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Turbine Bypass Engine – A New Supersonic Cruise Propulsion Concept

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E-855

Abstract

Engine performance and mission studies were carried out for a single-spool Turbine Bypass Engine (TBE) concept. Comparisons were made between the TBE, a conventional single-spool turbojet, and the Pratt & Whitney Variable Stream Control Engine (VSCE). The airplane assumed for the study was a Mach 2.32 commercial supersonic transport. The nominal mission was a 4000 n.mi. total range with a 300 n.mi. subsonic cruise leg. The figure of merit was the minimum takeoff gross weight for the mission. Comparisons of the three engines were also made for the 4000 n.mi. total range with longer subsonic cruise legs.

Nomenclature

BPR	bypass ratio
CET	combustor exit temperature
C_L	lift coefficient
FPR	fan pressure ratio
OPR	cycle pressure ratio
Po	free stream static pressure
SFC	specific fuel consumption
S.L.S.	sea level static
TIT	turbine stator inlet temperature
TOGW	airplane takeoff gross weight
$W\sqrt{\theta}/\delta$	corrected gas flow rate

Subscripts:

0	free stream
3	compressor exit
4	turbine stator entrance

Introduction

The relative simplicity, compactness and good supersonic cruise performance of the Turbojet makes it an attractive candidate for a supersonic airplane propulsion system. The Olympus engine on the Concorde supersonic transport is a two-spool turbojet. In the first United States SST program, the General Electric GE 4 turbojet was selected. However, on NASA's supersonic cruise research (SCR) program which began in 1972, alternatives were sought because the turbojet was considered to have a difficult noise problem and unacceptable subsonic cruise performance. Hence, SCR emphasis has been on new cycle concepts that are inherently quieter and have better low-speed performance.

However, there is recent renewed interest in the turbojet in the SCR program. The latest developments in mechanical noise suppressors (ref. 1) are encouraging. Also, a promising thermal acoustic shield (TAS) noise reduction scheme (ref. 2) has been suggested and is currently being investigated.

Variable geometry turbines would be a means of improving the turbojet subsonic cruise performance but are undesirable due to their complexity. However, Boeing has reported an innovative turbine bypass concept that may improve the subsonic cruise performance and increase the transonic thrust capabilities of the turbojet with more simplicity than the variable geometry turbine.

Although one and two spool versions of Boeing's turbine bypass engine (TBE) concept have been proposed, recent studies of the engine have indicated that the single spool version would be a more simple engine and would have about the same performance characteristics as a two spool version. NASA-Lewis has contracted with Pratt & Whitney to study the single spool TBE. In-house studies of this concept have also been carried out at NASA-Lewis. In these studies, the TBE, a variable-geometry-turbine turbojet and the Pratt & Whitney variable-stream-control (VSCE) turbofan were compared. Engine performance and mission studies were performed for the three engine concepts. The potential of the engines was assessed in terms of the performance of a future commercial supersonic transport. This paper provides the results of these studies.

Method of Analysis

The analytical procedures followed for this study are summarized in figure 1. Aerodynamic and weight data for the airplane were obtained from reference 3. In the engine performance and weight calculations, the same technology level was assumed for the three engines. The study reflected differences in pod drag and weight of the engines considered. The airframe and the engine data were then used in flight performance calculations to determine the takeoff gross weight as a function of engine sea level static design airflow for a fixed range and payload.

Mission

The baseline mission considered in this study was a Mach 2.32 supersonic cruise with a 300 n.mi. (556 km) subsonic cruise leg for a standard day + 14.4° F (8° C). The total mission range was fixed at 4000 n.mi. (7408 km) but variations in the subsonic cruise range were assumed to show the effects of the subsonic cruise performance of the engines. The mission profile is illustrated in figure 2. A constant 213 n.mi. (394 km) descent from the final cruise altitude at an estimated flight-idle fuel flow was assumed for all cases. The total of 4000 n.mi. (7408 km) was the total of climb/acceleration, subsonic and supersonic cruise and letdown ranges.

A part of the fuel load available was held in reserve for the following requirements:

1. (1) Retain an enroute contingency fuel allowance equal to 5 percent of the mission fuel.
2. (2) Provide for a 260 n.mi. (482 km) diversion to an alternate airport at Mach 0.9 at an optimum Brequet cruise altitude.
3. (3) Provide for a 30-minute hold at Mach 0.45 at an altitude of 15 000 feet (4572 m).

Airframe

The weight and aerodynamics for the baseline airplane used in this study were for the Langley-LTV arrow-wing airplane defined in reference 3. The major characteristics of the airplane are summarized in table I.

Propulsion System

The uninstalled engine performance was first calculated without inlet and nacelle drags using the NASA-NAVY Engine Program, reference 4. The engine component aerodynamic characteristics, efficiencies and cooling requirements used in the program were compatible with the Pratt & Whitney early to mid-1990's technology level. However, a three-count efficiency penalty was assumed for the variable area turbines compared to the fixed-area turbines.

The inlet sizes were determined by the supersonic cruise airflow. Inlet/engine airflow matching studies were conducted. The engine airflows were scheduled to match the Boeing inlet. Cowl pressure drag was not included since nacelle dimensional data for the TBE are not well defined. Bypass, bleed and spillage drags were determined for the inlet performance.

Nozzle performance includes internal losses and boattail drag. An internal nozzle velocity coefficient of 0.985 was assumed for all cases. Boattail drag was calculated with data from reference 5.

The installed engine performance is the uninstalled performance adjusted for the inlet, nozzle and nacelle drags.

The installed propulsion system weight includes the engine plus nozzle/reverser, inlet and nacelle. The TBE engine/nozzle/reverser weight was obtained from preliminary estimates from Pratt & Whitney. The turbojet/nozzle/reverser weight was assumed to be the same as the TBE. The VSCE engine/nozzle/reverser weight was obtained from reference 6. Weight estimates for the Boeing inlet and the nacelle were made with data from reference 7.

The major characteristics of the three engines are given in table II.

Results and Discussion

Single-Spool Fixed-Turbine-Area Turbojets

Figure 3 depicts the matching of a compressor and turbine for a single spool turbojet. The turbine is choked for nearly all operating conditions indicated by the constant value of turbine corrected airflow $W_4 \sqrt{\theta_4}/\delta_4$. For variations in turbine inlet temperature, the compressor will operate at pressure ratios and airflows to satisfy the constant value of turbine corrected airflow. For a prescribed compressor airflow, the compressor operates at increasing pressure ratios with increasing turbine inlet temperatures. The compressor surge margin, (usually about 20 percent) places a constraint on the upper limit of turbine inlet temperature. There are, of course, other constraints such as materials, cooling, etc. Decreasing the turbine inlet temperature at a fixed compressor airflow causes decreasing pressure ratios. Lower limits on the turbine inlet temperatures would have to be evaluated in terms of low compressor efficiencies or limits on nozzle area variations.

Selecting a particular compressor/turbine combination places limits on the turbine inlet temperature excursion a turbojet can achieve. Matching a compressor to a large annulus area, A_N, turbine (fig. 4) reflects a high temperature design and high thrust. For the same engine airflow, matching the same compressor to a small A_N turbine reflects a low temperature design and lower thrust. The smaller turbine could not be operated at the same high turbine inlet temperature as the large A_N turbine without surging the compressor. The limitations on the operating turbine inlet temperatures set by the compressor/turbine design are shown in figure 5. A minimum surge margin of 20 percent and a maximum operating turbine inlet temperature of 3160 R (1756 K) are assumed. The large A_N turbojet is matched for 3160 R (1756 K). The large A_N turbojet can be operated near maximum turbine inlet temperature for almost all conditions. The small A_N turbojet must be operated at much lower temperatures to maintain the 20 percent compressor surge margin. The acceleration thrust and SFC's of the two engines are compared in figure 6. The large A_N turbojet would have 60 percent more transonic thrust than the small A_N turbojet. It shall be noted, however, that the higher thrust of the large A_N turbojet is at the expense of higher SFC's.

A comparison of the subsonic cruise performance of the two engines is shown in figure 7. Although the high thrust of the large A_N turbojet is beneficial for acceleration, the engine must be substantially throttled back for cruise. In this case, the engine is throttled back along a 20 percent compressor surge margin as shown in figure 3. This reduces engine airflow resulting in lower propulsive efficiency. Also, the inlet air supply remains fixed so that inlet air must be bypassed overboard as the engine air demand reduces resulting in large bypass drag. As seen in figure 7, the large A_N turbojet is heavily penalized at the subsonic cruise operating point. The small A_N turbojet is operating closer to its maximum thrust and has an SFC 22 percent lower than the large A_N turbojet.

The Turbine Bypass Engine and the Variable Turbine Area Turbojet

One means of removing the restrictions associated with the choked turbine is with a variable area turbine (VAT). With the ability to vary the turbine area, the turbine corrected flow can vary, thus permitting wider excursions in the operating turbine inlet temperature. For a given flight condition this allows the compressor to operate at nearly a fixed point for wide variations in throttle. This avoids the part power performance penalties of the fixed turbine (fig. 7). Figure 8 shows typical operating characteristics of the variable area turbine (VAT) analyzed in this study. At Mach 0.9, the turbine area varies by 30 percent between low throttle cruise and maximum thrust acceleration. The compressor operating points for these two conditions are seen to be very close.

The objective of the turbine bypass concept is very similar to that of the variable area turbine. However, instead of varying the turbine area, the turbine airflow is varied without changing the compressor airflow.

During his propulsion studies at Boeing, Garry Klees found that regulating the airflow into the burner and turbine provided a convenient means of achieving a constant corrected airflow into a fixed geometry turbine with excursions in turbine inlet temperature. Figure 9 shows a schematic of this concept for a single spool engine. In this scheme, the compressor is matched with a small A_N turbine. A provision is made for bypassing some compressor discharge air around the burner and turbine and into the nozzle. As shown in the figure, the turbine inlet temperature for zero bypass is 1900 R (1055 K). As the turbine inlet temperature is increased the bypass airflow, WBP, is increased. The actual turbine airflow, W_4, is reduced to achieve the constant turbine corrected flow 82 lbm/sec (37.2 kg/sec). This enables a small A_N turbojet to be operated at the maximum turbine inlet temperature of 3160 R (1756 K) by bypassing some fo the compressor discharge air. Figure 10 shows the variation of the compressor discharge air with Mach number for a constant turbine inlet temperature of 3160 R (1756 K) and 20 percent compressor surge margin.

Since the compressor discharge total pressure is much higher than that of the nozzle, the bypass air may have to be throttled to the nozzle total pressure to prevent possible undesirable aerodynamic effects at the turbine exit. In this study, throttling of the bypass air represents total pressure losses of the bypass air as high as 80 percent.

Figure 11 shows the improvements in the turbojet subsonic cruise performance with the TBE concept and the VAT. Compared to the large-A_N fixed-area-turbine turbojet, the TBE and the VAT improve the cruise SFC by 20 percent. The cruise SFC's of the TBE and the VAT are about the same. At maximum power, the VAT has the highest thrust but also the highest SFC. The maximum thrust of the fixed area turbojet is about 6 percent lower than the VAT turbojet since it cannot be operated at maximum turbine inlet temperature without surging the compressor (fig. 5). Although the TBE maximum turbine inlet temperature, 3160 R (1756 K), is the same as the VAT turbojet, its maximum thrust is 16 percent lower because 22 percent of the engine air is bypassed around the burner and turbine. This also reduces fuel flow resulting in a lower SFC.

Engine Performance Comparisons - TBE, VAT Turbojet, P & WA VSCE

The performance of the TBE and the VAT turbojet are compared to Pratt & Whitney's VSCE which is a moderate bypass ratio duct burning turbofan. Because it is a bypass engine it has the potential for good subsonic cruise performance (maximum dry power cruise) and quiet takeoff. On the other hand, duct burning, leading to higher SFC's, is required for transonic and supersonic operation.

A comparison of the performance of the TBE, VAT turbojet and the P & WA VSCE at Mach 0.9 is shown in figure 12. At the cruise operating points, the SFC of the VSCE is about 6 percent better than those of the TBE and VAT turbojet. However, the high thrust performance of the VSCE is much poorer than the other two engines since duct burning is required. This characteristic is also shown in figures 13 and 14 (duct burner fuel/air ratios were reduced with larger engine sizes). In figure 13, the transonic thrust of the VSCE is seen to be 15 to 25 percent lower than the TBE and 30 to 40 percent lower than that of the VAT turbojet. At supersonic acceleration, the thrust of the TBE and VSCE are comparable. The VAT turbojet has the best acceleration thrust of the three engines. In figure 14, the VSCE exhibits the best subsonic acceleration SFC's. During transonic and supersonic acceleration, the SFC's of the VSCE are about 20 percent higher than the other two engines.

Since most of the acceleration fuel of the SST is consumed during transonic/supersonic acceleration, the VSCE would benefit from larger engine sizes than the TBE or VAT turbojet to reduce acceleration time and fuel.

Figure 15 shows a comparison of the supersonic cruise performance of the three engines. The SFC's of the TBE are somewhat lower than those of the VAT turbojet. The cruise SFC of the VSCE is about 9 percent higher than those of the other two engines.

Mission Studies

As shown in the previous section, the TBE and the VAT turbojet have better acceleration and supersonic cruise performance than the VSCE. As seen in table II, however, the VSCE weighs less than the other two engines for the same engine size (airflow). The VSCE engines can be larger than the other two engines without incurring as much weight penalty. This reduces acceleration time and lessens the penalties incurred by the high transonic/supersonic SFC's of the VSCE. Figure 16 shows range versus engine size for the three engines. The engine size for maximum range for the VSCE is 720 lb/sec (327 kg/sec); 30 percent larger than the best engine sizes for the TBR and VAT turbojet. The better SFC's of the TBE and VAT turbojet (compared to the VSCE) result in 400 to 500 n.mi. (741 to 926 km) more range for the best engine sizes. Figure 17 compares the mission performance of the three engines in terms of takeoff gross weight for a 4000 n.mi. mission range. The minimum TOGW of the TBE is 8 percent lower than that of the VSCE.

Figure 18 shows the effect of longer subsonic cruise range on total range. The reference point is the 4000 n.mi. (7408 km) total range with 300 n.mi. (556 km) subsonic cruise leg and the takeoff gross weights are the minimum values from figure 17. The subsonic cruise range is seen to have only a small effect on total range. This is especially true for subsonic cruise ranges less than 1000 n.mi. (1852 km) usually considered for an SST-mission. It should be pointed out that this result stems from the good subsonic cruise SFC's of all three of the engines compared to a fixed turbine turbojet.

Concluding Remarks

A study was made to compare the mission performances of the turbine bypass engine, TBE, to the mission performance of a variable area turbine, VAT, turbojet and the P & WA variable stream control engine, VSCE. The study included engine performance analysis and mission performance. The minimum takeoff gross weight (TOGW) of a commercial supersonic transport for a 4000 n.mi. (7408 km) range was used as the figure of merit. The maximum range for a fixed TOGW of 762 000 pounds (345 950 kg) was also used. The effect of subsonic cruise range was investigated.

The results of the study show that the mission performance of the TBE and a VAT turbojet are about the same. The TBE TOGW is about 8 percent lower than that of the VSCE for the 4000 n.mi. range. The maximum range of the TBE is 10 percent higher than the maximum range of the VSCE for the 762 000 puunds (345 950 kg) airplane. The mission performance of the TBE and VAT-turbojet are superior to the VSCE because they have significantly lower SFC's at transonic/supersonic acceleration and supersonic cruise. The length of the subsonic cruise leg has a small effect on mission range for all three engines. This results from the efficient low thrust cycle characteristics of the TBE, VAT turbojet and VSCE. Also, the high port-power airflow characteristics of these engines reduces the inlet bypass drag, which comprises a major part of the throttle-back drag at subsonic cruise.

It should be stressed that the mechanical and cycle features of the VSCE have been under study by Pratt & Whitney for several years. The same indepth studies of the TBE have yet to be accomplished. Final comparisons of the two concepts would have to await completion of these studies. It should also be stressed that these engines are compared on a mission performance basis only. Since the VSCE would be inherently quieter than an unsuppressed TBE at takeoff, noise constraints may have a more significant impact on the TBE than on the VSCE.

The novel feature of the TBE is the ability to operate at low part power with high propulsive efficiency. This feature should be exploited for other applications such as fighter aircraft with subsonic and supersonic flight requirements, cruise missiles and turboshafts for helicopters.

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TABLE I. - MAJOR AIRPLANE CHARACTERISTICS

Characteristic	Value
Takeoff gross weight:	
lbm	762 000
kg	345 637
Number of passengers	292
Payload:	
lbm	61 028
kg	27 682
Reference wing area:	
ft	9 969
m	926
Operating empty weight less propulsion weight:	
lbm	259 913
kg	117 897
Lift-off C_L	0.56

TABLE II. - ENGINE CHARACTERISTICS

	TBE	VAT turbojet	P & WA VSCE
Engine cycle description			
$W\sqrt{\theta}/\delta$, lbm/sec (kg/sec)	750 (341)	750 (341)	750 (341)
FPR	-------------	-------------	3.3
OPR	18	18	15
BPR	-------------	-------------	1.3
CET, R (K)			
Max	3160 (1756)	3160 (1756)	3160 (1756)
S.L.S.	*3160 (1756)	*2800 (1556)	2500 (1389)
Max DBT, R (K)	-------------	-------------	3060 (1700)
Engine weight			
Engine + nozzle/reverser, lbm (kg)	13 550 (6152)	13 550 (6152)	11 500 (5221)
Inlet + Nacelle	5 000 (2270)	5 000 (2270)	5 000 (2270)
Total, lbm (kg)	18 550 (8422)	18 550 (8422)	16 500 (7491)

*Maximum bypass.

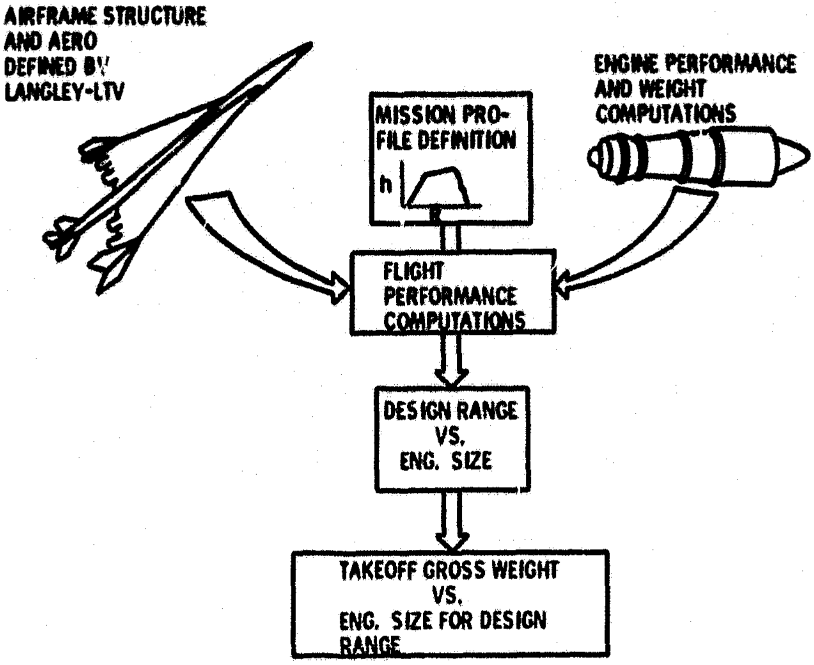


Figure 1. - Calculation flow chart.

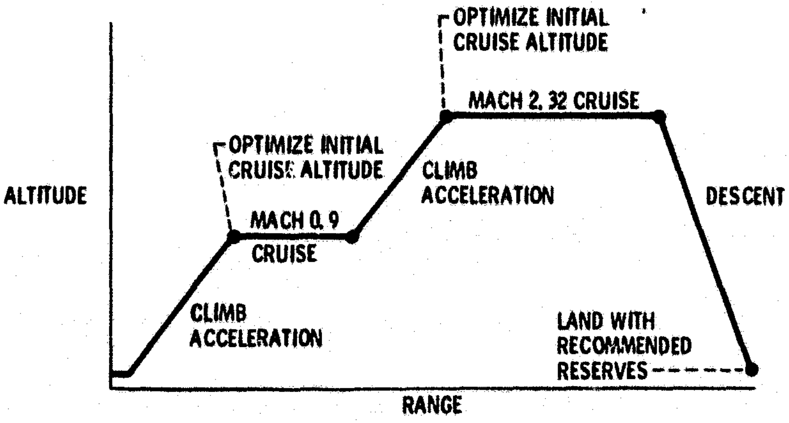
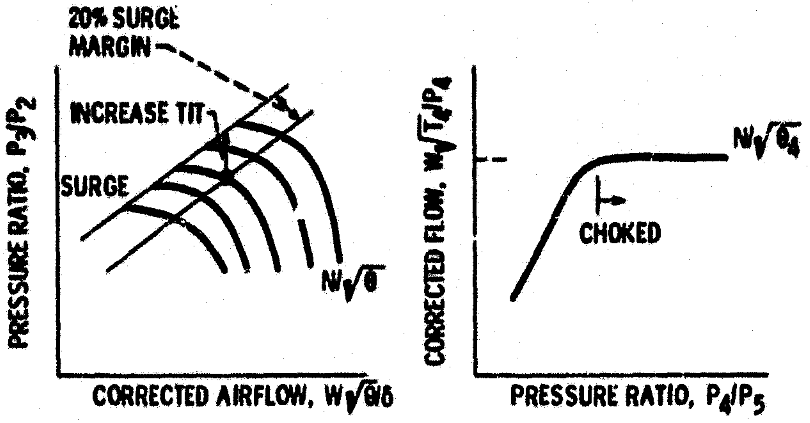


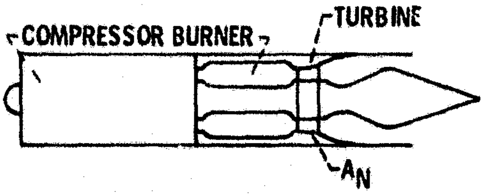
Figure 2. - Reference mission, std. + 14.4° F (+ 8° C) day.



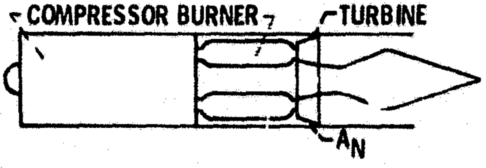
(a) Compressor.

(b) Turbine.

Figure 3. - Matching characteristics of a single spool turbojet.



(a) Single spool turbojet, large A_N



(b) Single spool turbojet, small A_N

Figure 4. - Turbine annulus area, A_N

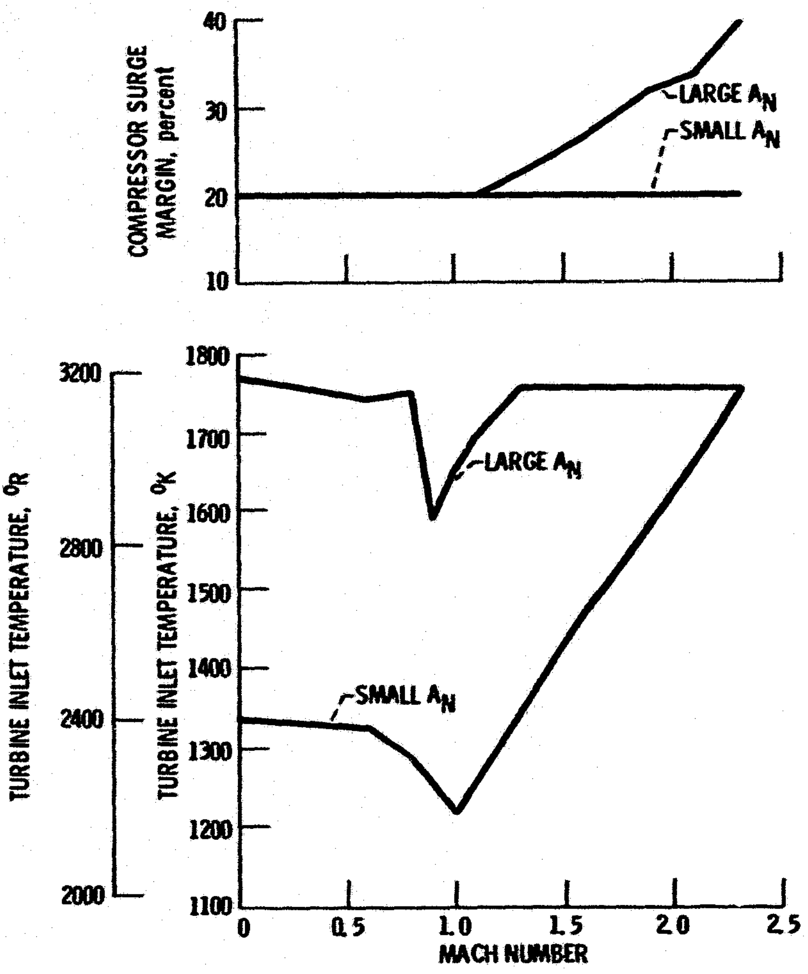


Figure 5. - Effect of turbine area on compressor surge margin and turbine inlet temperature - single spool turbojet.

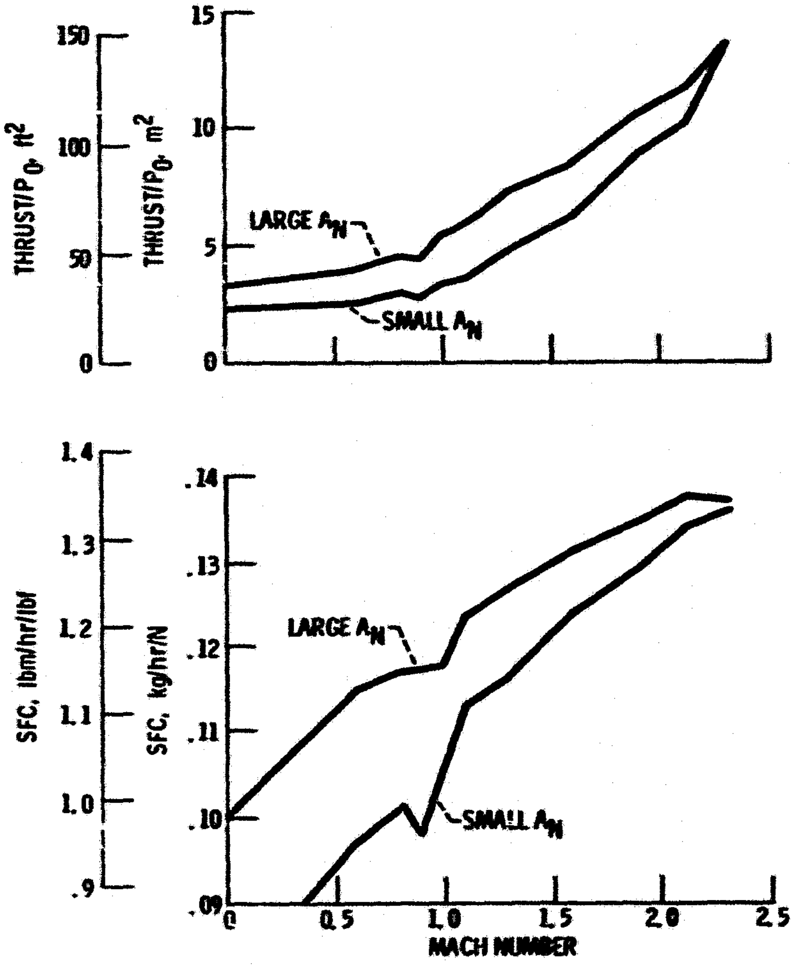


Figure 6. - Effect of turbine area on acceleration performance - Single spool turbojet.

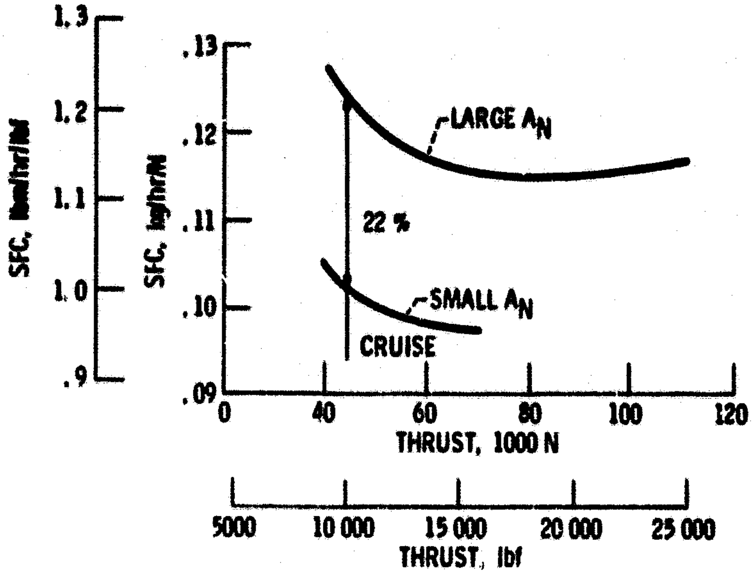
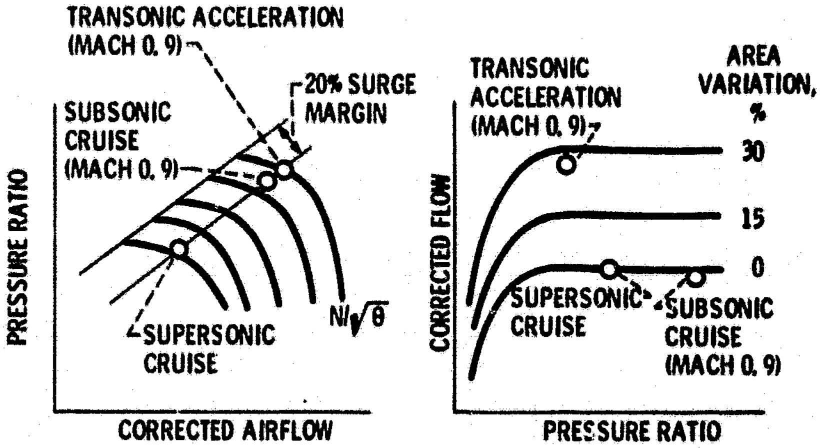


Figure 7. - Effect of turbine area on engine performance at MACH 0.9; single spool turbojet; sea level static airflow, 750 lbm/sec (341 kg/sec).



(a) Compressor.

(b) Variable area turbine.

Figure 8. - Operating characteristics of a single spool turbojet with a variable area turbine (VAT).

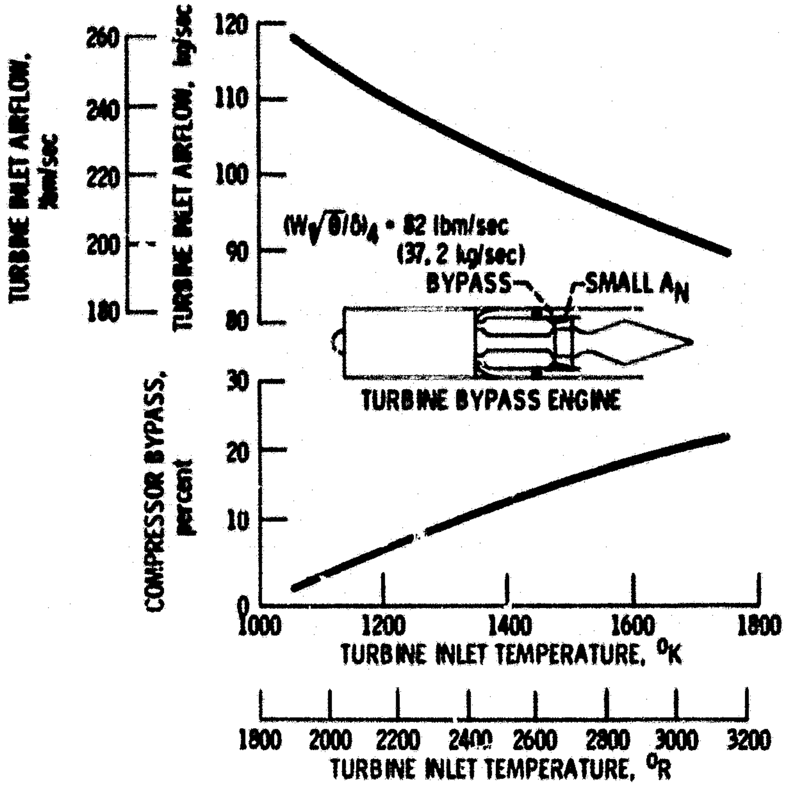


Figure 9. - Variation of bypass air and turbine inlet air with turbine inlet temperature; MACH 0.90.

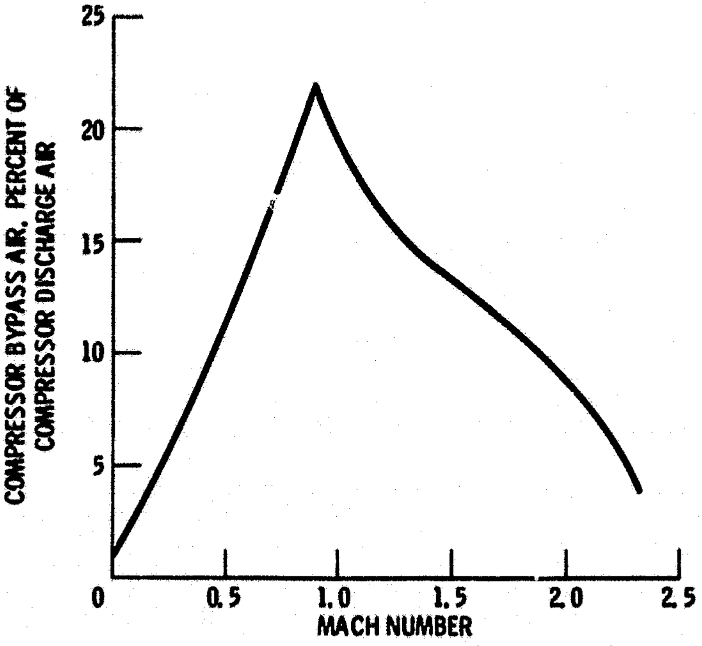


Figure 10. - Variation of TBE bypass air for acceleration; constant TIT = 3160 °R (1756 °K), 20 percent compressor surge margin.

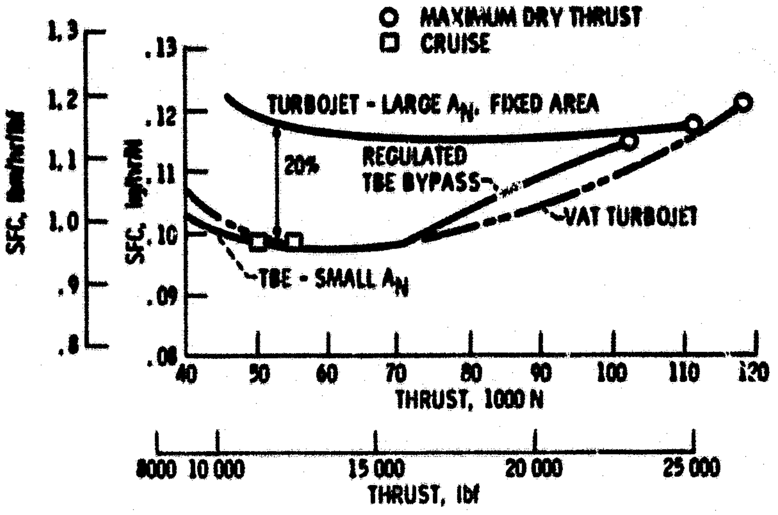


Figure 11. - Comparison of maximum power and part power characteristics of a TBE, a variable area turbine turbojet and a fixed area turbine turbojet; MACH 0.9; altitude, 36 089 ft. (11 000 m); sea level static airflow, 750 lbm/sec (341 kg/sec).

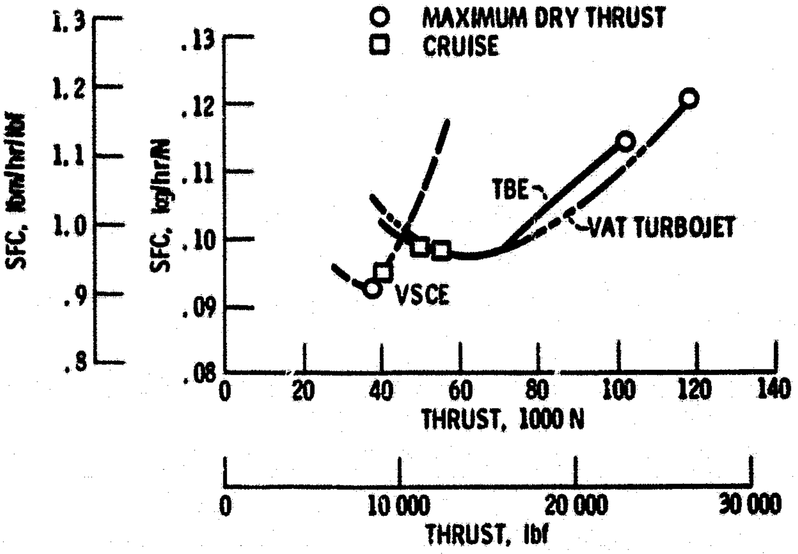


Figure 12. - Comparison of subsonic cruise performance of the TBE, VAT turbojet and the P&WA VSCE; MACH 0.9; altitude, 36 089 ft. (11 000 m); sea level static airflow, 750 lbm/sec (341 kg/sec).

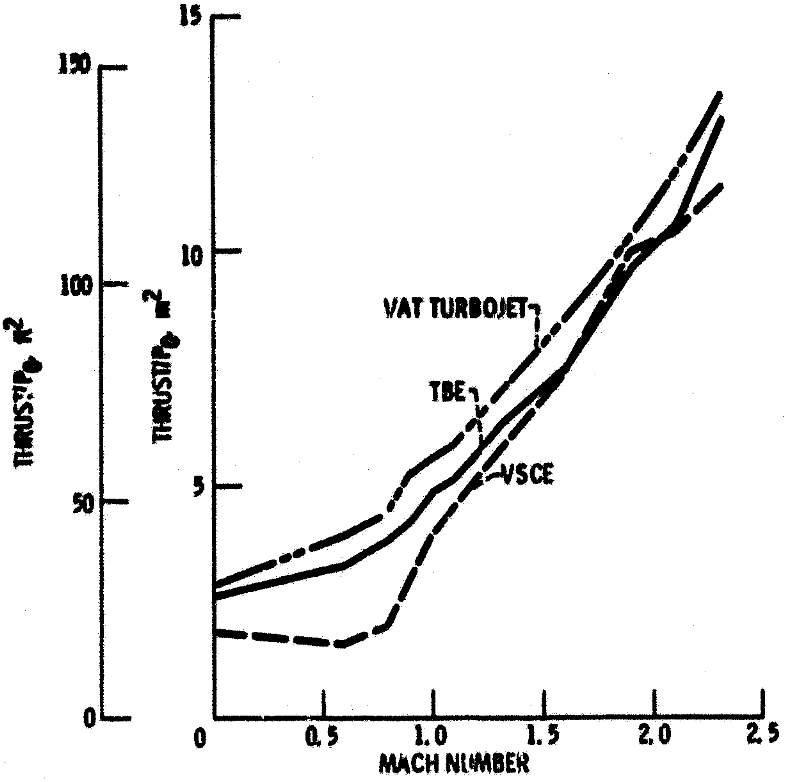


Figure 13. - Comparison of the TBE, VAT turbojet and the P&WA VSCE acceleration thrust; sea level static airflow, 750 lbm/sec (341 kg/sec).

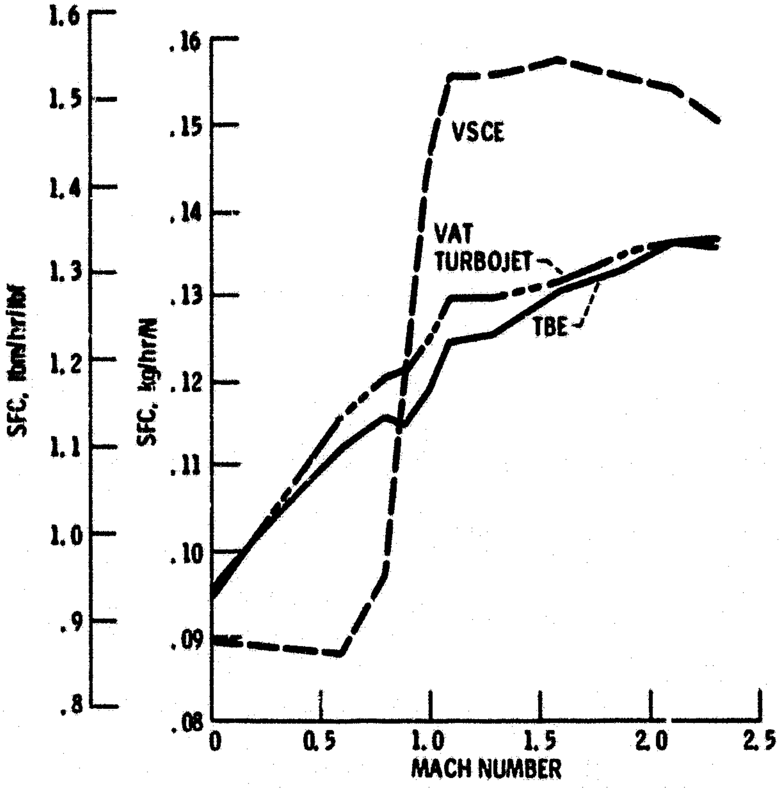


Figure 14. - Comparison of TBE, VAT turbojet and the P&WA VSCE acceleration SFC; sea level static airflow, 750 lbm/sec (341 kg/sec).

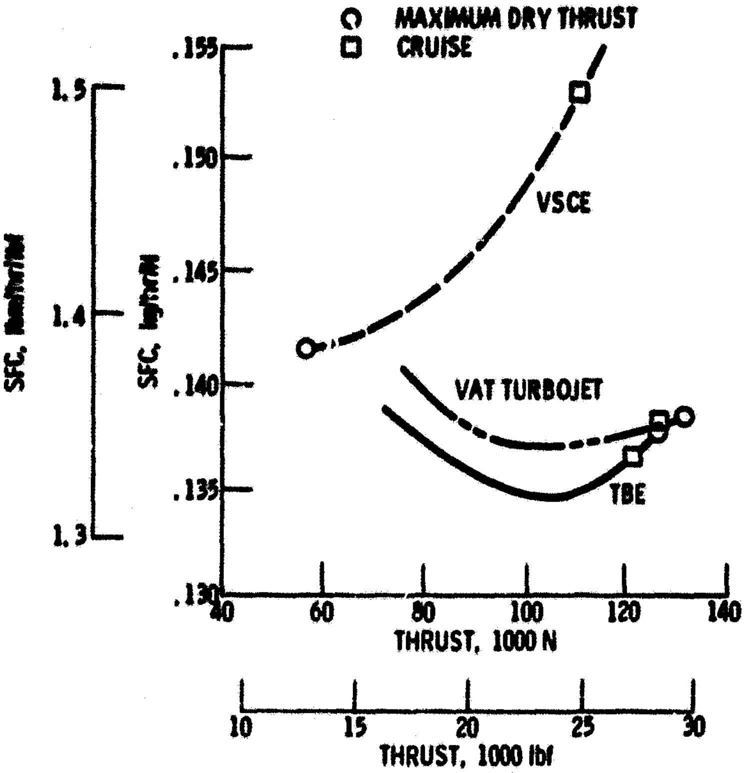


Figure 15. - Comparison of the TBE, VAT turbojet and the P&WA VSCE supersonic cruise performance; MACH 2.32; altitude, 53 000 ft (16 154 m); sea level static airflow, 750 lbm/sec (341 kg/sec).

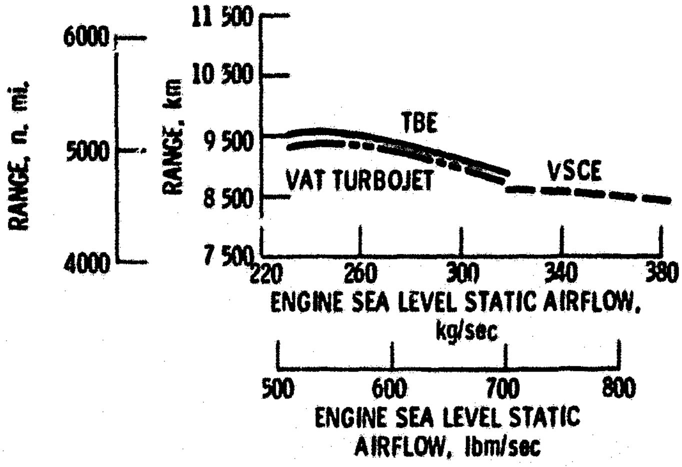


Figure 16. - Range versus engine size comparison for the TBE, VAT turbojet, and the P&WA VSCE; MACH 2.32 cruise; 300 n. mi. (556 km) subsonic cruise; TOGW 762 000 lbm (345 950 kg); 292 passengers.

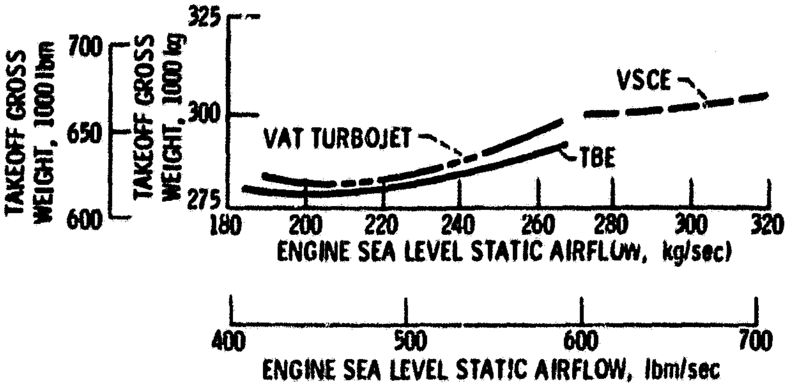


Figure 17. - Mission performance comparison of the TBE, VAT turbojet, and the P&WA VSCE; MACH 2.32 cruise; 300 n. mi. (556 km) subsonic cruise; 4000 n. mi. (7408 km) total mission range; payload, 292 passengers.

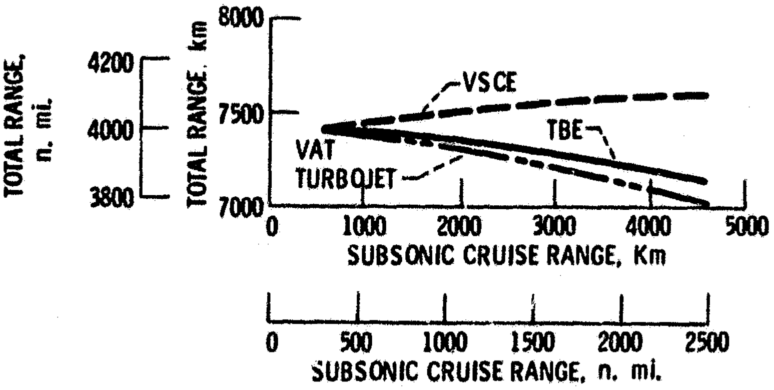


Figure 18. - Effect of subsonic cruise range on total range; MACH 2.32 supersonic cruise; MACH 0.9 subsonic cruise; payload, 292 passengers.