NASA Technical Memorandum 102304
AIAA-89-2139

Supersonic Through-Flow Fan Engine and Aircraft Mission Performance

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Prepared for the
Aircraft Design, Systems and Operations Conference
cosponsored by the AIAA, AHS, and ASEE
Seattle, Washington, July 31—August 2, 1989

(NASA-TM-102304) SUPERSONIC THROUGH-FLOW FAN ENGINE AND AIRCRAFT MISSION PERFORMANCE (NASA) 15 p
N90-21038
CSCL 21E
Unclas
G3/07 0278443

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Supersonic Through-Flow Fan Engine
and
Aircraft Mission Performance

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E-4991

ABSTRACT

A study was made to evaluate potential improvement to a commercial supersonic transport by powering it with supersonic through-flow fan turbofan engines. A Mach 3.2 mission was considered. The three supersonic fan engines considered were designed to operate at bypass ratios of 0.25, 0.5 and 0.75 at supersonic cruise. For comparison a turbine bypass turbojet was included in the study. The engines were evaluated on the basis of aircraft takeoff gross weight with a payload of 250 passengers for a fixed range of 5000 N.MI. The installed specific fuel consumption of the supersonic fan engines was 7 to 8 percent lower than that of the turbine bypass engine. The aircraft powered by the supersonic fan engines had takeoff gross weights 9 to 13 percent lower than aircraft powered by turbine bypass engines.

NOMENCLATURE

BPR	bypass ratio
CET	combustor exit temperature, R
FPR	fan pressure ratio
FT	feet
HR	hour
LBM	pound mass
LBF	pound force
M	Mach number
N.MI.	nautical mile
OPR	overall pressure ratio
SEC	seconds
TCA	turbine cooling air, LBM/SEC
TOGW	takeoff gross weight, LBM
SFC	specific fuel consumption, LBM/HR/LBF
TAB	afterburner temperature, R
U	fan tip speed, FT/SEC
W	mass flow, LBM/SEC
$W\sqrt{\theta}/\delta$	corrected air flow, LBM/SEC
θ	temperature ratio, T/518.67
δ	pressure ratio, P/2116.22
Subscripts	
0	ambient

INTRODUCTION

The National Aeronautics and Space Administration is sponsoring a program of advanced technology studies for a future commercial supersonic transport. A number of attractive propulsion systems have emerged from these and past studies such as the General Electric double bypass engine[1], the Pratt & Whitney variable stream control engine[2] and the turbine bypass engine first proposed by the Boeing Company[3,4]. An additional concept, the supersonic through-flow fan engine, was first proposed by Advanced Technology Laboratory Inc. and was studied under NASA contract[5]. This engine incorporates a single stage supersonic through-flow fan which is of a more advanced technology than the other concepts in terms of fan aerodynamics. The results of the studies by Advanced Technology Laboratory Inc. indicated that this concept may be a more efficient propulsion system for supersonic cruise aircraft than the other concepts. Continuing studies at NASA Lewis[6,7,8] and recent studies by United Technologies Research Center and Pratt & Whitney[9,10] under the NASA High Speed Civil Transport Study Program (HSCT), have shown similar attractive results.

The advantages of this concept can be attributed to improved SFC's especially for long range supersonic cruise and reduced propulsion system weight. These improvements are due mainly to a large reduction in inlet diffusion thus reducing inlet losses and weight. An additional feature of the supersonic through-flow fan (STFF) engine discussed in references 8 and 10 is the ability to reduce bypass ratio and increase specific thrust with increased flight Mach number. In conventional turbofan engines the bypass ratio increases and specific dry thrust decreases with Mach number.

Past studies of the STFF engine were carried out to show the potential mission payoffs resulting from the unique features of this concept. In most of these studies first-order estimates of the engine weight and the performance of the fan, main inlet, core inlet and core inlet bleed system had to be used since more detailed analysis of these items had not been accomplished. More recently the STFF propulsion system has been studied in greater depth in the NASA High Speed Civil Transport Program. These studies included fan aerodynamic designs by United Technologies Research Center, fan mechanical design by Pratt & Whitney, main and core inlet aerodynamic analysis

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by Sverdrup Technologies Inc., and main and core inlet mechanical design by Pratt & Whitney. Also complete engine layout and weight studies were accomplished by Pratt & Whitney. The purpose of the present study was to incorporate this data into the on-going performance studies being carried out at the NASA Lewis Research Center and investigate other cycle features such as core afterburning to augment thrust during acceleration.

These studies include engine performance, mission analysis and engine aircraft integration. The initial studies have focused on STFF cycle optimization by way of engine performance and mission analysis. Studies by the Boeing Company have shown the turbine bypass engine (TBE) to be a very attractive engine for a high speed transport based on performance and projected takeoff noise (using the NACA nozzle concept). TBE engines were included in this study to provide a high performances engine for comparison with STFF. Results from these initial studies are presented in this paper. A Mach 3.2 civil transport aircraft was used for the purpose of the study. The results are presented in terms of variations in takeoff gross weight for an aircraft carrying 250 passengers for a 5000 N.MI. range.

METHOD OF ANALYSIS

The study results reflected differences in engine thrust and SFC and installed nacelle drag and weight. Mission performance calculations were made to determine takeoff gross weight for a fixed range and payload.

The engine concepts are shown in figure 1. The STFF engine incorporates a high pressure ratio single stage supersonic through-flow fan. This design differs from earlier concepts in that the rotor and stator blades are split at mid chord and the forward part of the blades rotate to vary incidence angle and improve off-design performance. The performance of this fan is discussed later. The STFF core and duct nozzles are convergent-divergent variable area design. The engine was studied with and without afterburners in the core nozzle.

The TBE is a dry turbojet with a bypass system in which a part of the compressor discharge air is bypassed to the nozzle at high power setting. This feature permits the engine to be throttled back considerably without reducing engine airflow. This results in greatly reduced inlet spillage drag at low power settings used for a subsonic cruise or loiter. The nozzle is Boeing's naturally aspirated coannular (NACA) concept that has the potential to pump large amounts of external flow and reduce jet noise during takeoff.

The engine technology used in the study in terms of materials and structure is the same for both engines representing a technology availability date near the year 2000. Engine cycle characteristics for JP fuel are shown in Table I for takeoff operation.

The design and performance for the TBE conventional inlet and for the STFF main and core inlets were obtained from reference 11. Figure 2 shows the three inlets and some of their characteristics. The STFF main inlet is a relatively simple fixed geometry design which would reflect in favorable weight savings compared to the conventional inlet. Flow field analysis of the main STFF inlet has indicated only weak shocks and low pressure gradients on the centerbody thus potentially eliminating the need for boundary layer bleed.

The conventional TBE inlet is a sliding centerbody type. This inlet and the STFF core inlet require bleed for boundary layer control. Initial studies indicate the core inlet bleed for the STFF engine can be injected into the bypass stream, since the static pressure in the supersonic bypass stream is much lower than that at the core inlet throat.

The pressure recoveries and drag coefficients for the conventional and STFF main inlets are compared in figure 3. The pressure recovery and drag improvements of the STFF main inlet compared to the conventional inlet are significant especially during supersonic acceleration and cruise.

The STFF core inlet pressure recoveries are shown in figure 4. The pressure recoveries are a function of the inlet Mach number or the fan exit Mach number. The fan exit Mach number varies with flight Mach number and fan rotational speed. At a given flight Mach number, increasing the fan rotational speed results in higher fan exit Mach numbers and lower second inlet pressure recoveries. The operating line shown in figure 4 was used for the three STFF engines in this study. Pressure recoveries range from 95 percent at Mach 1.6 to 82 percent at Mach 3.2. Below Mach 1.6 the core inlet flow is subsonic. Starting requirements for the core inlet have not been determined . The core inlet boundary layer bleed system pressure recoveries and bleed requirements from reference 11 are shown in figure 5, consistent with the operating line in figure 4.

The supersonic through-flow fan design and performance was provided by United Technologies Research Center under contract NAS3-25117. A description of this design is given in reference 12. Figure 6 shows the aerodynamic characteristics of this design from reference 12. As mentioned before this design concept differs from earlier concepts studied in that the rotor and stator are split at mid chord and the forward part of the blades moves to reduce the angle of attack and improve off-design performance. This would also permit the fan to be operated in the subsonic mode during low flight speeds and still achieve good performance. In figure 6a the fan operates in the subsonic mode from sea level static to a Mach 1.6 flight speed. During this operating mode the fan entrance Mach number is 0.8 and the fan exit Mach numbers are subsonic. At Mach 1.6 the fan is "started" and operates in the supersonic through-flow mode. The operating line shown in the figure was used for the STFF engines analyzed in this study, consistent with the inlet operating line in figure 4.

The uninstalled engine performance for the STFF engines was calculated by the NNEP engine cycle computer code[13]. Although takeoff noise restrictions were not considered in this study the core nozzle of the STFF engines will require some type of supression device. With the bypass ratio of 0.75 (1.6 at takeoff) engine, the engine can be throttled back to about 95 percent maximum dry power and the bypass stream nozzle exit velocity is about 1400 feet per second. However, the core nozzle exit velocity is about 2300 feet per second and would require noise suppression. Therefore a 2 percent SFC penalty was included in the STFF performance to account for possible nozzle performance degradations due to mechanical suppressor stowage. The uninstalled engine performance for the turbine bypass engine was provided by Pratt & Whitney under contract NAS3-25117. Except for the supersonic fan, the technologies of the engine components (aerodynamics, cooling, structure) was the same for both engine concepts.

For both concepts installation losses (figure 3) include inlet spillage and boundary layer bleed (except for the STFF main inlet) and nacelle and pylon friction drag. Nacelle interference effects were not included in the installation analysis. For the supersonic fan engine the core nacelle friction drag was calculated assuming the core nacelle is scrubbed by the bypass air exit flow. The core inlet losses for the STFF engines were included in the uninstalled engine performance.

The base engine weights for the TBE and STFF bypass ratio 0.25 engines were provided by Pratt & Whitney under contract NAS3-25117. The TBE inlet weight was obtained from the Boeing Company from contract NAS1-18377 and the STFF main inlet weight was obtained from reference 15. The weight for the TBE NACA nozzle was estimated by the Boeing Company, under NAS3-18377. The STFF bypass ratio 0.25 unsuppressed nozzle weight was from Pratt & Whitney, NAS3-25117. To account for possible mechanical noise suppressor a weight penalty of 4 percent of the bare engine plus nozzle weight was used for the STFF engine. The bare engine plus nozzle weights for the other STFF engines (bypass ratio of 0.50 and 0.75) were scaled from the bypass ratio 0.25 engine using the method of reference 14.

The baseline airplane in the study, figure 7, was derived from a NASA Langley concept. As mentioned previously nacelle/airplane integration studies have been initiated but were not included in this study. Preliminary results from a recent NASA study of the nacelle airplane integration have indicated the nacelle interference effects on airplane aerodynamics would be similar for the STFF and the TBE engines[16]. Therefore in this study the airplane aerodynamics were assumed the same for both engine types. The payload of 50000 pounds (250 passengers) was fixed and the structural weight was scaled with gross weight. The takeoff gross weight varied to reflect differences in engine performance and weight.

The mission is shown in figure 8 and the climb/acceleration path is shown in figure 9. The mission is for all supersonic cruise. The total range of 5000 N.MI. is the sum of the climb/acceleration, cruise and descent. Fuel reserves include an enroute contingency of 5 percent of the mission fuel and provision for a 20 minute loiter. The figure of merit used is the takeoff gross weight required for the 5000 N.MI. mission range.

RESULTS AND DISCUSSION

Engine Performance and Weight - As mentioned previously most of the past studies of the STFF engine addressed the potential payoffs resulting from the unique features of this engine. In the present study the emphasis was to reassess the engine with more definitive estimates of engine losses and weights. Since the core inlet losses (pressure recovery and boundary layer bleed) have an impact of the cycle performance it was necessary to study various bypass ratios since it might be expected that the core inlet losses would have less effect on performance with increasing bypass ratio. Figure 10 shows a comparison of the performance of the three STFF engines addressed in this study. It should be noted that the bypass ratios shown in the figure are the Mach 3.2 values. At takeoff they are much higher (Table I) which would tend to reduce takeoff jet noise. The maximum difference in the SFC's of the three STFF engines is only 1 percent.

The three STFF engines were equipped with afterburners which were used only during transonic acceleration. The afterburning performance is not shown in figure 10 since the three STFF engines are operated dry at supersonic cruise. For comparison, the performance of the TBE is shown. The installed SFC at the operating point for the TBE is about 7 to 8 percent higher than for the STFF engines. It should be noted that the TBE is throttled back considerably at cruise. This is principally due to large differences in engine thrust requirements between transonic accelleration and supersonic cruise.

Figure 11 shows a comparison of the propulsion system weights for the minimum takeoff gross weight airplane for each engine type. Shown in the figure also are the engine sizes for minimum takeoff gross weight. The propulsion system weight for the STFF engines are about the same for the dry engines and afterburning engines respectively. Although engine weight decreases with increasing bypass ratio for the same engine size, the specific thrust decreases and larger engine sizes are required for the higher bypass ratio engines. The base engine plus nozzle weight of the TBE is the lightest of the dry engines in figure 11. However it is seen that the TBE inlet is almost as heavy as the bare engine weight and comprises over one-third of the total propulsion system weight. When the inlet weight is included, the total weight of the TBE propulsion system is the heaviest.

Mission Studies - Although the STFF engines are operated dry at supersonic cruise, mission studies for the STFF engines evaluated the effect of core afterburning during climb. Various degrees of core afterburning from dry to a maximum afterburning temperature of 4000 R were studied. Also included were afterburner power during the entire climb/acceleration or transonic acceleration only. It was found that afterburning during the entire climb resulted in a gross weight penalty compared to dry power. Transonic afterburning resulted in gross weight improvements. Propulsion system weights for these afterburning cases are also shown in figure 11. Figures 12 through 14 shows gross weight as a function of thrust loading (maximum sea level static thrust/gross weight) for various levels of transonic afterburning for each of the three STFF engines.

For the dry STFF engines in figures 12 through 14 the minimum thrust loading required to meet a typical 30 percent transonic trust/drag margin are slightly higher than the thrust loadings resulting in minimum takeoff gross weight. For these thrust loadings the STFF bypass ratio 0.25 has a 2 percent lower gross weight than the STFF bypass ratio of 0.75 engine. Transonic afterburning resulted in gross weight reductions. Maximum afterburning of 4000 R resulted in gross weight reductions of about 4 percent.

In figure 15 the takeoff gross weights of the TBE and the STFF bypass ratio of 0.25 are compared. The minimum thrust loadings to meet the transonic thrust margin are seen to be lower for the STFF engines than for the TBE. Although the TBE has a higher specific thrust than the dry STFF engines, its lapse rate is somewhat higher. As mentioned earlier the STFF engine thrust lapse differs from conventional turbofan engines in that the engine bypass ratio decreases with Mach number resulting in higher dry specific thrust than conventional turbofan engines. In comparing the minimum gross weights the dry STFF engine would have a 9 percent lower gross weight than the TBE. With maximum afterburning the improvement would be 13 percent. These improvements are due to the lower installed cruise SFC's of the STFF engine and lower climb/acceleration fuel consumption.

SUMMARY

A study was made to evaluate the potential improvements to a commercial supersonic transport mission by using supersonic through-flow fan engines. This paper reports some initial results from on-going studies of the supersonic fan being carried out at the NASA Research Center. The focus of this preliminary study was to incorporate more recent analytical data on fan performance, the main inlet, the core inlet and its bleed system performance and engine weight. Three STFF cycles (BPR=0.25, 0.50, and 0.75) were investigated. A turbine bypass engine was also studied for comparison. The mission was for a Mach 3.2 all supersonic cruise. The engines were evaluated on the basis of aircraft takeoff gross weight for a payload of 250 passengers and a 5000 N.MI. range. The study results show that of the three STFF engines the BPR=0.25 had slightly higher installed SFC's than the other two but the airplane takeoff gross weight was somewhat lower. Core afterburning of the STFF engines during transonic acceleration resulted in a 4 percent reduction in gross weight. When compared to the turbine bypass engine the installed SFC's of the TBE were 7 to 8 percent higher than those of the STFF engines. The aircraft powered by TBE engines was 9 to 13 percent heavier than those powered by STFF engines.

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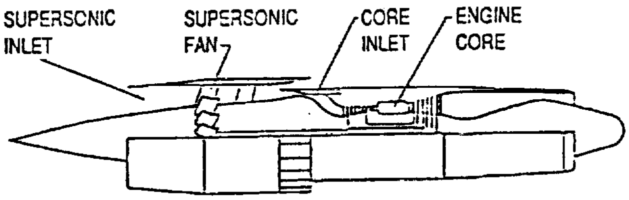
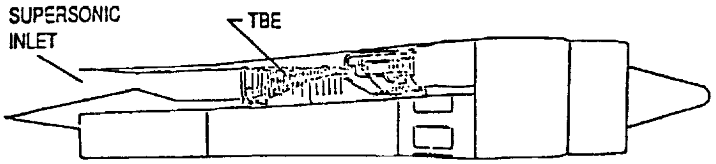
Table I. - Study engine characteristics.

	TBE	STFF
$W\sqrt{\Theta}/\delta$, LBM/SEC	600	814
FPR	-	3.23
OPR	11.2	12.44
BPR (M_0 = 3.2)	-	0.25, 0.50, 0.75
BPR (SLS)		0.9, 1.30, 1.60
CET MAX,° R	3620	3620
TCA, %	13	15

Takeoff conditions
Baseline airflow size engine

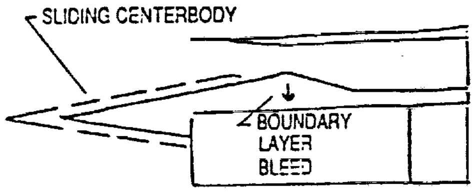


(A) SUPERSONIC THROUGH-FLOW TURBOFAN

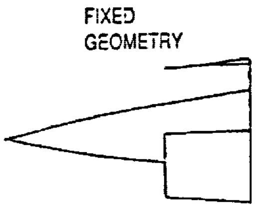


(B) TURBINE BYPASS TURBOJET

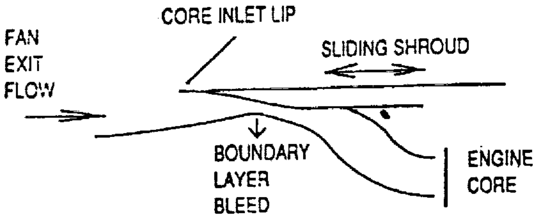
Figure 1. - Engine concepts.



(A) CONVENTIONAL SUPERSONIC INLET



(B) SUPERSONIC FAN MAIN INLET



(C) SUPERSONIC FAN CORE ENGINE INLET

Figure 2. - Inlet types.

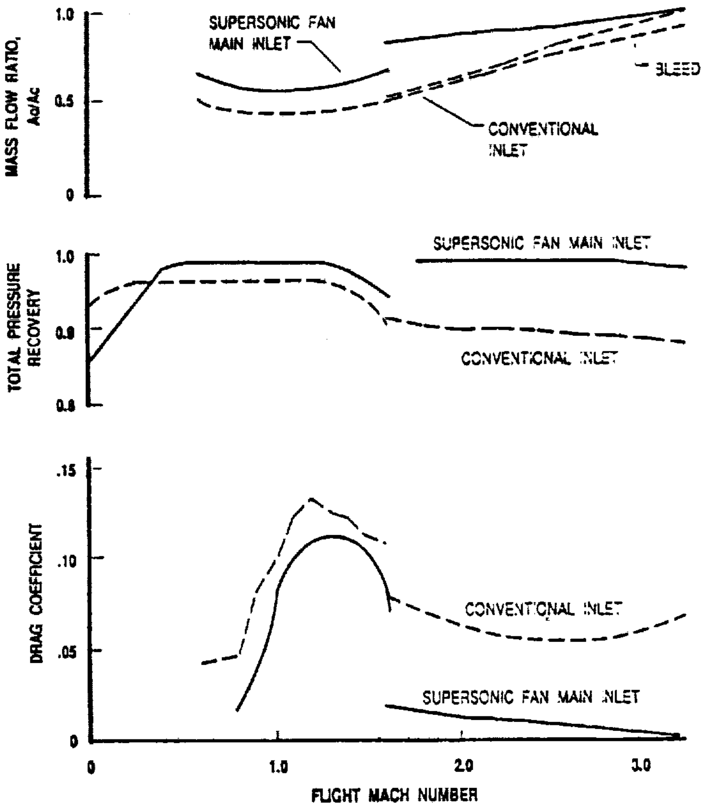


Figure 3. - Comparison of conventional and supersonic fan main inlet performance.

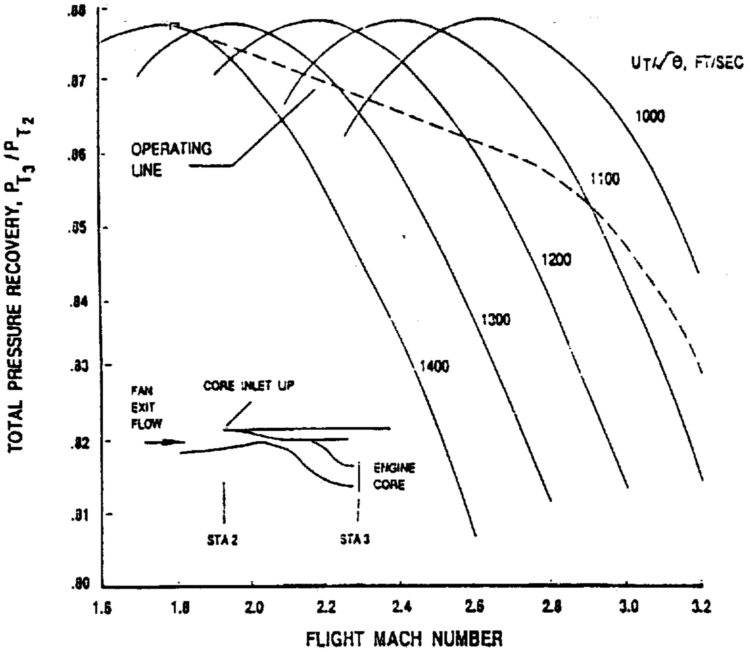


Figure 4. - Core inlet total pressure recovery.

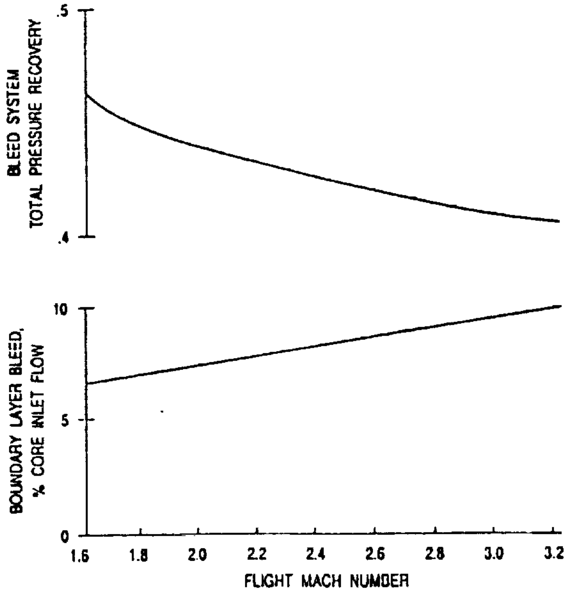


Figure 5. - Core inlet boundary layer bleed system performance.

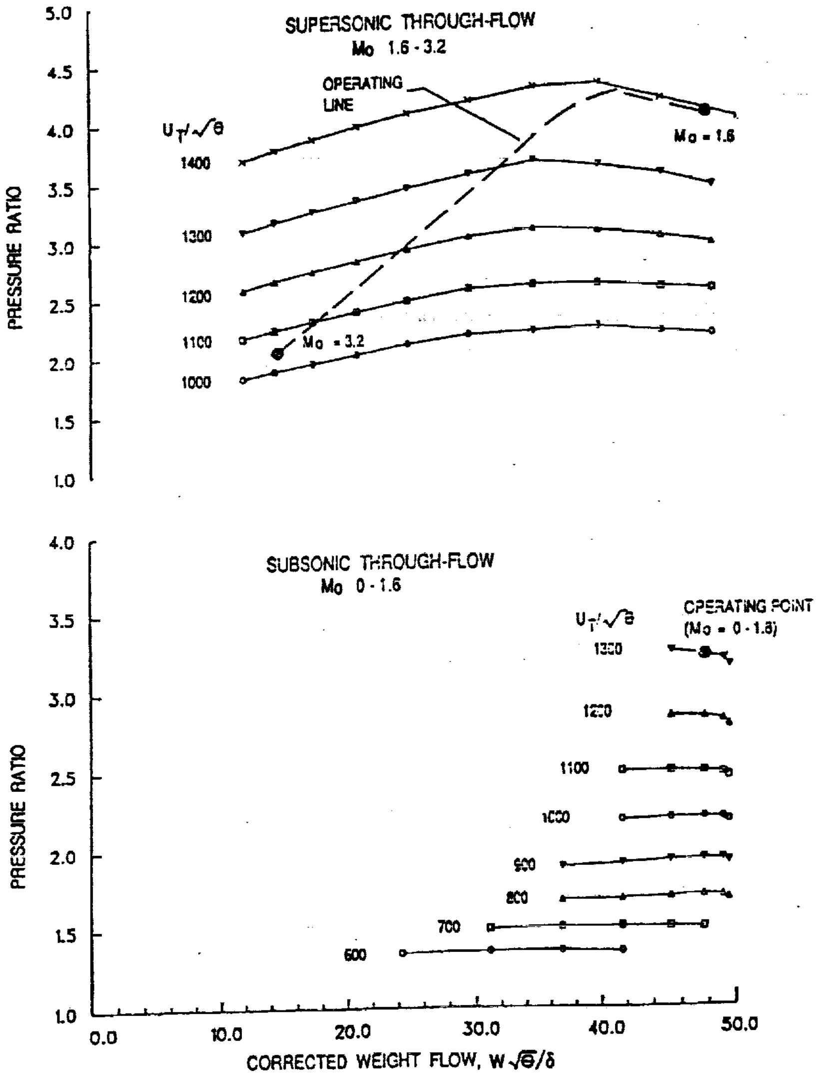


Figure 6a. - Variable pitch, split blade supersonic through-flow fan performance.

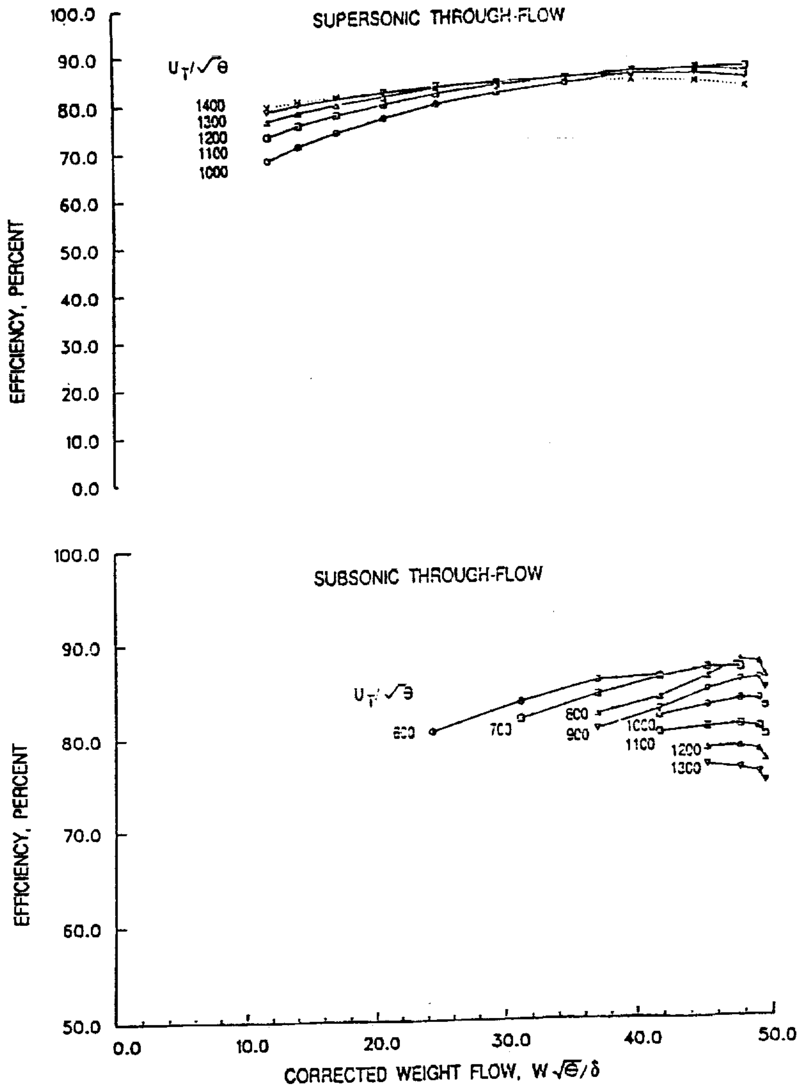


Figure 6b. - Variable pitch, split blade supersonic through-flow fan performance.

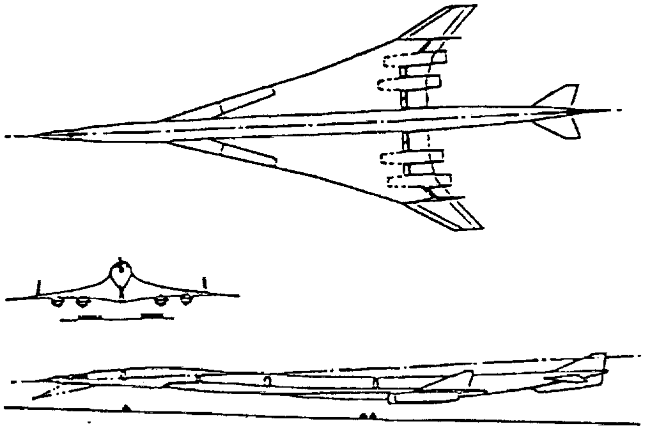


Figure 7. - General arrangement of the airplane; cruise mach number = 3.2; 250 passengers; 5000 N. MI. range.

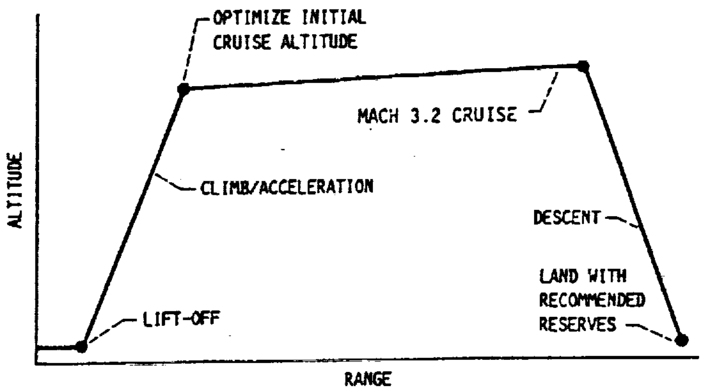


Figure 8. - Reference mission, standard day.

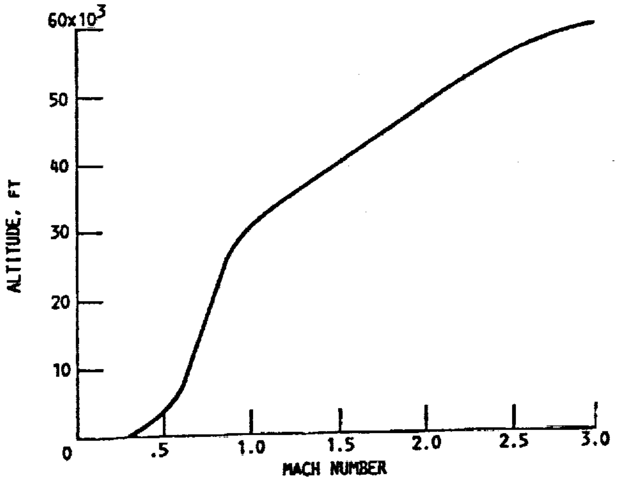


Figure 9. - Flight path used in climb/acceleration.

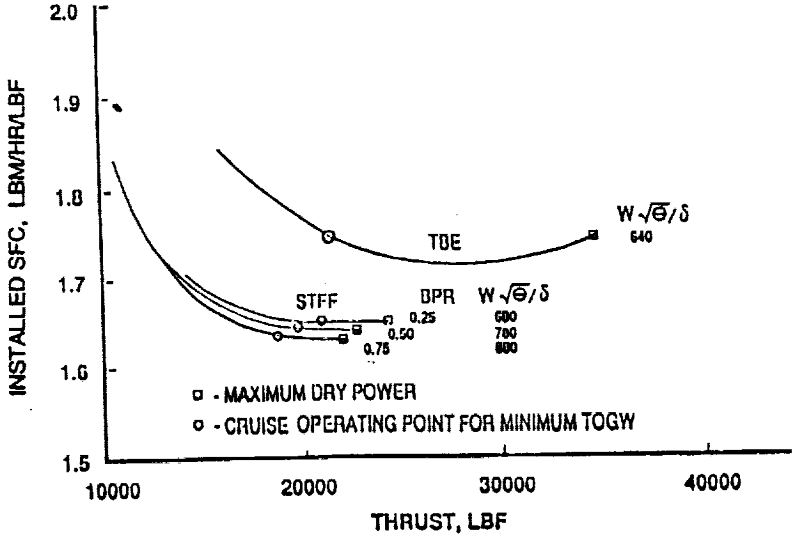


Figure 10. - Comparison of supersonic through-flow fan and turbine bypass engine performance; cruise mach number = 3.2; altitude = 60000 FT.

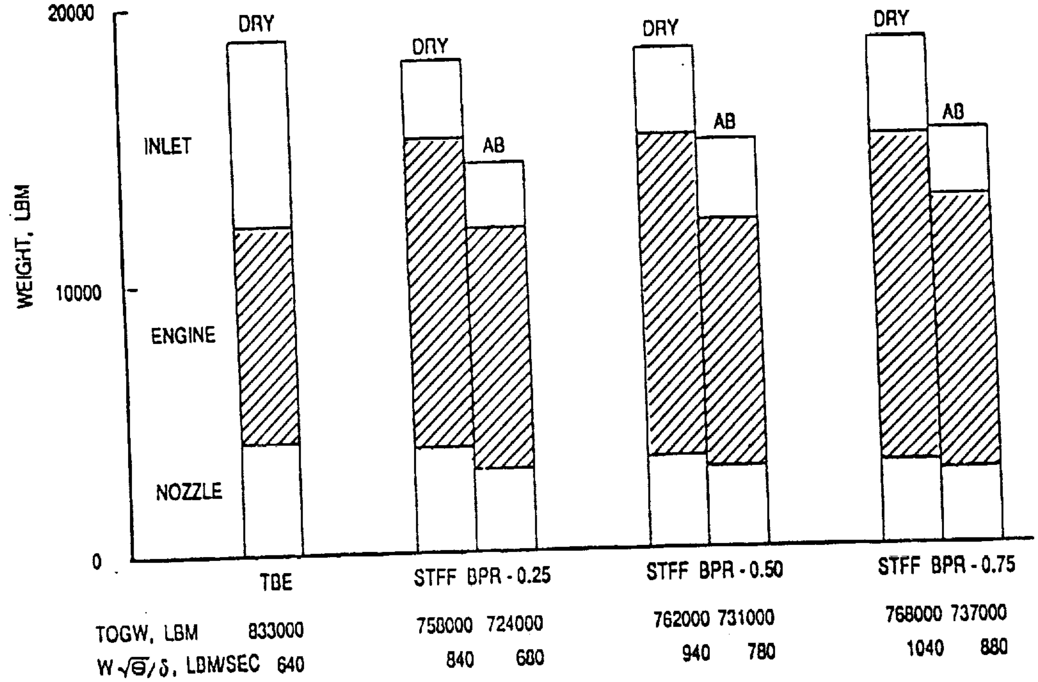


Figure 11. - Propulsion system weight comparison.

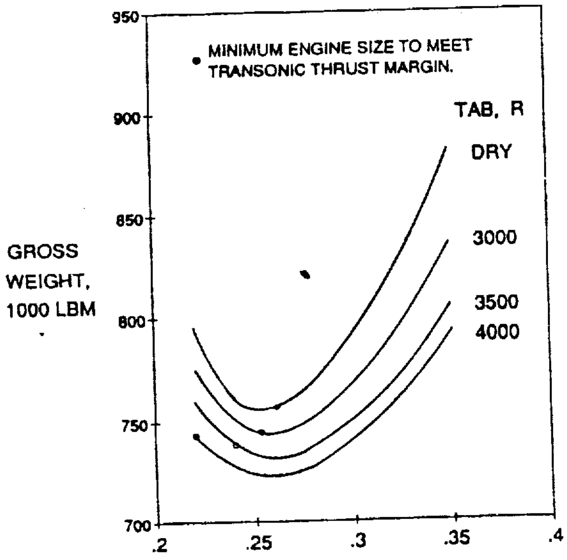


Figure 12. - Effect of core afterburning on takeoff gross weight; supersonic through - flow turbofan engines; cruise Mach number - 3.2; engine bypass ratio at Mach 3.2 - 0.25; transonic thrust margin - 0.3 at Mach 1.1.

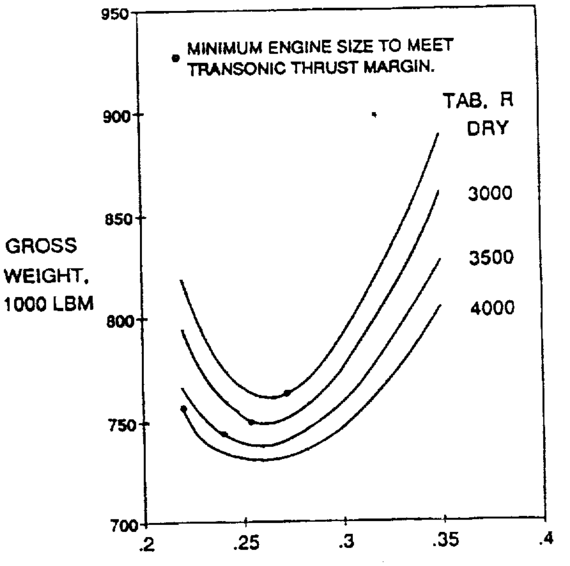


Figure 13. - Effect of core afterburning on takeoff gross weight; supersonic through - flow turbofan engines; cruise Mach number - 3.2; engine bypass ratio at Mach 3.2 - 0.50; transonic thrust margin - 0.3 at Mach 1.1.

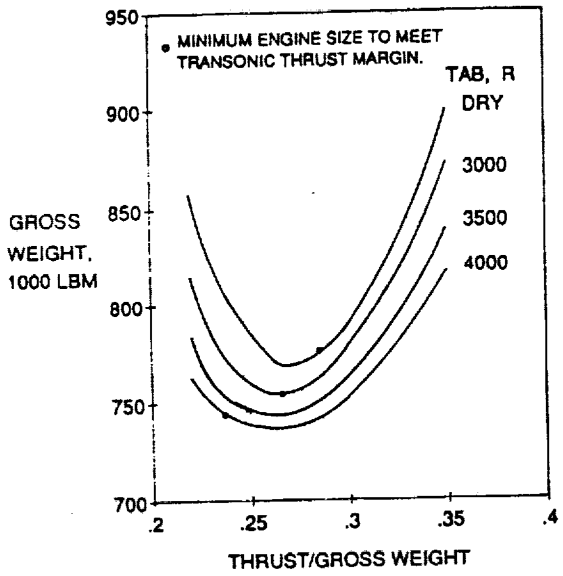


Figure 14. - Effect of core afterburning on takeoff gross weight; supersonic through - flow turbofan engines; cruise Mach number - 3.2; engine bypass ratio at Mach 3.2 - 0.75; transonic thrust margin - 0.3 at Mach 1.1.

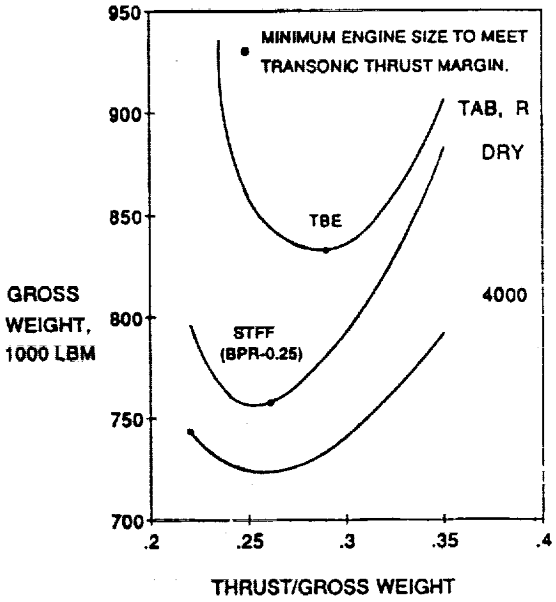


Figure 15. - Comparison of turbine bypass engine and supersonic through - flow fan engine takeoff gross weights ; cruise Mach number - 3.2 ; transonic thrust margin - 0.3 at Mach 1.1.

National Aeronautics and
Space Administration

Report Documentation Page

1. Report No. NASA TM-102304 AIAA-89-2139	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

Supersonic Through-Flow Fan Engine and Aircraft Mission Performance

5. Report Date

6. Performing Organization Code

7. Author(s)

Leo C. Franciscus and Jaime J. Maldonado

8. Performing Organization Report No.

E-4991

10. Work Unit No.

505-69-61

9. Performing Organization Name and Address

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

11. Contract or Grant No.

13. Type of Report and Period Covered

Technical Memorandum

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, D.C. 20546-0001

14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the Aircraft Design, Systems and Operations Conference cosponsored by the AIAA, AHS, and ASEE, Seattle, Washington, July 31—August 2, 1989. Leo C. Franciscus, NASA Lewis Research Center; Jaime J. Maldonado, University of Puerto Rico, Mayaguez Campus, Mayaguez, Puerto Rico and participant in Case-NASA Cooperative Aerospace R&D Internship/Fellowship Program.

16. Abstract

A study was made to evaluate potential improvement to a commercial supersonic transport by powering it with supersonic through-flow fan turbofan engines. A Mach 3.2 mission was considered. The three supersonic fan engines considered were designed to operate at bypass ratios of 0.25, 0.5 and 0.75 at supersonic cruise. For comparison a turbine bypass turbojet was included in the study. The engines were evaluated on the basis of aircraft takeoff gross weight with a payload of 250 passengers for a fixed range of 5000 N.MI. The installed specific fuel consumption of the supersonic fan engines was 7 to 8 percent lower than that of the turbine bypass engine. The aircraft powered by the supersonic fan engines had takeoff gross weights 9 to 13 percent lower than aircraft powered by turbine bypass engines.

17. Key Words (Suggested by Author(s))

Supersonic
Supersonic transport
Supersonic fan
Turbine engines

18. Distribution Statement

Unclassified – Unlimited
Subject Category 07

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No of pages 13	22. Price* A03

NASA FORM 1626 OCT 86

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