A) INLET SYSTEM DESIGN: TURBOPROP	-0.038	0.80	0.9	-0.034
K) MATERIALS DEVELOPMENT	-0.222	0.50	4.0	-0.028
B) EXTENDED IMPELLER CAPABILITY	-0.088	0.70	2.5	-0.025
G) DESIGN/MANUFACT. LCC REDUCTION	-0.074	0.70	3.5	-0.015
J) ENGINE STARTING SYSTEMS	-0.032	0.60	2.5	-0.008
H) MECHANICAL SYSTEMS	-0.011	0.50	1.2	-0.005

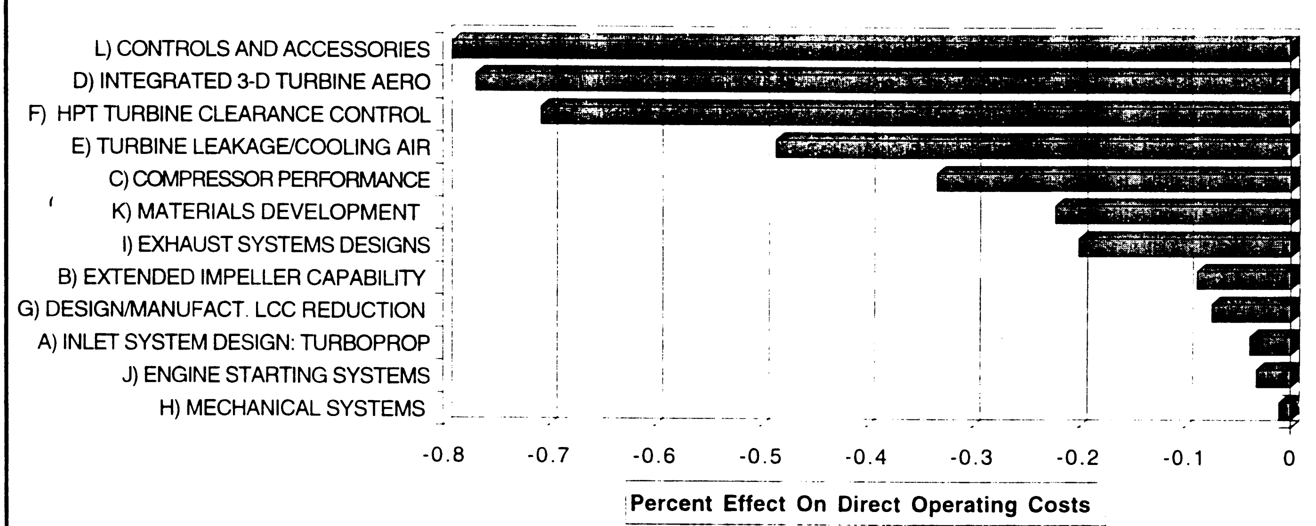


Figure 7-1. Effects On Airline DOC - Turboprop Technology Groupings.

Final Draft, Updated: September 7, 1995

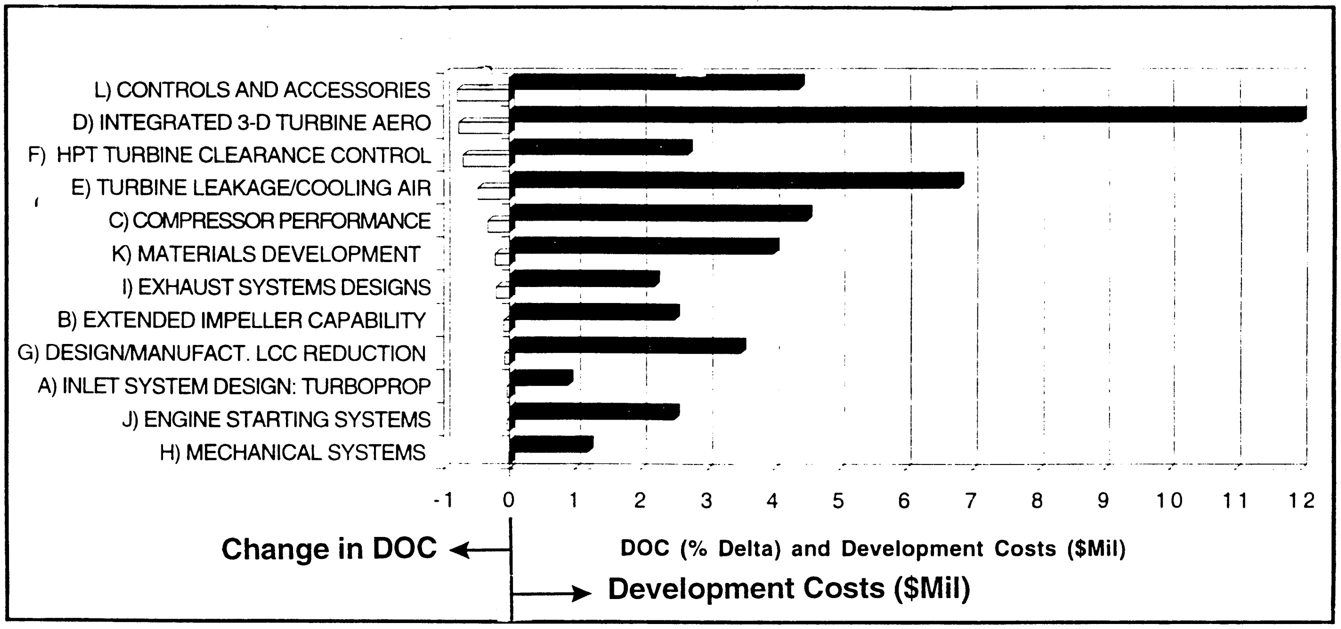


Figure 7-2. Turboprop Technology Groupings - DOC Benefits and Development Costs.

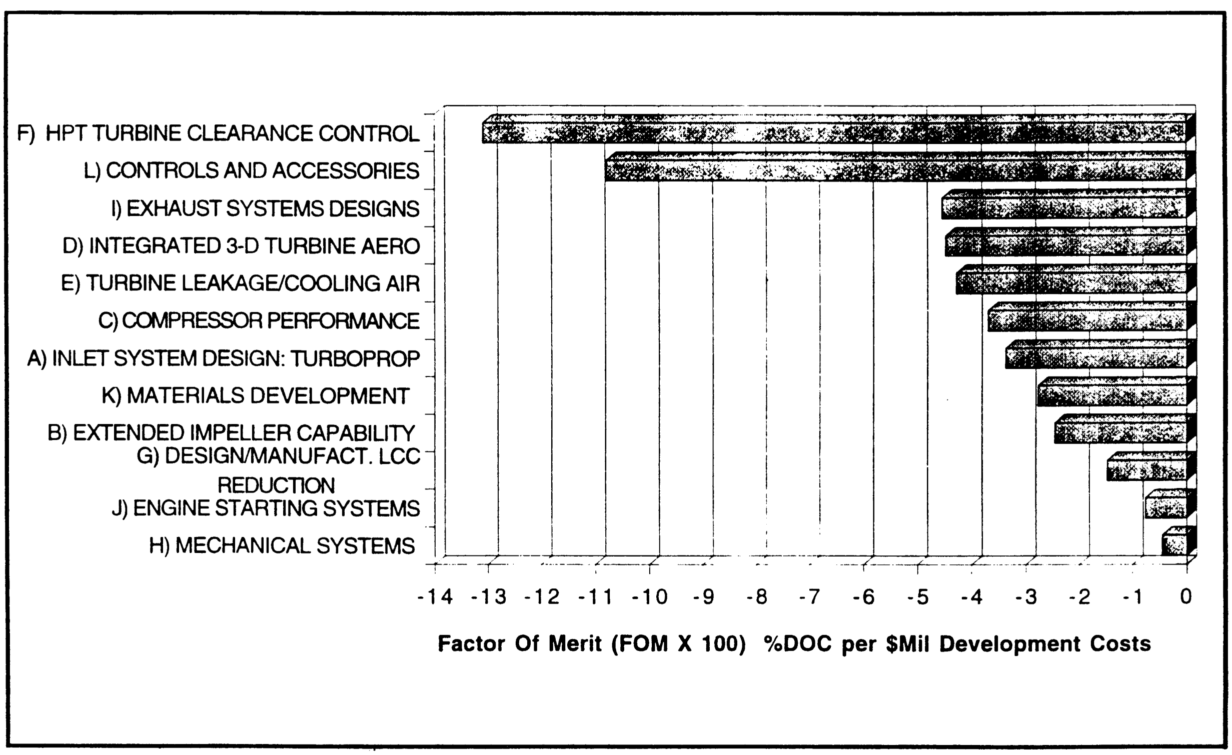


Figure 7-3. Ranking of Technology Groupings (Regional Applications).

7.2 TURBOFAN

The turbofan ranking is based on the baseline mission for the 50 passenger Canadair RJ with the CF34-3A1 engine. The baseline mission for this engine has a 600 NM sector as illustrated in Figure 5-2 with more specific details in Table 2-2. The influence derivatives as reported in Figure 5-8 were used to assess the potential benefits for each of the groupings from Appendix C and then these were ranked to obtain the best return. Each of the groupings represent a technology program.

Data for the ranking of the turbofan application is tabulated in Table 7-2 and is further illustrated in three figures. Figure 7-4 shows the ranking of the nine technology groups based on the improvement on direct operating costs for the regional turbofan airline application. Figure 7-5 shows this data along with the development costs for each the technologies. Figure 7-6 then shows the ranking based on the most favorable benefit per dollar invested.

Table 7-2. Turbofan Ranking.

Turbofan Technology Item	*DOC % of Costs*	*Probablity of Sucess*	*)evelopmen Cost $ Mil*	*FOM %DOC/$Mil*
F) HPT TURBINE CLEARANCE CONTROL	-0.447	0.5	2.0	-0.112
L) CONTROLS AND ACCESSORIES	-0.320	0.6	3.9	-0.049
E) TURBINE LEAKAGE/COOLING AIR	-0.345	0.6	6.6	-0.031
C) COMPRESSOR PERFORMANCE	-0.166	0.5	3.5	-0.024
K) MATERIALS DEVELOPMENT	-0.222	0.5	4.0	-0.028
D) INTEGRATED 3-D TURBINE AERO	-0.370	0.7	13.0	-0.020
G) DESIGN/MANUFACT. LCC REDUCTION	-0.047	0.7	2.5	-0.013
J) ENGINE STARTING SYSTEMS	-0.014	0.6	1.5	-0.006
H) MECHANICAL SYSTEMS	-0.013	0.5	0.8	-0.008

Based on DOC and FOM comparisons, two technology groupings similar to the results of the turboprop indicate technologies to address for the turbofan applications: the clearance control improvement and the control system development.

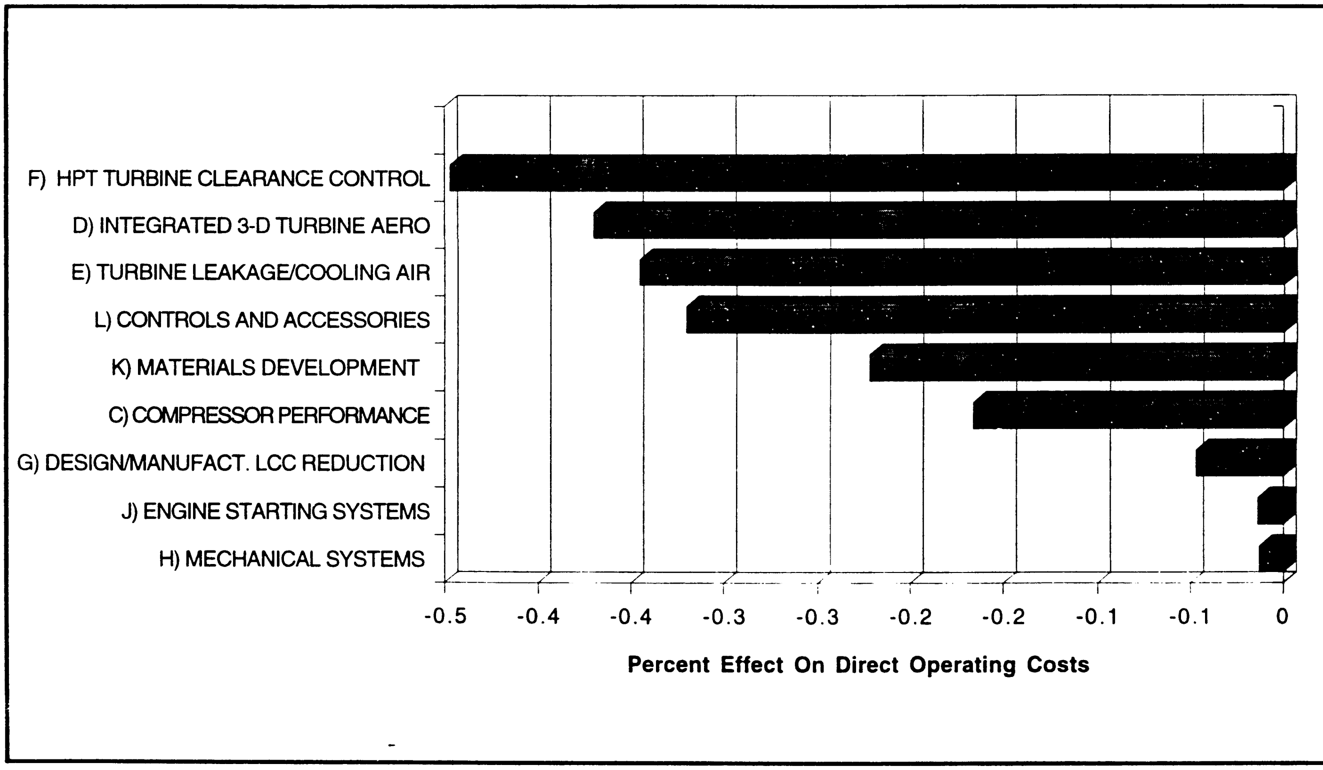


Figure 7-4. Effects On Airline DOC - Turbofan Technology Groupings.

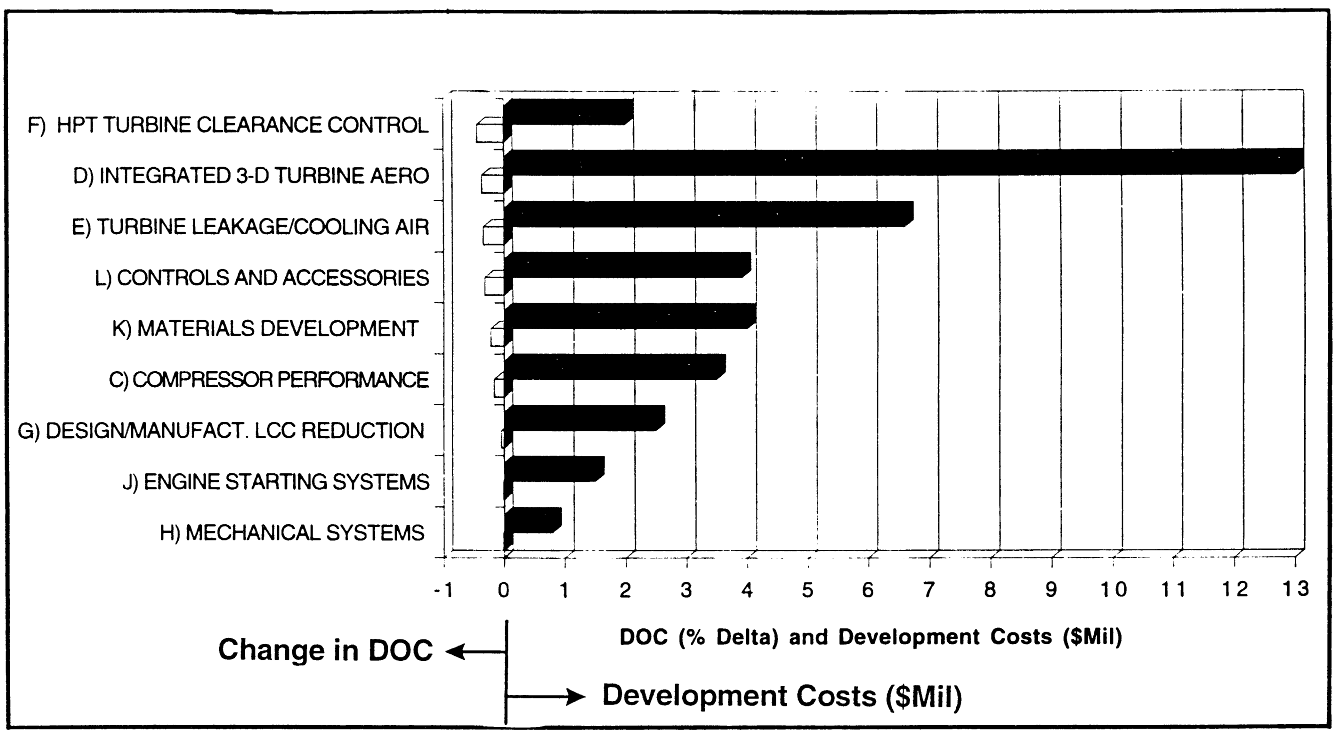


Figure 7-5. Turbofan Technology Groupings - DOC Benefits And Development Costs.

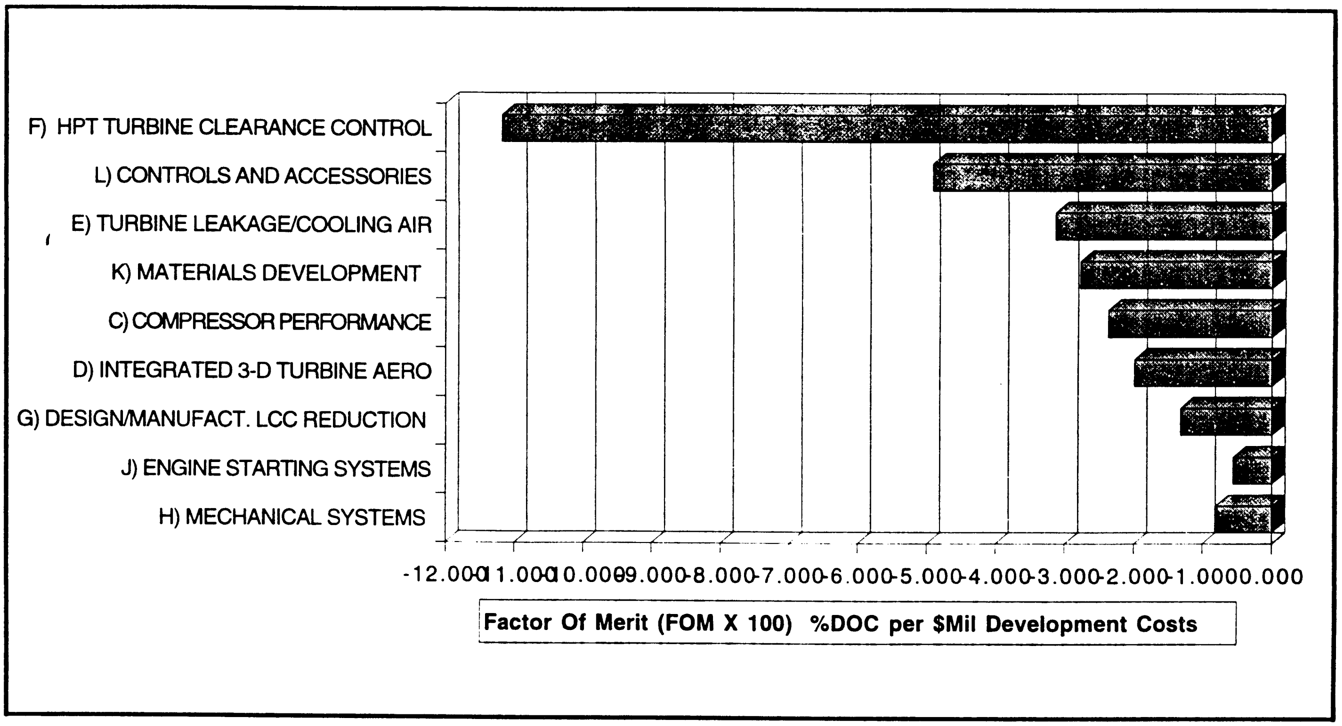


Figure 7-6. Ranking of Technology Groupings (Regional T/P Applications).

8.0 DESCRIPTION OF THE TECHNOLOGIES

The various technology advances within each of the technology groupings are described in the following 12 sections. The performance and economic goals that would be targeted are described and the activities involved in each grouping are given. Additionally, there is data in outline form for each of the groupings in Appendix B.

8.1 CONTROLS AND ACCESSORIES

Outlined below are three areas where system level improvements can be made using common control law technology designated as model based control (MBC), a system integrated control, and an automated control scheme designated as power management. These technology concepts have been developed by GEAE primarily for large military aircraft. It is planned to specifically apply this technology to small commercial engines.

Current engines control power, and thus life, relative to the turbine inlet temperature (T41) through a T41 that is represented and scheduled by the various control schedules. The control schedules will command or specify various parameters and limit other parameters in order to operate the engine to a specified turbine inlet temperature. The control schedule will govern to an engine cycle parameter which gives a predictable effect in the engine output (thrust or shaft horsepower). This parameter will be a measurable parameter, not thrust or T41. For example, fan speed is a measurable parameter and is directly correlated to thrust.

These controlled and limited parameters may consist of fuel flow, rotor speed, turbine exit temperature, compressor variable vane position, etc. The schedules for these parameters are established to limit the operating level of T41 based on how it would behave in the engine cycle. The T41 level is not measured nor used as a demand schedule. (This refers to a measured value that would measure T41 and demand additional fuel flow to raise the operating temperature to the scheduled value.) However in some applications the HPT blade temperature is measured by an optical pyrometer and T41 is deduced from that measurement. When this measurement is made the measured value maybe used as a topping limit to avoid an over temperature, but it is usually not used to schedule fuel flow.

The schedules inherently have built into them tolerance bands to represent engine-to-engine variations and allowances to account for the various levels of deterioration throughout the life of the engines and to account for the various power settings and flight conditions in the aircraft missions. A T41 estimation or calculation at a real time point-by-point evaluation by the control can be used if a model of the engine cycle is contained within the control. When measured parameters are introduced into the model for the exact operating conditions that the engine is experiencing, a precise determination of the turbine inlet temperature can made or calculated. When the exact operating conditions and the current health (deteriorated condition) of the engine is used to determine the turbine inlet temperature level, the controlling parameters can be scheduled precisely to cause the engine to operate at the desired temperature. Thus less safety margin is required and more power can be extracted or increased life can be achieved by effectively reducing the tolerance bands for the scheduled parameters.

Similarly, stall margin is controlled by approximating stall line using measured parameters such as the rate of change of the rotor speed (NgDOT) or fuel flow ratio units (fuel flow divide by compressor discharge pressure, Wf/Ps3). An improved estimation of stall line will be obtained by using an engine model to calculate stall and actual stall line. Integrated turboprop and turboshaft systems may be able to reduce fuel burned with a control which adapts power plant control parameters to optimize fuel burned in real time while meeting other engine limit constraints. Small commercial turboprop aircraft carry out power management using tables in manuals, and this is accomplished with each customer using somewhat different methods. Improved, consistent, and automated power management will reduce life usage during takeoff and climb.

The proposed program is based on the following assumptions: a) This program is based on a T700-T6E FADEC based turboprop control system (which is not developed yet), b) a turboprop T6E application will be available to test the system, c) no control hardware modifications are required, and d) the GEAE Lynn 40Y lab turboprop test rig is available and does not require modifications.

The proposed studies include three distinct areas, as follows below, and would be accomplished on one engine line. Since the performance seeking control would probably have the biggest payoff on a turboprop or turboshaft application, versus a turbofan application, a turboprop engine has been selected for this study.

1) MODEL BASED CONTROL (MBC)

- Design an engine computer model for inclusion in the control which will adapt to (or track) specific engine variations and deterioration to better estimate T41 and/or stall margin
- Use an engine model similar to the above adaptive engine model to estimate sensed engine parameters and potentially reduce redundant sensors

2) PERFORMANCE SEEKING CONTROL (PSC)

- Add an online optimization routine to an MBC system in order to vary power plant and aircraft propulsion system parameters to reduce fuel burned. For turboprop and turboshaft applications, those parameters may include a combination of prop/rotor speed, prop pitch and compressor variable geometry vanes.

3) POWER MANAGEMENT

- Provide a power management system like the CFE738/CFM56/CF6 for single throttle setting takeoff and climb. Then consider adding open loop flight control-like functions to allow the engine control to calculate reduced power takeoff and climb operation.

The estimated benefits for the program include the following: a) 2-3% potential power gain at maximum T41 through the use of MBC, b) potential reduction in control system weight by eliminating some redundant sensors using MBC, c) turboshaft applications have shown from 2-5% potential fuel burned savings, and it is assumed that a similar level of savings could be achieved on a turboprop using PSC, d) potential life saving for simple, consistent calculations of reduced power takeoff and climb operation.

8.2 INTEGRATED 3-D TURBINE AERO DESIGN

The proposed tasks are to design, analyze and test key small turbine components for a fully integrated turbine design demonstrating improved turbine performance for both the HPT and the LPT:

HPT

- 3-D viscous trade study
- Select best configuration

- Perform detailed 3-D viscous aerodynamic design
- Procure and test air turbine hardware
- Match stage test data and refine /redesign

LPT and TRANSITION DUCT

- Conduct 3-D parametric studies of the LPT and transition duct
- Select best configuration
- Perform detailed viscous aerodynamic design
- Procure and test transition duct and LPT stage one nozzle rig
- Match test data and refine/ redesign

The 3-D integrated aerodynamic design will result in improved performance primarily due to a reduction in secondary losses and lower flowpath Mach numbers.

The 3-D viscous trade studies for a higher efficiency turbine aero design will be conducted. Small engines have significant Reynolds effects losses due to the reduced size and the lower aspect ratio airfoils compared to the larger engines. The design point selection will consider tailoring full power operation, with the part power, and altitude operation to balance out the Reynolds number losses for the aircraft mission. The small turbines with low aspect ratio airfoils have high losses in the end wall secondary flows. Therefore, potentially greater efficiency payoff can be realized with reductions in the end wall secondary losses as compared to high aspect ratio airfoils found in the large turbines.

An example is a redesign which consisted of decambering the nozzle at the hub and locally leaning the airfoil toward the pressure side resulting in more uniform stage exit conditions, illustrated in Figure 8-1.

Designs that link the key components for an integrated design between the HPT and the LPT will be evaluated. This effort will also identify and prescribe the process of validation for testing in component air turbine rigs and describe the analysis procedures and potential for refinement of the detail design. Goals of the improved aero design, in addition to improved performance, include reduced cost and weight and improved reliability and maintainability for both the HPT and the LPT.

The design task will follow the trade studies with a 3-D aerodynamic design for both the low pressure turbine and the high pressure turbine. Both engines would benefit from a larger annulus flowpath to reduce the through flow Mach numbers and the turboprop might consider only increasing the annulus area on the last stage of the gas generator turbine by flaring the last stage. An example of the type of aerodynamic design studies that might be conducted is illustrated in Figure 8-2. In addition to larger annulus areas in the turbine, the turboprop exhaust frame could benefit from increased annulus area and an additional trade study of the incidence setting for the outlet guide vanes (OGV) would be conducted.

The objective performance improvements are as follows: For the turboprop gas generator turbine, a 2.0 point improvement in efficiency and for the power turbine, 1.4 points in efficiency. For the turbofan high pressure turbine 1.0 point in efficiency and for the low pressure turbine 1.5 points in efficiency. In addition, for the turboprop the pressure losses in the transition duct from the gas generator turbine to the power turbine would be reduced by 0.002% $\Delta P/P$ and a similar improvement would be targeted for the exhaust frame.

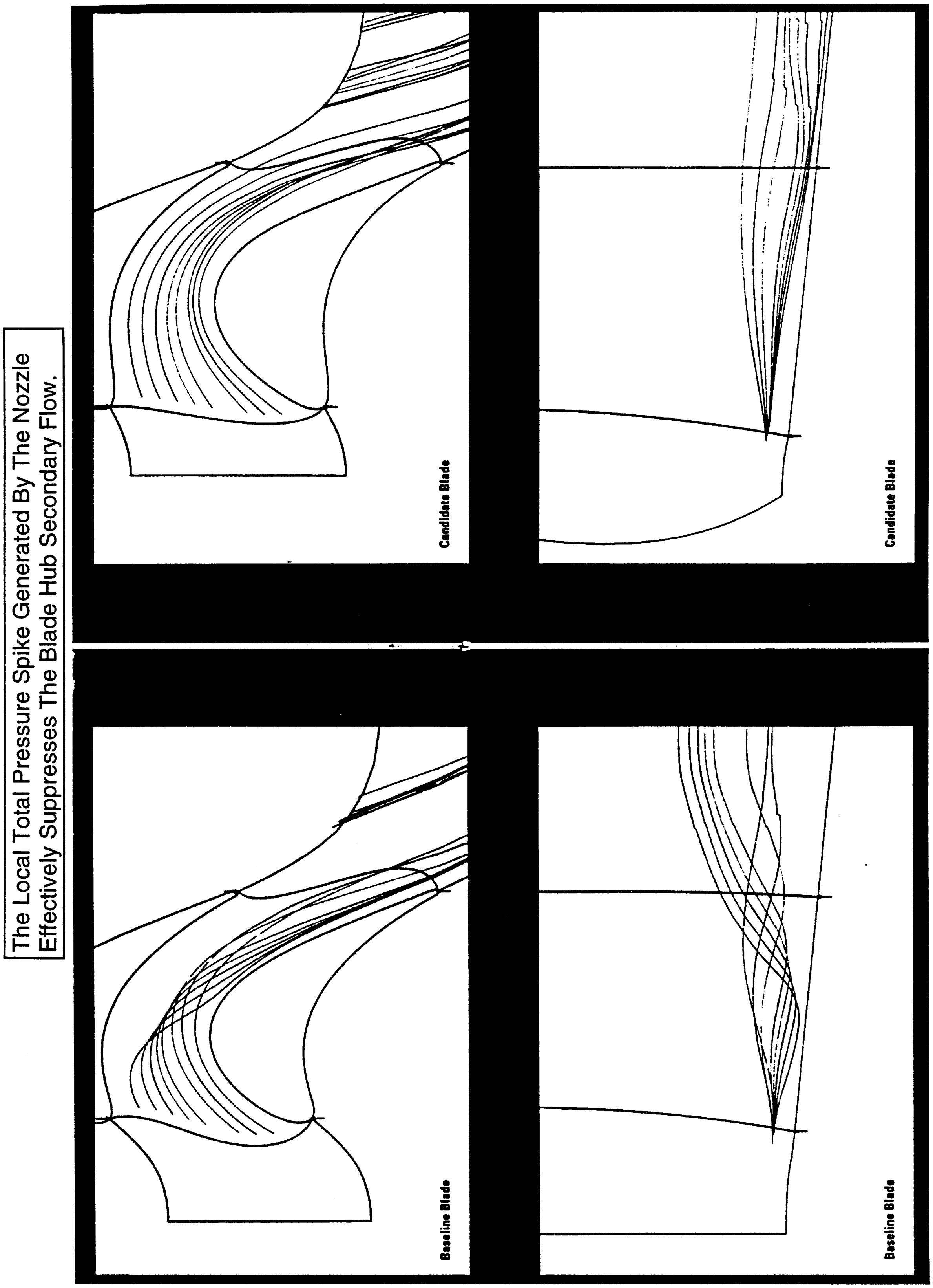


Figure 8-1. Comparison of 3- D Particle Traces Through Blade Passage.

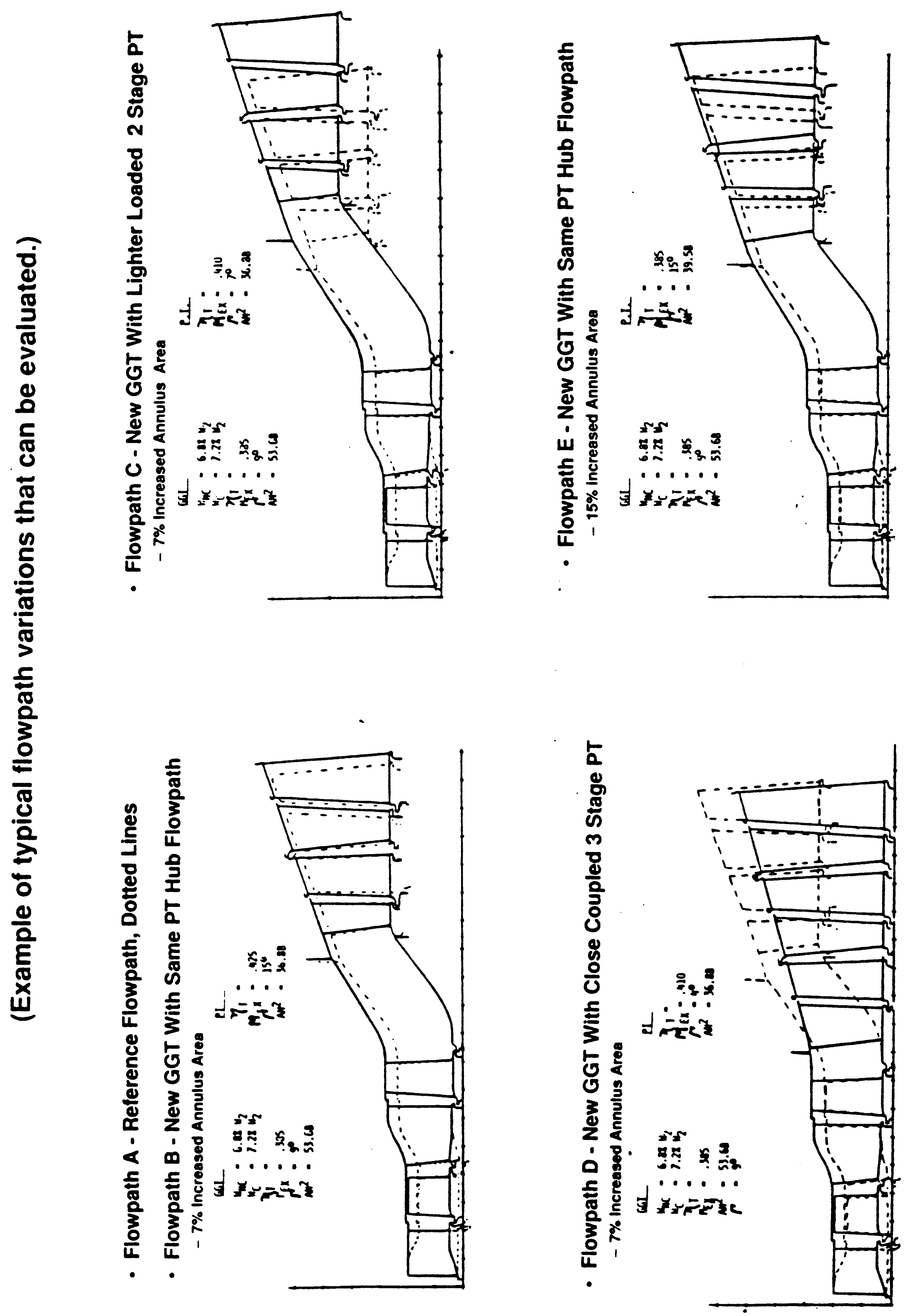


Figure 8-2. CT7 Turbine Aero Design Studies.

The costing for the aero designs is illustrated in Table 8-1 along with the projected efficiency improvements.

Table 8-1. Turbine Aero Costs And Efficiency Improvements.

Cost		CT7	CF34	Efficiency		CT7	CF34
	HPT	7.5	7.5m	Improvement	HPT	2.0	1.0
	LPT	4.5	5.5m		LPT	1.4	1.5
	Sum	12.0	13.0m				

8.3 HPT TURBINE CLEARANCE CONTROL

The proposed tasks are to introduce improved passive clearance control through the use of thermal isolation mass techniques for the stator and through an increased number of stator position control parameters for improved thermal matching throughout the flight envelope. In addition a configuration will be evaluated to reduce the relative rotor to stator mechanical deflection by creating a close coupled stator and rotor for turbines that are configured in an over hung arrangement. (Usually the relative deflections are controlled or reduced by making the casing stiffer.) The tasks will be initiated with trade study analyses, followed by the best choice selection and conceptual design.

The primary objective of this technology effort is to improve turbine clearances throughout the various power settings and to reduce installation clearance losses due to on wing deflections and maneuvers for reduced temperature margin requirements and reduced installed performance deterioration. Installed turbine performance loss is a continuing problem on small engines. Turbine performance could be preserved up to 30% longer if the turbine was not subjected to this initial loss. Techniques to reduce the rotor to stator deflection by creating a close coupled stator rotor will be evaluated, as will the benefits of isolation techniques.

The thermal mass isolation studies involve matching the transient thermal growth of the stator with the transit thermal growth and the mechanical growth of the rotor. The contributions of the stator and the various parts of the rotor are illustrated in Figures 8-3 and 8-4. Note that the blade transit thermal growth is very quick and the disk transient thermal growth is slow. This makes it difficult to match the transit thermal growth with a single position control parameter in the stator. A tabulated illustration of the parameters that are matched is shown in Table 8-2.

A configuration using multiple matching parameters in the stator will be evaluated in order to obtain better transient matching throughout the transients. Figure 8-5 illustrates a configuration where the position control ring is located inboard on the stage one nozzle and the load path is from the ring through the nozzle to the segmented stator support. The vane itself can be used to match the blade transient. A comparison of the parameters matched is tabulated in Table 8-2.

The analytical design sensitivity study and transient thermal analyses will utilize automated analyses with linked thermal/flow/mechanical modeling that feeds back transient clearance effects to the rotor stator model as illustrated in Figure 8-6.

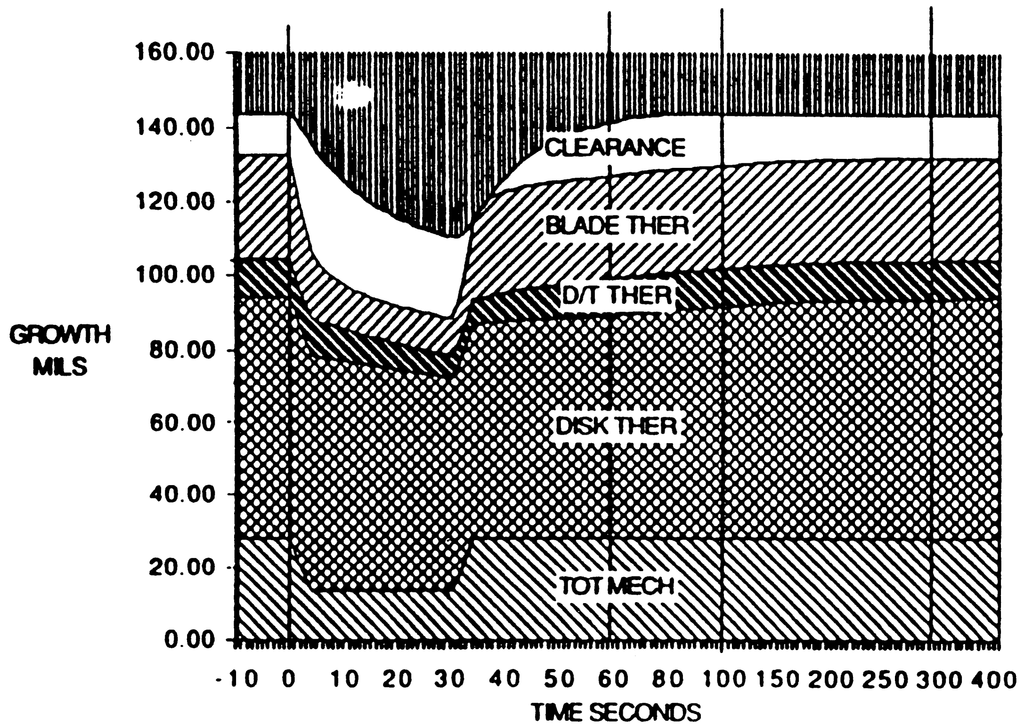


Figure 8-3. Baseline Configuration Shows Potential Rub And Open Operating Clearance.

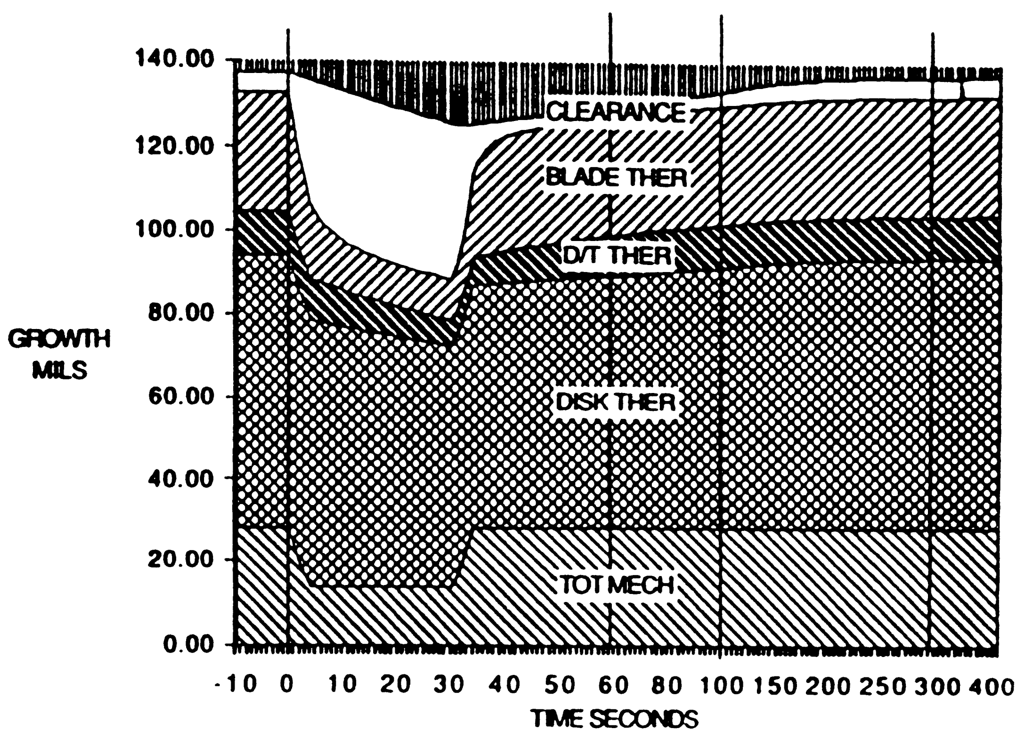


Figure 8-4. Transient Thermals With Thermally Matched Configuration Result In Tight Clearance Without Rub.

Table 8-2. Parameters For Thermal Matching Multiple Parameters.

Stator Position Control Approaches (Parameters For Thermal Matching)

Blade Tip Position Parameters	Single Parameter Matched	Multiple Parameters Matched
Blade Length: L Temperature: T4 and T3 Time Constant	Not Matched	Blade (Vane) Length: Matched Temperature: Matched Time Constant: Matched
Dovetail Length: L Temperature: T3 Time Constant	Not Matched	Dovetail (Vane Support) Length: Similar Temperature: T3 Time Constant: Similar
Rotor Disk Radius: Effective R Temperature: T3 Time Constant	Rotor (Shroud Support) Radius: Larger Temperature: Colder Match Combination Rotor Disk Dovetail Blade	Rotor (OBP Seal) Radius: Matched Temperature: T3 Match Rotor

Stator Position Control Approaches
(Parameters For Thermal Parameters)

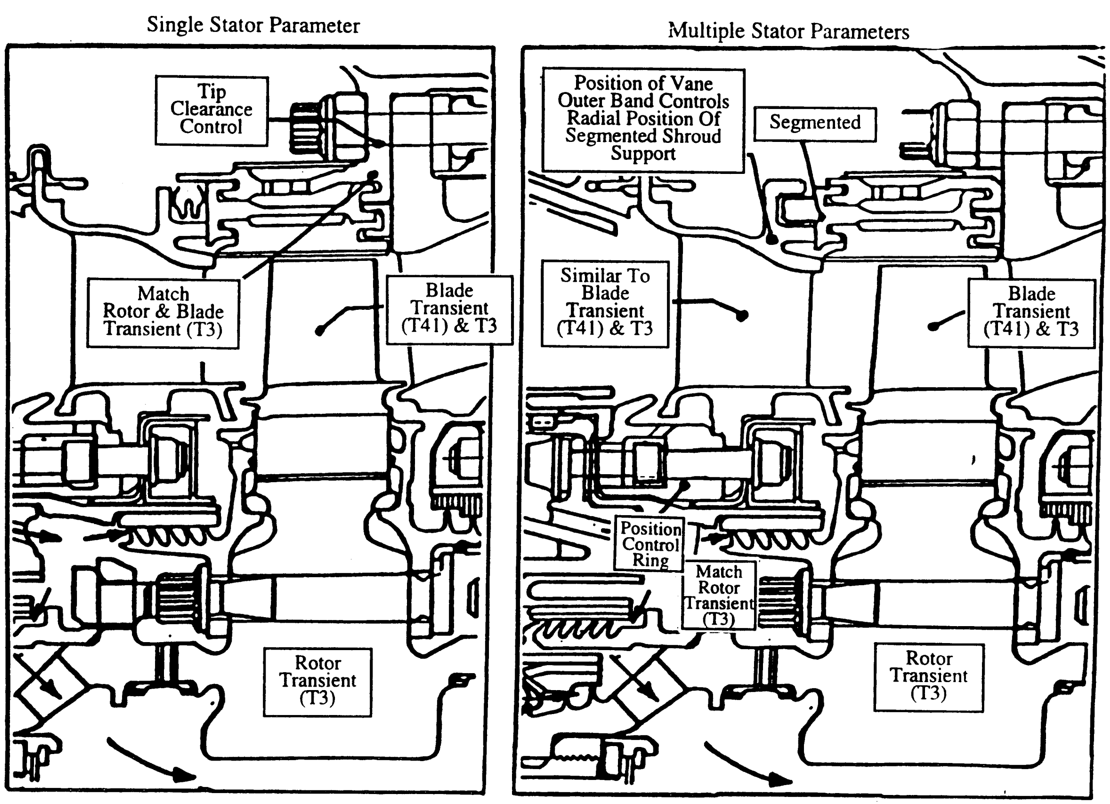


Figure 8-5. Configuration For Multiple Stator Clearance Control Parameters.

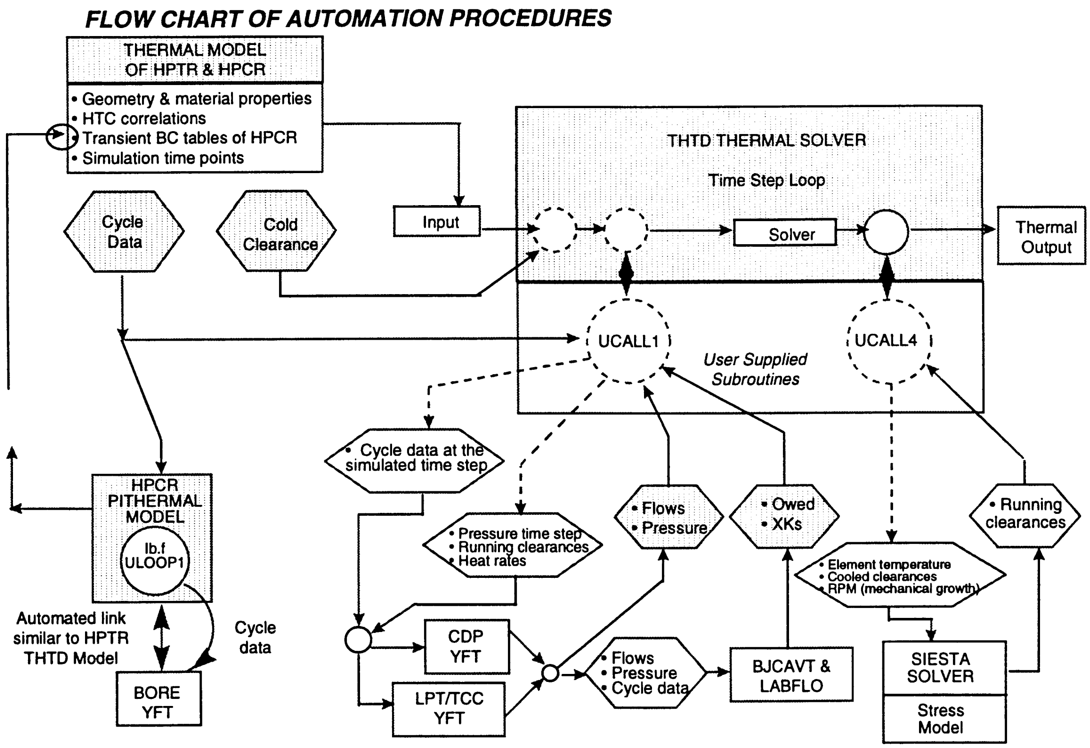


Figure 8-6. HPC/HPT Automated Thermal Analysis.

Performance deterioration will be addressed by conducting studies to reduce the relative rotor to stator deflections. These relative deflections cause blade tip rubs and subsequent deterioration in clearances. Very small clearance changes have a large performance effect in small engines since the clearance is a significant percentage of the annulus height. Architectural changes such as close coupled rotor and stator will be evaluated. Evaluations will include passive clearance and roundness control optimization studies. Active clearance control schemes will be included. Reducing the size of large engine clearance control concepts will be the challenge.

8.4 COMPRESSOR PERFORMANCE IMPROVEMENT

Compressor performance improvement is aimed at improving the clearance control of the blade tip and seal clearances through passive clearance control improvements. Studies will be conducted using an engineered, or non-linear alpha (coefficient of expansion), material in order to reduce the hot running clearance by half from approximately 0.020" to 0.010". It is anticipated that this will improve the compressor efficiency by up to 1.1%.

Other topics that will be investigated are a thinner (better controlled thickness) corrosion protection coating on the inlet airfoils in the turboprop application. It is anticipated that a potential 0.2% efficiency gain may be achieved by better controlling the thickness distribution of the coating and thus allow overall thinner coating with better preservation of the airfoil contours..

A study of the control and start bleed will be conducted with the intent of being able to increase the compressor operating line by approximately 0.2%. Also, studies will be conducted using data from the joint NASA/GEAE starting program on variable VG control with the objective of improving the axicentrifugal compressor dynamic matching. An overview of the NASA/GEAE starting program is given in Section 8.11.

The ROM cost for this task is $4,500K for the turboprop and $3,500 for the turbofan.

8.5 EXTENDED CAPABILITY IMPELLER

Improving impeller capability requires development of new materials and processes. A dual titanium alloy impeller which features an alloy with high temperature and creep capability near the tip and a different superior low cycle fatigue (LCF) alloy in the bore offers the potential to increase the tip speed and exit temperature. A metal matrix composite impeller provides still greater tip speed and temperature capability. Since the approach for this study did not increase the engine operative pressure ratio (OPR), it does not show the benefits of increased impeller capability. Increasing the impeller tip speed permits reduction in the number of stages required and reduces the overall cost. There are SFC benefits by increasing the OPR. Increased impeller capability is an enabling technology for future axicentrifugal engines with high OPRs. The discussion of materials and process assessments is included in Table 8-3.

8.6 TURBINE LEAKAGE AND COOLING AIR

The proposed tasks are to evaluate, design, manufacture, and test various new small engine cooling design schemes and materials applications in order improve part durability and cooling efficiency and to reduce parasitic losses. The significant efforts are to evaluate adding film cooling to small blades, to improve the cooling delivery system for improved efficiency, and to improve dirt/particle removal. The proposed tasks are to conduct studies to evaluate improved leakage management and reductions in turbine rotor cooling/leakage air. In addition airfoil cooling technology will be studied.

Optimization studies leading to configuration selection and demonstration tests will be conducted for improved cooling air delivery management and leakage reduction. These studies will include investigations of a floating nozzle configuration for improved leakage (objective of -0.2% cooling air), variable or modulated cooling air (objective of -0.5% cooling air at cruise), investigations of shroud cooling air reduction (objective of -0.3% cooling air), reduced rim cavity cooling (objective of -0.3% cooling air), a 360 degree ceramic shroud study (objective of-0.2% cooling air), an evaluation of an increased efficiency accelerator system (objective of -0.3% cooling air), reduced leakage labyrinth and brush seals will be investigated (objective of -0.2% cooling air), shroud diffusion shaped hole film cooling will be addressed (objective of -0.2% cooling air), blade platform cooling with wheel space purge injection will be evaluated (objective is +25F T41 temperature capability), and a flange design study for leakage reduction will be conducted (objective of -0.2% cooling air).

Airfoil cooling and optimization studies will be conducted for cooling air reductions and/or life improvements. These studies will include investigations of a five pass serpentine blade (objective of -0.5% cooling air), a study to investigate the effects of using improved materials such as ceramic and Nickel Aluminide (objective of +0.2% turbine efficiency), nozzle trailing edge cooling distribution for a tailored radial temperature profile at the nozzle exit (objective of +10F T41 capability), evaluations of making airfoil TBC coating prime reliable for increased life and a potential reduction of cooling air for 0.2% improvement in turbine efficiency, and an evaluation of a bonded blade (single crystal) with the intent of obtaining 1.0% reduction in blade cooling air.

Additional airfoil durability items which will be considered for study and evaluation of potential cooling air reductions and/or life improvements are: film cooling with diffusion shaped holes, blade tip cooling based on a CFD design, multi-stage gas temperature profile validation with blade time-unsteady average distortion, time-unsteady resolution/validation/design assessment of blade average film cooling, CFD analysis/design of internal/external heat transfer, blade serpentine channel turbulator

Table 8-3. Materials And Processes.

NASA -- Small Engine Technology Study

Materials and processes

Technology	Application	BENEFITS	Intro. Date	Further Development Required
Advanced third generation single crystal alloy	Turbine airfoils	Increased creep/rup. life (+50F), Increased LCF, Reduced cooling	Near term	None (only part scale-up)
Fourth generation SX alloy	Turbine airfoils	+100F over 2nd generation	Near/ Far	Alloy ident, prop, casting
Platinum-aluminide diffusion castings (Vapor Process)	Turbine airfoils	Improved environmental res. (>2X std), improved reliability surf. finish, chip resistance, coating uniformity)	Near term	None (only part scale-up)
Improved thermal barrier coatings (with enhanced bonding and thickness control/optimization)	Turbine airfoils combustor liners	Increased cyclic life, less cooling air, better environmental res., improved quality	Near term	None (only part scale-up)
Fabricated blades	Turbine airfoils	Enhanced cooling circuitry (reduced Cooling ~30%) better wall and dimen control	Near term	Bond development required for N6. Prop, verification
Ceramic Matrix Composite (SiC hogh conductivity and oxids low cond. systems to be considered)	Nozzle vanes	Higher temp. capability, reduced weight (~30%) better wall and dimen. control	Near term (1800F appl's.)	Trade-off studies required, material selection criteria to be identified, man"fg. scale-up required
			2005 (2400F appl"s.)	Trade-off studies, scale up
	Combustor Liners	Higher Temp. capability, reduced weight, less cooling	2005 (2400F)	Trade-off studies, scale up
Nickel-aluminide intermetallics	Nozzle vanes	Reduced weight (density=.22), Higher thermal cond. (2 to 5X) Higher melting point, R80 prop, Excellent oxidation resistance,	Near term	Better duct., str., and conductivity balance req'd.; Design studies/eval.

Table 8-3. Materials And Processes. (Continued)

Technology	Application	BENEFITS	Intro. Date	Further Development Required
Nickel-aluminide intermetallics	Turbine blades	Reduced wt, low inertia, N5 props	2005	Same as above
Ni-Al eutectics	Turbine airfoils	same as above+toughness/duct	2005	
Dual Property Disks KM4 rim/SR3 bore via forge enhanced bonding and/or single KM4 dual rim/bore heat treatment	Turbine/HPC	Higher rim creep resistance (+100F over R88DT), Higher bore LCF/tensile, reduced weight	Near term	Trade-off studies, heat treat fixturing, bond line definition/properties
Refined alloy	same	1500F capability	Near/far	Chem refine, process, prop.
Metal Matrix Composites (Ti6242/SiC)	Impeller	Reduced weight (~35%), improved clearance control, stiffness, low inertia	Near term	Current AF/Navy program JTAGG II proposal, scale-up req'd. from these efforts, need to reduce cost
	Shaft	same as above	Near term	Major design effort, need to reduce cost
MMC (Orthorhombic TiAlNb/SiC)	Shaft and Disk	same as above plus higher temp capability (1250F?)	2005	Mat'rl. ID, design studies, property database, man'f studies, NDE
Cast Gamma Titanium Aluminide (Ti-48Al-2Cr-2Nb)	LPT blades	Reduced weight, low inertia	Near term	Process scale-up, high temp prop. data, cost reduce, design methodology
	Exhaust Frame	Reduced weight	Near term	same as above
2nd Gen, Cast Gamma Titanium Aluminide	Blades, frames	Reduced weight (~50%), higher temps.	2005	Alloy/Process scale-up, prop. definition
Wrought Alpha-two titanium aluminides	HPC blades, exhaust parts	Reduced weight, improved duct. and lower modulus than gamma	2005	Alloy/Process scale-up prop. definition

Table 8-3. Materials And Processes. (Continued)

Technology	Application	BENEFITS	Intro. Date	Further Development Required
Orthorombic Titaniium Aluminide	Frames, strustures	Improved toughness and str. over other aluminides, lower COE (tip clearance)	2005	same as above
High Temperature Polymeric Composite	Front frame	Temperature appl. to 550F, Reduced weight	Near term	Process/part scale-up, prop. data
Advanced bearing materials (SiN and corrosion resistant alloy)	Bearings	Improved durability	2005	SiN currently inder test in JTAGG--would need design study and process scale-up plus property data. Corr. Res. alloy needs development

Note: Direct contract and/or IR&D funding has supported and in many cases continue material and technology developments. Many of the above technologies have been proposed for GE23A and JTAGG-II. Some will be demonstrated in conjunction with JTAGG-I plus.

based on CFD heat transfer evaluations with rotation/buoyancy considered, nozzle and blade 3-D-CFD heat transfer coefficient distribution, heat transfer enhancement using features such as: film cooling, blowing ratio/orientation/hole spacing, ultra-small film cooling hole design functionality, internal sand particle CFD trajectory serpentine separator, substitution of materials with hot section high temperature alloys, advanced third generation single crystal alloy, fourth generation SX alloy, and Platinum-Aluminide coatings.

For these studies the potential reduction in cooling air for the turboprop could be in the range of -2.4% cooling air at high power and -2.9% cooling air at cruise. Additional potential benefits include +0.2% high pressure turbine efficiency and an increase in the turbine temperature capability of plus 50 to 100^{O}F. For the other engine, the turbofan, these studies indicated that the potential reduction in cooling air could be in the range of -1.9% cooling air at high power and -2.4% cooling air at cruise. Additional potential benefits include +0.2% high pressure turbine efficiency, and plus 50 to 100^{O}F in turbine temperature. The estimated development cost for these efforts is $6,800K for the turboprop and $6,600K for the turbofan.

8.7 MECHANICAL SYSTEMS

All rotating machinery has to balance the axial thrust load for bearing life. High pressure ratio cycles are very sensitive and more difficult to size axial loads than lower pressure cycles. In order to assure designs that will not have potential of needing major design changes if the axial load sizing is missed, cavity pressure adjustment is needed to be able to set the loads on the thrust bearings.

Aspirating seals are low leakage seal leakage seals that can provide this adjustment feature either as a fixed adjustment or a modulated adjustment. Modulation may be desirable to reduce fuel consumption at low operating pressure ratios or to avoid thrust load crossovers and potential skidding situations due to low thrust loads. Development is needed for introduction of this type of seal.

For small engines with impellers, a double wall swirl plate for flow bypass to control the radial pressure gradient can be used as a fixed or modulated adjustment for thrust bearing loads. Tests will be conducted on prototype configurations to evaluate the range of control/adjustment available.

Another area associated with mechanical systems is the design of casing flanges. These features have to contain high pressure air with a minimum of leakage. In small engine configurations this leakage can become a significant portion of the engine airflow. This task will investigate features to reduce flange leakage and establish criteria for the various parameters to maintain the leakage at a low level. Parameters to be studied will include bolts (size and quantity), flange thickness, and geometry.

The overall goals are a reduction of 0.5% in cooling air and in increase in the operating line of 0.2% for the turboprop application. It is anticipated that the weight increase would be limited to six pounds and increases in engine costs would be limited to $3500. For the turbofan application the goals are to reduce the cooling air (leakage) by 0.3% and increase the operating line by 0.2%. It is anticipated that the weight increase would be limited to thirteen pounds and increases in engine costs would be limited to $3500. The development are estimated to be #1200K for the turboprop and $800K for the turbofan.

8.8 MATERIALS

The materials laboratory continuously has ongoing programs to enhance the capability of gas turbine engines. The main objectives are to increase life, temperature capabilities, improve dimensional control, reduce weight, etc. Table 8-3 was put together to illustrate the various programs that would benefit from AST programs. Various item which could be considered under this task include MMC material (Ti-6-2-4-2/SiC) for impellers (+life), NiAl for HPT Vanes (+life), Dual Alloy/Property Disks (-10% weight), advanced third generation single crystal alloy (+life, +50F), fourth generation SX alloy (+life, +100F), Platinum-Aluminide coatings (+life), thermal barrier coatings (+life, +0.2% efficiency), fabricated blades (-30% cooling) (-1.0% cooling air), ceramic matrix composites (nozzles) (-cooling air, +0.2% efficiency, -30% weight), Nickel Aluminide intermetallics (Nozzles & Blades) (-cooling air, -weight), metal matrix composites (Impeller & Shaft) (-35% weight), cast Gamma Titanium Aluminide (-weight), second generation cast Gamma TiAl (Blade/Frame) (-50% weight), high temperature polymeric composites (-weight), and advanced bearing materials (+life).

8.9 DESIGN/MANUFACTURING LCC REDUCTIONS

The team of specialists from the engineering sections working the two product lines that were used for the baseline engine cycles and various other engine programs within the small engine department contributed several items that were aimed at reducing costs and weight rather than performance improvements. The recommendations, again, were based on current and future technical requirements, production needs, and customer needs.

The items that were specified included using an environmentally friendly IGV material, Cast in trailing edge slots in the small turbine blades, replace curvic joints with rabbet joints, introduce a simplified cooling plate snap ring, use a low weight , low alpha (coefficient of expansion) material for weight reduction and possible reduced cooling air. The objectives are a cost reduction of $3500 for the turboprop and $2500 per engine for the turbofan, with 1 pound and 2 pound weight reduction objectives, respectively. The individual items are tabulated in Appendix B.

8.10 EXHAUST SYSTEMS DESIGN

This effort involves evaluating a low loss exhaust frame for the turboprop application The study will involve an aero study to determine if improved pressure loss characteristics can be achieved in the outlet guide vane which are used to reduce the swirl exiting the power turbine. This effort will involve a design with a rig or engine test to validate potential savings. If a turbine aero redesign is undertaken this effort would be consolidated with that task. Additionally an analytical engine cycle study will be conducted to determine potential benefits of considering a variable exhaust nozzle for the turboprop. The ROM costs are $2,200K.

8.11 ENGINE STARTING SYSTEMS

Technology advances achieving higher engine pressure ratios, improved performance, cost and emissions increase the challenge of starting engines. Limitations on starting system power weight and cost translate into reduced engine starting torque requirements. Starting technology improvements are required to reduce increases in starting energy. Unassisted (windmill) start and restart capability improvements are required for improved reliability.

An ongoing program with GEAE, GE's Corporate Research and Development (CR&D) Center, the Vehicle Propulsion Directorate, and NASA was initiated in 1994 to reduce starting power requirements. The overall objectives of that program are to develop methodology, feasibility of and concepts for improved starting for near term as well as longer range axial centrifugal product applications. The specific objectives of the program are:

1 Obtain fundamental starting stall transient data to fully characterize aero thermo transients and establish high potential concepts for near term starting torque, temperature and time reductions.

2 Complete generic starting methodology aero thermo transient overall system trade studies of improved starting concepts.

3 Develop and validate starting improvements.

The key activities of the program are to establish key concepts, perform a starting test on a T700 engine, create a generic axial-centrifugal starting model, and then conduct conceptual trade studies. This will be followed a validation of the key concepts at both sea level and altitude to validate the start model.

This program will provide studies to identify the concepts to be applied to product applications with the intent of obtaining performance improvements. Many of the potential performance benefits will be possible by improved starting stall control. Items to be investigated will include evaluation of a variable start bleed schedule, variable VG control, and a low mass impeller for reduced rotor inertia. The overall objectives are to achieve the capability of sizing the engine for 0.3% higher operating line for improved performance. The ROM costs are $2,500k for the turboprop and $1,500k for the turbofan.

8.12 INLET SYSTEM DESIGN FOR TURBOPROPS

The proposed tasks will consist of investigating the inlet design of the turboprop configuration. The various separate efforts to be undertaken include evaluation of a low pressure loss inlet particle separator (IPS) with an objective improvement of 0.002 pressure loss (dp/p), an improved bird separation capability (which may create an increase of 0.001 dp/p pressure loss and up to an increase of one pound in weight), improved ice and slush separation capability (which will help avoid in flight power interruptions), an ice tolerant stage one blade with improved performance of +0.1% efficiency. The anticipated overall effects of this study are a reduced inlet pressure loss of 0.001 dp/p, +0.1% efficiency, and +1.0 pound in weight of the inlet system. The estimated development costs for the evaluation are $900K.

9.0 DISCUSSION OF RESULTS

The ranking procedure was formulated to evaluate the best payback for the development dollar spent for each of the technology groupings. It is the same procedure used to rank technologies for the large engines in the NASA AST Program. The process involved the identification of technologies and the determination of the prospective economic benefits.

The ranking factor, or factor of merit (FOM), consists of multiplying the value to the airline, times the probability of success in implementing the technology, all divided by the development costs, as illustrated in the following equation:

FOM = (Value to Airline X Probability of Success) / (Development Cost)

The turbofan ranking was based on the baseline mission for the 50 passenger Canadair RJ with the CF34-3A1 engine. The baseline mission for this engine has a 600 NM sector as illustrated in Figure 5-2. Resulting data for the ranking of the turbofan application is tabulated in Table 7-4.

The turboprop ranking was based on the baseline mission for the 34 passenger SAAB-S-340B with the CT7-9 engine. The baseline mission for this engine has a 200 NM sector as illustrated in Figure 5-2. Resulting data for the ranking of the turboprop application is tabulated in Table 7-1.

Based on DOC and FOM comparisons, the five technology groupings that showed the highest reduction in %DOC/$Mil were similar for both the turbofan and the turboprop. The top two were the clearance control improvement and the control system development.

Trends for operating costs and capacity for the turbofan application is shown in Figure 5-4. The figure illustrates that the trends are towards increasing passenger size which improves the direct operating costs per available seat mile (ASM). However, the turboprop application will probably not experience as much increase in passenger capacity as will the turbofan.

The engine contribution to the aircraft direct operating costs (DOC) for the turbofan and the turboprop application is 36% and 28%, respectively with only 18% and 10% respectively, of the DOC affected by the fuel costs. This is illustrated in Figure 5-3. This low contribution of the fuel costs makes it difficult to influence the overall DOC by sfc improvements alone. In fact, a one percent improvement in engine sfc for the CF34-3A application would result in approximately 0.12% improvement in the DOC and for the Saab S340 application would result in approximately .088% improvement in DOC.

However, significant improvements in DOC can be achieved when the aircraft capacities can be increased (perhaps with a plug to increase the length and add one or more seat rows of passengers) when more power can be made available in the engine. For the turbofan study, Figure 5-7 illustrates this effect. For example, referring to the figure, if a seven percent increase in thrust could be made available to support an aircraft modification to add two seat rows, a ten percent reduction in DOC could be achieved.

For the turboshaft study, Figure 5-11 illustrates this effect. For example, referring to the figure, if a seven percent increase in shaft horsepower could be made available to support an aircraft modification to add two seat rows, a thirteen percent reduction in DOC could be achieved.

10.0 CONCLUSIONS, SUMMARY, AND RECOMMENDATIONS

The future 2005 turbofan regional engine will be a CF34 derivative in the 15 to 16,000 pound thrust range. GEAE has been conducting cycle calculations and parametric studies for growth beyond CF34-8C (GEAE's 1999 entry into service regional turbofan) for use in projecting our customers' future engine needs. These parametric studies have included variations in cycle parameters including: pressure ratio, airflow, bypass ratio, firing temperature, engine size and weight, etc.

For regional aircraft applications for the future, the GEAE conclusions are based on these studies and on business assessments of the airline growth trends. These growth trends point to the need to put more thrust into the same size engine to minimize aircraft costs increases and drag increases as the aircraft is increased in passenger capacity. Thus, the vision of the future 2005 product engine is projected to be a higher thrust derivative of the growth CF34-8C.

The future engine has goals that are consistent with NASA goals set forth in the AST program. These include increasing the overall cycle pressure ratio for improved performance/sfc benefits, operating the cycle at higher turbine inlet temperatures, airflow increases for the aircraft and engine system improved economics relating to DOC. The net improvement in DOC for the future derivative engine in the future aircraft application is anticipated to be 28% including the effect of higher number of passengers for the stretched aircraft with very little increase in the engine size.

	NASA Goals	*CF34-3A1 Baseline*	*CF34-3A1 Base T41*	*CF34-8C1 EIS 1999*	*CF34-xxx EIS 2005*
Fuel Efficiency (sfc)	**-10%**	Baseline	**-4.0%**	-3.7%	**-9.0%**
DOC (%/ASM)	**-5%**	Baseline	**-1.3%**	-11.0%	**-28.0%**
Passengers		50	**50**	72	**90**
Regional Technologies Applied		no	**yes**	no	**yes**

Engine cycle studies for turbofan engines in the CF34 family have shown that the technology improvements evaluated for the CF34-3A1 (baseline study engine cycle) which powers the commercial Canadair Regional Jet are directly applicable to the Canadair Business Jet engine CF34-3B and to the growth regional jet engine, the CF34-8C now in development for entry into service in 1999 on the Canadair RJX. The future 2005 derivative engine applies the study technologies to the CF34-8C in order to provide a path to successfully transition these technologies to a product that fits into the business projections of the size engine needed for the regional aircraft anticipated for the year 2005.

This growth derivative product will insert technology items from the Regional Aircraft Propulsion Technology Program with NASA, items from other NASA AST Programs, and also from technologies developed through GEAE IR&D programs and GEAE demonstrator programs such as the GE23A and the JTAGG programs.

The Regional Aircraft Propulsion Technology Program identified several areas where development of technology can significantly improve the DOC by supporting the future aircraft trends such as increased capacity to be achieved through aircraft modifications (for example, insertion of sections in the fuselage for increased passenger capacity). This translates to supporting a real customer need of increased thrust and increased power engines without engine envelope changes. Component programs such as those identified in the Regional Aircraft Propulsion Technology Program and examples listed as follows are essential for GEAE to be ready to insert the improvements into products when they are needed.

Turbine technology improvements are included in these technologies and were included in NRA abstracts combined with large engine NRA proposals for maximum funding efficiency. Turbine technology was a high benefit from the Regional Aircraft Propulsion Technology study and regional engines will utilize the results of the large engine turbine technology programs.

The low emissions combustor for the advanced engine will meet NASA's low emission goals. This component requirement doesn't affect the sfc and wasn't included in the acquisition costs used in the ranking. However, additional technology development is required to achieve low emissions needs. The initial results from current NASA program that GEAE is conducting has indicated that the effect on DOC (by way of acquisition costs) could vary up or down depending on the solution. The current approach under study may result in no increase to the combustor cost, depending in the outcome of the program.

Dual alloy impeller advantages did not rank high in the turboprop study due to the parameters used to conduct the ranking. However, the dual alloy configuration is a significant enabling technology providing significant advantages of life and weight. In fact, the dual alloy is required to achieve impelle life at high overall cycle pressure ratio (higher rotor speeds) planned for future engines with axicentrifugal compression systems.

Continued support of each of these development tasks is recommended along with consideration of initiating efforts on the top two technology groupings identified in this study. These top two items can be developed on the CF34 turbofan family of engines and be ready for transition into a product line by the year 2005.

APPENDIX A - LIST OF TECHNOLOGY INPUTS

- **Inlets, Particle Separators**

01 Low Pressure Loss IPS (T/S)
02 Cast Aluminum Frame
03 Bird Separation Capability
04 Improved Ice/Slush Separation Capability
05 High Efficiency Blower

- **Fan**

06 Larger Bird Strike Capability
07 TF34 EGV's Improve Aero Perf/Noise

- **Compressor (Turbofan)**

08 Improved Materials for Higher T3

- **Compressor (TP/TS)**

Axial Compressor:
09 Ice Tolerant Stage One Blade
10 Removable Stage One Blade (CT7 Family)
11 Thin Corrosion Protection Coating
12 Environmentally Friendly IGV Material
13 Control/Bleed Integration (Variable Start Bleed)
14 Variable VG Control
Centrifugal Compressor:
15 Improved LCF Impeller Alloy (Cast Wrought CH22)
16 Manufacturing Process to ECM Impeller
17 Low Mass Impeller (Ti, TiNio, Etc.)

- **Combustor**

18 LEC Technology applicable to Small Engine (Pre Mix/Pre Atomizing)
19 Advanced Auto-Relight System
20 Clean Source of Cooling Air
21 Ceramic
22 Low Pattern Factor Injector/Combustor
23 Anti-Coke Injectors

- **Stage One Turbine Nozzle**

24 Ceramic
25 Transpiration Cooled Tailored with Combustor for Stg 1 Blade
26 Optimized Radial Temp Profile
27 Floating for Improved Leakage

APPENDIX A - LIST OF TECHNOLOGY INPUTS (continued)

- **GG or HP Turbines**

28 Non-Powder High LCF Capable Material
29 Cast in TE Slots in Small Blades
30 Non-Linear Alpha Material
31 3-D Aero Design
32 Variable Cooling Air
33 Shroud Cooling Air Reduction
34 Improved Passive Clearance Control
35 Active Clearance Control
36 Reduced Rim Cavity Cooling
37 Five Pass Serpentine Blade
38 TBC Coating and Final Surface Finish
39 Bonded Blade (Single Crystal)
40 Roundness Control
41 360 Ceramic Shrouds
42 Flared Stage 2 HPT (CT7)
43 Film with Diffusion Shaped Holes
44 Blade Tip Cooling CFD Design
45 Multi-Stage Gas Temperature Profile Validation With Blade Time-Unsteady Average Distortion
46 Time-Unsteady Resolution/Validation/DesignAssessment of Blade Average Film Cooling
47 CFD Analysis/Design of Internal/External HT
48 Increased Efficiency Accelerator Rotor Cooling System.
49 Reduced Leakage Labyrinth Seals
50 Shroud Diffusion Shaped Hole Film Cooling
51 Blade Serpentine Channel Turbulator CFD heat TransferWith Rotation/Buoyancy
52 Nozzle and Blade 3-D-CFD Heat Transfer Coefficient Distribution
53 Blade Platform Cooling With Wheel Space Purge Injection
54 Heat Transfer Enhancement with Film Cooling Blowing Ratio/Orientation/Hole Spacing
55 Ultra-small Film Cooling Hole Design Functionality
56 Internal Sans Particle CFD Trajectory SerpentineChannel Separator

- **Power Turbine And Transition Duct**

57 Low Loss Interturbine Duct
58 Variable A45
59 Flared Flow Path (CT7)
60 Reduced Leakage Shrouds
61 Improved Case Cooling

- **Mechanical Systems**

62 Double Wall Swirl Plate (Rotor Thrust Control)
63 Hydraulic vs. Pneumatic (No BP Seal) (Rotor Thrust Control)
64 Brush Seals
65 Bearing improvements
66 Flange Design
67 Improved Carbon Seals
68 Reduced Oil Film Bearings

APPENDIX A - LIST OF TECHNOLOGY INPUTS (continued)

- **Exhaust Systems**

70 Low Loss Exhaust Frame
71 Variable Exhaust Area (CT7)
72 Integral IR Suppresser
73 Improved IR Suppresser
74 Noise Suppression
75 Mixer Development
76 Ejector Systems Design

- **Controls and Accessories**

77 FADEC Applications: Variable Schedules
78 FADEC: More Memory/Throughput
79 CPU: Compatible With Auto Code
80 Utilities Services: Integration With Aircraft Systems
81 Information Systems: Processing And diagnostics Improved On Board Monitoring
82 Starting Strategies: Starting Scheduling Studies
83 Starters/Systems: Electrical, Jet Fuel Starters
84 T2 Sensor: Fast Response CT7/T700
85 Torque Sensor: Cold Section Trimable Sensor
86 T41 Control (CT7): High Tech Control Mode
87 Power Management System (CT7)
88 Turbo Cooling: IR Suppression ,Case Cooling,
89 LEC, Cooled Turbine C/A
90 Harnesses/Cables: Light Weight

- **Propeller Gearbox**

91 Increased Capacity/Durability Eliminate: Damper Ring Wear, Idler Gear Failure
92 Increased Capacity/Durability Eliminate: Cadmium Protective Coating
93 Integrated Control With Engine Control
94 Improved Blade Deicing, Spinner Anti-icing
95 Capability For Counter Rotation

- **Training**

96 Generic 3-D Design Capability Integrated Modeling

- **Potential High Altitude Application**

97 Extract Power (AGB, Customer) From LP Spool Instead of Core
98 Combustion System- Air Starting: High Altitude Ignition
99 Combustion System- Air Starting: Improved Capability With Heavier Fuels (JP-8)

APPENDIX A - LIST OF TECHNOLOGY INPUTS (continued)

- **Materials**

100 New Materials Directly Applicable To Existing Designs: Hot/Section High Temp Alloys
101 New Materials Directly Applicable To Existing Designs: CMC, MMC for Weight Reduction
102 New Materials Directly Applicable To Existing Designs: J85 VEN Leaves/TF34 Fan Casing
103 MMC SiC(Ti-6-2-4-2) Impeller
104 NiAl HPT Vanes
105 Dual Alloy Disks
106 Improved Shaft Alloy
107 Advanced Third Generation Single Crystal Alloy
108 Platinum-Aluminide Coatings
109 Thermal Barrier Coatings
110 Fabricated Blades
111 Ceramic Matrix Composite
112 Nickel Aluminide Intermetallics
113 Dual Property Disks
114 Metal Matrix Composites
115 Cast Gamma Titanium Aluminide
116 High Temperature Polymeric Composite
117 Advanced Bearing Materials

APPENDIX B - GROUPINGS OF TECHNOLOGY CATEGORIES

Technology Items in Each Technology Grouping

AREA OF ENGINE / TECHNOLOGY GROUPING Rating Item		Development Cost
A) INLET SYSTEM DESIGN FOR TURBOPROP		
01	Low Pressure Loss IPS* (-.002 pressure loss (dp/p))	300K
03&04	Improved Bird Separation Capability (+.001 pressure loss, +1 lb) Improved Ice/Slush Separation Capability (avoid power interruptions)	300K
09	Ice Tolerant Stage One Blade (+0.1% efficiency)	300K
	*IPS= Inlet Particle Separator	
SUMMARY - OVERALL GOALS AND DEVELOPMENT COST	(-.001 pressure loss, +0.1% efficiency, +1.0 lb)	900K
B) EXTENDED IMPELLER CAPABILITY FOR INCREASING CYCLE SPEEDS		
15&17	Improved LCF Impeller Alloy(Cast Wrought CH22) (+ Life, -3 lb) Low Mass Impeller (Ti, TiNio, Etc.)(Target 30,000 cycles)	500K
16	Manufacturing Process to ECM Impeller (+0.2% efficiency, -$500[1])	200K
57	Replace Curvic Joints With Rabbet Joints (+Life, $1000[2])	300K
	1 One Third of Impeller Machining Cost 2 Per engine benefit would be <$1000	
	Investigate materials and testing of new hardware	1500k
SUMMARY - OVERALL GOALS AND DEVELOPMENT COSTS	(+Life, +0.2% efficiency, -$1500, -3 lb)	2500K

APPENDIX B - GROUPINGS OF TECHNOLOGY CATEGORIES (Continued)

AREA OF ENGINE / TECHNOLOGY GROUPING Rating Item		Development Cost
C) COMPRESSOR PERFORMANCE IMPROVEMENT		
08	Engineered Alpha materials for Clearances (+1.1% efficiency)	$1500K
11	"*Thinner*" Corrosion Protection Coating (T/P) (+0.2% efficiency)	$1000K
13	Control/Bleed Integration (Variable Start Bleed) (+0.2% operating line)	$ 500K
14&83	Variable VG Control for Starting Benefits (+0.2% operating line)	$ 500K
	Axi/Cent Compressor Dynamic Matching (-cost, -2 lb)	$1000K
SUMMARY -	T/P OVERALL GOALS AND DEVELOP COSTS (+0.3% operating line, +1.3% efficiency, -cost, -2 lb	$4,500K
SUMMARY -	T/F OVERALL GOALS AND DEVELOP COSTS (+0.3% operating line, +1.1% efficiency)	$3,500K
D) INTEGRATED 3-D TURBINE AERO DESIGN		
31	3-D Aero Design (T/P +1.4 to 2.0 points efficiency)	12,000K
	(T/F +1.0 to 1.5 points efficiency)	13,000K
42	Flared Stage 2 (CT7)(+0.2 points GGT efficiency, -.002 dp/p duct) note*	
60	Low Loss Interturbine Duct (-.002 dp/p duct) note*	
61	Variable A45 (T/P CYCLE STUDY) (improved cycle match, increased weight and complexity)	
62	Flared PT Flow Path (CT7) (+0.1 points efficiency, -.01 to .02 dp/p exhaust) note*	
74	Low Loss Exhaust Frame (-.002 dp/p) note*	1,000K
	note* T/P 3-D Aero would include these line items!	
SUMMARY -	T/P OVERALL GOALS AND DEVELOP COSTS (1.5 to 2.2 points efficiency, -.004 dp/p duct, -.022 dp/p exhaust)	12,000K
SUMMARY -	T/F OVERALL GOALS AND DEVELOP COSTS (1.0 to 1.5 points efficiency)	13,000K

Note:

Cost	CT7	CF34
HPT	7.5	7.5m
LPT	4.5	5.5m
Sum	12.0	13.0m

Efficiency Improvement	CT7	CF34
HPT	2.0	1.0
LPT	1.4	1.5

APPENDIX B - GROUPINGS OF TECHNOLOGY CATEGORIES (Continued)

AREA OF ENGINE / TECHNOLOGY GROUPING Rating Item		Development Cost
E) REDUCTIONS IN TURBINE LEAKAGE/COOLING & IMPROVED DURABILITY		
IMPROVED LEAKAGE MANAGEMENT and REDUCTION (Optimization studies/tests/selection)		
27	Floating Nozzle for Improved Leakage (-0.2% cooling air)	200K
32	Variable Cooling Air (Reduced @ Cruise,) (-0.5% cooling air at cruise)	300K
33	Shroud cooling air reduction (-0.3% cooling air)	100K
36	Reduced rim cavity cooling (-0.3% cooling air)	200K
41	360 Ceramic Shrouds (-0.2% cooling air)	100K
48	Increased Efficiency Accelerator System (-0.3% cooling air)	200K
49	Reduced Leakage Laby & Brush Seals (-0.2% cooling air)	100K
50	Shroud Diffusion Shaped Hole Film Cooling (-0.2% cooling air)	100K
53	Blade Platform Cooling With Wheel Space Purge Injection (+25F T41 temperature capability)	300K
70	Flange Design for leakage Reduction (-0.2% cooling air)	200K
AIRFOIL COOLING TECHNOLOGY (Optimization studies/tests/selection)		
37	Five Pass Serpentine Blade (-0.5% cooling air)	
24	Materials: Ceramic, Nickel Aluminide (+0.2% efficiency)	
26	Tailored Radial Temperature Profile at Nozzle Exit: TE Cooling Distribution (+10F capability)	
38/105	Prime Reliable TBC Coating (+Life, +0.2% efficiency)	
39/106	Bonded Blade (Single Crystal) (-1.0% cooling air)	
43	Film with Diffusion Shaped Holes (Study and select configuration)	
44	Blade Tip Cooling CFD Design (Study and select configuration)	
45	Multi-Stage Gas Temperature Profile Validation With Blade Time-Unsteady Average Distortion (Study and select configuration)	
46	Time-Unsteady Resolution/Validation/Design Assessment of Blade Average Film Cooling (Study and select configuration)	
47	CFD Analysis/Design of Internal/External HT (Study and select configuration)	
51	Blade Serpentine Channel Turbulator CFD Heat Transfer With Rotation/Buoyancy (Study and select configuration)	
52	Nozzle and Blade 3-D-CFD Heat Transfer Coefficient Distribution (Study and select configuration)	
54	Heat Transfer Enhancement: Film Cooling, Blowing Ratio, Hole Orientation, and Hole Spacing (Study and select configuration)	
55	Ultra-small Film Cooling Hole Design Functionality (Study and select configuration)	
56	Internal Sand Particle CFD Trajectory Serpentine Separator (Study and select configuration)	
96	Substitute Hot/Section High Temp Alloys (+Life) (Study and select configuration)	
103	Advanced Third Gen Single Crystal Alloy (+Life, +50F capability) (Study and select configuration)	
104	Fourth Generation SX Alloy (+Life, +100F capability) (Study and select configuration)	
105	Platinum-Aluminide Coatings (+Life) (Study and select configuration)	

SUMMARY -	T/P OVERALL GOALS AND DEVELOP COSTS (-2.4% cooling air, +0.2% HPT eta, +50-100F,± lb (tbd) (-2.9% cooling at cruise)	6,800K
SUMMARY -	T/F OVERALL GOALS AND DEVELOP COSTS (-1.9% cooling air, +0.2% HPT eta, +50-100F,± lb (tbd) (-2.4% cooling at cruise)	6,600K

APPENDIX B - GROUPINGS OF TECHNOLOGY CATEGORIES (Continued)

AREA OF ENGINE / TECHNOLOGY GROUPING Rating Item		Development Cost

F) CLOSE TOLERANCE HPT TURBINE CLEARANCE CONTROL

30&65	Non-Linear/Engineered Alpha Material Low Weight Low Alpha Case Material (-0.2% cooling air, +1% efficiency, -1 to 2 lb)	1000K
34	Passive Clearance Control, Reduce SS Clearances and Deterioration (-0.2% cooling, +1% cruise efficiency, -3 to 8 lb)	1000K
35	Active Clearance Control (T/P) (+1% cruise efficiency, +3 lb)	500K
40	Roundness Control (T/P) (+0.2% efficiency)	100K
41	360 Ceramic Shrouds (T/P) (-0.2% cooling air)	100K
	* Redline Margin Requirement: Less Deterioration	

SUMMARY - T/P OVERALL GOALS AND DEVELOP COSTS (-0.4% cooling, +0.2% efficiency, +50F, -4 lb) (+0.9% cruise efficiency)	2,700K
SUMMARY - T/F OVERALL GOALS AND DEVELOP COSTS (-0.3% cooling, +1.0% cruise efficiency, +50F, -10 lb)	2,000K

G) DESIGN/MANUFACTURING LCC REDUCTIONS

12	Environmentally Friendly IGV Material (-cost*)	(tbd)
28	Non-Powder High LCF Capable Material (+life, -cost, -weight)	(tbd)
29	Cast in TE Slots in Small Blades (-$500[1])	1000K
57	Replace Curvic Joints With Rabbet Joints(T/P) (-$1000[2])	1000K
58	Simplified Cooling Plate Snap Ring (-$2000[2])	500K
65	Low Weight Low Alpha Case Material (-0.2% cooling air, -1 to 2 lb)	1000K
92	Generic 3-D Design Capability Integrated Modeling (+life, -weight)	(tbd)

* Eliminate Undesirable Machining Process
1) Will vary depending on number of blades
2) Per engine cost benefit

SUMMARY - T/P OVERALL GOALS AND DEVELOP COSTS (-0.2% cooling air, -$3500, -1 lb)	3,500K
SUMMARY - T/F OVERALL GOALS AND DEVELOP COSTS (-0.2% cooling air, -$2500, -2 lb)	2,500K

APPENDIX B - GROUPINGS OF TECHNOLOGY CATEGORIES (Continued)

AREA OF ENGINE / TECHNOLOGY GROUPING Rating Item		Development Cost
H) MECHANICAL SYSTEMS/SEALS	(Rotor Thrust Control, Leakage, Bearing Life)	
66/67	Rotor Thrust - Double Wall Swirl Plate, Hydraulic vs. Pneumatic, No BP Seal (-0.2% cooling air, +0.2% op line, <+$2000, +4 lb)	400K
68	Brush /Advanced Seals (-0.2% cooling air, <+$2000, +1 to 12 lb)	500K
69/115	Bearing Improvements (+Life)	100K
70	Flange Design for Leakage Reduction (-0.2% cooling air, +$500, +1 lb) (Bolts, Thickness, Geometry)	200K
SUMMARY -	T/P OVERALL GOALS AND DEVELOP COSTS (-0.5% cooling air, +0.2% op line, +$3500, +6 lb)	1200K
SUMMARY -	T/F OVERALL GOALS AND DEVELOP COSTS (-0.3% cooling air, +0.2% op line, +$3500, +13 lb)	800K
I) EXHAUST SYSTEMS DESIGNS (T/P)		
74	Low Loss Exhaust Frame (-0.2% pressure loss)	2000K
75	Variable A8 (CT7) (Cycle Study)	200K
SUMMARY -	OVERALL GOALS AND DEVELOPMENT COSTS (-0.2% exhaust pressure loss plus Variable A8 Benefit)	2200K
J) ENGINE STARTING SYSTEMS		
13	Control/Bleed Integration (Variable Start Bleed) (+0.2% operating line)	500K
14	Variable VG Control For Starting Benefits (+0.2% operating line)	500K
17	Low Mass Impeller (Ti, TiNio, Etc.) (-3 lb)	500K
83	Axi/Cent Compressor Dynamic Matching, See 13/14(-cost, -weight)	1000K
93	Improved Power Extraction (AGB, Customer Power Extraction Possibly From LP Spool Instead Of Core (Study)	(tbd)
94	High Altitude Ignition Improvement (Study)	(tbd)
95	Improved Capability With Heavier Fuels (JP-8) (Study)	(tbd)
SUMMARY -	T/P OVERALL GOALS AND DEVELOP COSTS (+0.3% operating line, -3 lb)	2,500K
SUMMARY -	T/F OVERALL GOALS AND DEVELOP COSTS (+0.3% operating line)	1,500K

APPENDIX B - GROUPINGS OF TECHNOLOGY CATEGORIES (Continued)

AREA OF ENGINE / TECHNOLOGY GROUPING Rating Item		Development Cost
K) MATERIALS STUDY/EVALUATION ITEMS & GOALS		
	(Several Items are addressed in other lists)	
	New Materials Directly Applicable to Existing Designs	
96	Hot/Section High Temperature Alloys (-weight, -cooling air)	
97	CMC, MMC for Weight Reduction (-weight)	
98	CF34 Fan Casing (-weight)	
99	MMC SiC(Ti-6-2-4-2) Impeller (+life)	
100	NiAl HPT Vanes (+life)	
101/110	Dual Alloy/Property Disks (-10% weight)	
103	Advanced Third Generation Single Crystal Alloy (+life, +50F)	
104	Fourth Generation SX Alloy (+life, +100F)	
105	Platinum-Aluminide Coatings (+life)	
106	Thermal Barrier Coatings (+life, +0.2% efficiency)	
107	Fabricated Blades (-30% cooling) (-1.0% cooling air)	
108	Ceramic Matrix Composite (Nozzles) (-cooling air, +0.2% efficiency, -30% weight)	
109	Nickel Aluminide Intermetallics (Nozzles & Blades) (-cooling air, -weight)	
111	Metal Matrix Composites (Impeller & Shaft) (-35% weight)	
112	Cast Gamma Titanium Aluminide (-weight)	
113	2nd Generation Cast Gamma TiAl (Blade/Frame) (-50% weight)	
114	High Temperature Polymeric Composite (-weight)	
115	Advanced Bearing Materials (+life)	
SUMMARY - OVERALL GOALS AND DEVELOPMENT COSTS	(-1.0% cooling, +0.2% efficiency, + 50 to 100F, -lb)	$4,000K
L) CONTROLS AND ACCESSORIES		
81	Control Modes Study/Evaluation	1,852K
	A) Model Based (+2 to 3% power, -2% cost, -2% weight)	
89	B) Performance Seeking (-2 to 5% fuel burn, +1 to 2% power)	
	C) T/P Power Management (+Life)	
82	Low Cost Architecture With Reduced Part Count	
	Fuel, Lube & Gear Box Integration (-33% cost*, -30% weight*)	1,212K
84	Electrical System Integration (-cost, -weight)	851K
85	Advanced Torque Sensor (T/P) (+1% power, -cost, -weight)	500K
	* Fuel, Gear Box, and Lube System Reduction	
SUMMARY - OVERALL GOALS AND DEVELOP COSTS (t/p)	(+Life, -(2) to 5% fuel burn, +(3)-6% power, -$10k, -9 lb)	4,415K
-OVERALL GOALS AND DEVELOP COSTS (t/f)	(+Life, +(3) to 5% power, -$30K, -35 lb)	3,915K

APPENDIX C - ECONOMIC ASSUMPTIONS

The economic assumptions used in the overall airline economics evaluation are itemized the following table:

o Cost is direct operating cost including depreciation and interest
o Cost shown at maturity
o 1994 US dollars
o Fuel costs = 75 cents per US gallon
o Insurance = 1/2% aircraft price per year
o Engine spares = 30% engine price
o Aircraft Spares = 6% airframe price
o Depreciation: aircraft and spares straight-line over 15 years to 10% residual
o Interest: 7.5%, note 90% of total investment is financed over 10 years at 7.5%
o Landing fees = $4.25 per 1000 pounds aircraft weight
o Labor rate = $20/MMH (unburdened), burden + 200%
o Airframe maintenance per NASA Lewis AIRDOC4
o Flight crew pay = $150 per BH.
o Cabin crew pay = $50 per BH (2 crew members)

o Engine maintenance	CT7:	$50 per EFH contract cost
		$8 per EFH line maintenance
		0.1 MMH/EFH line labor
	CF34	$59 per EFH maintenance material
		0.32 MMH/EFH labor

o Aircraft sell price $17M (RJ), $9M (SF340B)

APPENDIX D - SYMBOLS AND NOMENCLATURE

AGB ---------- Accessory Gear Box
APR ---------- Auxiliary Power Rating
ASM ---------- Available Seat Mile
AST ---------- Advanced Subsonic Technology Program
BP ------------ Balance Piston (Related to Rotor Thrust Load on the Thrust Bearing)
BPR ---------- Bypass Ratio (Bypass Airflow Divided by Core Airflow)
C/A ----------- Cooling Air
CMC --------- Ceramic Matrix Composite
DOC---------- Direct Operating Costs
EFH ---------- Engine Flight Hour
EGV --------- Exit Guide Vane
EIS ----------- Entry Into Service
ESFC -------- Engine Specific Fuel Consumption
ESHP -------- Engine Shaft Horsepower
FADEC------- Full Authority Digital Electronic Control
FN ------------ Thrust - pounds
FOD ---------- Foreign Object Damage
FOM---------- Factor Of Merit
HPT ---------- High Pressure Turbine
ISA ----------- International Standard Atmosphere
IHPTET------- Integrated High Performance Turbine Engine Technology
IPS ----------- Inlet Particle Separator
kts ------------ knots
LCF ---------- Low Cycle Fatigue
LEC ---------- Low Emissions Combustor
LPT ----------- Low Pressure Turbine
JTAGG ------ Joint Technology Advanced Gas Generator
MBC --------- Model Based Control
MMC --------- Metal Matrix Composite
MMH --------- Maintenance Man Hour
MN ----------- Mach Number
MTDE--------- Modern Technology Demonstrator Engine
NgDOT ------ Rate of Change of Rotor Speed
NM ----------- Nautical Mile
OGV --------- Outlet Guide Vane
P/P ----------- Pressure Ratio
pps ----------- Pounds per Second
PSC ---------- Performance Seeking Control
PWSD ------- Power Standard Day
P3 ------------ Compressor Discharge Total Pressure
RAPT -------- Regional Aircraft Propulsion Technology
RJ ------------ Regional Jet
ROM --------- Rough Order of Magnitude
RT ------------ Rotor Thrust (Load on the Thrust Bearing)
SET ---------- Small Engine Technology
SFC ---------- specific fuel consumption
shp ----------- shaft horse power
SL ------------ Sea Level
SLS ---------- Sea Level Static
TBC ---------- Thermal Barrier Coating
TE ------------ Trailing Edge (Turbine Blades)
T/P ----------- Turboprop
T/S ----------- Turboshaft
T3 ------------ Compressor Discharge Temperature

APPENDIX D - SYMBOLS AND NOMENCLATURE (Continued)

T41 ----------- Turbine Rotor Inlet Temperature
T45 ----------- LPT Inlet Temperature
VEN ---------- Variable (Area) Exhaust Nozzle
VG ------------ Variable Geometry (Compressor Vanes)
Wf/PS3 ------ Fuel Flow Divided by Control Pressure
WCL --------- Cooling Airflow - lb/sec
W2 ----------- Inlet Physical Airflow - lb/sec
W2R ------- Corrected Inlet Airflow - lb/sec
W22R ------- Corrected Core Airflow - lb/sec
W41R ------- Turbine Flow Function (Corrected Turbine Airflow) - lb/sec

$\Delta P/P$ --------- Pressure Differential Divided by Pressure
η -------------- Component Efficiency

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 2003	Final Contractor Report—Jan. 1994–Jan. 1998

4. TITLE AND SUBTITLE

Small Engine Technology Investigation

5. FUNDING NUMBERS

WU–538–06–11–00
NAS3–CR–26617, Task Order 47

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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1000 Western Avenue
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8. PERFORMING ORGANIZATION REPORT NUMBER

E–14081

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CR—2003-212519

11. SUPPLEMENTARY NOTES

This research was originally published internally as AST21, in January 27, 1998. Project Manager, Joseph D. Eisenberg (retired). This report is a formal draft or working paper. It contains preliminary findings. Responsible person, Susan M. Johnson, organization code 2200, 216–433–2163.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category: 07 Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov

This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The primary objective of the small engine technology study task is to identify key, enabling jet engine component technologies for improved performance, primarily for commercial, regional subsonic aircraft. The study involved two regional engine applications: the CF34 turbofan engine, which is installed on a regional jet application and the CT7–9 turboprop, which is installed on regional turboprop applications. Technologies to improve the performance of these applications were identified. Estimates of the benefits and development costs for each technology were made. Performance sensitivities were calculated for each of the technology items identified. The technology improvements were then translated into component improvements and their impact on the aircraft economics was evaluated. A factor of merit based on sfc was calculated as the percent improvement in sfc times the probability of improvement divided by the development evaluation costs associated with that technology item. The technologies were ranked for both the turbofan and turboprop applications.

14. SUBJECT TERMS

Propulsion; Turbine engines; Regional engines; Technology study; Advanced subsonic

15. NUMBER OF PAGES

81

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102