NASA/CR—2003-212466

Advanced Propulsion System Studies for General Aviation Aircraft

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Williams International, Walled Lake, Michigan

July 2003

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National Aeronautics and
Space Administration

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This research was originally published internally as AST003 in October 1996.

This report contains preliminary findings, subject to revision as analysis proceeds.

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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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ABSTRACT

This is the final report of a study entitled "Advanced Propulsion Systems Studies for General Aviation Aircraft," submitted in accordance with NASA contract number NAS3-27636. The main factors covered in the study include:

1. MARKET IMPACT ANALYSIS
   - Assess general aviation, including commuter/regional, aircraft market
   - Impact of incorporating advanced technology into the propulsion system on
     - acquisition and operating costs
     - job creation/manpower demand
     - future fleet size
   - Select an aircraft and engine for the study. This study focused on the next generation 19-passenger commuter and the Williams International FJ44 turbofan growth engine

2. PROPULSION SYSTEM ANALYSIS
   - Conduct mission analysis studies and engine cycle analysis
     - define a new commuter mission and required engine performance
     - define acquisition and operating costs
     - select engine configuration and initiate preliminary design for required hardware modifications

3. PROPULSION SYSTEM BENEFITS
   - Assess and define engine emissions improvements
   - Assess and define noise reduction potential
   - Conduct a cost analysis impact study

4. REVIEW OF RELEVANT NASA PROGRAMS
   - Conduct literature searches using NERAC and NASA RECON services for related technology in the emissions and acoustics area

5. PRELIMINARY TECHNOLOGY DEVELOPMENT PLANS
   - Define plan to incorporate technology improvements for an FJ44-2 growth engine in the performance, emissions, and noise suppression areas

NOTE: An independent study entitled, "Preliminary Market Feasibility Analysis for the Trijet Commuter," is attached (under separate cover) as a supplement to this document. The data for the report were obtained with other than NASA funds and is provided with "Limited Rights" and is not for distribution outside of NASA.

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INTRODUCTION

There is a substantial threat to the civil aviation sector of the U.S. economy (aircraft with ≤120 seats). For many years, the U.S. aircraft industry was a leader in the manufacturing, marketing, and service support of civil aviation aircraft and in technology advancements for these aircraft. Civil aviation serves almost 18,000 airports and annually carries about 120 million passengers between cities; this is about 20 percent of all intercity traffic. There are over 540,000 jobs in manufacturing, sales, service, and flight departments. Currently, however, Canada, France, the United Kingdom, Sweden, Brazil, and Indonesia have made the aeronautical industry a high priority for their national economies, and there is strong government support in these countries. Since 1984, imports of civil aviation aircraft have exceeded exports, and foreign manufacturers continue to view the U.S. as an important market. This is especially true in the small commuter and regional jet market. None of the major manufacturers of 20- to 120-passenger airplanes (Aerospatiale/Alenia, Casa, Bombardier, Dornier, Embraer, Shorts, AVRO (BAE), Saab, Fokker and IPTN) are U.S. companies.

19-passenger aircraft have dominated the segment of aircraft with 80 seats or less. In 1990, the less-than-15-seat aircraft and the 15 to 19-seat aircraft quantities represented 42 and 30 percent of the total market, respectively. This is a substantial business. In 1992 ≤19-passenger commuters represented 50 percent of all the commercial airline hours flown and 29.5 percent of civil aviation revenue passenger miles at $2.79 billion. Forecast data shown below indicate by the year 2006 these market shares will drop to 21 and 11 percent, respectively.

DISTRIBUTION OF AIRCRAFT IN THE COMMUTER MARKET

	Passenger Seats				
	<15	**15 - 19**	**20 - 40**	**> 40**	**Year**
Percent of Total Aircraft	30	42	20	8	1990
Percent of Total Aircraft	11	21	40	28	2006

Today, the ≤19-passenger market is dominated by two American aircraft companies (Beech and Fairchild) using a mix of American and Canadian turboprop engines. This market segment is forecast to contract substantially in the future.

We believe this market will contract if the only airplanes offered are the relatively slow, noisy, low- altitude turboprops of today. This market can be revolutionized, however, by providing an advanced technology fanjet in the 2500 to 3000-lb thrust class designed specifically for the commuter application.

In the early 1980's, Dr. S.B. Williams noted a similar market condition related to turboprop business aircraft. Dr. Williams believed that then-current technology combined with Williams International's unique ability to produce low cost reliable turbofan engines made it possible for small fanjets to compete directly with turboprop aircraft in acquisition cost and direct operating cost (DOC). Advantages of low noise and fanjet over-the-weather comfort were significant added benefits.

The FAA and JAA certification of the Williams International FJ44 turbofan made possible a series of low-cost entry-level jets, led by the remarkable Cessna CitationJet which is priced below turboprop competitors and beats them on speed, comfort, and DOC. Noise levels are below the strictest U.S. standards and exhaust emissions are even below levels required for larger engines. These advantages resulted in the CitationJet being the number one selling aircraft in its class during the first two years following its introduction. Production of the CitationJet at brisk levels even during a world recession is further proof of the viability of this strategy.

The FJ44/CitationJet experience is presently demonstrating how a modern low-cost turbofan engine with an airplane designed specifically for it can capture a market previously dominated by turboprop power. This lesson can be applied to the ≤19-passenger commuter market. A strategy must be immediately developed and implemented to bring the jobs related to this revolutionized market to the U.S.

Turbofan engines available today are too heavy, have too high an acquisition cost, and are too high in SFC. The next generation small commuter aircraft will be characterized by:

- 19-passenger capacity
- Low noise
- Low emissions
- Acquisition cost comparable to today ($5 million)
- DOC comparable to today
- High speed/high altitude capability
- Stage duration of 60 to 90 minutes
- Stage length of up to 1000 nautical miles

The FJ44 can be readily uprated to satisfy the requirements of the small commuter market and is an excellent demonstration engine for the advanced technologies that will be needed.

The results of this study show that:

1. The small commuter market is a significant business that is evolving as it interacts with major carriers. With the aircraft available today, this market segment will decline.

2. This market can be substantially enlarged by introducing new fanjet-powered aircraft at acquisition cost and DOC comparable to today's turboprops.

3. The basic engine technology required is available today in the Williams FJ44 turbofan. The FJ44 is an excellent demonstration engine to incorporate the advanced technologies that will be required.

4. A preliminary study has defined an appropriate airframe/engine design for the next generation 19-passenger commuter that can revitalize this market segment in the U.S. economy.

1.0 MARKET IMPACT ANALYSIS

The regional/commuter aircraft market has enjoyed substantial growth during the last decade. For the last several years, total revenue passenger miles (RPM) and passenger enplanements have increased at approximately a 15-percent per annum rate (Figure 1-1). The FAA Aviation Forecasts[1] indicate a substantial growth for this aircraft sector continuing into the next decade. Forecast data indicate a 12-percent and 8-percent annual growth in RPM and passenger enplanements, respectively. This would indicate that the average trip length is increasing.

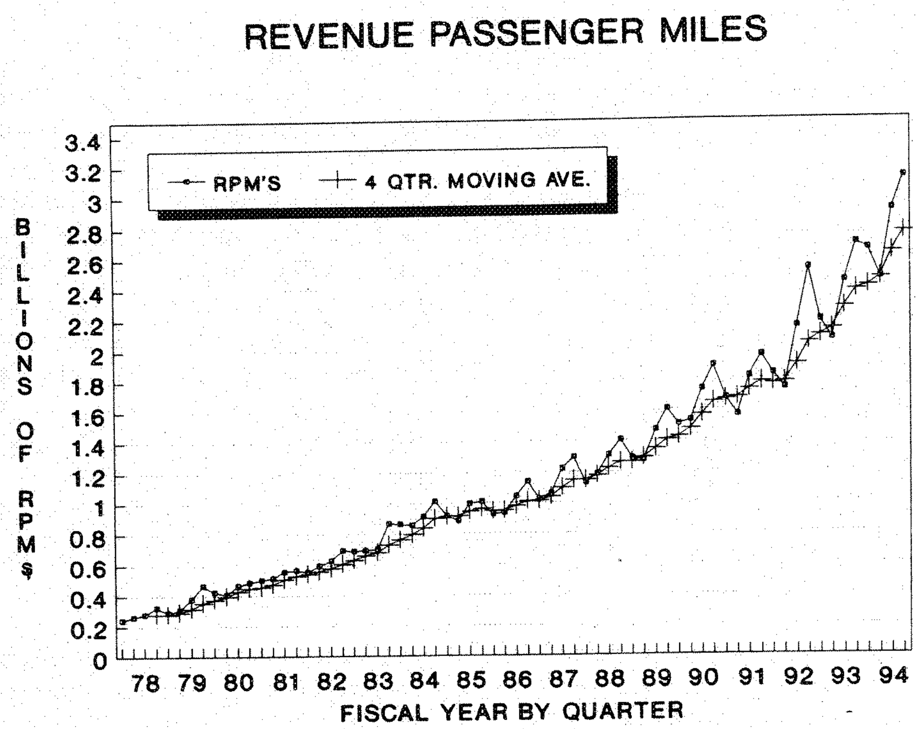
The FAA Aviation Forecasts data shown in Figure 1-2 illustrates the RPM and enplanement trends. The passenger trip length, average aircraft size, and passenger load factors are given in Figure 1-3. These data confirm that the average trip length has increased from approximately 140 miles in 1980 to over 205 miles in 1994, a 46-percent increase. By the year 2004 the average trip length is forecast to approach 250 miles. Also, the average regional aircraft size will approach a 35-passenger capability with passenger load factors indicated to be over 52 percent. Increased load factor means increased profitability for the commuter airlines, and therefore more revenue available to finance growth and procure/lease new equipment. By way of comparison, the larger commercial airlines have enjoyed passenger load factors in the 65-percent range and is forecast to remain flat at this level. From a load factor standpoint, the international carriers have experienced load factors in the 62 to 72-percent range as depicted in Figure 1-4.

The mix of aircraft size is broken down by seating capacity in Figure 1-5. Today's smaller turboprop commuters (<19-passenger) are predicted to surrender market share to the larger turbofan-powered regional airliners. They are forecast to decrease from 35-percent market share in 1994 to 21.2-percent market share by the year 2006. Correspondingly, the 20 to 40-passenger aircraft fleet will increase in market share from 28.7 percent to 40.4 percent. Those aircraft with over 40-passenger capability are also predicted to increase substantially from 9.6 to 27.4 percent. This seems logical if the following assumptions are made:

- The average commuter trip mileage is increasing
- Passengers will demand more comfort when spending two hours in a small aircraft
- Passengers will demand more value for their revenue dollar

The downside of this market forecast is that many travelers will be forced to spend more time to complete a typical business trip because of travel time to and from airline hubs that the larger aircraft will be operating from. The demise of flight service to the smaller, less profitable (low RPM, load factors) airports is already evident.

[1] FAA Aviation Forecasts, Fiscal Years 1995 - 2006, FAA-APO-95-1, March 1995.



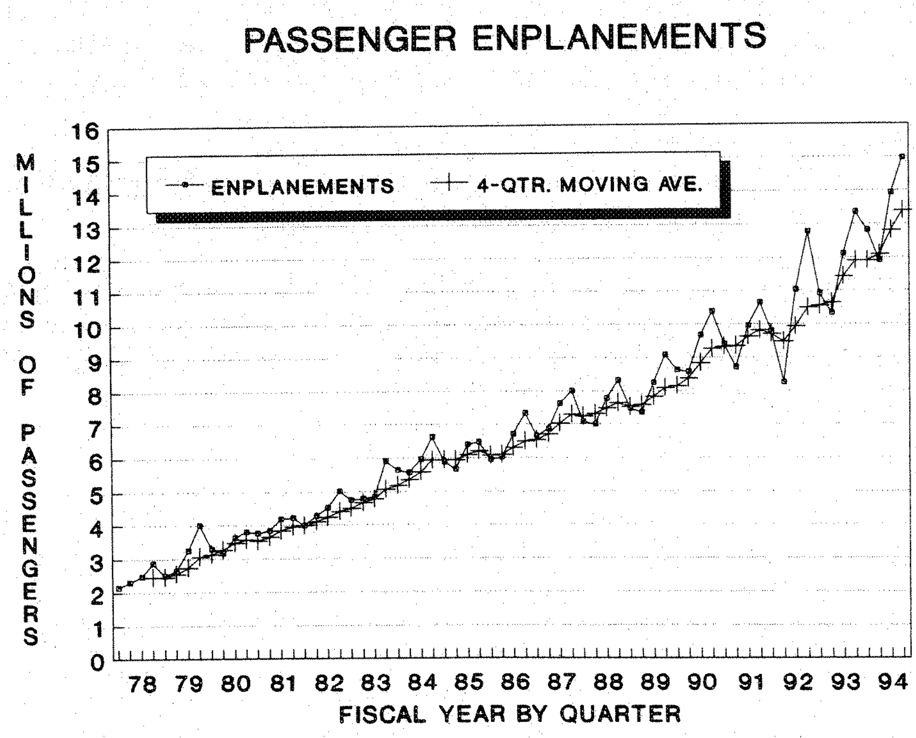


Figure 1-1. U.S. Regionals/Commuters Traffic Trends

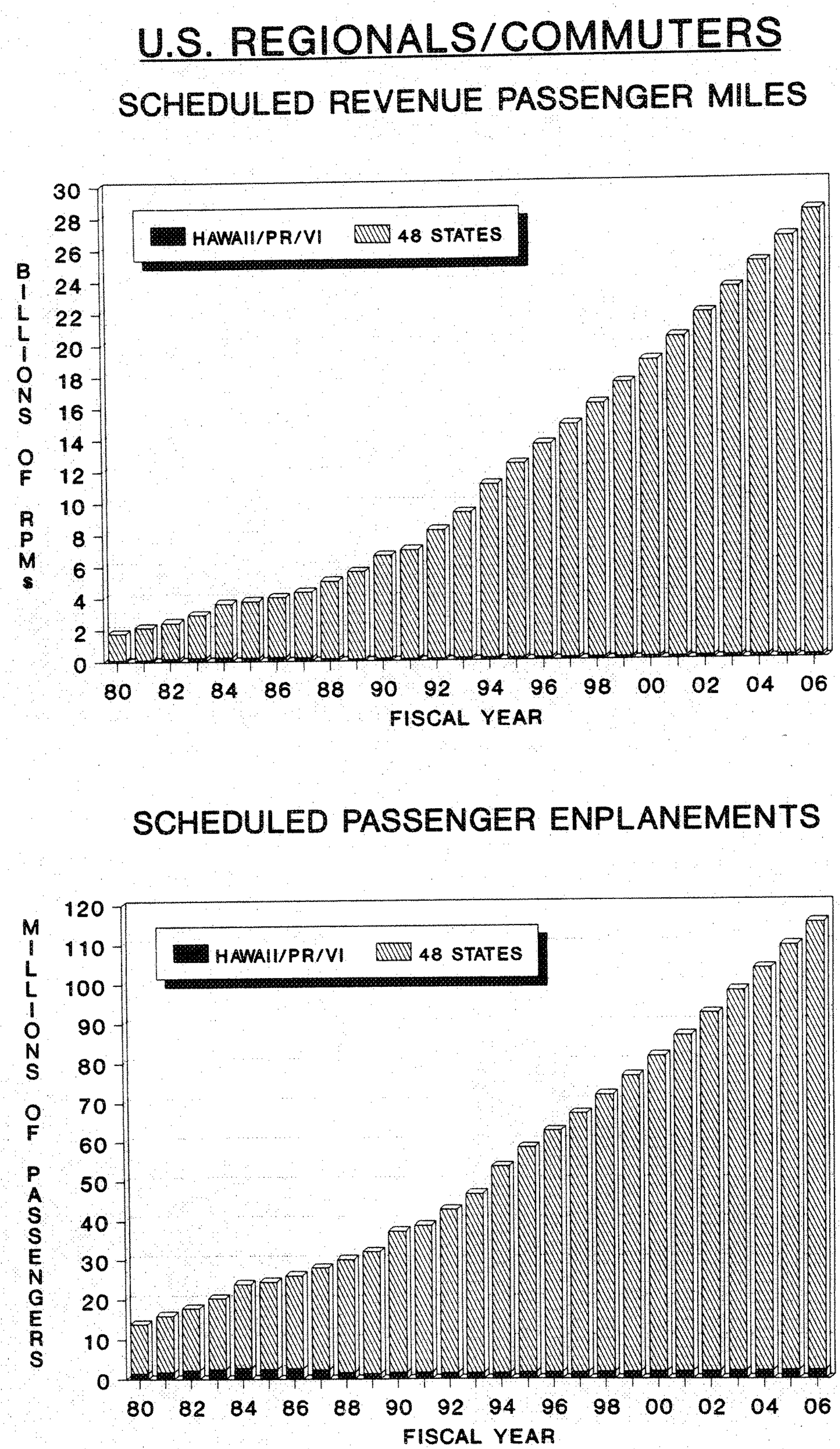


Figure 1-2. FAA Aviation Forecasts Trends

U.S. REGIONALS/COMMUTERS FORECAST ASSUMPTIONS

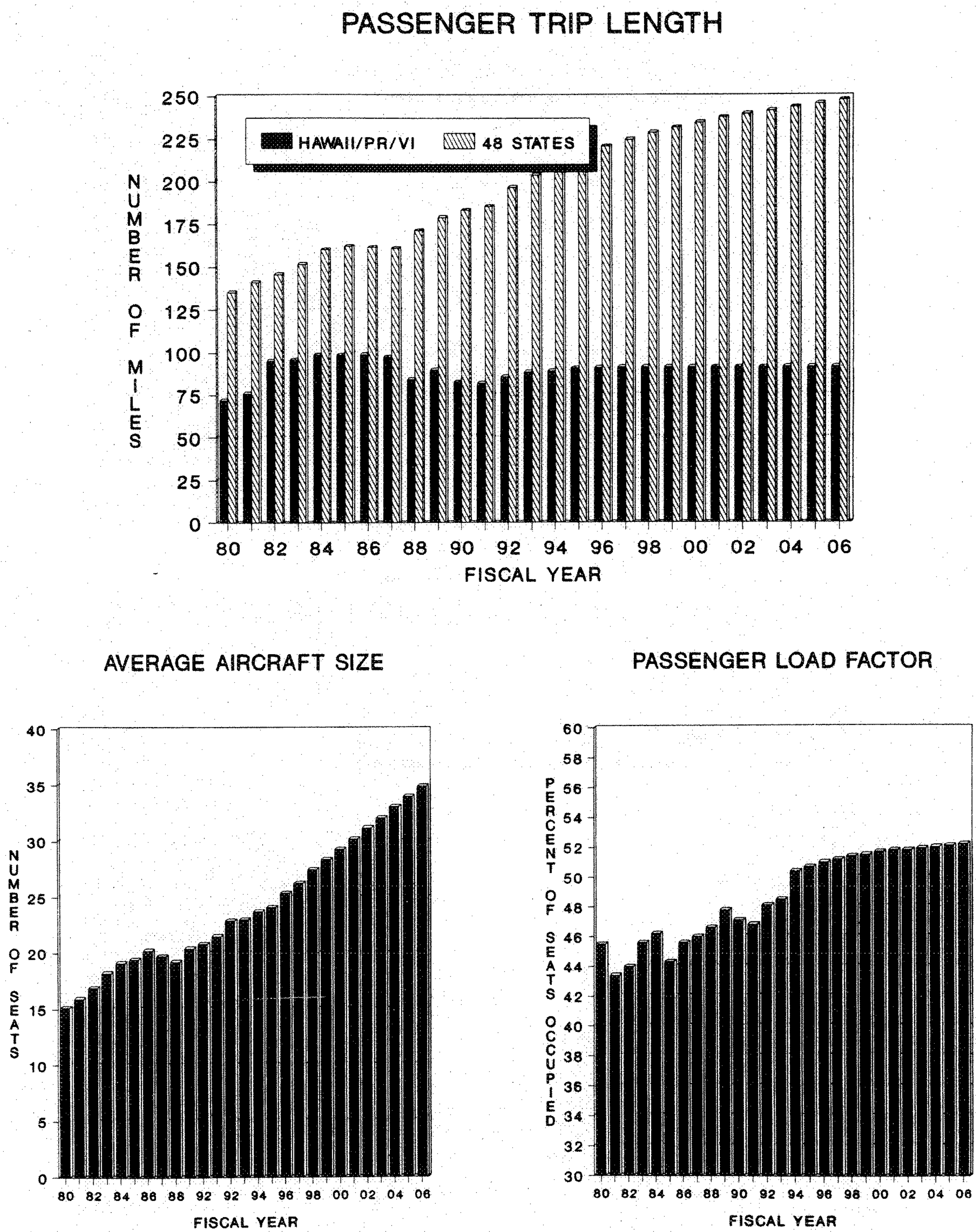


Figure 1-3. FAA Aviation Forecasts Trends

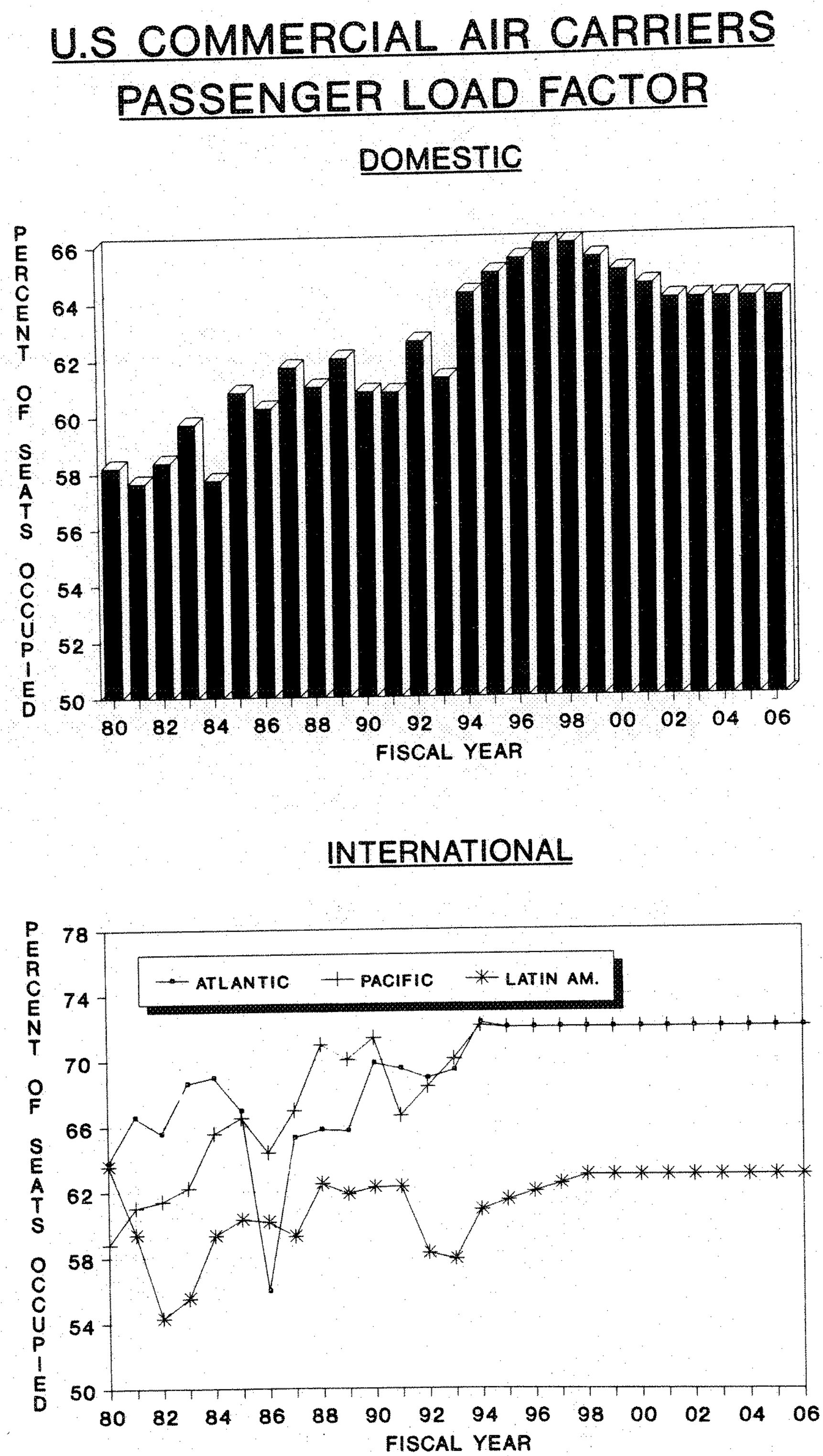


Figure 1-4. FAA Aviation Forecasts Trends

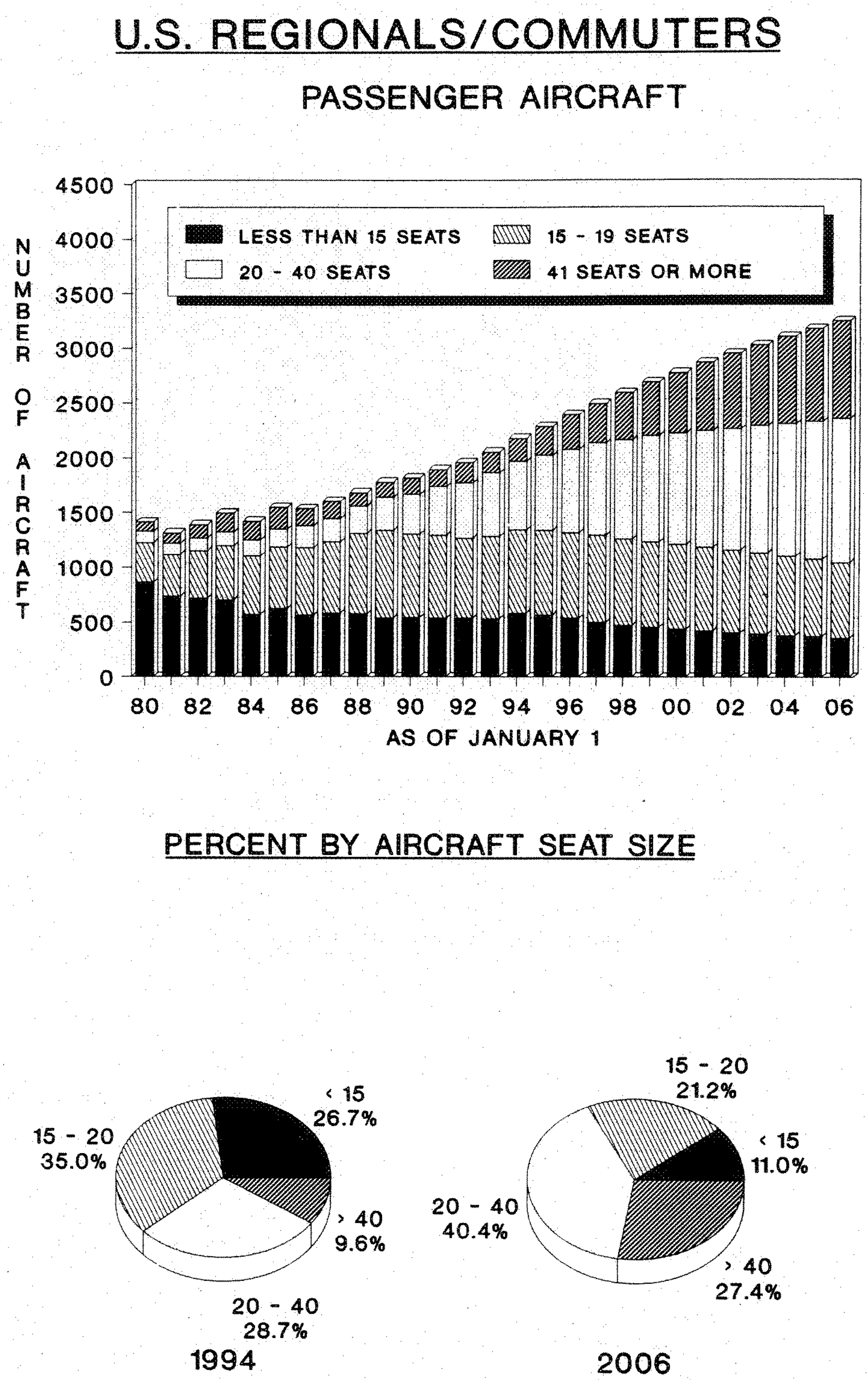


Figure 1-5. FAA Aviation Forecasts Trends

1.1 19-PASSENGER AIRCRAFT MARKET

The data shown in Figure 1-5 indicate that aircraft fleet size for less than 19 passengers will decline to about 1000 aircraft by the year 2006. Most of this is due to the fact that the smaller aircraft (<15 passenger) being phased out of service. The demand for the 15- to 19-passenger aircraft will remain flat to a slight decline. This is supported by historic production and forecast data for specific aircraft. The historical annual production rates peaked at 200 aircraft in 1990, and has declined to the current level of approximately 80 aircraft/year (Figure 1-6). The forecast for the specific aircraft noted in Figures 1-6 and 1-7 is predicted to remain fairly flat at about 90-aircraft/year for the next 10 years.

> ***The above forecast data are based on today's aircraft and engine technology. To make commuter airline travel accessible and comfortable, to increase operational profitability, and to improve safety and the environment, new aircraft and engine technologies are required!***

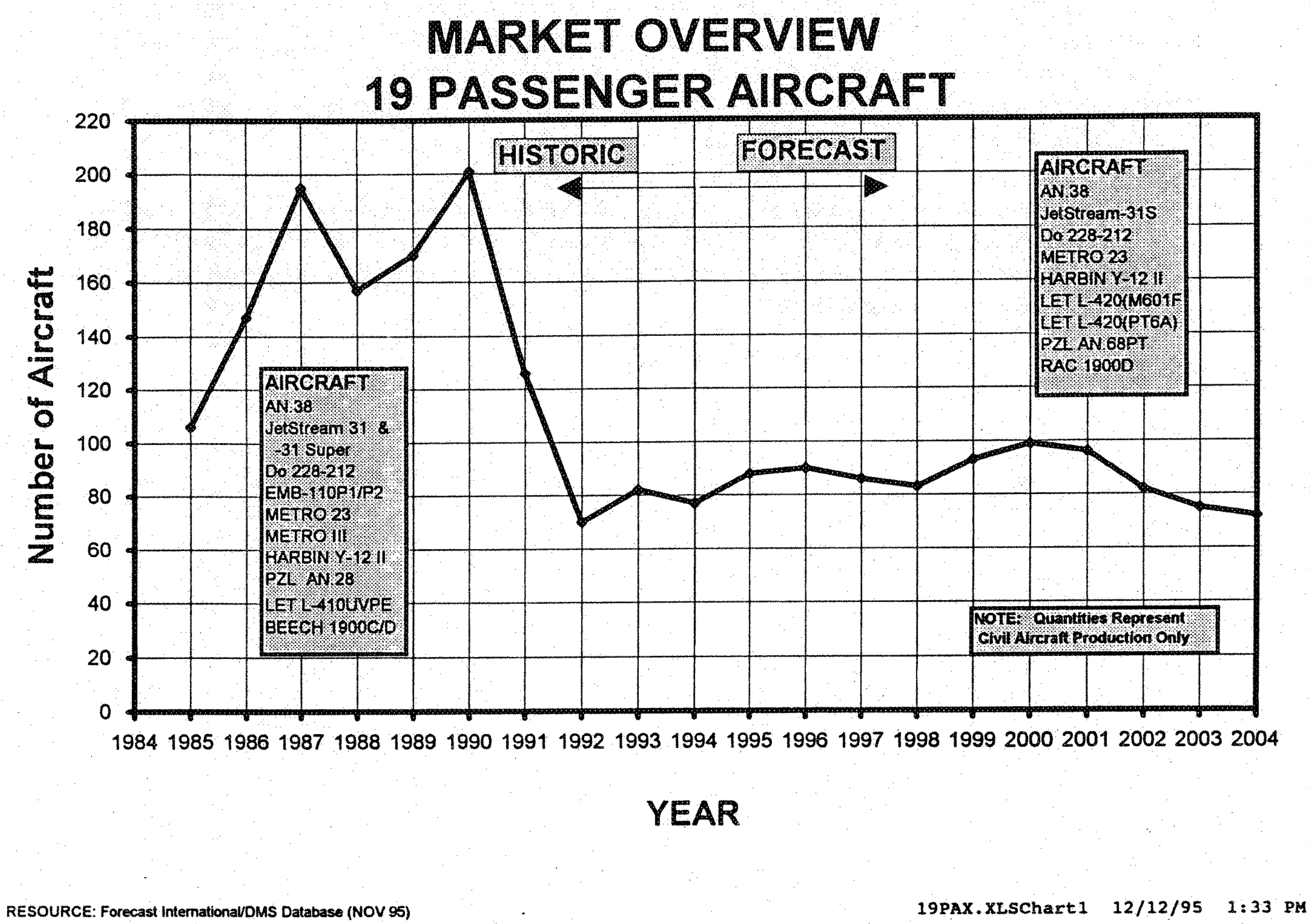


Figure 1-6. 19-passenger Aircraft Historical and Forecast Production

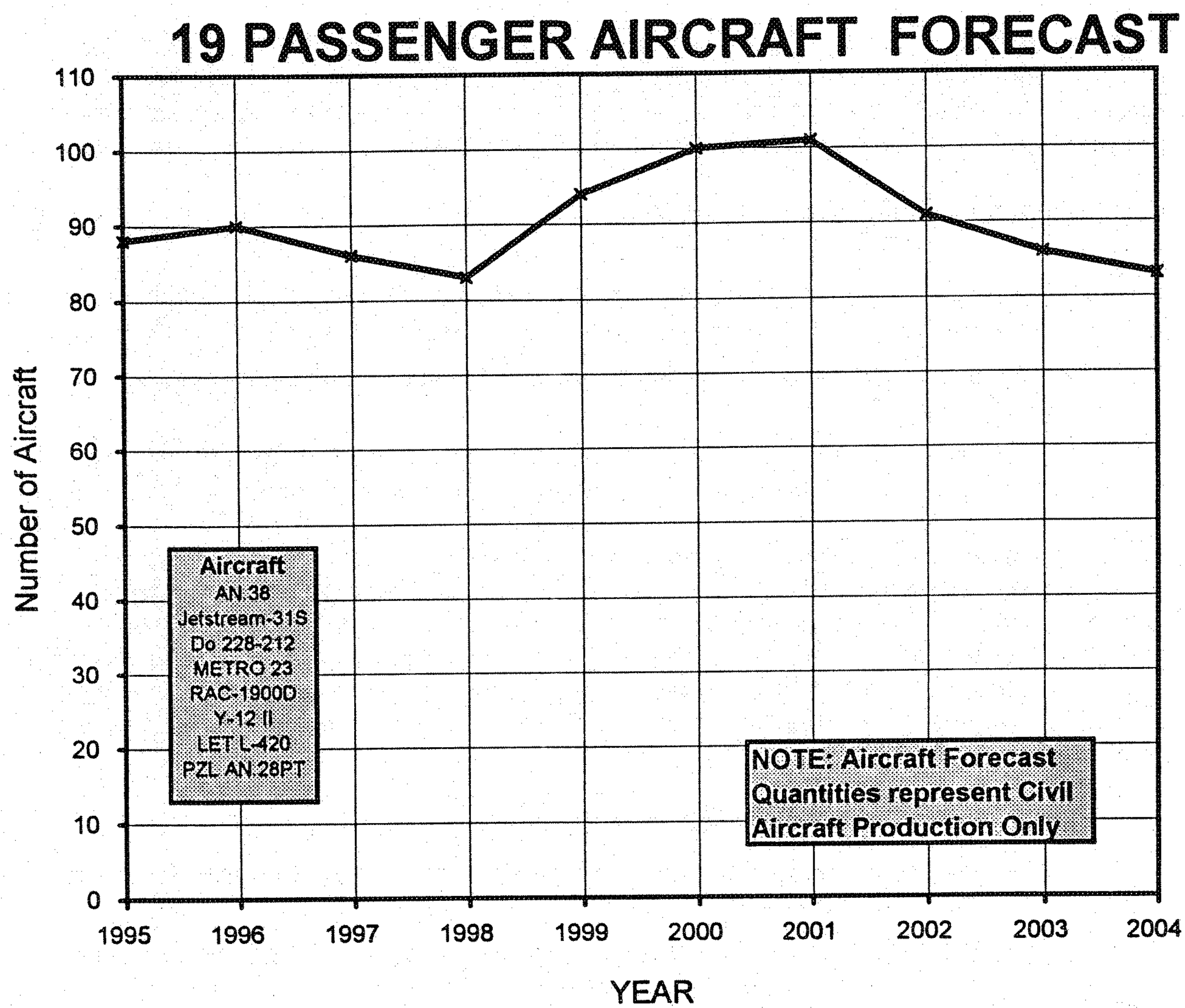


Figure 1-7. Predicted Production of 19-Passenger Aircraft

1.2 TECHNOLOGY IMPACT ON FLEET SIZE

Today's commuter aircraft in the 19-seat size are all turboprops. Breakthrough technology will be based on advanced technology components integrated into a proven, low-cost turbofan engine. The Williams International FJ44-1 turbofan engine is at the proper level of maturity to provide a growth version of the engine for the next generation 19-passenger commuter aircraft.

Component technologies would provide:

- Very low noise for passenger comfort and to the surrounding community because of advanced exhaust gas mixing concepts and ducting acoustical treatments
- Excellent exhaust gas emission characteristics that are better than federal requirements
- Low acquisition costs comparable to today's turboprops (Three small engines will be as cost-effective as two larger equivalent thrust engines; anticipate 75% of the cost.)

The advanced technology FJ44 will have excellent specific fuel consumption (SFC) as compared to competing engines (Figure 1-8). The advanced technology FJ44 engine, combined with a commuter aircraft designed to increase passenger comfort and reduce cost of operation, will provide improved low combustion gas and noise emissions, and will provide a significant impact on the fleet size. One approach to provide the necessary regional flight service to the predicted increase in passenger enplanements is to incorporate the following characteristics:

- A new low-cost-of-ownership 19-passenger trijet commuter
  - Long thin routes - Out of 3000 existing city pairs, a large number generate less than 200 passengers per day
  - Hub bypass - Hub congestion has created a demand for short haul low density markets to be served by a 19-passenger aircraft
  - New short/mid-range routes - New markets created via secondary hubs to avoid large carrier hub congestion
  - Three engines provide increased safety over a twin-engine aircraft - Less aircraft yaw during engine-out condition and improved over-water safety
- Low acquisition and operating costs of an advanced performance turbofan engine
- Over-the-weather flying comfort
- Low cabin sound and vibration
- Higher cruise speeds, longer trip legs and more legs per day
- Low cost, advanced engine also serves as APU to improve comfort at minimum costs

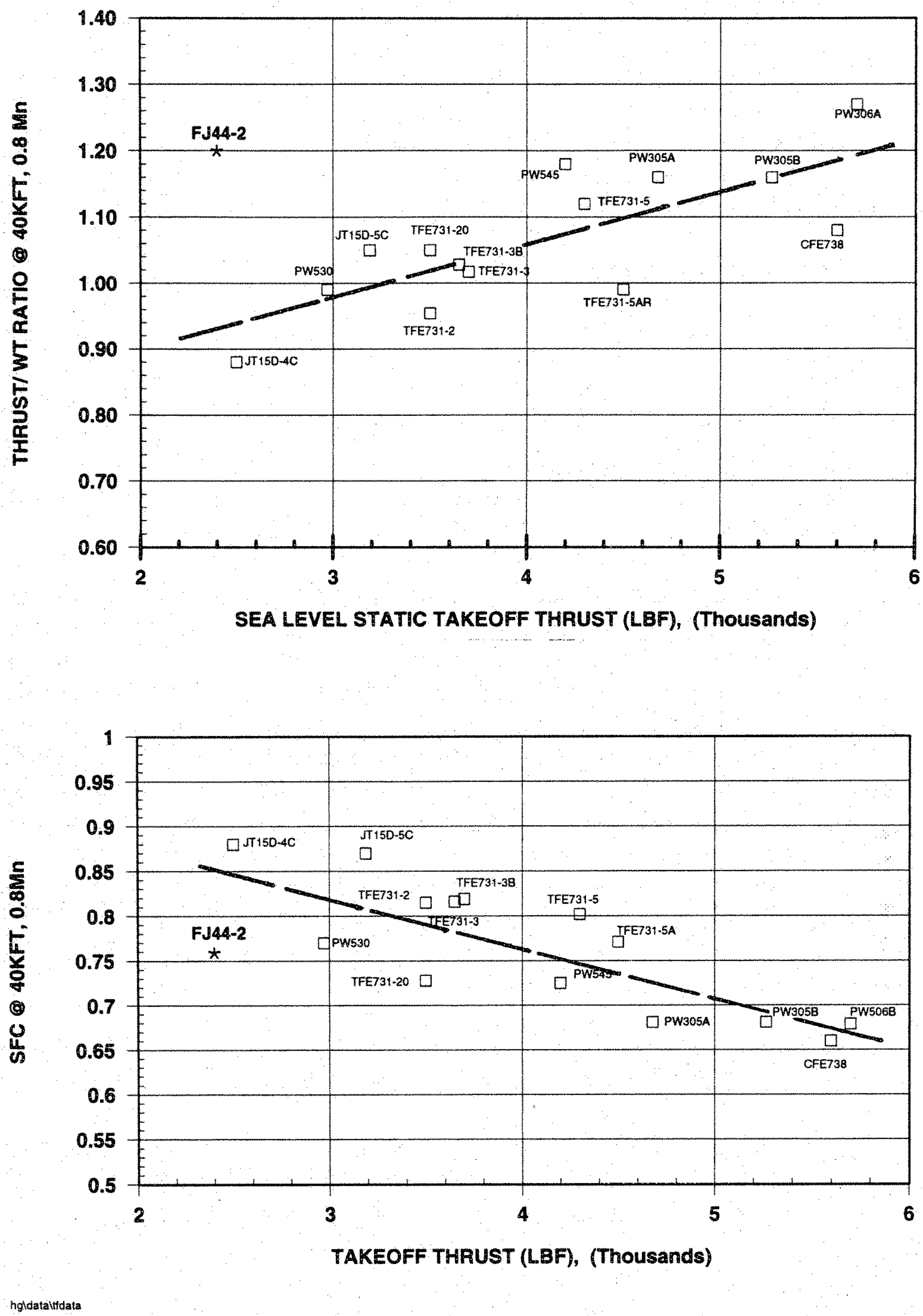


Figure 1-8. FJ44-2A Turbofan can provide the Superior Cruise Performance

A new 19-passenger trijet aircraft has many advantages by adding value for the traveler through:

- Low cabin noise and vibration
- Comfortable 32-inch pitch seating
- Less weather-induced discomfort
- Ability to travel between desired city pairs

For the commuter airline service it allows:

- Potential for higher load factors
- Higher block speeds
- Longer range
- Shorter balanced field length
- More legs per day

The key to developing a new generation 19-passenger commuter is to provide advanced technology turbofan engines that can beat or are very competitive to the Direct Operating Costs (DOC) of today's gas turbine turboprop engines. The combination of a low cost, high performance turbofan engine and a modern, comfortable wide body commuter will result in a reversal of the forecast decline of the less than 20-seat aircraft. A new market for the short haul, low density, hub-bypass will develop with significant impact for the U.S. economy. The forecast data in Figures 1-6 and 1-7, indicate that the demand for aircraft with less than 20 seats will decline, but at the same time the steady increase in passenger enplanements and RPM indicate a rising need. This need is predicted to be filled by larger, more expensive aircraft in the 20 to 60-seat category. It is believed that the infusion of an advanced engine in concert with the next generation 19-passenger aircraft will share in this market and provide a potential fleet growth, to a total of 1200 to 1600 new aircraft instead of the forecast of approximately 900 new aircraft in the next decade.

A conservative assumption of 400 new next generation 19-passenger aircraft at a $5.5 million unit price would represent a $2.2 billion market

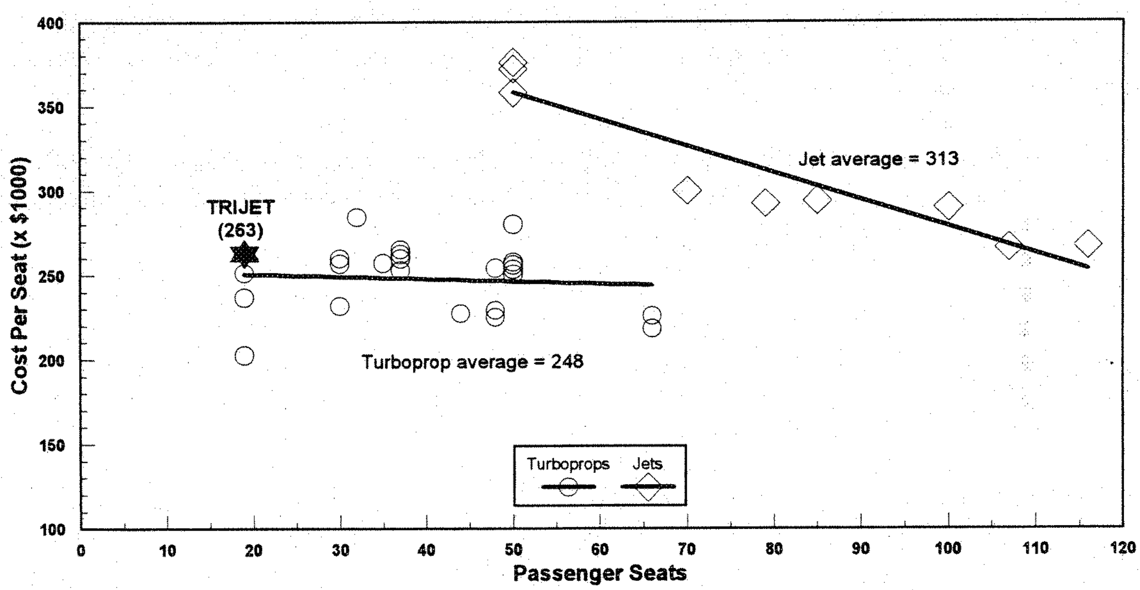
This is based on the outstanding success of the introduction of the FJ44 engine and its impact on the small business jet market growth. The same attitude of aircraft buyers that stimulated the business aircraft is expected to apply to commuter airlines. Of the current projected turboprop 19-passenger aircraft market, a percentage, perhaps 25-percent or more, will decide to trade-up from turboprops to the turbofan engine generation. Additionally, new market route structures are envisioned to be created by the increased capabilities of the next generation trijet commuter aircraft. This will significantly add to the U.S. and international commuter aircraft fleets.

1.3 ESTIMATED ACQUISITION AND OPERATING COSTS

In understanding the existing and potential market, the current acquisition and operating costs are essential. Current acquisition costs are listed in several sources. The *Regional Aircraft Association Annual* directory indicates that the acquisition cost for today's 19-passenger aircraft is $3.85 to $4.78 million with an average cost of $4.35 million. An overview of the acquisition cost of today's commuter/regional aircraft as a function of seat size is provided in Figure 1-9.

Operating costs are a function of several variables. Travel from City A to City B is often referred to as a "block". Operating costs are a function of the aircraft block speed and block time. Block time includes ground taxi time (usually 5 to 10 minutes), and the flight time to touch down at City B. Parameters included in evaluating operational cost include aircraft seat miles (ASM) per hour or per pound of fuel. Other parameters are cost per seat mile, total trip cost, and cost per aircraft mile. All are a function of the trip length, the speed of the aircraft, the rate of climb/descent, and the desired operational altitude. The bottom line for the operating commuter airlines is the annual profit.

Typical operating costs for today's 19-passenger turboprops are approximately $0.14 to $0.15 per seat statute mile or approximately $2.40 per aircraft nautical mile. Typical annual operating profit for a current 19-passenger aircraft, assuming nine 250-nautical mile trips per day, five days per week, with a 50-percent load factor, would be approximately $700,000.



Ref: Business & Commercial Aviation, May 1995.

Figure 1-9. Acquisition Cost Per Seat Regional/Commuter Aircraft

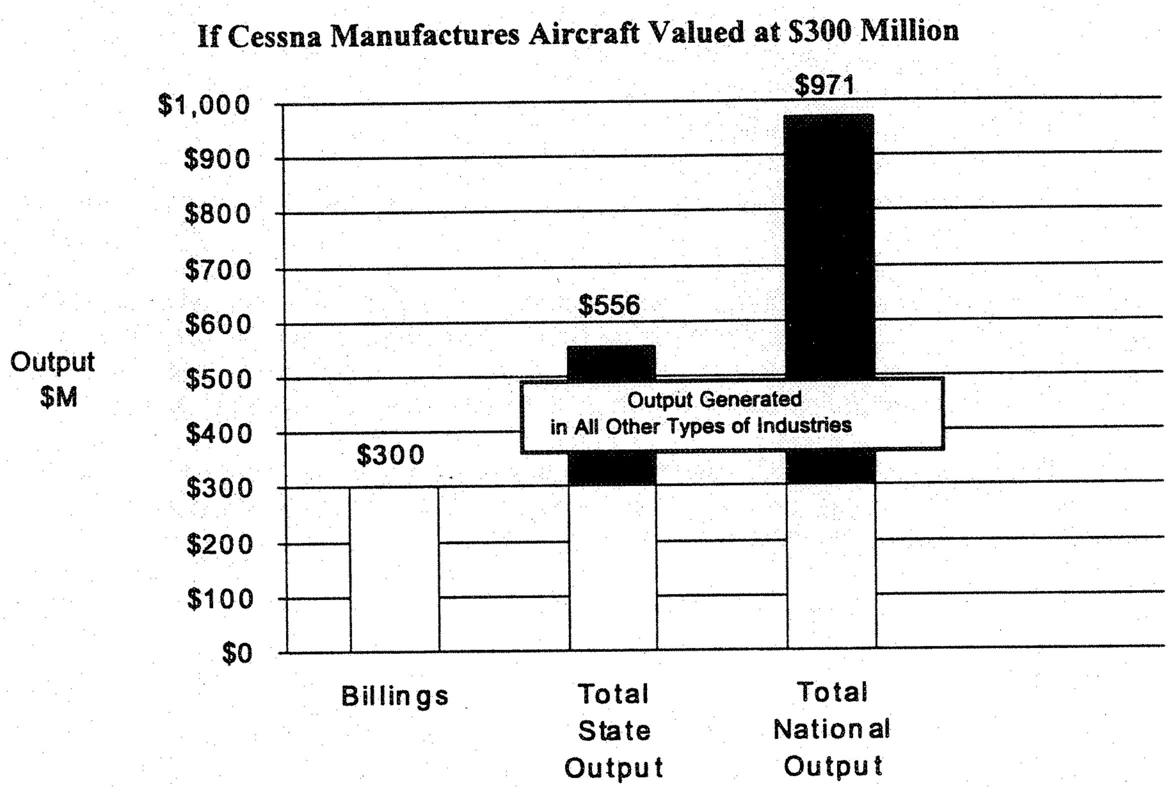
1.4 IMPACT ON JOB CREATION AND MANPOWER DEMAND

The U.S. economy can be significantly impacted by a new generation 19-passenger aircraft launch. Historically, for every $100 million in billings experienced by an aircraft company, the impact on the total national output increases by a factor of three. This is illustrated in Figure 1-10. If a 500 aircraft production run is assumed over the next ten years at a $6M unit billing, a total aircraft market of $3B would result. This would lead to economic growth of $9B based on the above factor of three. If these amounts were represented by $30,000 per year jobs, $3B would equate to 100,000 jobs; $9B would equate to 300,000 jobs.

If three airframe companies were involved in this scenario, each with its own supplier network, employment can be expected to increase by 200 to 400 jobs at each facility. This represents 600 to 1200 new jobs. Additionally, if 20 key suppliers/subcontractors for each airframer are included, this would produce an additional 12,000 to 24,000 new jobs in the supplier network. These new jobs will increase their demand for other goods and services, impacting other industries affecting the national economy output.

Continuing with this aviation industry scenario, the opening of new commuter routes and the interfacing of related markets will also impact the demand for new goods and services. For each new city hub opened up for the short haul, low density commuter market, an additional 100 new jobs could be created. Other private surveys indicate that 1000 to 1500 one-way city pairs that exist today would benefit. This can easily result in 10 to 100 jobs for each location. Assuming a 55 new job average, this represents the potential for from 5,000 to 82,500 new jobs. This scenario does not account for any U.S. job market impact due to other world markets (i.e., Pacific Rim, Europe, etc.) that the next generation 19-passenger could be expected to develop.

> ***This scenario for the U.S. aviation industry indicates the potential for 67,000 to 108,000 new jobs created through the infusion of new engine technology into a 19-passenger commuter aircraft.***



Ref. Fifth Annual FAA General Aviation Forecast Conference Proceedings, FAA-APO-95-3.

Figure 1-10. Impact of Passenger Billings on State and National Output

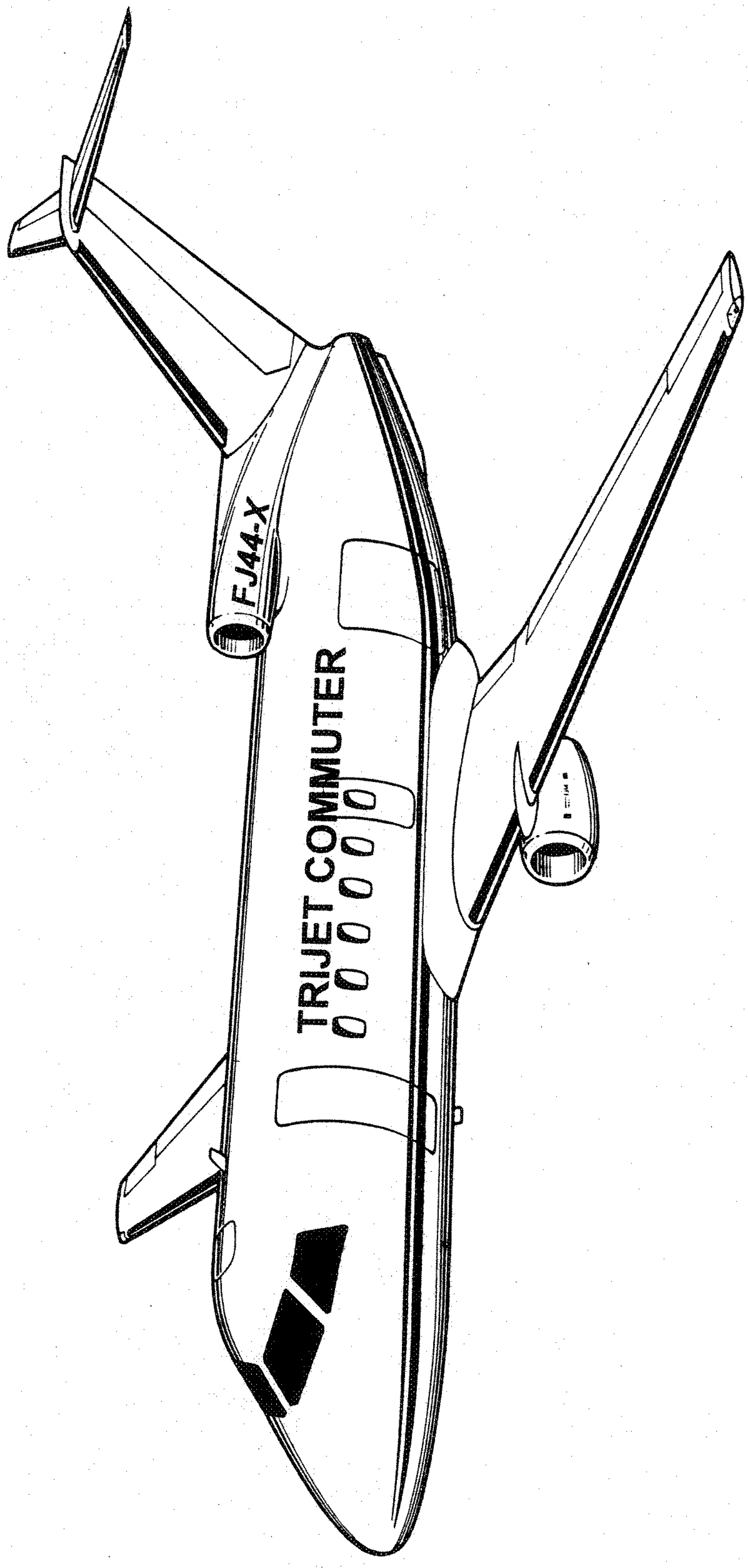
1.5 AIRCRAFT SELECTED

Several aircraft configurations were considered for this study. This study assessed new propulsion technologies for general aviation aircraft in the 4 to 19 seat catagories with regard to current and future environmental regulations. It was decided early for this activity to focus on the 19-passenger aircraft configurations. The initial study of twin-engine versions indicated that a much larger thrust growth step than thought economically feasible for the FJ44 engine would be required. Also, to provide sufficient seating capacity, at least a 19 passenger configuration was desirable. In considering economic value added (EVA) for this type of commuter, limiting the number of seats to 19 results in not requiring an additional flight attendant, galley, etc., thus reducing flight crew and meal service operational costs. Several airframer approaches to the potential engine configuration were considered, these included:

- Aft fuselage nacelle pylon mounts
- In-wing engine nacelles
- Over-wing nacelle pylon
- Under-wing nacelle pylon
- In each of the above cases the third engine was fuselage mounted similar to a Boeing 727

The aircraft selected for this study is shown isometrically in Figure 1-11. A three view layout in is shown in Figure 1-12. The wide body fuselage with three-abreast seating allows each passenger to have a window or aisle seat. The 32-inch seat pitch was chosen because it offers more comfort in comparison to the 29-to-30-inch pitch typical of current 19-passenger aircraft.

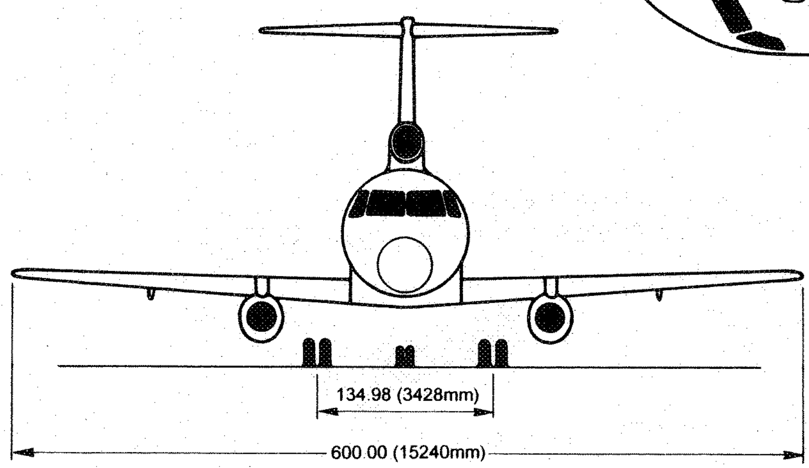
The low wing with the engine nacelles suspended under the wing allows excellent aircraft stability and ease of accessibility for engine maintenance. Other specific performance characteristics are discussed in Section 2.0 of this report.



A-55447

Figure 1-11. 19-Passenger Regional Transport

Target Price	less than $6 Million
Passengers	19
Crew	2
Seating	3-abreast
Max Cabin Width - Internal (in)	85
Seat Pitch (in)	32
Powerplants	Three FJ44-2 Turbofans
Output (SLST) (lb)	2400 each at 92°F
Max Fuel (lb)	5186
Ramp Weight (lb)	21,141
Max Takeoff Gross Weight (lb)	21,041
Cabin Pressurization (psid)	7.5



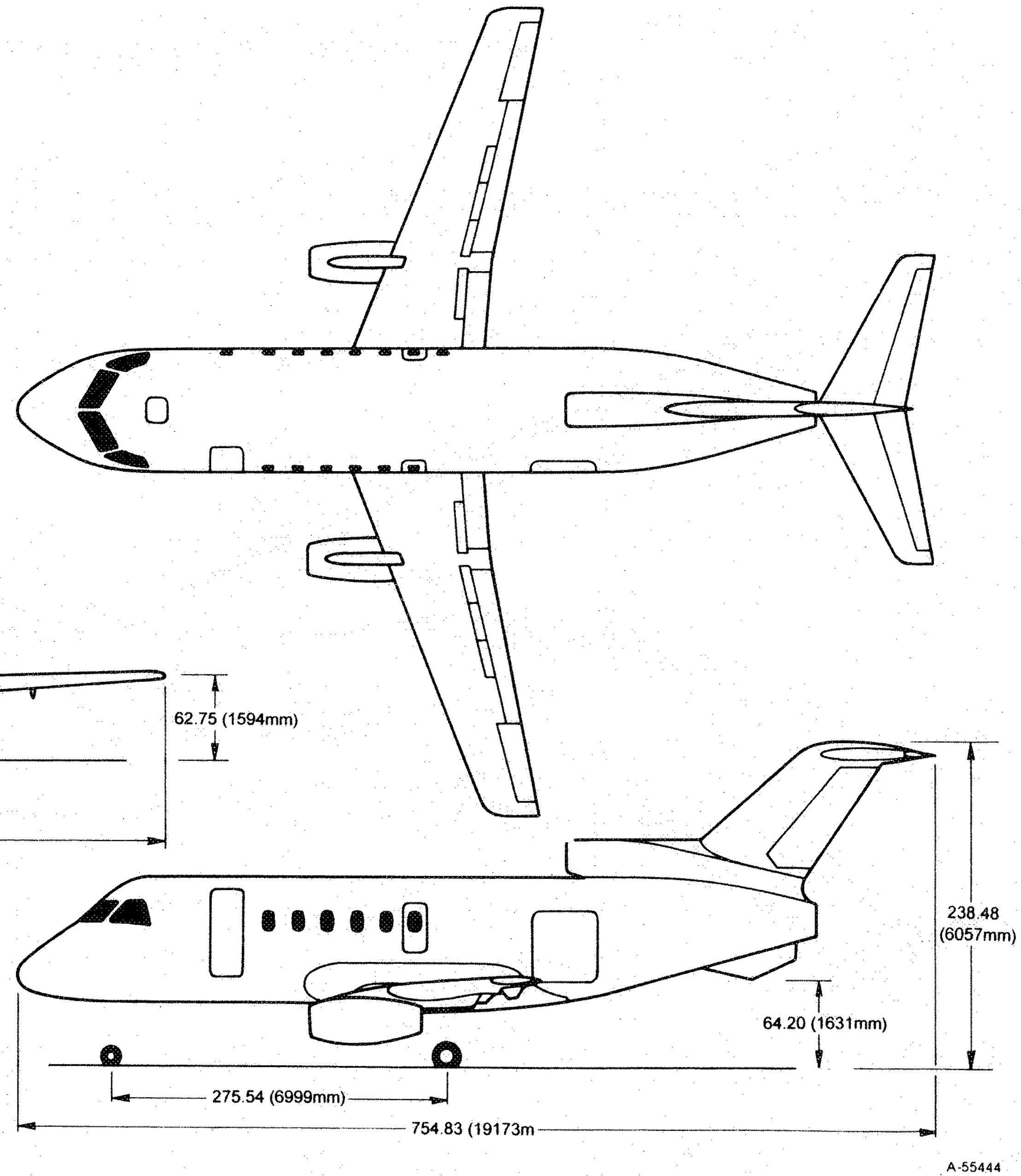


Figure 1-12. 19-Passenger FJ44-2 Powered Trijet Commuter/Regional Airliner

2.0 PROPULSION SYSTEM ANALYSIS

2.1 AIRCRAFT CHARACTERISTICS, PERFORMANCE, AND OPERATING COSTS

Currently, there are only four aircraft that make up the majority of the 19-passenger commuter fleet; all turboprop configurations. The external and internal dimensions, gross takeoff weight, payload, aircraft performance, and cost are given in Tables 2-I and 2-II.

The aircraft productivity factors are given in Table 2-III. This information supplies the factors needed to input into Williams International's operation cost model for comparative seat mile cost and overall profitability calculations. The data are separated by block distance in statute miles. The key parameters are:

Stage/Fuel - The number of trips or stages that can be made before refueling

No. Pass. - The maximum number of passengers carried

Eng. Hours - The engine run time including taxi for takeoff and flight time for all trips in a typical 14-hour operational day

Total Fuel - This is the fuel mass, in pounds, to complete all the days trips

Total Trips - The total number of trips, for that statute mile range, that can be completed in a typical 14-hour operational day

Seat Miles - Product of 19 seats x total trips x statute mile distance

sm/hr - Statute seat miles/hour; total seat miles/total engine hours

sm/lb - Total statute seat miles/total fuel

Block Speed - Average speed in knots to complete trip (includes taxi, climb and descent)

Mission Fuel - Fuel load, in pounds, required to complete a one-way trip

FL - Flight level (altitude); 260 = 26,000 feet pressure altitude

BFL - Balanced field length: minimum distance required to either clear a 50-foot obstacle or brake to a stop once reaching the V1 takeoff decision speed

Based on the referenced tables, current commuters have acquisition costs varying from $3.8 to $9 million for turboprops, and considerably higher for turbofan-powered regional jets. A balanced field length (BFL) of less than 4000 feet is very good. Typical cruise speeds are 230 to 290 knots for turboprops, with turbofan-powered commuters averaging well over 400 knots. The service ceiling for turboprops is typically 25,000 feet, whereas, turbofan regional jets have 40,000 feet capability. The current 19-passenger turboprops experience trips less than 500 statute miles; longer flights are too uncomfortable because of the limited cabin space and excessive cabin noise.

One factor affecting operational costs is the aircraft seat miles per hour (sm/hr). The average value for turboprop commuter aircraft is 4621 sm/hr for a 275 statute mile trip and 5059 sm/hr for the 400 statute mile trip. The greater the sm/hr value, the more profit is realized by the operator. Another factor is fuel usage. This is represented by seat miles per pound of fuel burned (sm/lb). The magnitude of this parameter for the average turboprop is 6.54 sm/lb for the 275 statute mile trip. The more statute miles achieved per pound of fuel burned, the higher the profit for the operator.

TABLE 2-I. REGIONAL AIRLINER COMPARISON PHYSICAL CHARACTERISTICS

Manufacturer Model	Dornier 228	Fairchild Metro 23-12	BAE Jetstream Super 31	Raytheon Beech 1900D	Saab SF340B	Canadair RJ100*
B/CA Price	$4,100,000	$3,850,000	$4,500,000	$4,775,000	$9,000,000	$17,900,000
Characteristics						
Seating	2 + 19	2 + 19	2 + 19	2 + 19	3 + 35	3 + 50
Seat Pitch	30.0	30.0	30.0	30.0	30.0	31.0
Wing	hi-wing	low wing	low wing	low wing	low wing	low wing
External Dimensions (Ft)						
Length	54.3	59.4	47.1	57.8	64.8	87.8
Height	15.9	16.7	17.7	15.5	22.6	20.4
Span	55.7	57.0	52.0	58.0	70.3	69.6
Turn Radius	48.5	38.5	41.1	41.2	52.0	75
Internal Dimensions (Ft)						
Length	23.3	25.4	24.3	25.0	34.1	48.4
Weight	5.1	4.8	5.9	5.9	6.0	6.1
Width	4.4	5.2	6.1	4.5	7.1	8.4
Bag. Vol. per Pass.	8.2	9.7	7.7	11.8	6.9	9.92
Power						
Engines	2 ASE TPE331-5A	2 ASE TPE331-12UAR	2 ASE TPE331-12UAR	2 P&W PT6A-67D	2 GE CT7-9B	2 GE CF34-3A1
Output (ea.)	776 shp	1,100 shp	1,020 shp	1,279 shp	1,750 shp	8,729 lbs
Pressurization	-	7.0	5.8	5.0	7.0	8.3
Weights (lbs)						
Max Ramp	14,175	16,600	16,314	17,060	29,300	47,700
Max Takeoff	14,109	16,500	16,204	16,950	29,000	47,450
Max Land.	13,448	15,675	15,609	16,600	28,500	44,700
Zero Fuel	13,095	14,500	14,850	15,000	26,500	42,200
OWE	8,249	9,500	10,136	10,615	17,945	30,100
Max Payload	4,846	5,000	4,714	4,385	8,555	12,100
Max Fuel	4,156	4,342	3,248	4,458	5,700	9,380
Pld. - Max Fuel	1,770	2,758	2,930	1,987	5,655	8,220
Fuel - Max Pld.	1,080	2,100	1,464	2,060	2,800	5,500
Fuel-Max Pass. Load**	2,126	3,300	2,378	2,645	4,355	7,600

Data from Business & Commercial Aviation May 1995
*Business & Commercial Aviation, May 1994 & 1995
** @ 200 lbs./passenger including baggage

TABLE 2-II. REGIONAL AIRLINER COMPARISON PERFORMANCE CHARACTERISTICS

Manufacturer Model	Dornier 228	Fairchild Metro 23-12	BAE Jetstream Super 31	Raytheon Beech 1900D	Saab SF340B	Canadair RJ100
Takeoff						
BFL SL ISA	2,600	5,460	5,147	3,737	4,337	5,265
5,000 ft + 20°C	4,500*	6,900*	6,386*	4,977	7,028	8,508
Climb Rate (fpm)						
All Engines	1,870	2,320	2,240	2,625	1,710	3,350
Engine Out	440	580	570	675	510	N/A
Climb Ceiling (Ft)						
All Engines	25,000	25,150	25,000	33,000	25,000	41,000
Engine Out	13,000	11,500	10,000	17,500	11,700	19,500
VMO (Knots)	223	246	250	248	250	330
Cruise						
TAS (Knots)	233	292	258	276	281	459
Fuel Flow (lb/hr)	720	762	637	746	1,031	2,600
FL	100	160	210	250	190	370

Data from Business & Commercial Aviation May 1995.

* WAT limited

VMO: Maximum operating velocity, airframe structural limit.

WAT: Weight, altitude, temperature limits for takeoff conditions to meet FAR climb gradient requirements. For example, when takeoff altitude and temperature are specified, the maximum takeoff gross weight is limited to that which permits the FAR takeoff climb gradient to be met. Refer to Figure 2-4 and Tables 2-IV aand 2-V.

TABLE 2-III. REGIONAL AIRLINER COMPARISON PRODUCTIVITY FACTORS

|----------------------------------TURBOPROPS -------------------------|-TURBOFAN-|

Manufacturer Model		Dornier 228*	Fairchild Metro 23-12*	BAe Jetstream Super 31*	Raytheon Beech 1900D*	Saab SF340B*	Canadair RJ100**
150 sm Mission	Stage/Fuel	2	4	2	2	4	
	No.Pass.	19	19	19	19	35	
	Eng. Hours	9.08	8.80	8.52	8.74	9.20	
	Total Fuel	5,863	5,871	5,590	7,821	8,826	
	Total Trips	12	13	12	13	13	
	Seat Miles	34,200	37,050	34,200	37,050	68,250	
	sm/hr	3,767	4,211	4,016	4,240	7,421	
	sm/lb	5.83	6.31	6.12	4.74	7.73	
	Block Speed	172	192	183	193	184	
	Mission Fuel	489	452	466	602	679	
	FL	100	160	180	170	140	
275 sm Mission	Stage/Fuel	2	3	2	2	3	2
	No.Pass.	19	19	19	19	35	50
	Eng. Hours	9.80	10.45	10.40	10.01	9.82	9.38
	Total Fuel	6,602	7,525	6,599	8,174	9,371	21,145
	Total Trips	8	10	9	9	9	11
	Seat Miles	41,800	52,250	47,025	47,025	86,625	151,250
	sm/hr	4,266	5,001	4,522	4,696	8,824	16,122
	sm/lb	6.33	6.94	7.13	5.75	9.24	7.15
	Block Speed	195	229	207	215	219	280
	Mission Fuel	825	752	733	908	1,041	1,922
	FL	100	150	210	240	170	340
400 sm Mission	Stage/Fuel		2	1	1	2	2
	No.Pass.		19	19	19	35	50
	Eng. Hours		10.00	10.99	10.61	10.37	10.02
	Total Fuel		7,181	7,031	8,401	9,935	23,074
	Total Trips		7	7	7	7	9
	Seat Miles		53,200	53,200	53,200	98,000	180,000
	sm/hr		5,322	4,840	5,016	9,453	17,965
	sm/lb		7.41	7.57	6.33	9.86	7.80
	Block Speed		244	222	230	235	313
	Mission Fuel		1,026	1,004	1,200	1,419	2,564
	FL		160	210	250	190	370
800 sm Mission	Stage/Fuel						1
	No.Pass.						50
	Eng. Hours						11.14
	Total Fuel						28,448
	Total Trips						6
	Seat Miles						240,000
	sm/hr						21,540
	sm/lb						8.44
	Block Speed						374
	Mission Fuel						4,741
	FL						350

*Business & Commercial Aviation, May 1995
**Business & Commercial Aviation, May 1994

2.2 AIRCRAFT MISSION DEFINITION

A study was conducted to ascertain the stage performance of a growth FJ44-2 engine to power a three-engine, 19-passenger commuter aircraft. Stage performance is presented for a given cruise altitude and mach number. These cruise conditions are selected to maximize profit for the airline operator. For a given passenger load and stage length, the principal productivity factors are the number of trips per 14-hour operational day, block speed, and average fuel used per stage. Other productivity parameters either contribute to these or are derived from them.

- Maximizing the number of trips per day maximizes the carrier's revenue/profit per aircraft.
- Maximizing block speed minimizes engine time per stage and associated maintenance per stage
- Minimizing average fuel per stage minimizes fuel cost. For a given stage length and passenger load, this is also measured by seat miles per pound of fuel

The minimum block speed is related to the number of trips per day and the number of trips per refueling as shown on Figure 2-1 for a 400 statute mile mission. Block speed is not only affected by the cruise Mach number, but for short flight, the cruise altitude. High cruise altitudes provide improved fuel economy, but reduce block speed for the same cruise speed due to the time required to climb and descend and the reduced time at cruise speed. A number of cruise altitude/Mach number combinations were investigated to establish the best productivity parameter values for the TriJet commuter.

Today's trend in commercial regional aircraft is toward higher passenger capacity, typically in the 70- to 120-seat range. These aircraft have a higher initial cost and greater operating costs than the historic smaller commuter aircraft. The trend toward larger aircraft gives the airline carrier a mismatch for a large number of city pairs that do not have the passenger per day density to be profitable. As a result, these potential markets are being ignored and left to the turboprop commuters to provide service. A market analysis indicated that there are hundreds of city pairs (i.e., Lansing, MI, to Chicago, IL, or Lafayette, IN, etc.) that will not be adequately served in today's developing regional airline market. City pairs up to 1000 miles apart are analyzed in Figure 2-2 for the passenger density of less than 100 potential seats per day. It can be seen that today's 19 passenger (19-passenger) turboprop can adequately serve up to 250 city pairs that are approximately 375 miles apart. The available city pairs from the 375 to 1000 mile flight distance are either serviced with the larger regional aircraft equipment via airline hub connections, or ignored as being unprofitable due to the low passenger per day density market size.

This inadequately serviced city pair segment from approximately 250 to 1000 miles is the target market for the 19-passenger Trijet commuter. The 19-passenger Trijet will maximize the number of trips and provide range, at a profit, extended well over today's turboprop aircraft and provide service to a new market segment that has little or no turbofan aircraft service today.

2.2.1 Commuter Airlines Survey

A questionnaire (provided in Appendix A) was provided and sent to the top 25 commuter airline operators to acquire market data. The table below gives these operators ranked according to passengers carried in 1993 (as published in the 1995 RAA Directory).

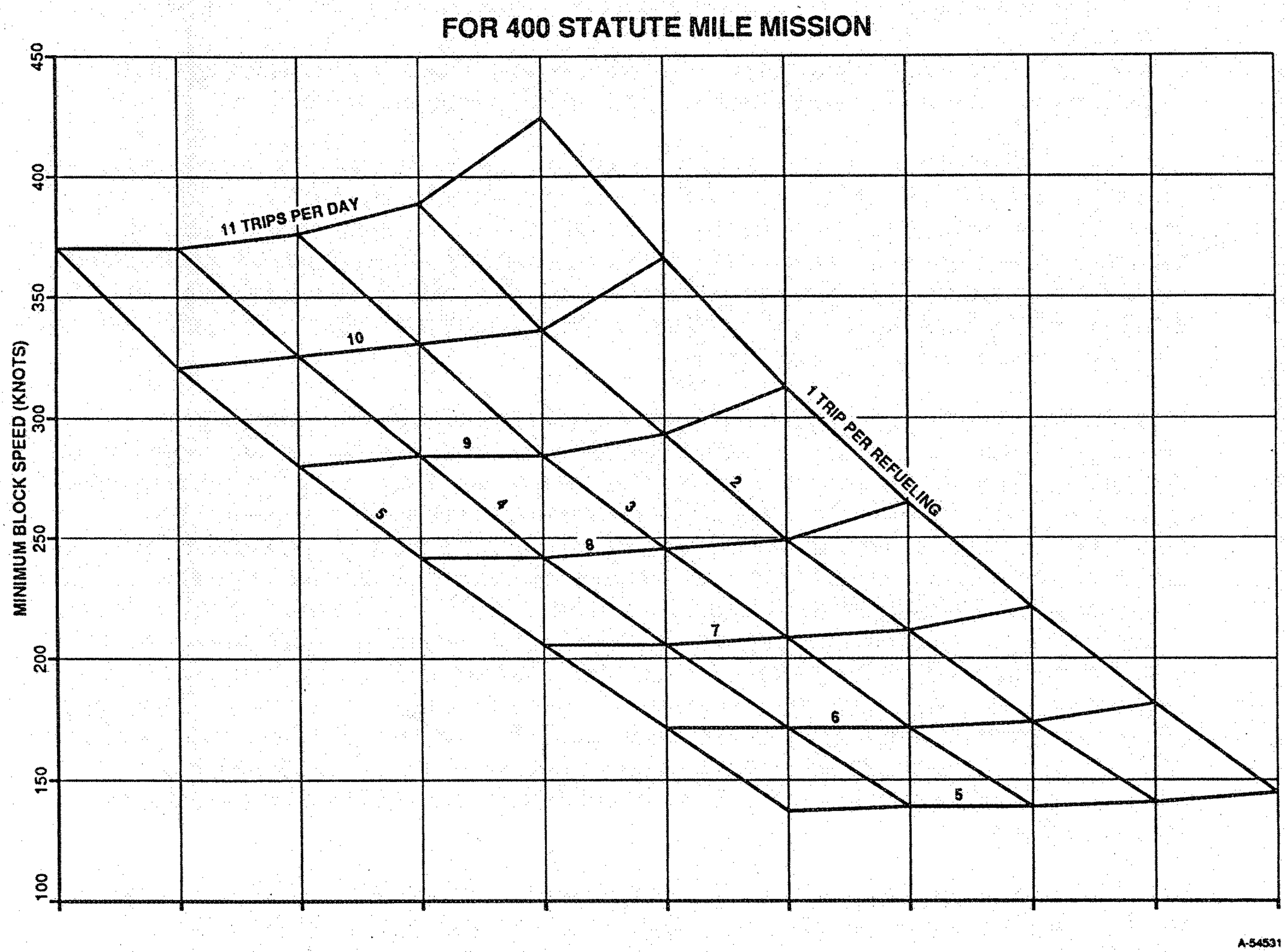


Figure 2-1. Regional Airliner Block Speed

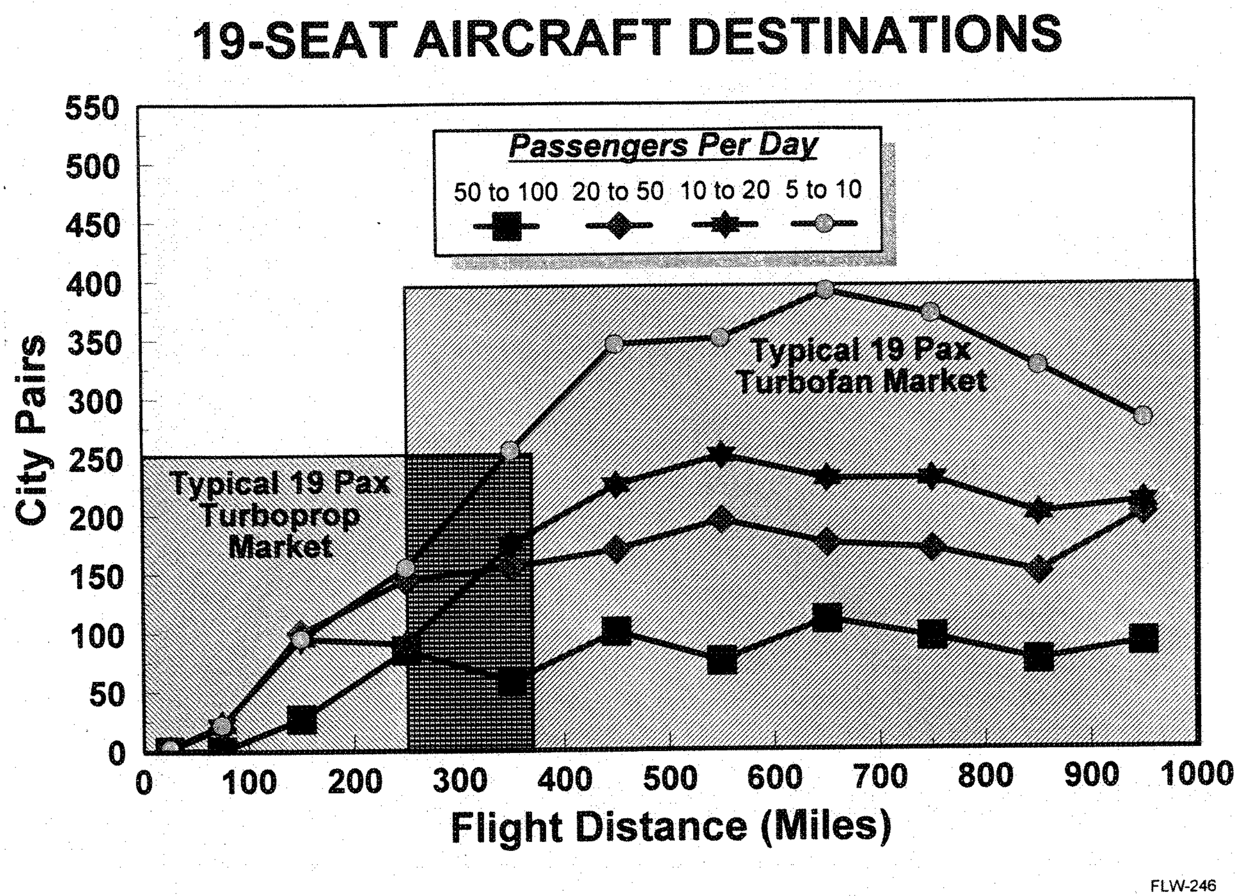


Figure 2-2. Target Market for 19-Passenger Trijet Commuter

RANK	COMPANY	PASSENGERS CARRIED (1993)
1	Continental Express	4,177,648
2	Simmons Airlines*	4,146,877
3	Flagship Airlines	4,108,551
4	Atlantic Southeast Airlines*	2,661,386
5	Comair	2,661,386
6	Horizon Air Industries	2,596,494
7	Piedmont Airlines*	2,481,176
8	Mesa Airlines	2,097,653
9	Allegheny Commuter Airlines*	2,090,060
10	West Air Airlines	2,086,922
11	Air Wisconsin*	2,066,012
12	Business Air Express	2,026,581
13	SkyWest Airlines	1,632,425
14	Atlantic Coast Airlines	1,444,006
15	Mesaba Aviation	1,400,222
16	Trans State Airlines	1,387,865
17	Wings West Airlines	1,251,672
18	Express Airlines I	1,193,410
19	Executive Airlines	908,853
20	CCAir	866,813
21	Jetstream International Airlines	852,931
22	Trans World Express	751,407
23	Great Lakes Aviation	612,028
24	Chautauqua Airlines	527,596
25	Commutair	476,703

*These airlines do not have 19-passenger aircraft in their fleet.
Ref: Data extracted from "The 1995 Regional Directory," Phillips Business Information, Inc.

2.2.2 Survey Results

The return rate at this report preparation time was 13 percent. This is a reasonable rate of return for an unsolicited blind survey. Typical responses for mail type surveys is usually more in the 3-to-5-percent range. Although our sample size is small, the following observations are noted from the responses received.

- Obtaining 1 to 2 more trips per day for 19-passenger aircraft is a plus and of interest to commuter airlines
- If performance can be improved with an acquisition cost competitive with today's turboprops, commuter airlines are interested
- Need to sell airlines the concept that three trijet configurations are necessary and cost-effective
- Agreement that the long routes, up to 1000 miles, are not productive for turboprops due to passenger discomfort

- Commuter airlines are interested in passenger service at the 1000 mile range, but the mind set is that a larger 30-to-50 passenger turbofan-powered aircraft is required to minimize block time. Again, *passenger comfort dictates the success and profitability of the aircraft used.*

It is interesting to note that a response received from Piedmont Airlines indicated no interest in a 19-passenger aircraft size. This was not unexpected because they currently do not have any operational 19-passenger aircraft. One of Piedmont's mergers/acquisitions involved Allegheny Airlines which operated in the Northeast region, and flew the Convair 440/540 series aircraft. These were very noisy, slow turboprops, but had a very comfortable cabin in terms of space as compared to today's commuter. These were fine for short trips, but companies like Piedmont shifted to the newer aircraft because of profitability and passenger response. If a new competitively priced aircraft that increased profitability, opened up new market routes and provided excellent passenger comfort were available, commuter airlines will be interested in getting their share of the new market.

The commuter service, Comair, which has a hub operation out of Cincinnati, OH, has been very successful incorporating regional turbofan-powered jets into its business operations. Mr. Charles Curran, Comair's Senior Vice President of Marketing, referred to the recently required 50-seat regional jets: "We have progressed to the point that as airplanes have available time, we fill in some of the short-haul segments where demand has grown and can support the larger piece of equipment. We wouldn't have gotten the airplanes just for those routes. But it has permitted us to attract more passengers into the Cincinnati hub because of the high public response to the aircraft. Passenger response has been tremendous. It's quiet, it's smooth, it gets up to altitude quickly, and it gives everybody the jet service they like...we've been able to bring jet service into markets that couldn't support 150-seat jets but can support this size of equipment. The passenger response is really why Delta has been interested in supplementing some of its market segments with our flights. It gives Delta the ability to add frequency to markets that give it added passenger flow at times of day when the market wouldn't support a bigger airplane." According to Mr. Curran, Comair has no further turboprops on order. He added, "There will continue to be markets that are profitable, but can't support a 50-seat aircraft."[1]

A revitalization of the 19-passenger commuter market requires a fresh approach to the propulsion system. The FJ44 turbofan engine can provide the baseline platform to launch new technology that will provide the performance needed for the Next Generation 19-Passenger Commuter. The approach requires:

- Incorporating lessons learned from large engine manufacturer's and basic component research activities that are produced by NASA and others are incorporated.
- Incorporating new technologies, like a cooled high pressure turbine rotor.
- High-strength materials and material systems that reduce weight or permit new low cost manufacturing techniques to be applied.

The FJ44 turbofan engine can provide the fresh platform to incorporate new technologies to revitalize the U.S. general aviation/commuter industry.

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[1] Aviation International News, "Regional Jets Attract Passenger Revenues, Help Comair Become Dominant Market Force," January 1, 1996.

2.3 MISSION ANALYSIS

2.3.1 Effect of Uprated Engine on Regional Jet Performance

Williams International has estimated performance for a regional jet powered by FJ44-2A engines flat-rated at 2100 lb to 84°F. The study aircraft (Figure 2-3), referred herein as the Trijet-2A, is a 19-passenger, trijet with two engines mounted on the wing via short pylons, and the third engine mounted in the tail with an S-duct supplying air from an inlet mounted above the fuselage. It has a maximum takeoff weight of 21,041 lb.

Performance estimates were made using this same study aircraft powered by the uprated version of the FJ44-2A engine, referred to as the FJ44-X, which is flat-rated at 2400 lb to 92°F. When powered by this uprated engine, this aircraft is referred to as the Trijet-X. Performance characteristics were estimated for both aircraft using Williams International's modified version of NASA's General Aviation Synthesis Program (GASP).

Takeoff and climb performance for the Trijet-2A (with the 2100 lb flat-rated engines) and the Trijet-X (with the 2400 lb flat rated engines) is summarized below.

Engine Flat Rating (lbs)	Altitude (ft)	Temperature (°C)	BFL (ft)	1.15 Times All Engine Takeoff (ft)	Time to Climb to 31K ft/35K ft from Brake Release (min)
2100	0	ISA	4082	3750	14.3/18.4
2100	5000	ISA+20	6069	5942	19.2/25.9
2400	0	ISA	3297	3296	12.9/16.6
2400	5000	ISA+20	5124	4506	17.2/22.6

The use of the uprated engine provides a reduction of 16 to 19-percent in balanced field length. This provides improved flexibility in operating from communities with small airports. The reduction of 10 to 13-percent in time to climb will result in increased passenger comfort and will reduce block time which reduces flight time sensitive costs per trip and enhances profitability.

Climb gradient performance data (Tables 2-IV and 2-V) show that neither the Trijet-2A nor the Trijet-X are weight-limited for these conditions, i.e., both meet the FAR-25 climb gradient requirements at their maximum takeoff and landing weights for the given altitude and ambient temperature conditions. The takeoff weight, altitude, and temperature characteristics shown in Figure 2-4, however, show that the Trijet-X has a significant advantage in flying out of high altitude airports, especially on hot days where it can take off with up to 3400 lb more fuel and/or payload.

Range/payload characteristics are virtually unaffected by the use of the FJ44-X engine and are shown on Figure 2-5. Reserve fuel requirement is that given in "Business & Commercial Aviation 1995 Planning and Purchasing Handbook," May 1995.

The Trijet-2A and Trijet-X are compared to current 19-passenger regional airliners (all turboprops) in Tables 2-VI, VII, and VIII. The data for the current aircraft were also obtained from the Business & Commercial Aviation Handbook. The physical characteristics are compared in Table 2-VI. Note that the trijets provide the greatest seat pitch which, together with the large interior cross section, provides roominess unmatched by any of the turboprops. It also provides the greatest baggage volume per passenger.

Target Price	less than $6 Million
Passengers	19
Crew	2
Seating	3-abreast
Max Cabin Width - Internal (in)	85
Seat Pitch (in)	32
Powerplants	Three FJ44-2 Turbofans
Output (SLST) (lb)	2400 each at 92°F
Max Fuel (lb)	5186
Ramp Weight (lb)	21,141
Max Takeoff Gross Weight (lb)	21,041
Cabin Pressurization (psid)	7.5

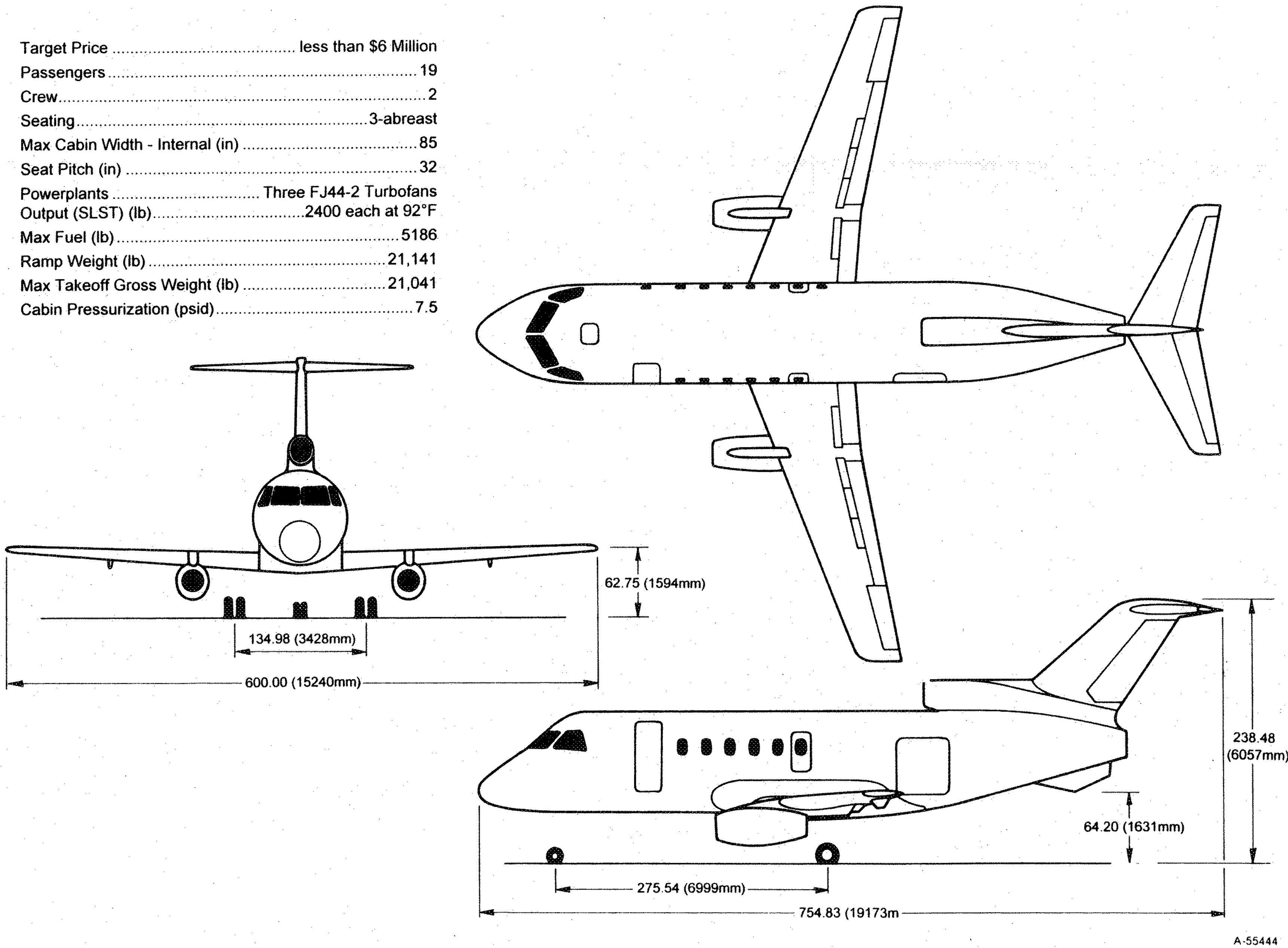


Figure 2-3. 19-Passenger FJ44-2 Powered Trijet Commuter/Regional Airliner

TABLE 2-IV. REGIONAL TRIJET CLIMB PERFORMANCE AT SEA LEVEL, ISA

2100 LB. FLAT RATED ENGINES

CLIMB PERFORMANCE VS GRADIENT REQUIREMENTS - FAR PART 25 FOR 3 ENGINE AIRPLANE

AIRPORT ALTITUDE= 0. FT; AMBIENT TEMP = 59. DEG F WHICH IS 0. DEG F ABOVE STD. DAY

TAKEOFF WEIGHT = 21041. LBS. MAX. LANDING WEIGHT = 20047. LBS

CONFIGURATION	ENGINES	GEAR	FLAPS (DEG)	ALTITUDE (FT)	WEIGHT (LBS)	VSTALL (KTAS)	VELOCITY (KTAS)	ROC (FPM)	ROC REQ (FPM)	GRADIENT (PERCENT)	GRAD. REQ (PERCENT)	CL REQ	L/D
1ST SEG:T.O.	ONE OUT	DOWN	25.0	35.	21041.	100.8	115.8	655.1	35.2	5.6	0.3*	1.46	8.55
2ND SEG: T.O.	ONE OUT	UP	25.0	400.	21041.	101.4	121.6	955.6	332.5	7.8	2.7*	1.34	10.60
FINAL T.O.	ONE OUT	UP	0.0	1500.	21041.	133.2	166.5	1554.2	252.9	9.2	1.5*	0.74	13.53
APPROACH	ONE OUT	UP	5.7	2000.	20047.	110.4	165.6	1475.5	402.5	8.8	2.4*	0.72	12.07
LANDING	ALL	DOWN	35.0	0.	20047.	97.5	126.7	1630.0	410.6	12.7	3.2*	1.16	7.37

* FAR PART 25 REQUIREMENT

2400 LB. FLAT RATED ENGINES

CLIMB PERFORMANCE VS GRADIENT REQUIREMENTS - FAR PART 25 FOR 3 ENGINE AIRPLANE

AIRPORT ALTITUDE= 0. FT; AMBIENT TEMP = 59. DEG F WHICH IS 0. DEG F ABOVE STD. DAY

TAKEOFF WEIGHT = 21041. LBS. MAX. LANDING WEIGHT = 20047. LBS

CONFIGURATION	ENGINES	GEAR	FLAPS (DEG)	ALTITUDE (FT)	WEIGHT (LBS)	VSTALL (KTAS)	VELOCITY (KTAS)	ROC (FPM)	ROC REQ (FPM)	GRADIENT (PERCENT)	GRAD. REQ (PERCENT)	CL REQ	L/D
1ST SEG:T.O.	ONE OUT	DOWN	25.0	35.	21041.	100.8	115.8	981.9	35.2	8.4	0.3*	1.46	8.55
2ND SEG: T.O.	ONE OUT	UP	25.0	400.	21041.	101.4	121.6	1297.8	332.5	10.5	2.7*	1.34	10.60
FINAL T.O.	ONE OUT	UP	0.0	1500.	21041.	133.2	166.5	1809.2	252.9	10.7	1.5*	0.74	13.53
APPROACH	ONE OUT	UP	5.7	2000.	20047.	110.4	165.6	1939.0	402.5	11.6	2.4*	0.72	12.07
LANDING	ALL	DOWN	35.0	0.	20047.	97.5	126.7	2169.1	410.6	16.9	3.2*	1.16	7.37

* FAR PART 25 REQUIREMENT

TABLE 2-V. REGIONAL TRIJET CLIMB PERFORMANCE AT 5000 FT. ISA +20C

2100 LB. FLAT RATED ENGINES

CLIMB PERFORMANCE VS GRADIENT REQUIREMENTS - FAR PART 25 FOR 3 ENGINE AIRPLANE

AIRPORT ALTITUDE= 5000. FT; AMBIENT TEMP = 77. DEG F WHICH IS 36. DEG F ABOVE STD. DAY

TAKEOFF WEIGHT = 21041. LBS. MAX. LANDING WEIGHT = 20047. LBS

CONFIGURATION	ENGINES	GEAR	FLAPS (DEG)	ALTITUDE (FT)	WEIGHT (LBS)	VSTALL (KTAS)	VELOCITY (KTAS)	ROC (FPM)	ROC REQ (FPM)	GRADIENT (PERCENT)	GRAD. REQ (PERCENT)	CL REQ	L/D
1ST SEG:T.O.	ONE OUT	DOWN	25.0	5035.	21041.	112.4	127.4	348.5	38.7	2.7	0.3*	1.50	8.47
2ND SEG: T.O.	ONE OUT	UP	25.0	5400.	21041.	113.0	135.7	658.7	370.9	4.8	2.7*	1.34	10.53
FINAL T.O.	ONE OUT	UP	0.0	6500.	21041.	148.7	185.9	810.6	282.3	4.3	1.5*	0.74	13.39
APPROACH	ONE OUT	UP	5.7	7000.	20047.	123.3	184.9	962.2	449.5	5.1	2.4*	0.72	11.96
LANDING	ALL	DOWN	35.0	5000.	20047.	108.7	141.3	1199.2	457.8	8.4	3.2*	1.16	7.34

* FAR PART 25 REQUIREMENT

2400 LB. FLAT RATED ENGINES

CLIMB PERFORMANCE VS GRADIENT REQUIREMENTS - FAR PART 25 FOR 3 ENGINE AIRPLANE

AIRPORT ALTITUDE= 5000. FT; AMBIENT TEMP = 77. DEG F WHICH IS 36. DEG F ABOVE STD. DAY

TAKEOFF WEIGHT = 21041. LBS. MAX. LANDING WEIGHT = 20047. LBS

CONFIGURATION	ENGINES	GEAR	FLAPS (DEG)	ALTITUDE (FT)	WEIGHT (LBS)	VSTALL (KTAS)	VELOCITY (KTAS)	ROC (FPM)	ROC REQ (FPM)	GRADIENT (PERCENT)	GRAD. REQ (PERCENT)	CL REQ	L/D
1ST SEG:T.O.	ONE OUT	DOWN	25.0	5035.	21041.	112.4	127.4	693.9	38.7	5.4	0.3*	1.50	8.47
2ND SEG: T.O.	ONE OUT	UP	25.0	5400.	21041.	113.0	135.7	1016.2	370.9	7.4	2.7*	1.34	10.53
FINAL T.O.	ONE OUT	UP	0.0	6500.	21041.	148.7	185.9	927.5	282.3	4.9	1.5*	0.74	13.39
APPROACH	ONE OUT	UP	5.7	7000.	20047.	123.3	184.9	1404.6	449.5	7.5	2.4*	0.72	11.96
LANDING	ALL	DOWN	35.0	5000.	20047.	108.7	141.3	1782.4	457.8	12.5	3.2*	1.16	7.34

* FAR PART 25 REQUIREMENT

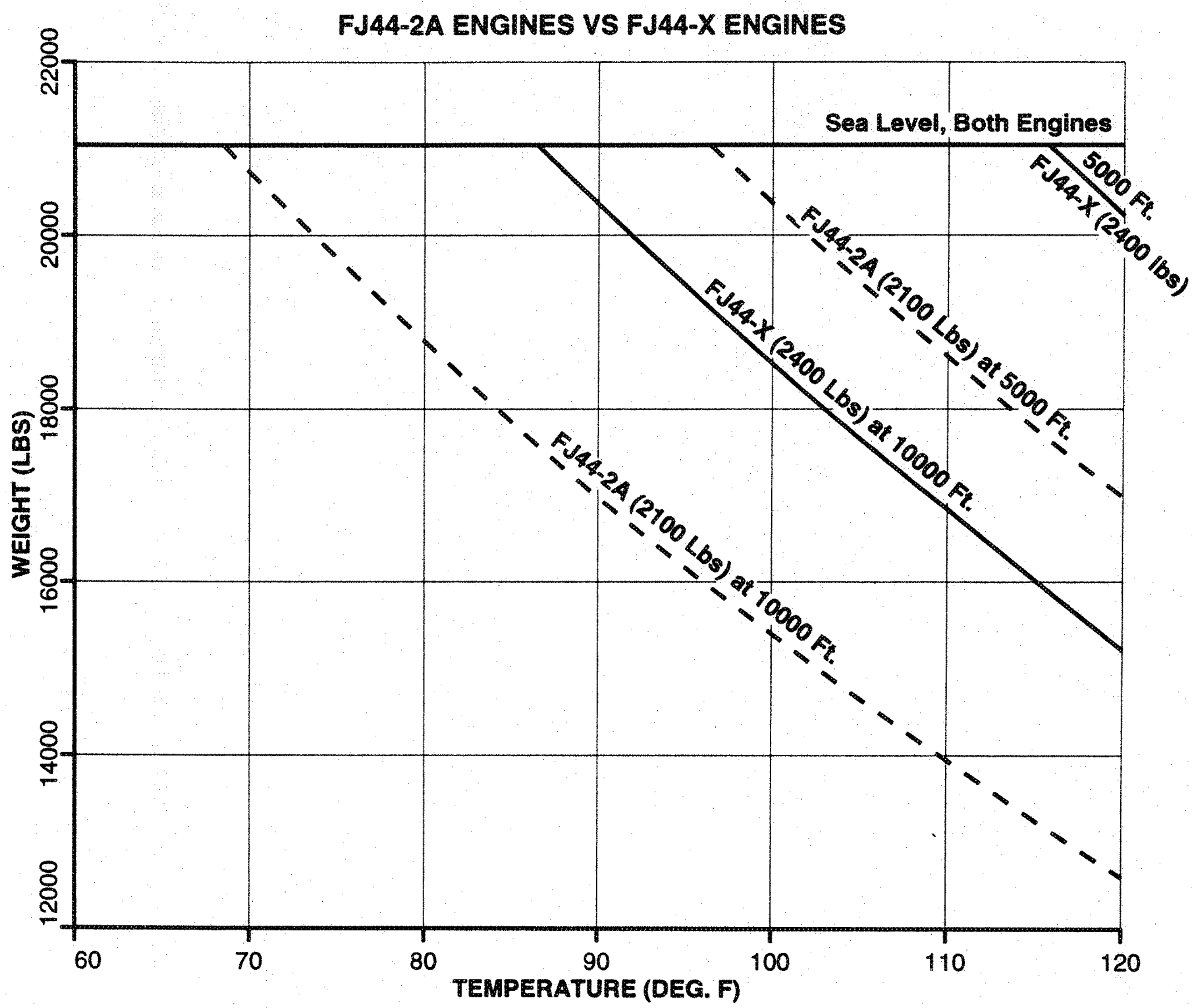


Figure 2-4. Regional Trijet Takeoff WAT Characteristics

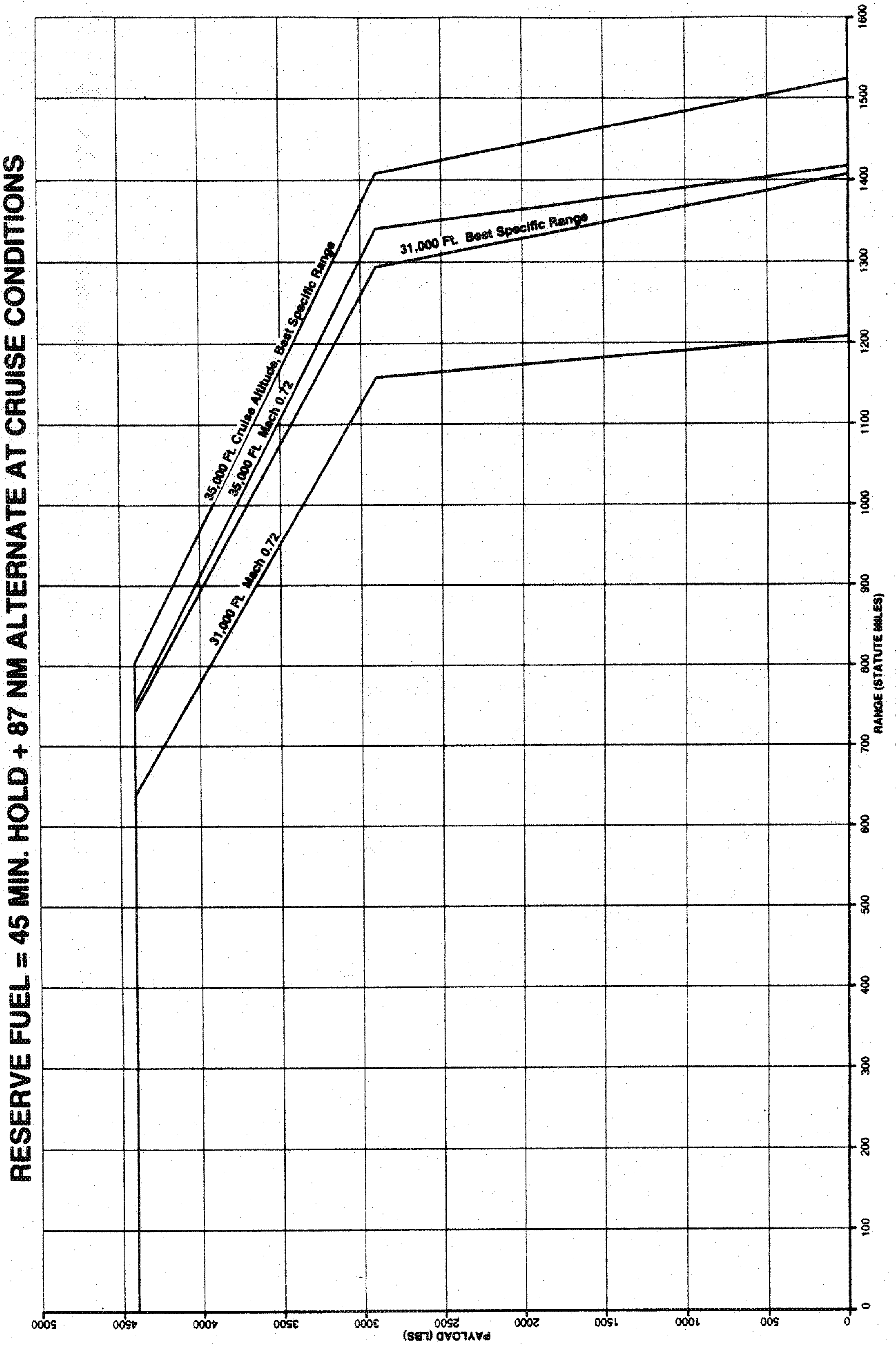


Figure 2-5. Trijet-2A and Trijet-X Range - Payload

TABLE 2-VI. 19-PASSENGER REGIONAL AIRLINERS PHYSICAL CHARACTERISTICS

Manufacturer Model	Trijet-2A	Trijet-X	Dornier 228	Fairchild Metro 23-12	BAE Jetstream Super 31	Raytheon Beech 1900D
B/CA Price ($)	6,000,000	6,000,000	4,100,000	3,850,000	4,500,000	4,775,000
Characteristics						
Seating	2 + 19	2 + 19	2 + 19	2 + 19	2 + 19	2 + 19
Seat Pitch	32.0	32.0	30.0	30.0	30.0	30.0
Wing	low wing	low wing	hi-wing	low wing	low wing	low wing
External Dimensions (Ft)						
Length	62.9	62.9	54.3	59.4	47.1	57.8
Height	19.9	19.9	15.9	16.7	17.7	15.5
Span	50.0	50.0	55.7	57.0	52.0	58.0
Turn Radius	26.5	26.5	48.5	38.5	41.1	41.2
Internal Dimensions (Ft)						
Length	23.0	23.0	23.3	25.4	24.3	25.0
Weight	6.0	6.0	5.1	4.8	5.9	5.9
Width	7.1	7.1	4.4	5.2	6.1	4.5
Bag. Vol. per Pass.	11.9	11.9	8.2	9.7	7.7	11.8
Power						
Engines	3 Williams/ Rolls FJ44-2A	3 Williams/ Rolls FJ44-X	2 ASE TPE331-5A	2 ASE TPE331-12UAR	2 ASE TPE331-12UAR	2 P&W PT6A-67D
Output (ea.)	2100 lbf	2400 lbf	776 shp	1,100 shp	1,020 shp	1,279 shp
Pressurization	7.5	7.5	-	7.0	5.8	5.0
Weights (lbs)						
Max Ramp	21,141	21,141	14,175	16,600	16,314	17,060
Max Takeoff	21,041	21,041	14,109	16,500	16,204	16,950
Max Land.	20,047	20,047	13,448	15,675	15,609	16,600
Zero Fuel	17,457	17,457	13,095	14,500	14,850	15,000
OWE	13,049	13,049	8,249	9,500	10,136	10,615
Max Payload	4,408	4,408	4,846	5,000	4,714	4,385
Max Fuel	5,186	5,186	4,156	4,342	3,248	4,458
Pld. - Max Fuel	2,906	2,906	1,770	2,758	2,930	1,987
Fuel - Max Pld.	3,684	3,684	1,080	2,100	1,464	2,060
Fuel-Max Pass. Load**	4,292	4,292	2,126	3,300	2,378	2,645

*Business & Commercial Aviation May 1995.
**at 200 lbs/passenger including baggage

TABLE 2-VII. 19-PASSENGER REGIONAL AIRLINERS PERFORMANCE CHARACTERISTICS

Manufacturer Model	Trijet-2A	Trijet-X	Dornier 228	Fairchild Metro 23-12	BAe Jetstream Super 31	Raytheon Beech 1900D
Takeoff BFL SL ISA	4,082	3,297	2,600	5,460	5,147	3,737
5,000 ft + 20^{0} C	6,069	5,124	4,500*	6,900*	6,386*	4,977
Climb Rate (fpm) All Eng.	3,431	3,792	1,870	2,320	2,240	2,625
Eng. Out	1,059	1,379	440	580	450	675
Climb Ceiling (ft) All Eng.	40,439	41,455	25,000	25,150	25,000	33,000
Eng. Out	21,432	22,763	13,000	11,500	10,000	17,500
VMO (Knots)	270	270	223	246	250	248
Cruise TAS (knots	432	432	233	292	258	276
Fuel Flow (lb/hr)	1,326	1,332	720	762	637	746
FL	350	350	100	160	210	250

Data from Business & Commercial Aviation May 1995.

* WAT limited

VMO: Maximum operating velocity, airframe structural limit.

WAT: Weight, altitude, temperature limits for takeoff conditions to meet FAR climb gradient requirements. For example, when takeoff altitude and temperature are specified, the maximum takeoff gross weight is limited to that which permits the FAR takeoff climb gradient to be met. Refer to Figure 2-4.

TABLE 2-VIII. 19-PASSENGER REGIONAL AIRLINER COMPARISON PRODUCTIVITY FACTORS

Manufacturer Model		Trijet-2A	Trijet-X	Dornier 228*	Fairchild Metro 23-12*	BAe Jetstream Super 31*	Raytheon Beech 1900D*
150 sm Mission	Stage/Fuel	4	4	2	4	2	2
	No.Pass.	19	19	19	19	19	19
	Eng. Hours	8.78	8.76	9.08	8.80	8.52	8.74
	Total Fuel	10,290	10,271	5,863	5,871	5,590	7,821
	Total Trips	14	14	12	13	12	13
	Seat Miles	39,900	39,900	34,200	37,050	34,200	37,050
	sm/hr	4,542	4,555	3,767	4,211	4,016	4,240
	sm/lb	3.88	3.89	5.83	6.31	6.12	4.74
	Block Speed	208	208	172	192	183	193
	Mission Fuel	735	734	489	452	466	602
	FL	260	260	100	160	180	170
275 sm Mission	Stage/Fuel	2	2	2	3	2	2
	No.Pass.	19	19	19	19	19	19
	Eng. Hours	9.68	9.59	9.80	10.45	10.40	10.01
	Total Fuel	13,013	13,010	6,602	7,525	6,599	8,174
	Total Trips	11	11	8	10	9	9
	Seat Miles	57,475	57,475	41,800	52,250	47,025	47,025
	sm/hr	5,941	5,994	4,266	5,001	4,522	4,696
	sm/lb	4.42	4.42	6.33	6.94	7.13	5.75
	Block Speed	272	274	195	229	207	215
	Mission Fuel	1,183	1,183	825	752	733	908
	FL	310	310	100	150	210	240
400 sm Mission	Stage/Fuel	2	2		2	1	1
	No.Pass.	19	19		19	19	19
	Eng. Hours	10.32	10.23		10.00	10.99	10.61
	Total Fuel	13,546	13,529		7,181	7,031	8,401
	Total Trips	9	9		7	7	7
	Seat Miles	68,400	68,400		53,200	53,200	53,200
	sm/hr	6,629	6,687		5,322	4,840	5,016
	sm/lb	5.05	5.06		7.41	7.57	6.33
	Block Speed	303	306		244	222	230
	Mission Fuel	1,505	1,503		1,026	1,004	1,200
	FL	350	350		160	210	250
800 sm Mission	Stage/Fuel	1	1				
	No.Pass.	19	19				
	Eng. Hours	9.79	9.73				
	Total Fuel	13,012	12,999				
	Total Trips	5	5				
	Seat Miles	76,000	76,000				
	sm/hr	7,767	7,812				
	sm/lb	5.84	5.85				
	Block Speed	355	357				
	Mission Fuel	2,602	2,600				
	FL	350	350				

*Business & Commercial Aviation, May 1995

Performance characteristics of the trijets compare quite favorably with these aircraft (Table 2-VII). Only the Dornier 228 and the Beech 1900D provide shorter balanced field lengths than the Trijet-2A, but under the high/hot conditions, the Dornier 228 is weight-limited by FAR gradient requirements. The uprated engines on the Trijet-X, however, provide balanced field lengths shorter than the Beech 1900D.

The Trijet-2A climb performance compares favorably with all of the aircraft and its engine-out capability is outstanding due to the 3-engine configuration. The Trijet-X adds to that advantage with a 10-percent increase in all-engine climb rate and an impressive 30-percent improvement in the already outstanding engine-out climb rate. High speed cruise capability clearly out performs the turboprops but at the expense of greater fuel flow. This results in lower flight-time-sensitive costs that are partly offset by higher fuel costs.

The Trijet-2A and Trijet-X productivity factors are compared to current aircraft in Table 2-VIII. Use of the uprated engine improves block time and mission fuel. The Trijet-X block speed and consequently trips per day are clearly superior to the turboprops. The seat-miles per hour are increased substantially, particularly at the 400 statute mile range where 20 to 27 percent improvement is evident. Seat-miles per pound of fuel still favor the turboprops. The net effect, however, is in favor of the Trijet as revealed in the cost analysis discussed in Sections 1.3 and 3.4. For the cost analysis, the Trijet-X stage characteristics were optimized for maximum trips per day and minimum fuel and time-sensitive costs (Table 2-IX).

In conclusion, there is a significant advantage in the application of the high technology, uprated FJ44 engine to a 19-passenger regional airliner by 1) increased takeoff and climb performance which gives it the ability to effectively use smaller and/or higher elevation airports at higher ambient temperatures, and 2) higher block speeds providing up to 27-percent improvement in seat-miles per hour and two extra trips per day over the current 19-passenger turboprop aircraft at a 400 statute mile distance.

TABLE 2-IX. TRIJET-X REGIONAL AIRLINER STAGE CHARACTERISTICS

Cruise optimized for: maximum trips per day
Total Per Flight Hour Cost = $237.57/hr
Fuel Cost = $0.60/gal
10 minute taxi time included in block time

(nautical miles)	Trips per Day	Stages per Refueling	Block Time (hours)	Block Fuel (lb)
50	19	8	0.370	396.9
100	16	5	0.518	640.9
150	14	4	0.653	841.9
200	12	3	0.776	1029.4
250	11	3	0.895	1197.0
300	10	3	1.026	1323.5
350	9	2	1.141	1493.6
400	8	2	1.256	1641.9
450	8	2	1.372	1791.9
500	7	2	1.489	1946.4
550	6	1	1.607	2124.1
600	6	1	1.723	2282.3
650	6	1	1.839	2435.1
700	5	1	1.955	2587.6
750	5	1	2.071	2739.7
800	5	1	2.187	2891.6
850	5	1	2.304	3043.1
900	5	1	2.381	3471.8
950	4	1	2.536	3345.3
1000	4	1	2.652	3495.9
1050	4	1	2.768	3646.2
1100	4	1	2.884	3796.2
1150	4	1	3.000	3945.9

2.4 BASELINE ENGINE DESCRIPTION

2.4.1 FJ44-1A Business Jet Engine

The reference engine is the Williams International FJ44 turbofan engine. It was designed for use in business jets, trainers, commuters, and RPVs. It was FAA certified in 1992, currently powers the Cessna CitationJet, and the Swedish Air Force SK60 trainer. A growth version, the FJ44-2A, will power the Raytheon Premier I business Jet.

In its present form, the engine has already demonstrated it can be competitive against turboprops in business jets and trainer aircraft, so it is a good candidate to form the basis for a derivative that will be optimized to power a 19-passenger advanced commuter aircraft. The typical small commuter experiences about 1.6 mission cycles per hour which drives a high cyclic content into the engine life formula. Typically, low operating and maintenance costs are incompatible with these high cyclic content missions, but testing on the FJ44 engine that was also designed for a trainer mission, has shown that it is possible to develop a small turbofan that will meet or exceed current standards established by the turboprop fleet.

Based on current commuter operation norms, it is expected that a turbofan-powered 19-passenger commuter would need a high bypass fan, low SFC, power enough to achieve at least 3500 ft/min climb with efficient cruise at 33,000 to 35,000 feet, and operating costs less than $0.16 per revenue passenger mile with 60 percent load factor. Maintenance costs should be competitive with current turbofans to include hot section inspection (HSI) and time between overhaul (TBO) reserve plus routine maintenance. A goal of 9000 hours mature TBO with HSI on the wing at 3000 hours would be established.

A cross section of the FJ44 is shown in Figure 2-6. The inlet diameter is 18.8 inches. The engine is 44 inches from the fan rotor inlet to the exit plane of the core exhaust nozzle. The engine has a single-stage fan followed by a single-stage axial compressor at the core inlet. This axial compressor is on the fan spool. The core consists of a high pressure ratio centrifugal compressor driven by a high pressure ratio axial turbine. Following this turbine, there is a two-stage axial turbine that drives the fan and the axial compressor. The combustor has a radial flowpath, and fuel is supplied to it by a rotating fuel slinger mounted on the shaft between the core compressor and turbine rotors. A summary of engine performance and component thermodynamic conditions is given in Table 2-X.

The FJ44 engine has a design service life of 10,000 hours for business jet applications. The duty cycle for the business jet consists of one flight cycle per flight hour. Major rotating and static structure components have component lives in excess of the 10,000 hours or cycles. The FJ44 is operated with fixed maintenance intervals. The FJ44-1A engine has been certified for hot section maintenance every 1750 hours and cold section maintenance every 3500 hours.

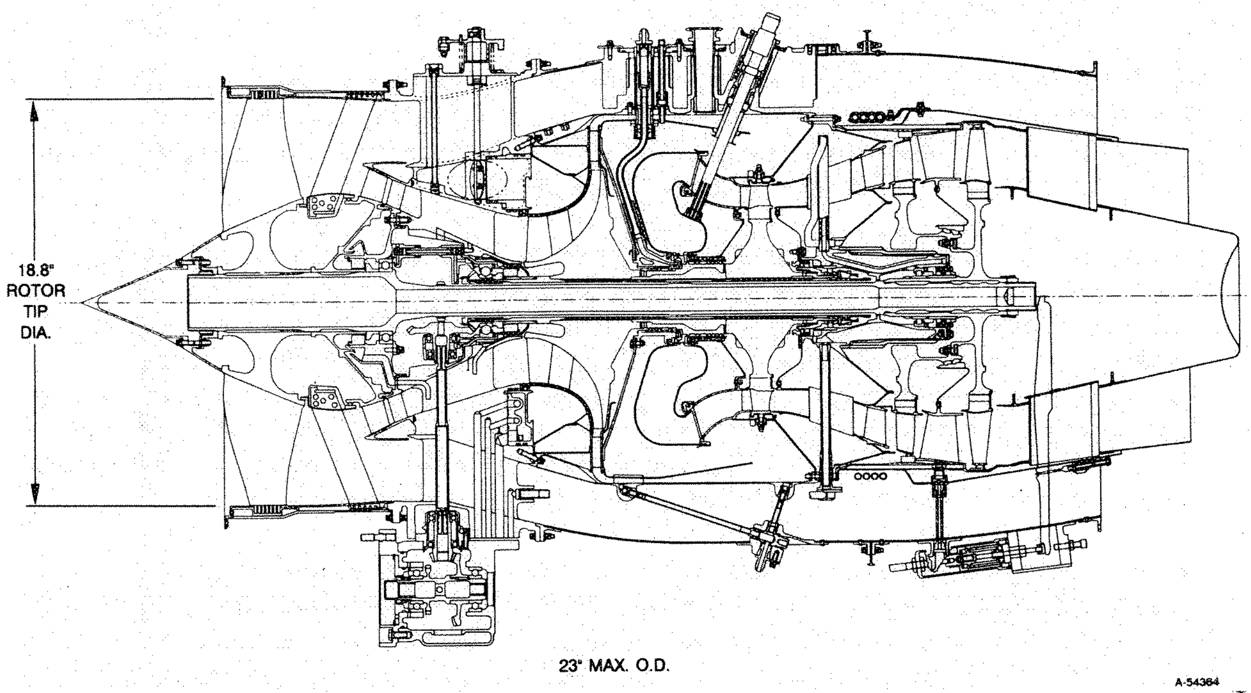


Figure 2-6. Williams International FJ44-1 Turbofan Engine

TABLE 2-X. FJ44 PERFORMANCE SUMMARY

Parameter	Sea Level Static	39,000 ft, Mach 0.7
Net Thrust (lb)	1900	411
SFC (lb/lb-hr)	0.48	0.78
Turbine Nozzle Inlet Temperature (°F)	2,002	1,948
Turbine Rotor Inlet Temperature (°F)	1,879	1,811
Overall Pressure Ratio	12.84	15.84
Fan Bypass Ratio	3.29	3.10
Fan Hub Pressure Ratio	1.61	1.77
Fan Tip Pressure Ratio	1.58	1.75
IP Compressor Ratio	1.24	1.30
HP Compressor Pressure Ratio	6.43	6.85
HP Turbine Pressure Ratio	3.21	3.20
LP Turbine Pressure Ratio	2.94	3.25

The engine has been designed to allow hot section inspection to be performed on the wing. This permits turbine removal without removing the entire engine from the wing. Removal and replacement of hot section parts can be accomplished within one eight-hour shift. The use of a small number of turbomachinery stages contributes to a low acquisition price, approximately 25 percent below current prices for engines of equivalent performance.

Current Materials and Processes

The materials used on all Williams International engines and the FJ44 engine in particular are chosen based on design requirements, cost (availability and ease of fabrication), and proven performance history in aircraft engines. Material property design data comes from available data bases, industry standards, or is generated for unique component sizes and thermal processing as used on the FJ44-1A. Figure 2-7 shows the materials used on the FJ44.

The FJ44-1A is a good example of the diversity of materials and processes used in the design and fabrication of Williams International turbofan engines. The FJ44 fan and IPC rotors are integrally machined from Ti 6-4 closed die forgings. The fan forging has a scalloped shape at the blade location to make that area nearer to net shape. The HPC rotor is also machined integral from a closed die forging but the material is Ti 6-2-4-2 because of higher operating temperature. In the compressor section, the fan case is fabricated from a Nitronic 33 ring forging for blade containment and the interstage housing is sand cast in A357 aluminum. The interstage housing is heat-treated to the overaged condition to minimize residual stress and corrosion. All aluminum parts are also anodized for added corrosion resistance. The HP compressor cover is an Inconel 718 brazed assembly with a thermal sprayed aluminum polymide material forming the flowpath abradable surface. The diffuser is a brazed and welded structure fabricated from Inconel 718 and Inconel 625.

In the FJ44 hot section, the combustor is fabricated from Incoloy 617. The combustor walls are laser drilled with numerous small holes patterned to achieve effusion cooling. The HPT nozzle is an integral investment casting in Mar-M 247 with supporting structure fabricated from Inconel 718, Rene 41, and Alloy 613LC. The nozzle flowpath is pack aluminide coated for hot corrosion resistance. The HPT rotor disk is an Inconel 718 forging and the blades are DS Mar-M-247 with an aluminide coating.

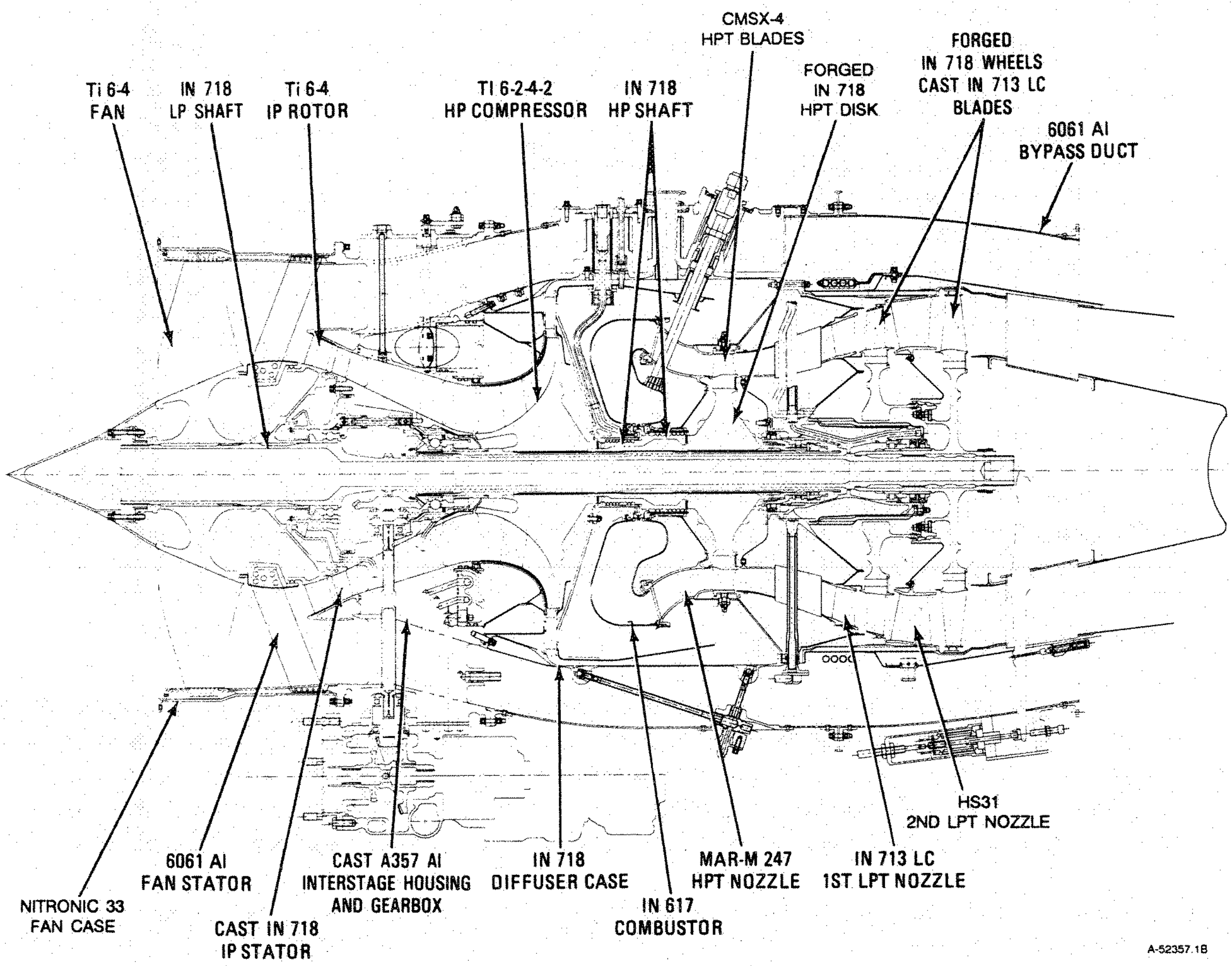


Figure 2-7. Materials used in the FJ44

In the LP section, the two turbine disks are Inconel 718 forgings and the blades are investment cast Alloy 713. The first LP nozzle is an Alloy 713 integral investment casting and the second LP nozzle is a Stellite 31 investment casting. Blade shroud rings are Hastelloy S and Iconel 625 ring forgings.

The FJ44 exhaust structure is primarily stainless steel. Other sheet metal components in the hot section are either stainless steel or nickel-base alloys depending on structural requirements. Inconel 718 is used for the HP and LP shafts. Seals are either thermal-sprayed materials or replaceable honeycomb structures. The front spinner and outer bypass ducts are anodized aluminum alloys.

2.4.2 FJ44-2A Commuter Baseline Engine

Williams International "wide sweep fan" technology has resulted in a major breakthrough in propulsion technology. Three years ago, the Williams-Rolls team introduced the 1900-lbf thrust FJ44-1 turbofan engine, which made feasible a new category of affordable light business jets. Williams-Rolls has now unveiled the 2300 lbf thrust FJ44-2 that makes feasible another category of low cost, yet larger and higher performance aircraft. Through the application of Williams International's wide sweep fan technology, the outstanding weight and performance of this upgraded engine allows a new, larger category of aircraft to attain cruise performance competitive with much larger, more expensive business jets while retaining the low operating and acquisition costs associated with turboprops.

Using the same core and low pressure turbine, the FJ44-2 builds on the success of the FJ44-1's unique design, providing a low risk approach to performance growth. The FJ44-2A fan and LP compressor are a direct result of over 30 years of experience with integrally bladed fans and compressors (blisks) used in a variety of Williams military turbofan engines. The FJ44-2 maintains the modest turbine temperatures of the FJ44-1 and retains all of the unique low cost turbofan technology, such as the uncooled, high pressure turbine, the effusion-cooled combustor, and the high work, two-stage LP turbine. These components have all been thoroughly tested and proven for long endurance and long cyclic life in the FJ44-1 program.

The hardware changes between the FJ44-1 and the -2 consist of the wide sweep fan stage, a three-stage blisk design, LP compressor, and the addition of the multi-lobed exhaust mixer for optimized cruise performance and reduced jet noise. A comparison of the FJ44-1 and -2 is given in Figures 2-8 and 2-9. The FJ44-2 has been selected to power the new Raytheon Premier I business jet. The FJ44-2 FAA certification is planned for the end of 1996 in support of the Premier I launch aircraft FAA certification in the fall of 1998. Additionally, the Sino Swearingen Aircraft Company has announced that an SJ30-2, based on the FJ44-2, will be pursued for FAA certification in 1998.

> ***The FJ44-2 will serve as the baseline engine for the NASA General Aviation Advanced Propulsion System Study to develop the FJ44-X to power the Next Generation 19-Passenger Commuter aircraft***

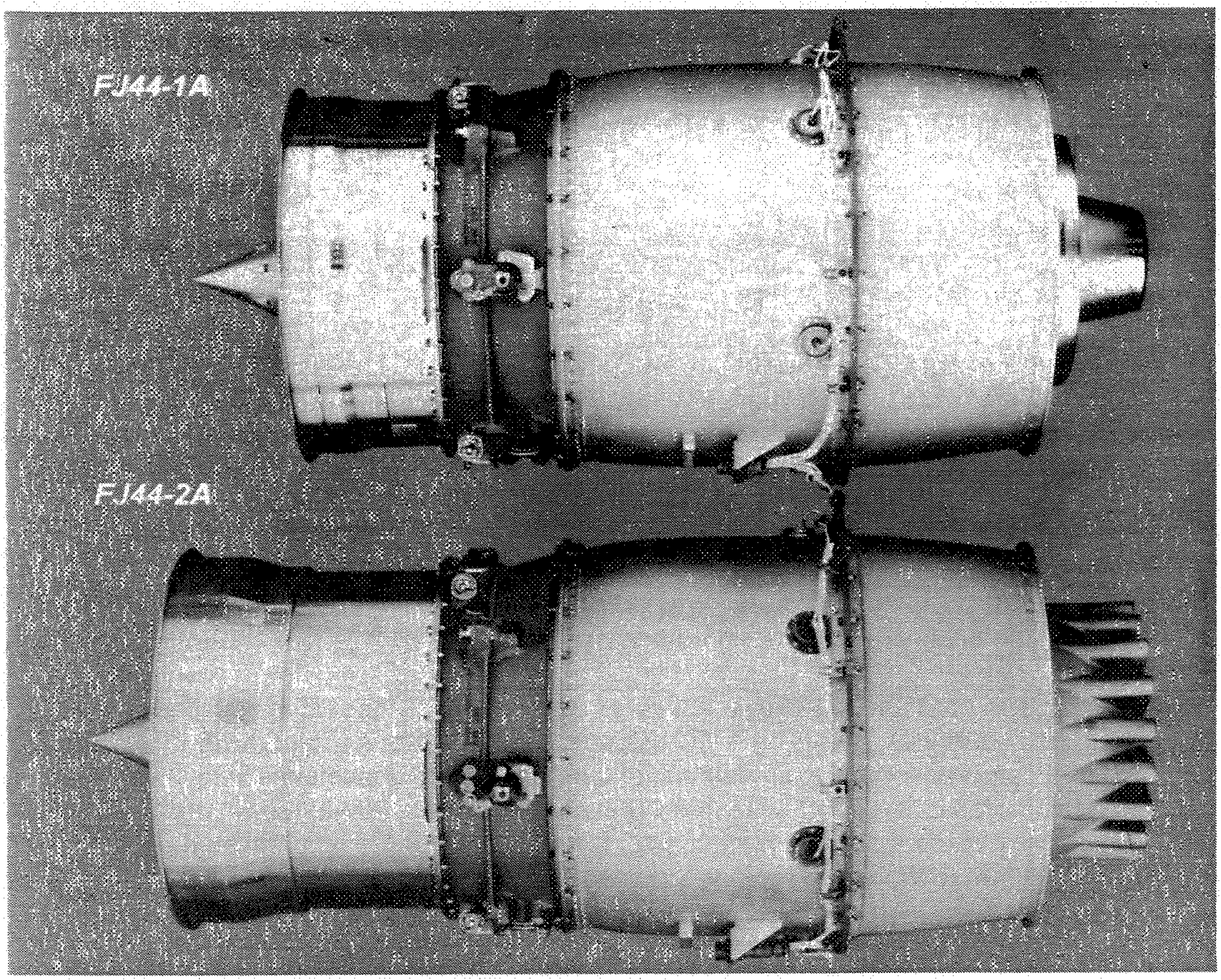


Figure 2-8. Top Views of the FJ44-1A and FJ44-2A

Fan

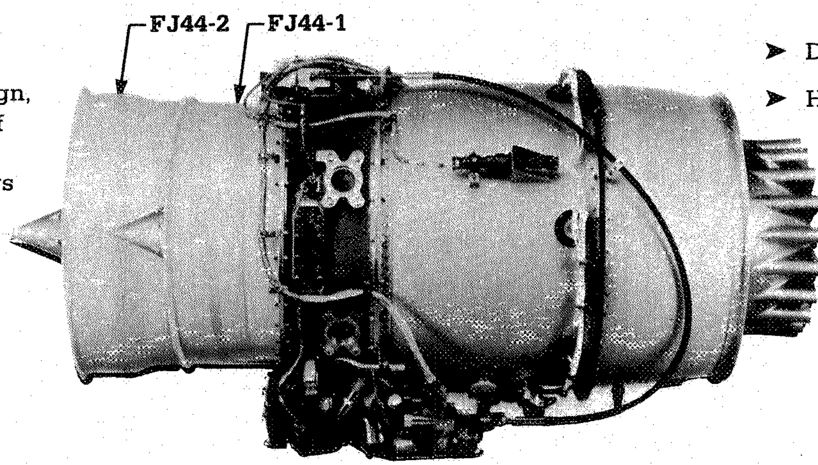
- ➤ Highly FOD resistant, third generation Williams International "Wide Sweep Fan" technology

LP Compressor

- ➤ Three-stage blisk design, the latest in a series of Williams International small axial compressors

Common Core with FJ44-1

- ➤ Proven high performance centrifugal compressor
- ➤ Long-life, clean-burning, effusion-cooled combustor
- ➤ Simple, circumferential fuel injection system for low thermal profile
- ➤ Proven uncooled single-stage HP turbine



Engine Distinctions

	FJ44-1	FJ44-2
Take-off thrust	1900	2300
SFC	0.47	*
Bypass ratio	3.2	*
Length (in)	40.28	47.24
Diameter (in)	20.9	21.7
Engine dry weight (lb)	448	*

* Performance and weight available on request.

Common LP Turbine Module

- ➤ Proven high work, two-stage turbine
- ➤ Added multi-lobe mixer for optimized cruise performance

Fuel Control Unit

- ➤ Digital electronics for simplified power setting
- ➤ Hydromechanical backup included

Common Accesory Gearbox Module

- ➤ Reliable, low-risk mechanical systems

Maintainable

- ➤ The FJ44-2 design retains the ease of maintenance and supportability demonstrated on the FJ44-1
- ➤ Unique design allows quick hot section disassembly/reassembly and fan removal/replacement while installed on aircraft
- ➤ Easy access to LRUs and multiple borescope inspection ports

Figure 2-9. Characteristics of FJ44-1 and -2

2.5 ENGINE CYCLE STUDIES

The FJ44 turbofan engine was designed for use in business jets, commuters, military trainers, and RPVs. It currently powers the Cessna CitationJet and the Swedish Air Force SK60 trainer and light attack aircraft. Other business jet and military applications are in development. A growth version, the FJ44-2A, has also been recently selected to power the new Raytheon (Beech) Aircraft Company Premier I business jet.

In its present form, the FJ44 has already demonstrated it can compete against turboprops in business jets and military trainer aircraft, so it is a good baseline for growth derivatives. The common factors that influence the performance cycle and associated hardware modifications are typically:

- Scaling
- Increasing overall cycle pressure ratio
- Increasing the bypass ratio
- Increasing turbine inlet temperature

Tradeoffs between structural and dynamic concerns with improved performance demands must be iterated. From the mission analysis the target sea level static takeoff thrust was 2400 lbf. Previous cycle studies have been conducted to determine the best way to uprate the FJ44 from its original 1900-lbf level. The cycle studies were based on using the current FJ44 centrifugal high pressure compressor and tip speeds. Therefore, with the centrifugal compressor setting the flow, a cycle study was conducted to add intermediate pressure (IP) compressor stages to increase the overall pressure ratio (OPR). The flight condition was set at 30,000, feet Mach 0.7 as a typical cruise condition. The impact of thrust growth with the addition of IP stages is illustrated in Figures 2-10 and 2-11. Figure 2-10 indicates that by adding two additional IP stages for a total of three, and by maintaining the same bypass ratio (BPR) and operating at the same turbine rotor inlet temperature (TRIT), a 26 percent increase in thrust is achievable. Figure 2-11 indicates that if the same fan diameter was maintained, a slight increase in SFC (Point 1 on 3 IP stage curve) would result due to the lower bypass ratio. If the bypass ratio was increased for the optimum SFC (Point 2 on the 3 IP stage curve), a larger diameter fan would be required and consequently larger or additional stages of low pressure turbine (LPT) would be required to drive it. This is illustrated in Figure 2-12. Maintaining the current two-stage LPT would still give a good performance match with the new three-stage IP compressor (Point 1 on Figure 2-12), but at a BPR approaching 2.0 with the slight SFC increase indicated above. ***This approach provides an excellent near-term growth capability, and was used to define the FJ44-2 for the Raytheon Premier I business jet application.***

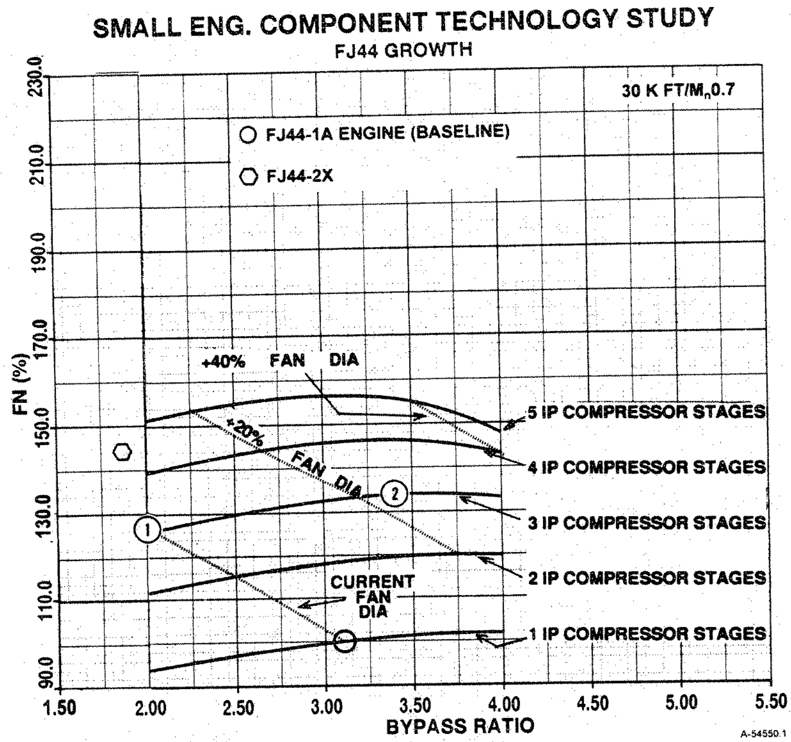


Figure 2-10. FJ44 Thrust Growth

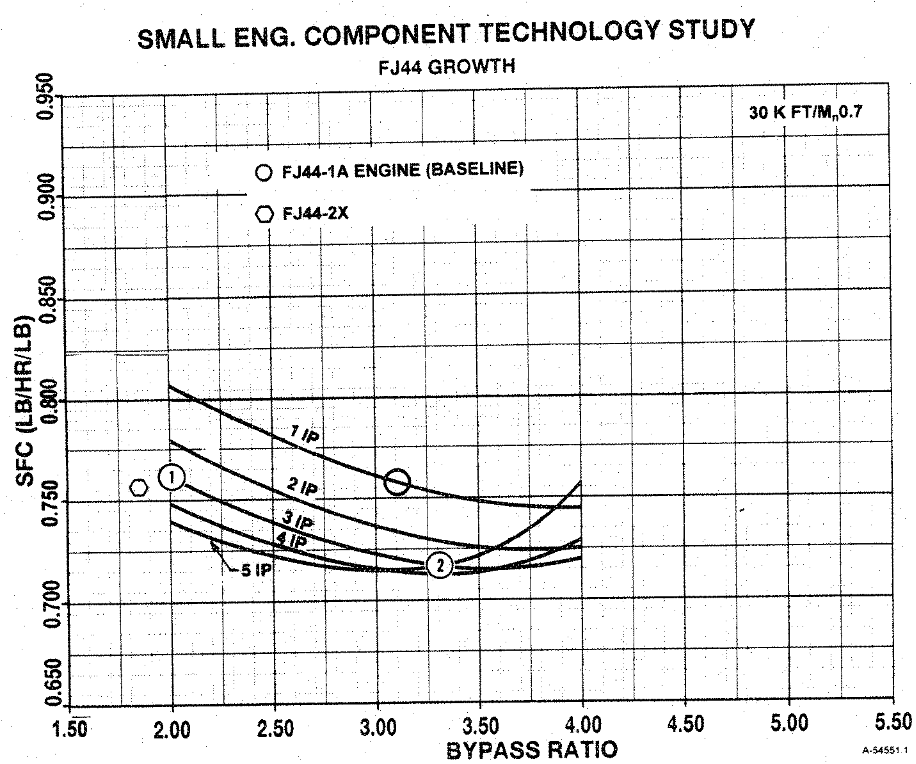


Figure 2-11. FJ44 Growth Effect on SFC

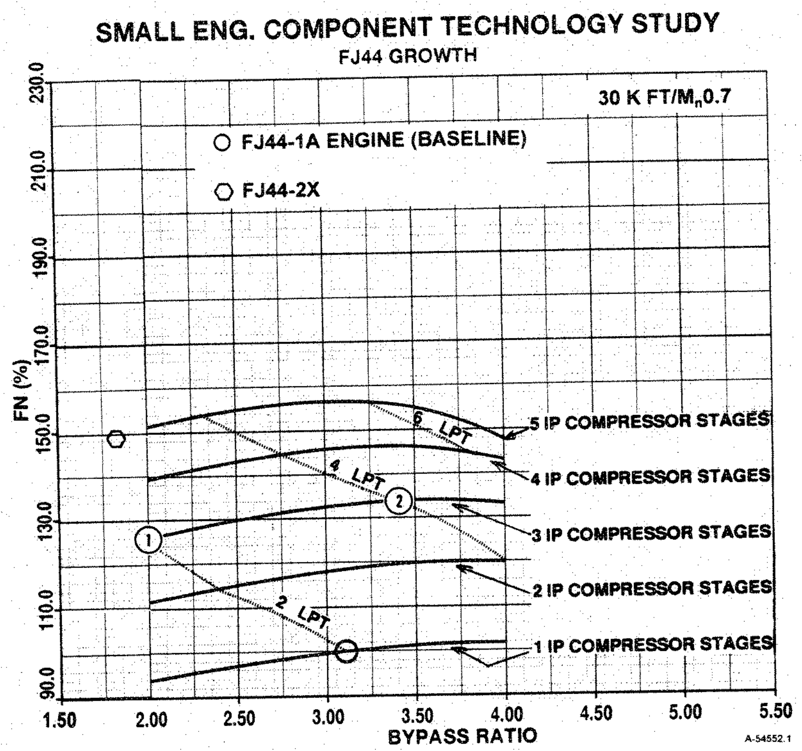


Figure 2-12. FJ44 Growth Larger Fan Cycle Requirements

2.5.1 Selected Engine Configuration

The current study defines the next step to provide the 2400-lbf sea level, takeoff thrust level, on a 92°F hot day required to meet the 19-passenger trijet commuter aircraft requirements.

A cycle analysis was conducted to define the performance parameters to meet this criteria. The results are provided in Table 2-XI. The reference baseline engine is the FJ44-2 with a standard day rating of 2300 lbf thrust. This analysis investigated maintaining the basic turbomachinery components, but running them hotter and faster.

TABLE 2-XI. FJ44-2 GROWTH ENGINE STUDY

	Baseline	Hotter and Faster to Fn = 2400/.975 @ Tamb = 92°
Altitude (ft)	0	0
T_{amb} (R)	531.70	551.70
P_{amb} (psia)	14.696	14.696
Mach Number	0.000	0.000
Fan Linear Scale Factor	1.0000	1.0000
Number of LPT Stages	2	2
LPT Avg Hub Dia (in)	10.90	10.90
$\Delta H/U^2$ LPT hub avg per stg	2.24	2.23
W2 (lb/sec)	68.88	68.68
BPR	2.162	2.122
TRIT (R)	2374.07	2482.68
N1 (rpm)	17,925	18,473
N2 (rpm)	39,477	40,398
OVERALL ENGINE PERFORMANCE:		
Nominal Engine Net Thrust (lb)	2,358	2,461
Nominal Engine SFC (lb/lb-hr)	0.5219	0.5363
Spec Engine Net Thrust (lb)	2,300	2,400
Spec Engine SFC (lb/lb-hr)	0.5353	0.5500
Specific Thrust	34.24	35.84
W2 (lb/sec)	68.88	68.68
BPR	2.162	2.122
OPR	17.11	17.67
Fan Tip PR	1.739	1.769
TRIT (R)	2,374	2,483
TRIT (F)	1,914	2,023
P_6P_{16}	0.9203	0.9262
Vs/Vp	0.7175	0.7088
A_6 (in^2)	98.48	98.73
A_{16} (in^2)	110.74	110.70
Jet Nozzle Type	Converg	Converg
A_{throat} (in^2)	164.08	163.67

The results consist of a slight increase in the fan (N1) and the core (N2) speeds of approximately 3.1 and 2.3 percent, respectively. This stayed within allowable structural limits on the rotating components. It required an increase in TRIT of approximately 109°F over the FJ44-2 and 144°F degrees over the original FJ44-1A. This would require a cooled high pressure turbine rotor.

2.5.2 Engine Modifications

In regard to the performance, a detailed structural and heat transfer/secondary flow analysis would have to be conducted before the impact on detail hardware items can be ascertained. The largest change would be incorporating the cooled HP turbine rotor stage. The shaft dynamics must be reinvestigated to determine if additional changes are required. The cooling air circuit must be analyzed for its impact on the compressor discharge pressure. Additional seals will be required to control leakage. The disk-to-blade retention slot must be modified. These details are discussed in the next section. Other hardware changes will be required related to the combustor emissions and noise reduction plans.

2.6 PRELIMINARY DESIGN RESULTS

A cutaway view of the FJ44-1 turbofan engine is shown in Figure 2-13. Its has a 20.9 in diameter and 40.3 inches flange-to-flange length. At its widest point, including the accessory gearbox, it has a 23-inch diameter. It is a two spool engine: the low pressure spool consists of the fan stage plus an intermediate compressor stage coupled to the two-stage uncooled low pressure turbine; the high pressure spool consists of the centrifugal compressor coupled to an uncooled single-stage axial turbine. The rotor group is shown in Figure 2-14.

The FJ44-2 has a three-stage intermediate stage compressor with integrally bladed rotors, an advanced wide sweep fan stage, and a mixed exhaust nozzle for improved performance and low noise. The overall length is approximately 47.2 inches and the diameter is 21.7 inches. The basic FJ44 design has a design life of 10,000 hours for business jet applications. The duty cycle for the business jet consists of one flight cycle per flight hour. Major rotating and static structure components have component lives in excess of the 10,000 hours or cycles. The FJ44-1 is operated typically with a fixed maintenance interval. The FJ44-1A engine has been FAA-certified for hot section maintenance every 1750 hours and cold section maintenance every 3500 hours. The engine has been designed to allow hot section inspection to be performed on the wing. This permits turbine removal without removing the entire engine from the wing.

2.6.1 Low Cost, Cooled High Pressure Turbine Rotor

To accommodate the higher TRIT levels of the FJ44-2 growth engine, referred to here as the FJ44-2X, the current HP turbine rotor blade would have to be redesigned for the addition of the required cooling flow. The TRIT increases approximately 110°F, which is approximately 60°F over the uncooled material blade capability. A low-cost method of cooling the blade to achieve long life is proposed. The rotor would be redesigned to add a simplified cooling scheme comprised of cast and electrostatic discharge machined (EDM) passages to reduce the airfoil temperatures to acceptable levels.

2.6.1.1 Modifications for Blade Cooling. Two engine modifications to accommodate the higher TRIT levels on the airfoils would include addition of a seal forward of the HP turbine disk rim and addition of cooling air passages for the blades. The addition of the seal forward of the HP turbine disk rim is required to minimize the ingestion of the hot primary gas flow into the forward disk cavity. The result of adding blade cooling passages increases the potential for the hot gas to enter the cavity. Currently, the FJ44-2 engine relies on an overlap of the flowpath walls between the nozzle inner flowpath wall and the HP blade platform to minimize ingestion. Figure 2-15 shows a preliminary design configuration that adds a lip seal to further enhance the sealing between the nozzle and the turbine blade platform.

The turbine blade cooling modifications will include introduction of a radial passage in the leading edge section of the blade combined with axial passages that will vent the cooling air through suction side holes at approximately 2/3 chord providing film cooling for the trailing edge on the exterior surface of the blade. The blade cooling air will be provided from the disk slot region (i.e., no air supply holes will be required in the disk). The disk slot region is cooled by a combination of the leakage through the burner seal and the tangential on-board injection (TOBI) holes located on the inner burner nozzle support cone.

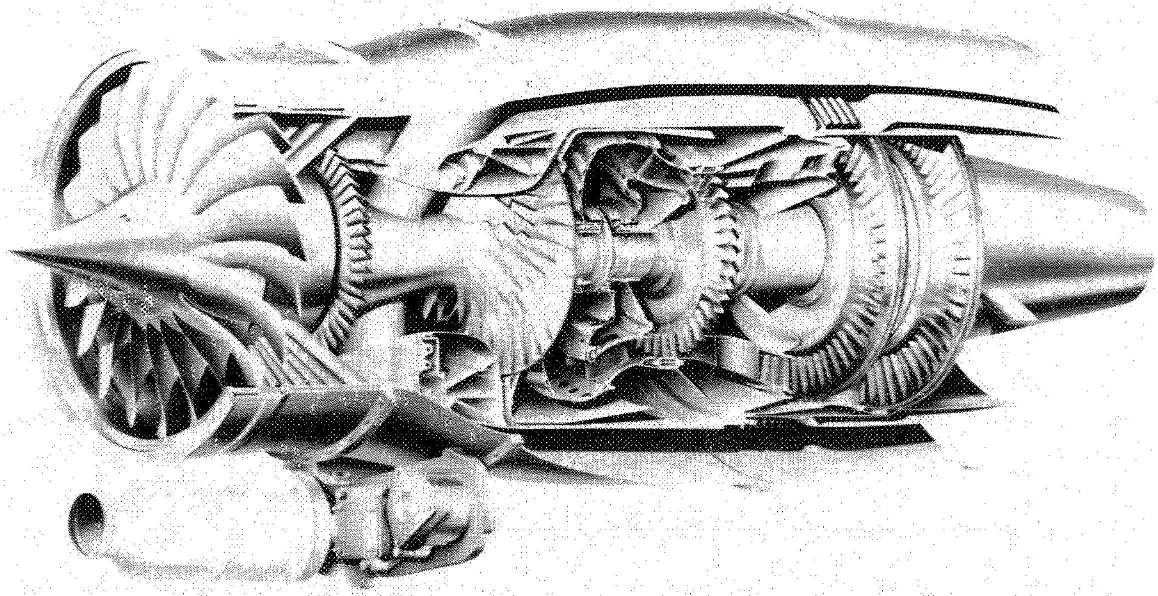


Figure 2-13. FJ44-1 Turbofan Cut Away View

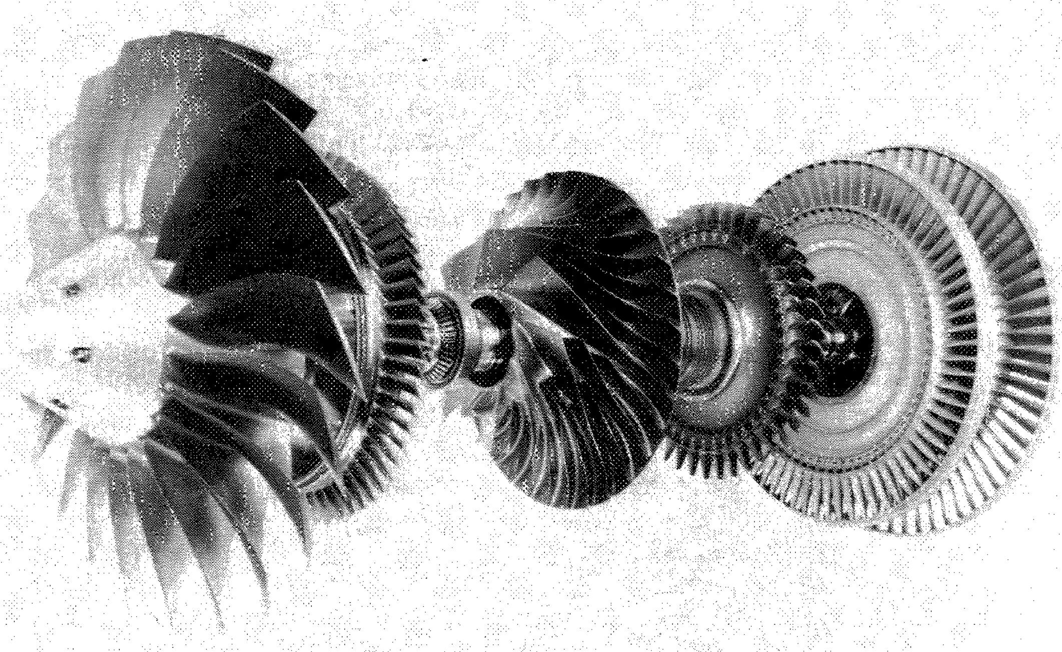


Figure 2-14. FJ44-1 Rotor Group

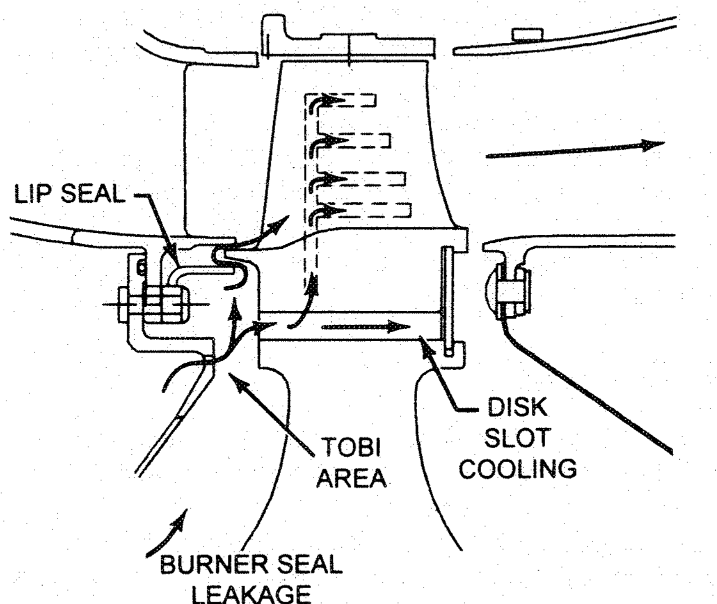


Figure 2-15. Cooled HP Turbine Concept

2.6.1.2 Blade Cooling Manufacturing Process.

The HP turbine blade passages will be manufactured through a combination of casting and EDM processes. The radial passage will be cast into the blade from the bottom of the blade fir-tree retention slot to the top of the passage. The axial holes will be EDM'd from the suction side.

This is a low cost approach. The final detail design may require multi-pass cooling passages or the addition of showerhead-type cooling holes in the leading edge, or possibly rectangular slots cast to the trailing edge to provide the necessary blade life. The design will iterate the life-cost-performance benefit analysis to provide the required blade life and performance.

2.6.2 Combustor Emission Reduction Impact

The primary impact of this effort will affect the design of detail parts for improved emissions. This may be accomplished by any one, or a combination of the following:

1. Optimize the primary jet size and location
2. Optimize diameter and distribution of the effusion cooling holes
3. Improve the fuel injection via a modified shaft slinger

These are not major design changes, but extremely important in reducing the levels of unburned hydrocarbons, CO or NOx.

2.6.3 Noise reduction Impacts

To reduce the takeoff jet exhaust noise and fan inlet noise for ground handling conditions of the 19-passenger commuter aircraft, some changes in the inlet and exhaust structure of the engine are envisioned. The combination of an exhaust mixer and acoustic exhaust duct treatment will result in some minor changes to the components. The current FJ44-2 design incorporates an 18-lobe exhaust mixer nozzle, which may be sufficient in combination with the acoustic duct treatment. The inlet duct will also be modified for acoustic frequency tailored sound absorption. Details are discussed in Section 3.0.

2.7 TECHNICAL AND MANUFACTURING CHALLENGES

Thrust growth of a proven design is always a challenge. The advantage of the FJ44 design concept is that it incorporates the latest technology, but is designed for ease of manufacture to reduce cost. Increasing TRIT to approximately 2000°F plus requires a cooled turbine blade. That can certainly be done with today's technology. The challenge is to develop a more cost-effective design approach and provide innovation to establish manufacturing techniques that provide the blade structural integrity required for long life at a reasonable cost. The manufacturing challenge is to develop processes and techniques to work with very small parts in a cost-effective manner. Improvements in analytical tools are needed to calculate the blade surface heat transfer effectiveness to better understand the impact of the very intricate small cooling passages, typical of today's larger engines, as applied to a scaled-down turbine blade.

3.0 PROPULSION SYSTEM BENEFITS

3.1 COMBUSTOR EMISSIONS IMPROVEMENTS

The primary objective of the gaseous emissions plan is to improve NOx margins over anticipated (near term) ICAO and EPA emission standards while increasing combustor exit temperature 110°F to 360°F, without impacting already low hydrocarbon and CO levels.

Reduction of gaseous emissions from gas turbine engines has become an important factor in the development of next-generation aircraft propulsion systems. However small their overall contributions are to global emissions, aircraft gas turbines have come under intense scrutiny in recent years for their contributions to local and regional pollution. Since 1984, all turbine engines manufactured must comply with U.S. legislative requirements for exhaust emissions. The FAA enforces EPA regulations 40 CFR Part 87 through FAR Part 34, Fuel Venting and Exhaust Emissions Requirements for Turbine Engine Powered Airplanes. These requirements strictly define limits to gaseous and smoke emissions for all gas turbine propulsion engines (Table 3-I). These regulations are based on international standards and are reviewed on a regular basis, with continual pressure from environmental concerns to reduce allowable emissions limits. Much of this pressure comes from the European Community, which is in the process of defining its own set of regulations defining aircraft gas turbine emissions. Most recently, the International Civil Aviation Organization (ICAO) approved a 20% reduction in NOx emissions limits. This reduction was subsequently adopted in FAR Part 34 and is applicable to all new engines certified for production after 1 January 1996. Additional reductions are currently under consideration by ICAO, including the regulation of gas turbine gaseous emissions in engines of less than 6000 pounds thrust.

TABLE 3-I. FJ44 EMISSIONS AND SMOKE LEVELS

	Emissions (g/kN)			Smoke Levels
	HC	CO	NO_x	
FJ44	4.9	149.5	36.2	6.0
Federal Regulations	19.6	118.0	65.6	46.5

This regulatory environment has driven a great deal of technological advancement in the areas of emission control and reduction. However, these advancements have focused mainly on larger engines (greater than 6000 pounds thrust), with their higher pressure ratios and turbine inlet temperatures, and where gaseous emissions are strictly controlled. The smaller gas turbine propulsion engines have, in recent years, implemented much of the low emissions technology available, resulting in cleaner, more efficient operation, with some units on par with regulated engines. Because of this, there is currently continued agreement that specific gaseous emissions requirements need not be specified for engines of less than 6000 pounds thrust.

In the near future this may not be the case. Aircraft utilizing these engines are smaller and fly much more often, into and out of smaller airports with the attendant visibility of environmental concerns. Regulation of smaller gas turbine engines is being considered and will result in a heavy burden on manufacturers, proportional to both the stringency of regulation and the schedule of implementation. In some cases large engine emissions reduction technology can be scaled, but not all of these technologies are applicable to the smaller engine designs, especially at the lower end (i.e., <3000 pounds) where lower pressures and temperatures, as well as lower costs, predominate.

The technology plan outlined here will investigate several emissions reduction methods applicable to the next generation of small gas turbine engines. Analysis and development testing will be based on the FJ44-2A engine and its planned growth derivatives.

3.1.1 Combustor Modifications

Combustor modification is grouped into three areas: stoichiometry, recirculation and cooling, and fuel injection.

Utilizing the FJ44-2A and its growth derivatives, a series of combustor modifications will be tested to determine their effectiveness in reducing gaseous emissions. The details of each modification will be determined based on analysis, computational simulation, and, if applicable, bench testing, utilizing available computational tools, test rigs, and experience from other in-house low-emissions programs. Evaluation of combustor emissions will be conducted through direct exhaust gas measurements from test engines, with baseline emissions levels established on the -2A engine.

Combustor modifications is grouped into three areas: stoichiometry, recirculation and cooling, and fuel injection.

Stoichiometry. NOx production is primarily a function of maximum flame temperature and residence time. The higher the gas temperature and the longer it is held there, the greater the rate of NOx production. The original FJ44-1 combustor was developed with a nearly stoichiometric primary combustion zone. A rich primary zone ensures good lean combustion stability and a wide ignition and relight envelope.

The radial-outflow geometry of the FJ44 combustor provides for a relatively small, low residence time primary combustion zone. The combination of a rich, low residence time primary zone has resulted in a very efficient, relatively low NOx combustor (see Table 3-I).

The FJ44-2 engine utilizes the same combustor as the -1, but operates at a higher fuel-to-air ratio and has higher inlet temperatures. Although there are no measurements to date, it is anticipated that in this configuration, -2 combustor efficiencies will remain high but NOx levels will increase. Optimization of primary zone stoichiometry will specifically target production of NOx and CO, while retaining or improving existing start and relight capabilities. Lowering the primary zone equivalence ratio from 0.95 to 0.80 should optimize CO production and at the same time reduce flame temperature and therefore NOx production. This can be achieved by modifying the combustor primary jets, cooling flow distribution, and slinger purge flow. Secondary air injection can also be modified to provide an optimized flame temperature distribution, which would contribute to CO reduction and improve temperature distribution into the dilution zone.

These types of modifications tend to work against lean stability and combustor efficiency, making it important to optimize primary fuel distribution and recirculation. Integrating improvements in start nozzle and slinger flows would be part of this type of combustor modification.

Recirculation and Cooling. The FJ44 combustor geometry, fuel injection, aerodynamic mixing, and cooling system interaction are unique and patented. Optimization of cooling flows, specifically reduction of cooling mass flows and film thickness, can have a significant impact on engine UHC and CO emissions. Effusion cooling in the FJ44 application allows a great deal of design flexibility with respect to distribution and control of local wall cooling flows. Finer, more effective cooling hole patterns can be implemented as required. Since cooling flows in the primary zone also contribute to hot gas recirculation, modification to primary air jets and slinger purge flows would be integrated into any cooling modifications.

Fuel Injection. The third area of potential combustor modification for emissions reduction is in the slinger and start nozzle fuel injection systems. Changes to the slinger and primary zone mixing can improve primary zone efficiency at lower primary equivalence ratios and improve stability. This concept will utilize a modified distribution of start nozzle and slinger fuel flows. As with the previously described modifications, the same basic FJ44-2 combustor geometry and aerodynamic scheme will be utilized. Two basic areas of modification are anticipated; slinger enhancements and start nozzle enhancements. Slinger changes would provide for an optimized slinger spray for stable lean operation. Various slinger hole modifications, including a staged spray, would yield improved Sauter Mean Diameter (SMD) for better evaporation and mixing characteristics. Auxiliary nozzle modifications would provide similar improvements by changing the number of nozzles utilized and altering nozzle spray characteristics.

3.1.2 Computational Tools

Fluent. Combustor modeling analyses will be conducted primarily using the latest version of the Fluent code (currently version 4.2). Fluent V4 is a general purpose computational fluid dynamic (CFD) computer program for modeling fluid flow, heat transfer, and chemical reaction. Fluent incorporates up-to-date modeling techniques and a wide range of physical models for simulating numerous types of fluid flow problems. These are accessible through an interactive menu-driven interface for problem definition, computation, and graphical post-processing, allowing application of computer simulation methods to analyze and solve practical fluid system design problems.

Fluent V4 can model a wide range of physical phenomena, including 2D/3D geometries in Cartesian, cylindrical, or curvilinear coordinates; steady-state or transient flow; compressible or incompressible flow; laminar or turbulent flow; mixing and reaction of chemical species; dispersed second phase particles/droplets, including evaporation; and heat transfer. These physical models make Fluent ideally suited for the type of combustor modeling to be conducted in this sample task.

Fluent models can resolve a wide range of phenomena by solving the conservation equations for mass, momentum, energy, and chemical species using a control volume based, finite difference method. The governing equations are discretized on a curvilinear grid to enable computations in complex/irregular geometries. A nonstaggered system is used for storage of discrete velocities and pressures. Interpolation is accomplished via a first-order, Power-Law scheme or a higher order QUICK scheme. The equations are solved using the SIMPLEC algorithm with an iterative line-by-line matrix solver and multigrid acceleration or with the GMRES full-field iterative solver.

Williams International has utilized the Fluent code for nine years, and has applied the code to numerous flow and combustion problems. Typical applications are full 3D combustor modeling, including liquid droplet spray injection and chemical reactions, dilution mixing and pattern factor analysis, fuel injection driven aerodynamics and primary zone mixing, as well as engine inlets, particle separators, and secondary flows. Typical output will include planar views of velocity vectors, temperature profiles, fuel distribution, and turbulence energy. An example of geometry modeling capability is shown in Figure 3-1 for a dilution mixing analysis involving internal wall contours, primary air feed struts, and nozzle leading edges.

NOx Prediction. Concept combustor NOx emissions will be predicted using the Fluent NOx Module, an add-on package to the current Fluent fluid flow modeling software. The model is implemented through the Fluent user-defined-subroutines option, and run as a post-processor to the main combustion calculation, which provides the base flow field, temperature, and major combustion product concentration predictions. Inputs specify chemical kinetic mechanisms and turbulent fluctuations. This code provides the capability to model thermal, prompt, and fuel NOx formation in combustion systems, individually or in combination, using algorithms developed at the Department of Fuel and Energy, The University of Leeds, England.

Heat Transfer and Structural Analysis. Temperature prediction is accomplished by applying known or predicted fluid conditions to an ANSYS finite element analysis of the component or system. The finite element analysis allows accurate prediction of both steady-state and transient temperatures. These analyses include conduction, convection, radiation, and fluid flows assuring the correct heat balance. A number of dedicated in-house codes are also utilized to determine specific boundary conditions. Recent contracted work in the area of effusion cooling has yielded large improvements in the accuracy of high temperature combustor wall temperature prediction. Analytical tools such as these are continuously improved to maximize predictive capabilities.

The results of these heat transfer analyses are then applied to predict component life by the stress group. Structural analyses are also conducted utilizing the ANSYS finite element analysis code. Typical combustor analyses include stress and buckling assessments, mapping of maximum and minimum principle stresses, optimum support location, and lifing.

Detailed analyses have been conducted on a number of combustor designs, concentrating in recent years on the implementation of effusion wall cooling into several production and research engines, including Williams International's FJ44 turbofan, and WTS117 and WTS124 turboshafts. Based on extensive experience in effusion wall cooling analysis and development, Williams International was contracted by BRR to conduct a complete effusion-cooled redesign and thermal/structural analysis of the BR710 development combustor. This work included coordinating and correlating rig panel testing, detailed combustor design, and presentation of results to the engineering team.

3.1.3 Test Rigs

3.1.3.1 Test Apparatus. Two test rigs (a slinger atomization rig and an ignition rig) and one test engine will be utilized for advanced combustor concept evaluation.

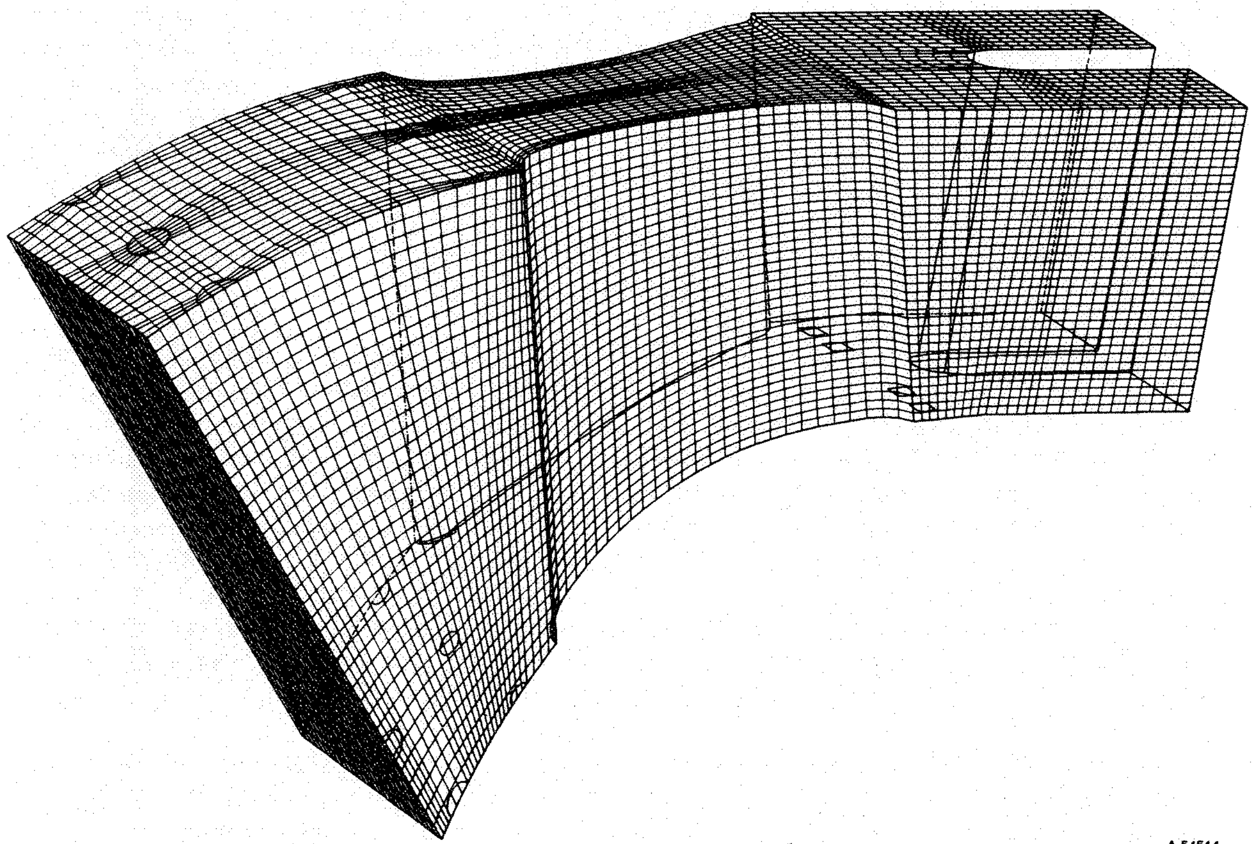


Figure 3-1. Example of Fluent Modeling Geometry: Dilution Mixing/Strut

Slinger Atomization Rig - Williams International has recently developed the capability to measure slinger droplet size directly by utilizing a Malvern optical laser spray analysis system integrated with a slinger drive and liquid feed and collection system. This bench top system allows atmospheric evaluation of slinger characteristic droplet size over a wide range of rotational speeds and fuel flows. Static spray nozzle evaluation is also possible. Figure 3-2 depicts the rig in schematic form, showing the slinger drive system, spray chamber, and Malvern laser system orientation. The rig is self-contained and cart-mounted for ease of installation into a test cell environment. Shop air is used to drive the air-turbine slinger drive system, and is capable of speeds to 50,000 rpm. Fuel pump, reservoir and spray chamber purge fan are all cart-mounted. Calibration fluid is typically used for spray analysis tests.

Ignition Rig - An ignition rig similar to that utilized for the development of the WTS124 turboshaft combustor will be fabricated and used for ignition and stability testing of the proposed combustor concepts. This rig is shown in Figure 3-3. The slinger is driven by an infinitely variable precision electrical motor. The rig itself is run in an existing Williams International environmental engine test chamber, with air flow provided by drawing on the rig with an existing high volume vacuum facility. An accurate combustor operating environment is provided with careful simulation of diffuser outlet conditions, primary plate annulus air feed, and annulus flow conditions. Air is metered through an upstream orifice. Cold and altitude environmental testing is provided through a system of liquid nitrogen heat exchangers, dryers, and orificing, providing a test environment from sea level to 50,000 feet, and from ambient temperatures to -40°F. Testing is limited to ignition and sub-idle lean stability only, due to time/temperature restraints on the vacuum system.

FJ44 Engine Testing. Due to the nature of the Williams International slinger fuel injection system, and the relative ease of combustor access in the FJ44 engine assembly, full engine testing of concept combustors is the preferred approach to combustor component performance and durability testing in this subtask. Subscale or sector testing becomes impractical in comparison, driven either by complexity of component rig design, lack of adequate air facilities, or poor 3D simulation of fuel spray/aerodynamic interactions. FJ44 engine testing can be accomplished in one of three fully instrumented on-site test cells. With its modular design and specially designed assembly tools, complete access to the FJ44 combustor and fuel injection components is possible without removing the engine from the test cell. In just a few hours, a combustor can be removed from the engine, modified or replaced, and reassembled for another test.

Some drawbacks exist in tying combustor testing to an engine operating line, but these have been historically outweighed by the tremendous economic advantages. Recent developments in electronic fuel control for the FJ44 have broadened the capabilities for engine combustor testing and development by allowing independent PC-based control of several engine operating parameters, allowing start flow, idle speed, and deceleration schedules to be modified to better evaluate combustor performance limits.

Engine Instrumentation Required. Basic engine performance instrumentation would be utilized to ascertain combustor operation, including airflow, fuel flow, CDP, CDT, and ITT(interstage turbine temperature), supplemented by combustor annulus flow static pressures and temperatures, combustor exit static pressure, and combustor wall skin temperature measurements. Gas sampling would be accomplished with direct core exit probe sampling.

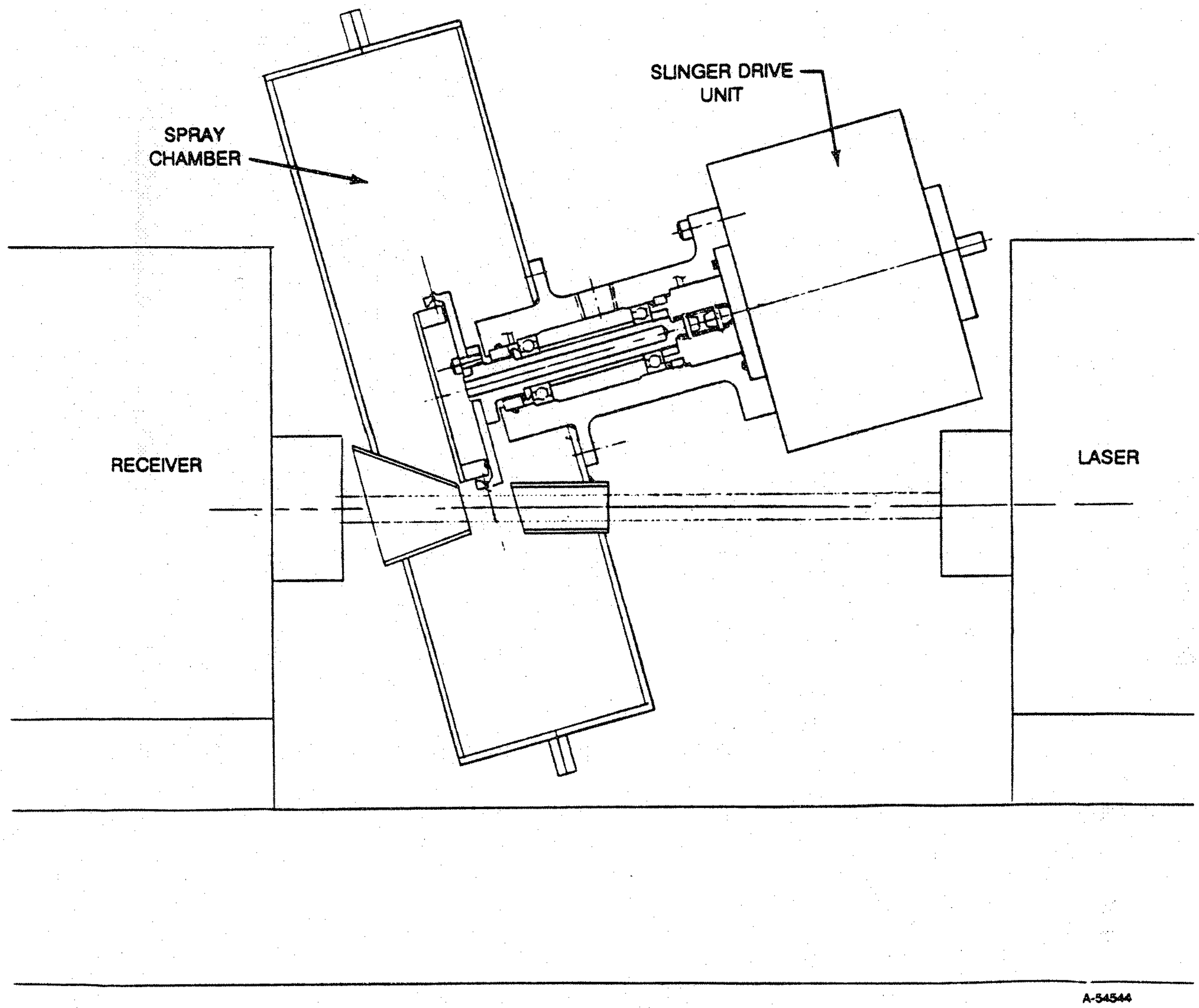


Figure 3-2. Slinger Atomization Rig

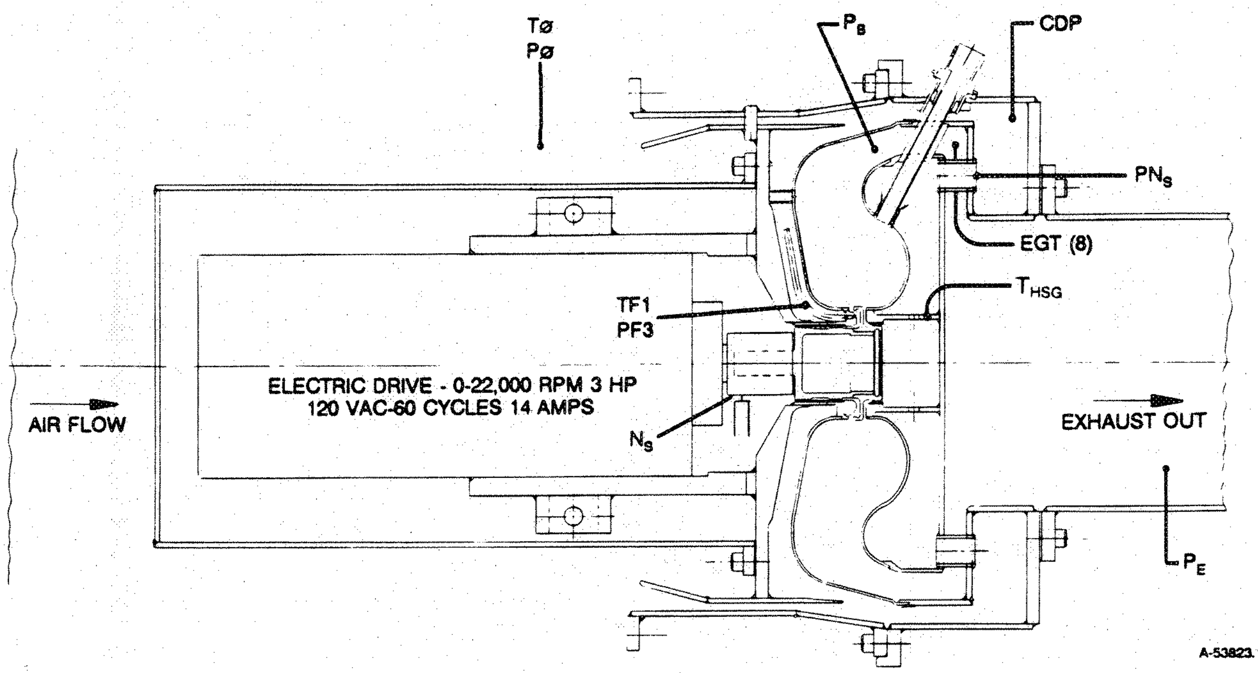


Figure 3-3. Combustor Ignition Rig with Instrumentation Locations

This array of instrumentation has proven sufficient for combustor performance evaluation in previous FJ44-1A engine testing. (Ref: Compliance Report for the FJ44-1A Engine Fuel Venting and Exhaust Emissions, Federal Aviation Regulation Part 34, Compliance Report CR34.1.1, 19 December 1991; FJ44 Altitude Test Report, Engine Model Derivative Program, USAF Contract F33657-88-D-4007, Task 0006, July 1991; and FJ44 Turbofan Engine Altitude Demonstration Test Final Report, USAF Contract F33657-86-C-2229, April 1987.) Additional gas sampling within the combustor could be accomplished using cooled probes, with access through one of two available igniter ports. Visual access could be accomplished similarly. Implementation of these more advanced techniques is currently outside Williams International experience and would be coordinated with NASA expertise if the information to be gained is deemed of sufficient value to the program.

Availability of Air Supply. Combustor evaluation in full-up, sea level engine tests precludes the need for a large independent air supply. Ignition rig testing, as described, utilizes in-house facility vacuum system capabilities, eliminating the need for a large capacity air supply. Some conditions tested may require a limited inlet air flow supply above ambient pressure; these are typically handled by renting portable diesel-powered air compressors.

Location of Gas Sample Collection Probes. Emission gas sampling will be taken directly from the core exit stream, downstream of the LP turbine stages, just prior to the core/bypass mixing plane. Figure 3-4 shows a sampling probe location at the FJ44-2A engine aft end. Three or four multi-port probes are manifolded to provide a uniform collection sample. Previous testing on the FJ44-1A engine utilized a similar arrangement, with a cruciform core sampling probe located just aft of the mixing plane (Figure 3-5).

3.1.3.2 Test Hardware and Experimental Test Data. Predictive data will be used to define and guide the formulation of detailed concept test requirements. These data, along with previous test experience, will be used in determining specific test hardware needs, and in defining the type and quality of data required to provide sufficient empirical information on each concept for final selection review and correlation with predicted results. A description of anticipated test hardware and data requirements follow.

Anticipated Test Hardware. Assuming predictive efforts indicate sufficient potential, each of the proposed combustor concepts will require individual ignition, stability and operational testing, using both the ignition rig and FJ44 test engine. Using the FJ44 combustor as a geometry baseline, each of these concepts will require a blank set of FJ44 combustor cover and primary plate, each to be laser-drilled to individual concept design requirements. One set of spares for each will also be required for contingencies.

In addition to combustor wall hardware, all concepts may require dedicated slinger designs, each to be characterized in the slinger atomization rig. A number of slinger test articles will be required to evaluate fuel spray. At least one concept will also require three to eight additional start nozzles and related plumbing hardware. These nozzles may or may not duplicate the current FJ44 start nozzle. A dedicated fuel control unit may also be required. FJ44 ignition hardware (e.g., igniter plugs, cables, exciters) will remain the same. Higher energy exciters may be employed for ignition experiments, but are not anticipated.

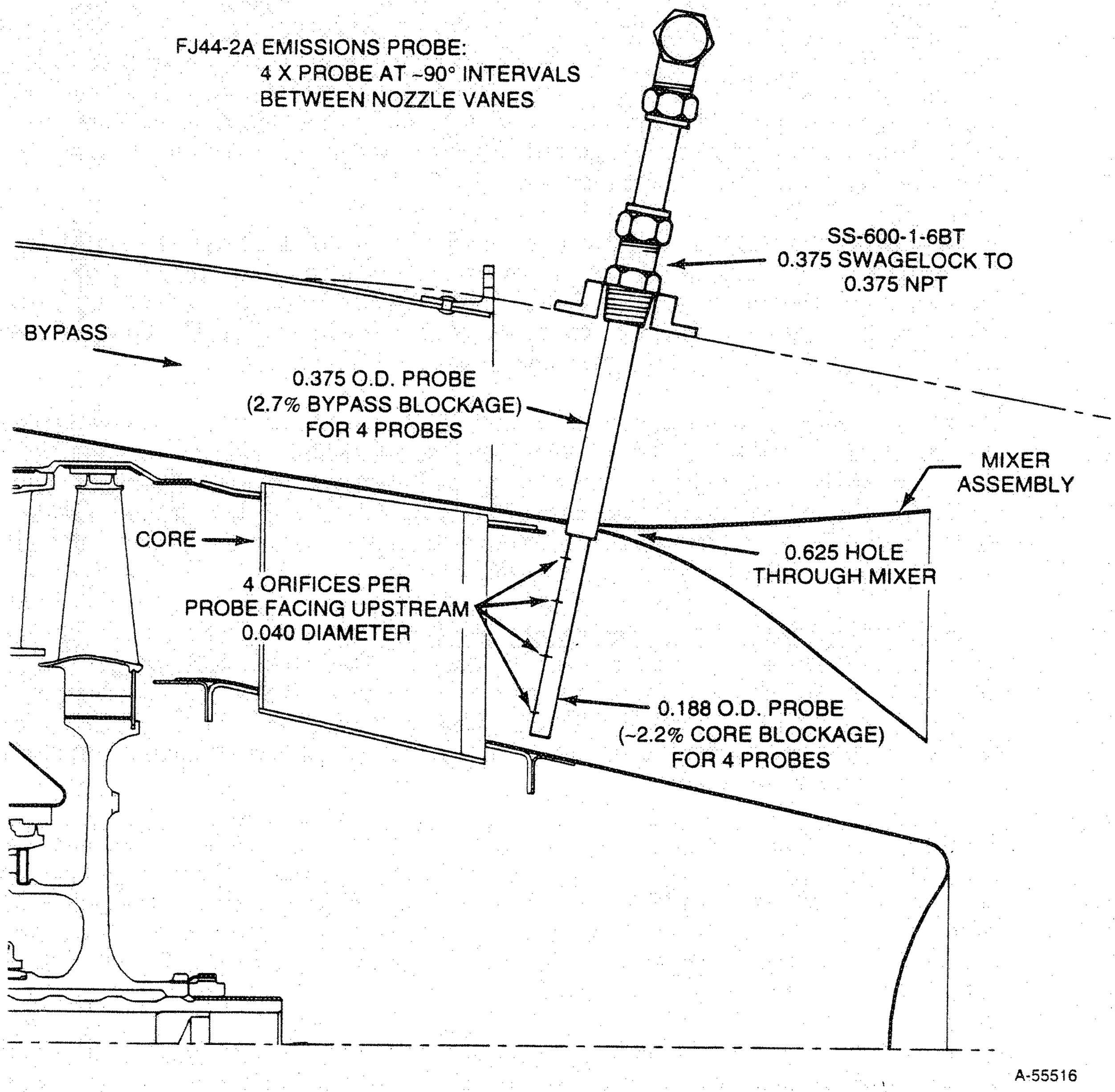


Figure 3-4. Location of Emissions Probe during FJ44-2A Engine Testing

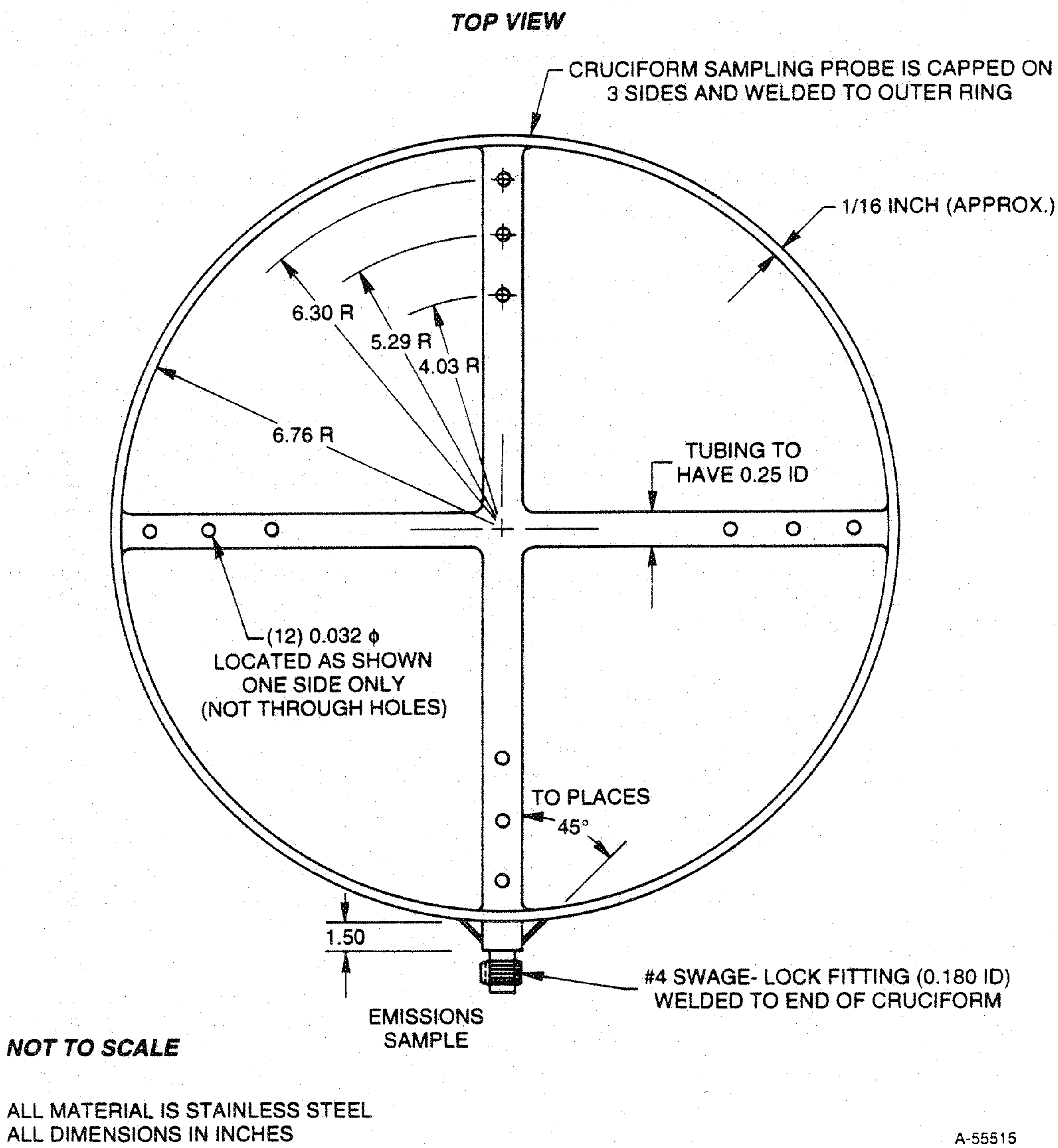


Figure 3-5. Location of Cruciform Sampling Probe during FJ44-1A Engine Testing

Rig Hardware/Modification. Slinger rig modifications will be relatively minor, and will include the chamber purge system to accommodate higher flows, slinger mounting and fuel manifold to accommodate a wider range of size and flows, and bracketing required to conduct measurements of stationary spray nozzles.

An ignition rig large enough to accommodate the FJ44 combustor does not currently exist. This mechanically simple and robust rig, essentially a 2X scale of the previous unit, will be fabricated in this subtask. The rig is designed to slip directly into the environmental test chamber, and is run identically to previous experiments.

Engine testing will utilize one of several FJ44 development engines. Modifications required for individual combustor concept testing are minor.

3.1.4 Emissions Measurement System

The emissions analysis system consists of instrumentation for the continuous, simultaneous measurement of CO_2, CO, unburned hydrocarbons, and NOx concentrations in gas turbine engines. The system was designed according to recommended procedures described in References 1 and 2[1] (Figure 3-6) for the measurement of gaseous emissions from gas turbine aircraft engines. Customized gas sampling probes designed for each measurement application will be used to extract the gas samples and transport it to the system through an electrically-heated sample line. The heated sample line is used to maintain the sample temperature above 325°F to avoid hydrocarbon and water condensation. The system can handle samples from both high-temperature, high-pressure combustor flows and atmospheric pressure engine exhausts. A high-pressure backpurge of the sample probe and lines is provided to prevent hydrocarbon saturation of the system during engine starts.

The system utilizes commercially available analyzers integrated into a single, portable instrument rack that can be readily moved to different test cells to accommodate various testing requirements. CO_2 and CO concentrations are measured using an integrated nondispersive infrared (NDIR) absorption analyzer (California Analytical Instruments Model ZRH). A permeation dryer is used to remove water from the samples before entering the CO_2 and CO analyzers in order to reduce interference with the infrared absorption measurements. CO_2 levels ranging from 0-10% can be measured while CO levels are measured from 0-2000 ppm. A heated flame ionization detector (FID) from Thermo Environmental Instruments (Model 51) is used to measure the unburned hydrocarbon levels in the sample. The sample temperature is maintained above 325°F throughout the measurement process to avoid the potential condensation and removal of heavy hydrocarbons in the system. Hydrocarbon levels ranging from less than 10 ppm up to 10,000 ppm can be measured. A Thermo Environmental Instruments (Model 42H) chemiluminescence analyzer (CLA) is used to measure NOx levels in the sample ranging from 0-5000 ppm. The system is designed to maintain the sample above

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[1]
1. SAE Aerospace Recommended Practice (ARP) 1256B - "Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Engine Turbines"
2. ICAO International Standards and Recommended Practices - Annex 16 - "Aircraft Engine Emissions"

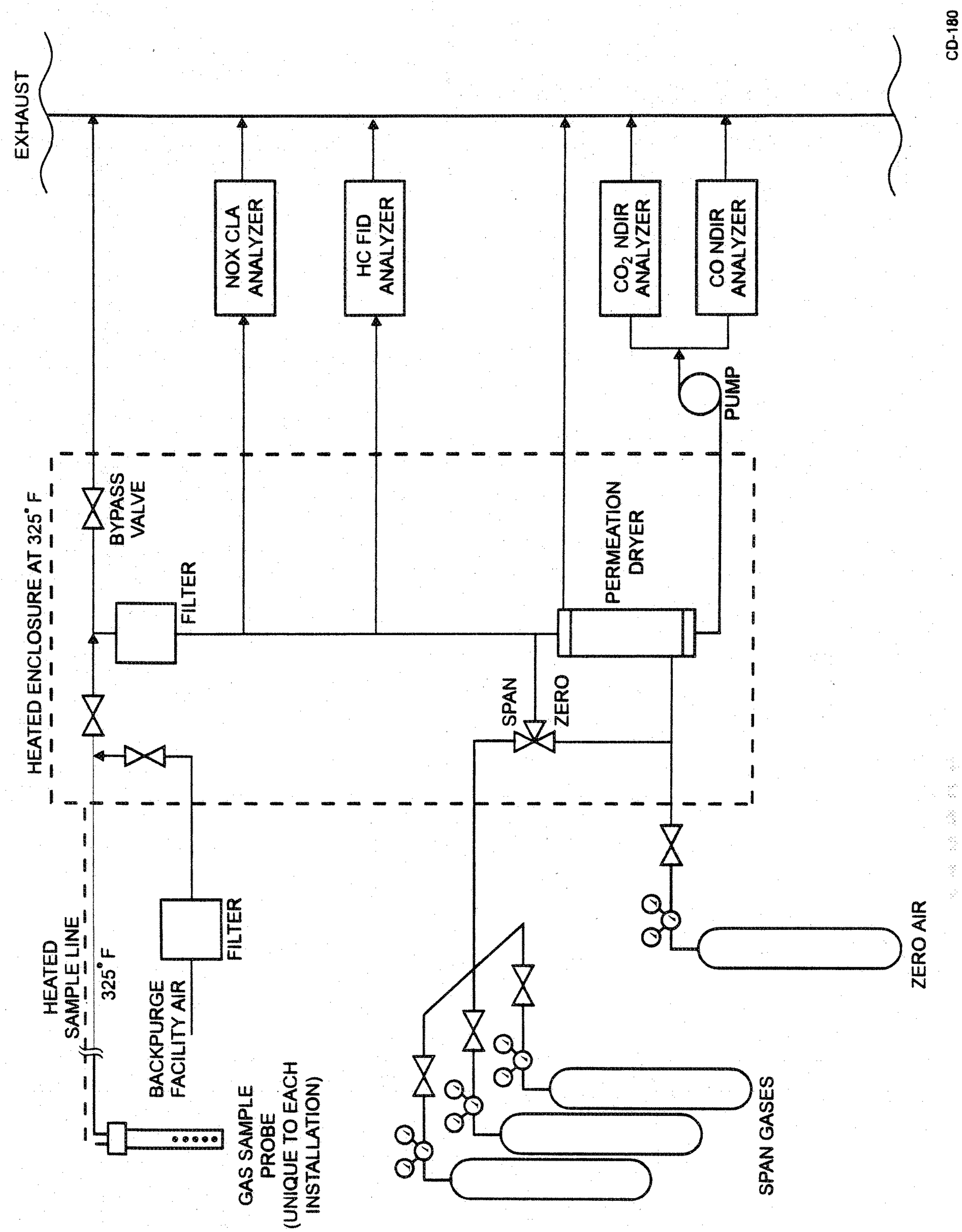

Figure 3-6. Gaseous Emissions Analysis System

the dewpoint temperature throughout the measurement process to avoid water condensation that could significantly perturb the measured NOx levels. Analog output voltages from each analyzer are used to integrate the system with the facility computer data acquisition system to provide real-time calculation and display of corrected "wet" gas concentrations, emission indices, fuel-air ratio, and combustion efficiency.

3.1.5 Combustor Emissions Development Plan

The detailed plan for technology development related to combustion and emissions reduction is given in Section 5.0.

3.2 NOZZLE ACOUSTIC PERFORMANCE AND DESIGN

The principal objective of the Nozzle Performance and Design Task is to define and plan technologies for improved aerodynamic performance and reduced noise associated with regional aircraft. New nozzle geometries will be defined that will have good installed aerodynamic performance at cruise, and will result in reduced jet noise at takeoff. The goal for noise reduction of the improved nozzle is 3 to 6 EPNdB relative to the current installed FJ44-1A engine. This task will develop technologies to achieve these goals.

A reference nozzle will be used on the Williams International FJ44 turbofan engine.

The engine has a mixed flow exhaust with the bypass and primary flows mixing only under the influence of free mixing. No forced mixer is used on the FJ44-1A. The performance of the current nozzle is near optimum with a nozzle thrust coefficient of 0.993 at Mach 0.7 cruise condition and operates at a pressure ratio of 2.25. The nozzle is a convergent nozzle fabricated of aluminum and contributes only 4.5 pounds to the overall engine weight. This simple geometry allows the excellent performance of the component to be achieved with a minimum of cost.

The FJ44 engine was designed to emit minimum noise, but without the application of any special acoustic treatment. The engine has no inlet guide vanes and the fan blades have sweep at the leading edge which reduces shock strength. Both of these features contribute to reduced inlet noise. The fan stator is leaned aft to provide maximum rotor-stator separation of 1.70 rotor chord lengths and the low aspect ratio fan allows a favorable rotor-blade-to-stator-vane ratio of 2.95. This fan configuration reduces the noise of the potential interaction field, viscous wake interaction, and fan blade passage. The high bypass ratio of 3.2 helps to achieve a low exhaust velocity and reduce the jet noise from the engine exhaust, which is the second major source of engine noise after the fan. Coupled with the size of the aircraft, these design features allowed the current noise limitations to be achieved with no further considerations.

Noise measurements have been made on the uninstalled engine at Williams International. The test measurements were made under less than ideal conditions for a sound level survey and are considered estimates of the actual noise levels emitted from the engine. The data is probably compromised by reflection from buildings and structures closer to the test site than ideally desired. In this task, additional noise surveys will be conducted to establish a true baseline of the production configuration.

To relate these acoustic test results to predicted results, the NASA General Aviation Noise Prediction computer program was run on the baseline FJ44 engine (Figure 3-7). For all positions, the data is below the predicted levels. In the aft quadrant, where the noise is dominated by the jet exhaust source, the correlations are in better agreement. While limited in extent, these data indicate that the nozzle acoustics are within the current expected levels for a small turbofan engine with no specialized acoustic design features.

The engine is quieter than current turboprops used on aircraft similar in size to Cessna's CitationJet. FAA certification testing of the CitationJet showed that the airplane is substantially quieter than the Stage 3 requirements (Figure 3-8).

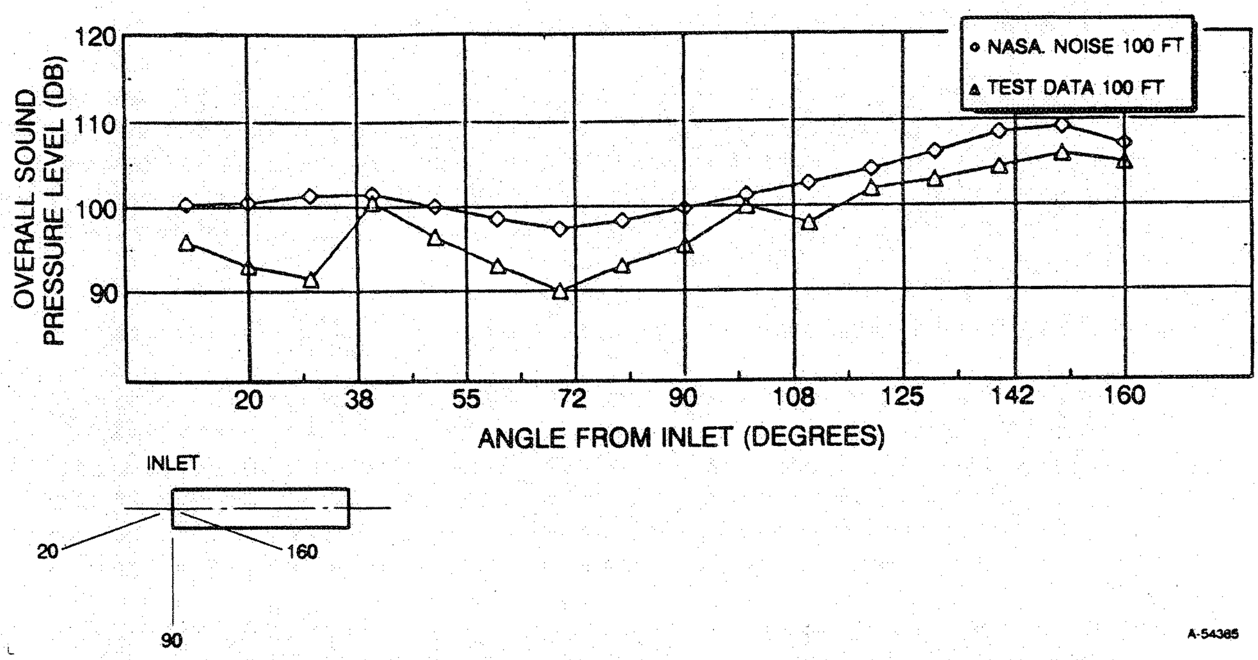

Figure 3-7. Computer Code Predicted Sound Levels Compared to Actual Test Data

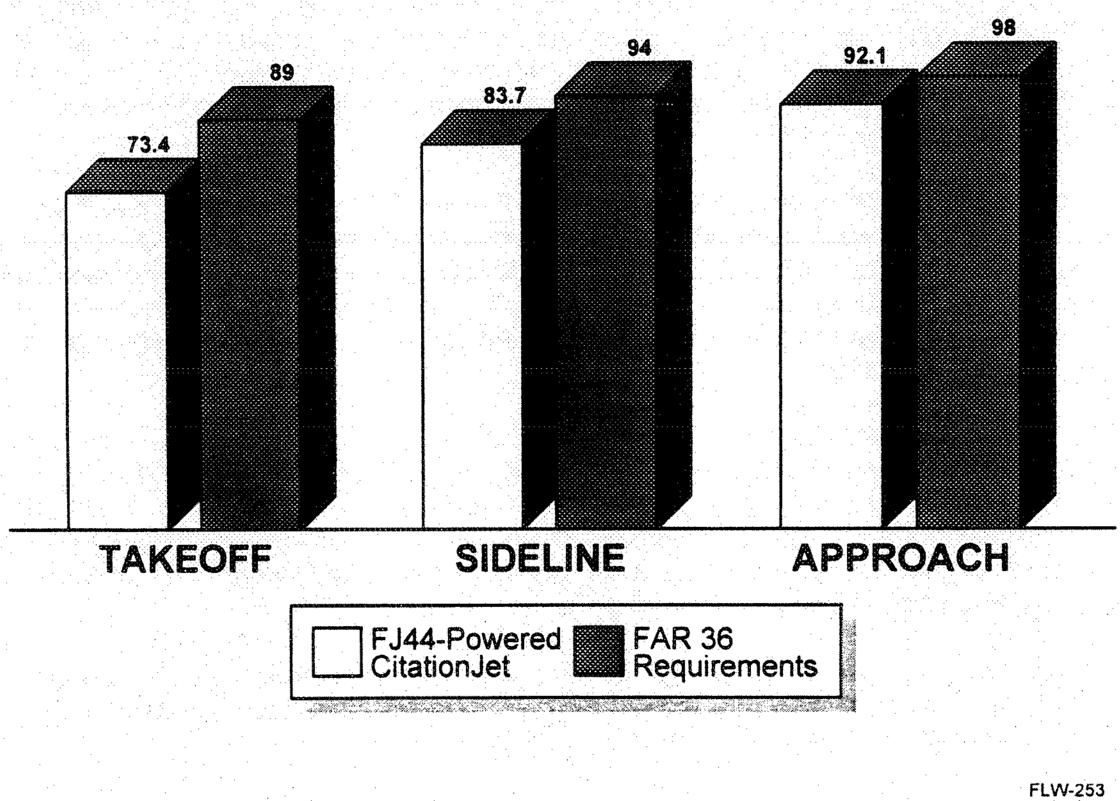

Figure 3-8. CitationJet Noise (EPNdB) Levels vs. FAR 36 Requirements

A detailed definition of the baseline engine noise characteristics will be obtained in a more controlled environment than available at Williams International. The engine will be sent to Rohr Brown Field Test Facility which is constructed to perform acoustic measurements. This full-scale engine acoustic test stand is approved by the FAA and is in compliance with current industry standards with ground and pole microphones over a concrete surface.

3.2.1 Exhaust Noise Reduction

The next generation of regional aircraft will be expected to provide improved performance, particularly in the area of reduced specific fuel consumption. At the same time, reduced noise emissions will be demanded. The purpose of the nozzle performance and design program is to define and plan the technology necessary to develop a regional aircraft engine nozzle configuration optimized for both aerodynamic and acoustic performances.

The gains in aerodynamic and acoustic performance for improved engine nozzle configurations will be quantified by comparison with an advanced engine nozzle system currently in service; the FJ44-1A engine nozzle system as installed in the Cessna CitationJet. An acoustical analysis of this installed engine using the NASA-Langley ANOPP or NASA-Lewis NOISE Prediction Program is available. A more precise assessment of the acoustic signature of the baseline engine nozzle system can be established by conducting a detailed acoustic test of the FJ44-1A system at Rohr's full-scale acoustic test facility. This data will then be used to predict fly-over noise levels for the baseline configuration.

Concurrently, nozzle system concepts with the potential for aerodynamic and acoustic performance improvement will be defined. Performance data bases available from model test programs at Rohr and from other published sources will be used in selecting promising concepts. It is anticipated that these concepts will include 1) configurations employing passive acoustic treatment with a conventional confluent nozzle system; 2) confluent nozzle systems containing a mixer nozzle, and 3) nozzle systems employing both a mixer and passive acoustic treatment.

The combination of mixer and acoustic treatment is used to reduce two types of noise sources. The first source is jet noise that is derived from high speed flow through the nozzle. The mixer that mixes the hot flow from the primary nozzle and cold flow from the secondary nozzle will significantly reduce the hot jet flow velocity and the flow turbulence. As a result, a good mixer nozzle increases propulsion efficiency and decreases the jet noise.

On some applications, a mixer has improved overall nozzle thrust coefficient and engine specific fuel consumption (SFC). Because of the cycle of the FJ44 engine, an ideal mixer could improve SFC at cruise by 7 percent improvement. When correlations for real mixers are incorporated, the predicted improvement is still 2 percent. Using the NOISE program, a reduction in acoustic signature of 6.7 EPNdB is predicted for the CitationJet at takeoff with application of a completely effective mixer. Predicted jet noise from the current FJ44 configuration is compared to that of an FJ44 with an ideal mixer in Figure 3-9.

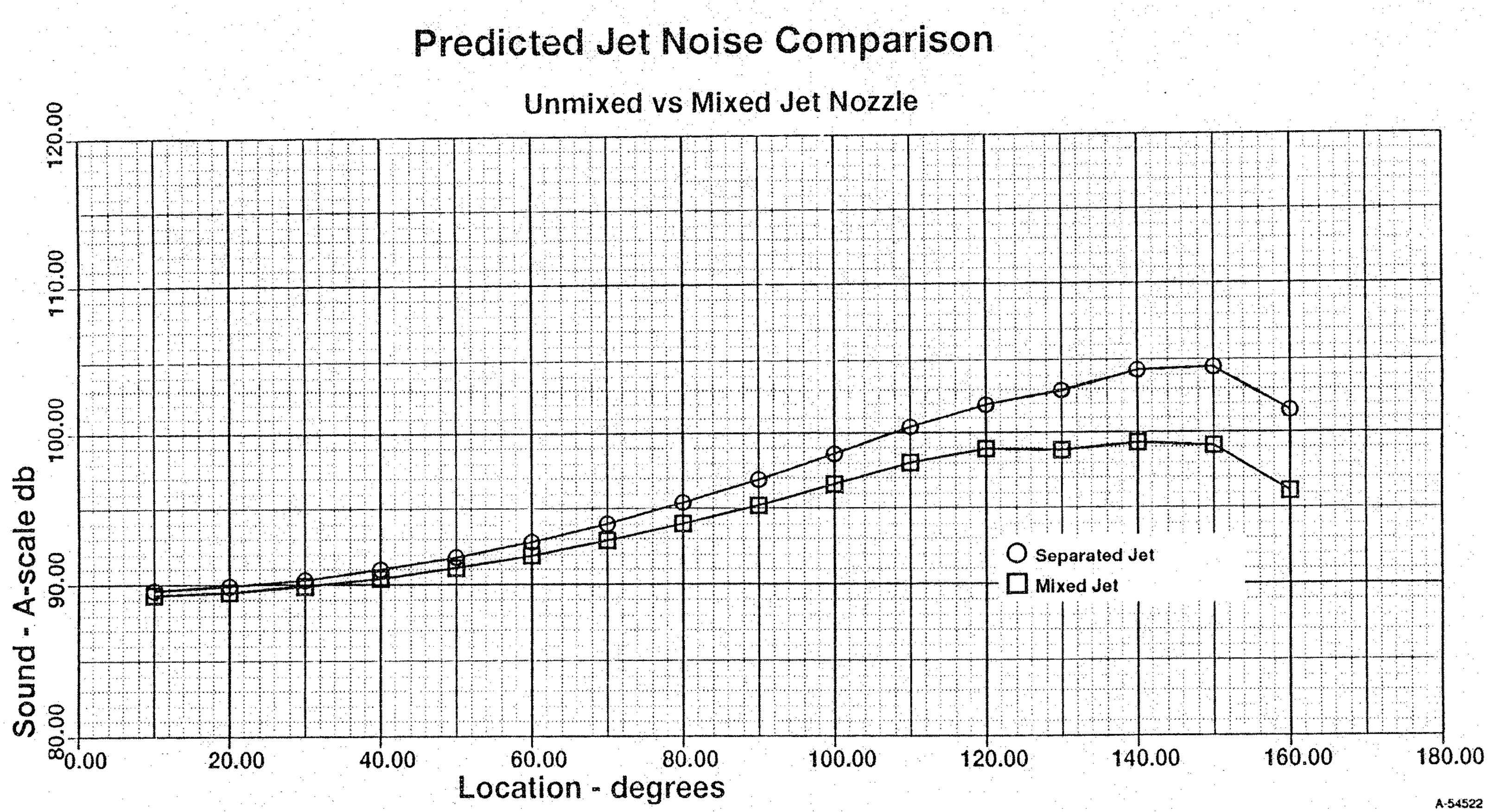

Figure 3-9. FJ44 Predicted Jet Noise Comparison, Unmixed vs. Mixed Jet Nozzle

The other type of noise source emitted from the nozzle is from the fan, turbine, and combustor sections of the jet engine. Nozzle acoustic treatment can be used to suppress this noise. The primary effort will be the development of a liner specifically tailored for the noise sources within the nozzle of the FJ44. The small size of the engine will make this a unique application for this type of sound suppression material. The task will concentrate on configurations aimed at the frequency content found in the exhaust of the FJ44. Other considerations will be to obtain a system with similar weight and cost to the baseline nozzle.

The design of passive acoustic liners and the analysis of the noise attenuation available from these liners will be conducted by Rohr. To obtain maximum noise suppression performance, advanced acoustic treatments, such as high temperature microporous metal alloy, ceramic foam structure, and other linear liner systems, will be evaluated. Once the noise source spectrum has been defined, the optimum impedance required for maximum attenuation of the most significant duct modes will be calculated. Next, a liner configuration will be selected that closely matches the optimum impedance and the actual impedance calculated. The in-duct and far-field attenuations of these liner configurations will be estimated. Finally, flight noise levels will be predicted using the NASA NOISE and ANOPP prediction codes. Initially, a single stream nozzle system will be used for mixer nozzle flight noise prediction. This prediction will be corrected using the mixed average temperature, reduced jet velocity, and potential frequency shift based on the past experience and analytical results.

Aircraft noise predictions are made using the NASA programs NOISE and ANOPP. The NASA General Aviation Noise Prediction computer program NOISE predicts far-field noise levels at FAA FAR Part 36 certification conditions. It will also predict near-field and cabin noise levels for turbofan and turboprop aircraft and static engine component far-field noise levels. NOISE is a useful tool for assessing the impact of GASP aircraft and engine design options upon FAA certification noise levels. Use of the program enhances the capability to systematically perform design trade studies and optimize an aircraft and engine design while minimizing the impact of the resultant noise. NOISE has been developed as a series of modules, each of which performs a specific task within the noise prediction process. The modules are integrated through the use of an executive control module and a data bank containing information to be passed between modules. ANOPP is a similar program but with more detailed correlations.

Performance analyses of various mixer configurations will be explored. Analysis will be conducted using the Rampant 3D viscous flow program, which is ideally suited for such application. The available turbulence model can be used to evaluate both the total pressure losses due to the skin friction and diffusion in the mixer and the losses due to the mixing of the hot core flow and the cool bypass flow. The k-e model is the traditional algebraic turbulence model. FLUENT is also in the process of incorporating the renormalization-group (RNG) modeling of turbulence into the k-e model. This method has proven more accurate in assessing the boundary layer separations and areas of high shear inherent in a mixer. Each of the models can be used to determine the extent of mixing that has been achieved. The Rampant program uses an unstructured, solution adaptive grid that allows the areas of greatest interest to be modeled with the most detail. This solution technique will allow an accurate assessment of the wake structure in the mixing region to aid in the acoustic analysis of the mixer configurations. A Rampant solution for the analysis of a single convergent jet nozzle is illustrated in Figure 3-10.

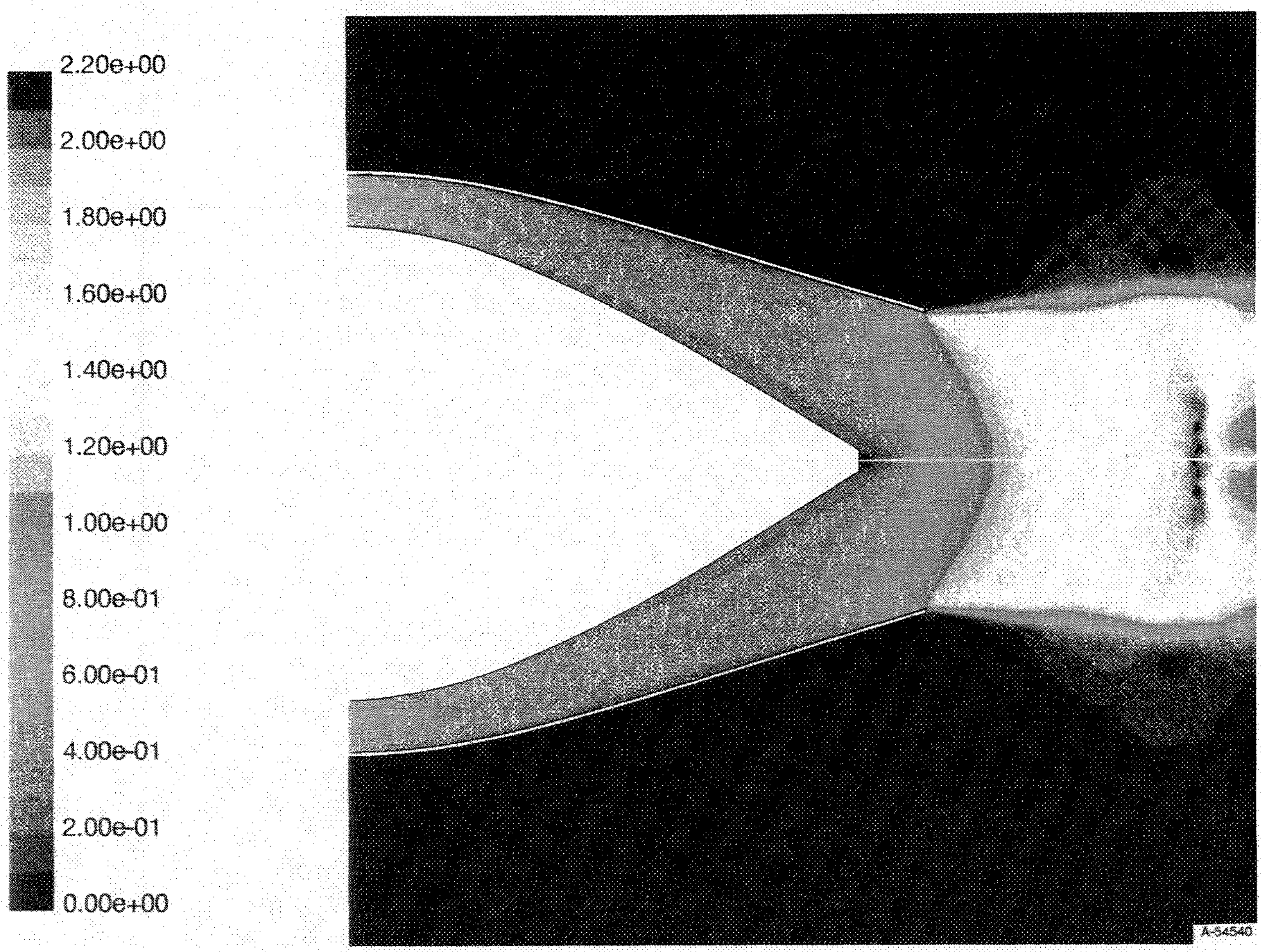

Figure 3-10. Axisymmetric Convergent Nozzle Contours of Mach Number

Several mixer concepts will be analytically explored. Geometric parameters such as mixer length, number of lobes, radial depth, and lobe cross section will be evaluated. These candidate concepts will be analyzed to estimate the level of aerodynamic and acoustic performance improvement that can be gained from each. Analyses of the exhaust duct noise sources and effects of forced mixing on jet noise, including frequency shift, will be carried out through a joint effort with Rohr and Professor Tam of Florida State University, a recognized expert in the field. Weight and cost of the mixer system will be estimated so these factors can also be considered in the study.

Aerodynamics and acoustic performance available for each candidate configuration will be assessed through comparison with the reference nozzle system. Based on these analyses, three nozzle concepts will be selected for evaluation. Selection criteria will be based equally on nozzle performance and its potential for achieving the goal noise reduction. The effect on engine weight will also be considered but to a lesser degree. A possible result of the study would be an untreated, forced mixer design; a free mixed, treated nozzle; and a combination where acoustic absorbing materials are incorporated into the nozzle structure.

3.2.2 Williams International Experience

Williams International has successfully designed a variety of unconventional nozzle configurations for gas turbines for missile applications in addition to the simple convergent nozzle currently used on the FJ44. The designs of these nozzles were accomplished through the use of 3D, viscous design tools. A bifurcated nozzle for the Williams International WJ119 integrated propulsion module for the U.S. Army NLOS Fiber Optic Guided Missile application was designed and tested. This nozzle required the exhaust to exit on both sides of the missile with a severe S-bend in each leg. This nozzle was designed using an adaptation of the DAWES turbomachinery code. More recently, a nozzle with rigid observability requirements was designed for the Williams International P8300 engine. The FLUENT code was used to design this axisymmetric nozzle. This nozzle was tested and achieved its predicted performance.

Williams International has also successfully designed mixers for other applications: a mixer for the F112 engine was designed and tested for the Advanced Cruise Missile program. The F112 engine is a low bypass ratio turbofan engine. The baseline nozzle incorporated a mixed flow with free mixing. The forced mixer design was based on a parametric study with the objective of improving nozzle performance. Two full-size variants of the mixer were built and tested. The two mixers, an eight-lobe and a twelve-lobe design, are shown in Figure 3-11. The component tests of each variant of the mixer were conducted at Fluidyne Engineering Corporation's Medicine Lake Aerodynamic Laboratory in Minneapolis, Minnesota. Both configurations had similar performance but the eight-lobe design was lighter and was selected for further evaluation. The final configuration of the mixer was installed and tested in a full-size engine. Engine performance testing confirmed the increase in overall nozzle thrust coefficient of 0.4 percent that was observed in the component tests. In this test series, no acoustic data were taken since it was not an objective of the program. Additional analysis using 3D-CFD codes have been done for the FJ44-2 investigating an optimum aerodynamic mixing using an 18-lobe mixer configuration.

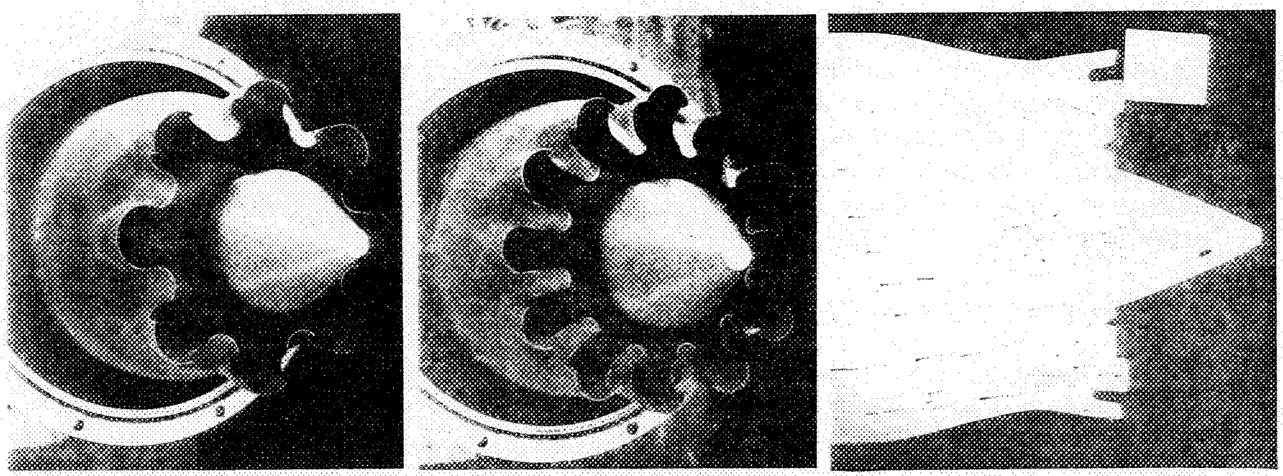

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Figure 3-11. Eight and Twelve-Lobe Mixer Designs and Flow Visualization Test Results

3.2.3 Rohr Experience.

Rohr is a leading manufacturer of nacelles for commercial aircraft turbofan engines, with FY1992 sales representing approximately 40 percent of the commercial market. Rohr supplies high performance acoustic liners for engine noise attenuation on many of these nacelle programs and provides a full range of acoustic services, including liner design, analysis, fabrication, test and repair. Rohr holds a number of patents on the use of advanced acoustic honeycomb sandwich structures for low and high temperature noise suppression system designs.

Rohr is engaged in a variety of research and development efforts to better understand and control the noise generated by jet engines for advanced subsonic aircraft. This activity includes passive noise control through advanced acoustic liner technologies, active impedance control concepts, and jet noise suppression concepts.

Advanced acoustic structures are being developed for low frequency tone and broad band fan noise reduction, such as light weight rigid foam and two-degree-of-freedom (2DOF) linear systems. Under funding from NASA-LeRC, Rohr and GEAE are studying scale model liners and the needed scaling laws for extrapolating model performance to full scale applications. High temperature broad-band acoustic liners are being developed for core and turbine noise suppression. In addition, using internal funds, Rohr is studying acoustic performance for jet noise suppression, and have tested several configurations of scale model mixer nozzles.

The active impedance control concept is being investigated to evaluate the feasibility of its implementation for aero-acoustic noise control. Rohr is studying an adaptive treatment concept in which the treatment impedance is actively controlled by electro-mechanical or fluidic means to achieve optimum values over a wide range of frequency or engine operating conditions. Effectively suppressing engine noise for advanced subsonic aircraft to meet significantly more stringent noise criteria may require a combination of passive and active control of engine noise. Our activities in these areas are designed to position Rohr to meet these challenges.

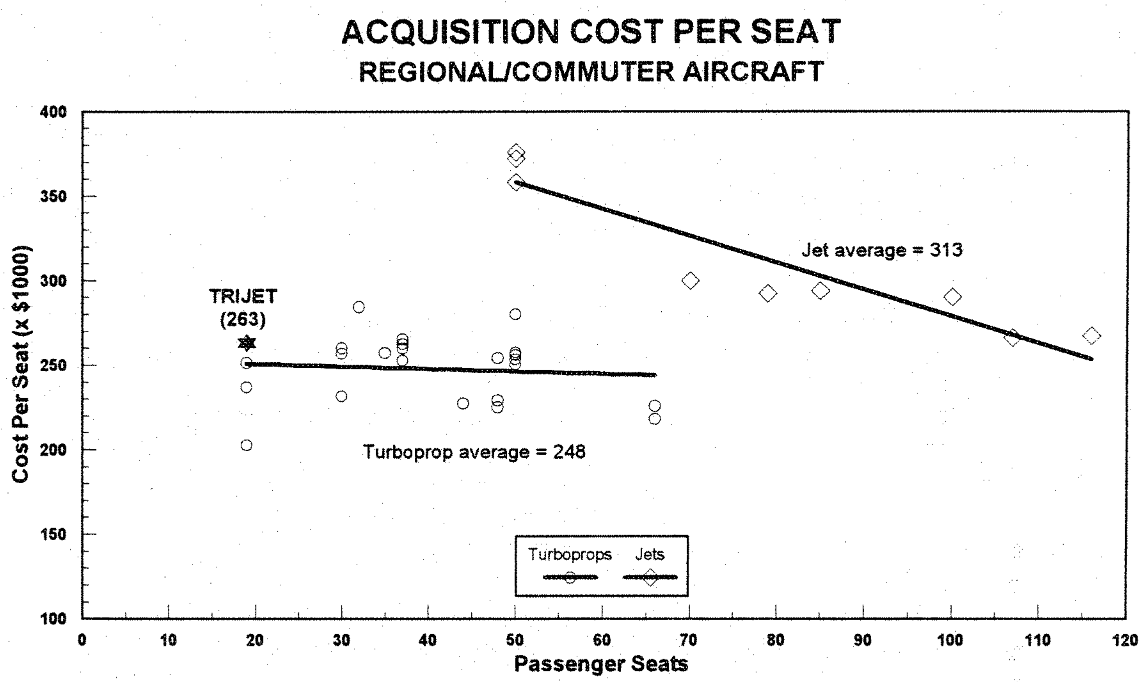
3.3 COST ANALYSIS

The Next Generation 19-Passenger Commuter Aircraft is anticipated to have an acquisition cost of $5M to $6M. The average price for today's 19-passenger aircraft varies from approximately $3.9M for a Fairchild Metro 23 to $4.8M for a Raytheon/Beech 1900D. The acquisition for the Next Generation Trijet Commuter is higher, but its value is very competitive when considering operating costs. Reviewing Figure 3-12 shows current aircraft from 19 to 118-seat capacity and their respective dollar per seat cost. The Trijet dollar-per-seat-cost is very comparable to today's turboprops and less than the average turbofan-powered regional/commuter jets. The operating costs will show even greater Economic Value Added (EVA). A profitability model was utilized to address the various operational cost elements and trade studies conducted that led to the selection of a trijet commuter aircraft configuration. The profitability model addresses the following cost elements:

- Fuel usage
- Flight crew
- Maintenance and direct maintenance
- Lease
- Hull insurance
- Spares
- Block time
- Block speed
- Trip distance

These are all elements that make up the direct operating costs (DOC) for comparison. Using the stage characteristics from Section 2.3, the output of the model provides an annual operating profit based on the sector (trip) distance. This is illustrated in Figure 3-13 for the Next-Generation Trijet Commuter along with a comparison of today's typical turboprop commuters. The first point is that the annual operating profit for the trijet excels beyond 200 nautical miles. The second point is that the trijet can be very profitable for out to a 1000 nautical mile trip. This is the result of a very low operating cost due to numerous improved aircraft performance factors (detailed in Section 2.0). For this analysis, the load factor was assumed to be a full 19-passenger load, or 100-percent load factor. The advantage of the trijet operating costs is revealed on the dollar-per-aircraft-mile and dollar-per-seat-mile calculations shown in Figure 3-14. These data show the crossover in improved operational cost at around a 300 nautical mile trip. A more detailed look at annual operating profit of current 19-passenger commuters is depicted in Figure 3-15. Here, the impact of acquisition cost is illustrated on the basis of a 60-percent load factor.

The EVA of the Next Generation Trijet commuter is very viable and extremely attractive to several airframe companies that are seriously considering the potential for this aircraft.



Ref: Business & Commercial Aviation, May 1995.

Figure 3-12. The Trijet Seat-per-Dollar is Very Competitive

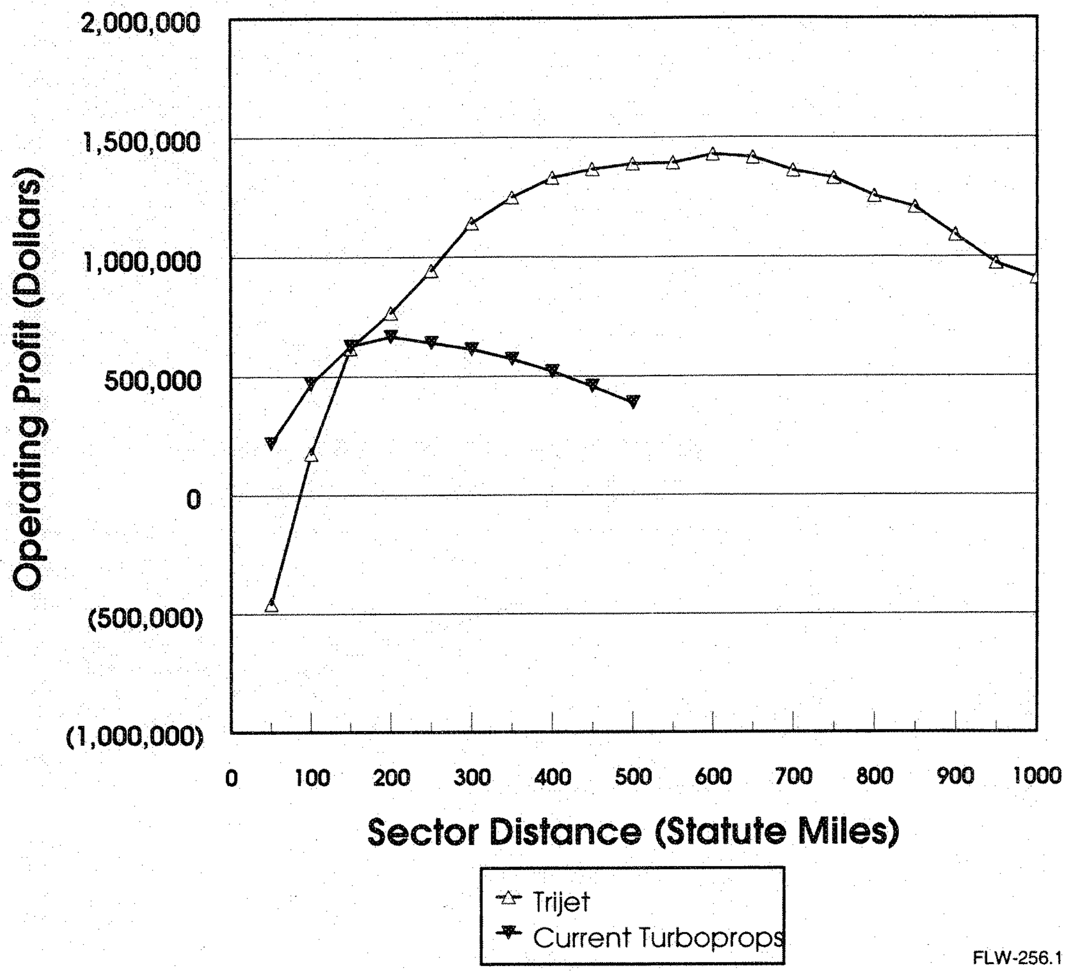


Figure 3-13. Annual Operating Profit

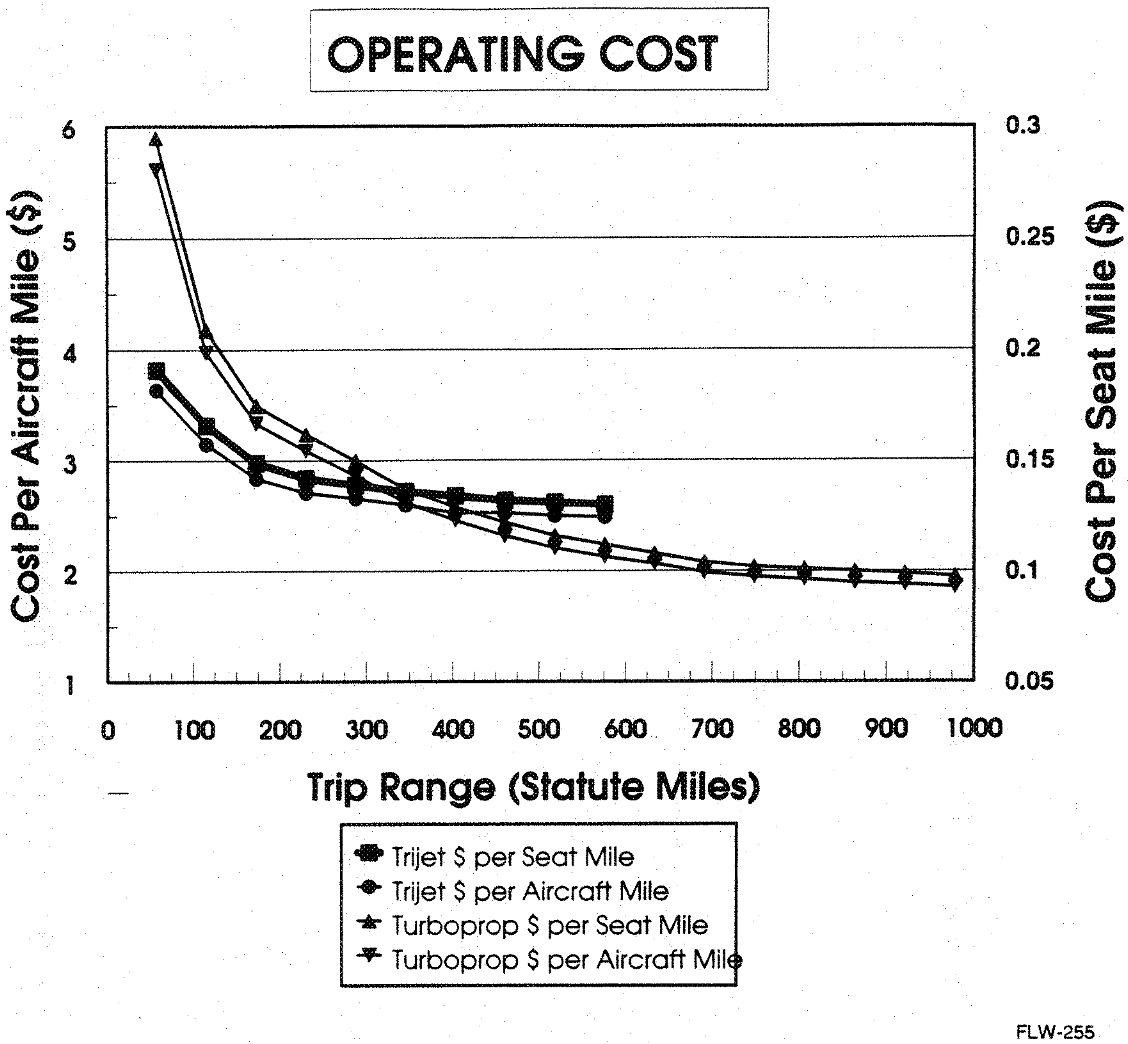


Figure 3-14. 19 Seat Trijet (NASA Study) Operating Cost

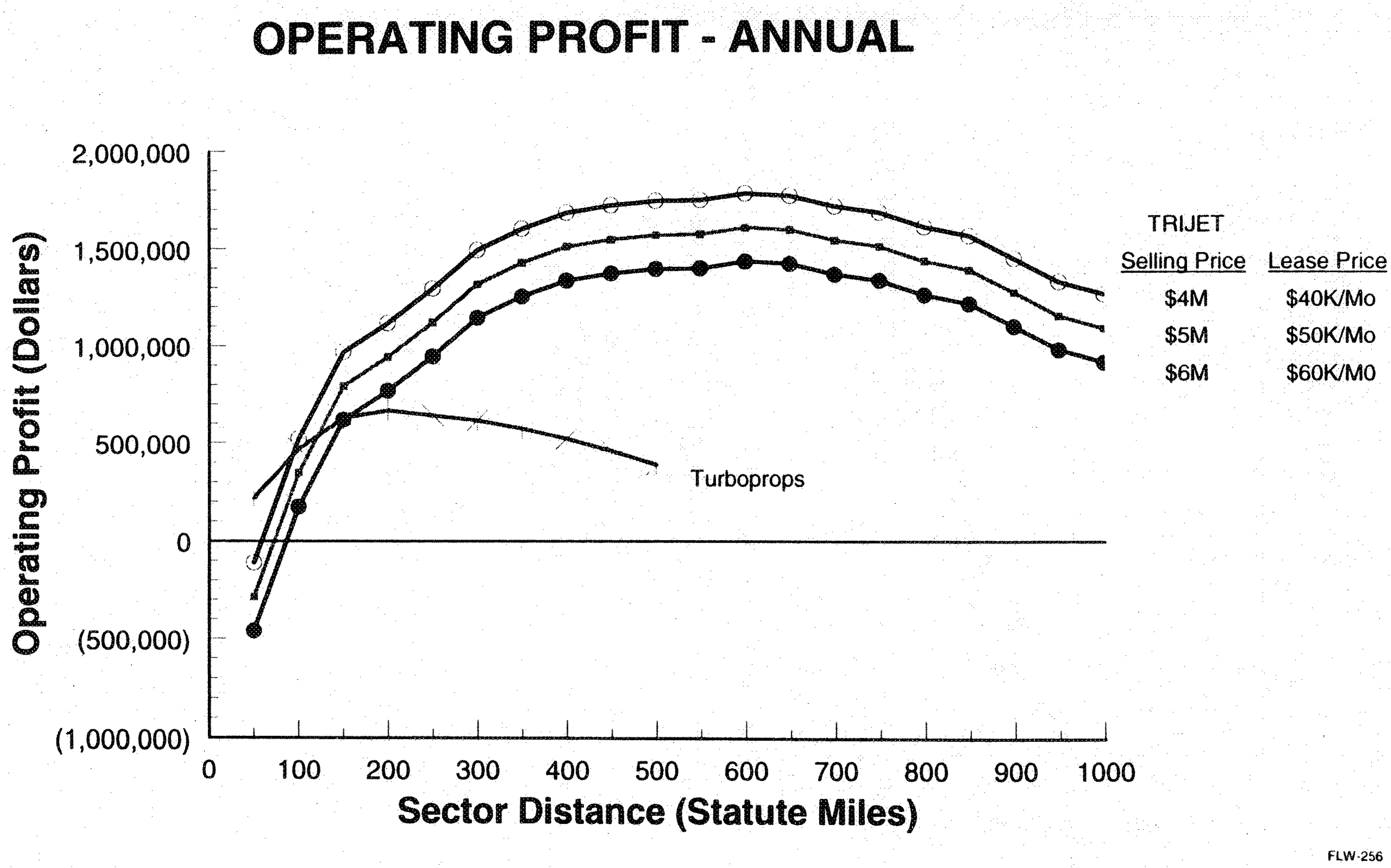


Figure 3-15. Trijet Operating Profits

4.0 REVIEW OF RELEVANT NASA PROGRAMS

A literature search was conducted using Williams International sources plus two outside technology search organizations. The outside organizations were:

1. NERAC, Inc., One Technology Drive, Tolland, CT 08084-3900, Telephone (203) 872-7000.

2. NASA RECON (Research Connection), NASA Center for Aerospace Information, 800 Elkridge Landing Road, Linthicum Heights, MD 21090-2934, Telephone (301) 621-0100.

The following three areas were chosen for search on available related technology:

1. Exhaust Emissions - related to gas turbine engines
2. Noise Emissions/Reduction - related to gas turbine engines
3. Operating Cost - related to gas turbine engines and general aviation

Hundreds of abstracts were available and reviewed concerning exhaust and noise emissions. Little information was available concerning operating costs. The search terms have been modified and resubmitted.

4.1 COMBUSTOR EMISSIONS RESEARCH

A tremendous amount of research for combustor emission data has been conducted by independent organizations, gas turbine engine companies, and Government research centers. Examples of NASA-related activity follows:

- Emissions Reduction by Varying the swirler Airflow Split in Advanced Gas Turbine Engines, ASME 92-GT-110.

- Applied Analytical Combustion/Emissions Research at the NASA Lewis Research Center - A progress report, AIAA 92-3339, NASA-TM-105731.

- Low NOx Potential of Gas Turbine Engines, AIAA 90-0550.

- NASA/GE Advance Low Emissions Combustor, AIAA 87-2035.

- Combustor Technology for Future Small Gas Turbine Aircraft, NASA-TM-106312.

- A Study of Low Emissions Gas Turbine Combustions, NASA-CR-195763.

- Spray Combustion Experiments and Numerical Predictions, AGARD/CASI HQ.

4.2 NOISE REDUCTION RESEARCH

Numerous (89 abstracts were received from the NASA RECON search), were reviewed for research areas of interest. A brief list of those related to NASA research are provided below:

- Active Control of Fan Noise from a Turbofan Engine, NASA Langley, HTN-95-61198 AIAA Journal, Vol 32, No.1, Jan 1994.
- Propulsion Technology Challenges for Turn-Of-The-Century Commercial Aircraft, ISABE 93-7003.
- Aircraft Turbofan Noise, ISSN 0889-504X, NASA-TM-106192.
- Unsteady Aerodynamic Analyses for Turbomachinery, NASA LeRC Workshop on Forced Response.
- Fan Noise Research at NASA, NASA-TM-106512.
- Noise Levels From a Model Turbofan Engine With Simulated Noise Control Measures Applied, NASA-TM-106318.
- An Evaluation of Some Alternative Approaches for Reducing Fan Tone Noise, NASA-TM-105356.
- Design and Performance of Duct Acoustic Treatment; NASA Langley, CASI HQ.
- Turbomachinery Noise, NASA LeRC, CASI HQ.

4.3 COST OF OWNERSHIP, OPERATING COSTS

Although initial efforts produced very little useful data on ownership and operating costs, additional literature searches are being conducted. Examples of information obtained to date include:

- The L500 and the Regional Airline Market, AIAA-90-2521.
- The Dash-8 Series 400 Regional Airliner, Aeronautics and Space Institute, 1989, p 26-1 to 26-16.
- General Aviation Cost Effectiveness, AIAA-85-4029.
- GASP-General Aviation Synthesis Program, Vol 7: Economics, Part 1: Theoretical Development, NASA-CR-152303-Vol-7-PT-1.

5.0 PRELIMINARY TECHNOLOGY DEVELOPMENT PLANS

5.1 LOW COST, COOLED HIGH PRESSURE TURBINE ROTOR DEVELOPMENT PLAN

This technology development plan addresses the FJ44 high pressure turbine. Advancements in turbine engine technology involve operating at higher overall cycle pressure ratios and higher turbine inlet temperatures. To be affordable in a lower thrust level turbofan, the turbine blade cooling passages must be much simpler than those of typical large engine cooled turbine blading. This plan will provide the design modifications to incorporate a cooled blade in the high pressure turbine disk. Procedures will be established to verify the design performance in a warm flow turbine performance rig. A follow-on plan will be defined to obtain the full-up engine performance validation.

5.1.1 Development Plan

5.1.1.1 Definition of Baseline Components. The high pressure turbine disk on the FJ44 engine is fabricated from an Inconel 718 forging in the solution annealed and aged condition. For an advanced application, additional strength and temperature capability is required. New materials will be investigated. One example is a powder metal Udimet 720 which has superior tensile strength over Inconel 718, especially at higher temperatures. Figure 5-1 indicates the level of disk strength improvement potential which would result in the higher disk low cycle fatigue and creep rupture life at the higher operating temperatures.

The high pressure turbine blades are cast from directionally solidified Mar-M-247. At higher operating temperatures, additional blade creep rupture strength is required. Figure 5-2 compares the rupture strength of DS Mar-M-247 versus single crystal alloys CMSX-4 and CMSX-6. Single crystal alloys have greater strength, but with some penalty in density. Both single crystal alloys have good castability in small turbine size in both solid and cooled configurations.

A relative size comparison of the FJ44 high pressure turbine to current industry advance engines is illustrated in Figures 5-3. The very intricate blade cooling passages are evident with their multipass cooling routes and various pins, ribs, and other turbulence-generation devices to maximize the heat transfer process. A third example of a typical low cost concept is shown in an even smaller F107 cruise missile engine size for comparison.

Additional industry status indicators are provided in Figures 5-4 and 5-5. These data indicate that the FJ44 is already operating at very high disk rim and rotor blade tip speeds when compared to the larger advanced technology engines. Several low pressure and high pressure turbine stages are indicated in Figure 5-5. The FJ44 is a very highly loaded stage when compared to engines with similar turbine hub $\Delta H/U^2$ levels.

5.1.1.2 Design Definition. The advanced low cost cooled high pressure turbine stage will be defined via a rigorous design process. A schematic of the axial turbine design system is depicted in Figure 5-6. This design process is briefly described in the following paragraphs.

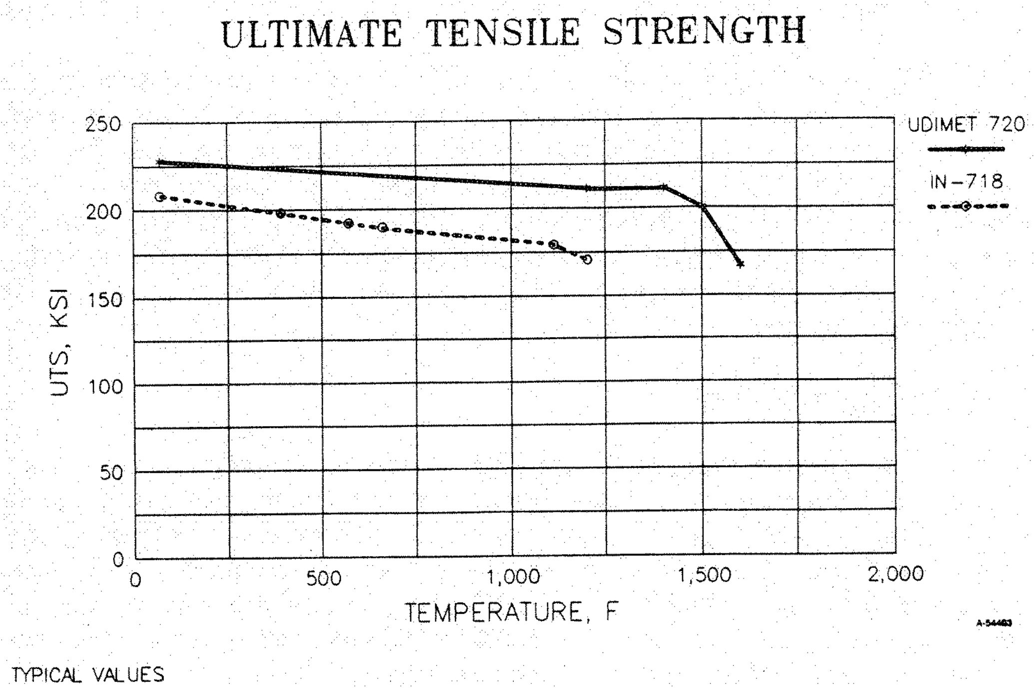


Figure 5-1. Udimet 720 Strength Advantage

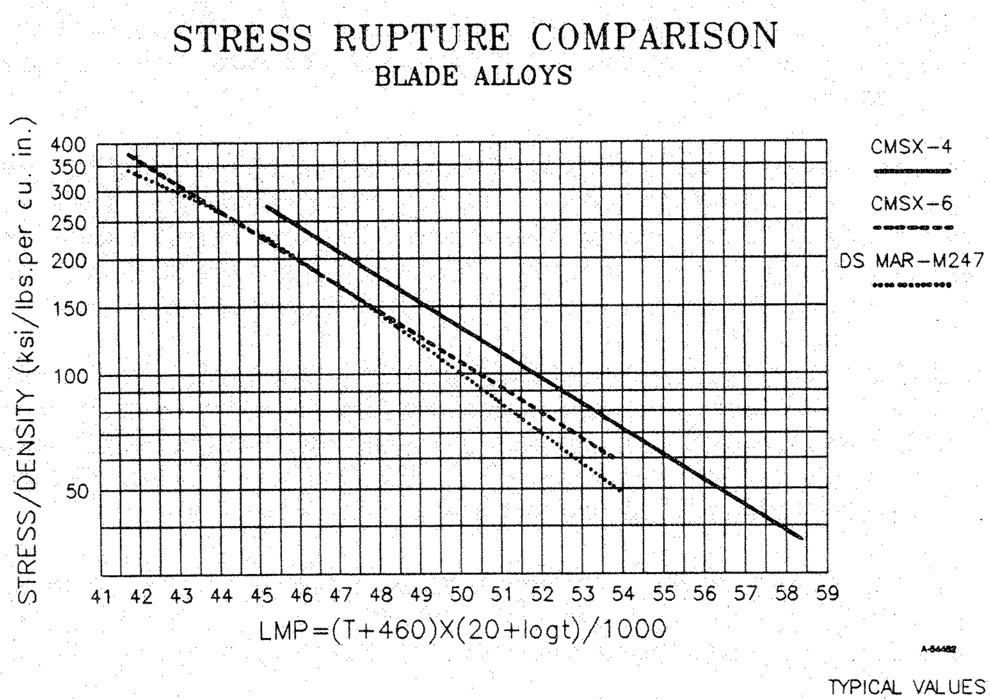


Figure 5-2. HPT Blade Candidate Materials Comparison

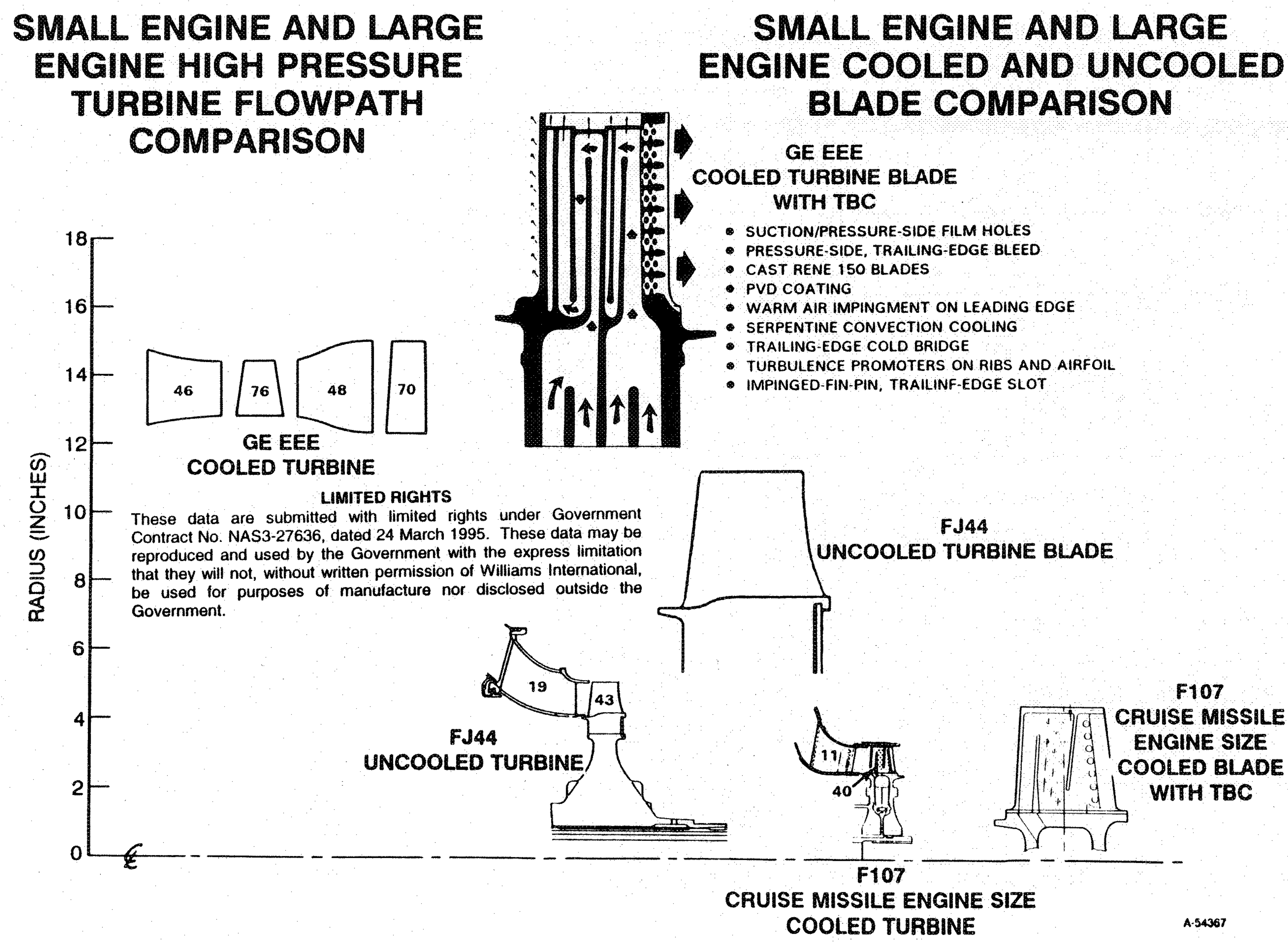


Figure 5-3. Small versus Large Engine Turbine Comparison

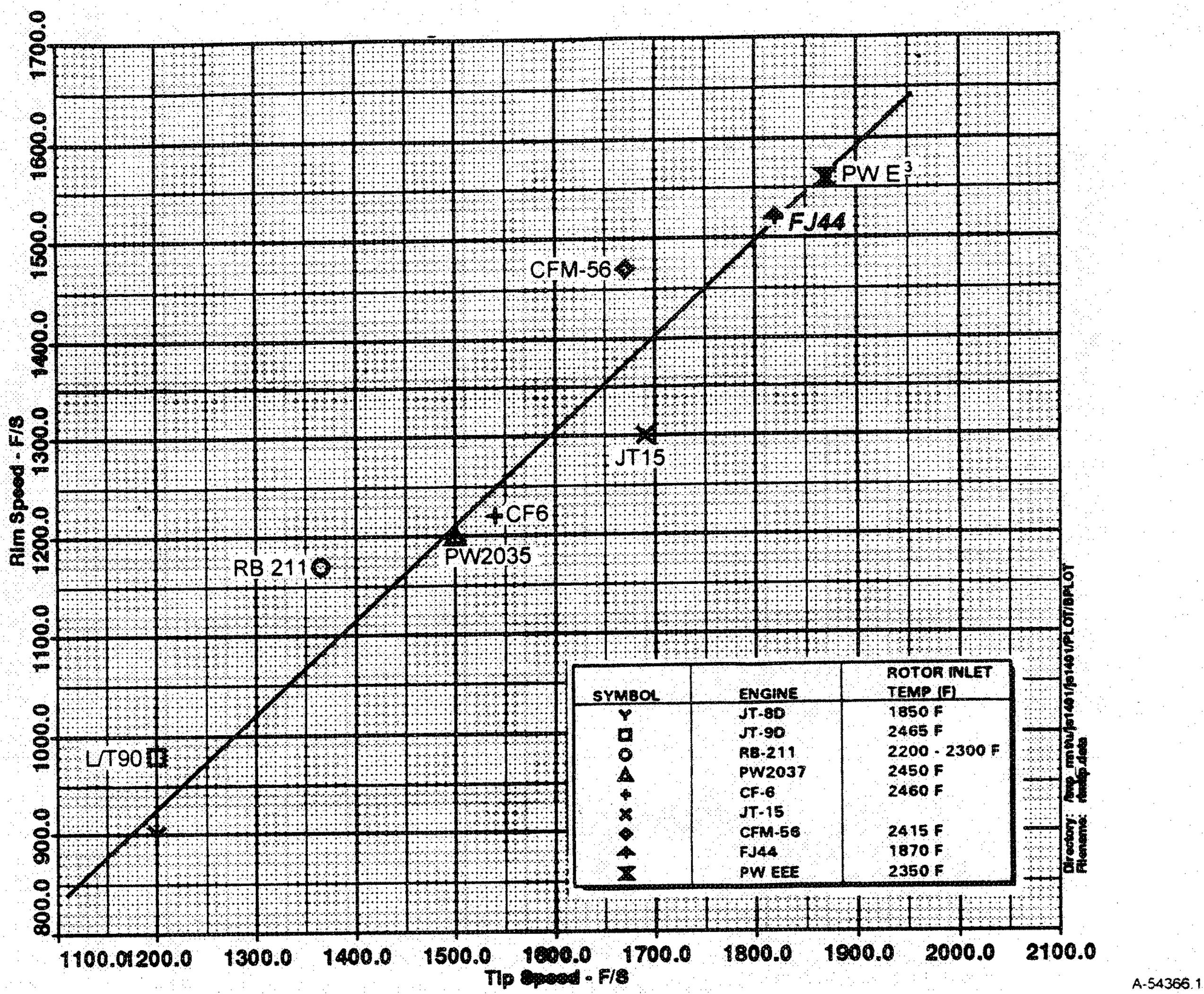


Figure 5-4. Cooled Large Engine HP Turbine Rotors vs. FJ44 Uncooled Rotor

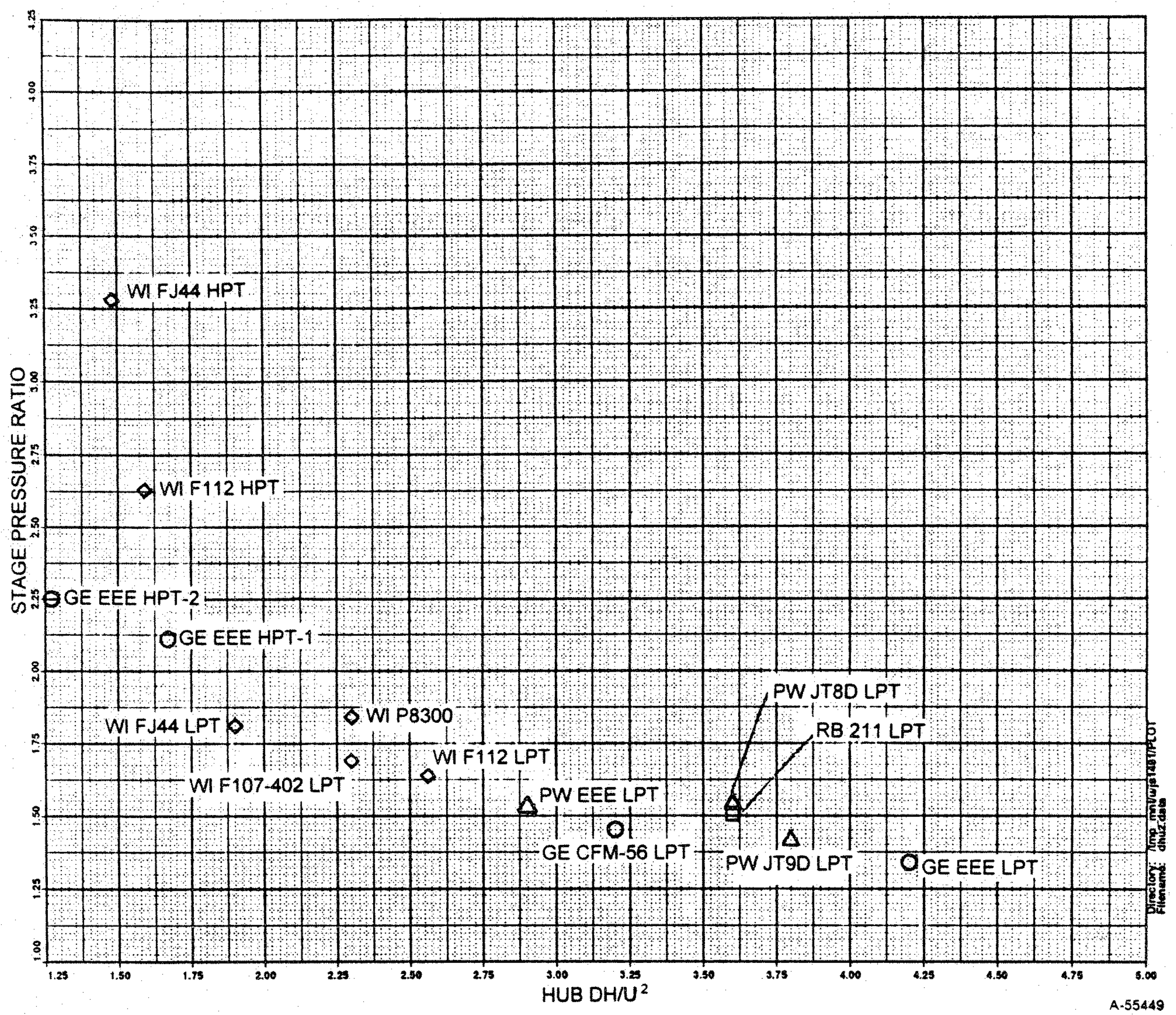


Figure 5-5. Stage Pressure Ratio vs. $\Delta H/U^2$ for Various Engine Turbines

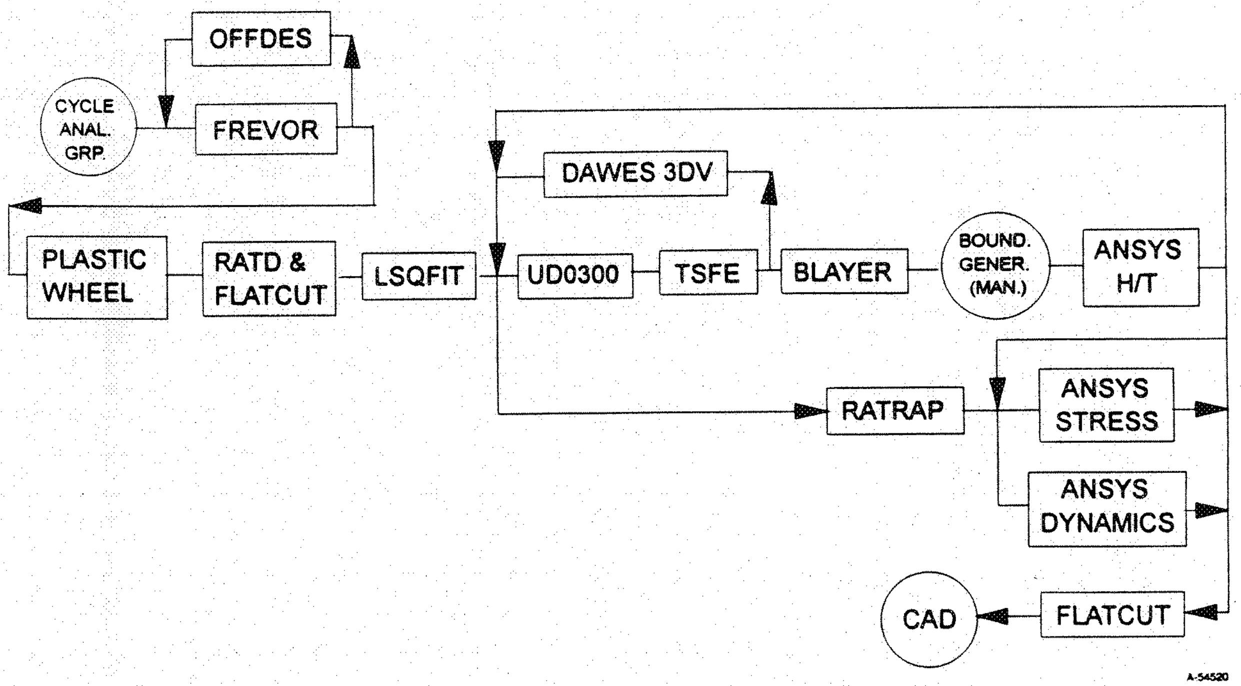


Figure 5-6. Axial Turbine Design Process

Preliminary Design

The preliminary aerodynamic design system at Williams International consists of three major elements: an aerodynamic design point model, an off-design performance prediction program, and a preliminary airfoil geometry generator. The aerodynamic model assumes a 3D axially symmetric flowfield in simple radial equilibrium. The predicted stage efficiency is determined from estimated losses of the individual blade and vane rows. The loss is derived using a method described by Kacker and Okapuu[1]. The calculated blade row loss is the sum of profile, secondary, trailing edge and tip leakage losses, where the profile losses are corrected for Reynold's number effects and inlet Mach number related shock losses. The Kacker and Okapuu modeling system has shown excellent agreement with available published turbine data and Williams International data. The preliminary aerodynamic design program is used to set basic turbine design parameters such as flowpath radii, blade and vane aspect ratio, solidity, work coefficient, and rotational speed.

The second feature of the preliminary design system is the turbine off-design prediction program OFFDES. In addition to utilizing the above described loss system to predict performance, an incidence loss correlation and a trailing edge shock loss model have been added. The program yields excellent low-speed turbine performance maps, which are used to predict engine start times.

The third feature of the preliminary design system is RATD[2], the Rapid Axial Turbine Design program, which utilizes the preliminary aerodynamic model to rapidly generate stacked preliminary turbine airfoils with specified thickness distributions. This program permits first-order heat transfer, stress, blade dynamics and blade life analyses prior to detail aerodynamic design which significantly reduces overall design time.

Detail Design

The detail aerodynamic design of axial flow turbines is primarily conducted using a modified version of the UD0300M computer program[3]. The program is a 2D steady, axisymmetric throughflow computation that permits intra-blade aerodynamic calculations that account for blade dihedral and meridional lean. These effects, combined with radial and axial distributions of total pressure loss and fluid angular momentum result in a quasi-3D flowfield approximation. The blade surface velocities are controlled by variations of the derivative of fluid angular momentum, with respect to meridional distance. This distribution is typically derived from the results of a blade-to-blade flowfield solution. The Williams International FJ44 HP turbine was redesigned with this program at loading levels 20 percent higher than the original design and is exhibiting excellent performance.

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[1]Kacker, S.C. and Okapuu, U. "A Mean Line Prediction Method for Axial Flow Turbine Efficiency," ASME Paper 81-GT-58, March 1981.

[2]Pritchard, L.J., "An Eleven Parameter Axial Turbine Airfoil Geometry Model".

[3]Law, C.H. and Puterbaugh, S.L., "A Computer Program for Axial Compressor Design (UD0300M)" AFWAL-TR-82-2074, September 1982.

The Williams International Transonic Finite Element (TSFE) Program, based in part on the NASA developed TSONIC program, is used to determine bladerow work distributions, blade surface velocities, and cascade deviation. The program is a 2D potential flow solver that can accommodate transonic blade surface velocities. The intra-blade distribution of stream tube height variation which results from the throughflow analysis is incorporated into TSFE to yield a fully quasi-3D flowfield calculation. This program is especially useful in the design of LP turbines, where cascade velocities are generally subsonic. The blade surface velocities that result from TSFE are analyzed in BLAYER, a compressible boundary layer analysis program used to determine cascade loss and potential separation. In the event of predicted separation, an aerodynamic iteration of the cascade would be required to eliminate this source of loss.

The MARGIN program, originally developed for transonic flows, is used to ensure that turbine cascade throat margins are successfully achieved. This program utilizes flowfield results from the quasi-3D streamline program in combination with a detailed analysis of the cascade geometry to determine minimum throat size and margin.

The above described detail design system does not fully account for the impact of secondary flows or tip clearance effects, nor does it yield accurate blade-to-blade flowfield results for fully supersonic cascades. These system limitations are addressed by BTOB3D, the Dawes code. This program is a fully 3D Reynold's-averaged Navier-Stokes solver. The level of aerodynamic results offered by this analysis includes blade trailing edge shock-boundary layer interactions, blade suction surface shock induced separation, and accurate blade surface temperature estimations. The Williams International turbine detail design system utilizes this program in all supersonic turbine design, or where secondary flow losses are predicted to be excessive. This would include most HP turbine designs and all highly loaded LP turbine designs.

5.1.1.3 <u>Hardware Fabrication and Performance Verification.</u> The hardware detail design components will be procured and fabricated in preparation for a component test rig evaluation. A Turbine test rig will be designed for a warm flow (400^{0}F) component test evaluation. A detail test plan will be prepared including the instrumentation and evaluation of the cooling effectiveness. The test plan will be submitted to the NASA program manager for approval. The component rig test will then be conducted and the resulting performance documented. A final report shall be prepared and submitted to the NASA program manager for approval.

Testing of axial turbines is conducted in the A8 turbine test facility or *in situ* on the actual engine for which the turbine was designed. The A8 test cell is a warm flow rig that absorbs power using an electric dynamometer. Research stages or designs that are particularly challenging are typically the ones that are evaluated in this facility. A full complement of pressure and temperature measurements can be made in this rig and power calculations and operating efficiencies can then be compared to mechanically measured results. In cases where an engine is used to assess turbine performance, measurements of sufficient accuracy and detail can be made to assess turbine performance within one or two percent. Measurements made in the engine have the added benefit of operation with the proper inlet velocity distribution, boundary layers, Reynolds numbers, heat transfer effects, secondary flows, and tip clearances.

Future work in the field of small axial turbines addressing long life man-rated engines, will concentrate on the special challenges of developing efficient, affordable, small cooled metallic designs. Progress in developing improved uncooled metallic designs is anticipated but is not expected to yield any major breakthroughs. The challenge for small cooled designs is the achievement of the combination of good aerodynamic efficiency and heat transfer effectiveness at a reasonable price. Improved analysis techniques for both external as well as internal flows will be as important as the development of improved low cost manufacturing processes.

5.1.2 Program Schedule

The program schedule to conduct the above technology development plan is shown in Figure 5-7. The ROM cost for this activity is $1.85 million in first quarter CY96 dollars.

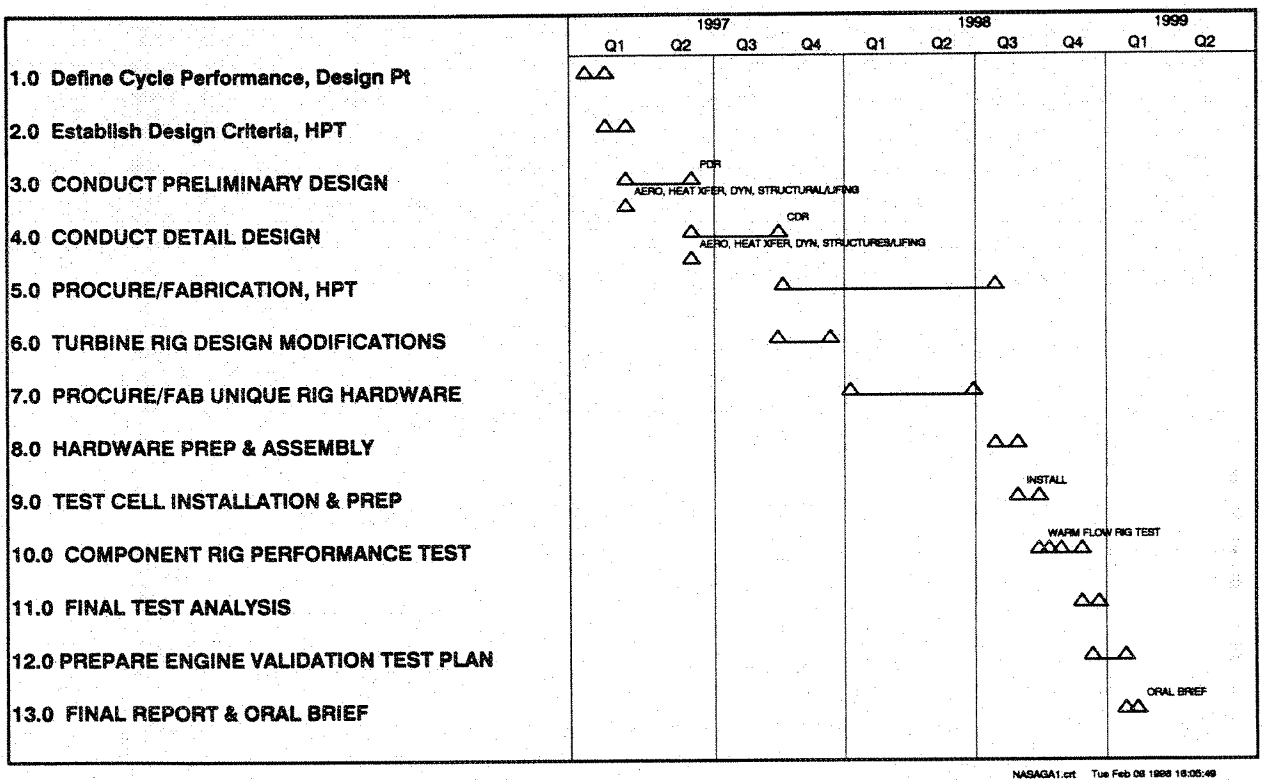

Figure 5-7. Low Cost, Cooled HP Turbine Technology Insertion Plan

5.2 ADVANCED COMBUSTOR TECHNOLOGY AND EMISSIONS REDUCTION PLAN

This technology development plan investigates advanced combustion concepts to meet the needs for advanced commercial, subsonic aircraft operating beyond the year 2000. The engine size targeted for this effort is the 2000 to 3000 lbf thrust class, specifically for the Next Generation 19-Passenger Commuter application. The advanced combustor goals include operating at higher temperatures and pressures, improving combustor exit pattern factor and radial temperature profiles, increasing combustor life, and improving operability by improving lean blow-out stability and increasing the maximum relight altitude. The result will be a very low emission combustor. This effort may very well establish the criteria for future FAR emission standards for this thrust class engine.

5.2.1 Development Plan

This plan investigates four advanced combustor technologies. Each concept will be designed and analyzed via rig testing and evaluated for further engine testing.

5.2.1.1 Design Baseline and Hardware. The FJ44 engine is unique among the new generation of small turbofans in its use of slinger fuel injection, highly effective effusion cooling, and in the patented integration of its wall cooling system in combustion zone aerodynamics. Figure 5-8 shows a detailed cross section of the combustor as installed in the FJ44 engine. The fuel is injected into the combustor in a circumferentially uniform manner utilizing a fuel slinger, which is attached to the core shaft, and a fixed fuel feed manifold located under the slinger. The slinger has about its periphery a pattern of holes and slots that serve to provide a uniform distribution of fuel droplets for a uniform combustion zone.

Figure 5-9 shows a detail of the slinger/manifold area. Combustor ignition is accomplished using two surface gap spark igniters and a single auxiliary start nozzle. Combustor operating parameters for the FJ44-1 and FJ44-2 engines are shown in Table 5-I.

TABLE 5-I. FJ44 ENGINE DESIGN POINT (Sea Level Static)

	FJ44-1	FJ44-2
Airflow (lbm/sec)	14.76	18.50
CDP (atm)	12.78	17.02
CDT (°F)	747	864
CET (°F)	1802	2014
Heat Release Rate (Btu/Ft^3 atm-hr)	6.1×10^6	6.2×10^6
Residence Time (ms)	5.5	5.3

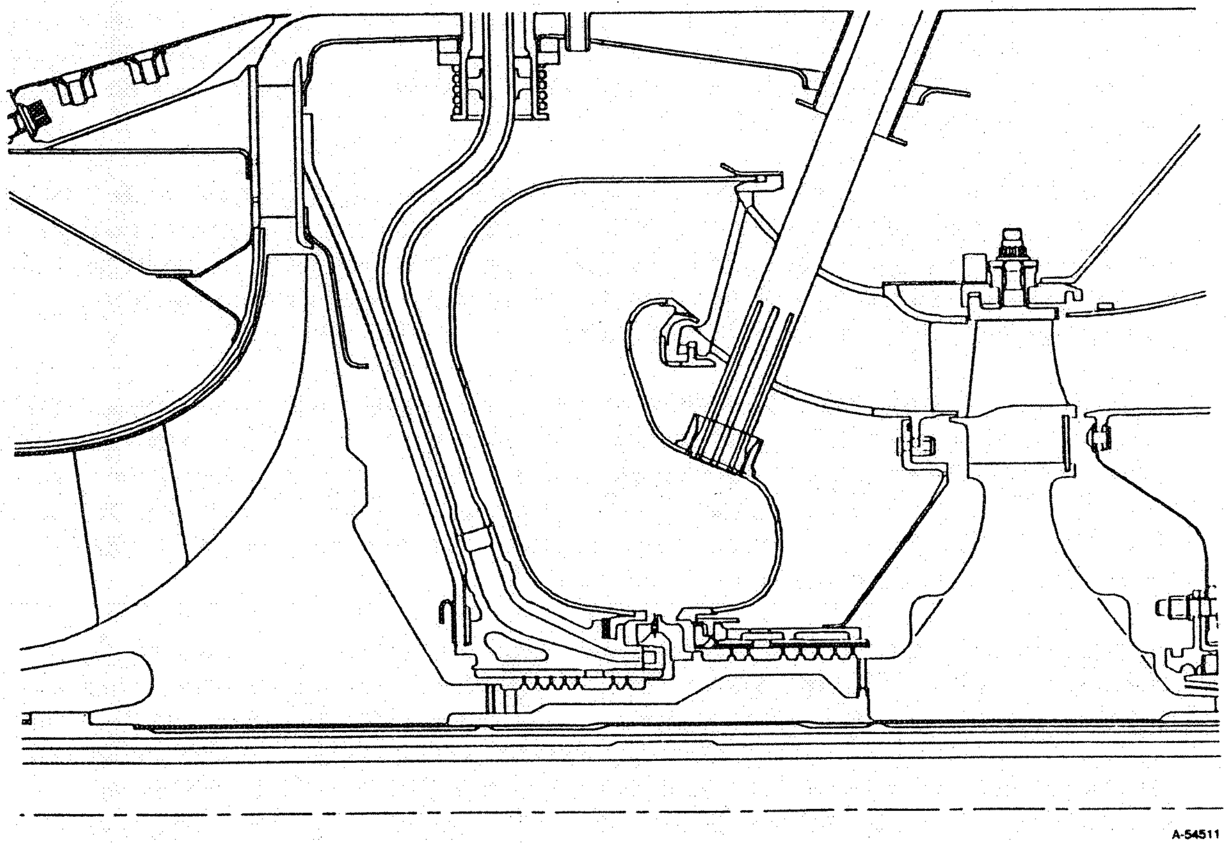

Figure 5-8. FJ44 Combustor

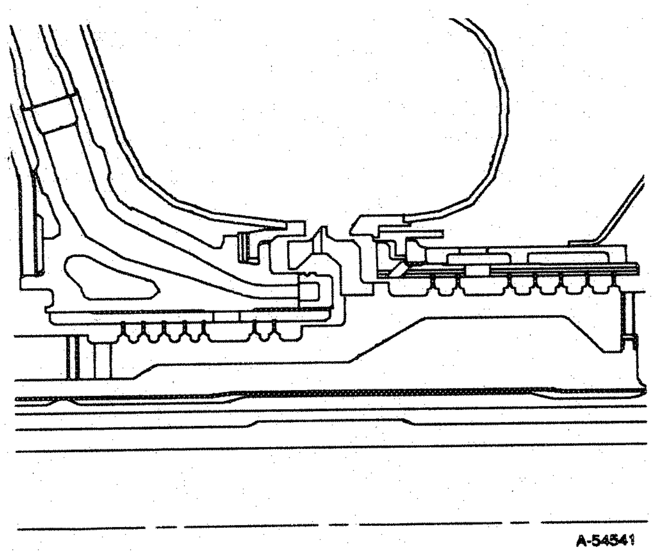

Figure 5-9. Slinger/Manifold of the FJ44 Combustor

The forward combustor wall, or combustor cover, is a two-piece, laser-welded assembly, and is effusion-cooled. The aft wall, or combustor primary plate, is a five-piece, laser-welded assembly with two igniter and one start nozzle boss tig-welded as shown, and is also effusion-cooled. The combustor wall material is INCO 617.

Effusion cooling was selected for this combustor design for its superior cooling effectiveness over conventional film cooling techniques, and for its potential in minimizing combustor weight and cost. Development and certification testing has shown effusion cooling to provide very low thermal gradients and excellent cyclic durability. Combustor weight and cost were also substantially reduced over earlier film cooled designs (Figure 5-10).

Effusion cooling of the combustor walls is accomplished by laser drilling a collection of cooling air holes at a shallow angle to the metal surface. The effusion cooling process is two-fold: cooling air flowing through the long, highly angled holes provides convective cooling within the wall itself, while air exiting the holes provides a very uniform and effective film cooling on the hot gas side (Figure 5-11). The effusion holes are sized, spaced, and oriented to provide complete wall surface coverage and aid in bulk flow circulation.

Aerodynamically, the combustor is designed to operate in a conventional manner (Figure 5-12). The combustion air distribution provides for primary and secondary combustion zones and dilution air for pattern factor control. A strong primary recirculation pattern provides exceptional flame stability, strong ignition and relight capability, and good primary efficiency. The recirculation is toroidal in shape and is driven strongly by the slinger fuel flow, primary air jets, and oriented cooling flows. Figure 5-13 shows the current FJ44 operating and ignition/relight envelopes.

The circumferentially uniform fuel distribution in the FJ44, and in other Williams International products, is a decided advantage in maintaining low combustor pattern factors. The design pattern factor used for the FJ44 is 0.15. In practice, however, pattern factors of 0.10 to 0.12 are typical, with <0.10 easily achieved.

Low exhaust emissions for the FJ44 have not been actively developed. Certification for engines at this thrust level requires only that a maximum smoke number not be exceeded. However, emission measurements taken late in the development process and during certification testing show the current FJ44 combustor to be an exceptionally clean burning configuration. Table 5-II shows the results of emission measurement during FJ44 certification testing.

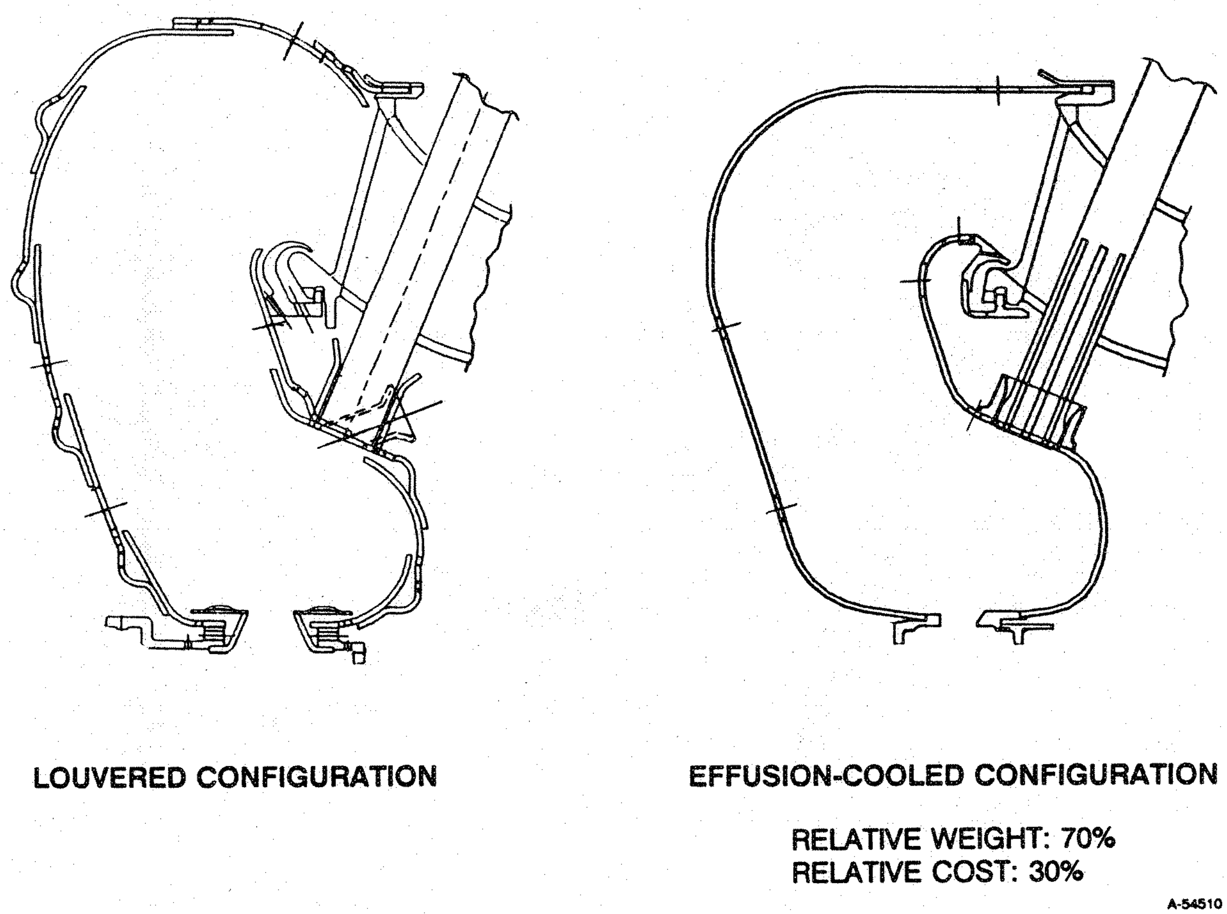

Figure 5-10. FJ44 Combustor Configuration Changes

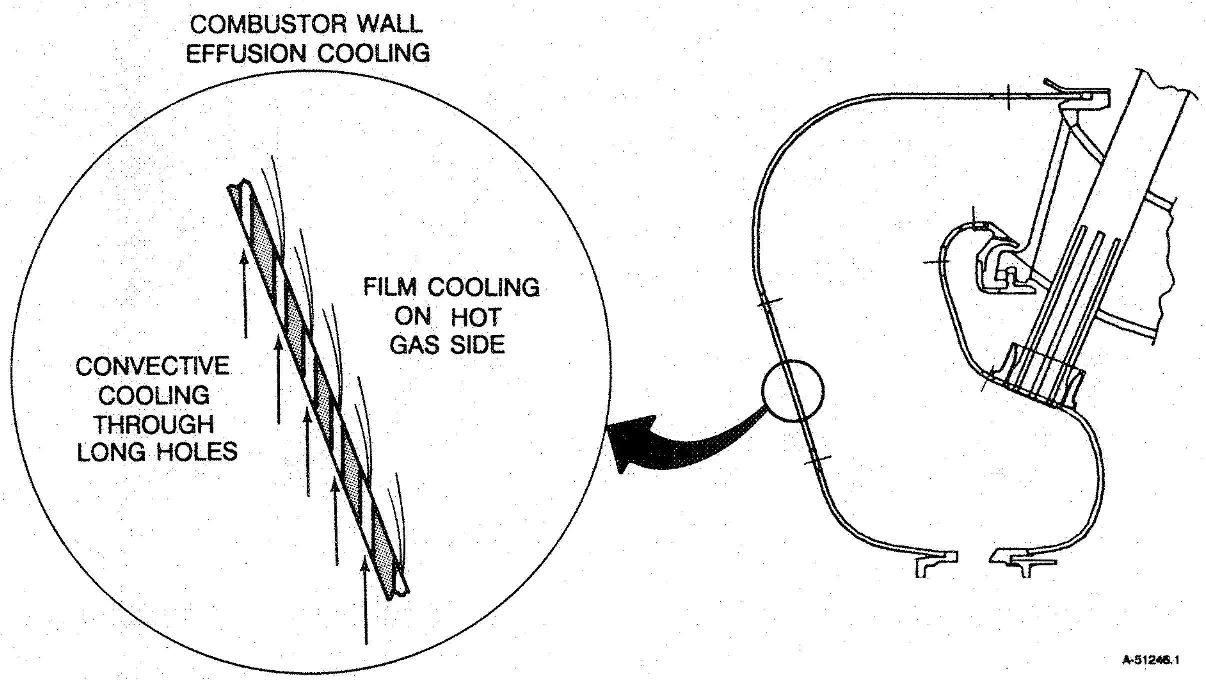

Figure 5-11. Detail of Effusion Cooling System of FJ44 Combustor

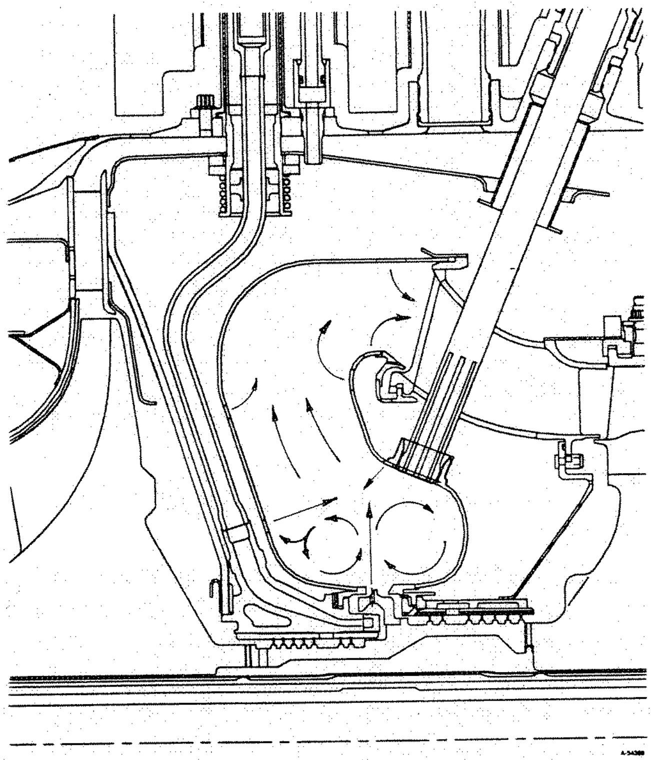

Figure 5-12. Aerodynamic Design

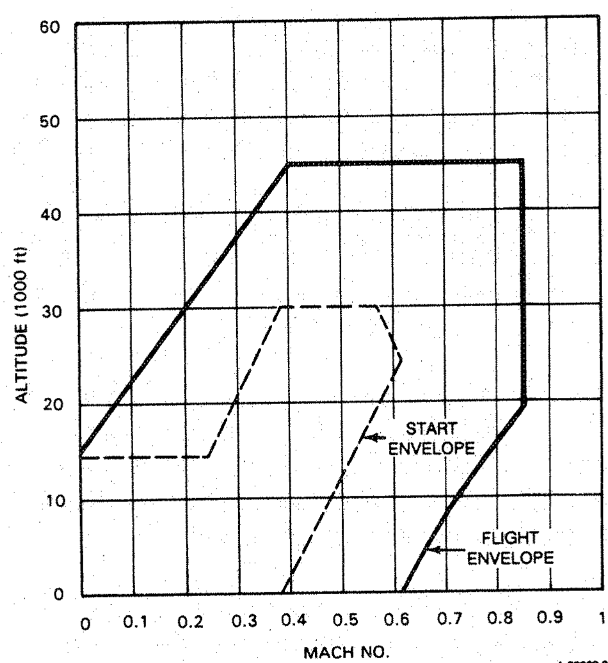

Figure 5-13. FJ44 Flight and Start Envelope

TABLE 5-II. FJ44-1 EMISSIONS COMPARISONS

Engine	Thrust (kN)	Manufacturer	Pressure Ratio	HC	dp/F_{oo} (g/kN) CO	NOx	NOx[1]	Smoke No.	Smoke[2]
FJ44	8.5	Williams	12.8	4.9	149.5	36.2	65.6	6.0	46.5
TFE731-2	15.6	Garrett	13.9	53.4	169.4	40.5	67.8	-	39.4
TFE731-3	16.5	Garrett	14.3	24.0	137.7	51.4	68.6	-	38.8
JT15D-1	9.8	Pratt	9.8	161.8	467.5	27.3	59.6	15.9	44.7
JT15D-4	11.1	Pratt	10.1	130.6	348.1	38.4	60.2	14.1	43.2
ICAO Standard (> 26.7 kN) (>6000 lb)				19.6	118.0	See Note 1		See Note 2	

Notes: 1. 40 + (2 x PR)
2. 83.6 $[Ro]^{-0.274}$, (Ro in kN) or not higher than 50.

As shown, smoke numbers are extremely low. Other gaseous emissions are also very low, and are compared with both current large turbofan (>6000 lb thrust) emission requirements and two other current production engines similar in size to the FJ44. Unburned hydrocarbons (UHC) were found to be quite low in the FJ44 and indicates an advantage in designing with effusion cooling, resulting in a minimum of entrained combustion reaction products in the coolant stream. Carbon monoxide (CO) is also low, though not quite to the regulated level of larger engines, but still indicates low cooling entrainment and reasonably optimized primary and secondary combustion zone stoichiometry. Oxides of nitrogen (NOx) are also low but similar to the other production engines shown, a product of similar cycle temperatures and primary flame temperatures.

These combustor attributes make the FJ44 combustor an ideal testbed for advanced combustor evaluation. Simple, low cost construction, easily modified/optimized cooling system, uncomplicated fuel system, and inherently low emissions provide a solid baseline design from which the low emissions combustor research activities can be investigated.

5.2.1.2 <u>Combustion/Emissions Reduction Technology - Concept 1</u>. This concept will attack emissions, pattern factor, and stability with modifications to combustion, dilution, cooling air distribution and slinger hole patterns only. The same basic FJ44 combustor geometry, fuel injection and aerodynamic scheme will be utilized.

Optimization of primary zone stoichiometry will target production of NOx and CO, while retaining or improving existing start and relight capabilities. Lowering primary zone equivalence ratio from 0.95 to 0.80 should optimize CO production and at the same time reduce flame temperature and therefore NOx production. Stability will be enhanced by maintaining or increasing start nozzle flow while providing enhanced slinger fuel distribution and mixing.

Secondary air injection will be modified to provide a more gradual flame temperature decrease, contributing to CO reduction as well as improving temperature distribution into the dilution zone.

Dilution air will be reapportioned to reduce pattern factor and optimize radial profile into the nozzle. Cooling/durability will be maintained in this concept through balanced modifications to the local effusion cooling patterns, based on local changes to bulk gas temperatures and velocities.

5.2.1.3 <u>Combustion/Emissions Reduction Technology - Concept 2.</u> Improving primary zone efficiency is the goal of the second concept; lowering CO and NOx while greatly enhancing startability, especially at altitude. This concept will utilize a modified distribution of start nozzle and slinger fuel flows to enhance primary zone atomization, resulting in an improved ignition environment and enhanced idle efficiency.

As in Concept 1, the same basic FJ44 combustor geometry, fuel injection, and aerodynamic scheme will be utilized. The major change from the basic combustor in Concept 2 is the addition of three to eight more start nozzles, and fuel control logic changes to yield an innovative staged-type fuel distribution within the combustor primary zone at start and lower operating speeds. This type of modification will greatly enhance cold and altitude ignition and startability by providing a much lower SMD in the primary zone and improved transient efficiencies throughout the early start transient. An improved fuel distribution and mixing environment will also contribute to an improvement in idle efficiency. Current idle efficiency is 0.985. An improvement to 0.993 should provide a major reduction in CO and HC at idle (40 percent and 65 percent, respectively), and provide an improved environment with respect to reduced NOx production (e.g., potential for lower primary zone equivalence ratios and residence times).

Secondary and dilution air distribution will be modified to optimize downstream emission effects and pattern factor. Cooling/durability will be maintained in this concept through balanced modifications to the local effusion cooling patterns, based on local changes to bulk gas temperatures and velocities.

5.2.1.4 <u>Combustion/Emissions Reduction Technology - Concept 3.</u> The third concept will concentrate on changes to the slinger and primary zone mixing to achieve increased primary zone efficiency and improved startability without the complexity of auxiliary start nozzles. A staged slinger would provide an improved primary fuel distribution and reduced SMD (Figure 5-14), contributing to improved ignition, and start transient and idle efficiencies. Again, the same basic FJ44 combustor geometry and aerodynamic scheme will be utilized, along with local changes to cooling. Improvements in CO and UHC emissions, similar to Concept 2, will be expected, while maintaining or improving overall performance.

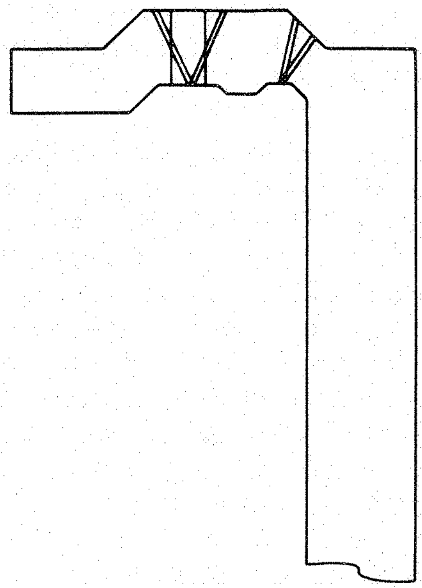

Figure 5-14. Staged Slinger Concept

5.2.1.5 Combustion/Emissions Reduction-Concept 4. Concept 4 will concentrate on achieving a minimally-cooled design aimed at reducing entrained emissions and providing similar or improved baseline performance utilizing a hot wall environment.

A high temperature composite material is envisioned to provide a combustor geometry similar to the baseline FJ44, but with little or no cooling film or oxidation-resistant coating required. Local cooling required for attachments or other component interfaces would be provided as needed. As with the other concepts, Secondary and dilution air distribution will also be modified to optimize downstream emission effects and pattern factor.

5.2.1.6 Candidate Combustor Concept Selection Methodology. Concept definition methodology is outlined in flowchart form in Figure 5-15.

Each candidate concept will be analytically defined, and a preliminary design established based on a common engine geometry and common engine performance goals. This engine will be based on an uprated version of the current FJ44 engine, with cycle operating points derived from engine cycle studies specifically targeted to advanced subsonic technology objectives.

Based on this preliminary design, operating point boundary conditions will be calculated and inputs established to conduct a detailed 3D CFD modeling analysis of each candidate concept. Modeling detail will include a complete cross-sectional portion of the combustor from slinger liquid fuel injection through dilution mixing and nozzle entry. Cooling flows will also be modeled; however, current computational capacity prevents modeling of individual cooling holes to scale and integrated wall thermal analysis. CFD results will yield information on bulk flow velocities, temperature distribution, fuel distribution including droplet tracking, exit temperature pattern factor and profile, mixing turbulence levels, and NOx prediction. Temperature distributions will be used to define boundary conditions for wall heat transfer analysis, utilizing dedicated effusion cooling programs.

These predictive efforts will be conducted over the full spectrum of operating conditions that the combustor is expected to operate to support the definition of the combustor concept. This will include, but not be limited to, sea level idle and full power, altitude maximum continuous power, and start conditions, both sea level and at altitude.

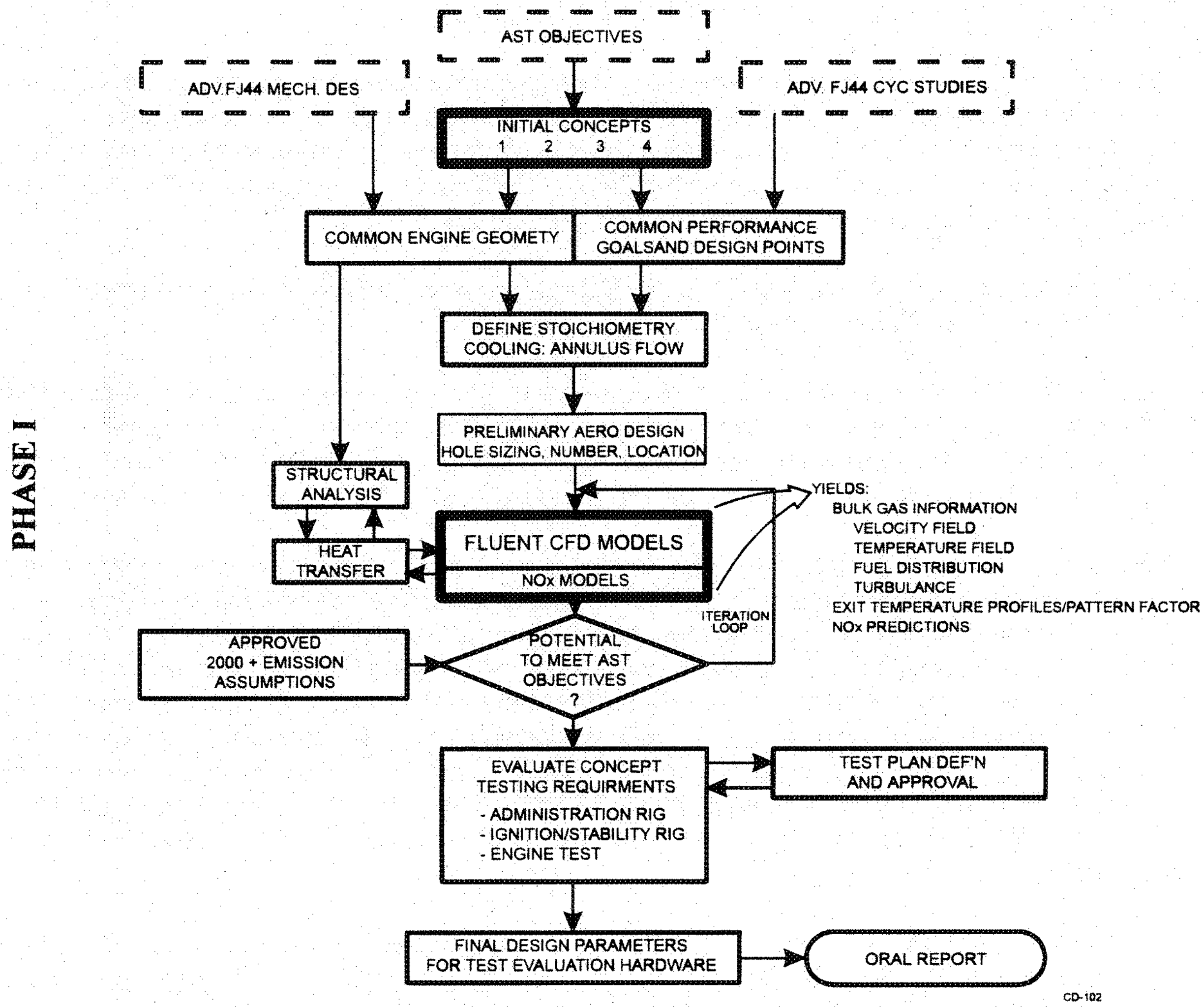

Figure 5-15. Combustor Concept Selection Methodology

These results will then be assessed with respect to each concept's potential to meet the stated performance objectives. These assessments will be made utilizing empirical correlations and experimental experience gained in the development of the baseline combustor, as well as previous model validation experience on a number of programs conducted at Williams International. Preliminary design modifications may be conducted and models iterated to maximize predicted design potential.

5.2.1.7 Emissions Assumptions. All turbine engines manufactured after 1 January 1984 must comply with U.S. legislative requirements for exhaust emissions. The applicable requirements are set forth in Title 40 of the Code of Federal Regulations, Chapter I, Environmental Protection Agency, Part 87, Control of Air Pollution from Aircraft and Aircraft Engines (40 CFR Part 87). The FAA enforces 40 CFR Part 87 in Federal Aviation Regulations (FAR) Part 34, Fuel Venting and Exhaust Emissions Requirements For Turbine Engine Powered Airplanes. For measurement techniques and supporting analytical methods, the FAA approves the use of International Civil Aviation Organization document ICAO Annex 16, Environmental Protection, Vol. II, Aircraft Engine Emissions, Appendices 2 through 6.

The FJ44 is currently certified in compliance with FAR Part 34 for exhaust smoke emissions. Current emissions certification standards for turbofan engines of less than 6000 lb thrust do not include UHC, CO, or NOx. For turbofan engines of 6000 lb thrust or more, FAR Part 34 requires specific certification levels for UHC, CO, NOx, and smoke (Table 5-II).

The emissions standards for the advanced turbine engines for which the combustor concepts are intended, are not yet established and, as in current standards, may vary with size. In order to provide a technology baseline with respect to emissions, data from this effort will provide the criteria for the emission standards for small gas turbine engines for use in commercial service for the year 2000 and beyond. The standards assumptions will utilize Williams International experience and judgment on the subject, and include consideration of potential ICAO regulations on gaseous and particulate emissions.

5.2.1.8 Component Test Plan. A test plan will be prepared detailing the testing apparatus, respective apparatus and concept hardware testing procedures and analysis criteria, and the specific matrix of testing planned for each concept. Test planning will be based on results of predictive data, previous test and correlation experience, and with respect to the task objectives.

The test plan will be submitted to the NASA task manager for concurrence at least two weeks prior to the start of testing. Testing and data analysis will proceed upon plan approval.

5.2.1.9 Final Combustor Concept and Simplified Hardware Evaluation. Based on the component rig test evaluations, a final combustor concept shall be selected. This selection and pertinent criteria will be submitted to the NASA task manager for concurrence. Upon approval, a work and cost plan will be prepared for experimental testing of the final combustor concept to determine the performance and emissions potential at conditions expected to be encountered by advanced small gas turbine engines beyond the year 2000. Analytical and testing results will be utilized extensively in defining an appropriate test plan. Testing will be conducted primarily for concept validation, and will take the form of simplified combustor rig or advanced small core engine testing.

5.2.1.10 Final Oral Review. An oral review will be conducted at NASA Lewis Research Center.

At the conclusion of the task efforts, all work performed will be documented. A final technical report will be submitted to the NASA task manager at NASA Lewis.

5.2.2 Program Schedule

This task program consists of a concept definition and analytical modeling phase, a rig and engine combustor test and performance evaluation phase, and a final selection and test planning phase. This program is shown schematically in Figure 5-16. Each concept will be independently analyzed, rig-tested, and engine-tested. This program provides a logical, high-payoff approach to evaluate advanced low emission small turbofan combustors for commercial application.

Williams International is well experienced in advanced combustor development programs and understands the types of challenges encountered in resolving combustion technology issues. The program master schedule is shown in Figure 5-17.

The first task of the program will define the initial combustor concepts, based on task objectives, and generate preliminary working concept designs for modeling analysis. Advanced CFD modeling techniques will be employed to generate estimates of individual concept performance and provide data for structural and thermal evaluations. Assumptions of future emission regulations will be made and included in the concept evaluation process. Concept testing requirements will be determined and a test plan will be developed.

The second task prepares the test component and rig design, fabrication, test engine assembly, and development testing which will yield information to substantiate modeling correlation and final concept evaluation data.

The rig and engine system design and operation will be conducted similar to Williams International's past successful combustor development programs. The test requirements, rig design, and test plan will be tailored to the specific requirements of this task.

The ROM cost for this activity is $1.3M in first quarter CY96 dollars.

All rig and test hardware will be produced through simultaneous engineering methods and produce quality test hardware. During the testing phase of the program, Williams International's experience in rig installation, testing and engine combustor development testing will contribute to successful results. The components will be tested in accordance with a mutually agreed upon test plan. Reporting of the results will include periodic oral reports and a final document. The final concept evaluation will be summarized by a recommended full scale engine test validation plan.

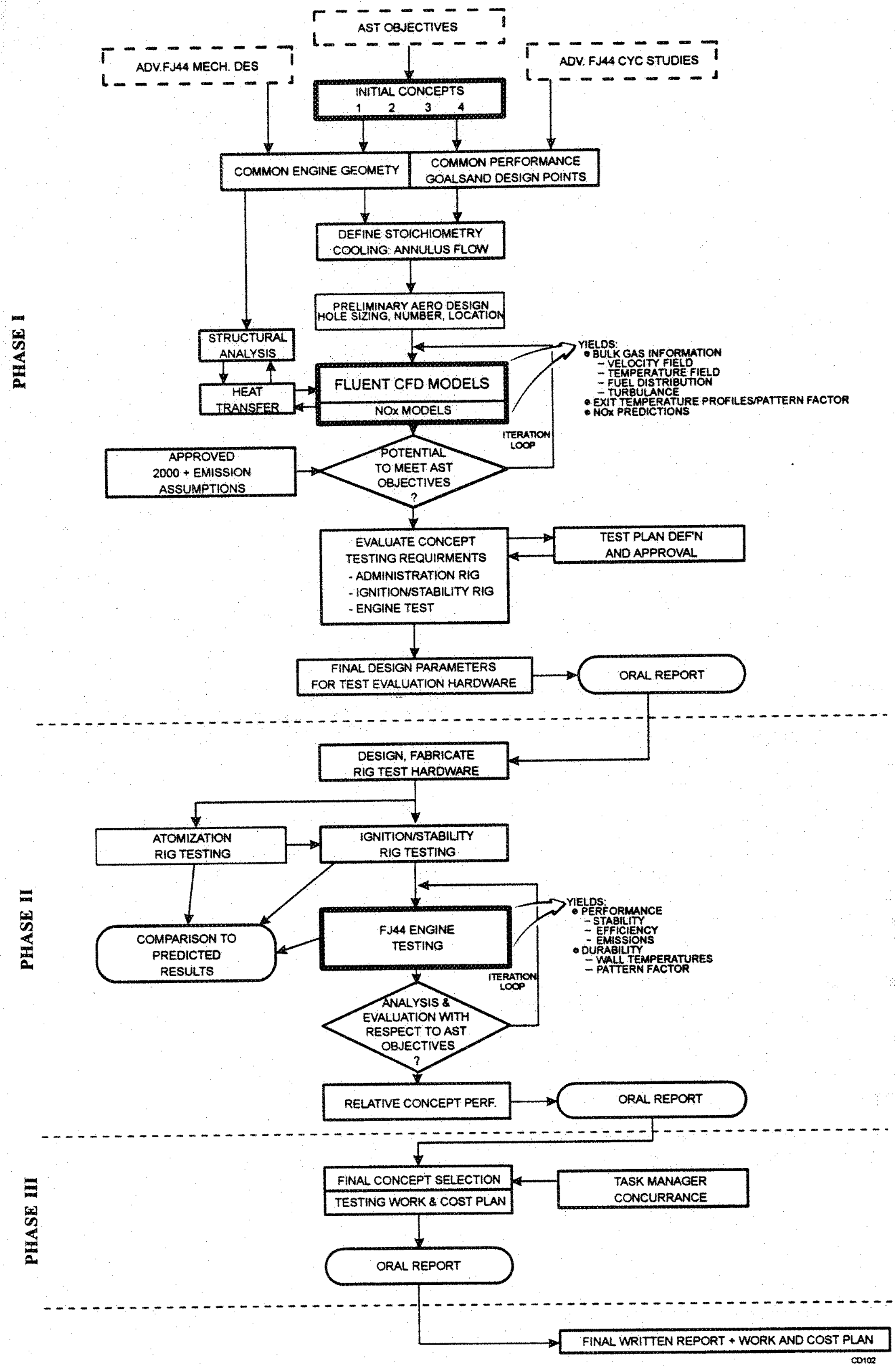

Figure 5-16. Low Emissions Combustor Program Plan

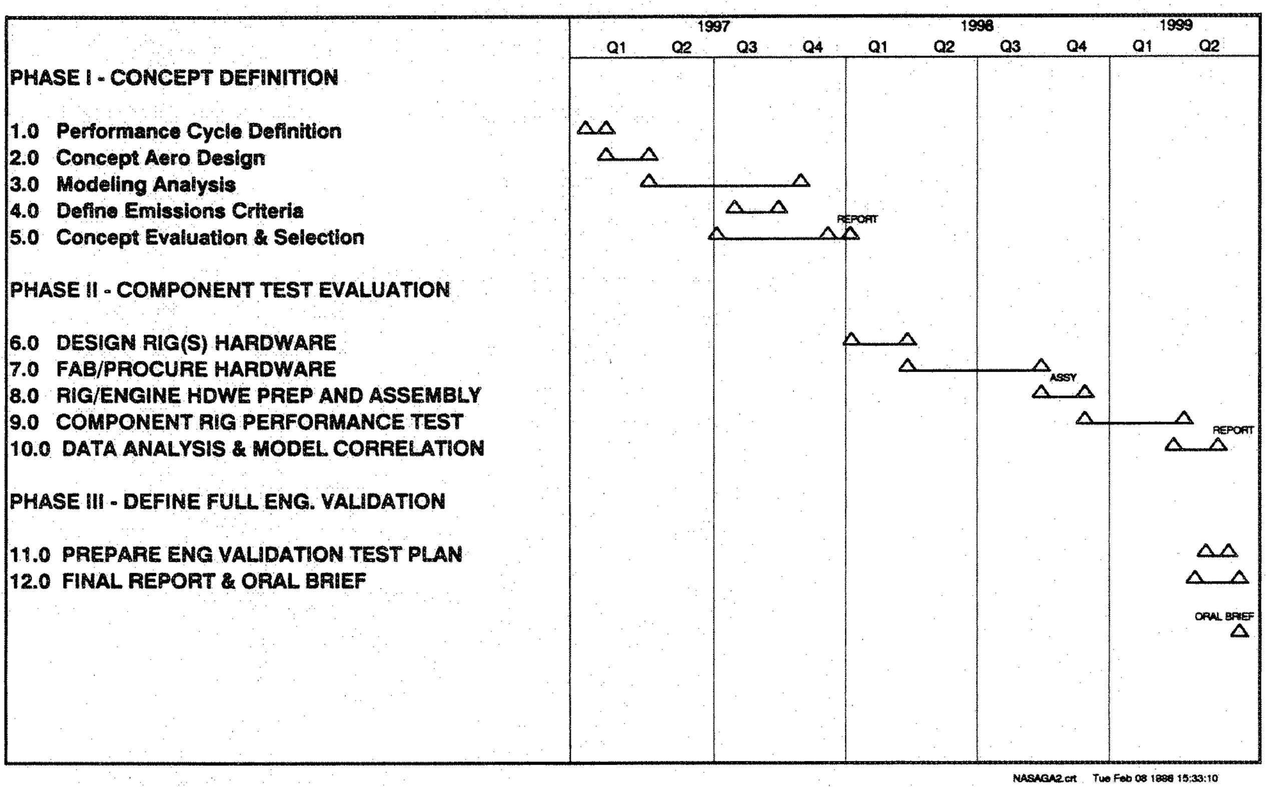

Figure 5-17. Low Emissions Combustor Technology Development

5.3 ADVANCED TECHNOLOGY NOISE REDUCTION PLAN

The principal objective is to define and plan technologies for the improved aerodynamic performance and reduced noise associated with commuter/regional aircraft powerplants. These technologies will address reducing the noise levels of the turbofan engine configuration only. New nozzle geometries will be defined that will feature good installed aerodynamic performance at cruise, and result in jet noise reduction at takeoff. Additionally, the inlet fan noise spectrum will be investigated for noise reductions to lower the EPNdB levels for ground handling personnel. The noise reduction goal is a 3 to 6 EPNdB relative to a current installed FJ44-1A engine, while minimizing loss to overall performance levels.

5.3.1 Development Plan

The scope of the plan will include defining the noise of the baseline inlet and nozzle configuration, the FJ44-1A, and through analytical trade studies, the preliminary design of several concepts will be conducted. The viability of the concepts to achieve the performance and acoustic objectives, as well as weight and cost impact, will be assessed. Analysis codes will be developed and calibrated with both performance and acoustic data from the baseline engine. Existing or newly developed codes may be used in these analyses of advanced technology designs. Combined with existing data bases of inlet and nozzle performance and acoustic characteristics, these codes will be used in the design of the candidate configurations with significantly improved characteristics.

Because of the size of the FJ44 engine, full scale components can be fabricated for component testing that will allow detailed performance and realistic noise data collection. Where appropriate, performance evaluation through test of scaled models to facilitate the selection of down selected concepts for the final full scale tests will be conducted.

A plan for the final performance and acoustic benefits will be developed and documented. The final development plan will consist of:

1. A detailed breakdown of the work tasks required for the design, fabrication, instrumentation, testing, evaluation, and reporting of results. The selection of the test facilities, and the coordination, design and fabrication of any facility unique hardware/adapters will also be included. Available NASA or other Government facilities will be included in the assessment.

2. A detail test plan will be prepared and submitted for approval. It will contain a test matrix defining the test conditions, test parameters, and test sequence for the model/full scale test articles.

3. A detailed schedule showing the time required for each task and major milestone.

4. A cost breakdown for the test program, covering all costs including any test facility charges to be incurred.

The most attractive noise reduction configurations, as determined from the component rig/engine tests can then be transitioned directly into a FJ44-2X turbofan engine for installed evaluation of both performance and acoustic measurements. An example of the type of follow-on program anticipated is shown in Figure 5-18.

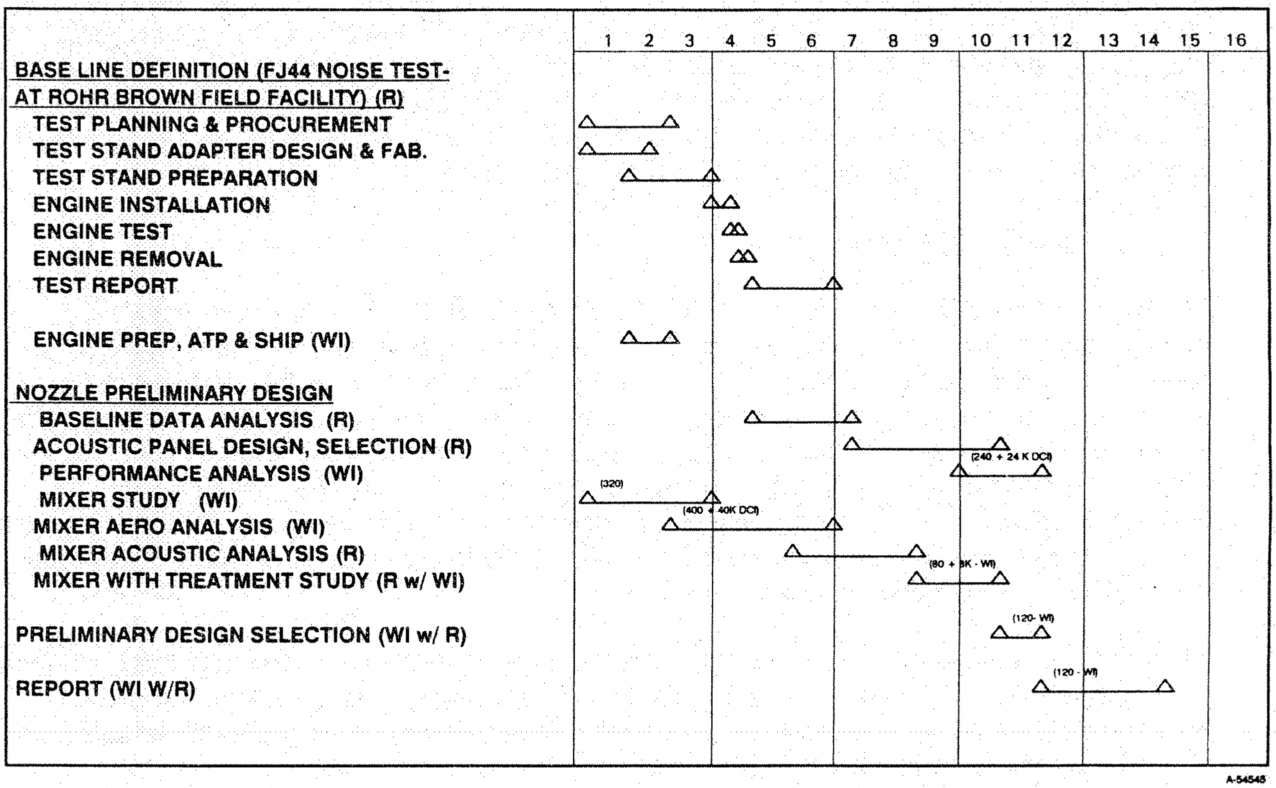

Figure 5-18. Noise Reduction Technology Plan - Full Engine Test Validation

5.3.2 Program Schedule

The above development plan will consist of five phases including the original baseline acoustic/performance assessment, the component design criteria and concept candidates, downselecting of candidates for further rig/engine test evaluation, fabricating hardware and conducting the component test evaluation and documenting the program results. The specifics of each program phase is as follows:

Phase I: Baseline Assessment - The first task will define the baseline characteristics for inlet and exhaust acoustic noise levels of todays small turbofan engine. The FJ44-1A will serve as the baseline for this activity since it has an existing database. Other engine acoustic data will be utilized where available.

Phase II: Noise Reduction Technology Criteria and Selection - After assessment of the baseline acoustic levels, and definition of noise reduction concepts for the inlet and exhaust, the design criteria shall be established to achieve the target noise reduction (3 to 6 EPNdB). A review of existing analytical tools to be used or developed will be conducted and design procedures will be established.

Phase III: Downselection of Candidate Concepts for Evaluation and Detail Design - A criteria for the downselection of the noise reduction candidates defined above will be developed and the most promising concepts chosen for further component test evaluation. The results of the downselection for the inlet and exhaust noise reduction candidates will be reviewed with the NASA program manager for concurrence. After NASA approval, the detail design of the test articles will be conducted. The component test facilities will also be selected and any required test adapters or special test equipment will be identified.

Phase IV: Fabrication and Component Test - The required component hardware shall be fabricated/procured for each of the test articles. Any special test equipment shall be procured. A detail test plan describing the test article(s), test facility, test procedures, data acquisition procedures, and test matrix for the component rig tests will be prepared and submitted to NASA for approval. Each of the noise reduction components will then be tested.

Phase V: Final Report and Briefing - The results of the above four phases shall be documented in a final contractor-format report. This report will include the details of a follow-on, full-up engine test validation plan. The final report shall be submitted to the NASA program manager for approval. A final oral briefing will also be presented to NASA

The schedule for this activity is shown in Figure 5-19. The ROM cost for this activity is $1.2 million in first quarter CY96 dollars.

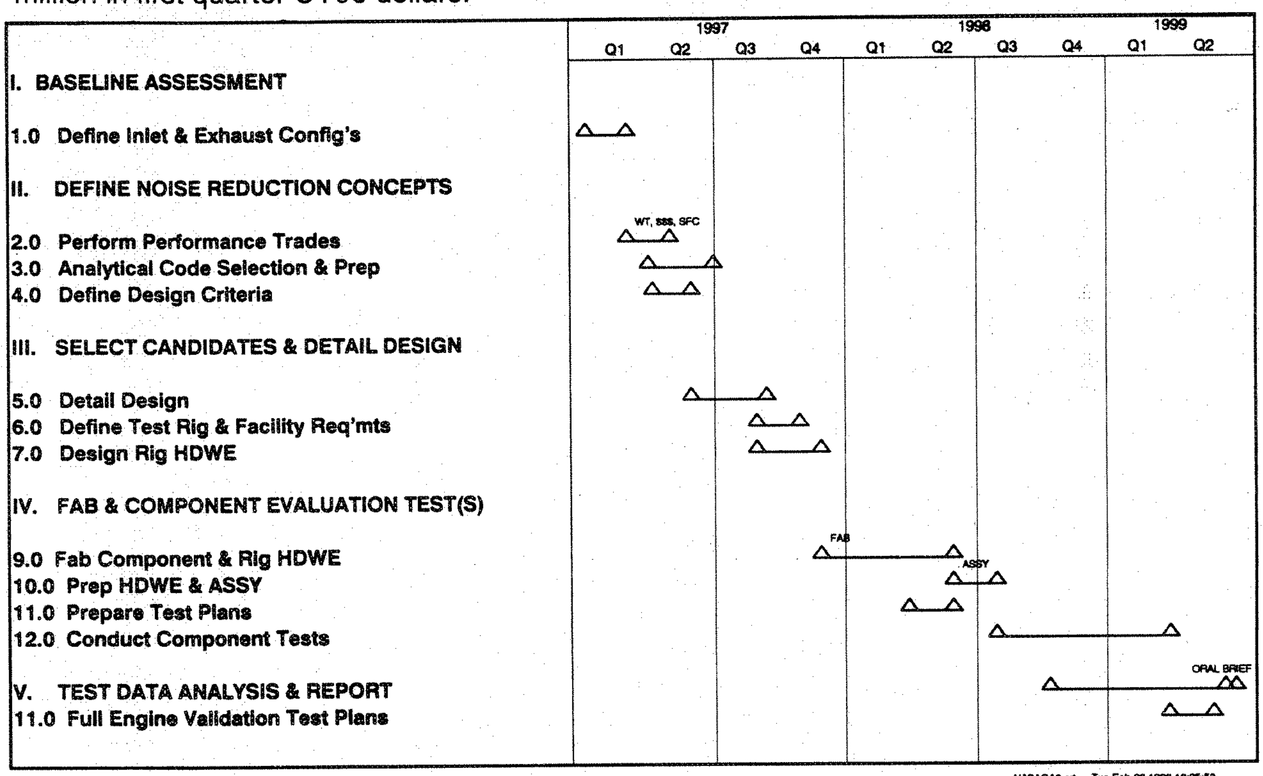

Figure 5-19. Advanced Technology Noise Reduction Plan

6.0 NEW TECHNOLOGY

In accordance with Section F.3, Reports of Work, this section addresses patentable and nonpatentable new technologies. In the performance of this contract there were no new technology discoveries or developments in either category of:

- Patentable inventions
- Nonpatentable discoveries or inventions

APPENDIX A

COMMUTER AIRLINE SURVEY

COMMUTER AIRLINE SURVEY

Williams International, the gas turbine designer and manufacturer of the Low Cost, High Technology FJ44 Turbofan engine, is very interested in your reactions and comments to questions listed in this survey. The FJ44 turbofan engine has successfully demonstrated its competitiveness with turboprop's on the Cessna Citationjet with its record of best selling business jet for the last 30 months. As a private corporation and as part of a study contract with NASA, we have developed concepts for the Next Generation Commuter Aircraft. The concept involves providing the comfort of a business jet in a commuter with extended operational range up to 1000 miles. Several aircraft manufacturers have expressed genuine interest in pursuing these concepts. NASA is interested in revitalizing the general aviation market. The market focus for this activity is the 19 passenger commuter service. It is felt that an aircraft designed with both the commuter traveler (convenience, comfort) and operator desires(DOC, profitability, safety, maintenance, increased range) will provide a means for improved travel, new jobs, and greater profitability for the Commuter Airlines.

This survey is to solicit your comments on the Next Generation 19 Passenger Commuter aircraft. Responses will be treated as anonymous for the NASA study. ***You are respectfully requested to return your response, via FAX within 5 days to be included in our NASA study results. Late responses are also very much of interest, but will not be part of the NASA study.***

1. Would you be interested in a 19-passenger aircraft that would provide your passengers with greater comfort (32 inch seat pitch, wide body cabin with stand up aisle separating window seat on one side and aisle and window seats on the other side)?

   YES_____ NO ____ Comment ___________________________

2. Would you be interested in a 19-passenger aircraft that would add 1 to 2 more trips per day to your current service?

   YES ____ NO ____ Comment ___________________________

3. Would you be interested in a 19-passenger aircraft that has the convenience and operating costs of today's turboprops, but with the low noise and performance of turbofan engines?

   YES ____ NO ____ Comment ___________________________

4. Would you be interested in a 19-passenger aircraft that would provide a shorter Balanced Field Length (BFL) take off capability?

   YES ____ NO ____ Comment ___________________________

5. Would you be interested in a 19-passenger aircraft that has the Rate of Climb and operational altitude of a turbofan powered regional jet (4000 fpm ROC, 350 FL or 1300 fpm ROC and 220 FL with engine out)?

   YES ____ NO ____ Comment ___________________________

6. If all of the above could be obtained for an aircraft acquisition cost of slightly higher than today's turboprop ($5M-to-6M), would you be interested?

YES ____ NO ____ Comment ____________________________

7. What if the engines were flat-rated for maximum take off power, No WAT limit (operate on a 100°F day at 5000 ft altitude without off loading passenger, payload or fuel) , and provided an engine out safety climb ceiling of FL 220. Is this significant to the success of your business operation?

YES ____ NO ____ Comment ____________________________

8. What if the above aircraft had three main engines, where one could be used as an APU for ground cabin air conditioning service. Would that be a concern if you were shown that the operating cost were less than today's turboprops?

YES ____ NO ____ Comment ____________________________

9. Would you be interested in a Commuter Aircraft that would provide all of the above, plus extend your Block Speed to allow service to cities up to 1000 nautical miles with today's Block times?

YES ____ NO ____ Comment ____________________________

10. Would you or your management be interested in hearing more about the Next Generation 19-Passenger Commuter aircraft characteristics and capabilities?

YES ____ Please contact: ____________________________________

NO ____

11. Do you have any comments on what you think the Next Generation Commuter aircraft should have with respect to the propulsion system?

____
____
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____
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Your time and consideration in answering the above questions is appreciated. If you would like the results of the survey, please indicate in the above comment section or feel free to contact Williams International directly at (810) 960-2582 or FAX (810) 624-5345

PLEASE FAX YOUR RESPONSE TO (810) 624-5345
ATTN: NEW BUSINESS DEV

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13. ABSTRACT ***(Maximum 200 words)***
This final report addresses the following topics: Market Impact Analysis—(1) assessment of general aviation, including commuter/regional, aircraft market impact due to incorporation of advanced technology propulsion system on acquisition and operating costs, job creation and/or manpower demand, and future fleet size; (2) selecting an aircraft and engine for the study by focusing on the next generation 19-passenger commuter and the Williams International FJ44 turbofan engine growth. Propulsion System Analysis—Conducted mission analysis studies and engine cycle analysis to define a new commuter mission and required engine performance, define acquisition and operating costs and, select engine configuration and initiated preliminary design for hardware modifications required. Propulsion System Benefits—(1) assessed and defined engine emissions improvements, (2) assessed and defined noise reduction potential and, (3) conducted a cost analysis impact study. Review of Relevant NASA Programs—Conducted literature searches using NERAC and NASA RECON services for related technology in the emissions and acoustics area. Preliminary Technology Development Plans—Defined plan to incorporate technology improvements for an FJ44-2 growth engine in performance, emissions, and noise suppression.

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