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THE SUPERSONIC FAN ENGINE - AN ADVANCED CONCEPT IN SUPERSONIC CRUISE PROPULSION

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Abstract

Engine performance and mission studies were carried out for turbofan engines equipped with supersonic through-flow fans. The mission was for a commercial supersonic transport with a Mach 2.32 capability. The advantages of the supersonic fan engines are discussed in terms of mission range comparisons with other engine types. The effects of fan efficiency, inlet losses and engine weight on engine performance and mission range are shown. The range of a supersonic transport with supersonic fan engines could be 10 to 20 percent better than with other types having the same technology core.

Nomenclature

BPR	bypass ratio
CET	combustor exit temperature, °R
C_v	nozzle velocity coefficient
DBT	duct burner temperature
FPR	fan pressure ratio
ft	foot
hr	hour
kg	kilogram
lbm	pound mass
lbf	pound force
m	meter
M	Mach number
N	newton
n. mi.	nautical mile
OPR	overall pressure ratio
SLS	sea level static
SFC	specific fuel consumption, lbm/hr/lbf
TOGW	takeoff gross weight, lbm

Subscripts

AB	absolute
C	compressor
D	duct
F	fan
HPT	high pressure turbine
LPT	low pressure turbine
MAX	maximum

Introduction

NASA has sponsored studies of advanced technology engines for supersonic cruise aircraft propulsion. Among the leading candidate engines studied are the Pratt & Whitney variable stream control engine, the General Electric double bypass engine and the turbine bypass engine suggested by Boeing.[1,2] A number of engines having unconventional components were studied such as Pratt & Whitney's valved engines and General Electric's triple rotor concept.[3,4] In 1973 Advanced Technology Laboratories, Inc. suggested engines with an unconventional fan concept, the supersonic through-flow fan. The results of their studies (sponsored by NASA) showed that engines equipped with supersonic through-flow fans might be more efficient power plants for supersonic cruise aircraft than any of the other types being considered.[5] Continued in-house studies at Lewis in which various conceptual supersonic fan engines were investigated showed similar attractive results.[6]

Only very limited experimental investigations have been attempted of supersonic through-flow fans.[7] They suggested that a device of this nature can function but did not yield fan efficiency data or a sufficient description of the operating characteristics (pressure ratio, airflow and speed relationships). Therefore the previous engine studies were based on analytical predictions of fan performance.[5,6] In view of the uncertainties of these predictions, continued in-house studies at Lewis have addressed the effects of perturbations of the fan performance and operating characteristics on the engine and mission performance of a supersonic transport aircraft. The results of these studies are presented in this paper.

The aft-fan version of the supersonic fan conceptual engines from Ref. 6 was used in this study. Perturbations were made on fan efficiency, stage discharge characteristics and engine weight. The results are compared with the Pratt and Whitney variable stream control engine and the Boeing turbine bypass engine. Cruise Mach number, takeoff gross weight and payload are fixed so that the figure of merit is mission range.

Description of the Engines

The three engine concepts studied are shown in Fig. 1. Engine cycle and component performance parameters are provided in Table 1.

Aft-fan supersonic fan engine. - The supersonic through-flow fan (SSTF) engine has a conventional core. Only the core of the engine requires a conventional supersonic inlet, the same as, but smaller than, the inlets of the other two engines. The core compressor and turbine are mounted on a single spool. The supersonic fan is mounted on an uncoupled low-pressure turbine. The core nozzle is equipped with an afterburner.

The supersonic fan is a single-stage impulse machine. Its operating characteristics could lead to significant improvements in engine performance. The fan face absolute Mach numbers range from 1 at takeoff to values slightly less than free stream during supersonic flight (fig. 2). Thus, little diffusion of the air is required and inlet losses are small. The fan stage exit Mach

*Aerospace Engineer, Mission Analysis Office numbers are supersonic for all flight conditions. In Fig. 2 the stage exit Mach numbers are seen to range from 2.3 at sea level static to 3 at supersonic cruise. This could simplify the duct nozzle mechanically (no throat required) resulting in better nozzle efficiency and reduced weight compared to a conventional nozzle. This characteristic of the supersonic fan can also be used to improve the core inlet performance. Because of the supersonic flow at the fan discharge the duct static pressures are significantly lower than the core inlet boundary layer bleed pressures. Thus, the boundary layer bleed air can be injected into the duct stream resulting in significant reductions in bleed losses. The effects of these fan operating characteristics on engine performance and mission range will be shown later.

Pratt & Whitney variable stream control engine. - The variable stream control engine (VSCE) is a two-spool duct burning turbofan (fig. 1). The engine has variable-geometry features in the fan, compressor and nozzle that provide flexibility in cycle operation to match flight conditions. The duct burner provides the capability of high thrust when required. The VSCE has been Pratt & Whitney's leading contender for a future supersonic propulsion system.

Boeing turbine bypass engine. - The turbine bypass engine (TBE) is a single-spool turbojet with a provision for bypassing some compressor discharge air around the burner and turbine. In this version the bypass air is injected into the nozzle. In another two-spool version (not considered in this study) the bypass air is injected ahead of the low pressure turbine. The bypass feature gives the turbojet the same flexibility in operation as a variable-area turbine. This flexibility is important for a supersonic cruise engine since high power is required for transonic acceleration and supersonic flight but low power for subsonic flight where the engine is throttled back. A conventional turbojet does not throttle back efficiently since it spools down leading to low pressure ratios (low propulsive efficiencies) and large inlet bypass drags. The turbine bypass feature permits the engine to be throttled back without spooling down and reduces these losses. The throttle valve on the engine shown in Fig. 1 throttles the high pressure compressor bypass air to the same pressure as the nozzle gas where it is injected.

Method of Analysis

The study reflected differences in engine performance, pod drag and propulsion system weight of the three engines considered. Mission performance calculations were made to determine the range as a function of sea level static engine airflow for a fixed takeoff gross weight and payload.

The mission is for a supersonic cruise aircraft for a Mach 2.32 supersonic cruise and a 300 n. mi. subsonic cruise leg.

The mission profile is illustrated in Fig. 3. A constant 213 n. mi. descent from the final cruise altitude at an estimated flight-idle fuel flow was assumed. The total range calculated was the total of climb/acceleration, cruise and letdown ranges. Fuel reserves include an enroute contingency of 5 percent of the mission fuel, 260 n. mi. diversion at Mach 0.9, and a 30-minute hold at Mach 0.45 at an altitude of 15 000 feet.

The airplane used in the study was the Langley-LTV arrow wing from Ref. 8. The airplane gross weight, payload and operating empty weight less propulsion weight remained fixed so that the total range varied with changes in engine performance and weight.

The uninstalled engine performance for the three engines was computed with the engine cycle computer program of Ref. 9 which performs cycle calculations, design and off-design, on a component by component basis. Except for the supersonic fan, the component aerodynamic characteristics, efficiencies and cooling requirements for conventional fans, compressors, turbines, combustors, etc., used in the program were for the same technology used in Ref. 1. For the supersonic fan, a baseline design adiabatic efficiency of 0.85 was assumed and the aerodynamics were obtained from Ref. 5. In the perturbation studies, the design adiabatic efficiency was reduced to 0.75. Installation losses include inlet and nozzle drags and nacelle friction drag.

The Boeing translating-centerbody inlet airflow schedule and performance was used for the VSCE and TBE. The inlet drag penalties include spillage, bypass and bleed. For the SSTF engine core inlet, the Boeing inlet airflow schedule and bypass and spillage losses were used. As indicated before, the bleed loss was eliminated by injecting the boundary layer bleed air into the fan duct. In the perturbation studies it was assumed that the fan discharge static pressures are too high to inject the bleed air resulting in overboard bleeding and a bleed loss. The inlet for the supersonic fan is a low-compression inlet. The pressure rise across the inlet at supersonic cruise would be only 1.6 compared to 10 for a conventional inlet. Preliminary performance estimates of the supersonic fan inlet were made in Ref. 6 and were used in this study.

For the nozzles of the VSCE and the TBE and the core nozzle of the SSTF engine, an internal velocity coefficient of 0.985 was assumed. For the supersonic fan duct nozzle (a more simple device) an internal velocity coefficient of 0.99 was assumed. Boattail drags for all of the engines was computed using the data of Ref. 10.

The installed propulsion system weight includes the engine plus nozzle/reverser, inlet and nacelle. The VSCE engine plus nozzle/reverser weight was obtained from Ref. 1. The TBE engine plus nozzle/reverser weight was obtained from a preliminary estimate from Pratt & Whitney. Weight estimates for the Boeing inlet and the nacelle for the TBE and VSCE were obtained from Ref. 11. The weight of the SSTF engine was taken from Ref. 6.

Results and Discussion

Engine comparisons. - As mentioned previously, the operating characteristics of the supersonic through-flow fan lead to significant reductions in installation losses. Since little diffusion of the air is required (fig. 2) spillage losses of the supersonic fan inlet are low. Also as mentioned before, core inlet bleed losses are eliminated. These features result in a very efficient inlet system for the SSTF engine. Figure 4 shows a comparison of the inlet pressure recovery and drag coefficients between the SSTF engine and the Boeing inlet. The pressure recoveries of the core inlet of the SSTF engine are the same as those of the Boeing inlet. The SSTF engine inlet drag coefficients include the drags of both the core inlet and supersonic fan inlet. The drag coefficients of the SSTF engine inlet are about 40 percent lower than the Boeing inlet at transonic speeds and about 90 percent lower at supersonic cruise. Figure 5 shows a comparison of the supersonic cruise performance of the SSTF engine, the VSCE and the TBE. The baseline supersonic fan adiabatic efficiency of 0.85 was used to compute this performance. The indicated cruise points on the curves are the operating points for engine sizes that maximize range. The cruise SFC of the SSTF engine is about 5 percent better than that of the TBE. This is due mostly to the reduced installation losses of the SSTF engine. The cruise SFC of the VSCE is about 20 percent higher than that of the SSTF engine. This is due to a better cycle match compared to the VSCE and the reduced installation losses of the SSTF engine.

The single-stage supersonic fan and the simpler inlet and nozzle result in reduced engine weight in comparison to conventional components. Figure 6 shows comparisons of the propulsion system weights for the SSTF engine, the VSCE and the TBE for the same engine size (same sea level static airflow). The inlet system of the SSTF engine is about 50 percent lighter than the conventional inlets of the VSCE and TBE. The engine plus nozzle weight of the SSTF engine is 20 percent lighter than the VSCE and 30 percent lighter than that of the TBE. In terms of total propulsion system weight, the weight of the SSTF engine is 30 percent lower than the VSCE and 40 percent lower than the TBE for the same engine size.

The impact of the improvements of the SSTF in engine weight and performance on mission range is shown in Fig. 7. For engines sized for a 10 500 ft takeoff field length the mission range of an SST with supersonic fan (SSTF) engines could be 11 percent longer than with the TBE and 20 percent longer than with the VSCE. The takeoff-sized SSTF engine is much larger than the other two types. For these engine sizes the SSTF engine weight would still be about 5 percent lighter than the TBE and 15 percent lighter than the VSCE. These results may change somewhat since other sizing constraints such as noise were not considered.

Perturbation Studies

Supersonic fan adiabatic efficiency. - As mentioned before, the efficiency of a supersonic through-flow fan has not been established. It may possibly have more problems with shock and viscous effects than a conventional fan. On the other hand, it is a single-stage fan compared to the three-stage fan of the VSCE. A typical value of adiabatic efficiency for a conventional fan is 0.85. This value may be optimistic for a supersonic through-flow fan. The lower value of 0.75 assumed in this study would seem to include a reasonable degree of pessimism. Figure 8 shows the effect of the lower efficiency on supersonic cruise performance. At the cruise operating points the decrease in fan efficiency results in less than a 1-percent increase in SFC and a 1-percent decrease thrust. Figure 9 shows the effect on mission range. The range penalty would be about 80 to 100 n. mi. or about 1.5 percent. It should be stressed that although the fan efficiency has a small effect on engine performance and range, other undesirable effects not considered here may be present. For example, shock/boundary layer interaction and boundary layer separation may cause structural problems. However, in Ref. 5 it is indicated that undesirable flow fields such as this can be eliminated by proper blade design.

Fan discharge characteristics. - Injecting the core inlet boundary layer bleed air into the fan discharge duct is dependent upon achieving an impulse fan stage and supersonic Mach numbers in the fan duct (fig. 2). If strong shocks occur in the fan that significantly reduce the duct Mach numbers, the static pressures will be too high to permit injecting the boundary layer bleed air and the bleed air must be ejected overboard. In reality, strong shocks in the fan would probably result in a lower adiabatic efficiency than the baseline 0.85 assumed. However, in this study the two effects are treated separately. The penalty in engine performance resulting from overboard bleeding is shown in Fig. 10 and is a 2 percent increase in supersonic cruise SFC and a 2 percent thrust loss. As seen in Fig. 11, this results in a mission range penalty of about 100 n. mi. or 1.7 percent.

Propulsion system weight. - The estimated weight of the core of the supersonic fan engine is within the same degree of confidence as those for the TBE and VSCE since it is similar to a conventional engine. However, the weight estimates for the supersonic fan system (fan, inlet and nozzle) is not as certain. The weight of the supersonic fan system comprises about 25 percent of the total propulsion system weight. If the weight of this system grows by 50 percent for example, the increase in total propulsion system weight would be 12 1/2 percent. Figure 12 shows that this would result in a 160 n. mi. or a 3 percent range penalty.

Concluding Remarks

A study was made to investigate the effects of the supersonic through-flow fan weight and performance characteristics on the mission performance of a supersonic transport aircraft. Perturbations were made on the fan performance and weight to show the effect on mission range. The effect of the fan operating characteristics on inlet drag was also investigated. The range of a supersonic cruise aircraft with a takeoff gross weight of 762 000 lbm was used as the figure of merit. The results are compared to the mission performance of supersonic cruise aircraft using Pratt & Whitney's variable stream control engine (VSCE) and Boeing's turbine bypass engine (TBE).

The results of the study show that the supersonic fan engine could provide major improvements in the mission performance of a supersonic cruise aircraft compared to the VSCE and TBE engines. For the fan performance and operating characteristics used in this study, the supersonic cruise engine performance (SFC) of the supersonic fan engine can be 5 percent better than that of the TBE and 20 percent better than that of the VSCE. The mission range of a supersonic cruise aircraft with supersonic fan engines could be 11 percent better than aircraft with TBE engines and 20 percent better than aircraft with VSCE engines.

If the fan performance used in this study proves to be optimistic, the perturbation studies show that a 12-percent degradation in fan efficiency results in a 1-percent increase in cruise SFC and a 1.4-percent range penalty. If impulse operation of the fan cannot be achieved, an inlet boundary layer bleed penalty would be incurred resulting in a 2-percent increase in cruise SFC and a 2-percent range decrement. Should the weight of the supersonic fan and its inlet and nozzle system be 50-percent heavier than estimated in this study, the mission range would be reduced by 3 percent. Added, these degradations would represent 6-percent lower range, which would still be 5 percent better than the TBE and 14 percent better than the VSCE.

It should be stressed that the supersonic fan would require advancements in fan aerodynamics. The favorable results of this study are dependent on the successful operation of a supersonic through-flow fan. It should also be stressed that even when pessimistic assumptions are made, the supersonic fan is attractive. More definitive results will not be arrived at until more research is expended on this novel concept.

There are other uncertainties not considered in this study. Noise characteristics, both fan and jet, have not been addressed. Low-speed inlet performance of the supersonic fan must be better defined. Structural design of the supersonic fan and its inlet and nozzle need more detailed studies. These uncertainties cannot be fully addressed until a better understanding of the supersonic through-flow fan is accomplished.

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TABLE 1.-ENGINE CYCLE AND COMPONENT PERFORMANCE PARAMETERS

	VSCE	TBE	SSTF
BPR	1.3	--	1.0
OPR	15	16	15
FPR	3.3	--	3.3
CET_{max}	3160 R	3160 R	3160 R
DBT_{max}	3060 R	--	--
η_F	0.85	--	0.85
η_C	0.84	0.84	0.84
η_{HPT}	0.89	0.89	0.89
η_{LPT}	0.91	--	0.91
C_{VJ}	0.985	0.985	0.985
C_{V8}	0.985	--	0.98

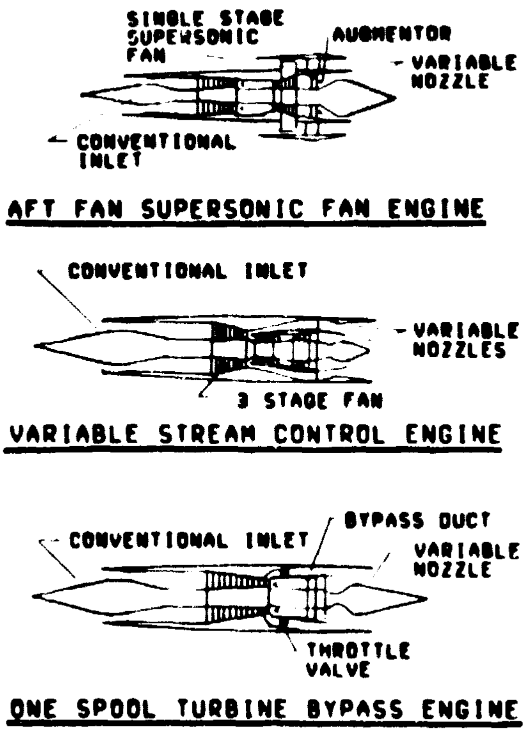

Fig. 1 - Engine Concepts

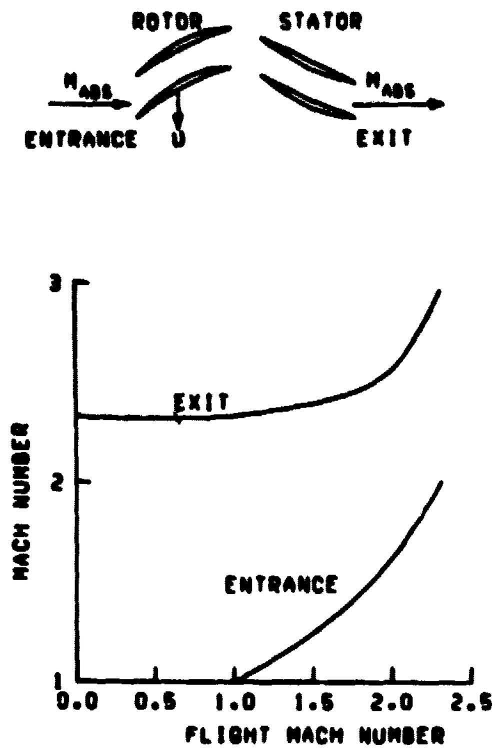

Fig. 2 Variation of Supersonic Fan Entrance and Exit Absolute Mach Numbers with Flight Mach Number

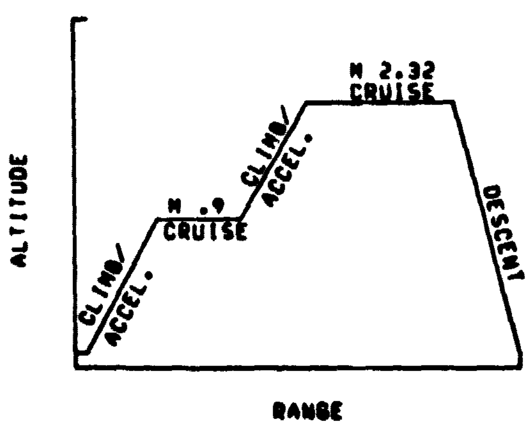

Fig. 3 - Reference Mission,
STD. + 14.4 ·F(+8 °C) Day

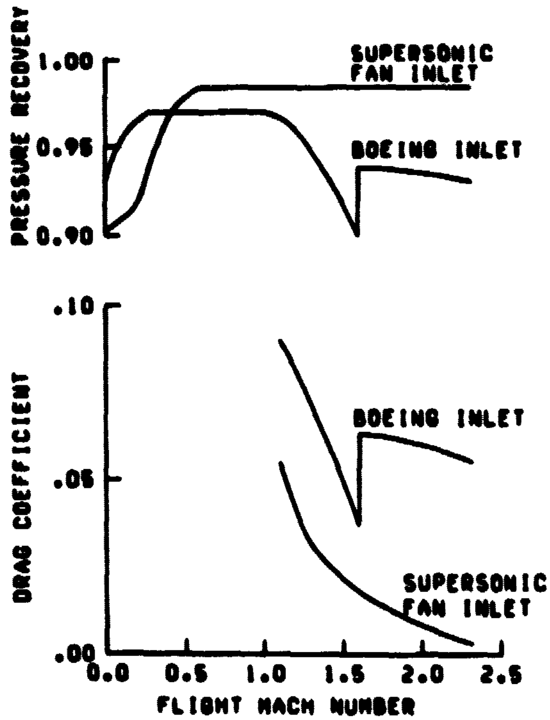

Fig. 4 - Comparison of the Supersonic Fan Engine Inlet Performance with the Boeing Inlet Performance; Matched with the VSCE or TBE

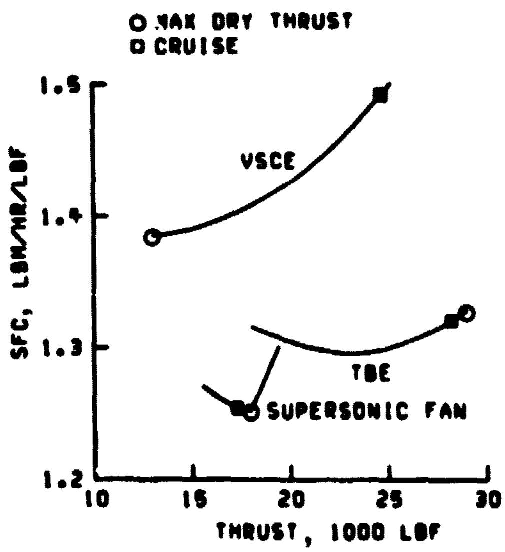

Fig. 5 - Comparison of the Supersonic Fan Engine, TBE and VSCE Supersonic Cruise Performances; Mach 2.32; Altitude - 53000 Ft.; Sea Level Static Airflow - 750 lbm/sec

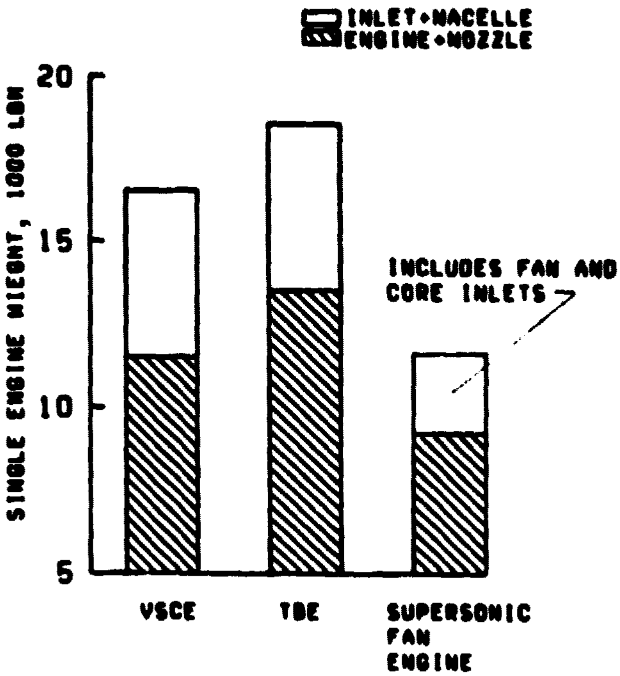

Fig. 6 - Installed Engine Weight; Sea Level Static Airflow - 750 lbm/sec

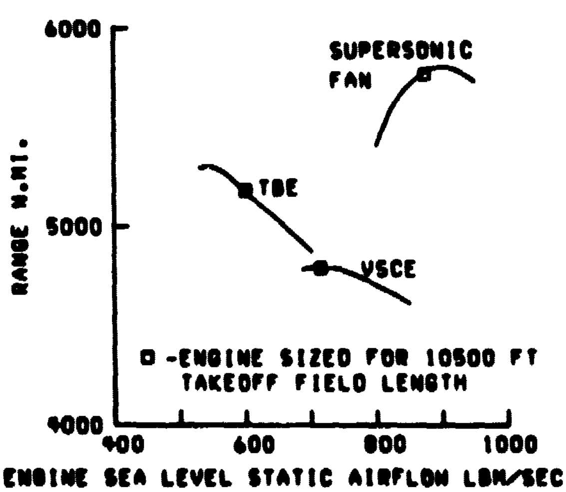

Fig. 7 - Mission Range Comparison; TOGW - 762000 lbm; Payload - 61000 lbm; Cruise Mach Number - 2.32

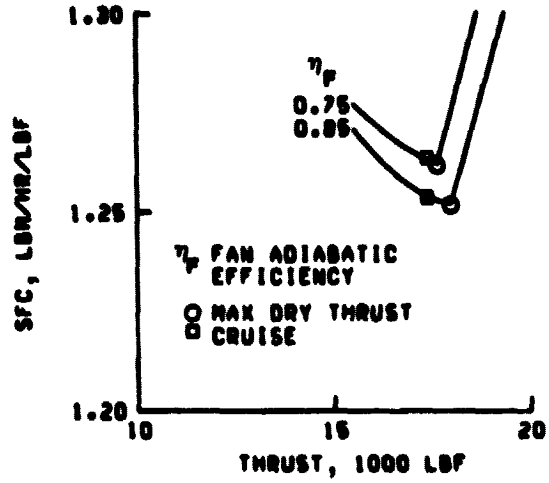

Fig. 8 - Effect of Supersonic Fan Adiabatic Efficiency on Engine Supersonic Cruise Performance; Mach - 2.32; Altitude - 53000 Ft; Sea Level Static Airflow - 750 lbm/sec

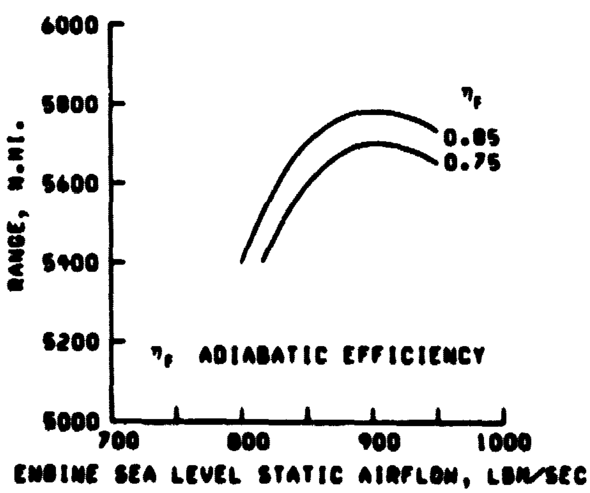

Fig. 9 - Effect of Supersonic Fan Adiabatic Efficiency on Mission Range; TOGW - 762000 lbm; Payload - 61000 lbm; Cruise Mach Number - 2.32

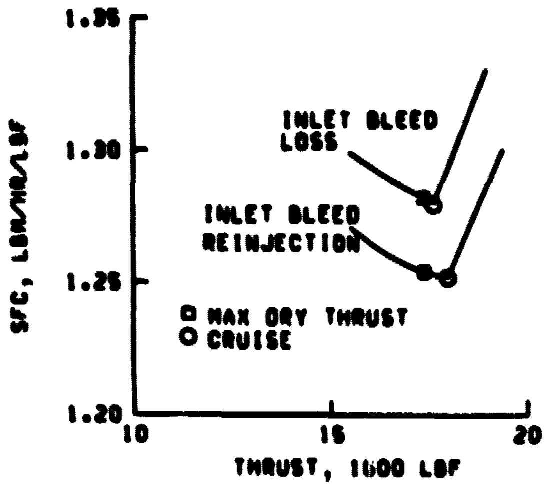

Fig. 10 - Effect of Supersonic Fan Engine Inlet Bleed Loss on Engine Supersonic Cruise Performance; Mach 2.32; Altutude - 53000 Ft.; Sea Level Static Airflow - 750 lb m/sec

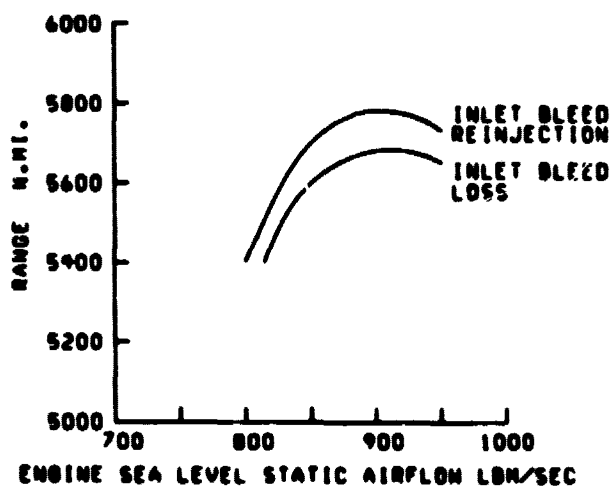

Fig. 11 - Effect of Supersonic Fan Engine Inlet Bleed Loss on Mission Range; TOGW - 762000 lb m; Payload - 61000 lb m; Cruise Mach Number - 2.32

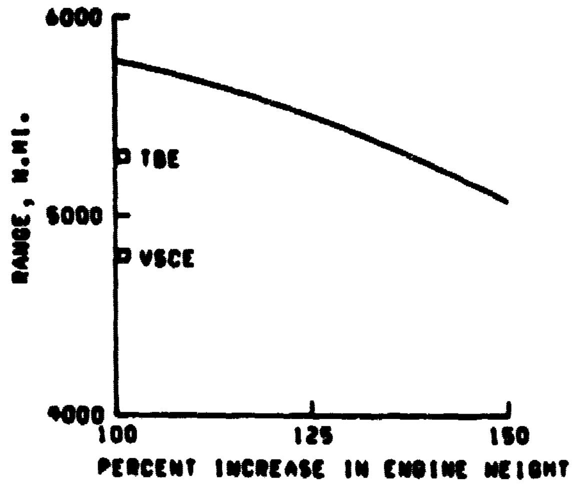

Fig. 12 - Effect of Supersonic Fan Engine Propulsion System Weight on Mission Range; TOGW - 762000 lbm; Payload - 61000 lb; Cruise Mach Number - 2.32