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16 Abstract
Engine performance, weight and mission studies were carried out for supersonic through-flow fan engine concepts. The mission used was a Mach 2.32 cruise mission The advantages of supersonic through-flow fan engines were evaluated in terms of mission range comparisons between the supersonic through-flow fan engines and a more conventional turbofan engine. The specific fuel consumption of the supersonic through-flow fan engines was 12 percent lower than the more conventional turbofan. The aircraft mission range was increased by 20 percent with the supersonic fan engines compared to the conventional turbofan

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SUPERSONIC THROUGH - FLOW FAN ENGINES FOR SUPERSONIC CRUISE AIRCRAFT

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SUMMARY

A study was made to evaluate the potential benefits of supersonic through-flow fan engines for supersonic cruise aircraft. Engine performance, weight and mission studies were carried out for four supersonic through-flow fan engine concepts and for a more conventional reference turbofan engine similar to the Pratt & Whitney VSCE 502B duct-burning turbofan. The advantages of the supersonic fan engines were evaluated in terms of mission range comparisons between the supersonic fan engines and the reference turbofan engine. A Mach 2.32 all supersonic cruise mission was used in the study. The airplane simulated in these mission studies was the NASA/Langley-LTV arrow wing airplane. Sideline noise levels of FAR 36 (1977-stage 2 noise limits) were adopted for a thrust level required for a takeoff field length of 10500 feet (3200m). The specific fuel consumption of the supersonic fan engines was about 12 percent lower than that of the reference turbofan engine. The propulsion system weight of the supersonic fan engines was about 30 percent less. When powered with supersonic fan engines the mission range improved by 20 percent compared to the range achieved by the reference turbofan engine. These favorable projections are based on the assumption that the supersonic fan performance will approach that calculated in the analysis and a number of potential problem areas can be satisfactorily overcome.

INTRODUCTION

Since 1972 NASA has sponsored studies by Pratt & Whitney Aircraft and the General Electric Company to identify propulsion systems that would be suitable for long-range supersonic cruise aircraft (refs. 1-7). These studies considered a variety of conventional and variable cycle concepts. An alternative concept, the supersonic through-flow fan variable-bypass-engine, was suggested by

Advanced Technology Laboratories Inc. and was studied under NASA contract (ref. 8). This engine (fig. 1) incorporates a single-stage supersonic through-flow -fan. This type of fan has supersonic absolute Mach numbers at the fan face and stator exit. In comparison to the Pratt & Whitney and General Electric best Phase I engines (refs. 1-2), it promised superior performance (fig. 2). Since that time further studies of the supersonic through-flow fan concept have been carried out at NASA-Lewis. This report provides the results of these studies. It should be emphasized that the results of the study are dependent on the supersonic fan performance approaching that calculated for this study and a number of potential problem areas can be overcome.

The results are compared with a 'reference turbofan' engine that is representative of Pratt & Whitney's most recent SCAR engine, the VSCE 502B which is a duct burning turbofan with some variable cycle features (the performance of the most recent Pratt & Whitney and General Electric SCAR engines is quite similar). In the Lewis simulations of the reference turbfan engine and the supersonic fan engines identical performance characteristics have been assumed for the components that are common to both types of engines.

A number of alternative versions of the supersonic through-flow fan engine were studied in order to minimize some of the technological uncertainties of the concept, some of which were identified by Pratt & Whitney and General Electric in references 5 and 7. The most promising concepts are considered in this report. The potential of the supersonic fan concepts is assessed in terms of the performance of a future commercial supersonic transport. Cruise Mach number, takeoff gross weight, payload, takeoff distance and noise are fixed so that the figure of merit is range.

DESCRIPTION OF THE CONCEPTS

The supersonic fan considered in these studies is a supersonic through-flow (superflow) fan stage, ie, supersonic absolute Mach numbers at the fan face and stator exit. This type of supersonic fan would be different from the type studied in the 1950's (refs. 9-12). At that time the absolute Mach numbers at the fan face and stator exit were subsonic and only the rotor relative Mach numbers were supersonic (see figure 3). The results from references 9-12 show that good efficiencies could be obtained from this type of supersonic rotor. However, the stators were designed to discharge the flow subsonically. Complete stage (rotor and stator) efficiencies were poor due to high stator losses associated with strong shocks within the stator passage. A complete superflow fan stage has the potential to reduce the stator shock losses leading to higher overall stage efficiencies.

A superflow fan would lead to improvements in the overall propulsion system. These improvements are a reduction in fan weight (single stage vs three stage), reductions in inlet losses and weight, smaller overall engine dimensions with lower nacelle drag and weight and more versatility in matching the engine cycle to the airplane thrust requirements. These improvements can be shown by comparing the operating characteristics of the superflow fan variable-bypass engine with those of a more conventional engine,a duct-burning turbofan similar to the Pratt & Whitney 502B, as shown in figure 4. For the remainder of this report the 502B type engine will be referred to as the reference turbofan. The superflow fan face absolute Mach numbers range from 1 at takeoff to values slightly less than free stream Mach numbers during supersonic flight. Thus, little diffusion of the air is required. This would be especially beneficial at supersonic cruise since significant reductions in inlet losses would result. Also, since the throat and subsonic diffuser required for conventional inlets are not required the inlet for a superflow fan would be much shorter and lighter than the conventional supersonic inlet. The fan stage exit Mach numbers are supersonic for all flight conditions. In figure 4 the exit Mach numbers are seen to range fron 2 at sea level static to 3 at supersonic cruise. This could simplify the duct nozzle mechanically (no throat required) with possible improvements in nozzle weight and efficiency. However, a second supersonic inlet would be required to diffuse the core airflow from the fan exit supersonic velocities to subsonic velocities at the compressor face. As mentioned earlier, the core compressor, burner and turbines of the superflow fan engine and the reference turbofan are about the same. The core of the superflow fan engine is equipped with an afterburner. As defined in this study the core nozzle is a plug type with a variable area throat. The overall length of the superflow variable-bypass engine is estimated to be about 25 percent shorter than the reference turbofan and would incur less drag and would have a shorter, lighter nacelle.

To achieve high pressure ratios in a single stage, the superflow fan in this study makes use of a high degree of turning in the rotor blade passage (about 40 degrees,ref. 8) and high fan face velocities (supersonic) during supersonic flight operation. These characteristics enable the superflow fan to achieve high pressure ratios at both takeoff and supersonic cruise. The superflow variable-bypass engine can exploit these characteristics to a greater extent than the other alternative superflow fan concepts considered in this study. As the name implies, the superflow fan variable-bypass engine achieves variable bypass features. As seen in figure 5, the superflow fan achieves about the same S.L.S. design pressure ratio at a much lower tip speed than the conventional fan, 1300 ft/sec (396 m/sec) compared to 1600 ft/sec (506 m/sec). At supersonic cruise it achieves a much higher pressure ratio than the conventional fan for about the same tip speed. In order to obtain this same high fan pressure ratio, the corrected tip speed of the conventional fan would have to be increased to about 105 percent (2200 ft/sec (671 m/sec) as indicated by the dashed circle in figure 5. This would increase the airflow by 30 percent. Operating the conventional fan in this manner would result in severe material problems and large weight penalties of the overall propulsion system of the conventional turbofan. The higher fan pressure ratio at cruise of the superflow fan permits the core compressor of the superflow variable bypass engine to accept more airflow than that of the reference turbofan core compressor. Therefore the superflow variable-bypass engine can operate at a lower bypass ratio at supersonic cruise than the reference turbofan even though it has a higher S.L.S. design bypass ratio. This leads to high specific dry thrust at supersonic cruise. In order to operate in this fashion, the superflow variable-bypass engine requires a variable capture area inlet to the core and variable area nozzles fot the core and duct.

The requirement for a variable-area, supersonic, second inlet is felt to be a major technological problem for this engine. Consequently, several alternative configurations were derived that do not employ this component. The alternative superflow fan concepts cannot vary the bypass ratio for a fixed fan airflow as the superflow variable bypass engine does. However, they operate at reduced bypass ratios at supersonic cruise and achieve the same high dry thrust characteristics as the superflow variable bypass engine. As pictured in figure 6, these versions all employ SCAR technology cores that employ conventional supersonic inlets. The two aft fan versions have the superflow fan rotor blades mounted to the outer ring or rotating shroud of an uncoupled low pressure turbine. In the forward fan version the superflow fan rotor blades are mounted to the outer ring or shroud of a subsonic low pressure ratio core fan driven by the low pressure turbine. The superflow fan cowl and stators for the three cycles are mounted to the engine structural casing. Except for the aft fan with the interburner between the high and low pressure turbines all of the superflow fan cycles have core afterburners.

METHOD OF ANALYSIS

The analytical procedures followed for this study are summarized in figure 7. Aerodynamic and weight data for the airplane were obtained from reference 13. In the engine performance and weight calculations the same SCAR technology level was assumed for the superflow fan engines and the reference turbofan engine. The study reflected differences in pod drag and weight of the five engines considered. The airframe and engine data were then used in flight performance calculations to determine the range as a function of engine S.L.S. design airflow for a fixed takeoff gross weight and payload. Takeoff field length, sideline noise constraints and thrust margin requirements were then used to determine the engine size and range from the range versus engine design airflow data.

Takeoff gross weight for a fixed range and payload is probably a preferred figure of merit. However, this study has used range for a fixed takeoff gross weight and payload as the figure of merit for consistency with the extensive studies of the NASA-Langley SCAR airframe contractors.

Mission

The nominal mission considered in this study was a Mach 2.32 supersonic cruise (standard day + 14.4 F) . The mission profile is illustrated in figure 8. The climb and acceleration flight path used in the study is shown in Mach number and altitude coordinates in figure 9. 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 calculated range used for the figure of merit in the study was the total of climb/acceleration, cruise and letdown ranges.

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

(1) retain an enroute contingency fuel allowance equal to five percent of the mission fuel

(2) provide for a 260 n mi (482 km) diversion to an alternate airport at Mach 0.9 at an optimum

Breqeut cruise altitude

(3) provide for a thirty minute hold at Mach 0.45 at an altitude of 15000 feet (4572m)

Airframe

The airplane weight and aerodynamics used in this study were for the Langley-LTV arrow wing airplane from reference 13. The major characteristics of the airplane are summarized in Table I. All of the tabulated items remained fixed so that the total range varied with changes in engine weight and performance.

The airplane drag polars were assumed to be parabolic and were put in the form:

$$C_D = C_{D_{MIN}} + (C_{D_i}/(C_L - C_{L_0})^2) \times (C_L - C_{L_0})^2$$

Schedules of $C_{D_{MIN}}$, $C_{D_i}/(C_L - C_{L_0})^2$ and C_{L_0} versus Mach number are given in figure 10. The $C_{D_{MIN}}$ schedule does not include any propulsion system items. These were charged to the engine performance.

Propulsion System Performance

Uninstalled engine performance was calculated without inlet and nacelle drags and losses. Inlet sizes were determined by the supersonic cruise airflow requirements. Inlet/engine airflow matching studies were made to determine the inlet losses. After determining the engine dimensions (length and diameter) the nacelle drags were calculated assuming isolated nacelles. The installed engine performance was then the uninstalled performance adjusted for the inlet and nacelle losses.

In determining inlet and nozzle performance, nacelle drags, etc. a number of simplifying assumptions were made due to the unique operating characteristics of the superflow fan engines. Much of the following description of the study methods is intended to emphasize these unique features.

The uninstalled engine performance (no inlet or pod drags) was calculated for all of the engines with the Navy-NASA Engine Program (ref. 14) which performs cycle calculations, design and off/design, on a component by component basis. The component aerodynamic characteristics, efficiencies and cooling requirements for conventional fans,compressors, turbines, combustors, etc., used in the program were compatable with the Pratt & Whitney Phase III SCAR technology levels (ref. 5). The superflow fan characteristics were obtained fron reference 8 and are shown in figure 11.

Airflows for the reference turbofan and the core airflow for the superflow fan engines with separate core and duct streams were scheduled to match a Boeing inlet design. This is a mixed compression, axisymmetric inlet with a translating centerbody and auxiliary doors for additional airflow at subsonic flight and bypass air for supersonic starting. Data for the Boeing inlet was obtained from reference 15 and is shown in figure 12. Very preliminary studies were made for the inlets for the superflow fan engines. The studies were in sufficient detail to reflect the inlet requirements and unique features of inlets for superflow fans. Figures 13 and 14 show the inlet performance for the superflow fan engines. These inlets are low compression with little internal compression. Over most of the flight regime the maximum deceleration of the air from free stream to fan face is only about 200 ft/sec(61m/sec) compared to 1800 ft/sec(549m/sec) for a conventional supersonic inlet. Cowl pressure drag was not included for any of the engines in this study since interference effects between nacelle and airframe are not well defined. The drag coefficients include spillage and 5 percent of the fan air for boundary layer control. In comparing the Boeing inlet drag with that of the superflow fan inlet drag it is seen that the conventional inlet would have as much as 5 times the drag of the superflow fan inlets at Mach 2.32 cruise.

For the superflow variable-bypass engine, a supersonic core inlet behind the fan is required to diffuse the core flow for the compressor. For this inlet a number of simplifying assumptions were made. A pressure recovery of 0.90 was assumed for all operating conditions. Ten percent of the core air (ref. 16) was bled from the centerbody slightly upstream of the throat for boundary layer control. This provides sufficient pressure head to inject the bleed air into the duct stream and the loss to the cycle is slight. It was assumed that core inlet spillage proceeds into the duct and possible losses due to interaction between the spillage and duct flows were not considered. Since the duct nozzle of the superflow fan engine appears to be a relatively simple device compared to conventional nozzles a velocity coeffient of 0.99 was assumed for all operating conditions. For the core nozzle of the superflow fan engines and the reference turbofan nozzle a velocity coefficient of 0.98 was assumed.

The engine dimensions,length including inlet and nozzle, and maximum diameter, were determined using the computer program of reference 17. With these dimensions, nacelle friction drag was calculated using the incompressible Prandl-Schlichting relation for a flat plate turbulent boundary layer corrected for compressibility effects. For the superflow fan engines the duct discharge velocity, temperature and pressure were used in determining the friction drag of the core nacelle immersed in the duct stream. For the other sections of the superflow fan engine nacelles and the nacelle of the reference turbofan engine, free stream conditions were assumed in the nacelle friction drag calculations.

Propulsion System Weight

The installed propulsion system includes the engine plus nozzle and reverser, inlets, nacelle, mounts and supports. The engine plus nozzle and reverser weight was computed on a component by component basis using the computer program of reference 17. The program requires component calibration factors for the particular application. For the conventional components of the SCAR engines (fan,compressor,combustor,turbines,etc.) the calibration factors provided in reference 17 were used in these studies. A comparison of the weight calculated for the 502B with Pratt & Whitney's weight estimate for the 502B is shown in figure 15. Close agreement was achieved, creating confidence that this estimation technique is adequate for the purposes of this study. For the superflow fan engine unconventional components (superflow fan,inlet, core inlet, fan cowl and duct nozzle) preliminary layout drawings and weight estimates were provided by the Engineering Design Division at NASA-Lewis Research Center. This data was used to determine the calibration factors for these components for use in the computer program. Weight estimates for the Boeing inlet were used for the reference turbofan engine and the core of the superflow fan engines with separate core and duct streams. These estimates were made from data from reference 3. The weight of the nacelle and supports was based on a procedure supplied by the Boeing Company and data from reference 3.

Sideline Jet Noise And Takeoff Field Length

The sideline noise limits and the takeoff thrust requirements determine the minimum engine size for the engines considered in this study since augmentors can be used to maintain adequate climb/acceleration thrust margins. Only sideline noise was considered, as previous calculations had shown that this was generally the critical point for the particular airplane configuration assumed in this study.

Sideline jet noise. - The sideline jet noise estimates were calculated using the procedures given in reference 18. Perceived noise level in units of PNdB was calculated for a four-engine aircraft at Mach 0.30 and an altitude of 800 feet(244m). Extra-ground attenuation was not included, but 3 dB of fuselage shielding was assumed for all cases.

Takeoff field length. - The takeoff thrust was determined for a FAR field length of 10500 feet(3200m) using the curve of figure 16 which was obtained from reference 19. As indicated on the figure the value of the parameter K is 550 for a field length of 10500 feet(3200m). Using the aircraft characteristics from Table I, the takeoff thrust is then calculated to be 53500 pounds(238 KN) per engine. The engines were sized for this thrust for the FAR 36 sideline noise constraint.

RESULTS AND DISCUSSION

Engine performance and weight are discussed and mission performance is presented in terms of range. The superflow fan variable-bypass engine parametric studies are discussed first. It was found that the performance and weight trends of all of the superflow fan engines considered in this study closely resembled those of the superflow variable-bypass engine. Therefore, only the best cycles for the remaining superflow fan engines are discussed. A comparison of the performance, weight and mission results of the superflow fan engines and the reference turbofan is then shown. A brief discussion on technology problem areas of the superflow fan engine is also given.

Superflow-Fan Variable-Bypass Engine Parametric Study

Parametric engine performance and weight study. - The cycle parameters considered were the bypass ratio, overall pressure ratio and fan pressure ratio. The effect of these parameters on engine performance, weight, mission range and noise was evaluated.

Figure 17 shows the effect of bypass ratio and overall pressure ratio (sea level static design values) on Mach 2.32 cruise performance. The specific fuel consumption, sfc, rises rapidly during afterburning so that only a minimum of afterburning can be tolerated during supersonic cruise. The general trend shown in the figure is that the minimum sfc occurs at maximum dry thrust and does not vary significantly for the range of overall pressure ratios and bypass ratios considered. The predominant effect of these parameters is on maximum dry thrust which increases with decreasing bypass ratio and overall pressure ratio. The best bypass ratio and overall pressure ratio depend on how the engine weight varies with these parameters. The consequent impact on engine weight will be shown in a later figure.

The effect of fan pressure ratio on Mach 2.32 cruise performance is shown in figure 18. It is seen that the effect of fan pressure ratio on performance is small. Although one value of overall pressure ratio is shown in the figure, the same effect of fan pressure ratio on performance was found for all of the overall pressure ratios considered.

Propulsion system weight (engine, nozzle, inlets, nacelle and pylon) is shown in figure 19 for various bypass ratios and overall pressure ratios. The propulsion system weight decreases with increasing bypass ratio for the same S.L.S. design airflow. The overall pressure ratio is seen to have practically no effect on the propulsion system weight for the same fan pressure ratio. Although the number of compressor stages and therefore compressor weight increases with compressor pressure ratio, the higher pressure leads to reduced turbine size and weight. However, larger excursions in pressure ratio than those considered here may require additional turbine stages resulting in higher engine weight.

<u>Noise studies</u>. - During the noise studies it was found that the S.L.S. design overall pressure ratio had only a small effect on sideline jet noise. The bypass ratio and fan pressure ratio had the most significant influence on noise. It is desirable to take advantage of the inherent noise suppression afforded by the coannular jet effect. That is, the noise of two coannular jets is up to about 8 dB quieter than the noise of two similar, separate jets provided that the velocity of the outer jet is enough greater than that of the inner jet . This is usually referred to as the inverse velocity profile (ref. 3). Since duct burning is not possible in the superflow fan duct stream, adjusting the fan pressure ratio to achieve high duct velocities is the only means of reducing the jet noise by means of the inverse velocity profile. Figure 20 shows sideline jet noise versus

specific thrust for fan pressures of 3,4 and 5 for a bypass ratio of 1.5. For each fan pressure ratio the duct velocity remained almost constant as thrust varied and the core velocity varied with throttle setting. The flat parts of the curves at low specific thrust represent throttled-back operation where the core velocity is lower than the duct velocity. Hence the noise levels are low due to the inverse velocity profile noise reduction. As the S.L.S. design fan pressure ratio is increased, the duct velocity increases and the engines can operate at higher thrust levels with lower jet noise. For fan pressures of 3 and 4 at higher throttle settings, the core velocity increases until it is equal to the duct velocity and the jet noise is seen to increase rapidly. For a fan pressure of 5 the core velocity is less than the duct velocity even at full power. For a FAR- 36 noise level of 108 PNdB and takeoff thrust requirement of 53500 pounds(238 KN) per engine (see Takeoff field length section) the engine sizes are 937 lbm/sec(425kg/sec), 950 lbm/sec(431 kg/sec) and 1130 lbm/sec(513 kg/sec) for fan pressure ratios of 5, 4 and 3 respectively. It should be pointed out that high fan pressure ratios probably increase fan noise which could be a serious problem for this type of engine since acoustic treatment may not be usable in the duct. On the other hand, the takeoff tip speed of the supersonic fan is much lower than that of the SCAR engine fans. The proper spacing between rotor and stators could alleviate this potential problem. However, this type of noise generation can not be estimated at this time for this type of fan. Since superflow fan weight for fan pressures above 4 had not been analyzed in this study, a fan pressure ratio of 4 was selected for the mission studies for all of the superflow fan engines.

Figure 21 shows the jet noise for various bypass ratios. The inverse velocity profile noise reduction is similar to that discussed for the previous figure 20. For comparison, the noise calculated for the reference turbofan is shown. Since the reference turbofan has a duct burner it can produce much higher duct velocities than the supersonic fan engine and obtain more benefit from the inverse velocity profile noise reduction. The reference turbofan engine size (S.L.S. design value) required for the 108 PNdB sideline noise level and takeoff thrust of 53500 pounds(238KN) is 780 lbm/sec(354kg/sec). The superflow fan engine sizes are 900 lbm/sec(409 kg/sec), 950 lbm/sec(413 kg/sec) and 1000 lbm/sec(454 kg/sec) for bypass ratios of 1.0,1.5 and 2.0 respectively.

<u>Mission studies</u>. - Mission studies were performed for the range of bypass ratios and overall pressure ratios discussed in the previous sections. The result in terms of range

versus engine S.L.S. corrected design airflow are shown in figure 22. Along any given curve, too large an engine results in increased sfc at part power cruise and excessive engine weight. Too small an engine requires afterburning and high sfc's. Hence, there is an optimum engine size for maximum range. The minimum engine sizes to meet the noise and takeoff thrust requirements, as discussed before, are indicated by the vertical lines. It is seen that the required engine sizes are close to the sizes that maximize range.

It was shown in figure 17 that maximum dry thrust decreases with increasing bypass ratio and overall pressure ratio with little change in sfc. Figure 19 shows that the overall pressure ratio has little effect on engine weight and the specific engine weight (lbm/Wa) decreases with increasing bypass ratio. Consequently, figure 22 shows that the optimum engine size increases with increasing bypass ratio. Also note that the maximum range of 5800 n mi (10740 km) does not vary significantly with bypass ratio. Other considerations not included in this study could alter this result. For example, a large subsonic cruise leg may favor high bypass engines, or engine/airframe installation effects may require low bypass engines.

Comparison Of Superflow Fan Engines And Reference Turbofan Engine

As mentioned at the beginning of the RESULTS AND DISCUSSION only the best of the superflow fan engines (fig. 6) would be discussed in this section. Since the parametric trends, including noise and takeoff thrust noted for the superflow variable-bypass engine were about the same for all of the superflow fan engines, one set of cycle parameters (OPR,BPR,FPR) is used for the comparisons in this section.

Engine performance comparisons. - Figure 23 shows Mach 2.32 cruise performance for the superflow fan engines and the reference turbofan for a nominal engine size of 900 lbm/sec(409 kg/sec). The performance of all of the superflow fan engines at the maximum dry cruise operating point is about the same. The operating points are fixed by the engine sizes required for FAR 36 noise, takeoff thrust requirement and the airplane cruise thrust required. The aft fan with interburner engine exhibits better performance potential for smaller engine sizes since smaller sizes (below 900 lbm/sec(409 kg/sec)) would move the operating points to higher thrust levels. This would require afterburning for the other superflow fan engines and a rapid increase in sfc. Another feature of the aft fan with interburner worth noting is that the maximum high pressure turbine inlet temperature is lower than that of the other engines (3000 R(1667) K compared to 3200 R(1778 K)). All of the superflow fan engines offer a 12 percent reduction in sfc compared to the reference turbofan type engine performance. This is due to the lower inlet and nacelle losses (figs. 12-13) and more versatility in cycle variations.

Engine weight comparisons. - A weight comparison of the engines is shown in figure 24 for a nominal 900 lbm/sec(409 kg/sec) S.L.S. corrected airflow. The heaviest superflow fan engine, aft fan with interburner, is about 30 percent lighter than the reference turbofan engine. A large part of this weight reduction is due to the lighter inlet and nacelle of the superflow fan engines. For a more conventional engine such as the reference turbofan, the inlet, nozzle and nacelle make up about 50 percent of the total propulsion system weight. The inlet systems for the superflow fan engines are about 50 percent lighter than the reference turbofan inlet. The engine and nozzles are also lighter since the superflow fan duct nozzles are simpler(no throat) and except for the aft fan with interburner, these engines are equipped with afterburners, which tend to be lighter than the duct burners of the reference turbofan. Afterburning penalizes the engine performance, as shown in figure 22, but it is used for thrust margin capability only in this application. The engine plus nozzle weight of the aft fan with interburner is heavier than the other superflow fan engines due to the added weight of the second burner. As seen in figure 22 ,however, it has lower sfc's at high power settings than the other superflow fan engines. Figure 25 compares the engine weights for the engine sizes required for FAR 36 noise and takeoff thrust. The S.L.S. airflow size for the reference turbofan engine is much smaller than for the superflow fan engines; 780 lbm/sec (354 kg/sec) compared to 950 lbm/sec (431 kg/sec). However, the engine weight of the reference turbofan is still 17 percent heavier than that of the superflow fan engines.

Mission comparisons. - Comparisons of the mission range for these engines is shown in figure 26. For the FAR 36 noise level and takeoff thrust requirement the superflow/subsonic fan engine and the superflow aft fan engine provide better range (5900 n mi(10927 km)) than the other superflow fan engines. All of the superflow fan engines have range capabilities 900 n mi(1667 km) to 1000 n mi(1852 km) higher than the reference turbofan engine. This represents about a 20 percent improvement in range for a future supersonic cruise aircraft.

In the General Electric and Pratt & Whitney evaluations of the superflow fan variable-bypass engine (refs. 5 & 7) they did not obtain the same attractive performance(figure 23) found in this study or in the Advanced Technology Laboratories Inc. study results of reference 8. The reasons for these conflicting results are explained in this section. Also, some technological problem areas and uncertainties uncovered in the engine company evaluations and in the Lewis studies are discussed.

In the General Electric evaluation of the superflow variable-bypass engine, the variable spool speed/variable-bypass capabilities of this cycle were not exploited. The variable spool speed/variable-bypass operation of the superflow fan variable-bypass engine is similar to Pratt & Whitney's inverse throttle schedule (ITS) as used for the VSCE 502B. That is, the cycle is matched at reduced turbine inlet temperature and 100 percent spool speeds at S.L.S. design. At supersonic cruise the turbine inlet temperature and spool speeds are increased to values higher than the S.L.S. design values. The superflow fan engine can exploit the ITS to a greater degree than the VSCE 502B. These capabilities are explained in the DESCRIPTION OF THE CONCEPTS section of this report. Instead of matching the cycle at takeoff (fig. 5) with a low tip speed(about 1300 ft/sec(396 m/sec) and then increasing the tip speed to about 1700 ft/sec(518 m/sec) at supersonic cruise to reduce the operating bypass ratio, General Electric assumed a constant low fan tip speed of 1319 ft/sec(402 m/sec) for all flight conditions. This resulted in a high bypass ratio at supersonic cruise with low specific thrust and poor sfc's. Because of the low specific thrust the engine size required for the cruise thrust was extremely large. Instead of engine sizes of 900-1000 lbm/sec(409-454kg/sec) as shown in this report General Electric reported engine sizes of 1600 lbm/sec(726 kg/sec). In addition, the high bypass ratio of General Electric's version of the superflow variable-bypass engine resulted in the need for additional turbine stages which further increased the engine weight.

In Pratt & Whitney's assessment of the superflow fan variable-bypass engine, reference 5, they assumed a 4 percent bleed of the fan air in front of the fan for boundary layer control and a 10 percent boundary layer bleed of the core air in the core inlet. In addition, 5 percent of the fan air was bled from the fan stator section. Since the static pressure in the fan stator section is low (supersonic Mach numbers) the 5 percent bleed air at the fan stators was a complete loss and severely penalized the overall engine performance. Had Pratt & Whitney not assumed the 5 percent bleed in the stators (since boundary layer control in front of the fan and in the core inlet may be sufficient) or approached the problem differently (some type of boundary layer energizing) the sfc's of the superflow fan variable-bypass engine would have been lower than those of the VSCE 502B. It is interesting to note that Pratt & Whitney's superflow fan engine weight estimates are in approximate agreement with the estimates in this report.

Pratt & Whitney and General Electric also reported a number of potential problems associated with the superflow variable-bypass engine. Some of the problems are lessened or eliminated by the alternative superflow fan engine concepts shown in this report. Other uncertainties are unanswerable at this time and require detailed studies or experimental investigations. Typical potential problem areas indicated by the engine companies are shown in Table II. As indicated in the table some of the potential problems of the superflow variable-bypass engine have been eliminated by the alternative concepts studied by Lewis. However, the operating characteristics of the fan is a major uncertainty. A number of potential problems or unknowns associated with mounting the engine and structural design still remain. Figures 27 through 30 depict typical examples. The pylon for the aft fan engine in figure 27 may cause undesirable flow fields at the fan face. The pylon for the superflow/subsonic engine in figure 28 would be in the fan exhaust and may result in high drag. Structural design of the engines may also lead to fan intake and exhaust flow interference. In figure 29 the superflow fan rotor blades mounted on the low pressure turbine interrupts the structure of the core casing. In this particular arrangement the structural load would have to be carried through the fan stators,nacelle and struts or inlet guide vanes as shown. The effect of the struts or guide vanes on the airflow at the fan face may not necessarily be detrimental to fan performance. However, this is an area of uncertainty. This same type of arrangement for the superflow/subsonic fan is shown in figure 30. The possible aerodynamic problems of the fan are the same as dicussed in figure 29.

CONCLUDING REMARKS

This study has been an exploratory investigation on the potential benefits of supersonic through-flow (superflow) fan engines for propulsion systems for supersonic cruise airplanes. Four different conceptual superflow fan engine configurations were studied. Except for the superflow fan, the technology assumed for the engines (materials, hot section cooling, turbine inlet temperature, etc.) was the same as that for the General Electric and Pratt & Whitney SCAR engines. The evaluation of these engines was made on the basis of maximum range achieved by a supersonic cruise airplane of 762000 pounds (345948 kg) takeoff gross weight and 61028 pounds (27707 kg) payload. The potential benefits of these concepts was determined by comparing the maximum range achieved with the superflow fan engines to that achieved with a reference turbofan engine similar to the Pratt & Whitney VSCE 502B.

The results of the study show that superflow fan engines can provide major improvements in the mission capabilities of airplanes that have large supersonic cruise requirements. For the mission considered in this report the airplane range capability improved by about 1000 n mi (1852km.) when powered by superflow fan engines compared to the reference turbofan. This represents a 20 percent improvement.

The sfc's of the superflow fan engines were estimated to be 12 percent lower than the sfc of the reference turbofan. A large part of this improvement is due to reduced installation losses. For a fixed airplane size and range requirement, this would represent sizable savings in fuel consumption. Although economic studies were not included in this study the improved range for a fixed airplane size or reduced airplane size for a fixed range would lead to a much more economically attractive airplane.

In order to place more confidence in these study results, more detailed studies are necessary to gain a better insight into the operating characteristics of superflow fans. The aero/mechanical unknowns such as mounting structures interfering with the air flow at the fan face and exhaust need study. These potential problems may be solved with proper aerodynamic design. Another approach would be alternative mechanical arrangements that would eliminate these problems.

It shoud be emphasized that there are major uncertainties in the aerodynamics and noise of this type of fan and in the overall mechanical design and operation of the propulsion system. Hence the predicted performance of the superflow fan concepts is not as well grounded as the present Pratt & Whitney and General Electric SCAR concepts. However, the indicated attractive potential of this concept seems great enough that more detailed effort is warranted to resolve the uncertainties and develop a better understanding of the concept.

SYMBOLS

BPR	bypass ratio
C_D	drag coefficient
C_L	lift coefficient
$C_{D_{MIN}}$	C_D where $C_L = C_{L_0}$
$C_{L_{TO}}$	C_L at liftoff
dB	decibels
ft	feet
F	net thrust, lbf (N)
FAR	Federal Aviation Regulation
FPR	fan pressure ratio
K	degrees Kelvin
kN	kilonewton
kg	kilogram
HR	hour
lbf	pound force
lbm	pound mass
M	Mach number
m	meter
N	newton
OPR	overall pressure ratio
R	degrees Rankine
S	airplane wing planform area
sec	second
S.L.S.	sea level static
Tamb	ambient temperature, R (K)
TOGW	airplane takeoff gross weight, lbm (kg)
TIT	turbine inlet temperature, R (K)
U	fan tip speed, ft/sec (m/sec)
Wa	airflow, lbm/sec (kg/sec)
W	gross weight, lbm (kg)
η_F	fan adiabatic efficiency
θ	corrected temperature ratio
σ	ρ/ρ_0, density ratio for air

Subscripts:

AB	absolute
F	fan face
i	induced
MIN	minimum
REL	relative

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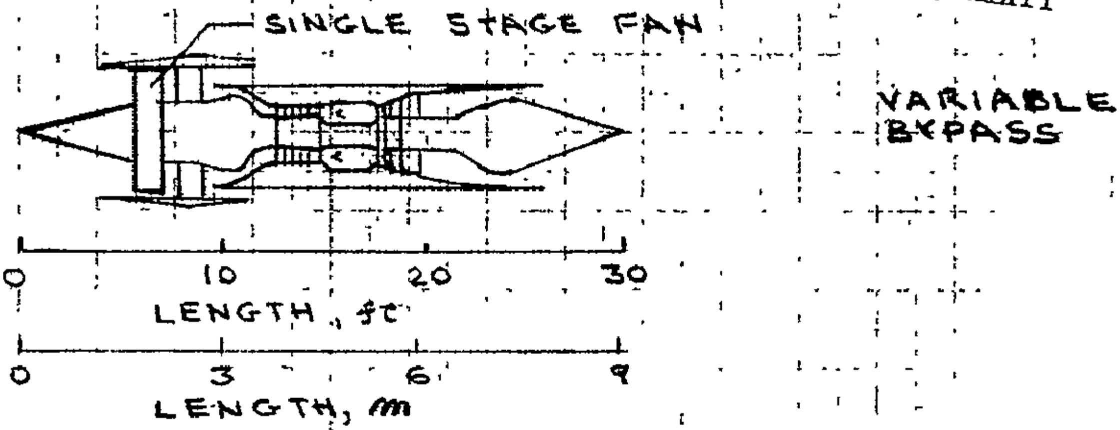
TABLE I.-MAJOR AIRPLANE CHARACTERISTICS

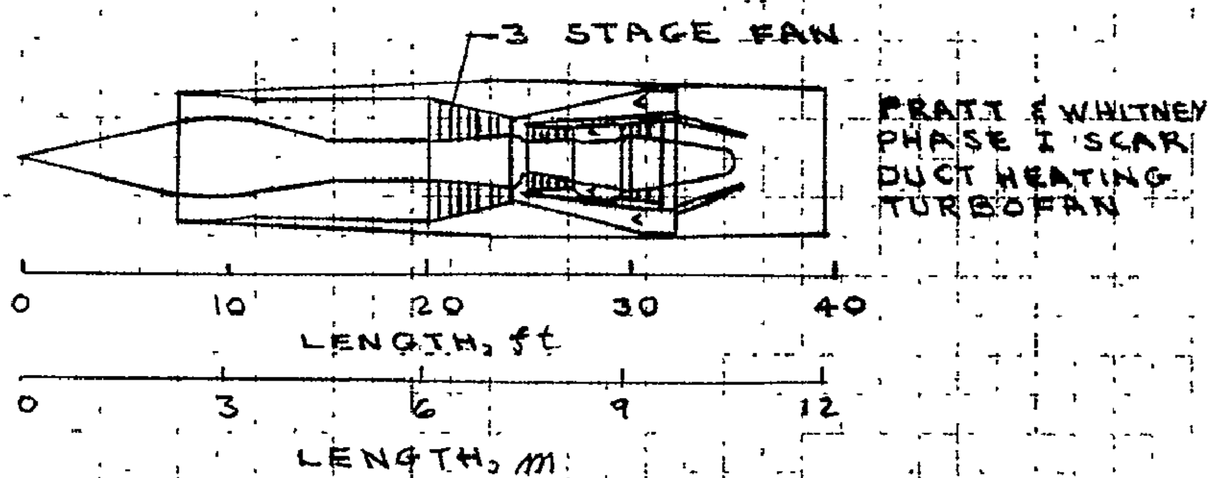
Characteristic	Value
Takeoff gross weight, lbm kg	762000 345637
Number of passengers	292
Payload, lbm kg	61028 27682
Reference wing area, ft m	9969 926
Operating empty weight less propulsion weight, lbm kg	259913 117897
Lift-off C_L	0.55

TABLE II.-POTENTIAL PROBLEMS OF THE SUPERSONIC FAN VARIABLE BYPASS ENGINE

Potential Problem	Note
Off design variations in supersonic fan blade incidence and effect on overall cycle performance	
Fan noise during takeoff and approach	
Foreign object damage to supersonic fan blades due to very sharp and thin leading edges may affect fan efficiency.	
critical speed problems with overhung support arrangement of supersonic fan and spike assembly	Eliminated with alternate supersonic fan concepts
Starting and stability problems with supersonic fan and related variable geometry control requirements	
Thrust margin characteristics of nonaugmented engine for transonic and supersonic climb	Eliminated with afterburners in alternative concepts
Fan distortion effects on supersonic diffuser bleed requirements and pressure loss characteristics	Eliminated with alternative concepts
Thrust reversing for supersonic stream	
Installation performance characteristics of engine, especially effect of support across supersonic stream	
Location of engine/airframe accessories and high spool towershaft which crosses supersonic stream	
Effects of rotating spike on inlet boundary layer control and bleed requirements. (In order to avoid having static structure upstream from the fan, a rotating spike was assumed for this evaluation	Eliminated with alternative supersonic fan concepts



SUPERSONIC FAN TURBOFAN



CONVENTIONAL FAN TURBOFAN

FIGURE 1.- SUPERSONIC FAN AND CONVENTIONAL FAN TURBOFAN ENGINES STUDIED IN THE SCAR PROGRAM.
S.L.S. CORRECTED AIRFLOW - 900 lbm/SEC (408 kg/SEC)

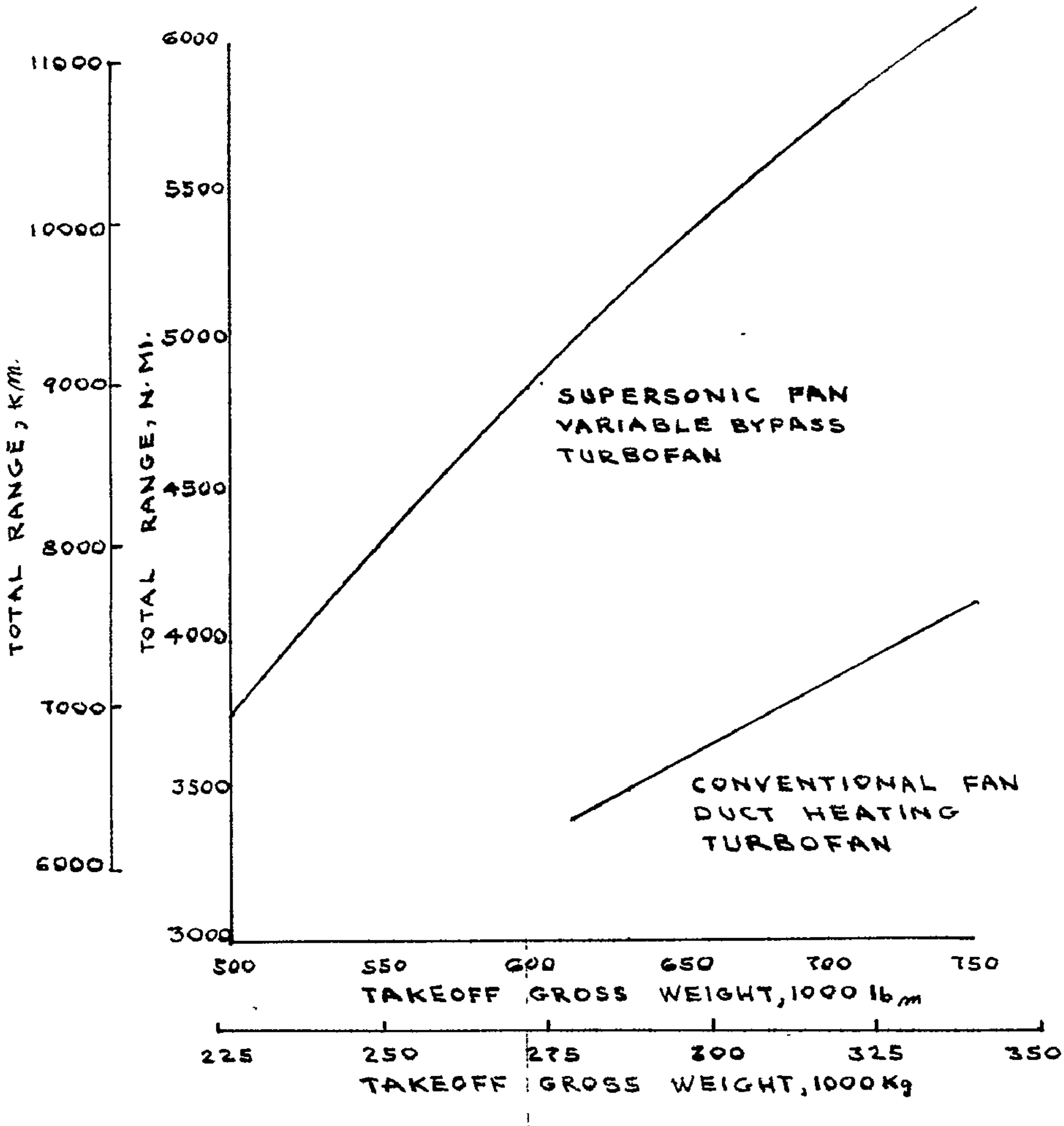
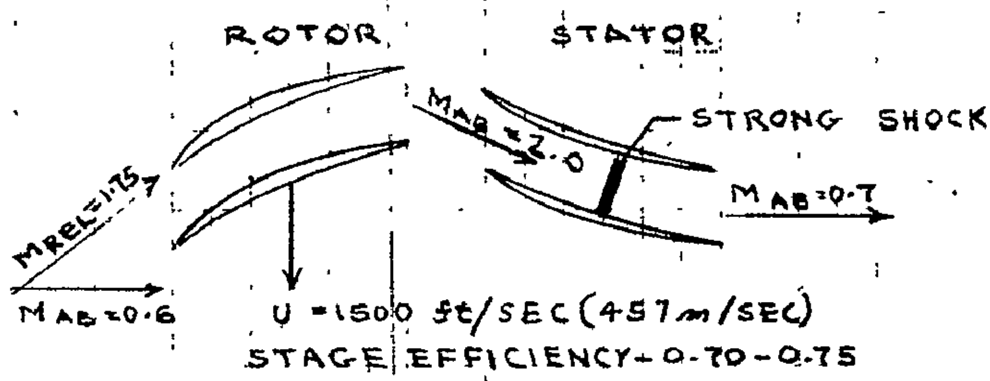
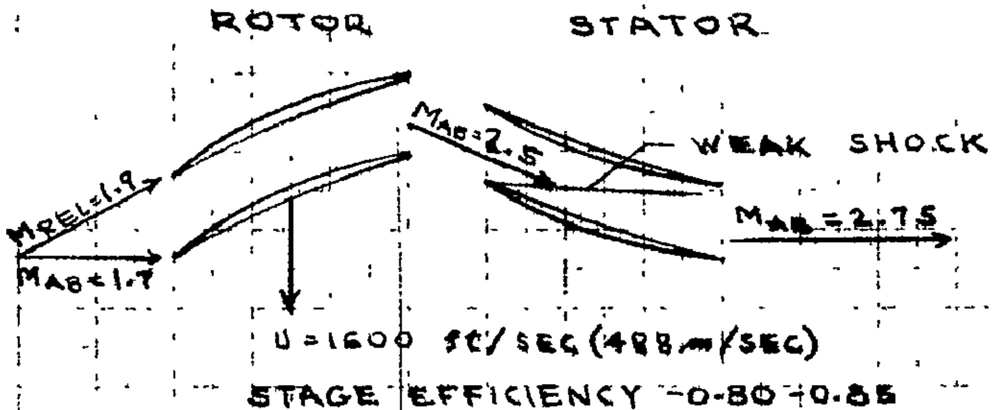


FIGURE 2. - EFFECT OF AIRPLANE SIZE ON RANGE FOR A MACH 2.7 BOEING 963-336C SCAT 15F TYPE AIRPLANE. SCAR PHASE I STUDY. REF. 8



TYPICAL - SUPERSONIC FAN TESTED IN THE 1950'S; REFERENCES 9-12

(a)

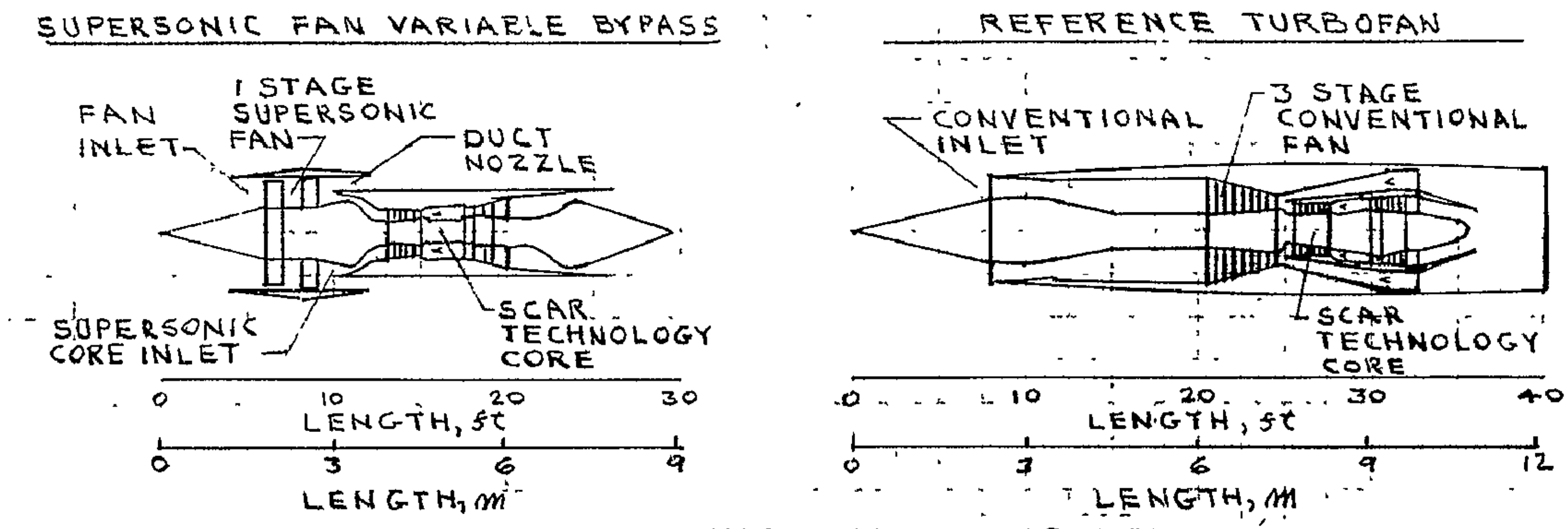


PRESENT CONCEPT = SUPERSONIC THROUGH-FLOW FAN STAGE

(b)

MAB - ABSOLUTE MACH NUMBER
MREL - RELATIVE MACH NUMBER

FIGURE 3. - COMPARISON OF SUPERSONIC FAN TYPES



ENGINE OPERATING CHARACTERISTICS

	SUPERSONIC FAN	REFERENCE TURBOFAN
SEA LEVEL STATIC		
BYPASS RATIO	1.5	1.3
FAN PRESSURE RATIO	3.1	3.3
CYCLE PRESSURE RATIO	15.0	20.0
FAN TIP SPEED, ft/SEC (m/SEC)	1300 (396)	1660 (506)
COMP. TIP SPEED, ft/SEC (m/SEC)	1500 (457)	1500 (457)
COMB. EXIT TEMP., °R (°K)	2800 (1556)	2700 (1500)
FAN ADIA. EFF.	0.85	0.85
FAN FACE ABS MACH NO.	1.0	0.60
STAGE EXIT MACH NO.	2.0	0.50
SUPERSONIC CRUISE		
BYPASS RATIO	1.0	1.5
FAN PRESSURE RATIO	3.5	2.4
CYCLE PRESSURE RATIO	12.0	11.9
FAN TIP SPEED, ft/SEC (m/SEC)	1750 (533)	1800 (549)
COMP. TIP SPEED, ft/SEC (m/SEC)	1725 (526)	1680 (512)
COMB. EXIT TEMP., °R (°K)	3200 (1778)	3160 (1756)
FAN ADIA. EFF.	0.83	0.85
FAN FACE ABS. MACH NO.	2.0	0.60
STAGE EXIT MACH NO.	3.0	0.50

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FIGURE 4.- COMPARISON OF THE OPERATING CHARACTERISTICS OF A SUPERSONIC FAN TURBOFAN AND A CONVENTIONAL FAN TURBOFAN

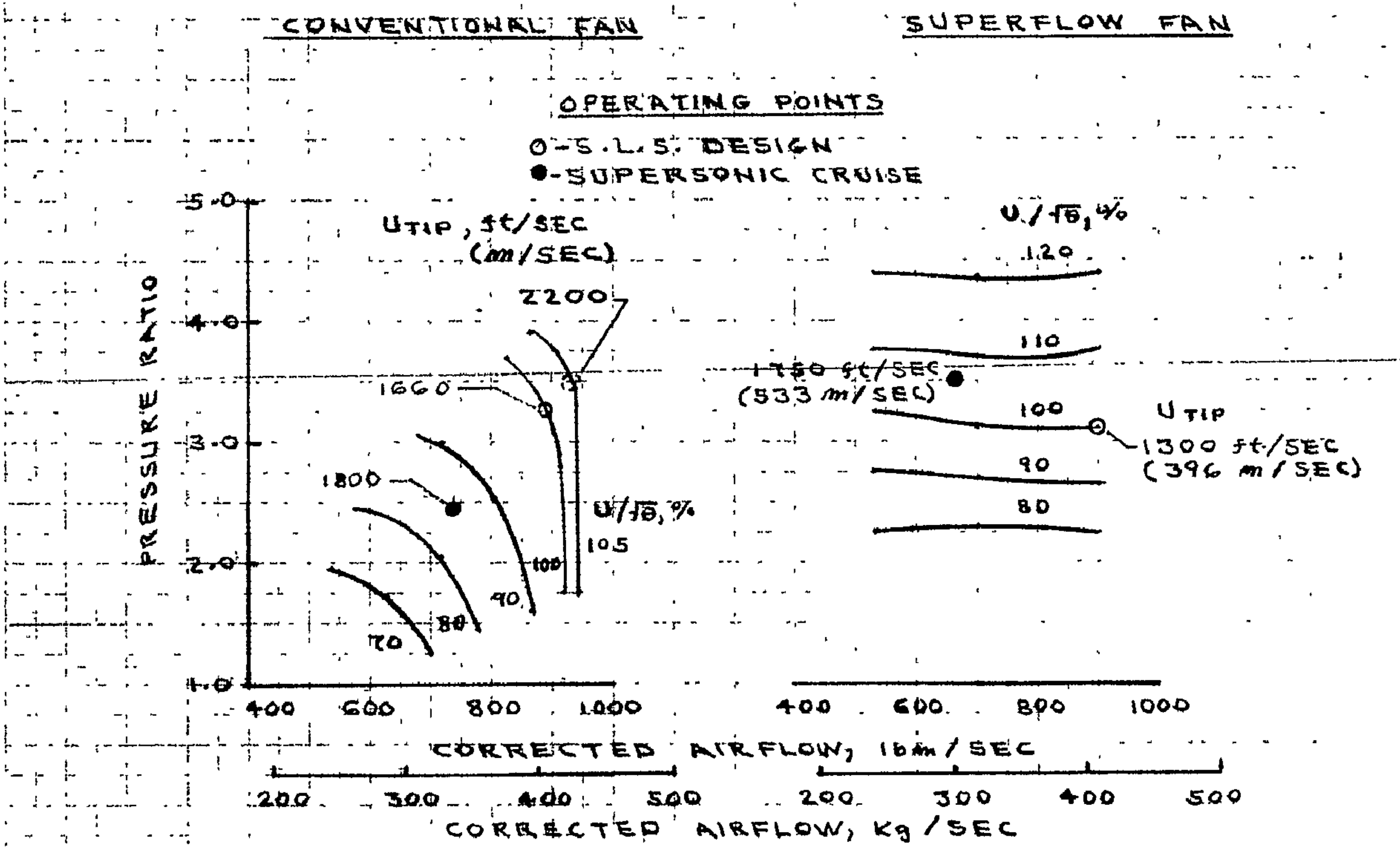

FIGURE 5 - COMPARISON OF CONVENTIONAL AND SUPERFLOW FAN OPERATING CHARACTERISTICS

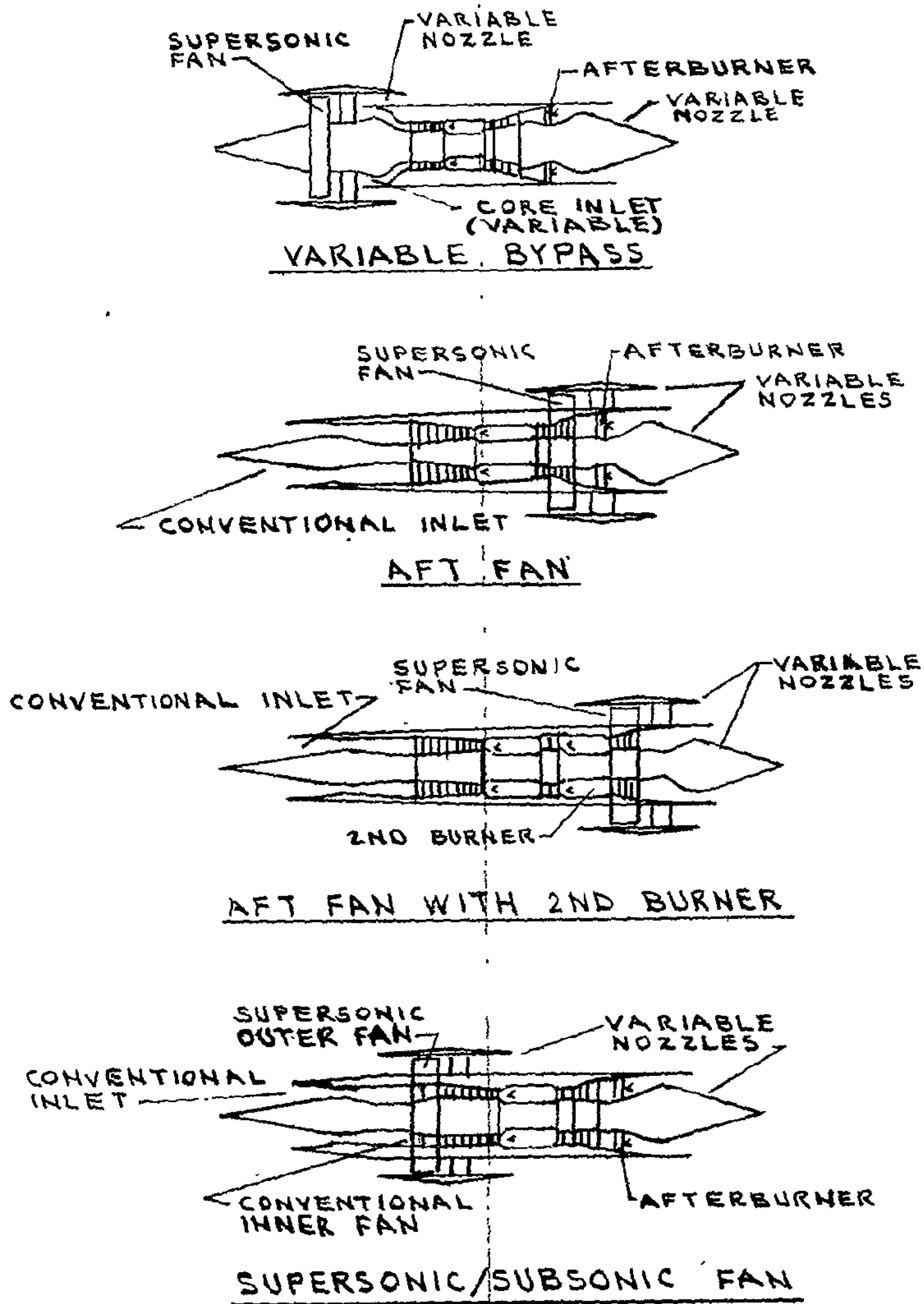

FIGURE 6.- SUPERSONIC FAN ENGINES EVALUATED IN THIS STUDY

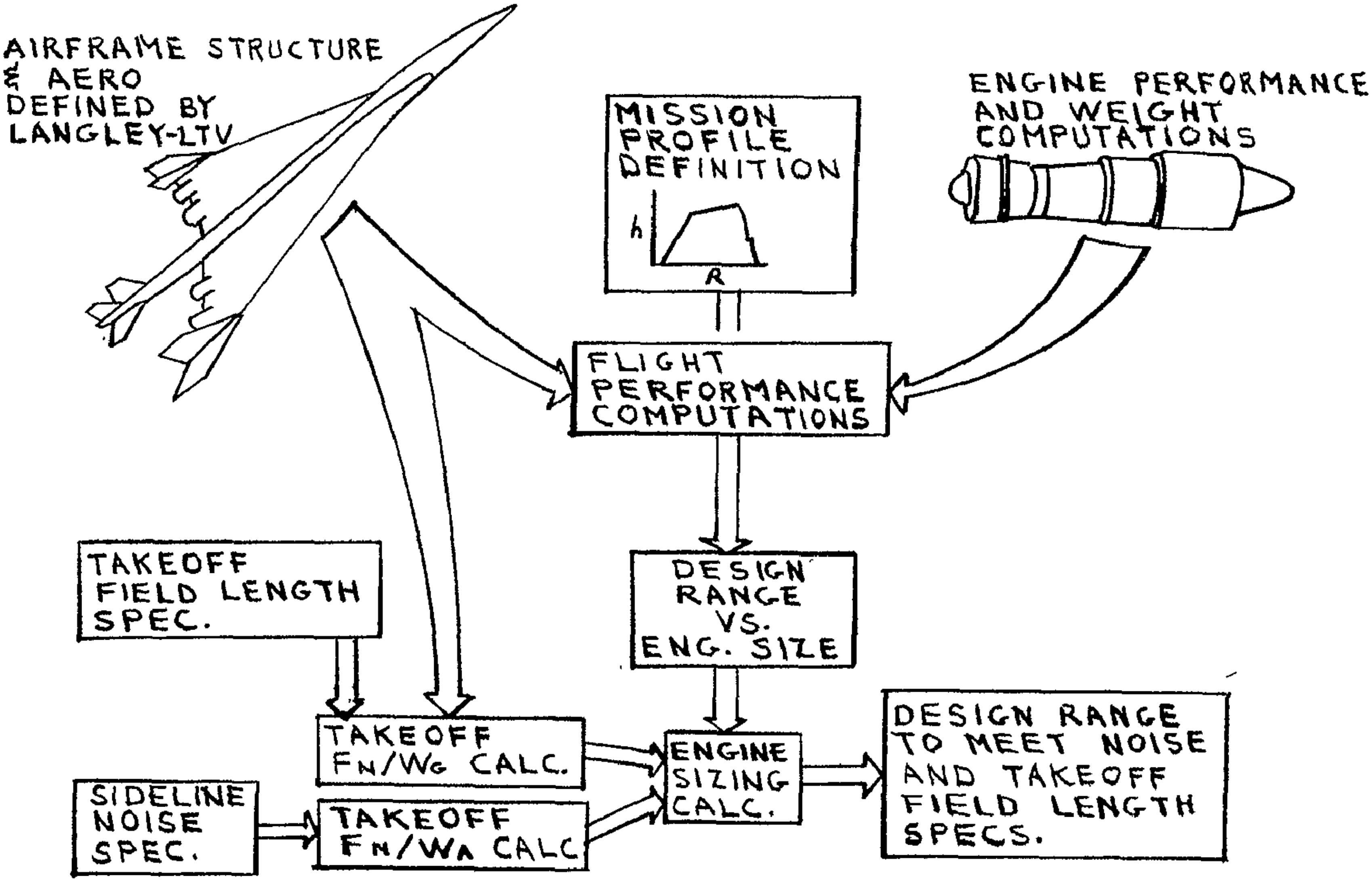

FIGURE 7. - CALCULATION FLOW CHART

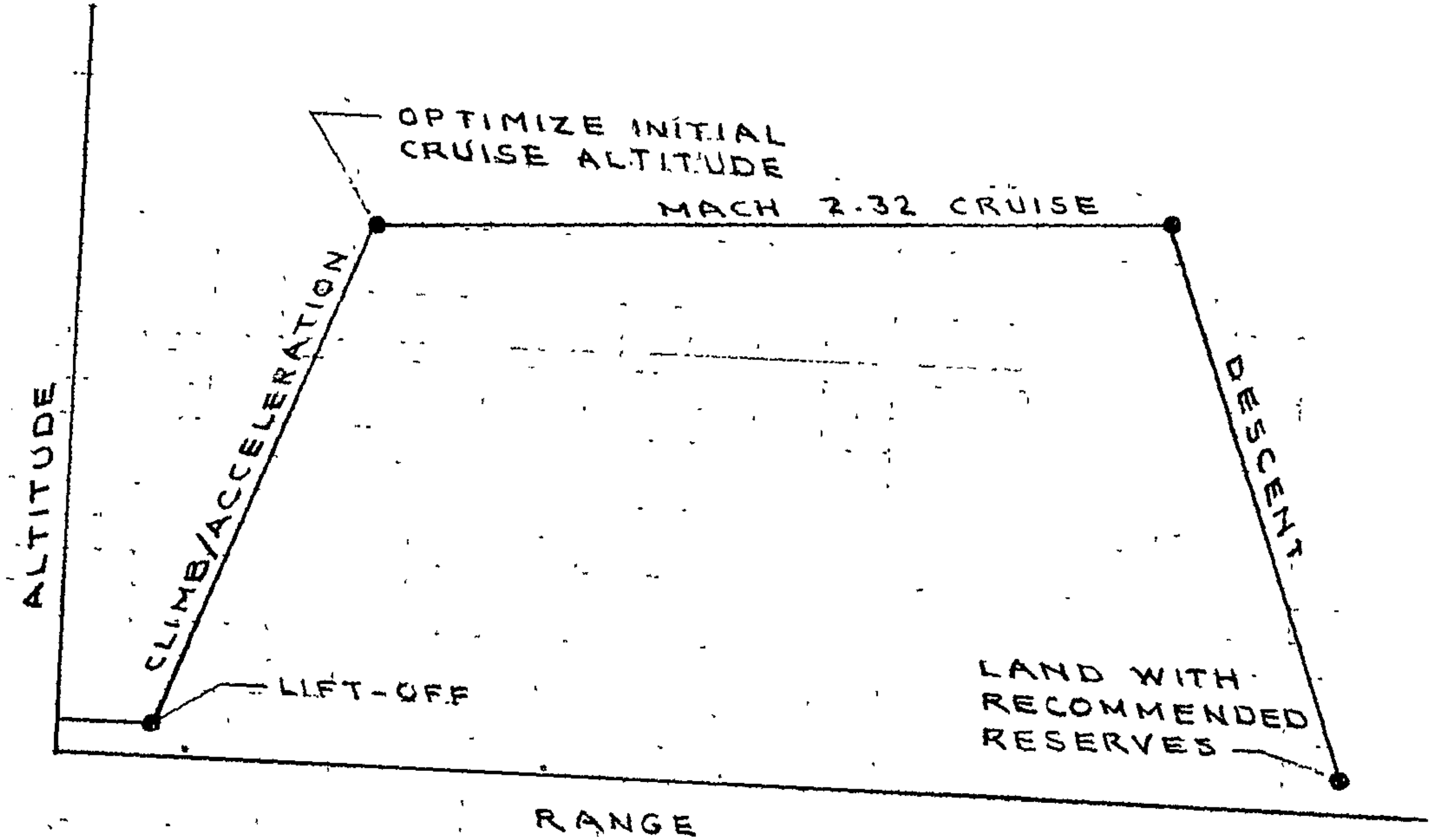

FIGURE 8. - REFERENCE MISSION, STD. + 14.4 °F (+8 °C) DAY

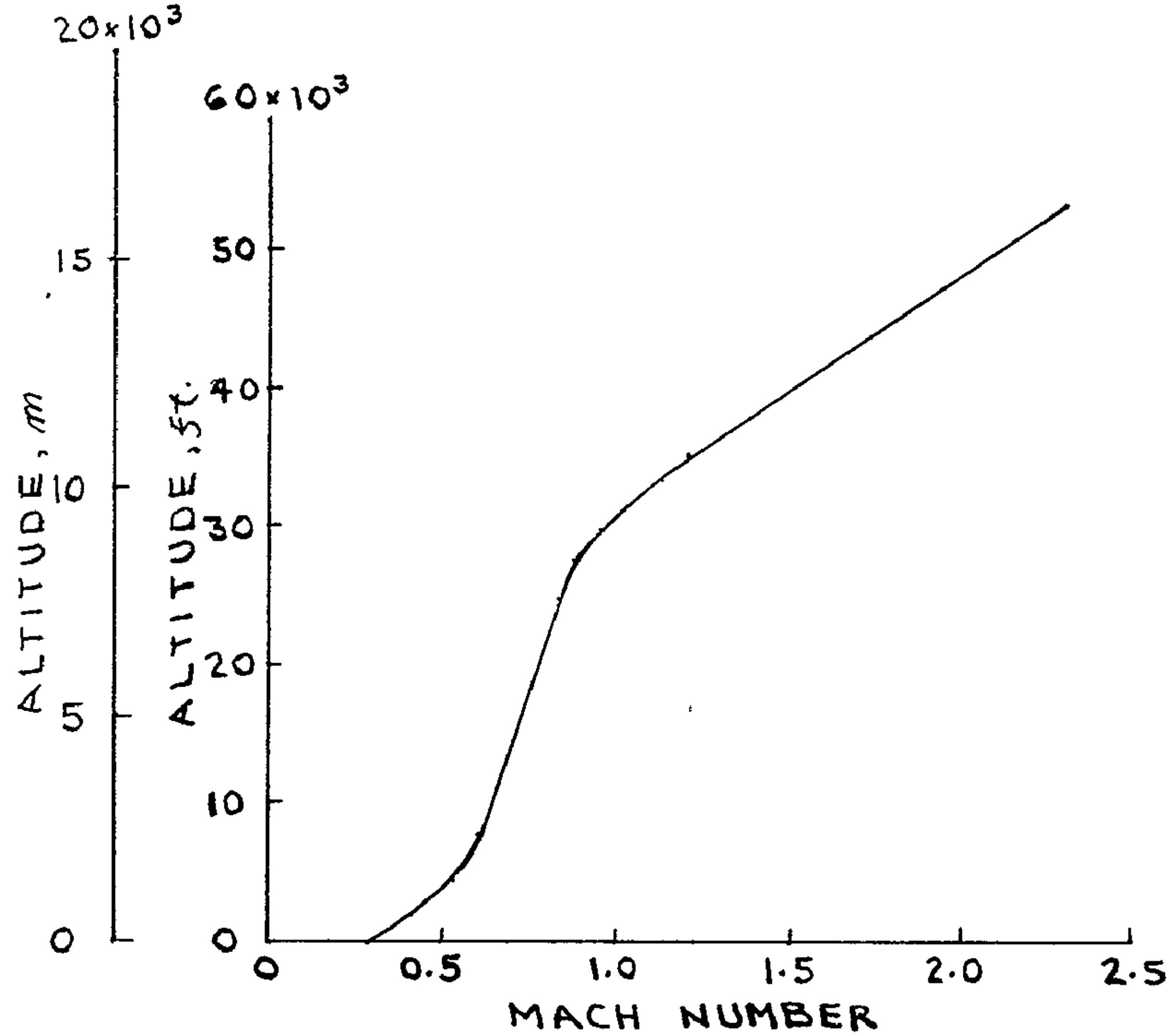

FIGURE 9 - FLIGHT PATH USED IN CLIMB/ACCELERATION

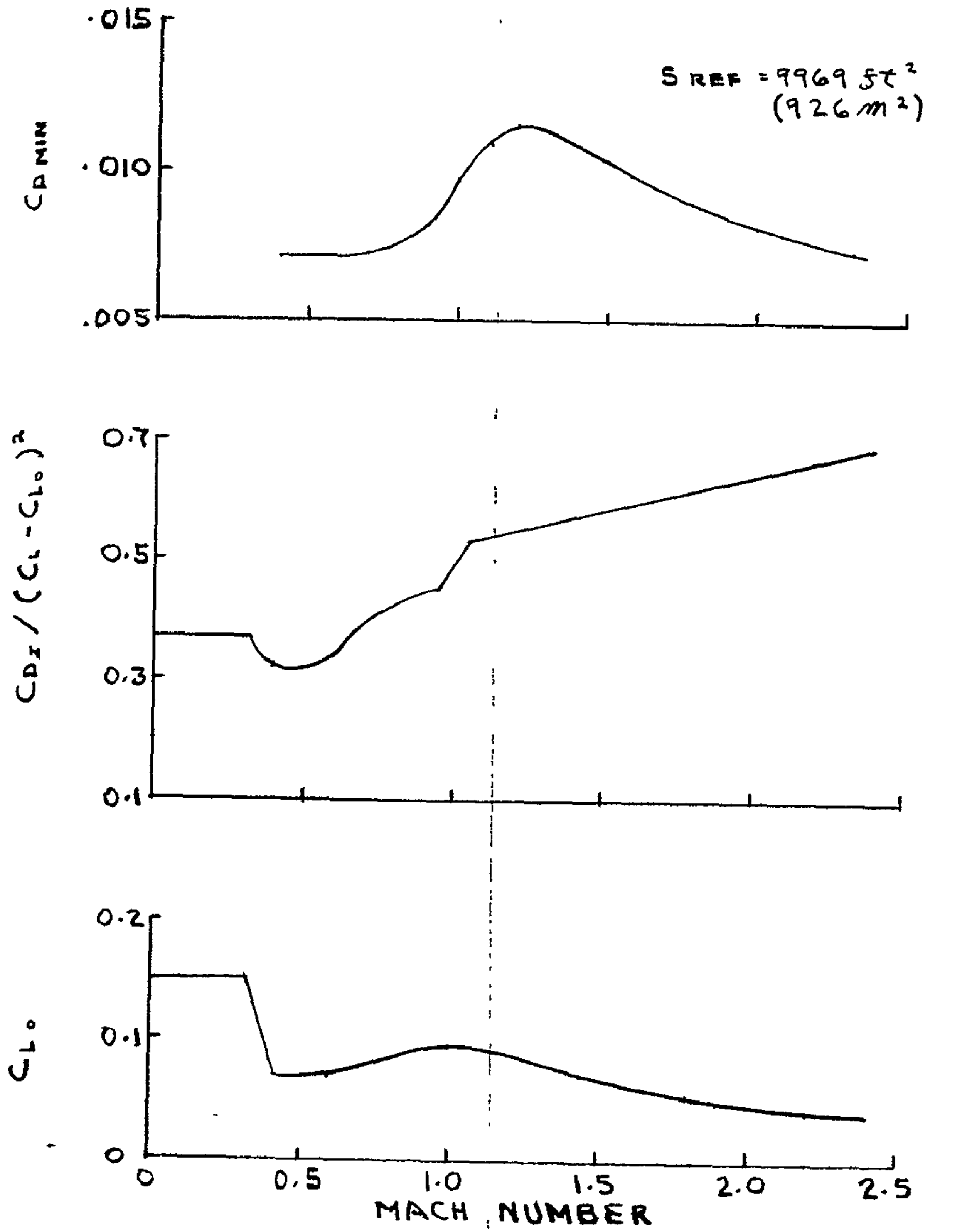

FIGURE 10. - AERODYNAMIC COEFFICIENTS USED TO SIMULATE THE NASA LANGLEY-LTV ARROW WING AIRPLANE

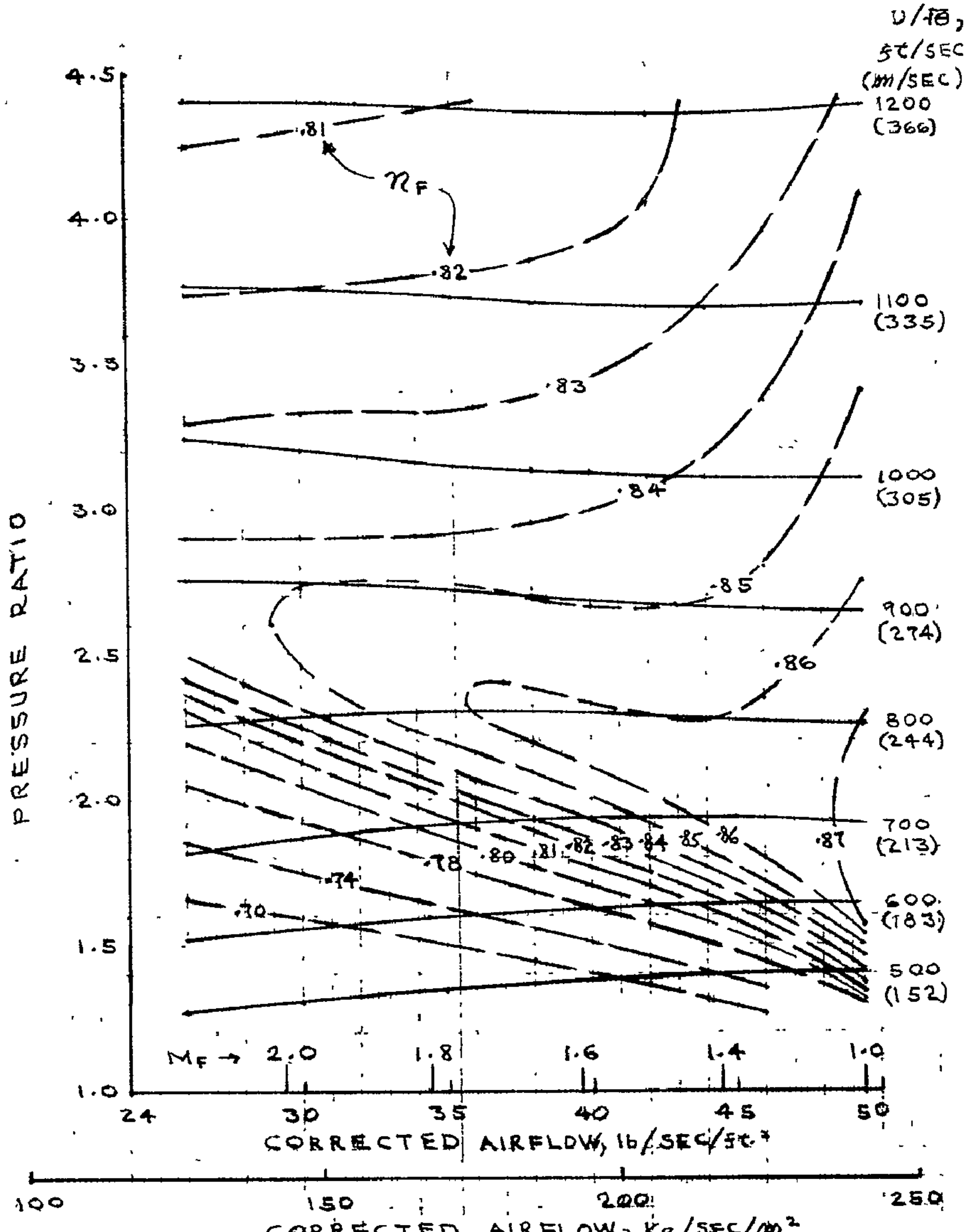

FIGURE 11. – SUPERSONIC THROUGH-FLOW FAN (EXIT STATORS) MAP FROM REF. 8

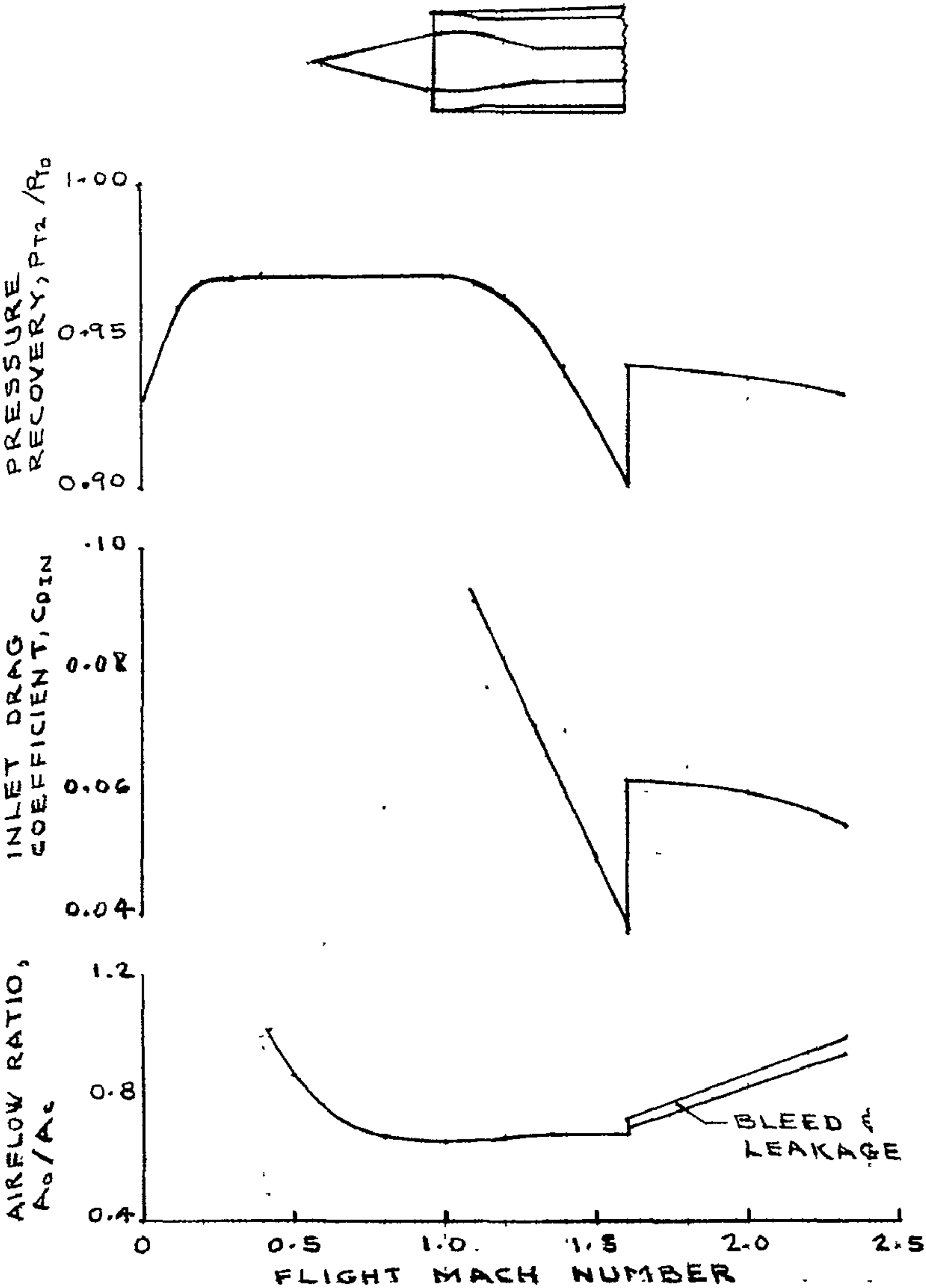

FIGURE 12.—BOEING MACH 2.4 INLET PERFORMANCE

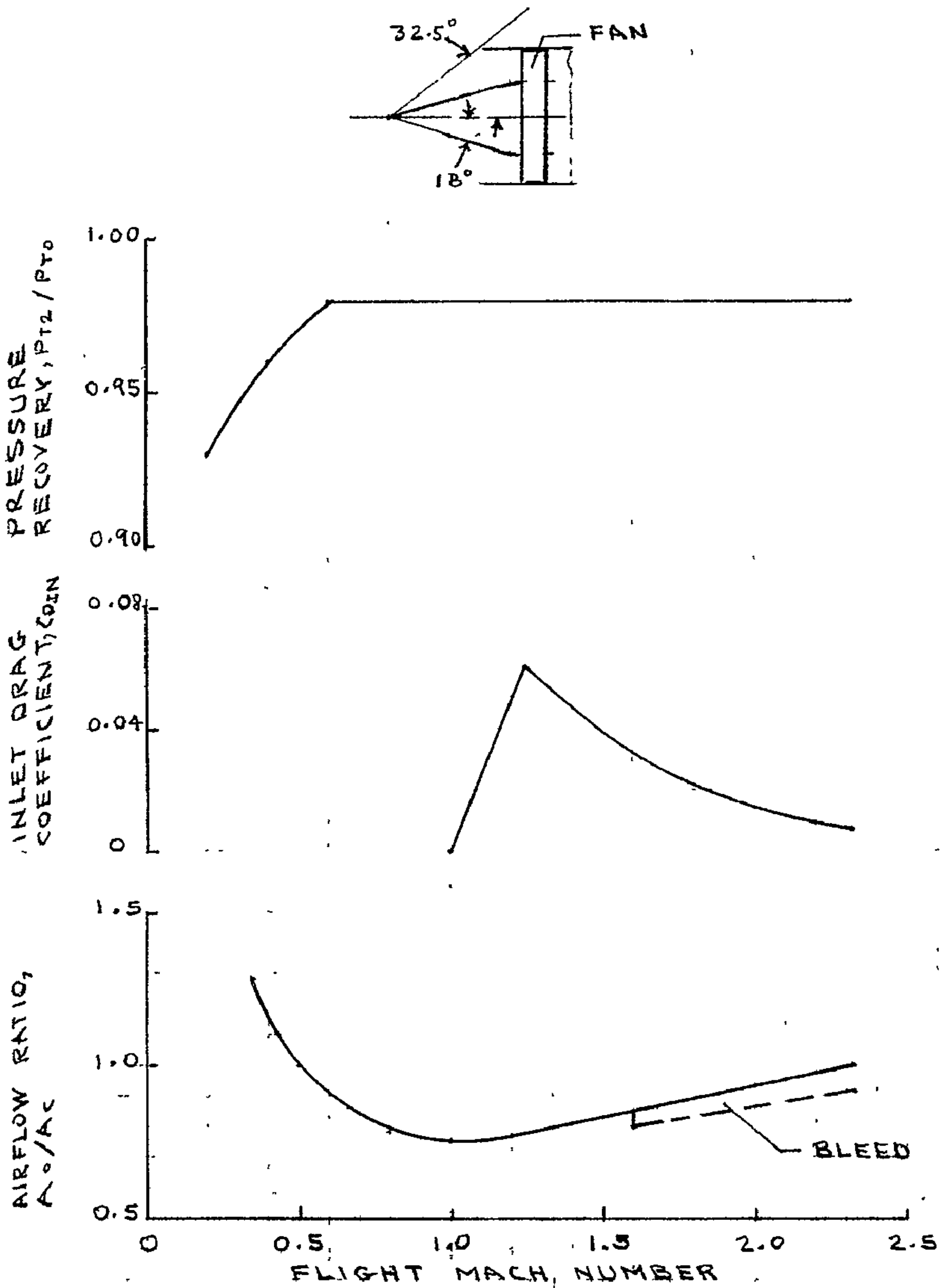

FIGURE 13 -- SUPERSONIC FAN VARIABLE BYPASS MACH 2.4 INLET PERFORMANCE

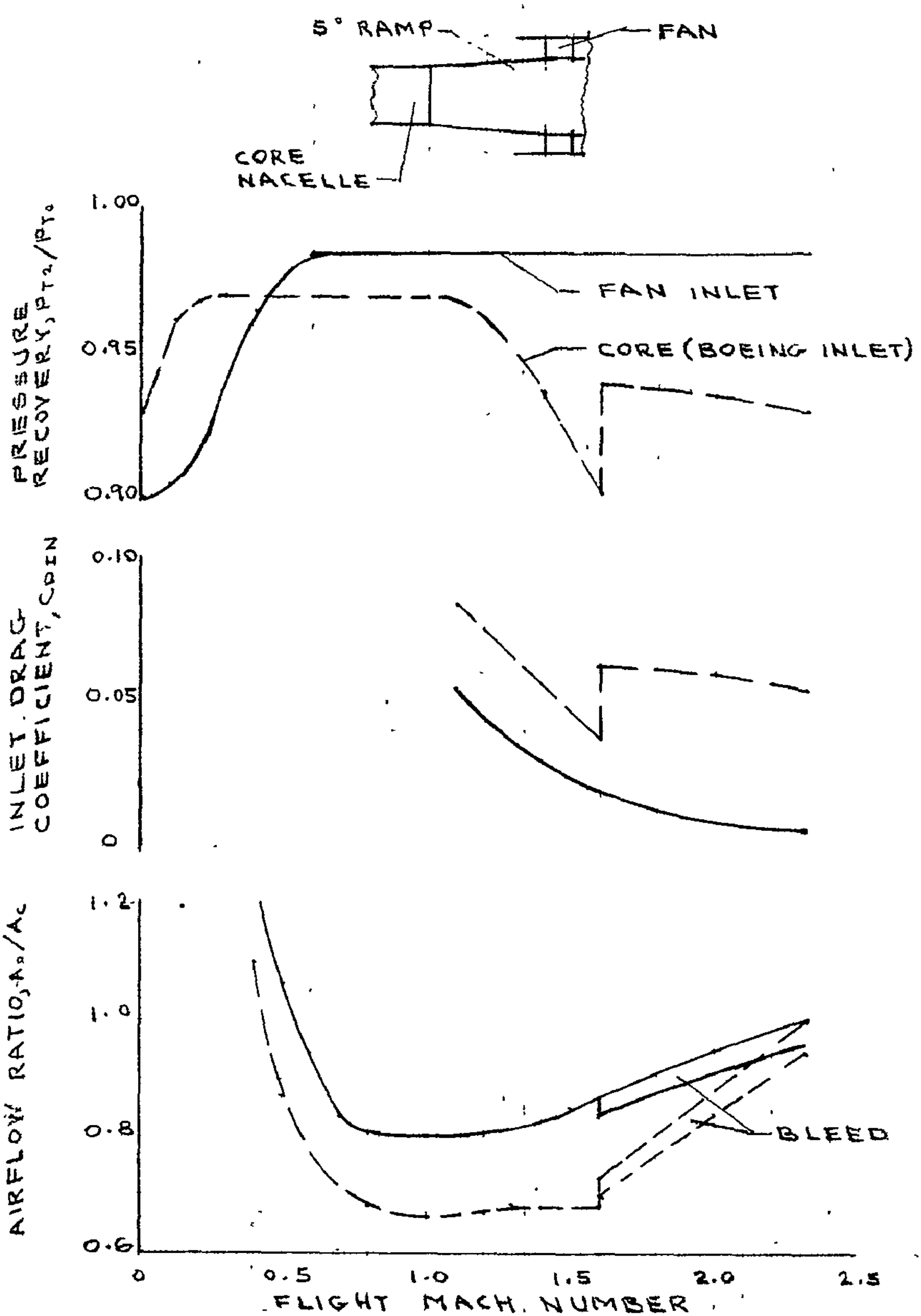

FIGURE 14.- INLET PERFORMANCE FOR AFT FANS AND SUPERSONIC/SUBSONIC FRONT FANS

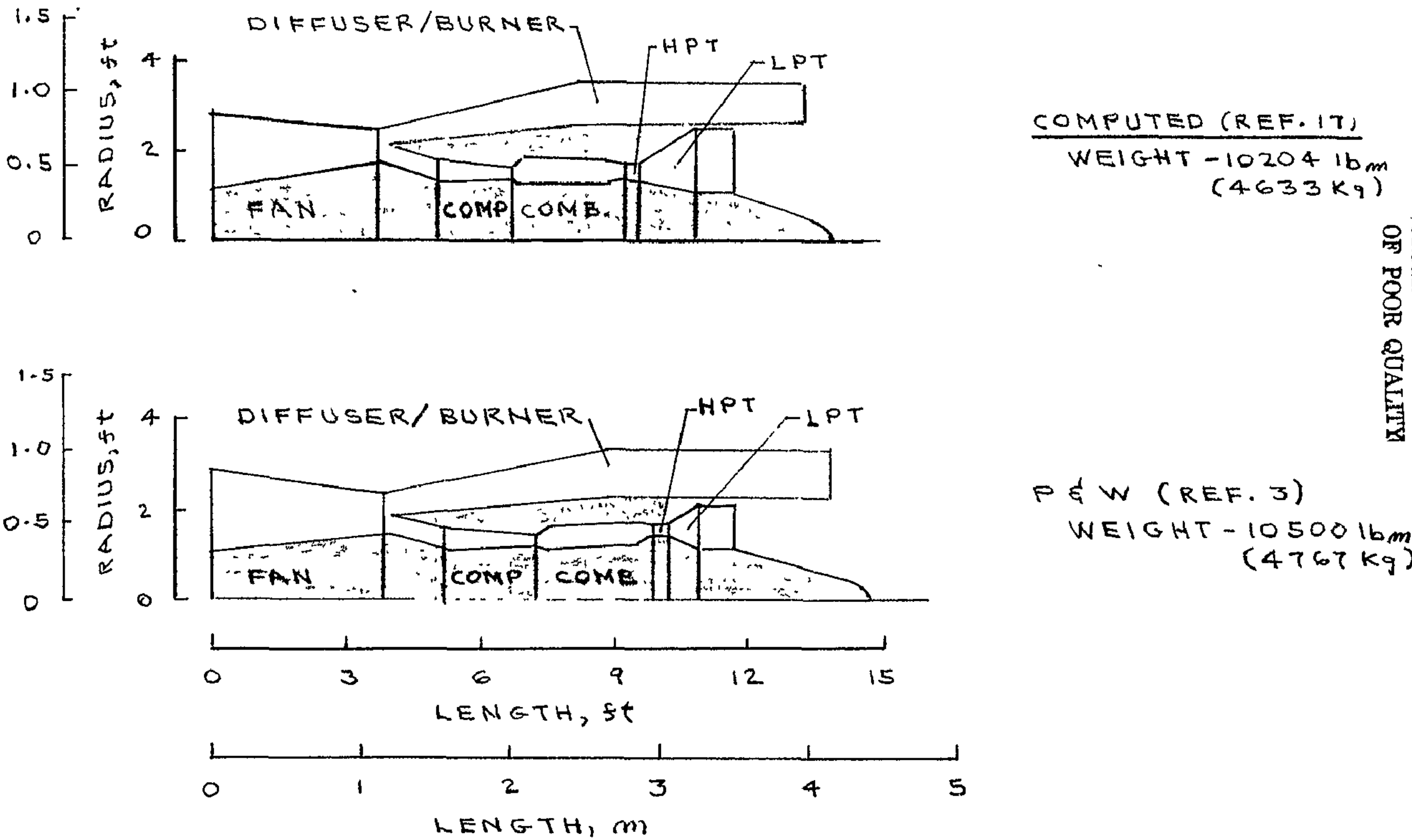

FIGURE 15.—COMPARISON OF ENGINE DIMENSIONS AND WEIGHT COMPUTED BY THE WEIGHT PROGRAM WITH THE PRATT & WHITNEY LAYOUT FOR THE 502B DUCT BURNING TURBOFAN ENGINE S.L.S. AIRFLOW - 900 lbm/SEC (409 Kg/SEC)

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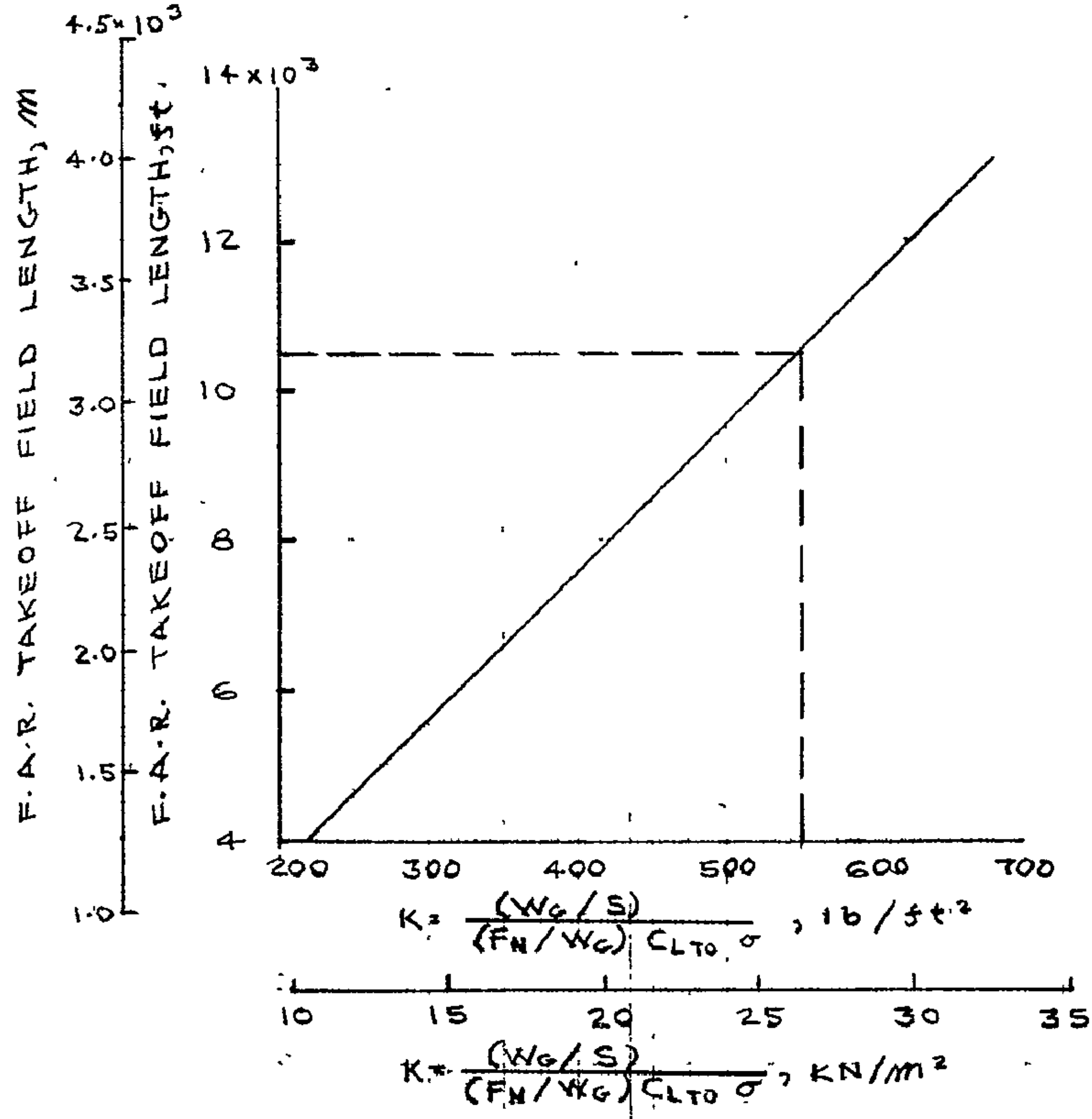

FIGURE 16 - F.A.R. TAKEOFF FIELD LENGTH EVALUATED AT LIFT-OFF. REFERENCE 19

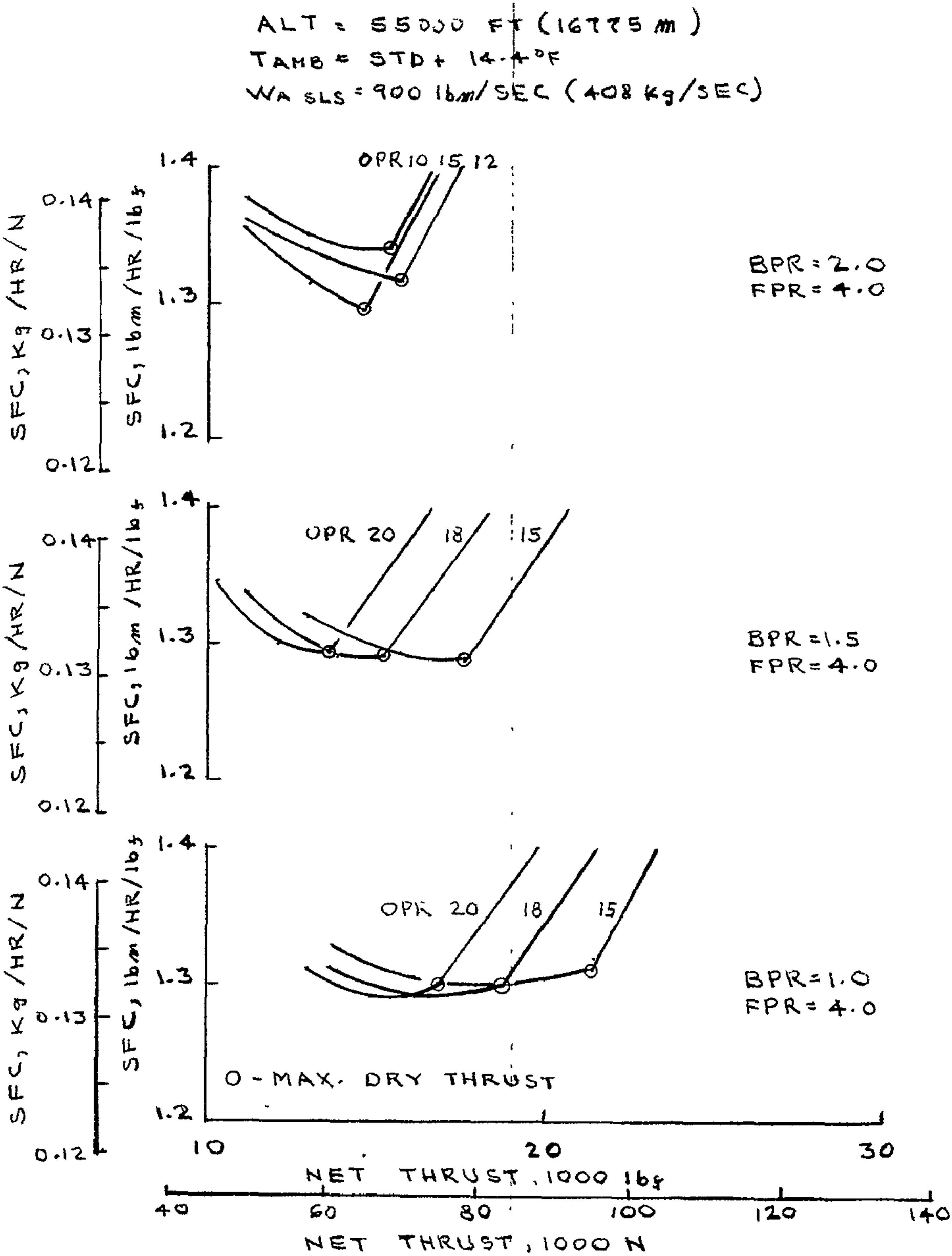

FIGURE 17 - SUPERSONIC FAN VARIABLE BYPASS ENGINE INSTALLED PERFORMANCE; MACH 2.32; MAXIMUM TIT - 3200°R (1778°K)

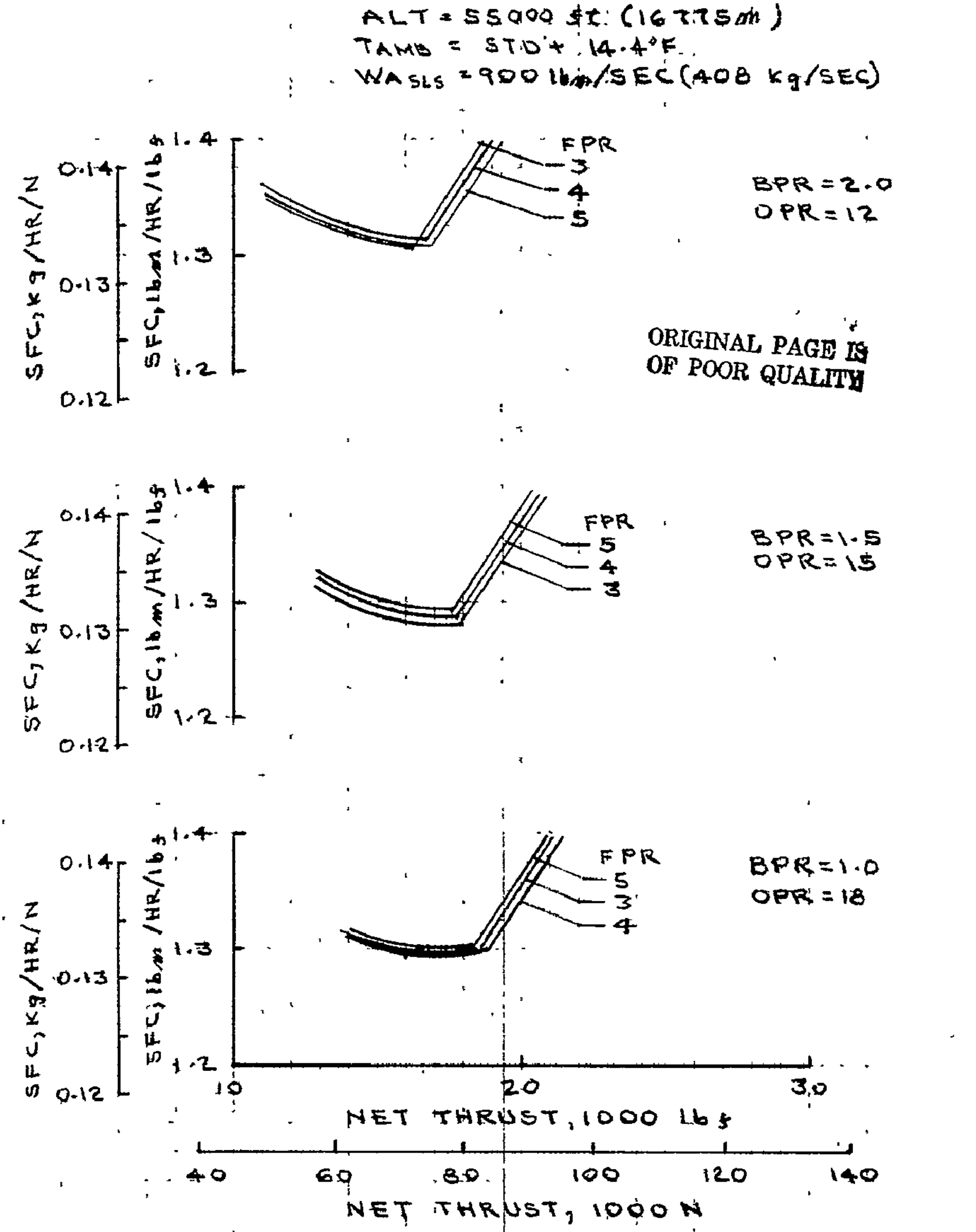

FIGURE 18 - SUPERSONIC FAN VARIABLE BYPASS ENGINE INSTALLED PERFORMANCE; MACH 2.32; MAXIMUM TIT-3200°R (1778°K)

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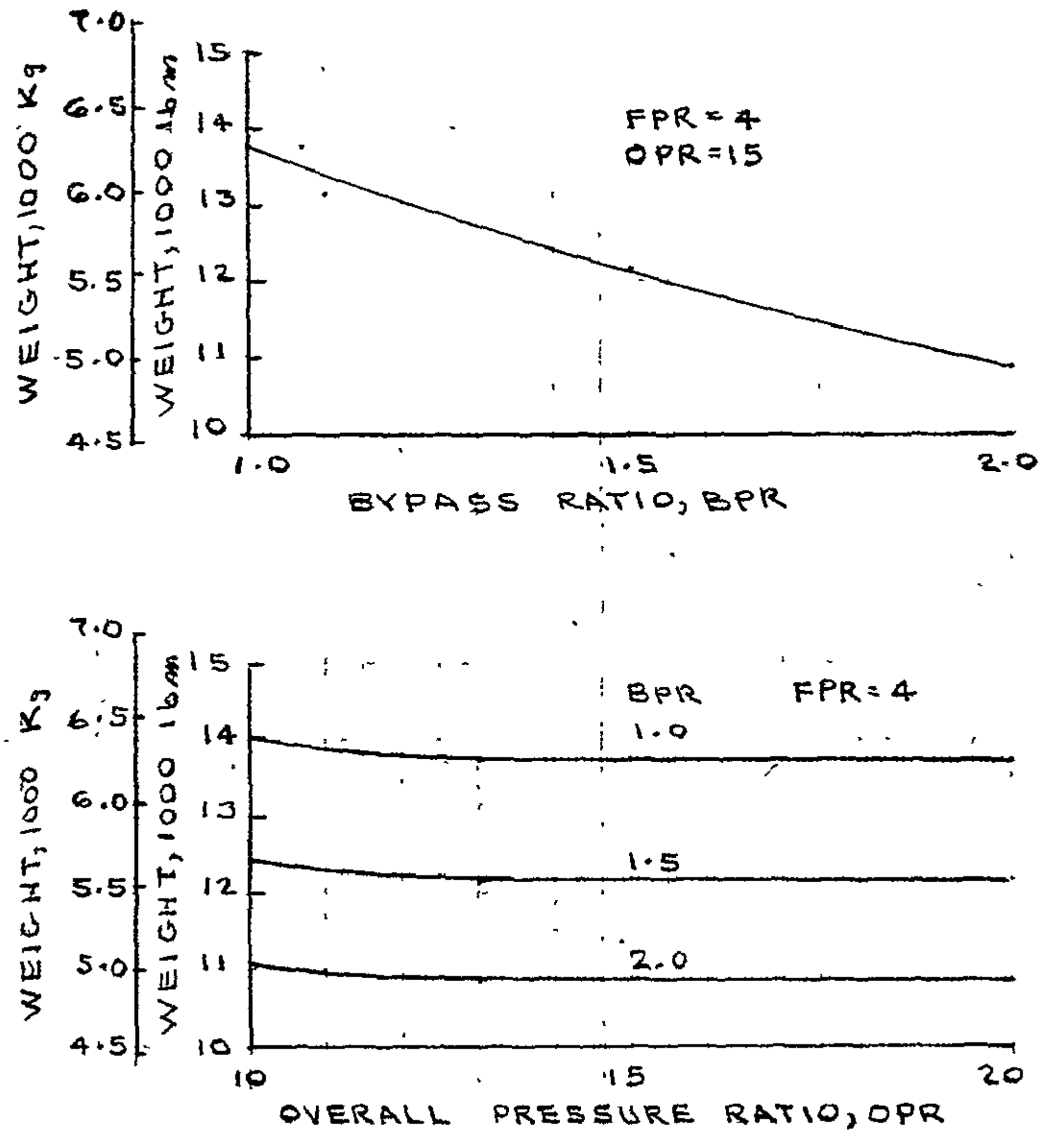

FIGURE 19. - EFFECT OF BPR AND OPR ON THE INSTALLED ENGINE WEIGHT OF THE SUPERSONIC FAN VARIABLE BYPASS ENGINE. $W_{A\,SLS}$ = 900 lbm/SEC (408 Kg)

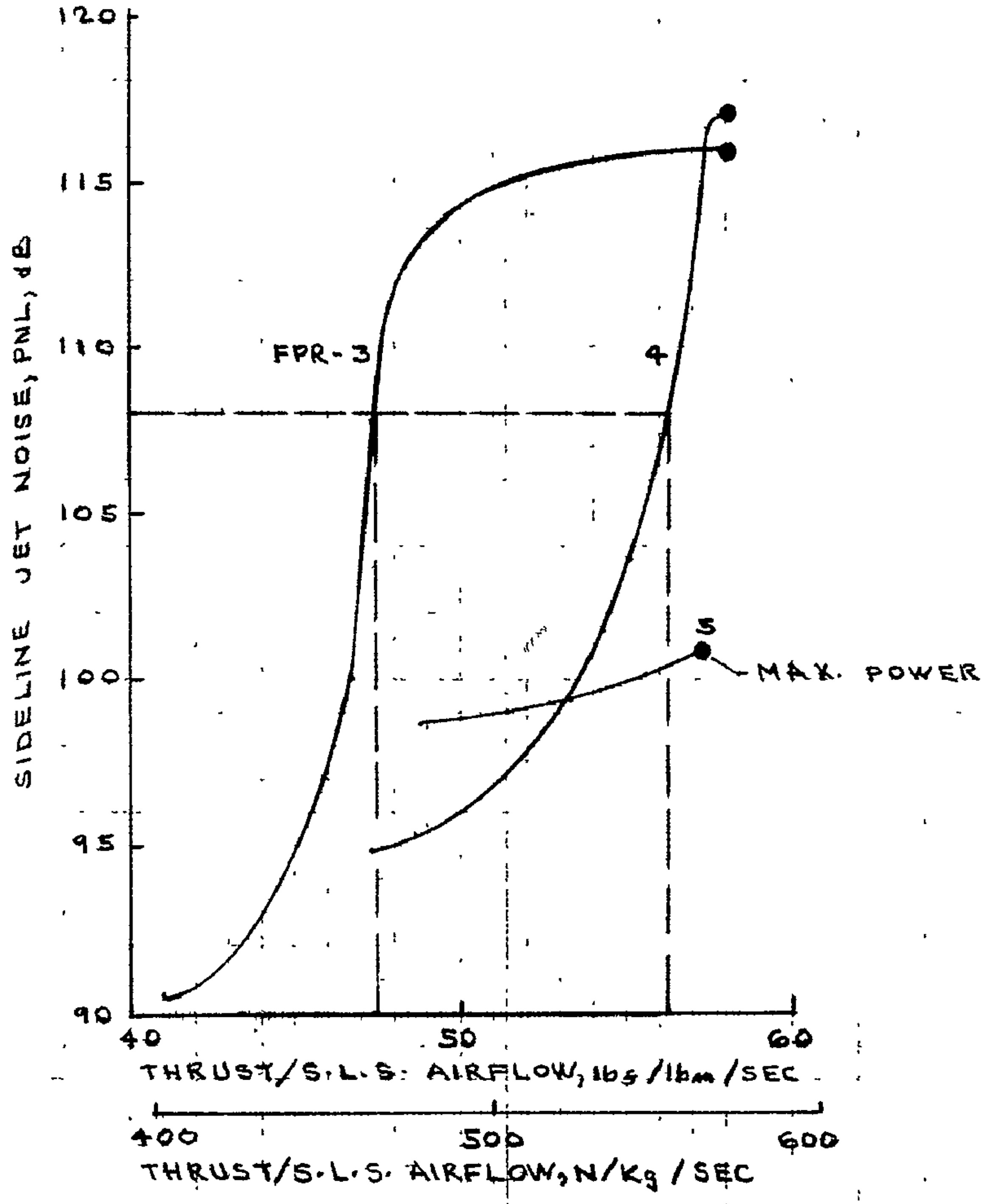

FIGURE 20. - EFFECT OF FAN PRESSURE RATIO ON SIDELINE JET NOISE; SUPERSONIC FAN VARIABLE BYPASS ENGINE; MACH 0.35; ALT - 800 ft (244 m); BPR - 1.5; OPR - 15

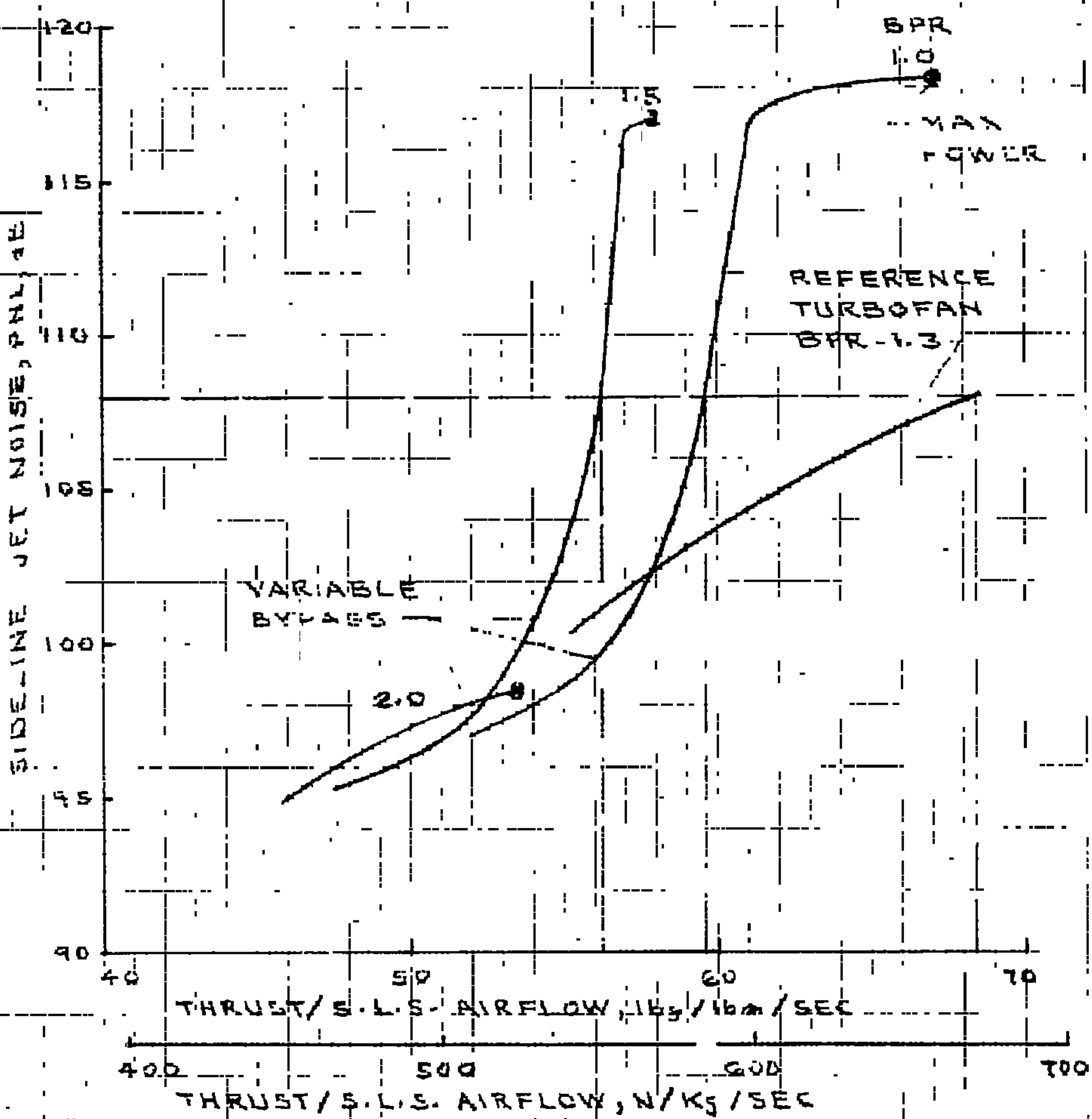

FIGURE 21.- EFFECT OF BYPASS RATIO ON SIDELINE JET NOISE; SUPERSONIC FAN VARIABLE BYPASS ENGINE; MACH 0.35; ALT - 800 ft (244 m); FPR - 4

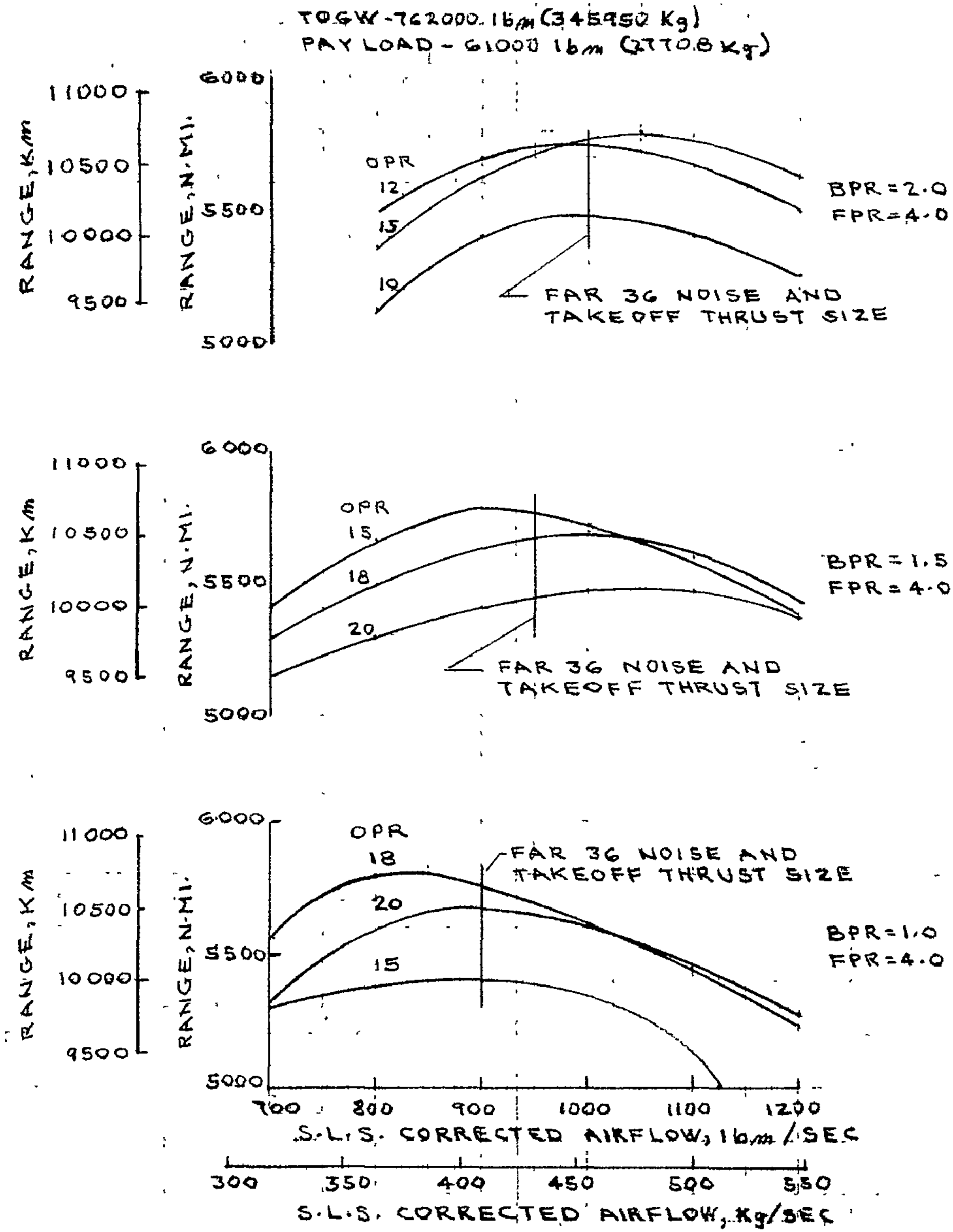

FIGURE 22 - SUPERSONIC FAN VARIABLE BYPASS ENGINE MISSION RANGE; CRUISE MACH NUMBER - 2.32

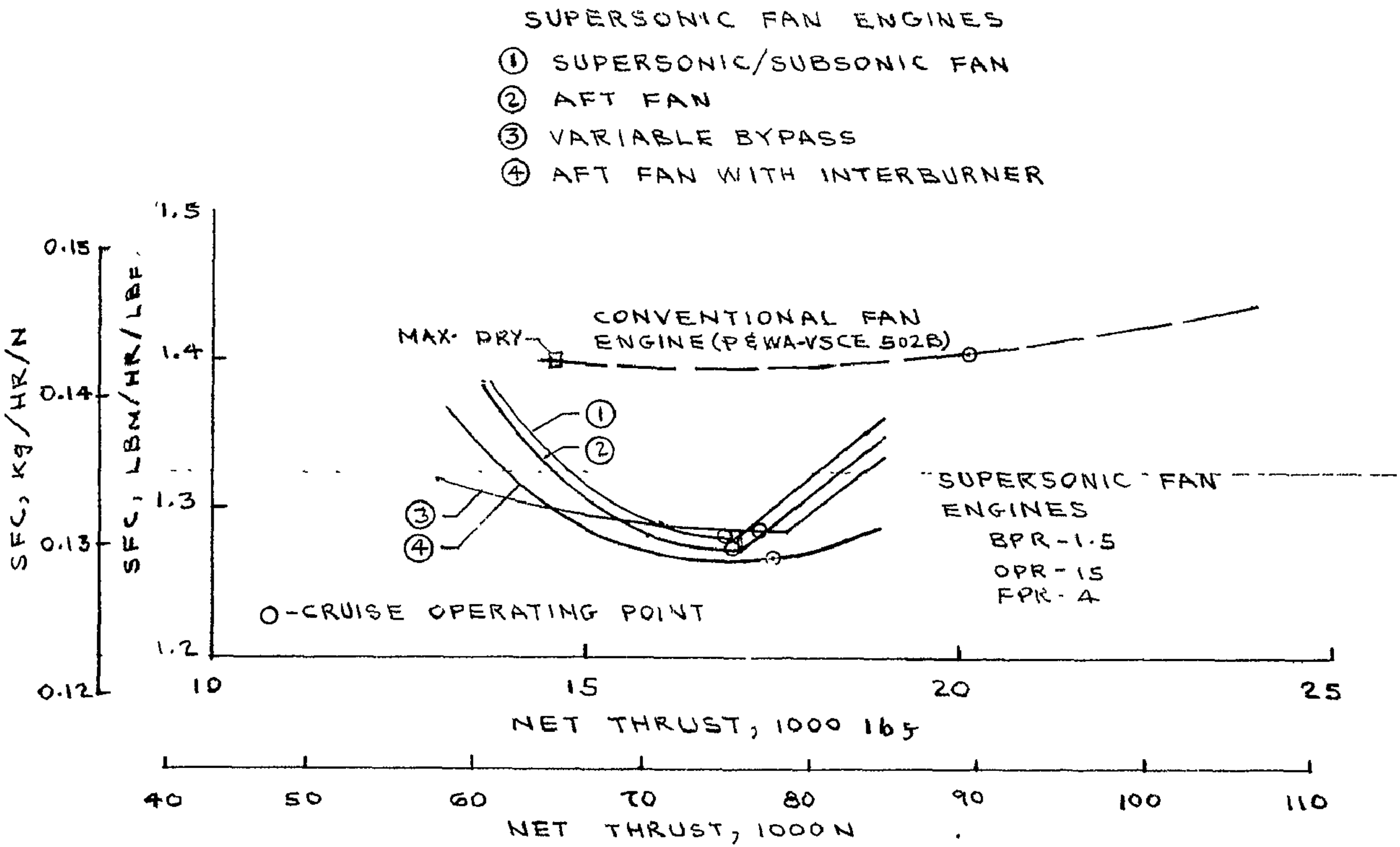

FIGURE 23 - COMPARISON OF ENGINE INSTALLED PERFORMANCE FOR MACH 2.32 CRUISE; ALT - 55000 ft. (16775 m); T_{AMB} - STD + 14.4°F $W_{A\ SLS}$ - 900 lbm/SEC (408 Kg/SEC); MAXIMUM TIT - 3200°R (1778°K)

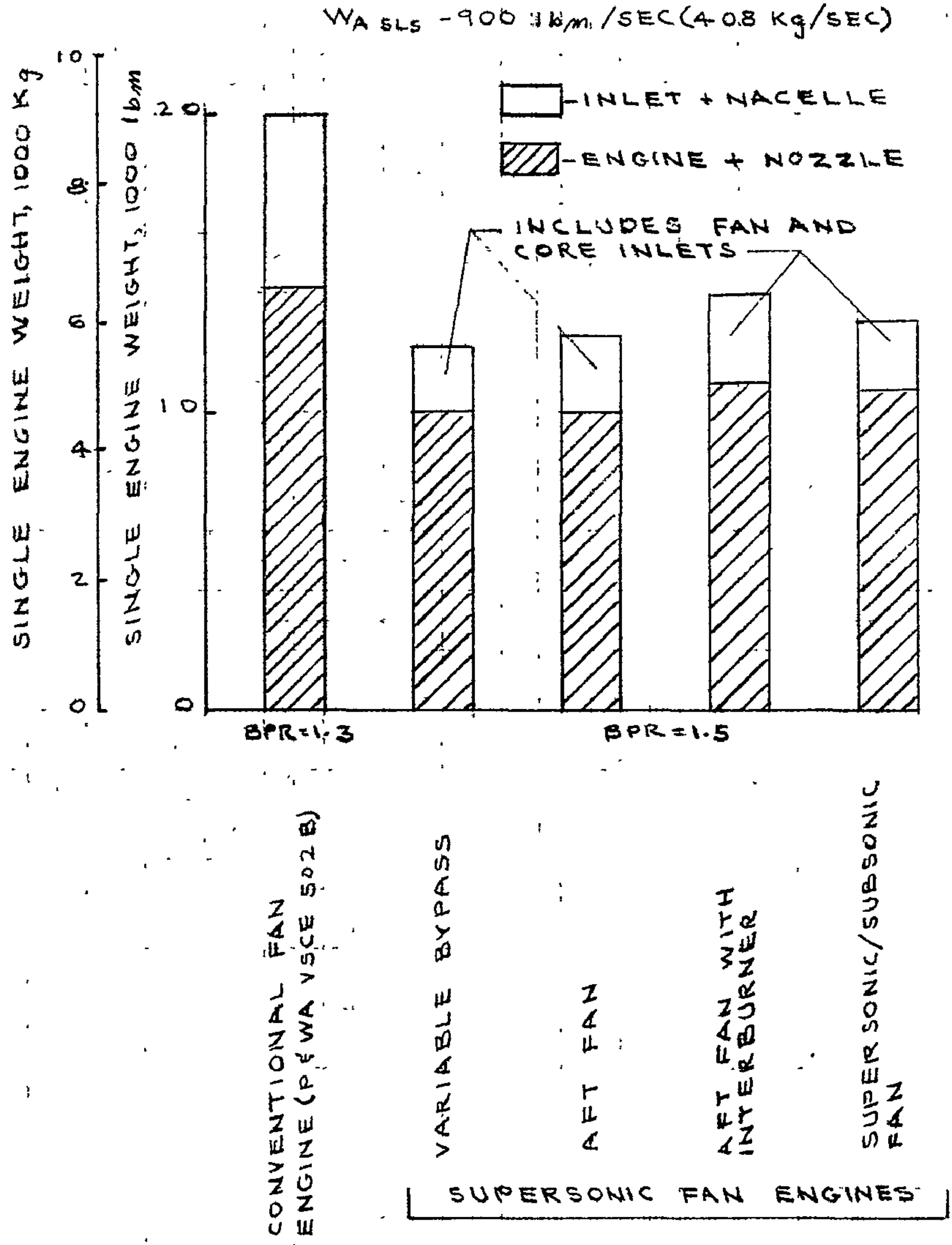

FIGURE 24.- INSTALLED ENGINE WEIGHT COMPARISON FOR THE SAME ENGINE AIRFLOW

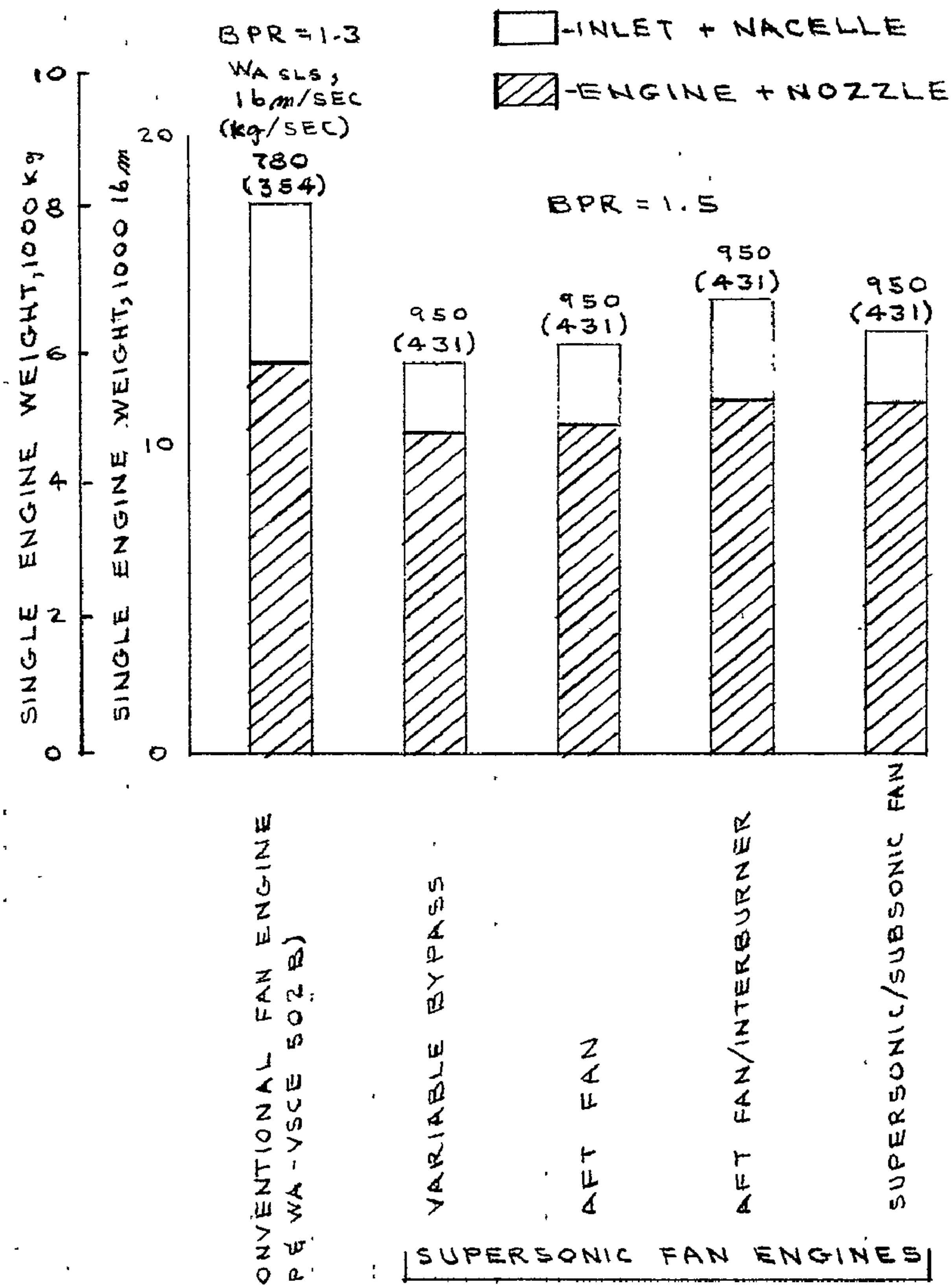

FIGURE 25 - INSTALLED ENGINE WEIGHT COMPARISON
ENGINE AIRFLOW REQUIRED FOR F.A.R. 36
NOISE AND 10500 FT. (3200 m) FIELD LENGTH

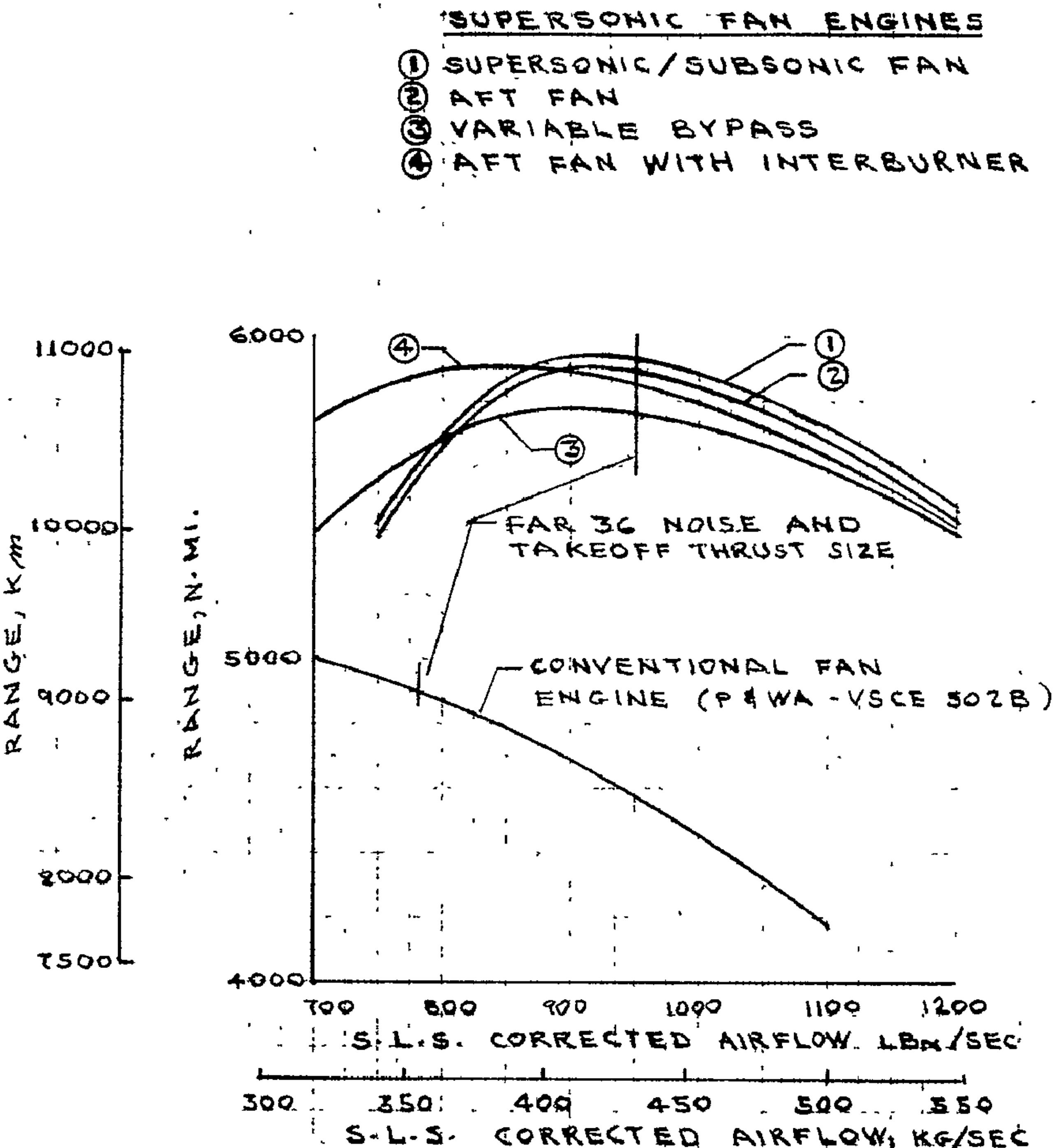

FIGURE 26.- SUPERSONIC FAN ENGINES AND CONVENTIONAL FAN ENGINE RANGE COMARISONS:
TOGW - 762000 lbm (345950 Kg);
PAYLOAD - 61000 lbm (27708 Kg)
CRUISE MACH NUMBER - 2.32

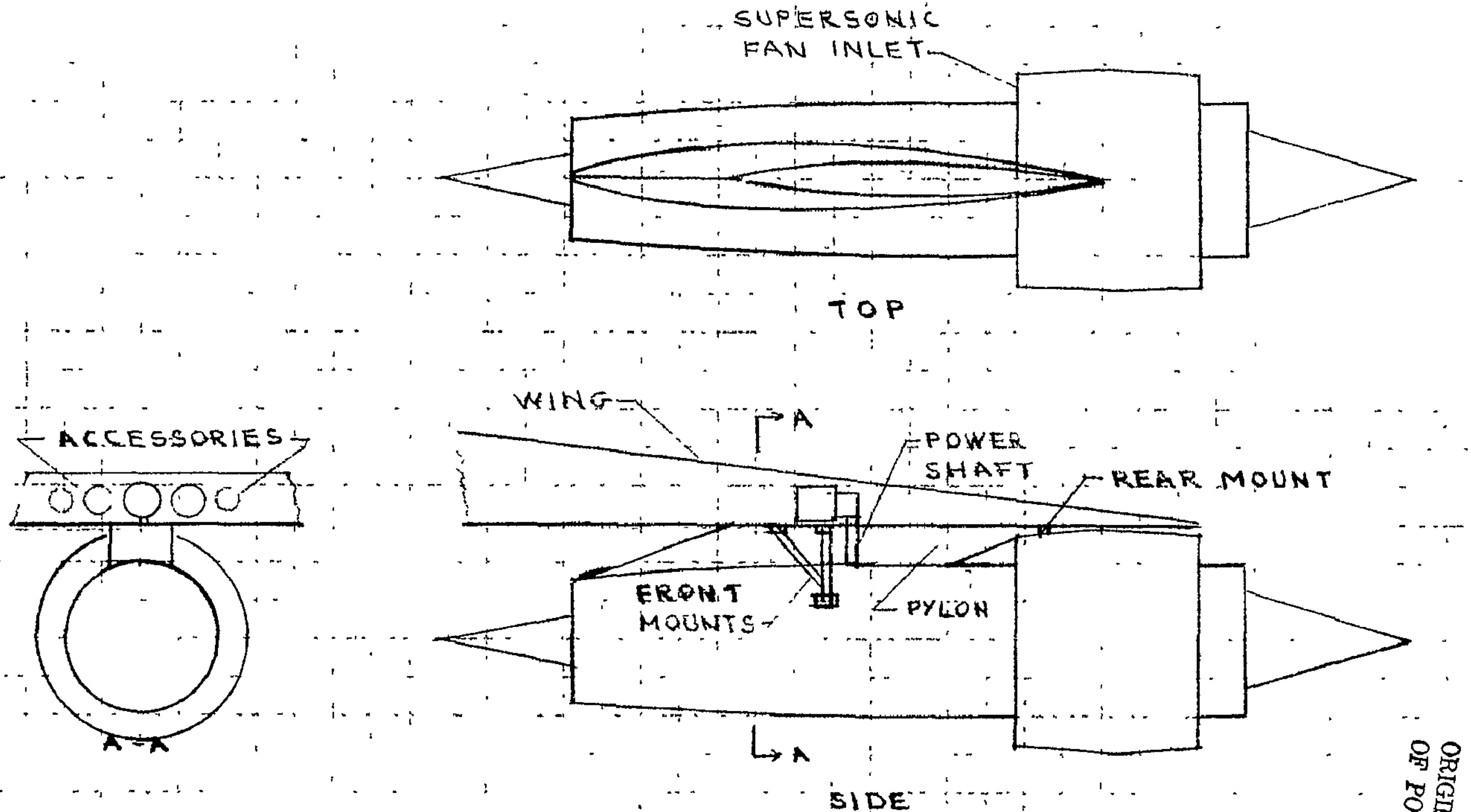

FIGURE 27 - SUPERSONIC AFT FAN ENGINE MOUNTING - POSSIBLE UNDESIREABLE FLOW AT FAN INLET

SUPERSONIC FRONT FAN ENGINE INSTALLATION

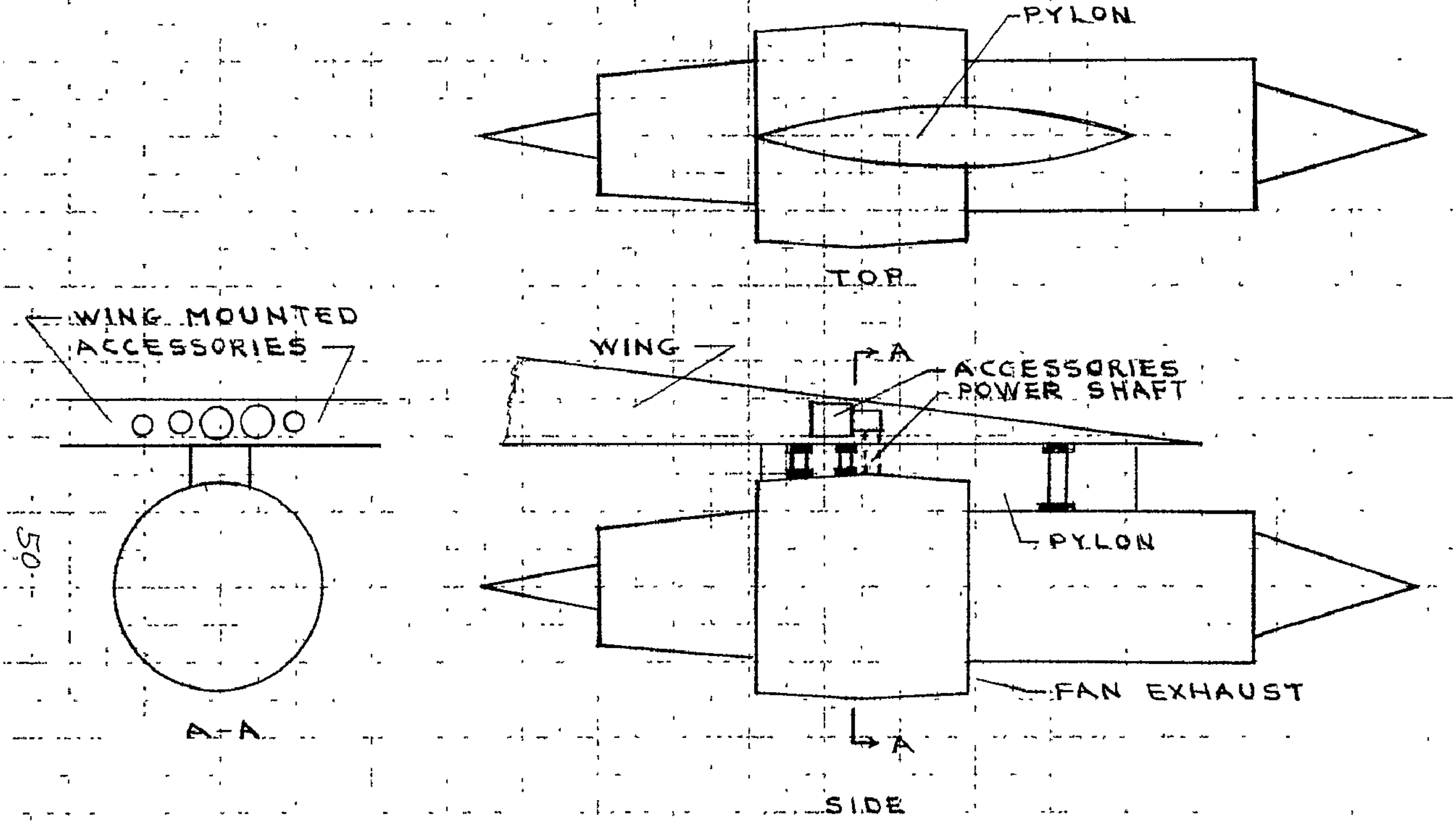

FIGURE 28. - SUPERSONIC/SUBSONIC FAN ENGINE MOUNTING - POSSIBLE HIGH DRAG OF PYLON IN FAN EXHAUST

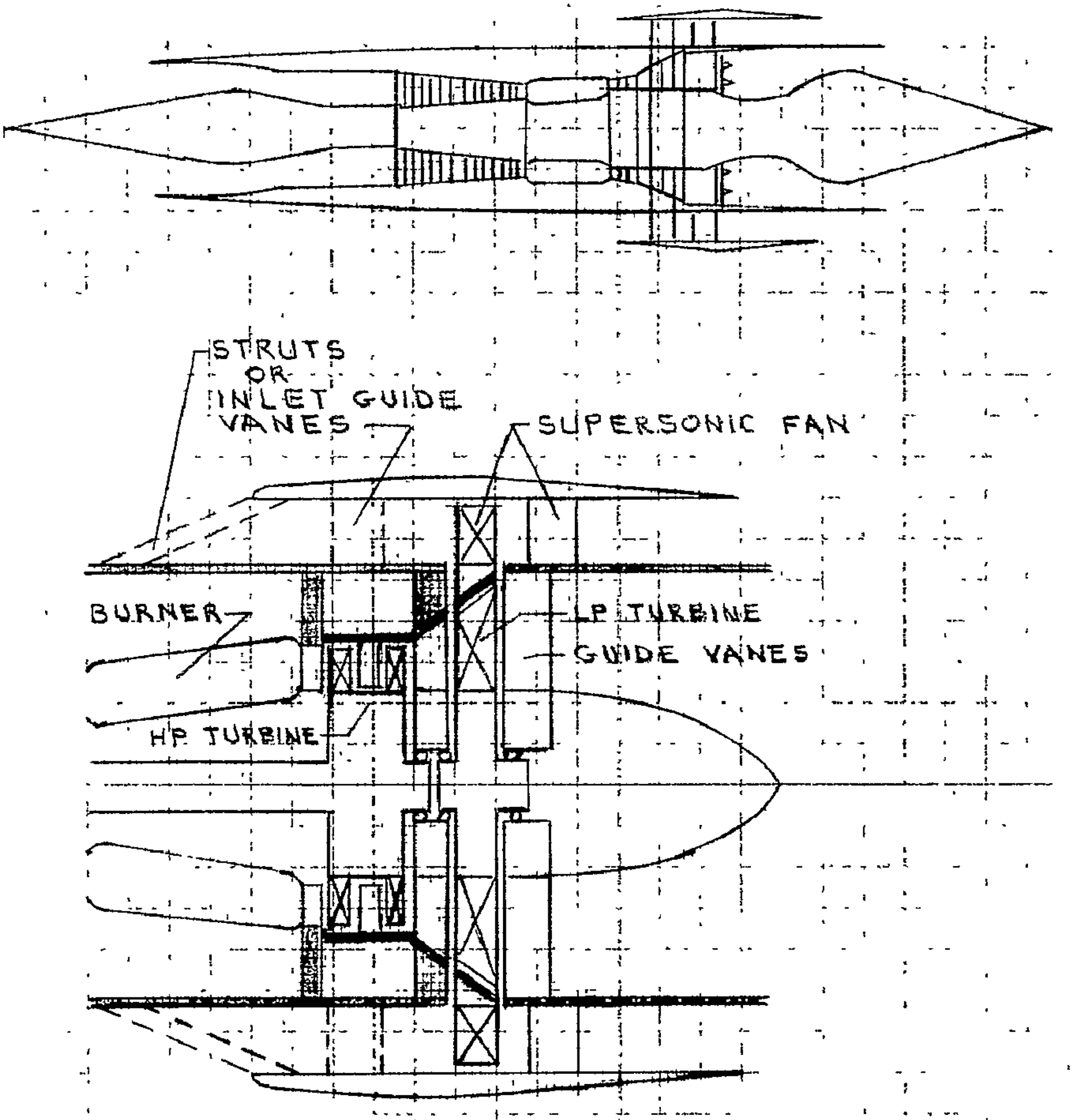

FIGURE 29 - AFT SUPERSONIC FAN STRUCTURAL SUPPORT

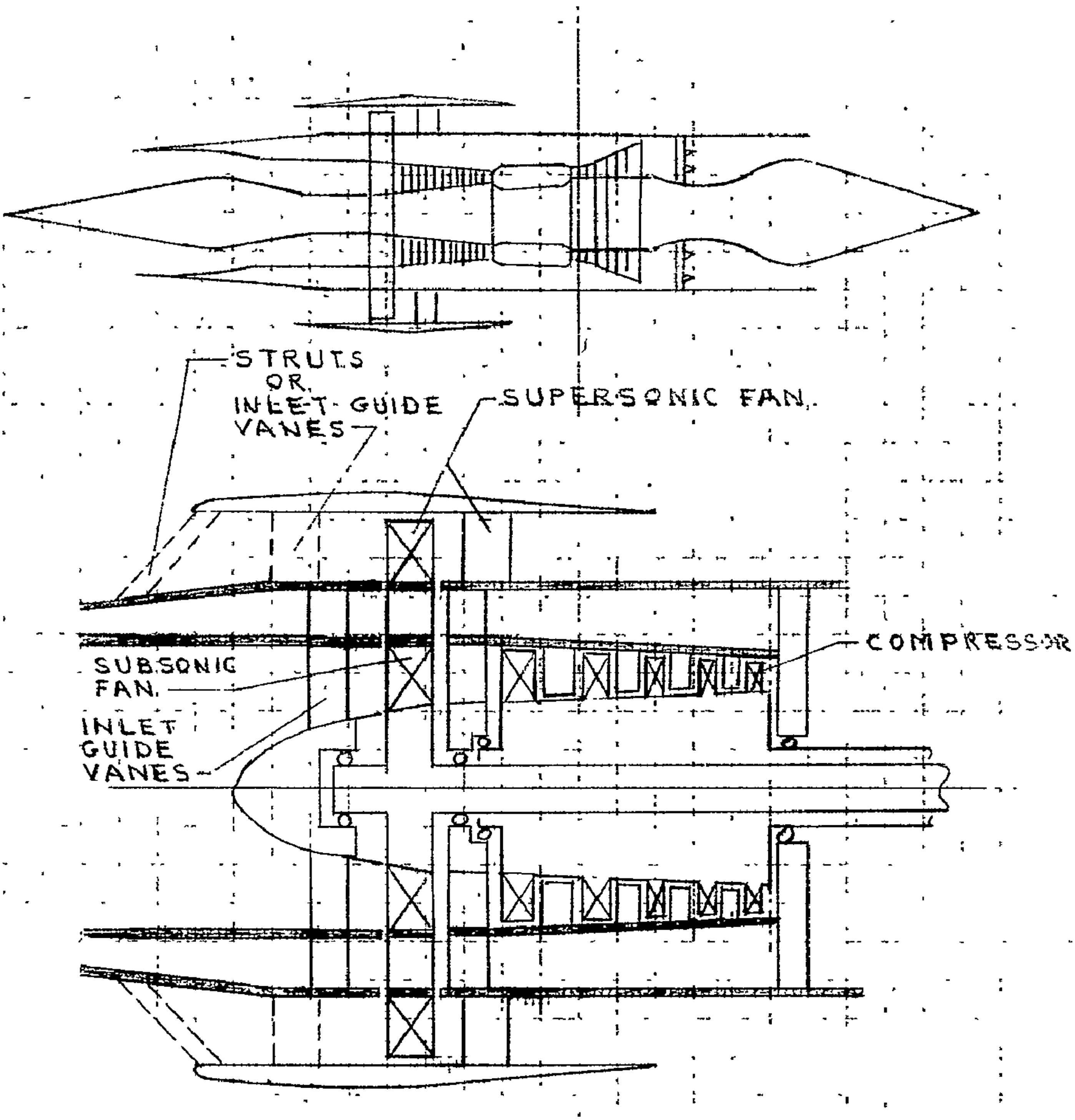

FIGURE 30 — SUPERSONIC/SUBSONIC FAN STRUCTURAL SUPPORT