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CONCEPTUAL DESIGN OF A V/STOL LIFT FAN COMMERCIAL SHORT HAUL TRANSPORT - SUMMARY

by V/STOL Aircraft Advanced Engineering Group

Prepared by
MCDONNELL AIRCRAFT COMPANY
MCDONNELL DOUGLAS CORPORATION
St. Louis, Mo.
for Ames Research Center

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16. Abstract

Conceptual designs of V/STOL Lift-Fan Commercial short-haul transport aircraft for the 1980-85 time period were studied to determine their technical and economic feasibility. Engine concepts studied included both integral and remote fans. The scope of the study included definition of the hover control concept for each propulsion system, aircraft design, aircraft mass properties, cruise performance noise, and ride qualities evaluation. Economic evaluation was also studied on a basis of direct operating cost and route structure.

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FOREWORD

McDonnell Aircraft Company (MCAIR), a division of McDonnell Douglas Corporation, conducted a study entitled "Advanced Lift Fan V/STOL Aircraft System Study" in 1969-1970 under Contract NAS2-5499. The results of this study are presented in Reference 1. Volume I of Reference 1 presents the Model 253 V/STOL Research Aircraft, and Volume II presents the Program Plan and Budgetary Costs. An extension to Contract NAS2-5499 was awarded in July 1971 covering the period from July 1971 to mid-1972 for the purpose of updating the Model 253 V/STOL Lift Fan Research Transport study (Part I) and exploring Conceptual Design of a V/STOL Lift Fan Commercial Short Haul Transport (Part II) to assure that the proposed research aircraft will provide proper data leading to the future V/STOL commercial transport.

This work is reported in Report MDC A1602, consisting of the following four volumes:

Part I Research Aircraft Study
- Volume I Update of Model 253
- Volume II Program Plan and Budgetary Price

Part II Commercial Aircraft Study
- Volume III Summary
- Volume IV Technical Data

A patent is pending for the Propulsion System Control herein called the Energy Transfer Control (ETC) System.

SUMMARY

Conceptual design studies of V/STOL Lift-Fan Commercial Transports based on the NASA defined advanced second generation lift-fan propulsion systems were accomplished. The engine concepts included the integral fan concept (ILF) and two versions of the remote fan concept (RLF). The engine for these two included a tip turbine fan powered by: (1) a turbojet gas generator and (2) a turbofan air pump. The aircraft were sized by the guideline mission requirements including 100-passenger payload, 400 nm stage length, and 0.75 M cruise speed.

The air pump propulsion system was eliminated early in the study because of excessive complication and noise.

All aircraft configurations using the RLF, gas generator propulsion systems feature gas interconnection of propulsion units for low speed control and safe operation in emergency conditions with a gas generator or fan inoperative. ILF configurations do not have interconnected propulsion units and use throttle modulation for low speed powered control. Lift symmetry in emergency engine-out conditions is obtained with ILF units symmetrically paired with respect to the aircraft center of gravity, so that an engine opposite the failed engine is also shut down.

Four, six, and eight engine RLF aircraft configurations and eight, ten, twelve, fourteen, and eighteen engine ILF configurations were developed. ILF configurations used either lift/cruise engines or turbofan engines for cruise. RLF configurations used lift/cruise engines exclusively for cruise.

Sufficient parametric design and performance analyses and layouts for each configuration were made within the guidelines to establish a basis for comparison and to narrow down the number of configurations within each family of aircraft. Contending configurations were continuously refined and evaluated until a best compromise aircraft was selected.

Return on investment which is dependent on direct operating cost, among other things, is of greatest influence in the selection of an aircraft by an airline customer. Aircraft initial cost, weight, dispatch reliability, maintenance and maintainability, terminal time in through-stop and turn-around route operations are factors having major effect on direct operating costs and thereby return on investment. The number of engines installed in an aircraft has important effects on all of these parameters.

The advantage of interconnected propulsion units is clearly apparent in curves plotting gross weight versus number of engines for aircraft configurations with and without engine interconnection. The penalty incurred without interconnect results in a very steep upward slope of the line as number of engines is reduced as compared to the interconnected configuration. This results from the need to retain thrust symmetry with the loss of an engine and corresponding shutdown of a symmetrically opposite engine. The emergency thrust required of the remaining engines for lift and control is amplified. Therefore, as number of engines reduces, the propulsion system size and weight increase more rapidly for aircraft without interconnect as compared to aircraft with interconnect.

When engines are interconnected, propulsion system thrust to weight ratio is increased additionally through use of Energy Transfer Control. With the use of this system the gas generator portion of the engine is sized by the nominal steady state lift required by the guidelines. Nominal control excursions are accommodated by the gas generator without an increase in size. The resulting smaller gas generator provides greater cruise fuel economy. These three effects combine to reduce power plant plus fuel weight sufficiently to more than overcome the weight of interconnect hardware and thereby reduce gross weight of aircraft using interconnect as compared with non-interconnected propulsion systems.

With the importance placed on reduction of engines for commercial aircraft, the compromise of increased gross weight with reduction in number of engines becomes acceptable for the interconnected aircraft. The compromise in increased gross weight is considered unacceptable for reducing the number of engines in a non-interconnected aircraft. A penalty equal to a gross weight increase of 15% is incurred in reducing from 12 to 8 engines in the ILF configuration compared to only an 8% increase in gross weight with a decrease from 12 to 6 engines in the RLF configuration.

For the above reasons, plus the fact that a qualitative analysis shows it superior, the 6 engine RLF aircraft using 2 lift/cruise engines is selected as the best compromise to satisfy the requirements for the future V/STOL commercial transport.

A study was made which varied RLF fan pressure ratio from the ground rule 1.25 value to 1.35. The related 6 engine RLF configuration with a fan pressure ratio of 1.35 shows 6% reduction in gross weight and 5% reduction in direct operating cost. Noise signature is increased 2 PNdB. The 95 PNdB noise footprint area is approximately 12 acres greater. The study indicates that a 4 engine aircraft configuration is a distinct possibility if pressure ratio is allowed to increase, particularly in the case where it is increased for the cruise mode. The fewer number of engines make it more acceptable on an operational basis.

The selected future V/STOL transport aircraft characteristics can be confirmed with a near term research vehicle, the Model 253 reported in Volume I, which is large enough to provide valid and credible data contributing appreciably to the introduction of a V/STOL transportation system. The Model 253 research aircraft is approximately 80% of the overall size and 50% of the gross weight of the future aircraft and is very similar in configuration.

The direct operating costs (DOC) of the RLF and ILF aircraft are estimated to be in the range of 2.1 to 2.7 cents per available seat mile for the 400 nm VTOL mission and 1.7 to 2.2 cents per seat mile for the 800 nm STOL mission. These DOCs are quite sensitive to engine prices and engine maintenance cost estimates since for V/STOL aircraft the propulsion system is a larger percentage of the total aircraft both from a price and maintenance standpoint. Comparisons with current short-haul turbofan aircraft indicate that the incremental cost of VTOL capability will be between 0.50 to 1.00 dollar per aircraft mile, at 400 nm.

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NOTATION

C.G., CG, cg	center of gravity
CHI	Chicago
C_L	lift coefficient, lift/qs
CTOL	conventional takeoff and landing
DOC	direct operating cost
ENG	engine
ETC	Energy Transfer Control
fps	feet per second
g	acceleration of gravity
GW, W, WT	gross weight, lb
ILF	integral lift fan, non-interconnected
KTAS, KTS	true airspeed in knots
LAX	Los Angeles
L/C	lift/cruise
M	Mach number
NM, nm	nautical mile
NY	New York
O&D	origin-destination
OWE	operating weight empty
PAX	passenger
PSF, psf	pounds per square foot
q	dynamic pressure, psf
R_f	fan pressure ratio
RLF	remote lift fan, interconnected
rpm	revolutions per minute
S	wing area, square feet

SFC, sfc	specific fuel consumption
SFO	San Francisco
ST. MI., st. mi.	statute mile
STOGW	short takeoff gross weight, lb
STOL	short takeoff and landing
t	time, sec, min, hours
T	gross thrust, lb
TOGW	takeoff gross weight, lb
T/W	thrust-to-weight ratio
V	velocity, fps, kts
V_{stall}, $V_{stall\ power\ off}$	power off stall speed, kts
V/STOL	vertical/short takeoff and landing
VTO	vertical takeoff
VTOGW	vertical takeoff gross weight, lb
VTOL	vertical takeoff and landing
WAS	Washington
W/S	wing loading, PSF, psf
θ	deck angle, degrees, (Positive Nose Up)

1. INTRODUCTION

MCAIR has investigated and analyzed each of the major V/STOL lift system concepts in depth during the last ten years. MCAIR strongly supports the NASA conclusion that the V/STOL lift-fan concept offers many attractive advantages and has the potential of being the best overall system for V/STOL transport type aircraft for commercial and military applications within the short-haul spectrum.

In support of this conclusion, MCAIR has conducted extensive analytical studies and testing, including NASA funded work, in the areas that influence installed lift-fan propulsion system performance. This effort resulted in deriving an integrated propulsion/control/airframe V/STOL system that is considered necessary for an acceptable future V/STOL transport aircraft.

The overall plan concerning V/STOL transports has the near-term objective of obtaining a V/STOL lift-fan research aircraft and a long-term objective of advancing lift-fan technology to provide confidence for design of a 1980-85 time period V/STOL lift-fan transport. Consequently, MCAIR entered into additional contracted effort with NASA-Ames to advance these objectives.

Part II of the NASA contracted effort consisted of conceptual design studies of V/STOL Lift-Fan Commercial Transports based on the NASA defined advanced second generation lift-fan propulsion systems. Part II is intended to define long-term research requirements and provide long-term visibility to help insure that the best near-term research transport has been selected in the Part I activity.

This report is Volume III of four volumes and summarizes the work accomplished under Part II. Volume IV presents substantiating data and analyses to verify the conclusions presented in Volume III.

2. STUDY OBJECTIVES AND GUIDELINES

The objectives for the commercial aircraft study were to:

- o Investigate conceptual designs of quiet V/STOL lift fan commercial short haul transports
- o Assess suitability of near term research aircraft to provide confidence for design of a V/STOL lift fan transport aircraft for 1980-1985

The three major aircraft sizing guideline parameters having the greatest effect in establishing aircraft size and gross weight are:

Design payload - 100 passengers
Design range - 400 nautical miles VTOL
Design cruise speed - 0.75 Mach number

Guidelines contributing to aircraft configuration and size are:

Noise goal - 95 PNdB at 500 feet (takeoff power)
Failure philosophy - engine out capability - gas generator or fan
Ride qualities - gust sensitivity 0.0295 g/fps
Control criteria - engine/fan sizing

Ninety-five PNdB is a difficult goal to meet. Aircraft size is affected if rigid attainment of the goal is sought. Maximum noise reduction effort results in low fan pressure ratio and maximum acoustic treatment leading to reduced fan thrust and larger fan size, all contributing to increased aircraft gross weight and size.

The aircraft are designed to accept an engine component failure (gas generator or fan) in any flight mode and continue in controlled flight.

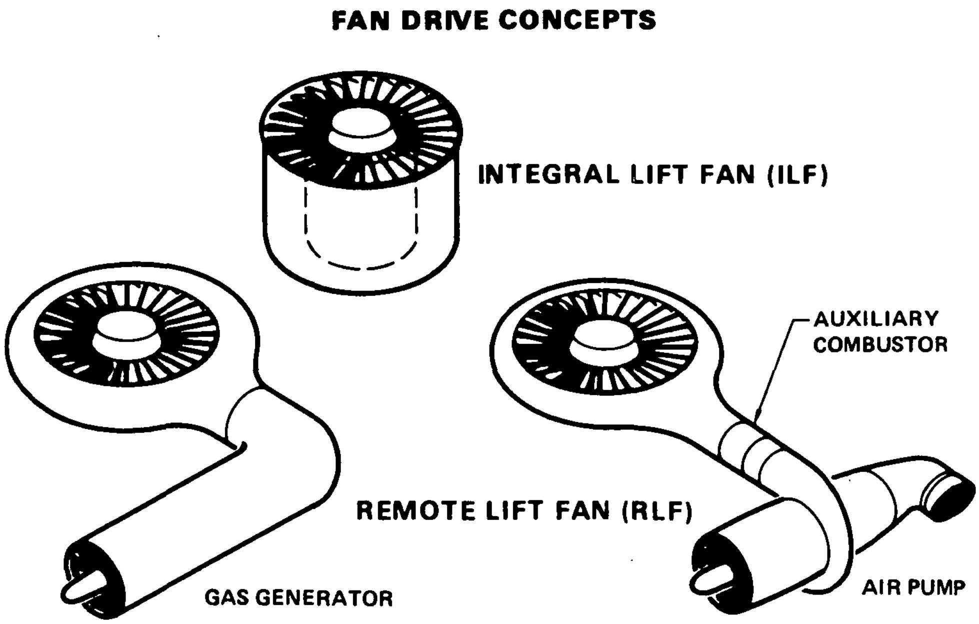
The gust sensitivity factor dictates maximum wing loading.

The control powers required to meet the guideline aircraft angular accelerations have a significant effect on propulsion system sizing. Most of the RLF aircraft using interconnected propulsion systems for control permitted the propulsion components to be sized for normal lift and control criteria. All of the ILF aircraft required propulsion systems sized for emergency, engine-out, lift and control requirements.

The two-aisle cabin selected by MCAIR for the study also contributes to aircraft gross weight and size. Although not specifically required by the guidelines, the two-aisle arrangement was selected to be in consonance with the strong recommendation in the guidelines to provide a level of comfort equal to that provided in the tourist section of modern commercial jet airliners.

The three lift fan propulsion concepts considered in the commercial V/STOL transport study are illustrated below.

Figure 2-1

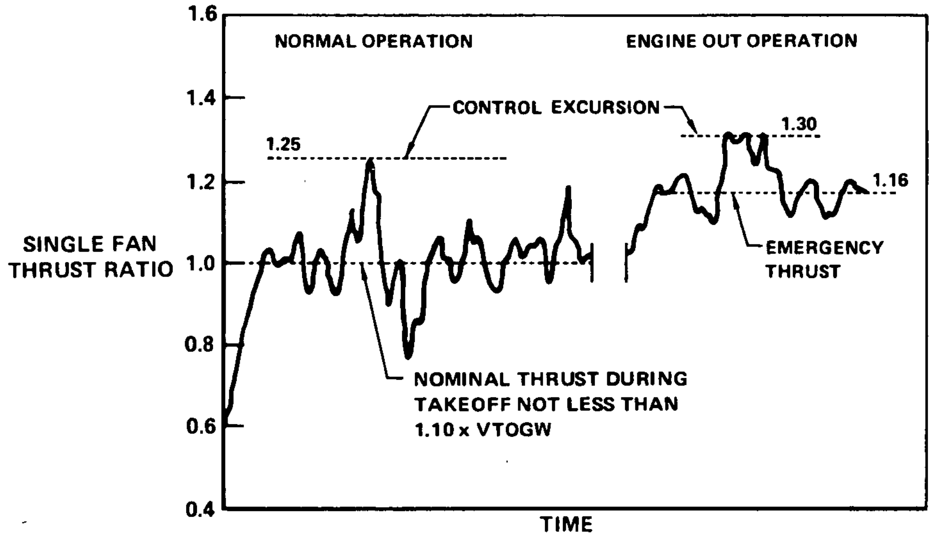


The ILF is similar in concept to current turbofan engines in which the fan supercharges the core gas generator. The fan turbine is coaxial with the core gas generator and is located immediately downstream of the core turbine exit. The core and fan turn in opposite directions. The RLF concepts have the fan turbine located on the fan perimeter. In the gas generator RLF configuration shown at the lower left, all of the gas generator exhaust is ducted to the closely coupled fan turbine. In the air pump RLF system, only the cold bypass flow of the turbofan gas generator is used in powering the remote fan; an auxiliary combustor is used to produce a high-enthalpy gas (equivalent to that of the gas generator exhaust) to drive the fan turbine. The gas generator core exhaust has a separate exit nozzle.

The engine sizing guidelines were established by NASA. They are depicted in Figure 2-2, which is a reproduction of the guidelines presented in ASME Paper 72-GT-65, Reference 2.

Figure 2-2

ENGINE SIZING GUIDELINES



The normal control thrust excursion allowed without requiring a power plant size increase must be less than 25% of the nominal fan thrust design level. Similarly, the emergency thrust allowable increase is 16% without attitude control application, and 30% with application of attitude control, without requiring a propulsion system oversize. These guidelines were applied to the configuration studies.

3. SELECTION PROCESS

Preliminary designs of representative configurations of aircraft using the ILF and RLF propulsion systems were developed. Aircraft derived from the RLF (Air Pump) propulsion system were eliminated from the selection process early due to excessive complication and excessive noise signature.

Aircraft configurations using the RLF propulsion system embodying the tip turbine driven fan powered by a gas generator had the benefit of considerable previous study. These studies had led to the Model 253 research aircraft. Configuration variations then stemmed from the Model 253 and therefore were not as extensive as the configuration variations using the ILF propulsion system. Many configurations and engine arrangements using the ILF propulsion system were considered to fully explore the trade-offs to assure that near optimum advantage was achieved for the propulsion system.

Sufficient parametric design and performance analyses and layouts for each configuration were made within the guidelines to establish a basis for comparison and elimination of configurations within each family of aircraft. Contending configurations were continuously refined until a best compromise aircraft was selected.

3.1 STUDY MATRIX

The initial study matrix was set up to evaluate aircraft using the three proposed propulsion systems. The parameter variations indicated in Figure 3-1 were intended to lead to the best compromise aircraft in each category.

Figure 3-1

INITIAL STUDY MATRIX

	R_f OPERATING	W/S	TOGW	ENGINES
TURBO TIP FAN (ENGINE DRIVEN) VT 102 SERIES	1.2 1.25 1.35	80 100 120	70,000 85,000 100,000	4 6 8
TURBO TIP FAN (AIR PUMP DRIVEN) VT 103 SERIES	1.2 1.25 1.35	80 100 120	70,000 85,000 100,000	{3, 6} 4 8
INTEGRAL FAN (LIFT ENGINE) VT 104 SERIES	1.2 1.25 1.35	80 100 120	80,000 100,000 120,000	8 & 10* 12 & 14* 18*

*INCLUDES 2 CRUISE ENGINES

Early elimination of the air pump reduced the propulsion system configurations to the integral lift fan (ILF) and the remote lift fan (RLF) types. The reduced matrix, Figure 3-2, was selected to investigate the:

Type of propulsion system
Number of propulsive units
Airplane design gross weight
Airplane design wing loading
Direct operating cost

Figure 3-2
Revised Study Matrix

	R_f DESIGN PRESSURE RATIO	W/S (PSF)	TOGW (LB)	ENGINES (NO.)
INTERCONNECTED RLF VT102 SERIES	1.25	80 100 120	85K 100K 115K	4 6 8
NON-INTERCONNECTED ILF VT104 SERIES	1.25	80 100 120	80K 100K 120K	8 & 10* 12 & 14* 18*

*Includes 2 Cruise Engines

The number of engines varied from 4 to 18 depending on the propulsion system type. The weight range was selected to bracket the airplane size for a 100-passenger payload, and the wing loading range was selected to permit evaluation of gust sensitivity, transition speed overlap, and cruise efficiency.

Target values of 100,000 pounds VTOGW and 100 psf wing loading were selected for initial configuration layouts to evaluate the influence of lift system arrangements on configuration design for both the ILF and RLF systems. A fan design pressure ratio of 1.25 selected by NASA, primarily to limit the noise characteristics, minimized the basic parametric study. A special study to determine the influence of fan pressure ratio variation on aircraft size and aircraft noise signature for the guideline mission was accomplished for the RLF aircraft and is reported in Section 8.

3.2 INTERCONNECTED FAN (RLF) AIRCRAFT

3.2.1 RLF AIR PUMP - Air pump configurations having four, six, and eight engines were investigated. Systems using lift/cruise fans and systems using air pump flow for cruise thrust were investigated.

Figure 3-3

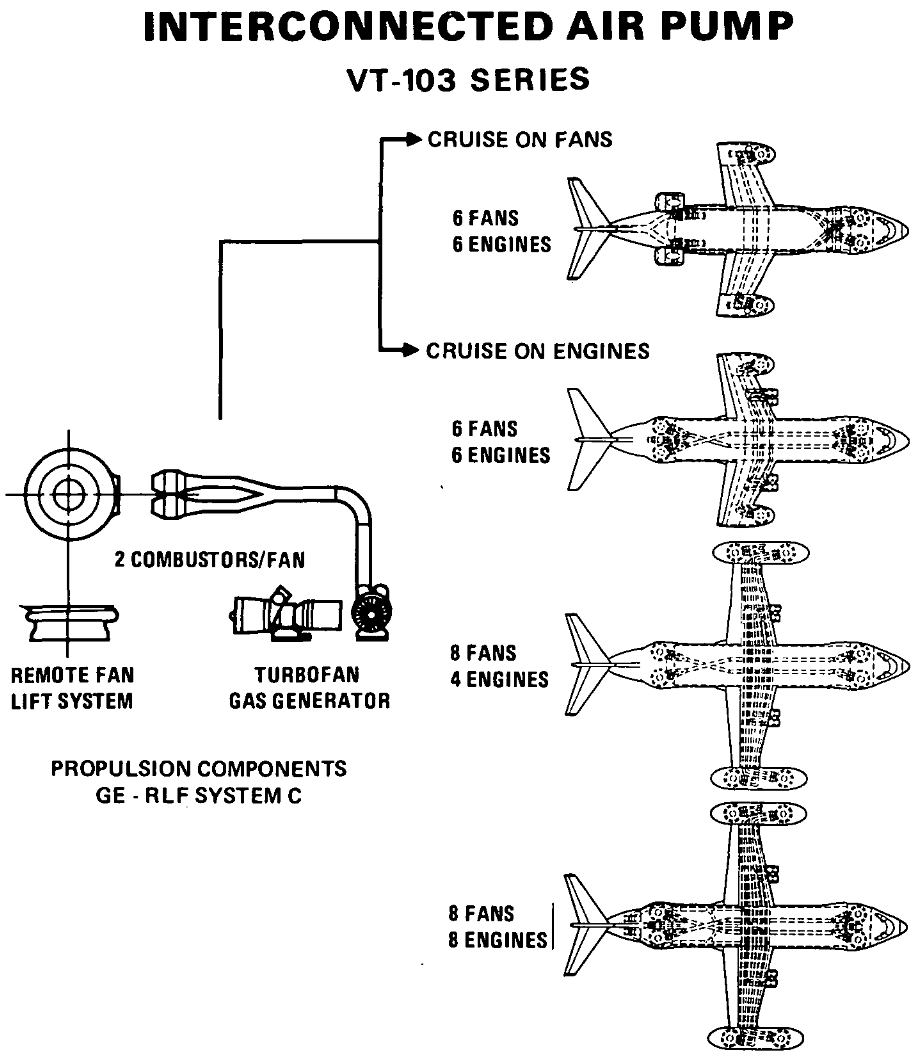


Figure 3-4 shows quantitative air pump and gas generator system comparisons. All air pump propulsion configuration items compared rate poorer than the gas generator system. Air or gas for powering tip turbine lift and lift/cruise fans must be at the same pressure ratio and energy level as provided by a turbojet gas generator in order to effectively power the fans. In the air pump concept the drive air is obtained from a high pressure ratio fan on the gas generator (turbofan).

Therefore this high pressure air is relatively cool compared to the turbojet turbine discharge gas and additional burning is required prior to entering the fan scroll in order to match the turbojet gas energy level. Thus the total fuel flow (air pump plus burner) required to generate the same gas energy level as the turbojet exhaust is excessive resulting in a high SFC in the lift or cruise flight mode.

An alternate to cruising with the lift/cruise fans is possible by diverting the high pressure drive air from the air pump through a cruise nozzle without the additional burning of fuel. However, this cruise configuration represents a very high fan pressure ratio cycle (low bypass ratio) in which a considerable mismatch exists between the core and the fan discharge pressure ratio. These conditions also result in a poor cruise SFC and also a high noise signature as shown.

Figure 3-4
RLF SYSTEM COMPARISON

	GAS GENERATOR	AIR PUMP	
	6 ENG	6 FAN 6 AIR PUMPS	8 FAN 4 AIR PUMPS
CRUISE MODE	LIFT/FAN	LIFT/FAN	JET NOZZLE
SFC (PPH/LB) M 0.7 AT 20K	0.85	1.15	1.05
FAN + ENG WT / GW	0.16	0.20	0.22
SEPARATE COMBUSTORS	0	12	16
TOTAL COMBUSTORS (INCL. ENGINES)	6	18	20
DUCT LENGTH (FT)	270	310	670
FLOW IN DUCT AT ZERO CONTROL (% DUCT LENGTH)	0	20	100

The air pump system was eliminated because of the following:

	<u>Increase*</u>
Extended duct system	115%
High cruise sfc	124% to 135%
Propulsion weight	125%
Number of combustors	300%
Noise - 500 ft sideline	+15 PNdB at transition

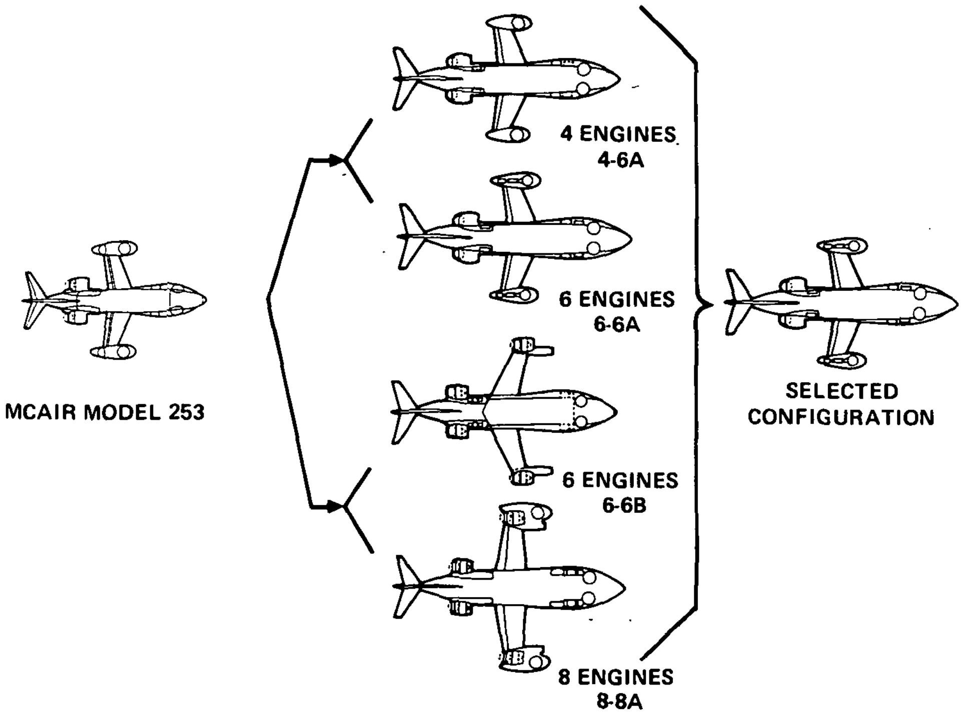
*Compared to the gas generator system

3.2.2 RLF GAS GENERATOR - The interconnected gas generator fan system VTOL study matrix (Figure 3-5) stems from the MCAIR Model 253 configuration. The Model 253 was developed as the result of many prior studies to adapt a VTOL fan system to various airframes. All RLF configurations feature gas interconnection of propulsion units for low speed control and safe operation in emergency conditions with propulsion units inoperative. For these functions the Energy Transfer Control (ETC) System as described in Section 8 is used.

Figure 3-5

INTERCONNECTED FAN SYSTEMS

VT102 SERIES



Preliminary designs of the candidate aircraft were prepared at the 100,000 pound gross weight level and wing loading of 100 psf as a representative size for comparative and selection purposes.

A quantitative and qualitative evaluation of significant characteristics of the four configurations resulted in selection of a best compromise aircraft using the RLF power plant. Figure 3-11, with accompanying explanations, shows the factors entering the qualitative evaluation.

Descriptions and plan views of the parametric aircraft follow (Figure 3-6 through 3-9).

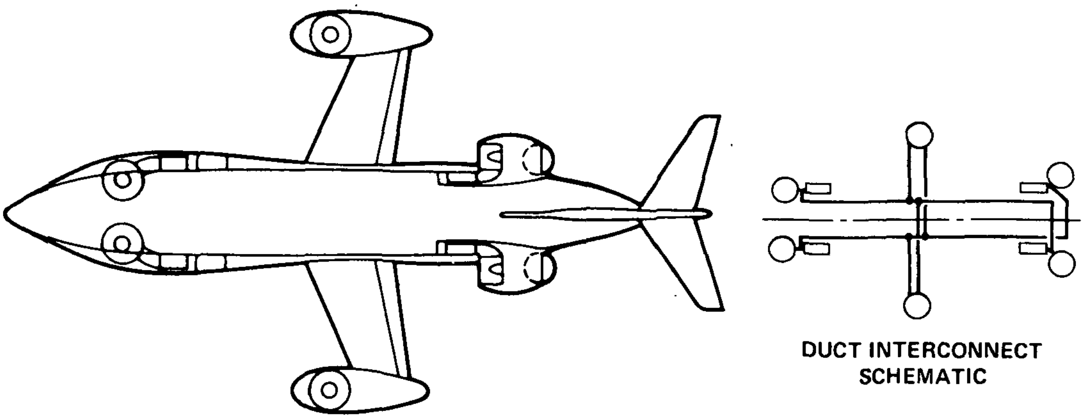
Figure 3-6

INTERCONNECTED FAN AIRCRAFT

VT102 RLF SERIES

4 ENGINES

4-6A



This configuration has two lift fan engines in the forward fuselage, two lift/cruise fan engines with rotatable hoods on the aft fuselage, and an associated lift fan in each wing tip pod. The lift fans located in the forward fuselage and wing tip pods have louvers for thrust vectoring. Thrust vectoring of the aft fuselage engines in the fore and aft direction is accomplished by extending or retracting the hood and laterally by hood rotation about the engine's longitudinal axis. The forward, left lift fan engine is interconnected with the aft, right lift/cruise engine with a branch interconnect supplying one-half of the fan power to each wing tip lift fan. The forward, right lift fan engine is interconnected with the aft, left lift/cruise engine with a branch interconnect supplying one-half of the fan power to each wing tip lift fan.

The aircraft attitude control in powered lift flight is obtained by modulating and deflecting the thrust of the lift and lift/cruise fans. The gas generators are connected in pairs, diagonally across the fuselage, with each pair supplying the power to two fuselage fans and half of the total power to each of the two wing fans. Since the gas generators are all located in the fuselage, the aircraft roll inertia is lower than with gas generators located at the wing tips.

The aircraft roll attitude is controlled by channeling additional gas generator power to one of the wing fans, while the thrust of the other wing fan is reduced by thrust spoiling. Similarly for pitch control, additional power is supplied to the two fans at one end of the fuselage, while thrust spoiling reduces the thrust of the opposite fuselage fans. For either pitch or roll control, the variation in gas generator power distribution is accomplished by the Energy Transfer Control (ETC) system (presented in Section 8), and thrust spoiling is performed by the spoilage segment in the hood of the rear fuselage fans and by staggered louvers in the other fans. For aircraft yaw control the thrust of the fuselage fans is deflected sideways by means of louver deflection in forward fans and hood rotation in the rear units.

In the event of gas generator failure in powered lift flight, the power output of the remaining generators is increased by advancing the throttle. The ETC system distributes the power from the gas generators to all fans so that the moment unbalance is minimized. For fan failure, emergency backup nozzles are located adjacent to the fans. If a fan fails, the ETC system distributes the gas generator power between the emergency backup nozzle and the remaining fans so that the upsetting moments are minimized.

The forward thrust component required for transition to cruise flight is generated by gradually retracting the hood of the rear fuselage fans and by rotating the louver assembly in the other fans. When the cruise conditions are reached, the forward gas generators, forward fuselage fans, and wing fans are shut off. Conventional aerodynamic surfaces are used for attitude control in cruise, and cruise thrust is provided by the two lift/cruise fans and the adjacent gas generators.

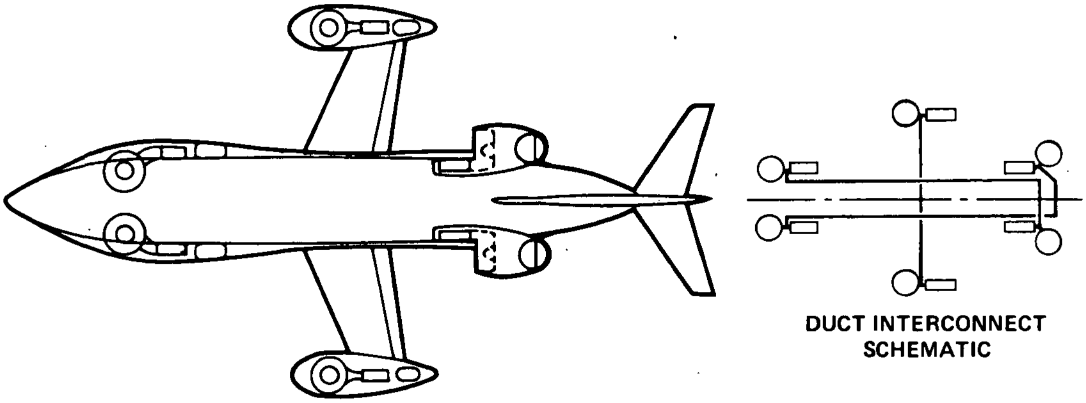
Figure 3-7

INTERCONNECTED FAN SYSTEM

VT102 RLF SERIES

6 ENGINES

6-6A



This configuration has two lift fan engines in the forward fuselage, two lift/cruise fan engines with rotatable hoods on the aft fuselage, and two lift fan engines in the wing tip pods. The lift fans located in the forward fuselage and wing tip pods have louvers for thrust vectoring. Thrust vectoring of the aft fuselage engine is accomplished by extending or retracting the hood and also by hood rotation about the engine's longitudinal axis.

The arrangement and functioning of controls in VT102-6-6A aircraft are essentially the same as that proposed for the Model 253 research aircraft. The pitch and roll control for powered lift flight is obtained by differentially modulating fan thrust. To provide the required thrust modulation, the fans and the associated gas generators are connected in pairs, using the ETC system to channel increased power to one of the fans while the thrust of the other fan is lowered by thrust spoiling. The two wing fans are paired in this way for roll control, and the four fuselage units are connected diagonally to provide two pairs of propulsion units for pitch control. The aircraft yaw angle is controlled by side deflection of fuselage engine thrust. The thrust of the rear fuselage engines is deflected by hood rotation, while louvers are used to deflect the thrust of the forward engines. The aircraft height is controlled by throttling the six gas generators, using a common throttle lever.

In the event of gas generator failure, the ETC system distributes the power from its paired gas generator equally to both fans, such that the moment imbalance is minimized. For fan failure, emergency backup nozzles are located adjacent to the fans. In a fan failure during powered lift flight, the ETC system distributes the power from both gas generators to the emergency nozzle and the remaining fan such that the nozzle and fan thrust levels are equal.

During transition to cruise flight, the thrust of the aft fuselage fans is slowly moved into the cruise position by retracting the hoods. Simultaneously, the thrust of the remaining four fans is vectored by rotating the cascaded louver assemblies. The thrust vectoring from vertical lift to the cruise direction diminishes the effectiveness of thrust and modulation for attitude control. However, since aircraft velocity is increased during this time, the conventional aerodynamic control forces replace thrust modulation in attitude control. When cruise velocity is reached, the forward fuselage and wing tip power units are shut off, and the power for cruise flight is provided by the two rear fans and gas generators.

The transition from cruise to powered lift flight is a reverse of the above sequence.

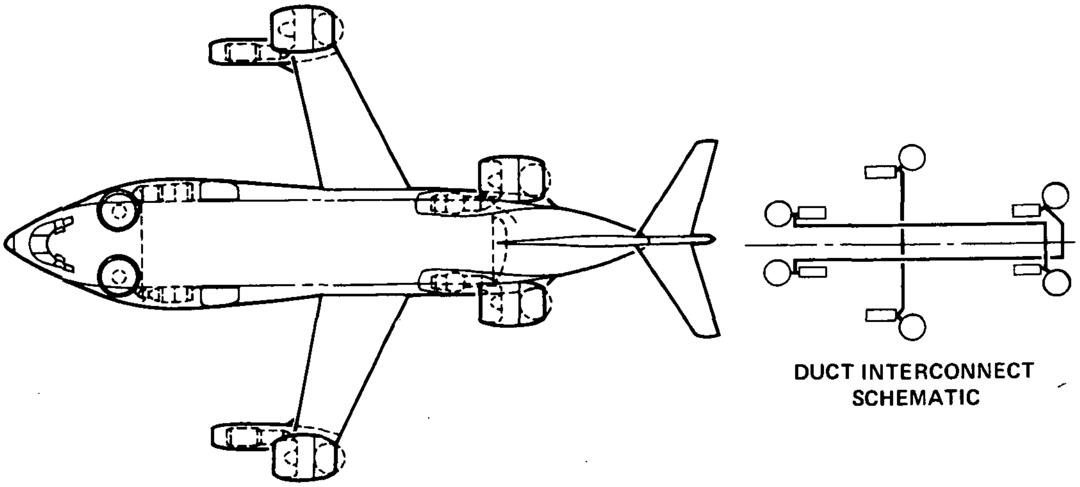
Figure 3-8

INTERCONNECTED FAN AIRCRAFT

VT102 RLF SERIES

6 ENGINES

6-6B



This configuration has two lift fan engines in the forward fuselage, two lift/cruise fan engines with rotatable hoods on the aft fuselage, and two lift/cruise fan engines with rotatable hoods in the wing tip pods. The lift fan engines located in the forward fuselage have louvers for thrust vectoring. Thrust vectoring of the aft fuselage and wing tip fan engines is accomplished by extending or retracting the hood. In addition the hoods on the aft fuselage lift/cruise fan engines can rotate about the engine's longitudinal axis for yaw control.

The main difference between 6-6B and 6-6A configurations is in the wing mounted propulsion units. The 6-6B wing units are lift/cruise fans with nested toroid thrust deflectors, while 6-6A has lift type wing units with louvered thrust deflectors. The wings in the 6-6B aircraft are swept forward so that the thrust application points for wing units can be located symmetrically with respect to the aircraft center of gravity.

The aircraft attitude and height are controlled in essentially the same way as in the 6-6A configuration, except that the thrust spoiling at the wing fans is performed by the spoilage segment in the hood and not by staggered louvers. The ETC system is used to control the power distribution of the gas generators in normal attitude control as well as in emergencies, and backup nozzles are used in the event of fan thrust failure.

The forward thrust component for transition to cruise flight is generated by retracting the hood of the four lift/cruise fans and by rotating the louver assemblies on the forward fuselage fans. When cruise conditions are reached, the forward fuselage fans and gas generators are shut off, and cruise power is provided by the remaining propulsion units at the wing tips and at the rear fuselage. Use of conventional aerodynamic controls is gradually phased in during transition, and in cruise flight only conventional aerodynamic controls are used.

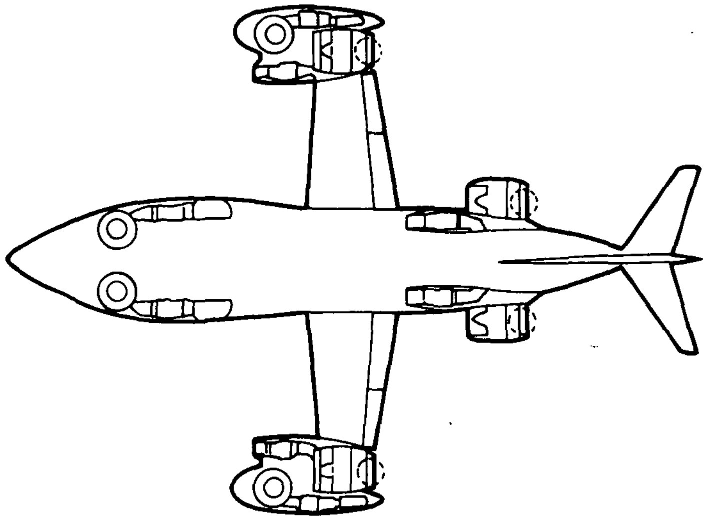
Figure 3-9

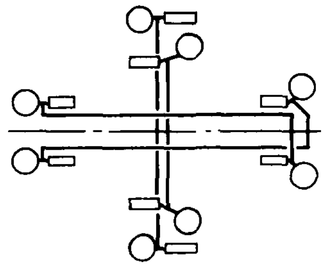
INTERCONNECTED FAN AIRCRAFT

VT102 RLF SERIES

8 ENGINES

8-8A





DUCT INTERCONNECT SCHEMATIC

This configuration has two lift fan engines in the forward fuselage, two lift/cruise fan engines with rotatable hoods on the aft fuselage, and two lift/cruise fan engines with rotatable hood plus two lift fan engines in wing tip pods. The lift fan engines located in the forward fuselage and forward wing tip pods have louvers for thrust vectoring. Thrust vectoring of the aft fuselage engine and aft wing tip pod is accomplished by extending or retracting the hood. In addition the hoods on the aft fuselage lift/cruise fan engines can rotate about the engine's longitudinal axis for yaw control.

Four pairs of propulsion units are used for attitude control in powered lift flight. Pitch and yaw control is provided by the four fuselage mounted units, connected diagonally across the fuselage. Attitude moments for roll control are generated by the four wing tip units; these are connected to form one pair of lift fan units and another pair of lift/cruise units. Each pair of propulsion units functions as the propulsion pairs in the six-engine aircraft, Figure 3-8. The ETC system is used to control the distribution of the gas generator power, and thrust spoiling is used to balance the net lift force and to increase the speed of response.

As in the six-engine aircraft, the transition to cruise flight is accomplished by vectoring the thrust of all eight propulsion units. When the aircraft reaches conversion velocity, the four lift fan propulsion units are shut off and cruise thrust is provided by the four lift/cruise fans. Only conventional aerodynamic control surfaces are used in cruise flight.

Significant physical, performance, and operational characteristics were determined for the candidate configurations and a comparative qualitative as well as quantitative evaluation of the configurations made. Figure 3-10 presents a summary of some of the most significant parameters from the analyses for comparison of configurations. Figure 3-11 summarizes the complete qualitative analysis followed by a discussion of the factors entering the analysis. Comparison of RLF configurations based on the 100,000 pound aircraft presented in this section provides a sufficient basis to make a proper selection of the best compromise RLF airplane. Payload and other characteristics are near enough to the mission requirements so that it is not necessary to exactly size the aircraft.

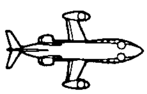
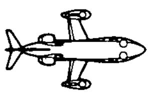
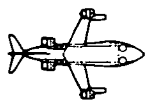
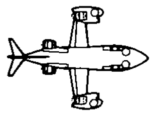
All configurations have lift systems that are distributed on the airframe such that lift and control requirements are matched efficiently without compromising engine-out safety. Neither normal lift and control regime nor emergency engine-out conditions require engine oversizing. Configuration 6-6A, cruising on two of six engines, requires engine oversizing to meet the cruise speed. The other configurations cruise on a larger percentage of installed power.

Figure 3-10

INTERCONNECTED FAN SYSTEM

VT 102 RLF SERIES

EVALUATION SUMMARY

CHARACTERISTIC	LIFT SYSTEM ARRANGEMENT			
	4-6A 	6-6A 	6-6B 	8-8A 
ENGINES	4	6	6	8
NOMINAL T/W (90°F INSTALLED)	1.10	1.24*	1.10	1.10
% MODULATION FOR CONTROL	19.2	24.9	22.8	24.0
PAYLOAD @ 100,000 LB G.W.	15,475	15,477	16,742	19,332
CRUISE MACH @ 20,000 FT	0.75 (0.82)**	0.75 (0.75)**	0.75 (0.84)**	0.75 (0.79)**
QUALITATIVE EVALUATION SCORE	60.5	61.5	54.5	56.5

*THE NOMINAL T/W OF CONFIGURATION 6-6A BECOMES 1.14 ON THE AIRCRAFT SIZED FOR THE MISSION.

**MAXIMUM POWER CAPABILITY.

Figure 3-11

INTERCONNECTED FAN SYSTEM
VT102 RLF SERIES

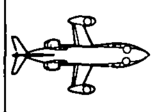
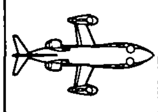
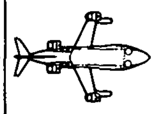
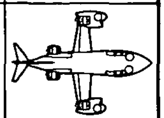
QUALITATIVE CONFIGURATION RATING BY APPLICABLE GROUPS	LIFT SYSTEM ARRANGEMENT			
	4-6A	6-6A	6-6B	8-8A
GOOD (3) FAIR (2) POOR (1)				
• CONTROL – ROLL	3	3	3	3
– PITCH % MODULATION REQUIRED	3	3	3	3
– YAW	3	3	3	3
• SIMPLE FLIGHT CONTROL SYSTEM	2	3	3	2
• SIMPLE CONTROL – ENGINE OR FAN OUT	2	2	2	2
• GROSS THRUST VECTORING RANGE AND METHOD	3	3	3	3
• AERODYNAMICS/PROPULSION INTERF. EFFECTS	1.5	2.5	2.5	3
• $C_{L_{MAX}}$ (FLAP AFFECTED AREA)	3	2.5	1	2
• GROUND EFFECT	2	2.5	2	3
• REINGESTION	2	2	2	2
• PROPULSION SYSTEM COMPLEXITY	2.5	2	2	1
• FUEL SPACE NEAR C.G.	1	3	2	3
• LANDING GEAR LENGTH	3	3	2	2
• AEROELASTIC PROBLEMS	2	2	1	1
• RELIABILITY – SAFETY	2	2.5	1.5	1.5
– DISPATCH	3	2	1	1
• MAINTAINABILITY (NO. ENGINES PLUS ACCESS)	3	2	2	1
• NOISE – INTERNAL	2	2	2	2
– EXTERNAL	3	3	2	2
• AESTHETICS – CUSTOMER APPEAL	2	2	1	1
QUANTITATIVE/QUALITATIVE RATING				
• PROPULSION SYSTEM LIFT T/W INSTL (TOTAL)	1.5	1.5	2	3
• THRUST/TOGW	3	2	3	3
• FUEL/TOGW (100 PAX)	3	3	3	3
• V_{CRUISE} (MACH)	3	3	3	3
• RELATIVE GROSS WEIGHT/PAX	2	2	2.5	3
TOTALS	60.5	61.5	54.5	56.5

Figure 3-11 presents the qualitative evaluation of the configurations. Each of the technology groups evaluated the aircraft for the parameters within their specialty areas. Following is a discussion of the technical elements considered in the evaluation.

o Control - Roll, Pitch, Yaw - (% Modulation) - The required thrust modulation is computed based on vehicle inertias, engine locations, and guideline acceleration requirements. The resulting modulation thrust increments are rated with respect to the available thrust modulation capabilities. Configurations with thrust modulation increments requiring gas generator or fan oversizing receive the lowest ratings.

o Simple Flight Control System - The flight control systems are rated on number and complexity of components needed to perform the required control functions. Systems which are least complex and require the smallest number of components receive the highest ratings.

o Simple Control - Gas Generator or Fan Out - The gas generator or fan out control task is rated similarly to the basic control functions. Configurations requiring the smallest number and least complex additional components to be used in the event of gas generator or fan failure receive highest ratings.

o Gross Thrust Vectoring Range and Method - The best rated configurations are those where thrust vectoring can be performed with minimum additional complexity, least interference with other control functions, and with the smallest power penalty.

o Aerodynamic/Propulsion Interference Effects - The effects of engine and nacelle size and location on flow fields about the aircraft, wing circulation, and downwash at the horizontal tail are considered. Wing tip pods may be designed to act as wing tip end plates, whereas wing pods located at mid-span create high drag and reduce lift. Large nacelles on the aft fuselage may necessitate larger horizontal tail exposed spans outboard of the nacelles for high angles of attack. Fan and engine inlets with low flow distortion are desirable.

o C_{Lmax} (Flap Affected Area) - A clean wing without wing pods provides the largest flap span, but wing tip pods provide favorable end plate effects. Flap span deteriorates progressively as more or bigger pods are added to the wing.

o Ground Effects - The presence of a jet efflux near the ground causes the air to be entrained around the lower surfaces of a vehicle, which induces a download on the vehicle. Fountain effects may also occur between multiple jets. The fountain and entrainment effects result in either a negative or positive ground effect depending on the distribution of engines and the height of the exhaust above the ground. Engines located close to the ground are downgraded because of reingestion and suck-down effects. Jet exhaust canted a few degrees outboard is favored because of the reduced reingestion and suck-down losses in some configurations.

o Reingestion - Fan or gas generator inlet ingestion of both fan turbine hot gases or foreign objects is considered. Inlets well shielded from the ground or mounted well away from the ground are favored. Inlets in the proximity of possible ground reflection paths of high velocity hot gas exit flow, where circulation can occur, are downgraded. Gas generator inlet hot gas ingestion was rated more severe than fan inlet hot gas ingestion.

o Propulsion System Complexity - The number and size of fans and gas generators as well as associated equipment (doors, control, valves, starting systems, and vectoring systems) are important considerations. In general, the smaller the number of engines the better. Interconnect ducting requirements are an important discriminator for RLF configurations.

o Fuel Space Near CG - The fuel is carried in the wing between the front and rear spar. Therefore, this rating is based on wing size, planform, location of pods, and requirements for internal equipment.

o Landing Gear Length - The landing gear length is established to provide adequate ground clearance for structure (nacelles and lower fuselage) and the propulsion wake occurring in the vertical lift mode. Fuselage clearance is checked for aircraft rotation during rolling "takeoff" and "landing" modes of operation.

o Aeroelastic Problems - Wing aeroelastic stability and the dynamic load amplification factors become important considerations when using wing tip mounted lift fan pods. The primary variables used in the evaluation are pod surface area and shape; pod weight; location of the pod relative to the wing elastic axis;

spanwise location of the pod; and sweepback angle of the wing.

o Reliability - The reliability evaluation was made on a comparative qualitative basis including considerations of type, quantity, and required activity of propulsion units for dispatch and redundancy available for safety; simplicity with which the units could be interfaced for control; method of providing symmetrical thrust in the event of a failure; thrust-to-weight ratio; distribution of thrust; and flight control - the combination of which dictates potential problems, quickness of takeoff, effectiveness of control, and emergency requirements.

o Maintainability - The number and type of engines is an important factor. Lift/cruise engines are apt to have more service problems than pure lift or pure cruise engines. Accessibility is also a consideration, such as engines buried inside fuselage structure versus external nacelles.

o Internal Noise - Cockpit and cabin engine noise are of concern because of the high predicted levels which affect communication and annoyance. The noise levels are controlled by the size and acoustical treatment of the engines, their proximity to the crew and passengers, their time of operation (takeoff and landing being most critical to communication), and the transmission path of the noise into the compartments.

o External Noise - Aircraft engine noise measured in the far field is a function of the thrust, quantity, and orientation of the engines. An increase in thrust or in the number of engines will cause an increase in the overall aircraft noise. Engine orientation has varying effects depending on whether the inlets are pointed forward or up.

o Aesthetics (Customer Appeal) - The most appealing aircraft is generally the least radical in appearance; the one the customer has confidence in because it looks like something he has experience with and likes. Also, customer appeal is affected by its utility. It must be easily loaded with passengers, luggage, and cargo and easily serviced with fuel, food, etc.

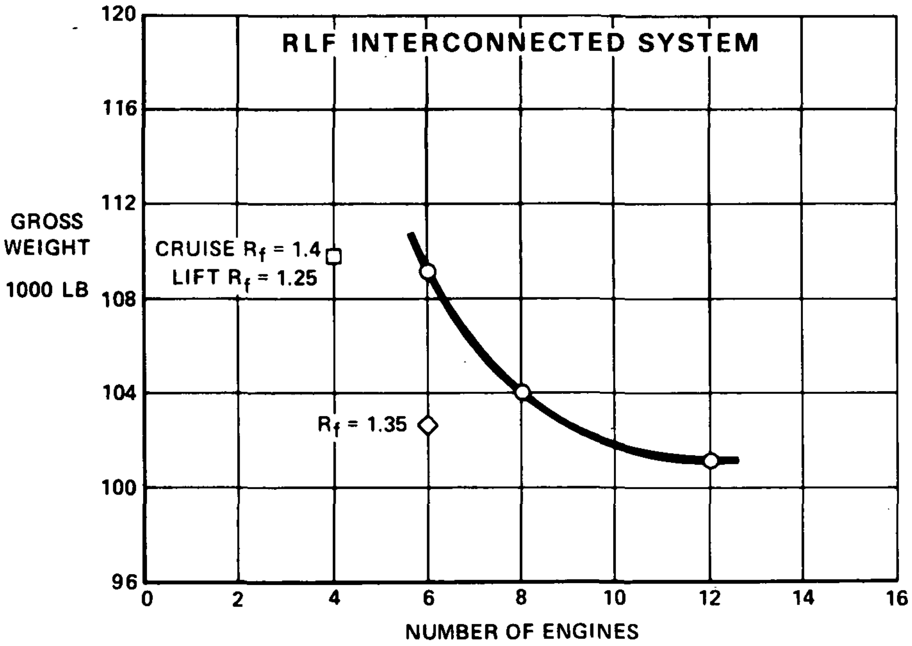
The number of engines has a significant effect on aircraft size. In accordance with the engine sizing ground rules established by General Electric, engine weight varies approximately as thrust to the 1.25 power. Therefore, as number of engines is increased, installed propulsion system weight reduces, providing a lower takeoff gross weight for an equivalent mission as shown in Figure 3-12. Reducing from 12 to 6 engines requires an 8% gross weight increase. It is of interest to observe that this increase in gross weight can almost be canceled by an increase in pressure ratio from 1.25 to 1.35 for the 6-engine configuration reducing VTOGW by about 6%.

A 4-engine configuration is plotted for comparison and shows promise (has almost same size as 6-engine configuration) but requires two different fan sizes. The basic ground rules dictated that a fan pressure ratio of 1.25 be used in the study for both the RLF and ILF configurations.

Figure 3-12

IMPACT OF NUMBER OF ENGINES ON AIRCRAFT SIZE

EQUAL MISSION PERFORMANCE



The 6-6A aircraft shown below is selected as being the best compromise of the RLF configurations.

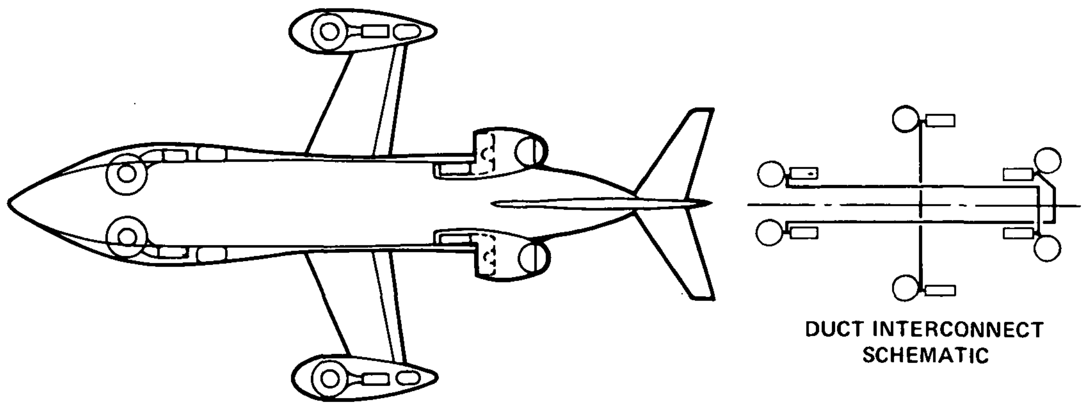
Figure 3-13

INTERCONNECTED FAN SYSTEM

VT102 RLF SERIES

6 ENGINES

6-6A



SELECTED AIRCRAFT

As indicated in Figure 3-12, the 8 or 12 engine aircraft provides the greater payload capability. The 8% increase in VTO gross weight to the selected aircraft is considered a reasonable trade-off for reducing from 12 to 6 engines. Operational effects of number of engines are discussed in Section 6.

In some respects, the 6-6B configuration is superior to the selected aircraft. This is mainly due to the specified engine sizing guidelines for the study and the relationship of this sizing to the number of engines and the "guideline" cruise speed of 0.75 M.

Qualitative evaluation favors the selected aircraft, 6-6A. The distribution of the lift system provides an efficient match for normal and engine-out lift and control requirements. The integration of the wing planform and wing tip lift engine nacelle results in the best arrangement, matching center of lift and center of gravity while retaining wing sweep satisfactory for high speed cruise. The large uninterrupted flap span gives the configuration good high lift characteristics. The overall layout has good potential for passenger loading and operational servicing. There is no flow in the interconnect ducting except during control applications or emergency operations.

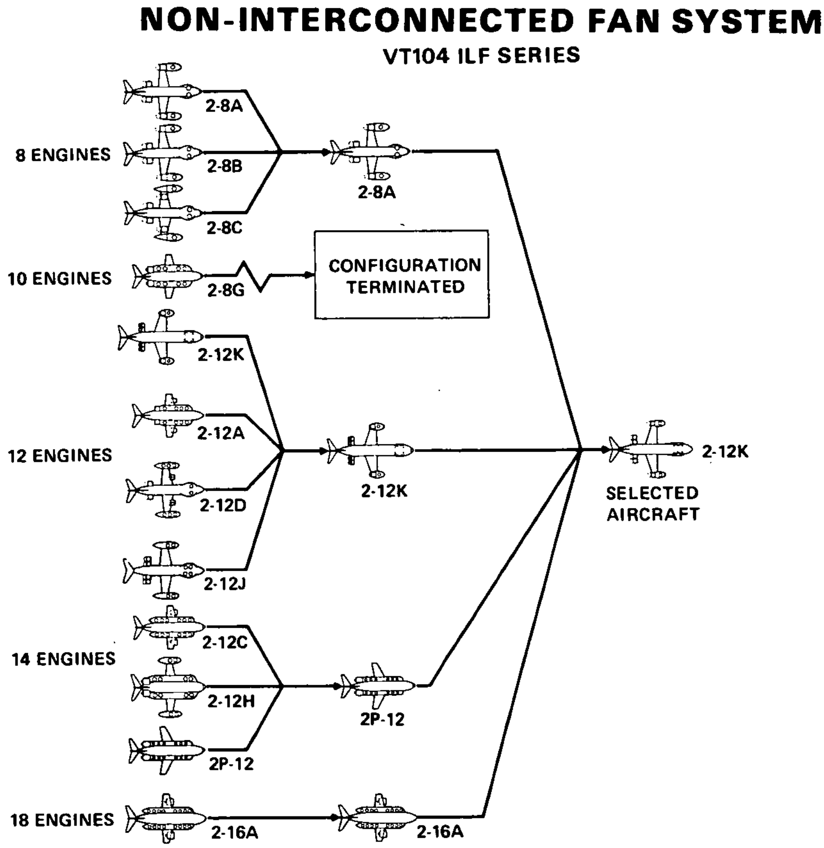
The 4 engine aircraft is a possible strong contender when number of engines is considered. The aircraft as presently configured has some areas of design needing additional study and requires two fan sizes because of the higher pressure ratio lift/cruise engines. Ducts interconnecting wing tip fans are active during the V/STOL mode.

3.3 NON-INTERCONNECTED FAN (ILF) AIRCRAFT

The non-interconnected fan system VTOL matrix shown below includes 8, 10, 12, 14, and 18 engine configurations. The greater variety of number of engines required more configurations to be investigated. All of these configurations use throttle modulation of propulsion units for low speed powered control and retain lift symmetry in emergency engine-out conditions by shutting off a symmetrically paired ILF unit.

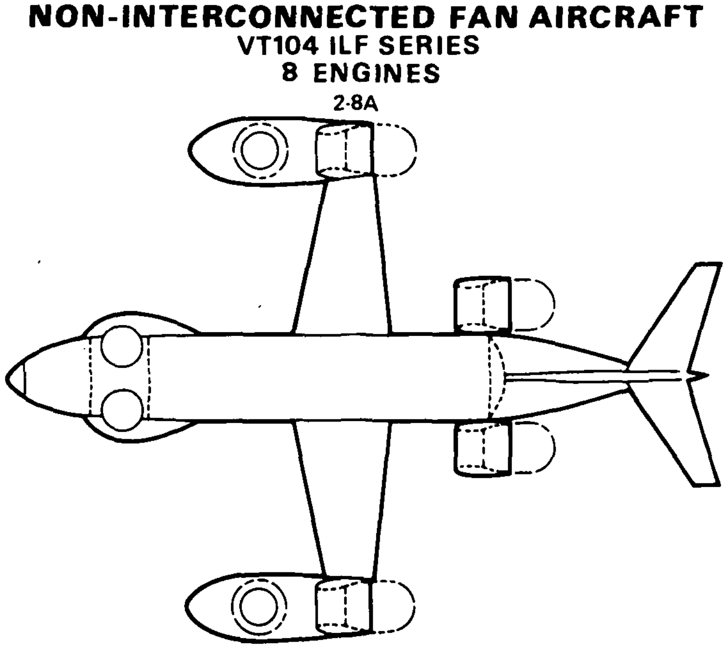
During the early stages of the study, 12 basic configurations were selected for comparison and evaluation. Some of the configurations consisted of pure lift and pure cruise engines, whereas other configurations added the lift capability to the cruise engines by the utilization of a thrust vectoring hood. Location of the engines varied and included the fuselage, fuselage sponsons, mid-wing span pods or nacelles, and wing tip pods. As a result of this early study, the most promising 8, 12, 14, and 18 engine configurations were selected for refined evaluation to facilitate designation of the "selected aircraft."

Figure 3-14



Descriptions of the parametric aircraft follow.

Figure 3-15



This configuration has two lift engines in the forward fuselage, two lift/cruise engines with rotatable hoods on the aft fuselage, and a lift/cruise engine with rotatable hood plus a lift engine in each wing tip pod. The lift engines in the forward fuselage and forward wing tip pods have louvers for thrust vectoring. Thrust vectoring of the aft fuselage engines and aft wing tip pod engines is accomplished by extending or retracting the hoods.

Aircraft height is controlled with interlocked throttle linkage simultaneously modulating thrust of all engines. Aircraft roll moments are generated by differentially modulating the thrust of the four wing tip engines, and aircraft pitch is similarly controlled by modulating the thrust of the four fuselage engines. Thrust moments for aircraft yaw control are provided by forward and aft deflections of lift thrust generated by the two wing-mounted lift engines.

In the event of engine failure during powered lift flight, the most symmetrically located opposite engine is shut down, and the required lift thrust and attitude control moments are provided by the remaining six engines operating at increased power setting.

The forward thrust component for transition is generated by vectoring the thrust of all engines except the wing-mounted lift engines, which are used for yaw control. The wing lift engines are not used for transition thrust because, if thrust is deflected for transition while yaw moments are generated, roll disturbances are introduced. During transition to cruise flight, the effectiveness of thrust modulation for attitude control is gradually reduced, while the conventional aerodynamic controls become more effective. Only aerodynamic control surfaces are used for attitude control in cruise flight.

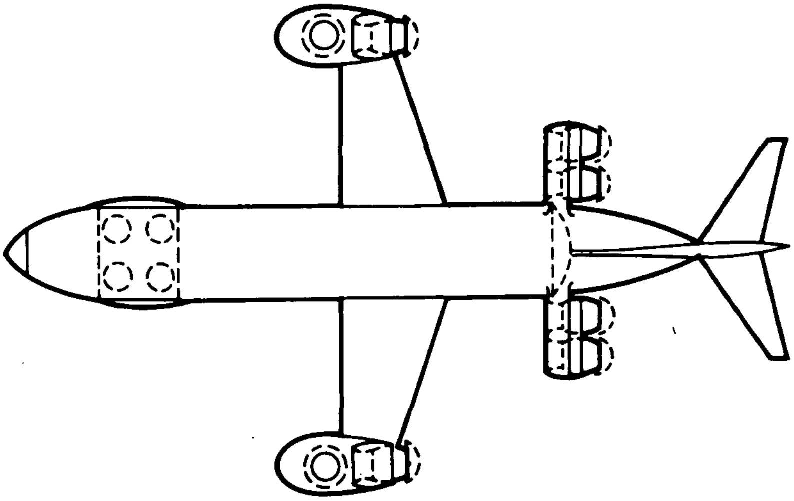
Figure 3-16

NON-INTERCONNECTED FAN AIRCRAFT

VT104 ILF SERIES

12 ENGINES

2-12K



This configuration has four lift engines in the forward fuselage, four lift/cruise engines with rotatable hoods on the aft fuselage, and a lift/cruise engine with rotatable hood plus a lift engine in each wing tip pod. The lift engines in the forward fuselage and forward wing tip pods have louvers for thrust vectoring. Thrust vectoring of the aft fuselage engines and aft wing tip pod engines is accomplished by extending or retracting the hood. In addition, the hoods on the aft fuselage lift/cruise engines can rotate about the engine's longitudinal axis for yaw control.

In this configuration the aircraft height, pitch, and roll attitude are controlled as in VT104-2-8A, Figure 3-15; however, a different mechanization is used for yaw control. The thrust moments to control aircraft yaw attitude are generated by deflecting the thrust of the fuselage engines sideways, using louvers for the front engines and rotating hoods for the aft engines.

If an engine fails during powered lift flight, the most symmetrically located opposite engine is shut down. Since this configuration has 12 lift units, the percentage thrust loss due to engine failure is smaller than for the previous configuration. The remaining engine can provide the required lift and attitude control without oversizing.

During transition from powered lift to cruise flight the hoods on the lift/cruise engines are retracted and the louvers on the lift engines are tilted to provide forward thrust for transition flight. During cruise only the lift/cruise engines are operating, and attitude control is provided by conventional aerodynamic control surfaces.

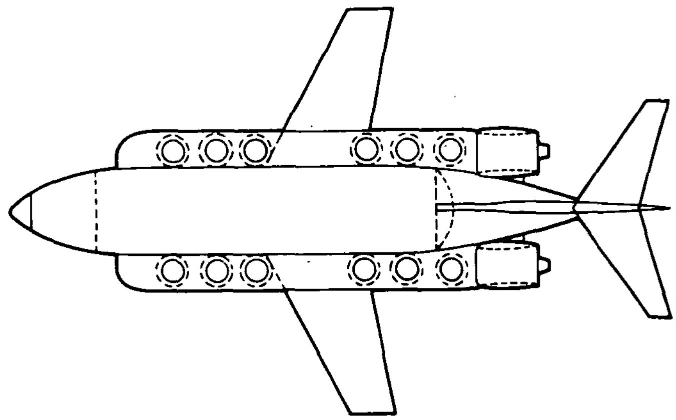
Figure 3-17

NON-INTERCONNECTED FAN AIRCRAFT

VT104 ILF SERIES

14 ENGINES

2P-12

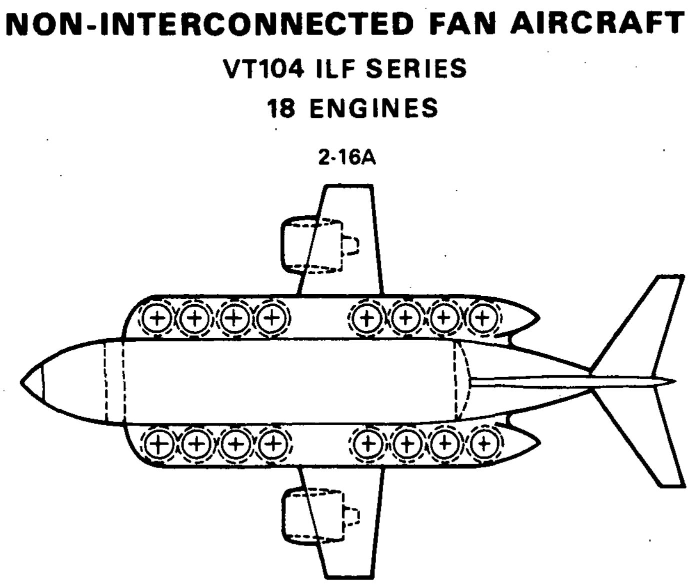


This configuration has 12 lift engines mounted in fuselage sponsons and 2 cruise engines mounted on the aft fuselage. The lift engines have louvers for thrust vectoring.

The aircraft attitude control in powered lift mode is provided by differentially modulating and deflecting the thrust of the sponson-mounted lift engines; the cruise engines are not used for control. The pitch and roll control is obtained by modulating engine thrust, while yaw control is obtained by using louvers to deflect the thrust sideways. In case of lift engine failure, the symmetrically located opposite engine is shut down and the reduced attitude and height control required in emergency is adequately provided by the remaining lift engines.

The transition to cruise flight is accomplished by deflecting the thrust of the lift engines forward and by cruise engines generating additional forward thrust. The aerodynamic controls are gradually substituted for thrust modulation, and in cruise flight only aerodynamic controls are used. When conversion velocity is reached, the lift engines are shut down.

Figure 3-18



This configuration has 16 lift engines mounted in fuselage sponsons and 2 cruise engines mounted under the wing. The lift engines have louvers for thrust vectoring.

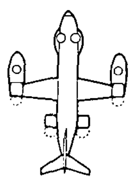
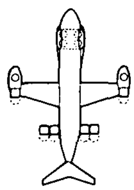
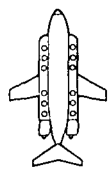
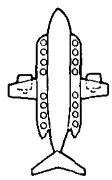
The mechanization of attitude and height controls is essentially the same as in configuration VT104-2P-12, Figure 3-17. The control functions, in normal flight as well as in the event of lift engine failure, are again performed as described for VT104-2P-12.

The four ILF configurations in the final selection comparison shown below were sized for 100-passenger payload per the "guideline" mission and performance. Significant physical performance and operational characteristics were determined for the candidate configurations and a comparative qualitative as well as quantitative evaluation of the configurations made. The figure presents a summary of some of the most significant parameters from the analyses for comparison of configurations. The 2-12K configuration showed the lowest gross weight in the initial investigation. Although fewer engines are desirable, the 2-8A arrangement showed a disproportionately high gross weight.

Figure 3-19

NON-INTERCONNECTED FAN SYSTEM

VT104 ILF SERIES EVALUATION SUMMARY

CHARACTERISTICS	LIFT SYSTEM ARRANGEMENT			
	2-8A	2-12K	2P-12	2-16A
				
ENGINES	8	12	14	18
NOMINAL T/W (90^{O}F, INSTALLED)	1.29	1.10	1.17	1.13
% MODULATION FOR CONTROL	21.0	17.2	34.8	31.2
GROSS WEIGHT (100 PAX)	115,500	93,000	103,500	103,400
CRUISE MACH AT 20,000 FT	0.75 (0.78)*	0.75 (0.76)*	0.75 (0.76)*	0.75 (0.76)*
QUALITATIVE EVALUATION SCORE	53.5	54.5	50.5	47.5

*Maximum power capability

The VT104-2-12K configuration shown below was selected as the best compromise among the ILF configurations. It was the smallest configuration considered. The distribution of the lift system makes the thrust modulation for VTOL control reasonable. The cruise performance is good. Fifty percent of the lift system is used in the cruise mode which is more than ample for a cruise Mach number of 0.75 at 20,000 feet. Wing tip lift/cruise engine failure is trimmed by shutdown of the opposite engine. The remaining four lift/cruise engines are adequate to complete a mission and make a STOL landing. The large uninterrupted flap span gives the configuration good high lift characteristics. The overall arrangement has good potential for passenger loading and operational servicing. Remote location of fuselage mounted engines enhances solving acoustic problems.

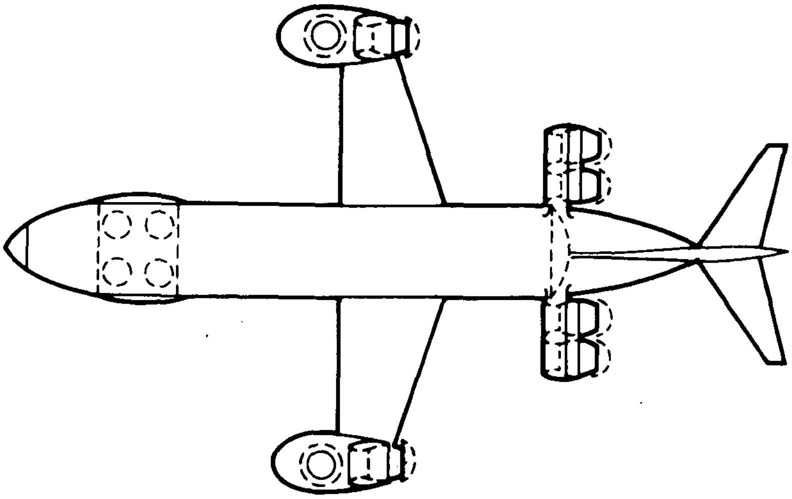
Figure 3-20

NON-INTERCONNECTED FAN AIRCRAFT

VT104 ILF SERIES

12 ENGINES

2-12K



SELECTED AIRCRAFT

4. REFINEMENT OF PARAMETRIC SELECTION

The technology evaluation of the ILF and RLF configurations is consistent within each family of aircraft (weights, propulsion installation, etc.) but not necessarily consistent between families. This is due to configuration differences between families such as propulsion installation effects. Parametric evaluation of many configurations requires a certain amount of generalization. This process does not affect the selection of the best compromise within a family, but it is considered mandatory to refine each selected configuration to a common technical base before final comparison of ILF and RLF configurations. Refinement of parametric selections thus involved:

- Reevaluation of propulsion system
- Reevaluation of guideline restraints
- Reevaluation of empty weights
- Noise assessment

These refinement processes are presented in the following paragraphs.

Propulsion System - The propulsion system component efficiencies used to estimate VTOL installed performance of the ILF and RLF commercial aircraft are shown below. The inlet recovery and the lift/cruise exhaust system thrust coefficient values are based on MCAIR experimental results for the research aircraft components, extrapolated to anticipated 1985 levels. The exhaust system thrust coefficients and the gas generator to fan turbine pressure loss are based on SAE Aero-Space Applied Thermodynamics Manual data, Reference 3, and previously obtained test results. Bleed, power extraction, and leakage losses are neglected. The base drag values are established from the basic GE-supplied data, adjusted to represent the addition of terminal fairings to the splitters and hub. This adjustment is based on an estimate that 86.7% of the base drag can be eliminated by applicable fairings. The thrust and fuel flow margins used to size the propulsion system were estimated from GE-supplied data for the RLF concept with the ILF data adjusted to match the RLF values.

Figure 4-1

LIFT FAN PROPULSION SUMMARY

INSTALLATION EFFECTS

ITEM	RLF 6-6A	ILF 2-12K
GAS GENERATOR INLET RECOVERY	0.995	0.997 (WING); 0.994 (OTHERS)
GAS GENERATOR TO FAN TURBINE PRESSURE LOSS	8%	–
FAN INLET RECOVERY	0.997 (WING; 0.994 (OTHER)	0.997 (WING); 0.994 (OTHERS)
EXHAUST SYSTEM THRUST COEFFICIENT	0.987 (LIFT); 0.95 (LIFT/CRUISE)	0.987 (LIFT); 0.95 (LIFT/CRUISE)
BASE DRAG (LB)	126	64
MARGINS (THRUST/FUEL FLOW)	0.965/1.00	0.965/1.00

The installed performance is summarized in Figure 4-2. The performance shown for the RLF and ILF systems in column A is quoted directly from GE sources. These data were adjusted considering the installation factors shown in column B, and the resulting calculated installed performance for these unscaled engines is shown in column C at the bottom of the figure. Scaling or sizing these engines for the VT-102 and the VT-104 aircraft designs results in the performance and physical characteristics presented in column D. The RLF thrust increased due to the reduced base drag. The ILF thrust decreased due to increased base drag, decreased thrust coefficient, and decreased thrust margin. The resulting weights are essentially identical. The combined effects of these corrections is an 11% improvement of the RLF performance, relative to the ILF concept, using the uninstalled data as a reference base. The ILF concept has a small advantage in diameter as measured by the fan tip diameter. The RLF system has approximately a 43% cruise thrust and a 5% sfc advantage over the ILF system.

Figure 4-2
Lift Fan Propulsion Summary

	RLF			ILF		
	Unity GE Data A	VT-102 B		Unity GE Data A	VT-104 B	
Installation Effects						
Gas generator inlet recovery	1.0	0.995		1.0	0.997 (wing lift) 0.994 (others)	
Gas generator to fan turbine pressure loss	10%	8%		-	-	
Fan inlet recovery	*1.0*	*0.997 (wing)* 0.994 (other)		*1.0*	*0.997 (wing lift)* 0.994 (others)	
Exhaust system thrust coefficient	0.987	0.987 (lift) 0.96 (L/C)		0.995	0.985 (lift) 0.95 (L/C)	
Base drag (lb)	943	126		0	64	
Margins (thrust/fuel flow)	0.965/1.00	0.965/1.00		1.00/1.03	0.965/1.00	
Results		Unity(1) Uninstl C	Instl & Resized D		Unity(2) Uninstl C	Instl & Resized D
Thrust (lb)	12,500	13,330	(12,500)	12,500	11,900	(12,500)
Weight (lb)	1234	1234	(1188)	1064	1064	(1184)
T/W	10.1	10.8	(10.5)	11.7	11.2	(10.6)
Fan tip diameter (in.)	62.1	62.1	(61.2)	57.1	57.1	(59.6)
Cruise thrust (lb) (20,000 ft, 0.75 M)			4300			3000
SFC (20,000 ft, 0.75 M)			0.86			0.91

(1) Adjusted to account for reduced base drag.
(2) Adjusted to match RLF values of exhaust system thrust coefficient and margins, and indicated base drag.

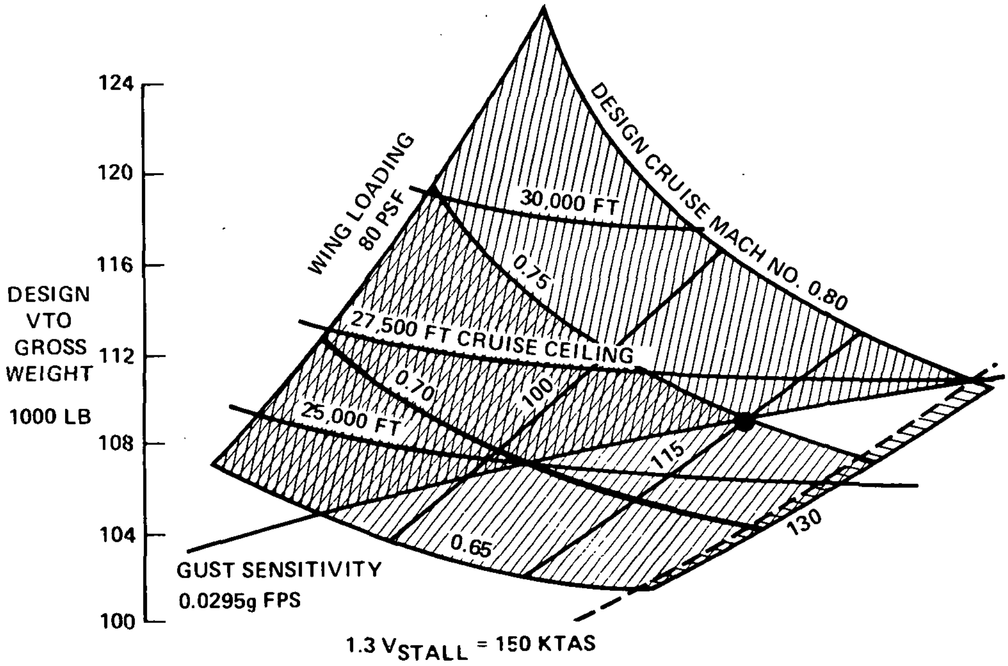
Guideline Restraints - The effect of guideline restraints on the RLF aircraft size are illustrated below.

Figure 4-3

EFFECT OF GUIDELINE RESTRAINTS

RLF INTERCONNECTED SYSTEM

VT102 SERIES 6 ENGINES



The "design window" illustrated was established by the following parameters.

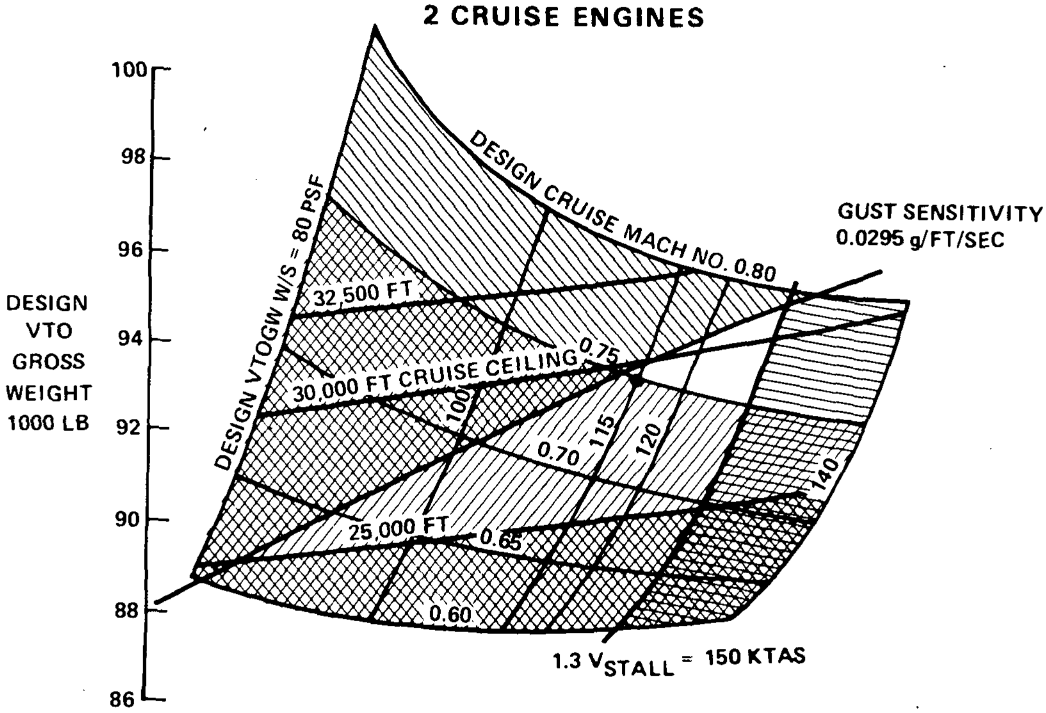
Parameter	Factor	Design Guideline or Design Goal	Selected Airplane
Maximum Cruise Ceiling	Operational Flexibility	$\geq$ 25,000 ft	26,500 ft
Design Cruise Altitude	Operational Flexibility	~ 20,000 ft	20,000 ft
Gust Sensitivity	Ride Quality Passenger Comfort	0.0295 g/FPS	0.0295 g/FPS
VTO Wing Loading	Economy, Safety	Fallout	115 PSF
Design Cruise Mach Number	Operational Flexibility	$\geq$ 0.75	0.75
Transition Speed	Safety	< 150 KTAS 90°F	143 KTAS
400 NM Stage VTO Gross Weight	Economy	Smallest that will do the mission	109,000 lb

A wing loading of 115 PSF was selected to favor lower conversion speeds and higher cruise ceilings while meeting the gust sensitivity requirements with a slight increase in VTO gross weight.

The effect of guideline restraints on the ILF aircraft size are similar to that for the RLF configuration, as shown below.

Figure 4-4

EFFECT OF GUIDELINE RESTRAINTS
ILF NON–INTERCONNECTED SYSTEM
VT 104 SERIES 12 LIFT ENGINES
2 CRUISE ENGINES



Empty Weight - A weight comparison of the selected configurations is shown below. The weights reflect consistent allowances for all items including weight penalties associated with wing tip mounted pods.

Figure 4-5
Weight Comparison of Selected Configurations

Group	VT102-2P-6-6A	VT104-2-12K
Wing	6800	6000
Empennage	2080	2055
Fuselage	10,185	9900
Landing Gear	3532	3328
Surface Controls	1134	1142
Engine Section	2300	1300
Propulsion System	28,300	23,099
APU	711	711
Instruments	606	606
Hydraulics and Pneumatics	729	610
Electrical	1430	1430
Electronics	859	859
Furnishings	6300	6300
Air Conditioning	1260	1260
Anti-Ice	504	430
Auxiliary Gear	40	40
Weight Empty	66,770	59,070
Non-Expendable Useful Load	1430	1430
Operating Weight Empty	68,200	60,500
Payload (Fuel + 100 Passengers)	40,800	41,300
Takeoff Gross Weight	109,000	101,800

The ILF propulsion system weight is less, primarily due to the reduced weight of larger numbers of smaller engines, because smaller engines have a higher thrust-to-weight ratio. The higher weight of the RLF propulsion system is partially compensated for by a reduction in fuel required. Non-expendable useful load consists of crew, crew bags, trapped fuel, oil, oxygen, lavatory fluids, passenger slides, and galley supplies.

Noise Assessment - The 500-foot sideline noise for the 100,000 pound TOGW class RLF and ILF powered aircraft is nearly alike, as shown in Figure 4-6. Noise levels for other conditions shown on the table are also similar except for the takeoff-flyover, which employs different takeoff profiles. The exhaust acoustic treatment configurations as furnished by General Electric are shown on Figures 4-7 and 4-8. GE treatment for the RLF also includes exhaust louvers on the lift engines and inlet splitters on the lift/cruise engines. The ILF has treated inlet splitters on the lift/cruise engines.

Figure 4-6
Aircraft Noise Comparison

	RLF	ILF
500 ft sideline on takeoff	98.7 PNdB	100.2 PNdB
500 ft sideline on landing	97.9 PNdB	99.4 PNdB
Flyover 1 mile after takeoff	83.6 PNdB	90.5 PNdB
Flyover 1 mile prior to landing	79.0 PNdB	80.3 PNdB
2000 ft altitude cruise flyover	72.4 PNdB	71.0 PNdB

Figure 4-7

REMOTE LIFT FAN

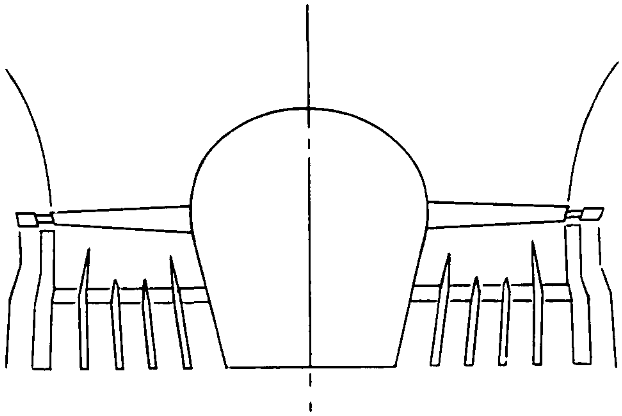
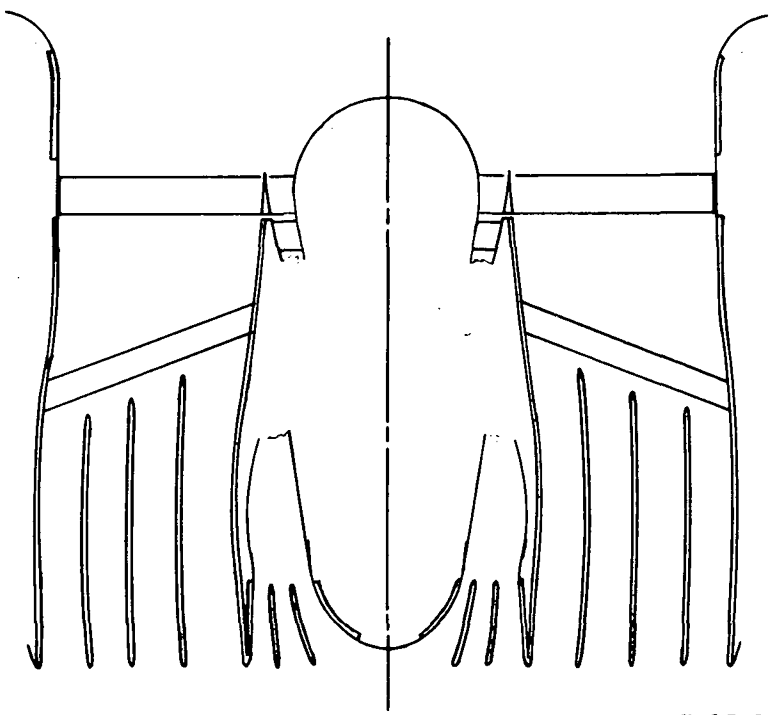


Figure 4-8

INTEGRAL LIFT FAN



Comparative takeoff profiles and 95 PNdB footprints are shown in Figures 4-9 and 4-10, respectively, for the selected RLF and ILF aircraft.

Figure 4-9
Takeoff Profile

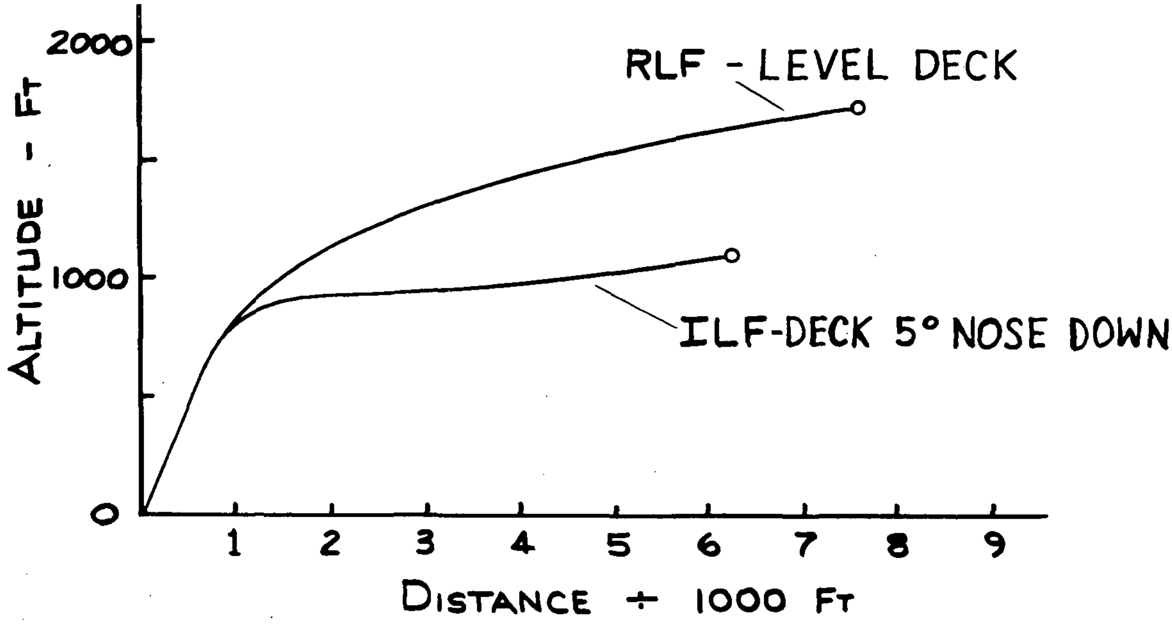
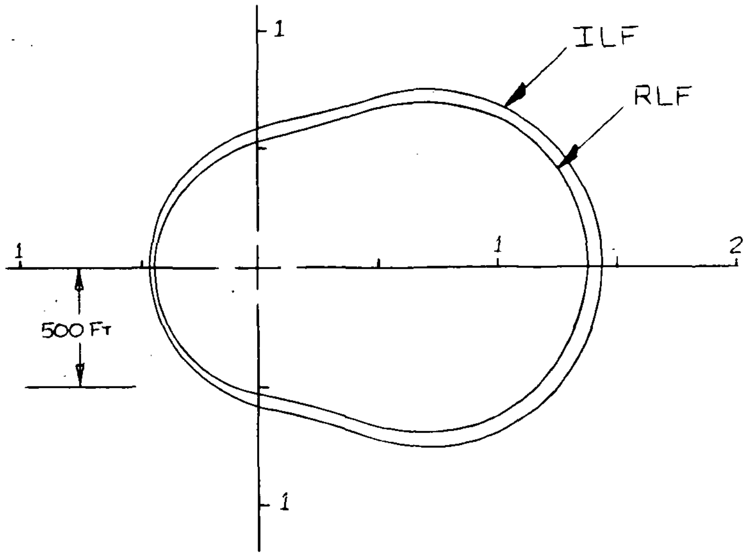


Figure 4-10
95 PNdB Takeoff Noise Footprint Comparison



Comparative 95 PNdB footprints are shown in Figure 4-11 for the same landing profile, Figure 4-12, for the selected RLF and ILF aircraft.

Figure 4-11
95 PNdB Landing Noise Footprint

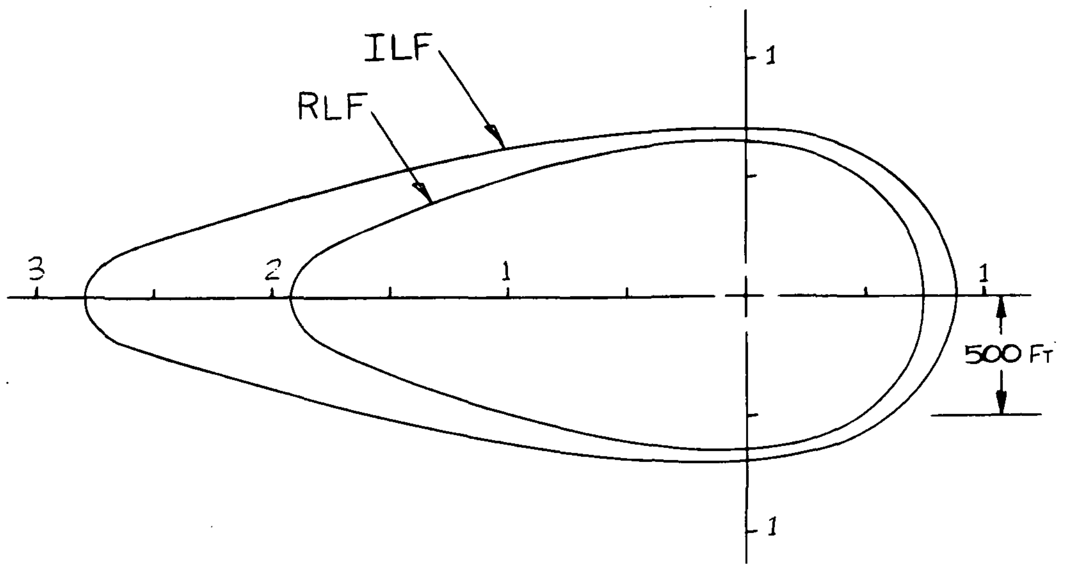
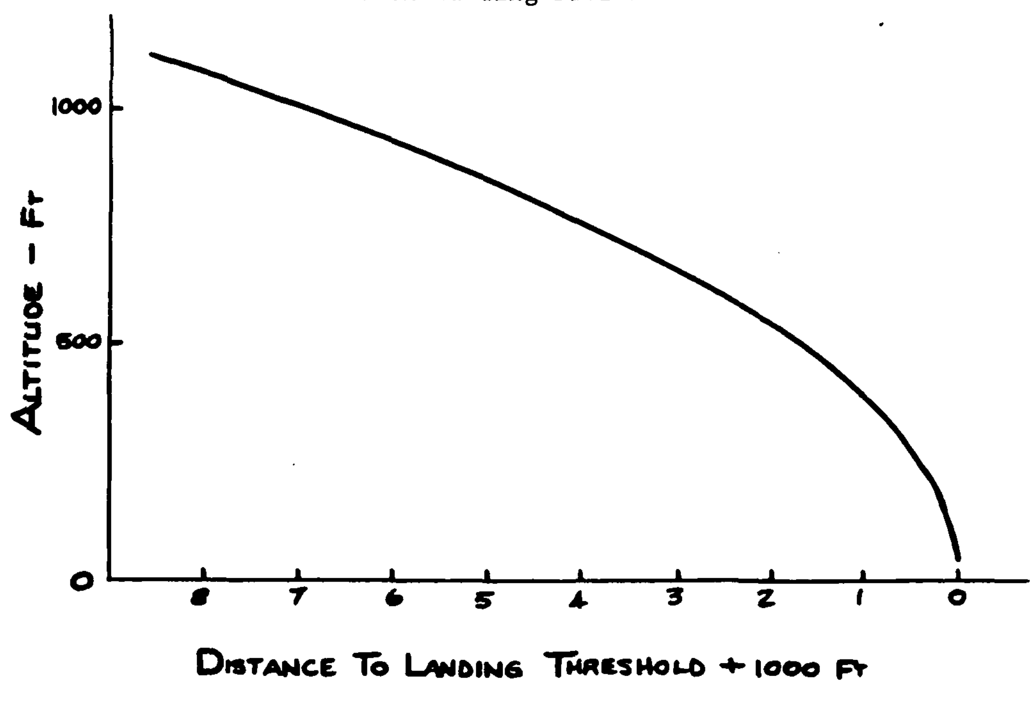


Figure 4-12
VTOL Landing Profile



5. FINAL AIRCRAFT SELECTION

The selected ILF aircraft, which resulted after reevaluation and refinement of the design, is shown in Figure 5-1. A comparison of major characteristics which were refined is shown in Figure 5-2. This aircraft fully satisfies the guideline mission requirements.

Figure 5-1

SELECTED ILF AIRCRAFT

12 ENGINES

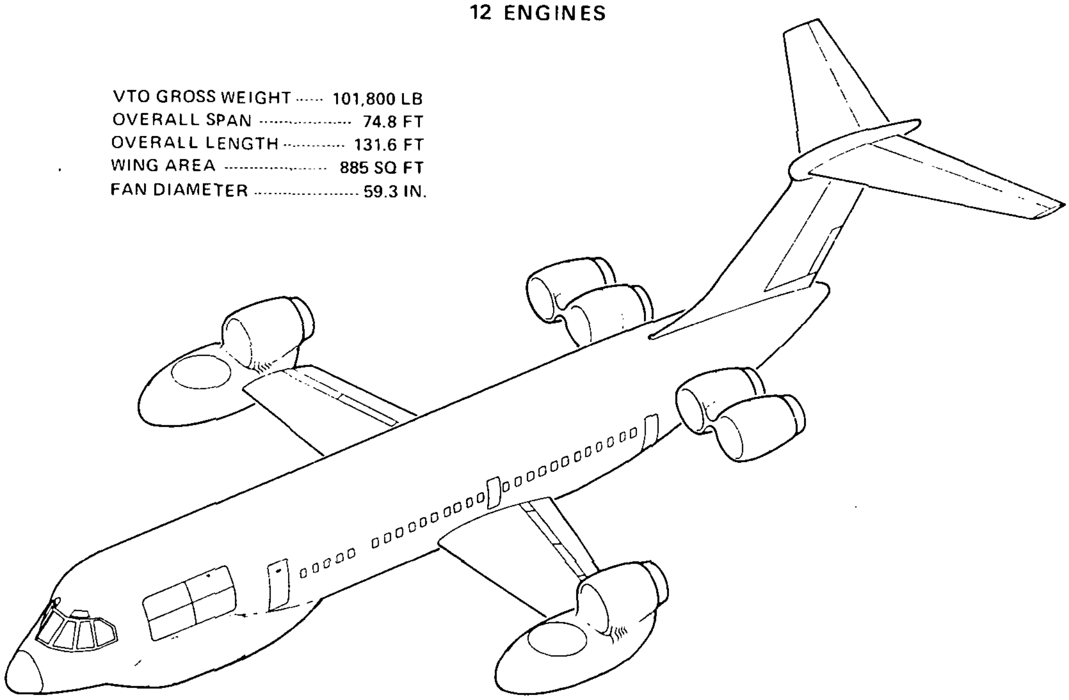


Figure 5-2
ILF Refinement Changes

	Initial	Updated
Wing loading (psf)	100	115
Propulsion system installation efficiency	0.938	0.9731
Wing weight factor (wing pod)	1.0	1.30
Roll moment of inertia factor	1.0	1.13
Thrust/weight ratio	1.10	1.18*
Engine oversize factor	1.0	1.07*
Gross weight (lb)	93,000	101,800
Payload (lb)	20,000	20,000

*Established by emergency lift and control.

The selected RLF aircraft, which resulted after reevaluation and refinement of the design, is shown in Figure 5-3. A comparison of major characteristics which were refined is shown in Figure 5-4. This aircraft fully satisfies the guideline mission requirements.

Figure 5-3

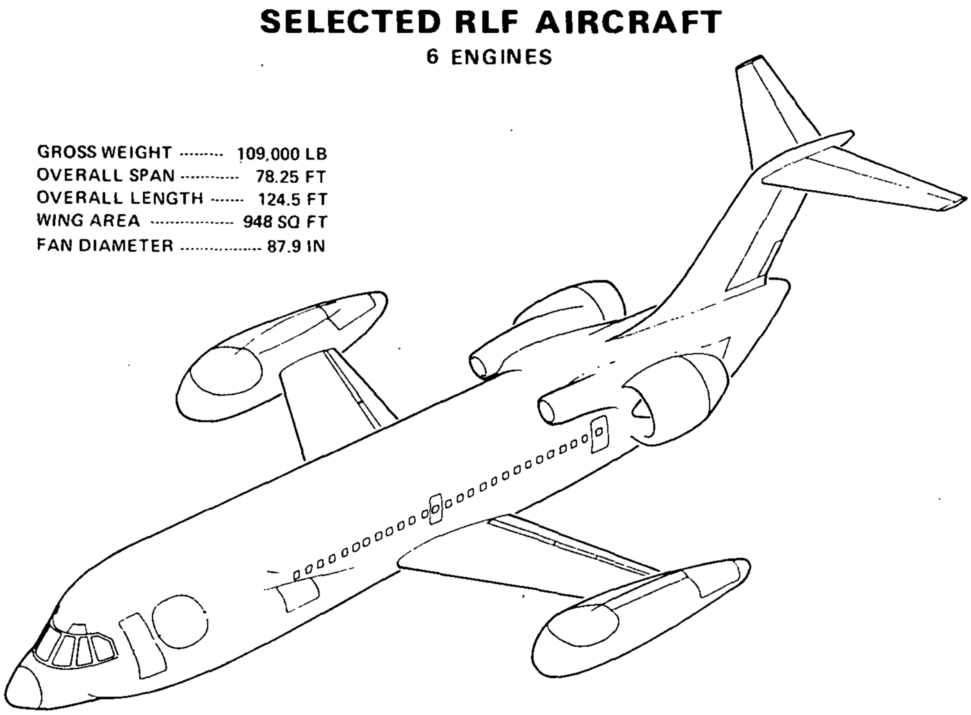


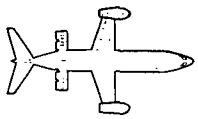
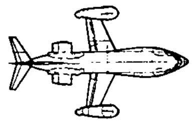
Figure 5-4
RLF Refinement Changes

	Initial	Updated
Wing loading (psf)	100	115
Wing weight factor (wing pod)	1.30	1.30
Roll moment of inertia factor	1.0	1.0
Thrust/weight ratio	1.24*	1.146*
Engine oversize factor	1.13*	1.04*
Gross weight (lb)	100,000	109,000
Payload (lb)	15,477	20,000
*Established by M = 0.75 cruise speed.		

The final evaluation summary of the selected ILF and RLF configurations is shown in the following figure.

Figure 5-5

FINAL EVALUATION SUMMARY

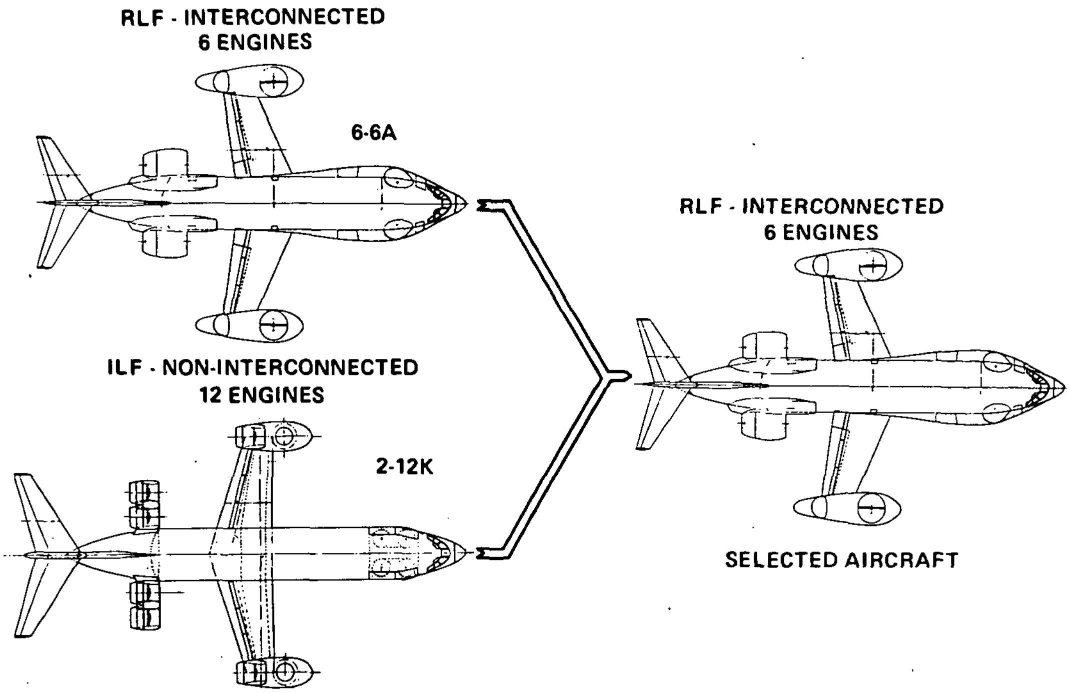
CHARACTERISTICS	2-12K 	6-6A 
ENGINES	12	6
NOMINAL T/W (90°F, INSTALLED)	1.18	1.146
% MODULATION FOR CONTROL (MAX)	39	23
GROSS WEIGHT	101,800 LB	109,000 LB
CRUISE MACH @ 20,000 FT ALTITUDE	0.75/0.76*	0.75/0.75*
DIRECT OPERATING COST RATIO	1.045	1.0
QUALITATIVE EVALUATION SCORE	54	61

*MAXIMUM MACH NUMBER @ 20,000 FT

Comparing the selected RLF and ILF configurations on a common basis shows that the ILF configuration is 7% lighter. The thrust-to-weight ratio of the ILF configuration was established by one engine out plus trim and maneuver control, while the RLF configuration thrust-to-weight ratio was established by the cruise speed requirement. The RLF configuration has a slight advantage in direct operating cost resulting from the fewer number of engines. The qualitative analysis favors the RLF configuration. The principal factor was the number of engines. Detailed quantitative and qualitative analyses of these aircraft are given in Volume IV. Additional economic analyses and discussions are given in Section 9.

Figure 5-6

FINAL AIRCRAFT SELECTION



The six-engine RLF interconnected aircraft is selected as the best compromise to satisfy the requirements for the future V/STOL commercial transport aircraft. The number of engines installed in the aircraft has had a major effect on the selection of configuration. Therefore, this subject is discussed in detail in the next section.

6. NUMBER OF ENGINES

Return on investment which is dependent on direct operating cost, among other things, is of greatest influence in the selection of an aircraft by an airline customer. Aircraft initial cost, weight, dispatch reliability, maintenance and maintainability, terminal time in through-stop and turn-around route operations are factors having major effects on direct operating costs and thereby return on investment. The number of engines installed in an aircraft has important effects on all of these parameters.

Figure 6-1

IMPACT OF NUMBER OF ENGINES ON AIRCRAFT SIZE

EQUAL MISSION PERFORMANCE

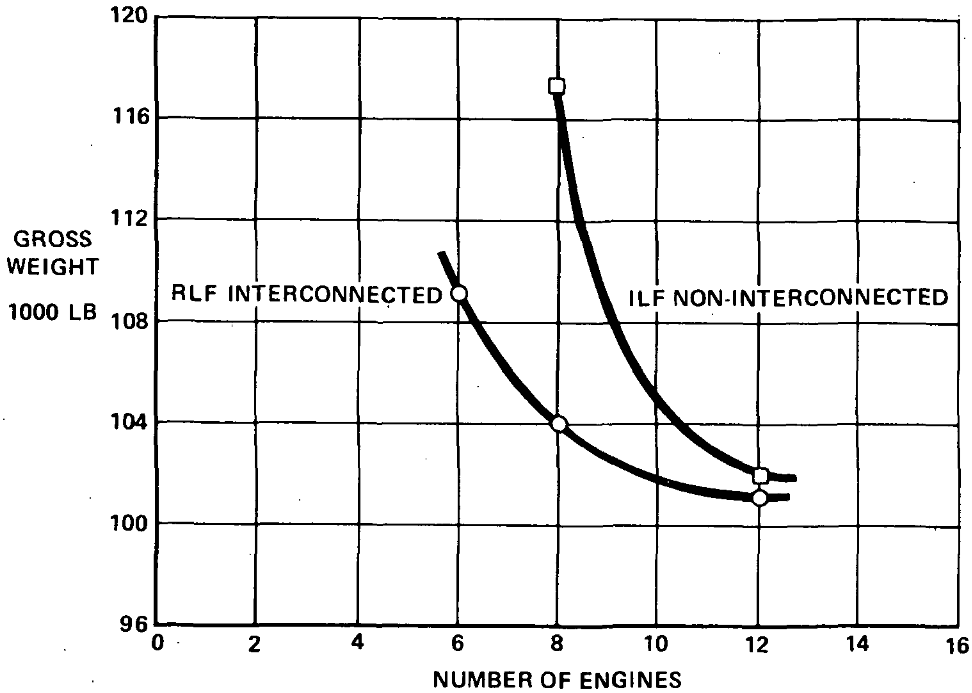


Figure 6-1 presents the variation of gross weight with number of engines for both the RLF and ILF aircraft. The factors which contribute to the establishment of the gross weight curves are:

1. Engine scaling factors supplied by General Electric dictate the characteristic shape of the curves, i.e., decreased gross weight with increased number of engines.

2. The lift and control guidelines, coupled with the arrangement and capability of the propulsion system to satisfy the requirements with minimum size and thrust units, define the magnitude of the slope of each curve.

3. Each basic engine installed efficiency, particularly T/W and SFC, determines the relative location of the ILF curve with respect to the RLF curve.

Engine weight varies as thrust to the 1.25 power in accordance with engine sizing curves supplied by General Electric. Therefore the propulsion system weight, and consequently gross weight, reduces with a greater number of smaller engines. The gross weight curves of Figure 6-1 appear to have a characteristic bucket, bottoming approximately with a 12 engine aircraft. This is due to the structural and installation complexities experienced in satisfactorily arranging greater number of engines.

The penalty incurred in the ILF aircraft without interconnected propulsion units results in a very steep upward slope of the line as number of engines is reduced as compared to the interconnected RLF aircraft. This results from the need to retain control and thrust symmetry with the loss of an engine. Without interconnect, a symmetrically located opposite engine must be shut down when an engine failure occurs; thus, the emergency thrust, required by the guidelines, of the remaining engines for lift and control is rapidly amplified as the number of engines decrease leading to oversized engines. In the aircraft using gas interconnect, power and thrust are conserved as described in Section 8, thereby providing for emergency lift and control with engines sized for the nominal lift plus control required by the guidelines. Therefore as number of engines reduces, the propulsion system size and weight increase more rapidly for aircraft without interconnect as compared to aircraft with interconnect.

This effect is demonstrated by the aircraft plotted on the curve. The twelve engine and eight engine ILF aircraft plotted have T/W ratios of 1.18 and 1.29, respectively, whereas the twelve engine and eight engine RLF aircraft plotted each have T/W ratios of 1.10. The six engine RLF aircraft is a special case since it uses only one-third of its installed power for cruise and therefore the engines are sized by the cruise speed requirement. Thus the T/W ratio of this aircraft is 1.146. Using a greater portion of the installed power for cruise as is the case for the 6-6B RLF aircraft reduces the T/W ratio for the six engine aircraft to 1.10 resulting in a lighter aircraft.

Figure 4-2 compares the installed efficiencies of the ILF and RLF engines for the baseline 12,500 pound thrust engines. This is approximately the proper size for the ILF and RLF twelve-engined aircraft. As indicated in Figure 4-2, engine T/W of the two base engines are approximately equal and SFC of the RLF is somewhat better. This comparison is made based on using the engines in a non-interconnected arrangement. When RLF engines are interconnected the T/W is increased additionally through use of Energy Transfer Control as described in Section 8, Figure 8-5. With the use of this system the gas generator portion of the engine is sized by the nominal steady state lift criteria required by the guidelines. Nominal control excursions are accommodated by the gas generator without an increase in size. The smaller RLF gas generator resulting pays a bonus in providing greater cruise fuel economy in addition to the SFC benefit shown on Figure 4-2.

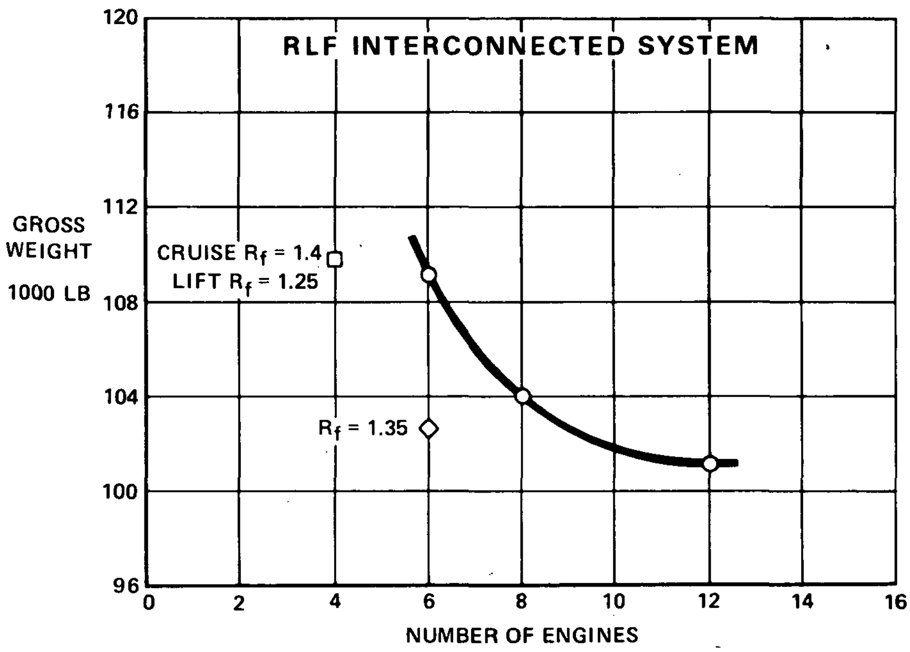
All of these effects combine to reduce the power plant plus fuel weight sufficiently in the twelve engine RLF aircraft to overcome the weight of the interconnect hardware. Thus the curves of Figure 6-1 meet approximately at the twelve engine aircraft point. A penalty equal to a gross weight increase of 15% is incurred in reducing from 12 to 8 engines in the ILF configuration compared to only an 8% increase in gross weight with a decrease from 12 to 6 engines in the RLF configuration.

If the selection criteria were airplane size and weight alone, the selection would be obvious; but other considerations temper the selection as illustrated on the following figures.

Figure 6-2

PRESSURE RATIO CONSIDERATIONS ON SELECTION OF NUMBER OF ENGINES FOR COMMERCIAL AIRCRAFT

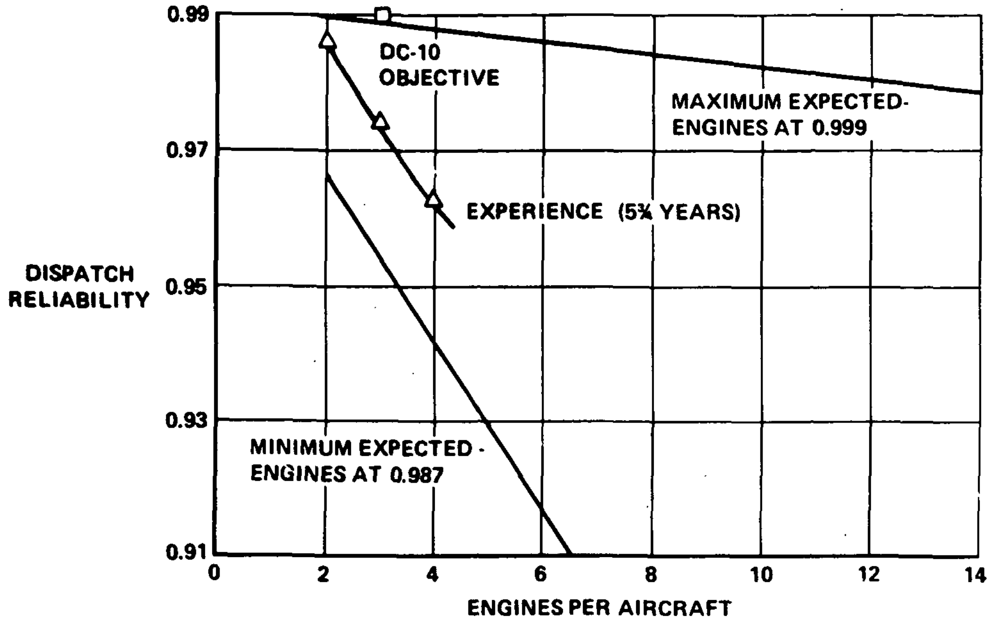
EQUAL MISSION PERFORMANCE



Fan pressure ratio has a significant influence on airplane weight as shown. For the 6 engine RLF configuration, increasing the fan pressure ratio from 1.25 to 1.35 reduces airplane weight by about 6%. A promising configuration with four engines is shown for comparison. The fans operate at a 1.25 pressure ratio for lift with the two lift/cruise fans operating at a fan pressure ratio of 1.4 during cruise. Two different fan sizes were assumed in the initial analysis, but only four engines are used. Additional analyses may show that equal fan sizes, but operating at different pressure ratios for the lift mode, may be used for the 4 engine configuration. The combination of variable fan pressure ratio takes advantage of the best operating efficiency of each fan pressure ratio. For lift and noise, low fan pressure ratio is desirable; for high speed cruise, increased fan pressure ratio is desirable. Although this configuration was not selected because the study ground rules dictated a fan pressure ratio of 1.25, the configuration does present the possibility of obtaining an aircraft with only four engines. Additional detail study of this configuration is required.

Figure 6-3

EFFECT OF ENGINES ON AIRCRAFT DISPATCH RELIABILITY
15 MINUTE DELAY

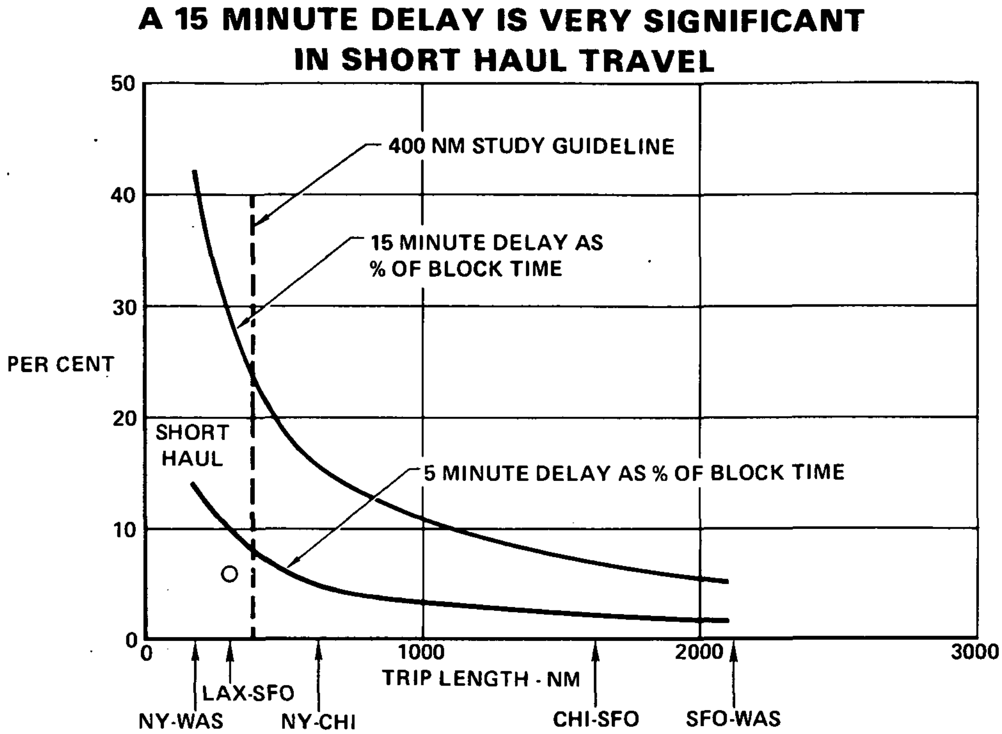


Dispatch reliability of VTOL aircraft is expected to decrease as the number of engines per aircraft increases, the gradient depending on the reliability of each propulsion unit, the installation complexity, and the effects of integrating with other systems such as fuel, hydraulic, and flight control.

In the figure, triangle symbols show conventional 2 engine, 3 engine and 4 engine aircraft dispatch reliability at an equal experience level of 5 3/4 years. Although the data points approximate a straight line, the data cannot be extrapolated in linear fashion since the addition of engines has a pyramiding effect in decreasing total aircraft reliability. For example, increasing the number of engines affects other systems such as fuel, instrumentation, controls and structure which in turn affect their support systems such as electrical, hydraulic and pneumatic. In addition, different aircraft manufacturers are involved which also induce variations in dispatch reliability since design details and philosophies differ.

To eliminate the above variables, maximum and minimum expected curves were calculated keeping the reliability of each system constant and only varying the number of engines. Only engine dispatch reliability accounts for the difference between the 0.987 and 0.999 lines; the effect of adding engines is reflected in the slope of each line. It is noteworthy that the minimum expected curve and the curve connecting the data points are nearly parallel. The DC-10 objective lies well above the "current experience" for three engine aircraft. Therefore, it appears mandatory that efforts be made to minimize the number of engines.

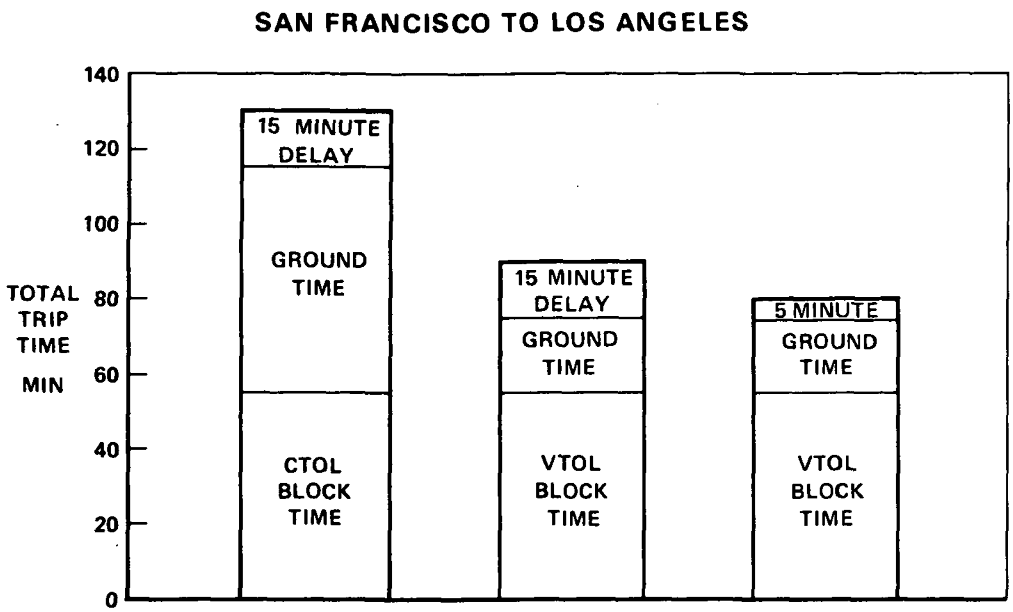
Figure 6-4



The current measure of airline dispatch reliability is a delay of more than 15 minutes. The figure of delay as a percentage of block time indicates that 15 minutes is a small percentage of the block time for long-haul operations. In short-haul operations, 15 minutes can be as much as 40% of the block time. Therefore, for short-haul operations, 5 minutes would be a better measure of dispatch reliability.

Figure 6-5

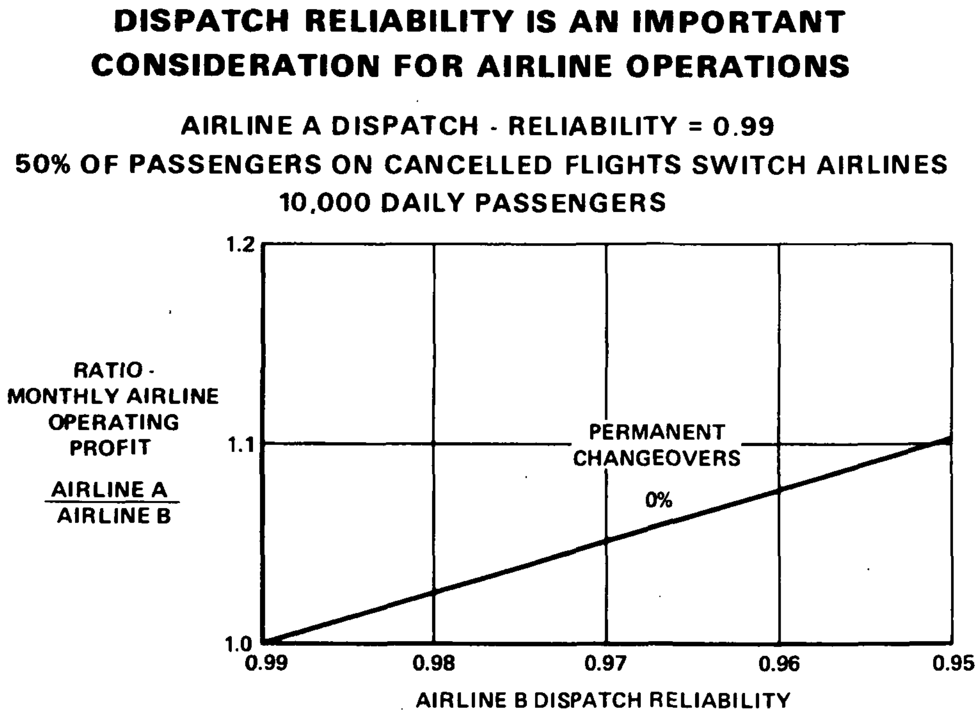
COMPARISON OF DELAYS ON A SHORT HAUL TRIP



Another measure of dispatch reliability is the comparison of the delay with the total trip time; that is, door-to-door time including ground access on both ends of the trip. The specific example shown is the short-haul trip from Los Angeles to San Francisco. The first bar compares a 15-minute delay to a CTOL trip with a 1/2-hour ground access time on each end. For VTOL the ground access time should be more like 10 minutes on each end. As can be seen, the 5-minute delay maintains the balance between delay and total trip time. This further emphasizes the importance of striving for high dispatch reliability and consequently the lowest practicable number of engines.

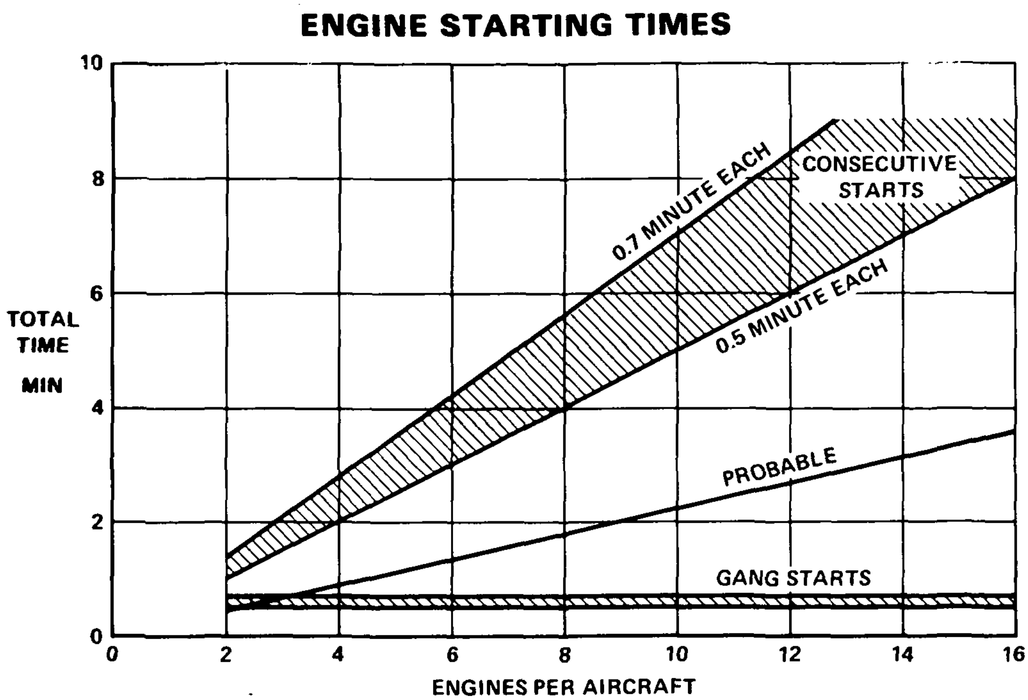
The figure below indicates the results of a study of the effects on airline profits of operating aircraft with different dispatch reliabilities. Two airlines are assumed to be operating on the same system, 100 daily flights with 100-passenger aircraft at a 50% load factor. All things are assumed equal (cabin service, gate locations, schedule, etc.) except the dispatch reliability of the aircraft. On those flights which are cancelled, some of the passengers will switch airlines. The other airline adds these passengers to existing flights and, in effect, boosts its load factor. The cancelling airline still absorbs some cost penalties associated with the cancelled flight and switching passengers.

Figure 6-6



The difference in airline profits will reflect the difference in dispatch reliabilities, the percentage of passengers who switch from cancelled flights, and the percentage of those who decide they like the alternate airline and thereafter book space on it. The figure indicates the ratio of monthly profits for Airline A with a 99% dispatch reliability as a function of Airline B dispatch reliability. Fifty percent of the passengers on a cancelled flight switch airlines; however, there are no permanent changes. For a difference in dispatch reliability of 4% (99 versus 95) the ratio is 1.1, or Airline A holds a 10% advantage. If just 2% of the switches are permanent switches, the advantage becomes 16%.

Figure 6-7



Large numbers of engines pose additional operational problems in that each engine must be started and checked out before flight as well as during flight in preparation for takeoff and landing. Although consecutive engine starts are desirable for minimizing flight crew work load as well as primary and secondary (induced) failure probabilities, multiple and/or short-sequence starts (paired or triple) will be essential to conserve time and fuel. Multiple starting will introduce complexities such as automatic starting and automatic monitoring equipment, in order to keep the work load within human capability, in proportion to the number of engines. This figure shows the calculated time range for various numbers of engines per aircraft, twelve engines taking almost twice as long to start as six engines for an "optimum" starting sequence.

7. SELECTED AIRCRAFT PERFORMANCE

A three view and the performance of the selected study aircraft are shown on the following figures.

Figure 7-1

SELECTED AIRCRAFT

6 ENGINE RLF AIRCRAFT

VT102-6-6A

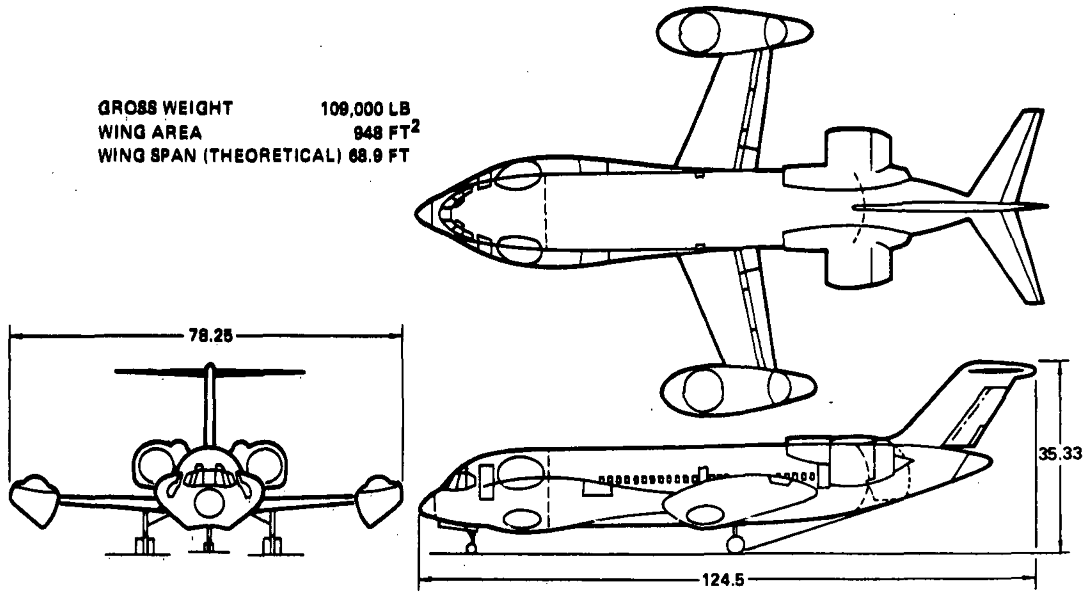
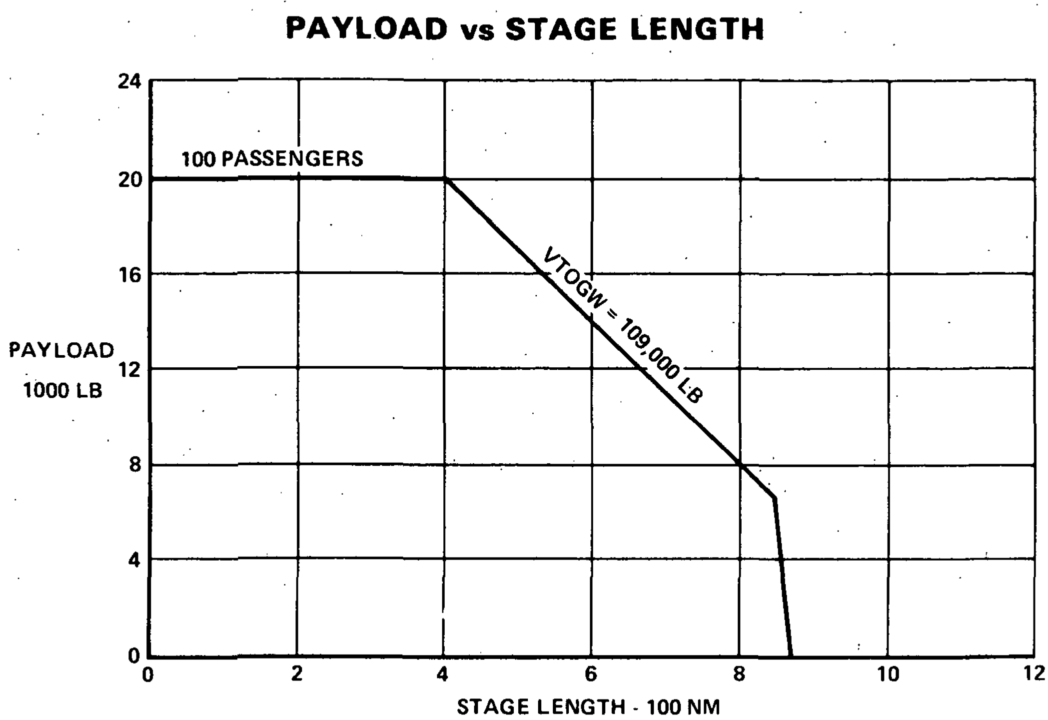


Figure 7-2

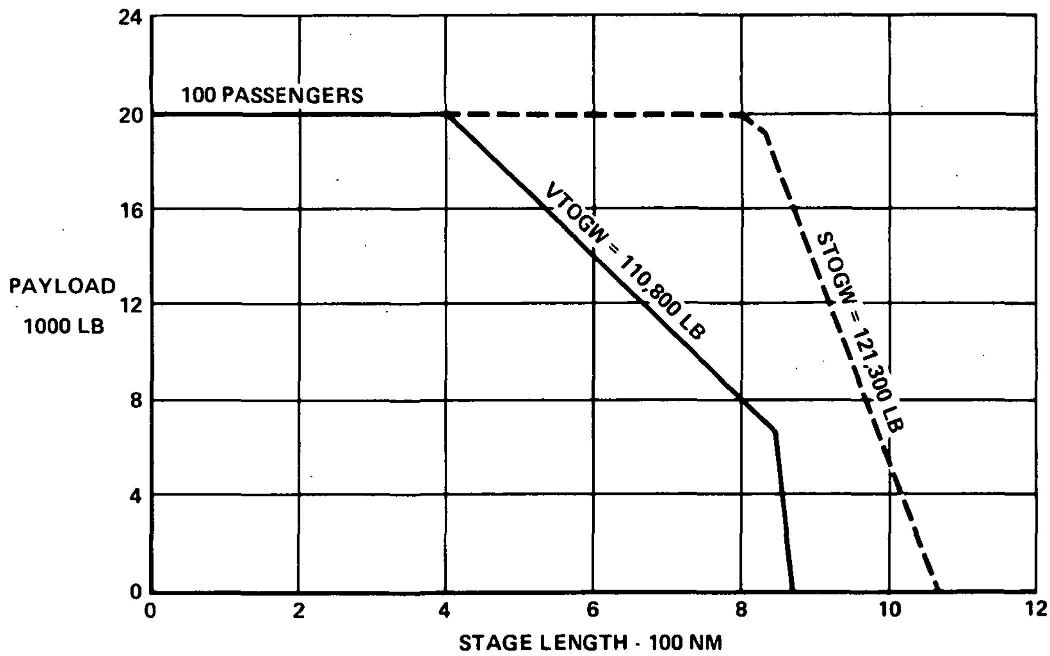


Payload-stage length capability of the selected 6 engine RLF configuration is shown for a cruise altitude of 20,000 feet and a VTOGW of 109,000 pounds. The maximum stage length is limited by the maximum internal wing fuel volume. Wing fuel tanks occupy the total available volume between the wing spars.

The basic RLF configuration is sized for a 400 nm VTOL mission at a TOGW of 109,000 pounds. In order to provide the structural capability for the alternate 800 nm STOL TOGW, changes to the OWE of the basic design are required if performance of the VTOL mission is to remain unchanged. These changes result in a revised design TOGW of 110,800 pounds for the 400 nm VTOL aircraft. A takeoff gross weight of 121,300 pounds is required for the 800 nm alternate STOL mission.

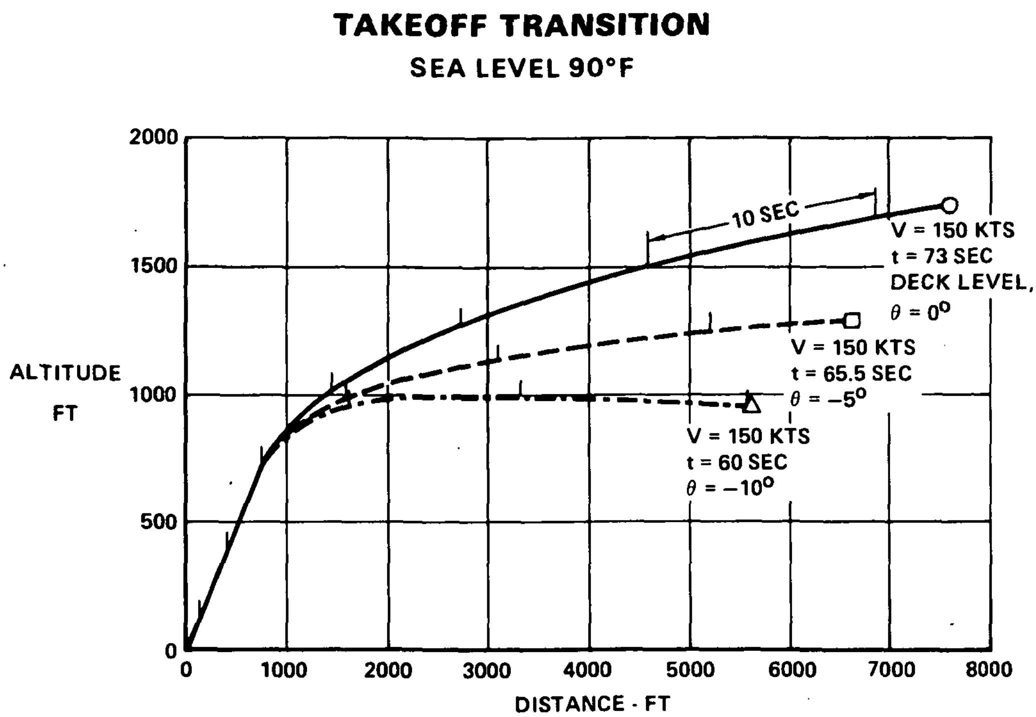
Figure 7-3

PAYLOAD vs STAGE LENGTH



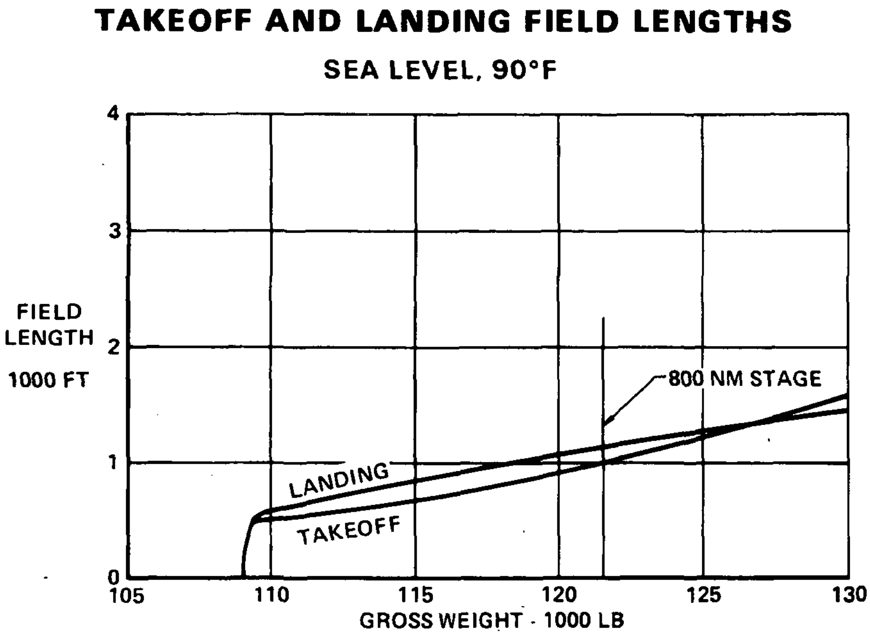
STOL payload-stage length capability of the selected RLF configuration is shown for the aircraft designed to the 800 nm STOL mission. The 800 nm stage length requires almost 100% of internal wing fuel. The STOL mission is flown at the average cruise ceiling to obtain better specific fuel consumption at altitude for the longer distances. Maximum distance is limited by internal wing fuel. The VTOGW shown has been adjusted for the structural weight increase required for the alternate 800 nm STOL mission.

Figure 7-4



Takeoff transition performance of the selected RLF configuration is shown at maximum VTO gross weight. The takeoff consists of a vertical lift-off and high rate of climb to 600 feet (to minimize noise) followed by a climbing acceleration to conversion speed. Conversion speed is 1.3 V_{stall} power off. The aircraft deck attitude is held constant as indicated to show the trade-offs in deck angle versus altitude and time to conversion speed.

Figure 7-5



The STOL performance shown is in accordance with study design guidelines and safety factors including gas generator and fan out considerations. Takeoff field length is 1000 feet for the 800 nm stage length aircraft. The STOL aircraft incorporates the required structural weight necessary for the STOL mission. Nearly equal takeoff and landing distances are indicative of a well-balanced STOL configuration.

8. FAN PRESSURE RATIO AND ENERGY TRANSFER CONTROL (ETC)

The interconnected propulsion control system is called the Energy Transfer Control (ETC) system. The V/STOL propulsion system consists of gas generator/lift fan units interconnected in pairs. Only one duct is used to interconnect each two lift units. This duct is sized to carry slightly more than half of the gas flow from one gas generator as required during a gas generator failure. During normal operation, the duct Mach number is essentially zero except for control inputs, at which time the maximum duct Mach number is approximately 0.10. This results in very low pressure losses during energy transfer. The method of providing the differential thrust moments required for V/STOL aircraft control utilizes the inherent short-term power increase capability of the engines and the interconnect system to transfer some of the flow to further increase the power available at one of the lift fans. This is achieved by simply modulating a valve ahead of one of the fans.

Figure 8-1
Six RLF Engine Propulsion System Arrangement

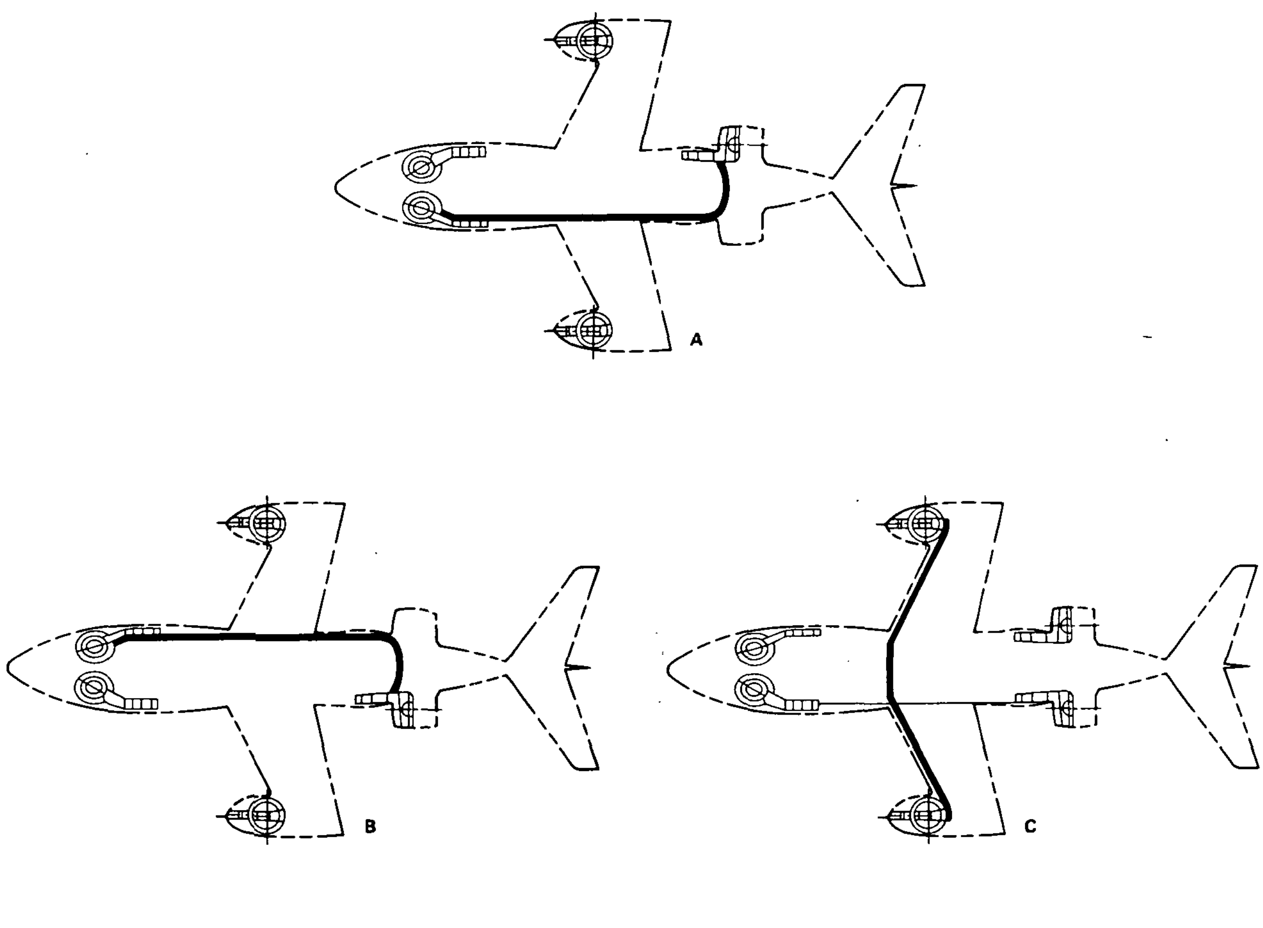
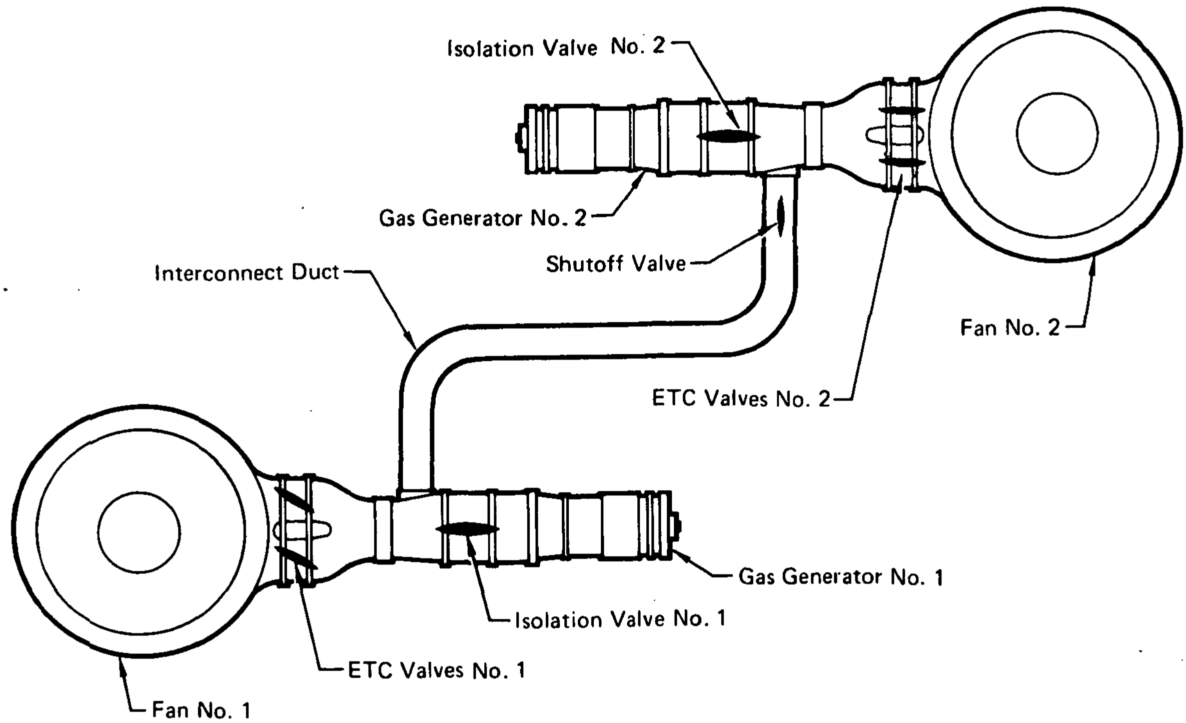


Figure 8-2

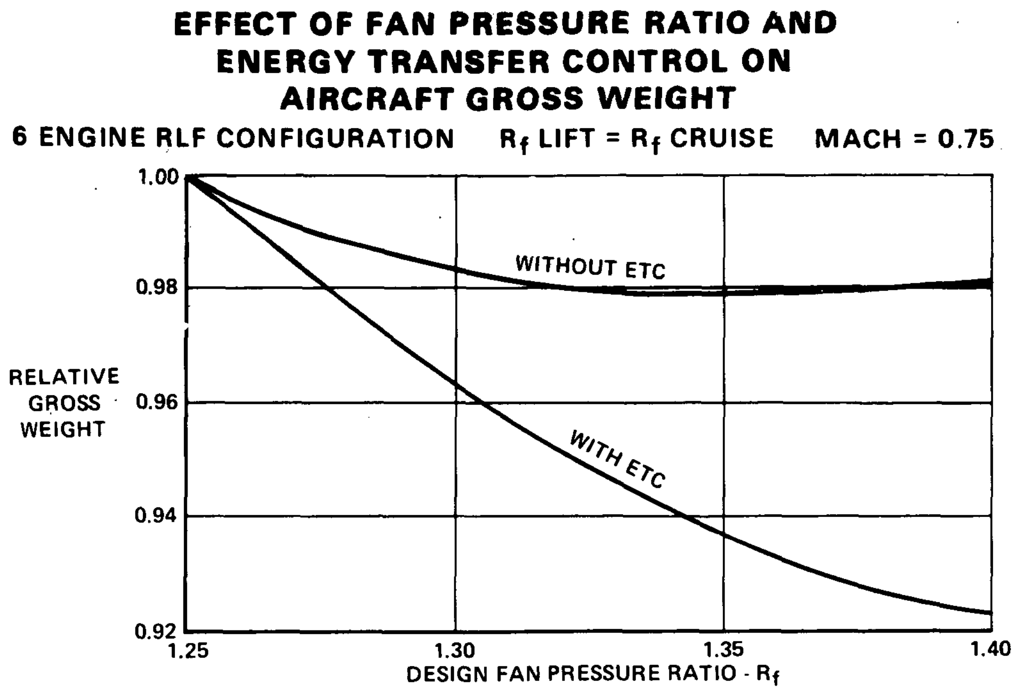
ETC VALVE ARRANGEMENT



The control system uses an interconnected duct between the gas generator and the lift fan. Valves are located at the entrance to the fan scroll to modulate the gas power into the lift fan and also to isolate half of the scroll should a gas generator fail. Additional valves are located at the exit of each gas generator to isolate the gas generator in case of failure. In this concept, gas generator rpm and the flow to the fan turbine are controlled with the valve to vary the fan rpm and thrust. With the rotation of Valves No. 1, an increase in pressure loss occurs across these valves. The choked tip turbine nozzle then passes less flow to the Fan No. 1 turbine and forces this increment in flow to transfer to the Fan No. 2 turbine. This condition increases the pressure behind the turbine on both gas generators and tends to reduce gas generator rpm. To maintain rpm, the fuel control increases flow and increases the turbine exit pressure and temperature. The increase in gas pressure, temperature, and flow produces a substantial increase in gas horsepower available at Fan No. 2 for control with extremely good time response. The increase in horsepower is a transient condition during control application. Only a small increase represents a steady state condition for trim purposes.

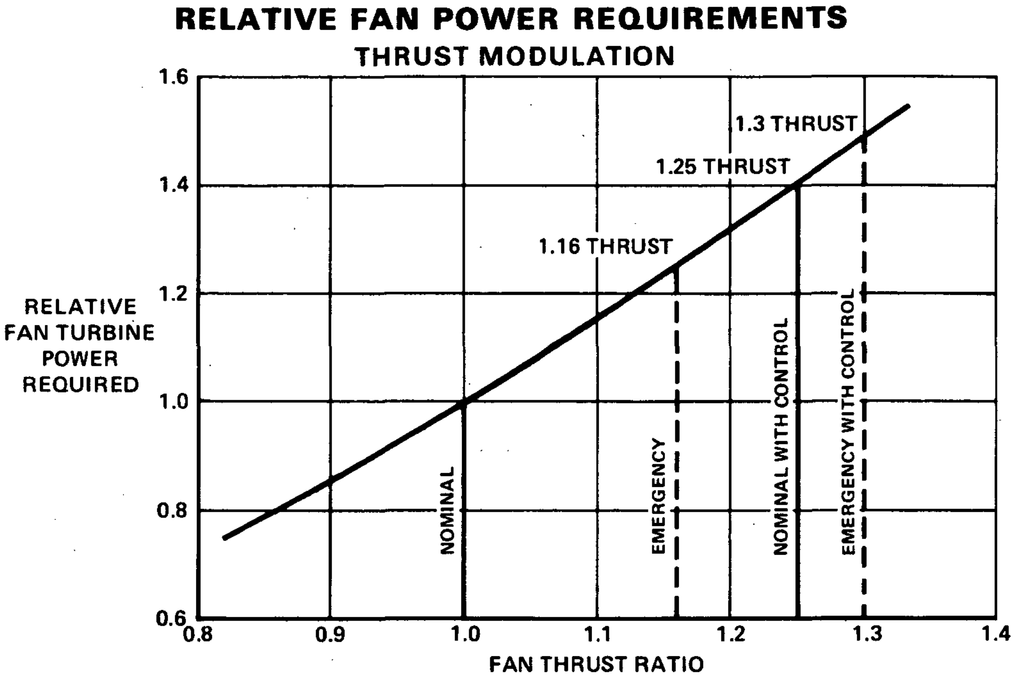
Both the Energy Transfer Control (ETC) system and fan pressure ratio have a direct effect on aircraft size. Increased fan pressure ratio alone has little effect on airplane size, but pressure ratio combined with the ETC system has a significant effect. These effects are presented in the following figures and discussion.

Figure 8-3



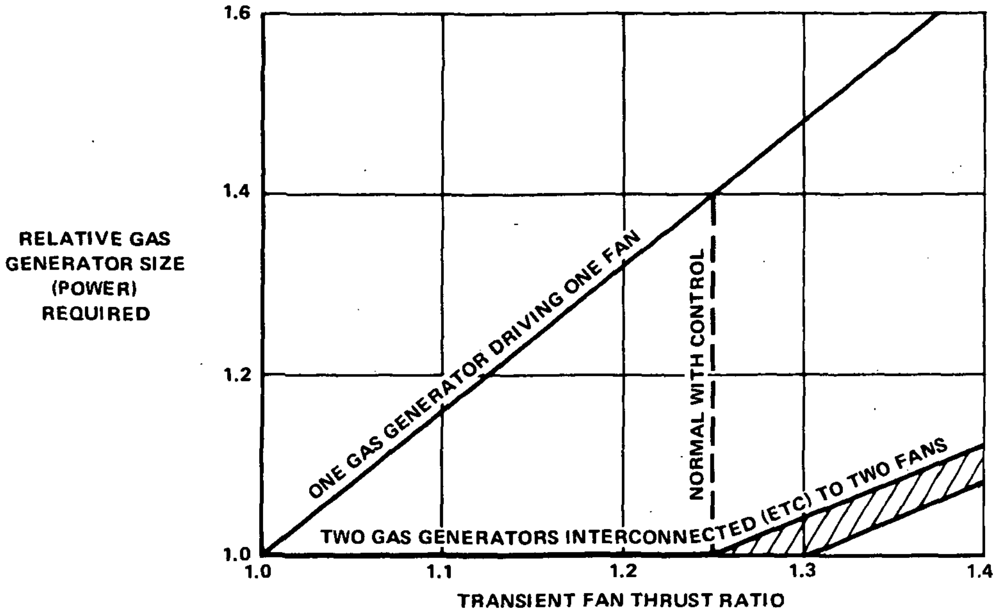
The size of the gas generators can be reduced to match cruise requirements as fan pressure ratio increases. An 8% smaller aircraft results by use of a fan pressure ratio of 1.4 in combination with the ETC system. Full advantage of the ETC system is not available at lower fan pressure ratios.

Figure 8-4



In Figure 8-4, nominal thrust is defined as not less than 1.10 times the VTOL gross weight. A 25% thrust increase above nominal requires a tip turbine power increase of 40%. Therefore, sufficient reserve must be built into the gas generator to permit transient rpm and temperature increases to obtain the 40% increase. This is equivalent to a 40% oversizing of the gas generator for a single gas generator powering one fan.

FIGURE 8-5
RELATIVE GAS GENERATOR SIZE FOR CONTROL THRUST

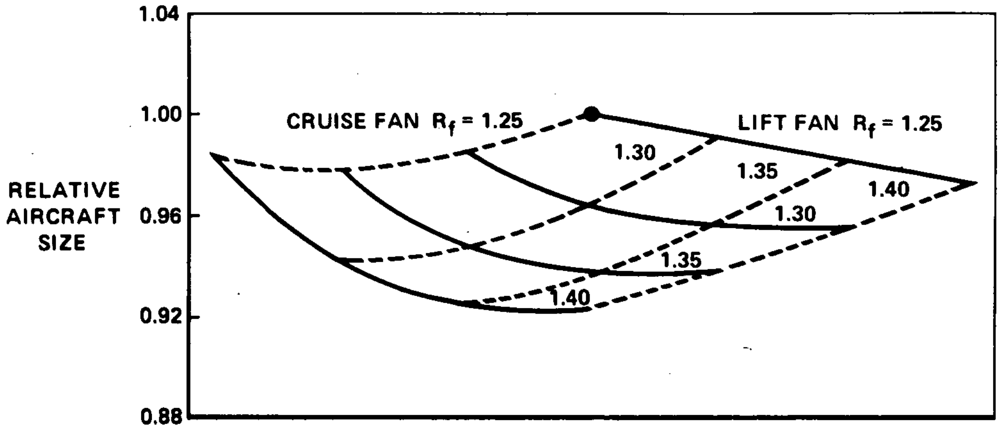


In the system where two gas generator/fan units are interconnected, the increased power to one fan is obtained by use of ETC where the engine rpm remains unchanged, but the gas generator exit temperature and pressure transients are increased during control application but remain within the gas generator limits. This method of obtaining control through use of ETC requires no oversizing of the gas generator for fan thrust excursions up to approximately 25% above the nominal design value. The relative sizes of gas generators for the two concepts are shown.

Figure 8-6

EFFECT OF DESIGN FAN PRESSURE RATIO ON AIRCRAFT SIZE

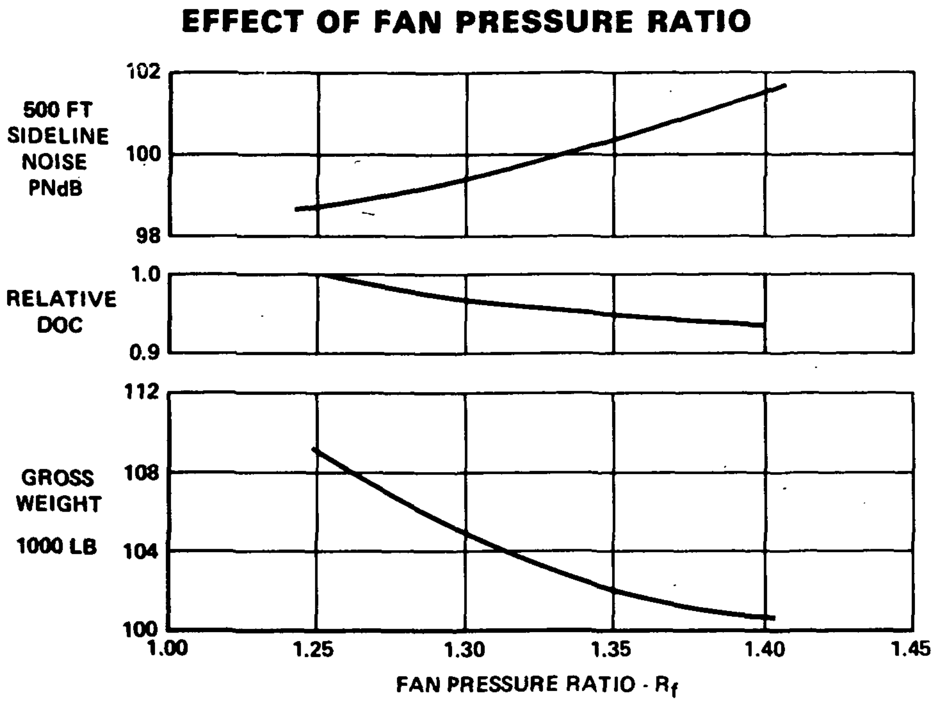
VT102 RLF SERIES



Several combinations of fan pressure ratio for the 6 engine RLF configuration have been explored for a constant mission performance. The best combination for minimum airplane size is for a 1.4 fan pressure ratio for both cruise and lift fans. The mixed fan pressure ratio configurations having low fan pressure ratio for lift and high fan pressure ratio for cruise do not have the expected payoff because of the engine/fan matching required for interconnecting the forward fuselage lift fans with the aft fuselage lift/cruise fans.

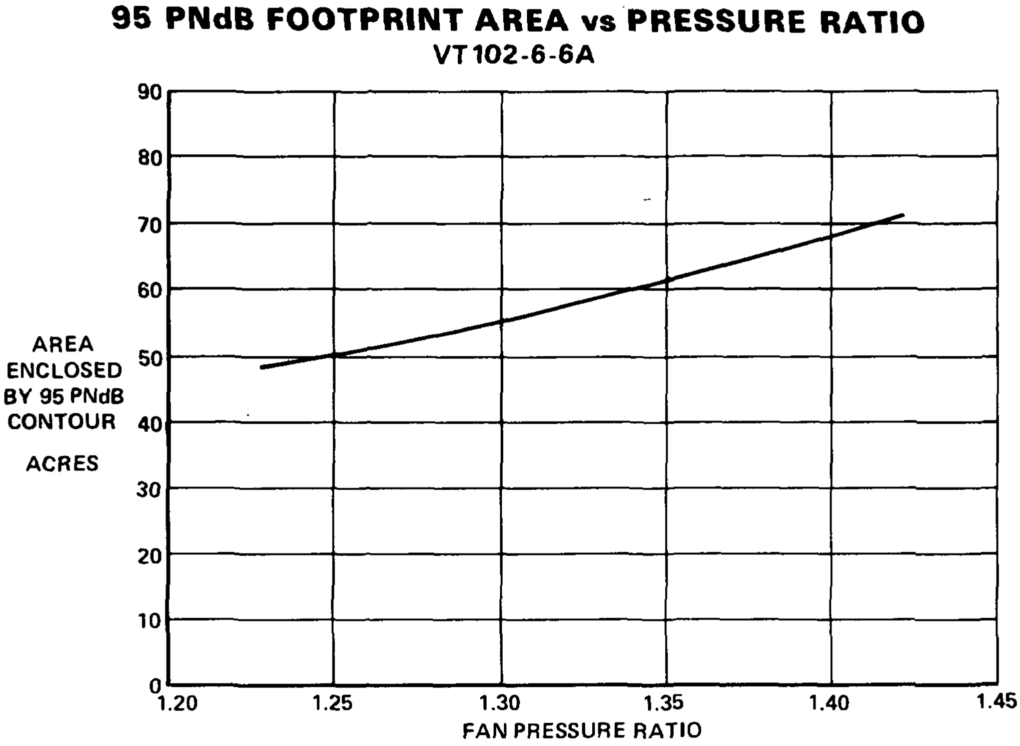
Each aircraft combination has a common size gas generator. For example, in a mixed fan pressure ratio configuration all the gas generators are the same size. For the configurations where the fan pressure ratio for the lift/cruise fans is different from the lift fans, each fan type is operated at its design pressure ratio during V/STOL operations. There are many different combinations of fan and gas generator that can be used to integrate the propulsion system of a mixed fan pressure ratio configuration. The method used resulted in the lightest and lowest cost propulsion system without compromising the Energy Transfer Control system.

Figure 8-7



The effects of fan pressure ratio on aircraft gross weight, relative DOC, and 500-foot sideline noise are summarized in Figure 8-7. Changing from a fan pressure ratio of 1.25 to 1.35 reduces DOC by 5% and aircraft gross weight by 6% with approximately 2 PNdB increase in 500-foot sideline noise. The gross weight change is apparent from Figures 8-3 and 8-6. Noise levels are computed using only GE-furnished inlet and exhaust treatment in the fans. The DOC reduction is a result of reduced airframe weight, yielding lower airframe prices. The reduction in block fuel as pressure ratio decreases also reduces DOC.

Figure 8-8



The area enclosed by the 95 PNdB ground contour of the 100-passenger class RLF aircraft is shown on this chart as a function of fan pressure ratio. The increase in PNdB acres as pressure ratio is increased is small in comparison to the large areas of current or projected conventional transport aircraft.

Conclusions - The following observations become apparent when reviewing the results of the pressure ratio study: The ground rules are satisfied with 6 engines and 1.25 design fan pressure ratio. The benefits of ETC are not realized since the propulsion system must be oversized to attain 0.75 M cruise speed. ETC benefits are realized at a 0.75 M cruise speed with a design fan pressure ratio of 1.35 at a penalty of 2 PNdB increase in aircraft noise. Because of the operational and cost factors involved, the goal is to seek a solution with an aircraft having a small number of engines. Therefore, the full ETC benefits should be applied to the 4 engine aircraft, which may prove to be an attractive solution.

9. ECONOMICS

9.1 INTRODUCTION

A critical parameter in the evaluation of aircraft designs for commercial applications is the direct operating cost (DOC). This section presents the results of a direct operating cost (DOC) analysis of the lift fan V/STOL aircraft. The method used to estimate DOCs is the 1968 AIA V/STOL Standard Method, Reference 4, with one exception, the maintenance costs for lift engines are supplied to MCAIR. Airframes are priced at $100 per pound of empty weight. Engine prices are also supplied for the study. However, an analysis (Section 9-4) of current cruise engines indicates these costs are apparently higher than might be expected. Therefore, DOCs are shown as bands. The upper limit represents the DOC if the "Input" prices are used, and the lower limit indicates DOC if the current engine experience is used to estimate "Should Cost" prices.

9.2 SUMMARY

Figure 9-1 indicates the DOCs for the VT102-6-6A, remote lift fan (RLF), interconnected aircraft and for the VT104-2-12K, integral lift fan (ILF), non-interconnected aircraft for the 400 nm VTOL mission and the 800 nm STOL mission. The different values represent the effects of using different engine prices. All DOCs are quoted in terms of cents per available seat statute mile. The DOCs for the two aircraft are reasonably close, with a slight edge going to the RLF interconnected aircraft.

9.3 DOC VERSUS STAGE LENGTH

Figure 9-2 indicates DOCs as a function of stage length. Since the DOCs are so close for the two aircraft, a single line is used for both. The band of values is used to indicate the range of engine prices.

9.4 ENGINE PRICES

The DOC of a V/STOL aircraft is extremely sensitive to the cost of the engines, since the engines represent a larger portion of the investment than for conventional aircraft. This section discusses the analyses used to develop the "Should Cost" engine prices used in the DOC computations. The data base consisted of 10 commercial cruise engines, the JT3D, JT8D, and CF6 including various versions.

The first analysis used a regression of price per pound of engine dry weight versus engine thrust-to-weight ratio. The results of this analysis are shown in Figure 9-3 . The second analysis correlated price per pound of thrust against total thrust. The results of this analysis are not shown; however, they do corroborate the results of the first analysis that the "input" engine prices are higher than those which might be extrapolated from current experience.

9.5 SENSITIVITY TO FAN PRESSURE RATIO

Figure 9-4 is a carpet plot of the results of a DOC sensitivity to fan pressure ratio study. In this case, the engines are priced using the data provided as "input" for the study. As can be seen, the case where both lift and lift/cruise fans are at a 1.4 fan pressure ratio yields the lowest DOCs.

Figure 9-1
Direct Operating Cost Summary

1971 Dollars; 1968 AIA Method

Aircraft	400 nm VTOL Mission (460 st. mi.)		800 nm STOL Mission (920 st. mi.)	
	DOC (¢/available seat mile)*	Relative DOC	DOC (¢/available seat mile)*	Relative DOC
VT-102-6-6A RLF Interconnected	2.11-2.53	1.0	1.74-2.07	1.0
VT-104-2-12K ILF Non-Interconnected	2.19-2.66	1.045	1.81-2.19	1.05

Aircraft priced at $100 per pound of airframe weight plus engines.
*Statute miles.

Figure 9-2

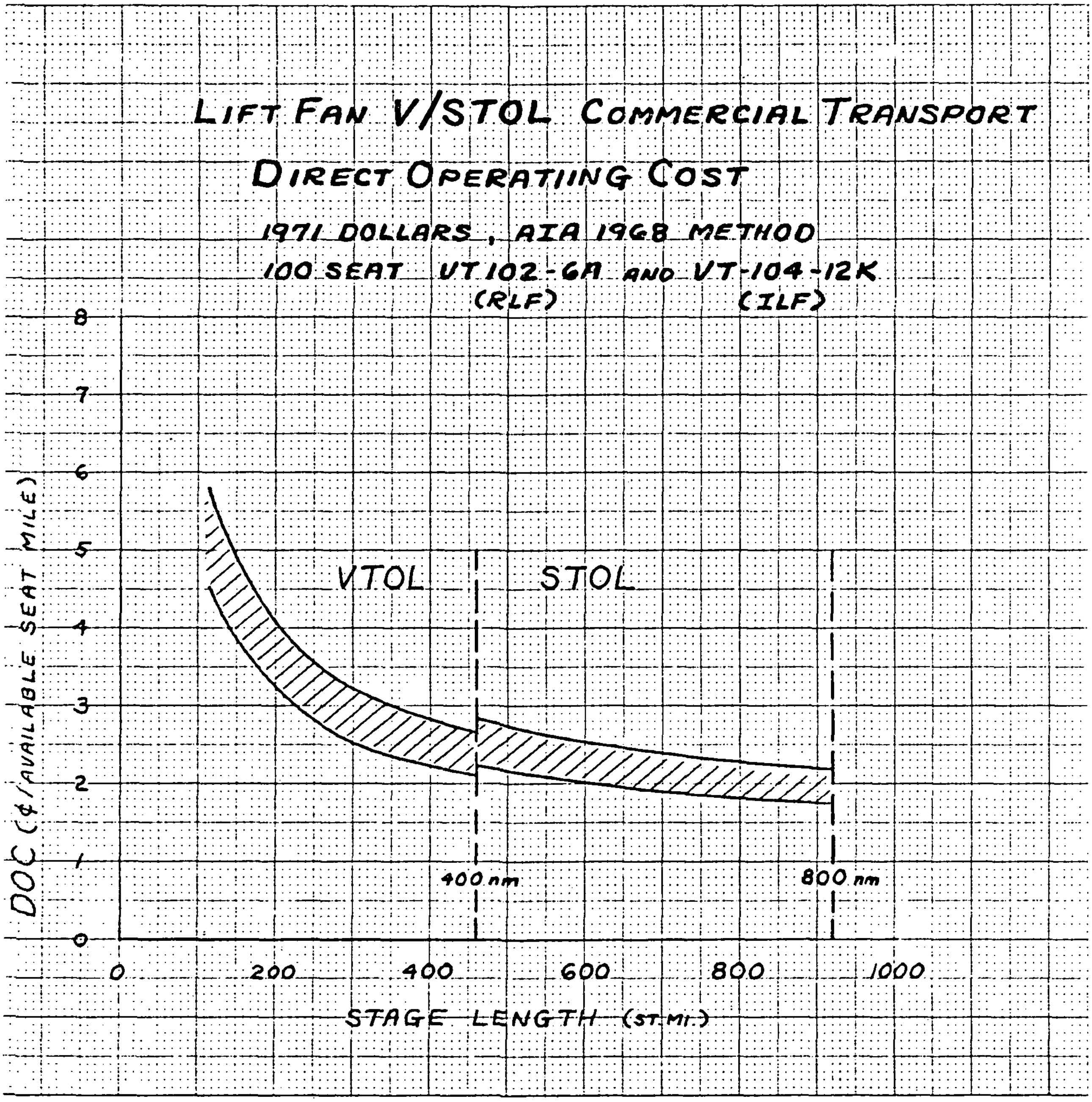

LIFT FAN V/STOL COMMERCIAL TRANSPORT
DIRECT OPERATIING COST
1971 DOLLARS, AIA 1968 METHOD
100 SEAT VT 102-6A AND VT-104-12K
(RLF) (ILF)
DOC (¢/AVAILABLE SEAT MILE)
8
7
6
5
4
3
2
1
0
VTOL
STOL
400 nm
800 nm
0
200
400
600
800
1000
STAGE LENGTH (ST. MI.)

Figure 9-3

A Comparison of Lift Fan Prices Supplied for the Study with Current Trends in Commercial Cruise Engines

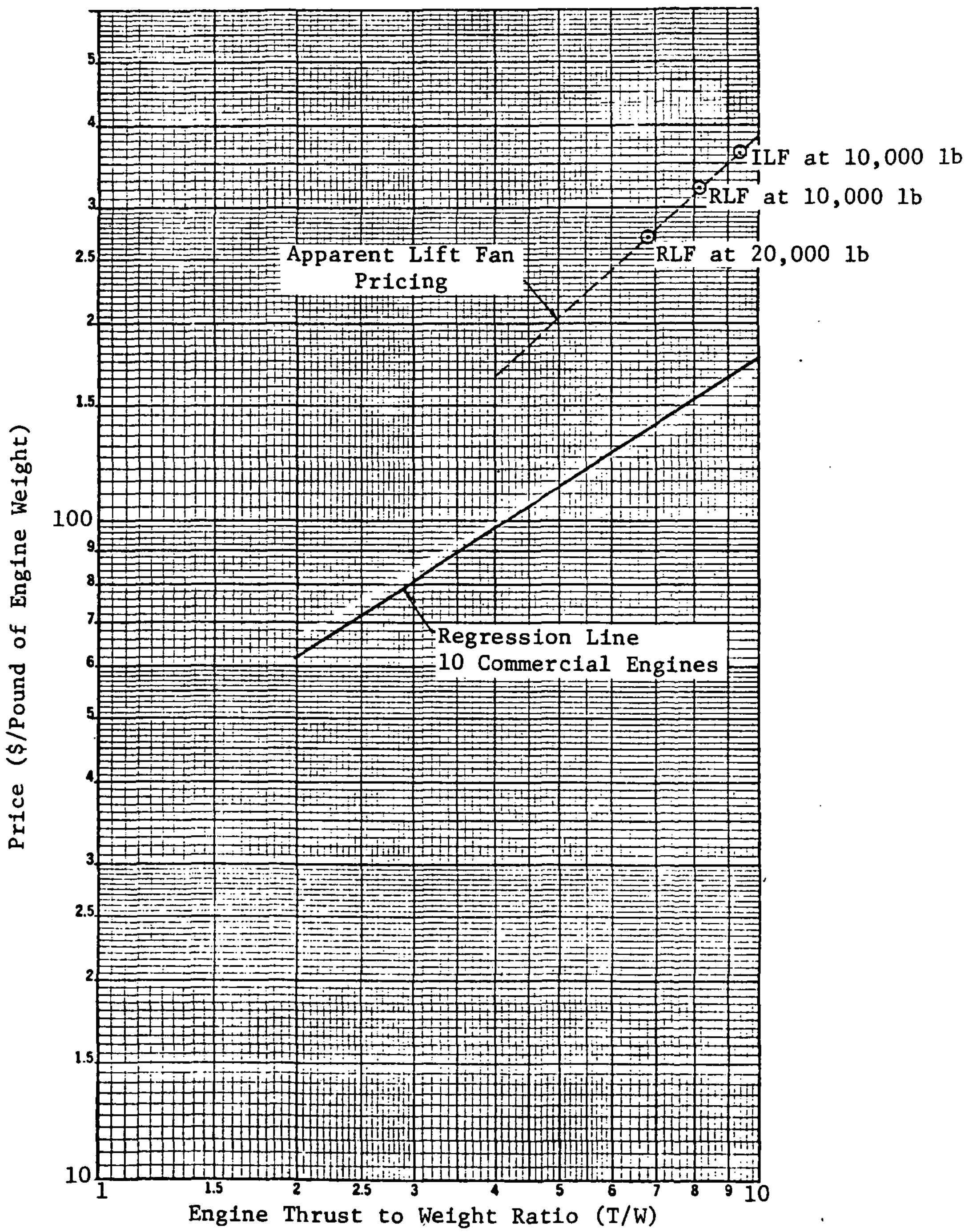
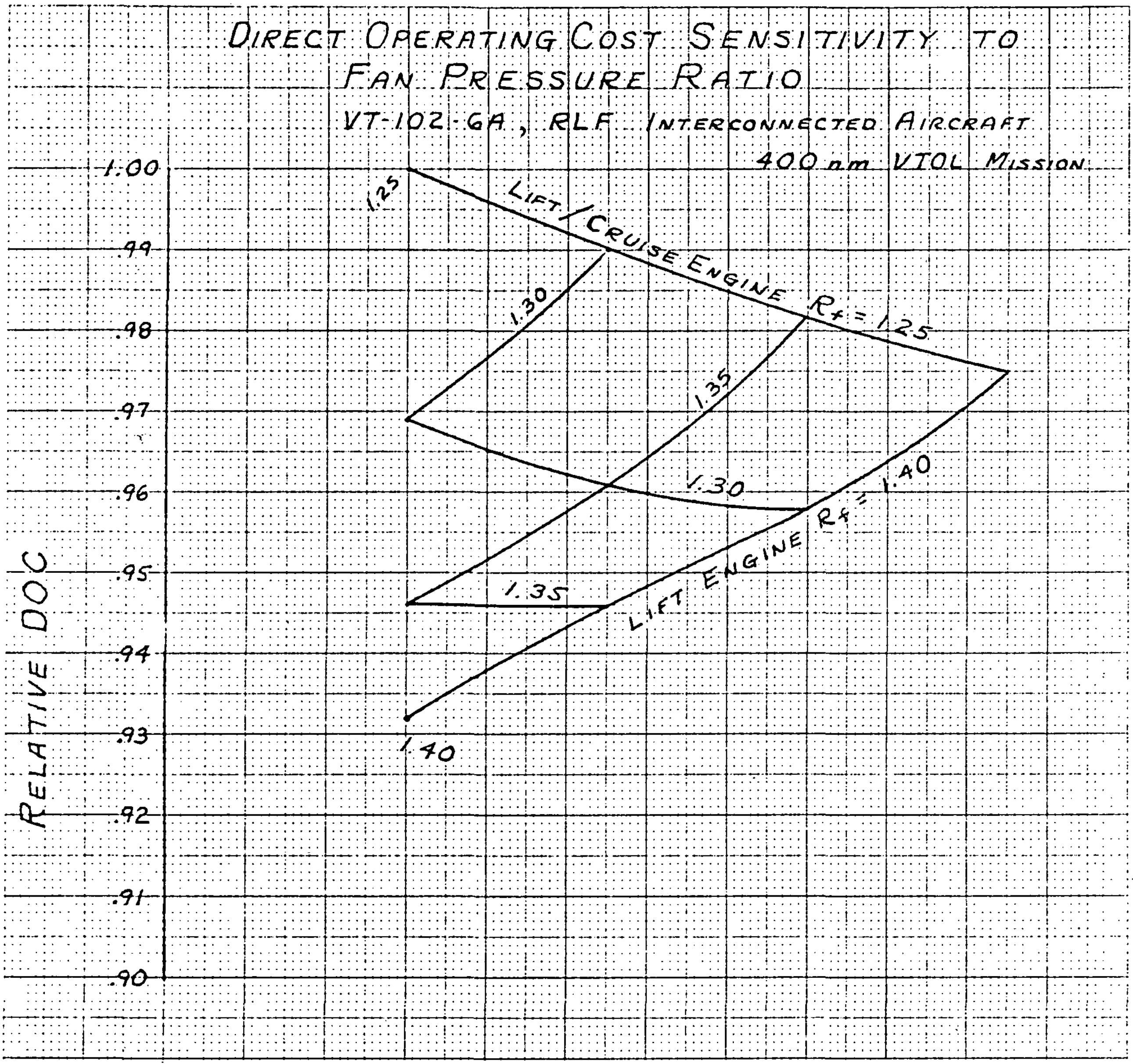


Figure 9-4

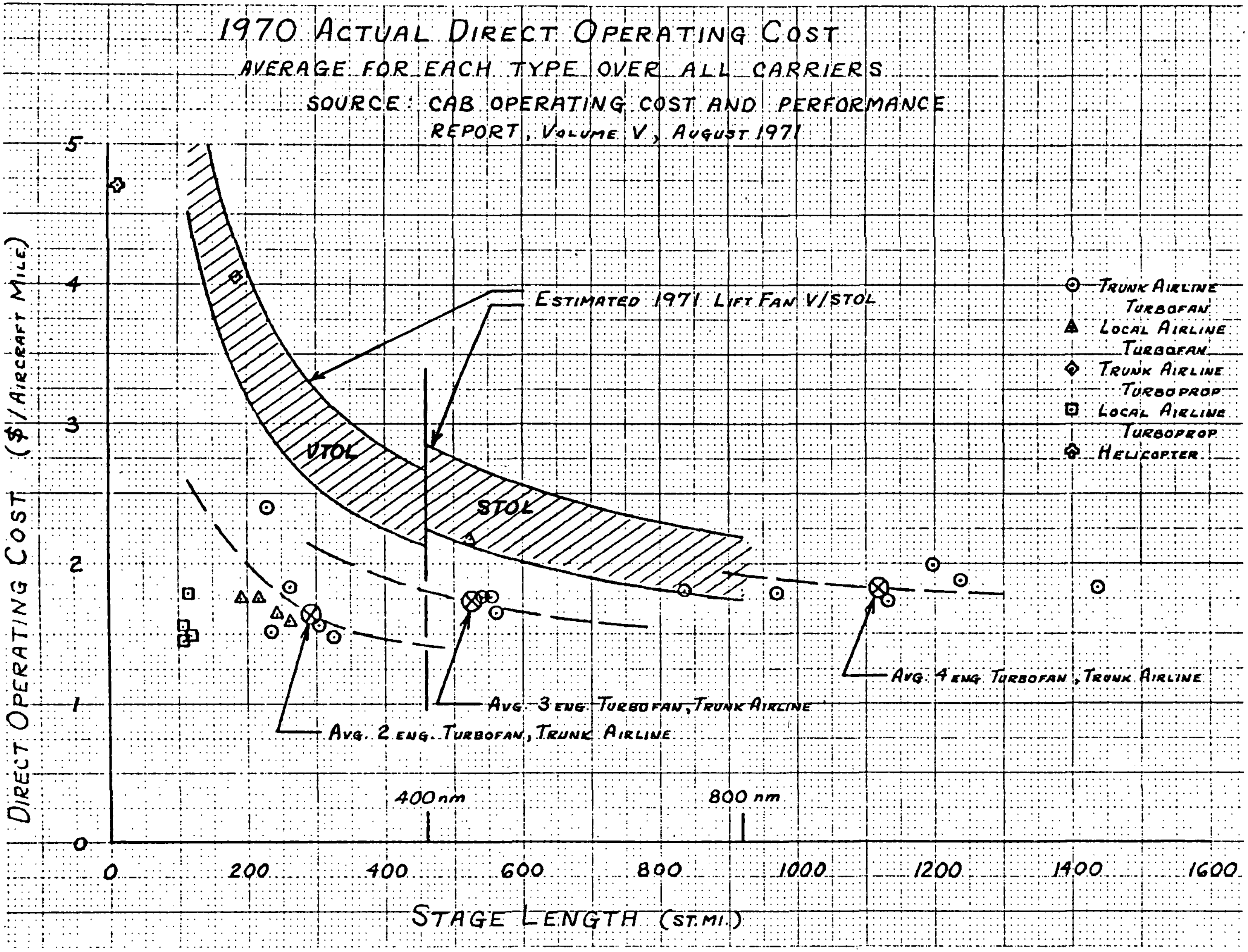


DIRECT OPERATING COST SENSITIVITY TO
FAN PRESSURE RATIO
VT-102-6A, RLF INTERCONNECTED AIRCRAFT
400 nm VTOL MISSION
1.00
.99
.98
.97
.96
.95
.94
.93
.92
.91
.90
RELATIVE DOC
1.25
LIFT/CRUISE ENGINE R_f = 1.25
1.30
1.35
1.30
1.35
1.40
LIFT ENGINE R_f = 1.40

9.6 COMPARISON WITH ACTUAL DOCs

Figure 9-5 compares the lift fan DOCs with 1970 published values for current regular-bodied aircraft. The DOCs are shown in terms of cost per aircraft mile, which is the true cost to the airline for operations. The average values for 2, 3, and 4 engine regular-bodied turbofans are shown. It is true, that the newer wide-bodied jets cannot be compared on this basis. However, the short-haul market for which the V/STOL aircraft is designed is frequency sensitive; that is, the passenger market depends on the number of flights per day. Large wide-bodied jets depend on being able to eliminate multiple flights by smaller aircraft to achieve the economies of scale. In the short-haul market, if the service is too infrequent, the passengers may find alternate modes of travel. Figure 9-5 indicates that although V/STOL operations are more expensive ($0.50 to $1.00 per statute mile), they are not so high as to be out of the question. The range of V/STOL values indicates the range of results depending on engine prices.

Figure 9-5



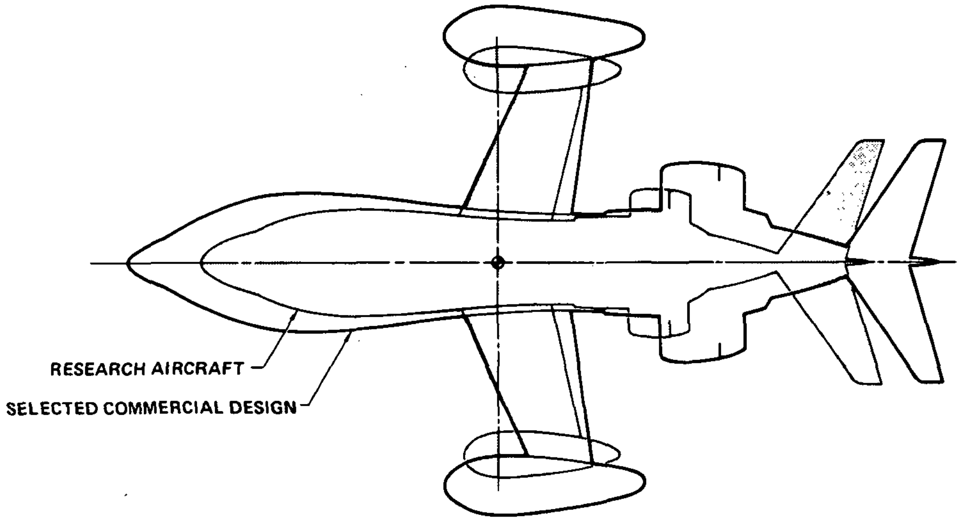
1970 ACTUAL DIRECT OPERATING COST
AVERAGE FOR EACH TYPE OVER ALL CARRIERS
SOURCE: CAB OPERATING COST AND PERFORMANCE REPORT, VOLUME V, AUGUST 1971
ESTIMATED 1971 LIFT FAN V/STOL
VTOL
STOL
TRUNK AIRLINE TURBOFAN
LOCAL AIRLINE TURBOFAN
TRUNK AIRLINE TURBOPROP
LOCAL AIRLINE TURBOPROP
HELICOPTER
AVG. 2 ENG. TURBOFAN, TRUNK AIRLINE
AVG. 3 ENG. TURBOFAN, TRUNK AIRLINE
AVG. 4 ENG. TURBOFAN, TRUNK AIRLINE
400 nm
800 nm
0
1
2
3
4
5
0
200
400
600
800
1000
1200
1400
1600
DIRECT OPERATING COST ($/AIRCRAFT MILE)
STAGE LENGTH (ST. MI.)

10. COMPARISON OF RESEARCH AND SELECTED COMMERCIAL CONFIGURATION

The studies to date lead to a 6 engine interconnected RLF configuration as the most representative candidate configuration for a 1985 VTOL civil transport. The study efforts validate the initial research transport configuration (Model 253). The MCAIR Model 253 is about an 80% size model of the 1985 100-passenger aircraft. Characteristics of the research and selected aircraft are shown below. Capabilities of the research transport aircraft are presented in the following paragraphs.

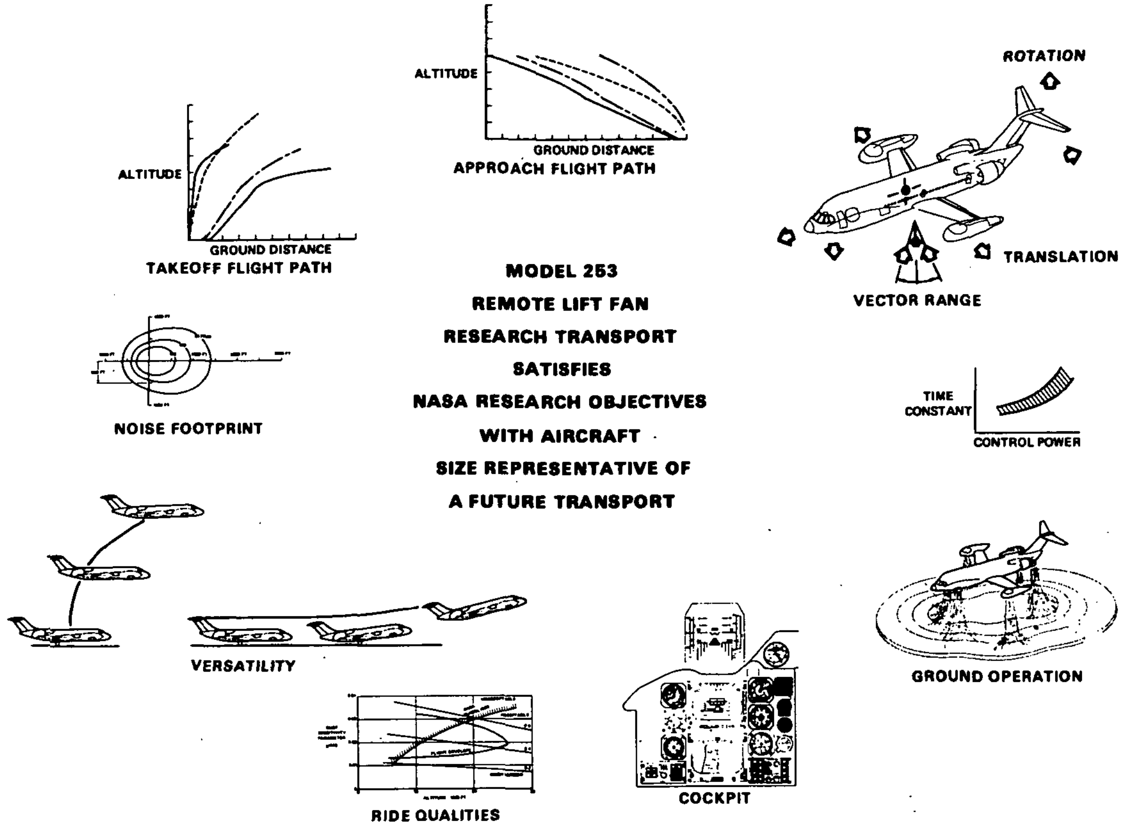
Figure 10-1

COMPARISON OF RESEARCH AND SELECTED COMMERCIAL CONFIGURATION



CHARACTERISTICS	RESEARCH AIRCRAFT	SELECTED AIRCRAFT
GROSS WEIGHT - POUNDS	60,000 - 80,000	109,000
OVERALL SPAN - FEET	65.16	78.25
OVERALL LENGTH - FEET	104.3	124.5
ENGINES		
NO.	6	6
DESIGN FAN PRESSURE RATIO R_f	1.39	1.25

Figure 10-2



The Model 253 overall size (approximately 80%), VTO gross weight (greater than 50%), and configuration as compared with the selected future V/STOL transport aircraft, as well as its versatility, make it an ideal research vehicle preceding the introduction of the V/STOL transportation system.

The lift and control concepts, and control power allow complete exploration of a wide variety of vertical and short takeoff, approach, and landing paths and techniques. Therefore, determination of the terminal requirements and performance and flying qualities necessary to support a V/STOL transportation system may be accomplished. The size and inertias of the aircraft will assure significance of the data.

Studies have shown that the airline type cockpit and instrument display area in the Model 253 will allow introduction and development of necessary avionics and pilot displays for precision navigation and communication in the critical V/STOL system terminal environment.

The expanded cruise flight envelope will allow ample variation of parameters to establish acceptable ride quality criteria.

The noise signature of the Model 253 can be attenuated by proper acoustic treatment to explore the noise acceptability of this type of aircraft in the operational environment.

11. IMPACT OF STUDY GUIDELINE RESTRAINTS

11.1 DESIGN COMPROMISES TO EXPAND MARKETABILITY

The study guidelines specify that the study aircraft be designed for a VTOL range of 400 nautical miles and that the STOL range at maximum payload be 800 nautical miles but the latter should be regarded as a target rather than a requirement. When these guidelines are combined with a fan pressure ratio as low as 1.25 which was specified for the study, the aircraft is less competetive for markets in the 400 to 800 nautical mile range.

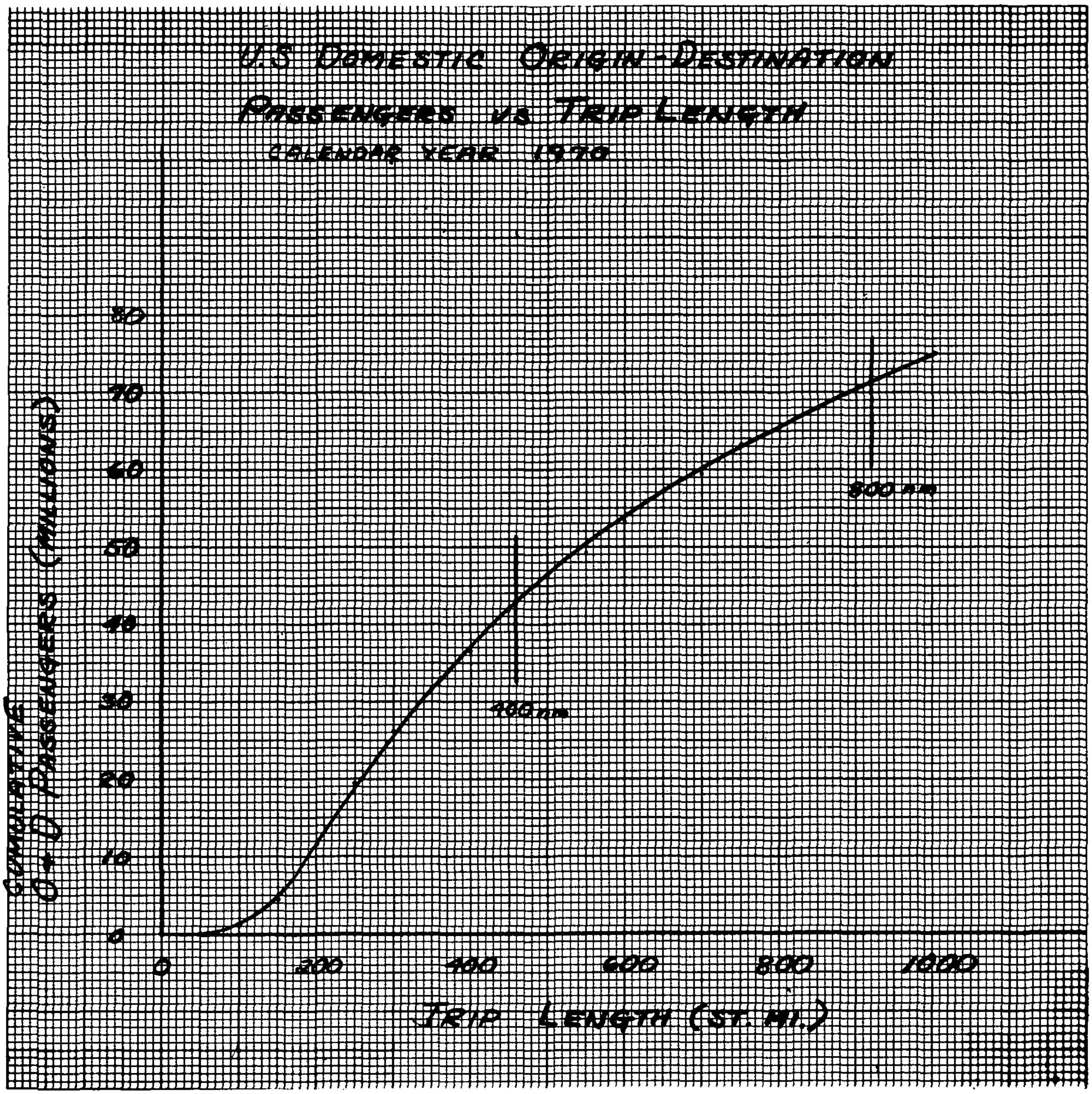
The passenger market segment in which V/STOL aircraft must compete falls between stage lengths of 50 and 800 nautical miles. V/STOL aircraft enjoy a definite advantage in the passenger markets of less than 400 nautical miles, both from the standpoint of locating the terminals closer to the origin and destination of the passenger and from the standpoint of lowering trip times by reducing enroute delays and helping to eliminate terminal area congestion.

However, in terms of number of aircraft, the short-haul market (400 nm and less) is probably not large enough to utilize the price economies of large production runs. Therefore, operations in the medium-haul market (400 to 800 nm) must be considered.

Figure 11-1 indicates U.S. Domestic cumulative origin-destination (O&D) passengers versus trip length for calendar year 1970, Reference 5. The segment zero to 400 nautical miles includes 43 million passengers, while the 400 to 800 nautical mile segment includes 28.5 million. Thus the 0 to 400 nautical mile segment represents 60% of the V/STOL passenger market. However, passengers are not the complete story. Aircraft requirements are roughly proportional to passenger-miles. Figure 11-2 is a plot of cumulative passenger-miles versus trip length (these are statute-miles) for calendar year 1970, Reference 5. The 0-400 nm segment includes only 35% of the passenger-miles in the 0-800 nm range. Therefore, an aircraft designed only for short-haul is ignoring 65% of the aircraft market. The question is how to design an aircraft to serve both markets. The MDC Model 102-6-6A approach is to serve the 0-400 nm segment with VTOL operations and the 400-800 nm segment with STOL operations. However, the V/STOL aircraft does not hold as large a competitive advantage in the STOL range. The fixed time is a lesser proportion of the total trip time than in the VTOL short-haul. The stage lengths for STOL operation are long enough such that cruise speed is important. In the STOL mode the aircraft must operate at cruise speeds which are competitive with current CTOL aircraft (above M 0.8).

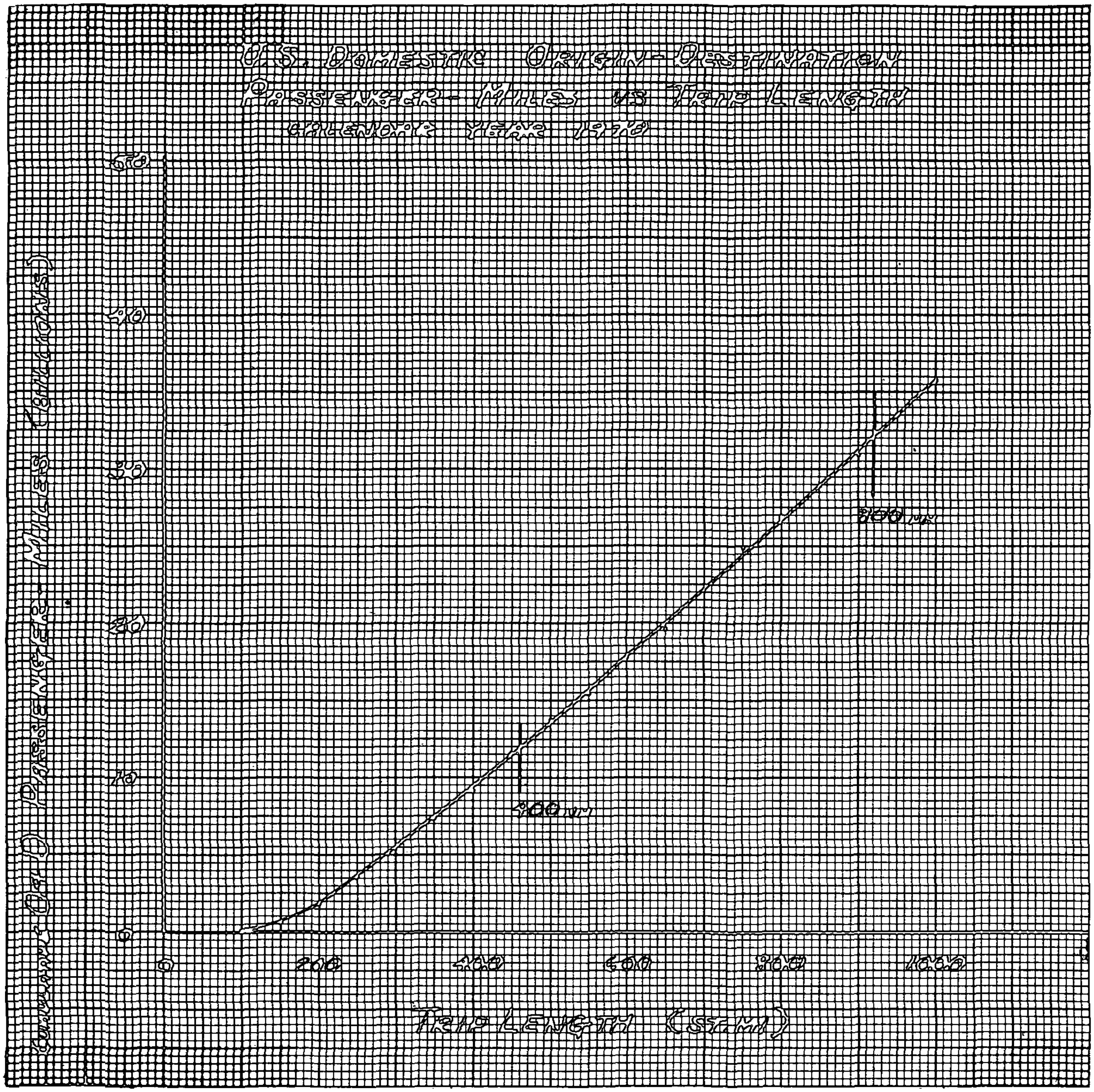
In short-haul operations increasing cruise speed is not critical since the cruise portion of the mission does not overshadow the other portions, ground maneuver, air maneuver, climb and descent, as it does in missions of longer duration. Therefore, allowing cruise speed to be a fallout, a 1.25 fan pressure ratio aircraft may be optimized for short-haul, particularly in the 150-250 nm range. However, the pressure ratio of the cruise system should be increased or oversizing of the engines would be required simply to increase the speed. In the case of Model 102-6-6A, the Energy Transfer Control system makes it possible to reduce the installed gas energy, but full advantages of the ETC system can only be realized if the fan pressure ratio is increased, or if a larger portion of the VTOL gas energy is used for cruise, both of which provide the higher cruise Mach number of 0.8.

Figure 11-1



U.S DOMESTIC ORIGIN-DESTINATION
PASSENGERS VS TRIP LENGTH
CALENDAR YEAR 1970
CUMULATIVE
O+D PASSENGERS (MILLIONS)
0
10
20
30
40
50
60
70
80
0
200
400
600
800
1000
400 nm
800 nm
TRIP LENGTH (ST. MI.)

Figure 11-2


U.S. DOMESTIC ORIGIN-DESTINATION
PASSENGER-MILES VS TRIP LENGTH
CALENDAR YEAR 1970
CUMULATIVE O&D PASSENGER-MILES (BILLIONS)
50
40
30
20
10
0
0
200
400
600
800
1000
400 MI
800 MI
TRIP LENGTH (STAT MI)

There is a 7% reduction in DOC for the RLF airplane at 400 nm if fan pressure ratio is changed from 1.25 to 1.4.

Therefore, it is recommended that fan pressure ratio should be a fallout of design trade-offs which consider total market appeal, noise, mission performance, and economics. Aircraft should be designed to provide the greatest market appeal without seriously degrading the use of the aircraft in high-density, short-haul operations utilizing the VTOL mode.

11.2 ENGINE SIZING AND TECHNOLOGY

The basic gas generator for both the ILF and RLF configuration was sized to power the fans for a 25% thrust margin for control. Thus the power capability of the one gas generator powering one fan must be 40% greater (thrust to 3/2 power) than that required for the nominal no control thrust level. In addition, the gas generators were designed to provide emergency thrust with control equal to 16% above the nominal for steady state and up to 30% above the nominal during control application. These values were tailored to the requirements of non-interconnected engines. The gas generators in the interconnected ETC system, whereby two gas generators and their related turbine tip driven fans are connected in pairs, can be sized for the nominal thrust level and yet obtain a 25% control thrust modulation on one fan. Therefore, it is recommended that the present guideline concerning normal lift operation with control be retained but interpreted to apply to the fan thrust. Then the gas generators may be sized to account for the benefits of an interconnected system.

11.3 ENGINE TECHNOLOGY AND DEVELOPMENT RISK

The propulsion data supplied for the study was intended to provide equal technology levels for both the ILF and the RLF systems based on an assumed go-ahead of the engine in 1975. Although the technology levels are similar, the engine ground rules established initially were based on design for the lift mode only. However, there are many differences due to the nature of the design of the propulsive units and past experience with similar V/STOL conditions that can have significant effects on performance as well as development risk for the ILF and RLF systems. Some of the prime areas are:

Technology Level

ILF	RLF	
	Gas Generator	Tip Turbine Fan
Benefits from advanced technology developments of CTOL turbofan cruise engines o High turbine temperature with known cooling techniques o High stage loadings o Composite fan blades	Benefits from same technology as ILF gas generator regarding high stage loadings, but is limited by turbine inlet temperature Available specific energy limited by turbine inlet temperature at compressor pressure ratio selected for optimum lift system - cruise not originally considered	Uncooled tip turbine blades, nozzles, and scroll limit gas generator exit temperature Selection of steel for fan blades influenced by best known methods of attaching tip turbines to blades

Development Risk

ILF	RLF	
Unknown cross-flow effects on multistage, high stage loading engine	Controlled inlet flow	Well known cross-flow effects on single stage fans, low stage loading
No experience with large thrust modulation combined with rapid response for control	Experience already available from large scale tests	
Unknowns due to backpressures of thrust spoilage systems and thrust vectoring systems behind multistage, high stage loading engines	Experience already available	

The above assessment shows an advantage for the ILF in gas generator specific energy because the cycle can be based on projections of current advanced turbofan cruise engine developments. The RLF gas generator is similar to or may be derived from the core of a fan engine; the same stage loading improvements were considered for the RLF gas generator with the exception of the turbine inlet temperature. The turbine inlet temperature was approximately 300°F lower than that for the ILF engine.

This temperature was established as a limit on the RLF system due to the original intent to optimize the ILF and RLF systems for the lift mode. A much higher compressor pressure ratio in the RLF system would permit use of the higher turbine inlet temperature. This would provide a significant increase in the specific energy of the exhaust gases resulting in a corresponding reduction in the gas generator size, interconnect ducting size, and fan turbine area without increasing the gas temperature at the fan turbine. A reduction in sfc would also result, thus having a significant effect on the aircraft due to the accumulating effect of a lower sfc in the lift mode as well as in cruise flight when used as a lift/cruise fan engine.

The selection of steel blades for the RLF compared with composite blades for the ILF penalizes the RLF from a weight standpoint, but has a byproduct major advantage in invulnerability to damage.

The comparison of development risks shows up areas that could have large effects on ultimate performance. There appears to be a big difference in the known characteristics of an installed RLF unit as compared to the ILF unit. Therefore, the credibility of the RLF aircraft sizing is considered better than that of the ILF aircraft. The areas identified under "Development Risk" can overshadow the areas under "Technology Level" since V/STOL designs are heavily influenced by the "snowballing" effect on aircraft sizing, cost, and resulting operating cost.

12. CONCLUSIONS AND RECOMMENDATIONS

12.1 CONCLUSIONS

o The lift/cruise fan V/STOL transport aircraft appears to be economically viable for the short-haul segment of the commercial transport market. A wider market, and therefore less economic risk, is available with a lift/cruise fan V/STOL aircraft designed to accommodate the short-haul market in the VTOL mode while also having the capability to operate competitively in the 400 to 800 nautical mile market in the STOL mode.

o The overall operational suitability of the lift/cruise fan V/STOL transport: i.e., the V/STOL performance characteristics; the precise control capability and flying qualities; the compatibility of and interface of pilot, auto-pilot, airplane controls, and precise navigation avionics with attendant displays; the adaptability of the aircraft to conventional passenger and baggage accommodations; the low noise profile; the inherent safety - all contribute to the compatibility of the aircraft to conventional and "close-in airport" airline operational requirements both in the air and on the ground.

o The 6-engine RLF aircraft using 2 lift/cruise engines is selected as the best compromise to satisfy the requirements for the future V/STOL commercial transport.

o Significant reductions in direct operating cost accrue with increased fan pressure ratio for the selected lift/cruise fan V/STOL transport. A modest increase in noise signature is the penalty sustained. A 4-engine aircraft may be possible using increased fan pressure ratio; this would improve the operational suitability.

o The selected future V/STOL transport aircraft can be provided with valid and credible data contributing appreciably to the introduction of a V/STOL transportation system by utilizing the Model 253 research vehicle which has an overall size of approximately 80%, a VTOL gross weight greater than 50%, and is a similar configuration.

12.2 RECOMMENDATIONS

The following actions are recommended as a result of the commercial aircraft study.

Guidelines

o That operations in the medium-haul market, 400-800 nautical miles, be considered. The short-haul market, 400 nautical miles and less, is probably not large enough to utilize the price economics of large production runs.

o That the aircraft be designed to provide the greatest market appeal without seriously degrading aircraft use in the high density, short haul operations utilizing the VTOL mode.

o That the fan design pressure ratio be a fallout of design tradeoffs which consider market appeal, noise, mission performance and economics.

o That the gas generator and fan power and thrust sizing incorporate the benefits of interconnected propulsion units. The present guideline concerning normal lift operation with control be retained but interpreted to apply to the fan thrust. In the interconnected design, the gas generators may be sized to account for possible size reduction when more than one gas generator supplies power to the fans.

Additional Work

o That effort be continued on development of the four engine RLF configurations. The number of engines is certain to have a large influence on aircraft acceptance by the airlines.

o That research work continue in the areas of interconnected propulsion system, duct and valve development, control system development, and flight simulation with the efforts directed toward a research vehicle.

13. LIST OF REFERENCES

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