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PRELIMINARY NOISE TRADEOFF STUDY OF A
MACH 2.7 CRUISE AIRCRAFT

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STAFF OF THE LANGLEY RESEARCH CENTER

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PRELIMINARY NOISE TRADEOFF STUDY OF A MACH 2.7 CRUISE AIRCRAFT

by
Staff of the Langley Research Center

EXECUTIVE SUMMARY

This report presents preliminary results of an ongoing study being conducted at the Langley Research Center to understand the design, performance, and cost implications which are related to the reduction of future supersonic cruise aircraft noise at the FAR-36 noise certification measurement points. The complete extent of the NASA study of this subject covers a number of cruise Mach numbers and configuration concepts, and includes both NASA in-house and contractor studies. This report, however, is restricted to the NASA-generated Mach 2.7 arrow wing configuration studied by the Langley Research Center. Contractor studies of other aircraft configurations and cruise Mach numbers, and NASA's subsequent analyses of these industrial configurations will all be reported separately.

The Mach 2.7 arrow wing configuration studies were based on the use of NASA computer codes in the areas of preliminary sizing and enroute performance, takeoff and landing performance, aircraft noise prediction, and economics. Aerodynamic configuration data were based on wind-tunnel model tests and related analyses. Aircraft structural characteristics and weight were based on advanced structural design methodologies, assuming conventional titanium technology. The most advanced noise prediction techniques available were used, and aircraft operating costs were calculated using accepted industry methods. The four engine cycles included in the study were based on assumed 1985 technology levels, and all engine physical parameters and performance characteristics used were provided by the engine study contractors (Pratt and Whitney Aircraft and General Electric).

The nominal mission used for the study was a design range of 8334 km (4500 n.mi.), payload of 273 passengers and takeoff field length constrained to 3810 m (12500 ft.). Takeoff and landing performance was computed meeting existing FAR-25 safety requirements (refused takeoff, one engine out climb gradients, balanced field length) and current FAR-36 operating procedures (constant throttle and flap settings during takeoff and a constant velocity 3⁰ glideslope on approach). Noise results were based on the complete takeoff time history from brake release until the aircraft was sufficiently past the 3.5 nautical mile measuring point such that measurements at that point were no longer affected. Similarly, noise results were obtained for the 1.0 nautical miles point based on an approach flight path time history.

Noise results were calculated both with and without jet shock-cell noise because it is not known at this time whether the assumed variable convergent-divergent nozzles would generate significant shock-cell noise. Both fore and aft radiated fan noise, while calculated, was excluded from composite noise levels on the assumption that these noise sources would be suppressed by the use of adequate duct treatment or inlet choking.

The study included two augmented variable cycle engines (Pratt and Whitney and General Electric designs) both utilizing coannular inverted velocity profile nozzles without mechanical jet noise suppressors, and a Pratt and Whitney unaugmented low bypass ratio turbofan engine with and without an advanced design mechanical suppressor (a McDonnell Douglas design). The variable cycle engines (VCE) used in the present study were originally optimized for maximum coannular effect at full throttle on the sideline and did not achieve the maximum coannular noise abatement effect at cutback. Further design iteration remains to be done to attain the maximum coannular effect at cutback. The study did not consider the noise and system effects of applying mechanical suppressors to the variable cycle engine designs, nor did the study consider advanced takeoff procedures. Sideline noise shielding effects are not included in the study, because shielding occurs in a narrow shadow zone and the maximum sideline perceived typically occurs outside that zone. Advanced takeoff procedures could change this result and require that shielding be included. Potentially significant duct burner noise was not included since no accepted prediction method is available.

The results of the study with the above assumptions indicate that the minimum weight airplanes which were sized for takeoff field length have traded noise levels neglecting design margins from 110 to 118 EPNdB. The higher noise level includes a shock noise penalty of 3-4 EPNdB if this noise source cannot be controlled. Engine oversizing of 14-24 percent relative to the minimum size engine needed to perform the mission would have traded noise levels of 108-114 EPNdB with up to 3 percent increase in direct operating cost. Further engine oversizing provided negligible reductions in noise, but introduced even larger penalties in cost and fuel consumption.

Other results of the study to date indicate the following:

- o Changing the design range or payload has a negligible effect on flyover and sideline noise level
- o Reducing design takeoff field length (increased thrust) significantly reduces flyover noise for a maximum power takeoff. However, sideline noise increases slightly
- o Flyover noise is reduced rapidly with offloading fuel for shorter range operation. Sideline and approach noise remain essentially constant
- o Aircraft designed with oversized engines (and all aircraft operated at lower weight) provide flexibility in that different throttle settings and flap settings can be used to minimize either sideline or flyover noise, depending upon the particular community.
- o The noise sensitivity to flap and throttle settings suggest the use of advanced operating procedures in the terminal area.
- o The performance and operating cost penalties to achieve noise reduction by engine oversizing underscore the need for more study in the area of advanced takeoff procedures

The preliminary study results are not considered to be sufficiently comprehensive enough to determine what the optimal aircraft and engine combination would be to achieve any specified noise level for the specified aircraft mission, nor to establish precise tradeoff relationships among all the variables which must be considered. Additional studies, as a minimum those outlined below, are needed before definitive statements of feasible noise levels for future advanced design supersonic cruise aircraft can be made.

1. Determine the potential for noise reduction by incorporating advanced operating procedures for the various engine cycles.
2. Determine the practical limits for shock cell noise control.
3. Determine the feasibility of engine operation at very low power settings, required for decelerating approaches.
4. Determine the noise reduction and feasibility of incorporating simple mechanical suppressors on variable cycle engines.
5. Determine the cost/noise sensitivity to increasing fan size (varying bypass ratio), rather than scaling the entire engine as assumed in this study.
6. Provide an iteration with engine manufacturers to provide engine operating characteristics to maximize coannular noise benefit consistent with best aircraft operating conditions for low noise.
7. Conduct study of industry-generated aircraft concepts to determine uncertainties in noise and performance for different aircraft characteristics.

The above studies are important to the basic understanding of achievable noise levels and their design and cost implications. In addition, however, it must be recognized that additional empirical data is needed to refine both noise reduction features and other operating characteristics of all engine cycles under study. Data on VCE design parameters, coannular nozzle inverted flow noise reduction and advanced mechanical suppressors is urgently needed to reduce the present uncertainties in all studies of the type reported herein.

INTRODUCTION

U.S. Certification noise regulations for current type supersonic cruise aircraft are in the notice of proposed rulemaking (NPRM) stage. The notice states that rules/guidelines for future (post 1985) supersonic aircraft will be forthcoming pending the results of current analytical studies. With the Anglo-French Concorde and Soviet TU-144 in commercial service, international studies are underway within the framework of the International Civil Aviation Organization (ICAO) to establish certification noise rules for supersonic cruise aircraft.

In support of this effort, the FAA, Office of Environmental Quality, which heads the U.S. delegation with the ICAO Committee on Aircraft Noise, requested

NASA early in 1977 to conduct a noise sensitivity study applicable to future supersonic cruise aircraft. Accordingly, NASA, through its Langley Research Center, undertook a study to determine the sensitivity of cost and performance to aircraft noise levels for future supersonic aircraft concept. Technical factors which significantly affect the noise level of this class of vehicle were to be identified.

The acoustic data used for all the NASA studies are based upon small scale tests and analytic studies, and has received only limited validation for scale and flight effects. The noise levels quoted herein do not include a design margin for noise. (Typically, subsonic aircraft have a design margin of 3 EPNdB. The design margin for supersonic aircraft could be as much as 5 EPNdB because of increased uncertainty.)

The data base which is required to perform this noise study has been assembled in 5 years of work under the NASA Supersonic Cruise Research program (SCR) (ref. 1). The SCR program has supported technology programs in the principal disciplines of propulsion, aerodynamics, structures and materials, noise, and flight controls. In addition, the system studies area of the overall SCR program includes the integration of inputs from all technical disciplines into practical aircraft concepts. Design and integration teams have been maintained in the major commercial airframe companies (Boeing Commercial Airplane Company, Lockheed-California Company, and Douglas Aircraft Company) and in-house at NASA Langley supported by Vought Corporation (Hampton Technical Center). Four study configurations have evolved under the SCR program as shown in figure 1. The configurations reflect differing philosophy as to timing, cruise speed, and degree of advanced technology. Only the Langley study configuration is reported herein.

Parallel to the NASA Langley and company systems studies, propulsion studies managed by NASA Lewis Research Center sought to identify engine cycle concepts which would produce highest levels of performance consistent with environmental constraints on noise and exhaust constituent pollution. A wide range of possible engine cycles was studied early in the SCR program, which led to the refinement of a family of variable cycle engines. These cycles have higher airflow capability and dual stream exhaust which utilize coannular inverted velocity profiles leading to noise reduction. While the variable cycle engine concepts appear promising, comparable technology low bypass ratio turbofan engines with mechanical suppressors remain under study as an alternative.

Progress in the last five years has led to the refinement of specific aircraft configurations and engine cycles. These designs have been chosen for the noise sensitivity studies in support of the FAA and ICAO. The present study is restricted to the Mach 2.7 NASA arrow wing concept. The industry configurations have been studied independently by Boeing, Lockheed, and Douglas, and are available as separate reports.

Parallel to study reported here, a more detailed investigation of the configurations generated has been conducted, which include such effects as balance and flutter requirements. The results of those studies will be reported separately.

STUDY APPROACH

In order to accomplish the objectives of the study, an interaction between design, performance, economics, and noise prediction was required. Specifically, four computer programs were manually interfaced as shown in figure 2. The study approach consists of utilizing individual programs for aircraft preliminary sizing and performance, economics, takeoff and landing performance, and noise prediction.

Configuration Inputs

The aerodynamic characteristics used herein are based upon scaled wind tunnel data, on a Mach 2.7 arrow wing design (refs. 2-3) with a subsonic leading edge wing and plain high lift devices (fig. 3). The data includes trimmed drag polars throughout the operating Mach number and altitude range. Engine manufacturer data consists of fuel flow versus thrust as a function of Mach number and altitude, with engine size and weight scaling curves. Installed engine performance is based upon a NASA mixed compression inlet (refs. 4-5) with airflow matching and propulsion drag items such as bleed, spillage, and bypass drag included. Weight estimation is based upon correlation methods from industry weight statements for supersonic cruise configurations, with titanium airframe structure utilizing sandwich cover material for all aerodynamic surfaces and skin-stringer-frame construction for the fuselage.

Aircraft Sizing and Performance Program

The purpose of the aircraft sizing program (ref. 6) is to determine the effects of aircraft and operational variables on aerodynamics, propulsion, weights and range. The baseline aircraft can be resized for changes in thrust/weight, wing loading, number of passengers, or gross weight. New aerodynamics, propulsion, and weights are generated and mission profile flown to find new range capability. Enroute performance analysis used a step-wise integration of the equations of motion including minimum fuel climb and acceleration, and hot day (standard day +8°C) supersonic cruise at optimum range factor as shown in figure 4. Fuel reserves are computed based upon 5 percent trip fuel (ref. 7), missed approach, 463 km (250 n.mi.) subsonic cruise to alternate airport, and 30 minute hold at 3052 m (10,000 ft). The output of the aircraft sizing program is a matrix of airplanes' thrust/weight ratio (sea level static installed maximum thrust) and wing loading (takeoff gross weight/wing area) combinations which meet the specified range and payload (8334 km/4500 n.mi. - 273 passengers). Design constraints such as takeoff field length (3810 km/12,500 ft), climb and cruise thrust margins, and fuel volume margins are determined. An approach speed of 153 knots was maintained for all configurations studied.

Takeoff and Landing Performance

The purpose of this computer program is to determine takeoff performance in accordance with FAR Part 25 safety requirements. The program was developed for detailed analysis of specific aircraft designs. Takeoff profiles are generated by stepwise integration of the equations of motion. The method searches for critical engine failure speed and balanced field length. Power cutback and acceleration is available during climbout for noise alleviation. Approach profiles are also generated, with options for two-segment and/or decelerating approaches. However, the current study included only the standard 3^0 constant velocity approach. Extensive time histories of noise critical parameters are developed for input to the NASA noise prediction program (ANOPP).

Aircraft Noise Prediction

Noise predictions were made with the ANOPP (ref. 8). This program utilizes time-dependent trajectory and engine data from the takeoff and landing performance program to predict the time-dependent one-third octave band spectra at a set of observer positions. These spectra are then integrated to obtain perceived noise and effective perceived noise.

ANOPP includes noise source prediction modules for jet mixing noise, jet shock cell noise, fan noise, combustion noise, turbine noise, and airframe noise. It will be shown later that the most significant sources are the jet mixing and the jet shock cell noise, so that the bulk of the computations made during the study were based on these two sources.

The variable cycle engines feature the inverted-flow jet exhaust (refs. 9, 10) shown to provide a significant benefit in jet mixing noise relative to a single jet or relative to a conventional coaxial jet where the outer stream has lower velocity than the inner stream. In order to provide a method (ref. 11) for predicting noise from these variable cycle engines, the large model scale data sets (refs. 9, 10) were utilized. The correlation utilizes a mixed equivalent jet having the same mass flow, thrust, and enthalpy flux as the inverted flow jet. Measured noise from the inverted flow jets was compared to the prediction (ref. 12) of the noise from the mixed jet. It was found that the inverted flow jets produced less acoustic power, with a difference of up to about 4 dB, than the mixed jet. Correlation curves were also developed for the directivity and spectrum of the inverted flow jet so that these effects could be properly accounted for in the predictions.

Predictions for simple circular jets were made with the SAE ARP 876 method (ref. 12). For coaxial jets, where the outer stream is slower than the inner, an alternate method (ref. 13) was used. Predictions for the cases with a jet suppressor were based on model data supplied to Langley by McDonnell Douglas.

Jet shock cell noise predictions for the coannular nozzles were made with the method given in reference 14. It was assumed in this study that the nozzles were convergent and that the shock cell noise from the conventional coannular

and inverted flow jets was the sum of the shock cell noise from the individual streams. There remains a question of whether the shock cell noise can be reduced or even completely eliminated, through the use of variable convergent-divergent nozzles. It is known that shock cell noise can be eliminated in a well designed convergent-divergent nozzle if the jet is operating at the design pressure ratio.

It is not known, however, how the shock cell noise varies for nozzle pressure ratios near the design pressure ratio. It is expected that actual engine operations will result in a pressure ratio which gives an underexpanded jet. For this study, it was assumed that the noise output is very sensitive to the pressure ratio so that, for off-design operation, the full shock cell noise is included. The potential benefit of a convergent-divergent nozzle with careful pressure ratio control is then shown by comparing the case where there is pure jet mixing noise to the case when shock noise is included.

Fan noise (ref. 15), if uncontrolled, will dominate the total noise during landing. During takeoff, the jet mixing and shock cell noise are dominant, but unsuppressed fan noise is still significant. Specific examples of these situations will be shown later for each engine. As a basis for the parametric study, however, fan noise was neglected. It has been demonstrated that fan noise may be controlled by duct liners. Thus, if unsuppressed fan noise is a dominant source, then the aircraft nacelle would be modified to suppress this noise. The prediction of fan noise with duct liners in place requires specialized knowledge of details of the fan, inlet, and bypass ducts which are not available at this elementary level of system parametric study. Thus, the only alternatives are to include unsuppressed fan noise, to assume some arbitrary fan noise suppression, or to leave it out altogether. It has been elected here to leave it out altogether, recognizing that, when suppression in the proper amount is added, there will be some weight and cost penalty which is unaccounted for here. In addition, forward quadrant generated fan noise is assumed to be controlled by inlet choking.

Combustion noise was predicted using the method of reference 16. Specific examples will be shown later which indicate that this source may be safely neglected in a preliminary study.

Airframe noise was predicted using the method of reference 17. Although there is a valid question of the suitability of this method for predicting noise of the arrow-wing airframe, the levels were so low, when compared to other sources, that it was decided that this noise source could be neglected.

Atmospheric attenuation of the sound was predicted using the proposed ANSI standard method given in reference 18. The method predicts attenuations which are identical with the more familiar SAE ARP 866 method at the standard conditions used in the present study. The advantages of the proposed ANSI method are that it shows better agreement with data for nonstandard conditions, that the method is directly traceable to molecular relaxation phenomena, and that it is computationally simpler.

Ground effects include reflections and attenuation of sound. ANOPP implements a theory (refs. 19,20) which relates the noise received by a raised microphone (1.2 meters) over a ground surface, to the noise that would be present in the free-field. Application of the theory to this study has shown that there is

about a 4.5dB sideline attenuation, relative to the flyover, due to ground effects. This benefit is, however, very sensitive to elevation angle and decreases to about 1.5dB at 70° elevation angle. A very slow diminution of the effect then occurs as the elevation angle increases to 90° (overhead). The ground reflections cause the noise as measured by a standard 1.2 m microphone to be about 2.5dB above the free-field noise.

Sideline noise shielding effects are not included in the case reported here, because shielding occurs in a narrow shadow zone (about 11° from wing plane) and the maximum sideline perceived noise typically occurs in the range of 10° to 30° from the wing plane.

Economics Methodology

The computation of direct operating cost (DOC) is based primarily on the Air Transport Association (ATA) method as modified in reference 21 and includes algorithms for computing flight operations costs, maintenance costs, and depreciation costs. Assumptions and groundrules for economic calculations are the following:

- o Costs computed in 1976 U.S. dollars
- o All international flights with no subsonic cruise leg other than reserve requirements
- o Aircraft economic life of 16 years
- o Aircraft utilization of 3600 hours/year
- o Salvage value of 5 percent of aircraft and spares cost
- o Interest rate of 10 percent/year
- o Labor rate of \$9/hour
- o Overhead rate twice labor rate
- o Ground maneuver time as 10 minutes/flight
- o Passenger load factor was 100 percent
- o Configuration will be all tourist with no cargo other than baggage
- o Cabin attendants assigned as 1/35 seats
- o Fuel costs were \$0.42/U.S. gallons JET-A fuel
- o Aircraft spares are 10 percent of airframe cost

- o Engine spares are 30 percent of total engine cost
- o Aircraft costs are predicted based on a production run of 250 aircraft with development costs assumed to be equivalent to 60 aircraft

ANALYSIS OF RESULTS

Calculations of noise are presented herein for the standard certification point positions: centerline at 6482 m (3.5 n.mi.) from brake release, sideline at 648 m (0.35 n.mi.) at the point where the noise is the greatest, and in approach at 1852 m (1 n.mi.) from touchdown. Results are presented for three climb procedures. These include procedure 1 - constant velocity climb at $V_2 + 10$ knots climb without cutback over the flyover monitor (V_2 is the speed of the aircraft at the 10.7 m (35 ft) obstacle); procedure 2 - $V_2 + 10$ knots climb with cutback over the monitor; and procedure 3 - accelerating climb to 250 knot maximum if possible with cutback above 213 m (700 ft) altitude. All climb procedures are accomplished within FAR 36 procedures; that is, constant flap and throttle setting during climb prior to cutback over monitor. Thrust cutback occurs at 5943 m (19500 ft) from brake release except where limited by the 213 m (700 ft) altitude restriction.

Pratt and Whitney Variable Cycle Engine (PW-VSCE)

The Pratt and Whitney VSCE (ref. 22) is an advanced technology two-spool duct burning turbofan engine employing a concentric, annular (coannular) two-stream ejector nozzle. A flexible throttle schedule allows independent variation of two coannular exhaust streams. The unique scheduling capability provides the benefit of the coannular nozzle at takeoff, while at subsonic and supersonic conditions the exhaust velocities can be matched to provide a flat profile for high propulsive efficiencies. The cycle is a twin-spool configuration similar to a conventional turbofan. The low spool consists of an advanced technology, multistage, variable geometry fan and a low pressure turbine. The high spool consists of a variable geometry compressor driven by an advanced single-stage high-temperature turbine. The primary burner is a low-emissions, high efficiency combustor concept.

The output of the preliminary sizing and performance program is shown in figure 5. The results are generated by calculating performance for 35 separate aircraft or combinations of thrust/weight and wing loading (weight/wing area). The individual aircraft are scaled up in gross weight by adding fuel to meet the range goal of 8334 km (4500 n.mi.). For a given range and payload, there exists an optimum thrust/weight ratio and wing loading since large engines and wings represent significant structural weight penalties. The unconstrained optimum is not necessarily obtainable since other design constraints become more important. A major operational constraint is design takeoff field length. For the P&W variable cycle engine, the minimum weight constrained design (takeoff field length = 3810 m (12500 ft)) is quite close to the global optimum engine thrust/weight ratio. The constrained design at minimum takeoff weight is referred to as the "performance" airplane, or minimum cost aircraft. One can choose any

combination of thrust/weight and wing loading between the fuel volume limit line, and wing area limit line and still perform the mission at heavier weight. Noise calculations were performed initially on a matrix of fifteen aircraft within the permissible bounds of wing loading. Results indicated that the incremental noise reduction from the performance aircraft did not change significantly with wing loading. Therefore, to reduce the scope of the study, oversized engine aircraft were generated at constant wing loading.

The "performance" airplane is sized for a takeoff field length of 3810 m (12500 ft) with the optimum flap setting (30°) at maximum power setting for the engine. Reduced flap or power setting cannot be used by the performance aircraft in takeoff since field lengths greater than 3810 m (12500 ft) would result.

Figure 6 shows the climb profiles for the performance sized aircraft for the three climb procedures analyzed. Altitudes over the flyover monitor are between 213 and 305 m (700 and 1000 feet) depending on the procedure. The low altitudes over the flyover monitor results in the high noise levels shown in figure 7, which shows the noise levels (PNLT) as a function of inlet angle at the flyover point. Figure 8 shows a breakdown of the noise sources for the $V_2 + 10$ knot climb with no cutback, indicating jet and shock cell noise dominate the results.

However, aircraft sized with oversized engines have some flexibility to change both flap and throttle setting in takeoff and remain within the takeoff field length constraint. Therefore, flap setting and throttle setting emerge as variables. These aircraft can operate at maximum throttle and 30° flap resulting in shortest field length, lowest flyover noise, and increased sideline noise as shown in figure 9, which includes jet and shock noise only. With this takeoff operation, flyover noise decreases rapidly with engine oversizing but sideline levels remain high. Approach noise decreases with engine oversizing due to matching at a lower part power throttle position.

The aircraft with oversized engine can be operated at a derated throttle setting and 20° flap setting, such that the takeoff field length is extended to 3810 m (12500 ft). The variable cycle engine provides maximum airflow at reduced thrust levels, with a resulting decrease in jet velocity. The lower flap setting provides a high lift-to-drag ratio after cutback at the flyover monitor. The derated thrust takeoff operation shows reductions in both sideline and flyover with engine oversizing, as shown in figure 10, for jet and shock noise only. During the course of this study, the derated thrust takeoff provided the lowest traded values of takeoff noise.

Figure 11 shows results for the derated thrust takeoff considering jet noise only. Controlling shock cell noise would significantly reduce the noise at the observer positions.

The previous results are summarized in figure 12. Cost expressed as relative DOC and relative fuel burned is shown as a function of traded noise level. A 20 percent increase in engine size provides 4dB reduction in noise for a 4 percent penalty in DOC and a 1 percent increase in fuel burned. Beyond the first oversized engine point, the costs become increasingly large for a small reduction in noise level.

The effect on noise of operating the performance airplane on shorter stage lengths has been determined. They are shown in figure 13 for maximum power takeoff case, 30° flap settings, and the $V_2 + 10$ knot climb path with cutback. The off-loaded fuel for shorter ranges results in lower takeoff weight and higher thrust-to-weight ratios, reducing field length and providing higher altitudes over the flyover monitor. Flyover noise is therefore significantly reduced. Since the takeoff jet velocities and landing weights do not change significantly, sideline and approach noise remain approximately the same as the design range case.

Noise Sensitivity to Design Constraints

The three major design constraints which have been assumed in this study are: payload = 273 passengers, range = 8334 km (4500 n.mi.), and takeoff field length = 3810 m (12500 ft). Of interest is the effect on noise of changing these design constraints. The study was conducted with the performance aircraft sized with PW-VSCE engine.

The results are shown in figure 14 for all performance aircraft sized and flown with maximum power takeoff, 30° flap setting, and $V_2 + 10$ knot climb procedure with cutback. Takeoff noise levels are insensitive to design payload and range. When resizing the aircraft, the thrust-to-weight ratio and wing loading do not change appreciably from the design case. The jet velocities do not change and, therefore, the noise varies as a weak function of engine airflow. The approach noise increases for the shorter range design, since the ratio of landing weight to gross weight increases resulting in higher power settings and higher noise.

The flyover noise is reduced when the aircraft is sized for a shorter field length. The increased thrust-to-weight ratio required for a short field provides steeper climb gradients and higher altitudes over the flyover monitor. The higher, slower climb has an adverse effect on sideline noise. The design takeoff field length of 3810 m (12500 ft) was maintained as a design constraint for this study, since it provides the lowest takeoff weight and operating costs to perform the mission.

General Electric Variable Cycle Engine (GE-DBE)

The General Electric double bypass engine (ref. 23) is a low bypass ratio two-spool afterburning turbofan engine with a translating shroud plug nozzle. The fan is divided into two separate elements. These elements are designed so that engine air can be bypassed downstream of each element. The engine is operated at takeoff in such a manner as to achieve the inverted velocity profile for coannular noise relief.

Aircraft sizing results using the GE-DBE are shown in figure 15. The takeoff field length line was established for the optimum partial afterburning power setting which corresponded to the minimum takeoff gross weight to perform the mission. As is shown, the performance airplane is close to the unconstrained optimum. As was the case with the previous engine, the performance airplane and

two aircraft with oversized engines were chosen for takeoff and noise analysis. Climb paths for the performance airplane are shown in figure 16. Altitudes over the flyover monitor vary from 213 to 305 m (700 to 1000 ft), depending on the climb procedure. The flyover noise level as a function of observer inlet angle for the various climb paths is shown in figure 17. Noise component breakdown is shown in figure 18, indicating the importance of uncontrolled shock noise. Noise levels versus takeoff gross weight are shown in figure 19 which includes jet and shock noise. Jet noise only results are shown in figure 20. As was the case with the previous engine, different combinations of flap settings and throttle settings for the oversized engine aircraft were calculated. The lowest traded noise levels were achieved with the derated thrust takeoff for 3810 m (12500 ft) field length and 20° flap settings. The cost and fuel sensitivity to traded noise is shown in figure 21. Engine oversizing beyond the first oversized aircraft provides no reduction in noise for large increases in cost and fuel consumption.

Pratt & Whitney Low Bypass Ratio Engine (PW-LBE)

The third engine studied is an advanced, nonaugmented, twin-spool turbofan engine with a bypass ratio which varies from 0.4 to 0.6. The primary and bypass streams are assumed to be mixed, and the exhaust gases are discharged through a common, variable area ejector nozzle. The engine was fitted with an advanced technology mechanical suppressor. Proprietary performance and acoustic data were provided by McDonnell-Douglas Corporation. Nominal mechanical suppressor characteristics were: $\Delta = 7\text{dB}$ suppression, 5 percent thrust loss when deployed, and 590 kg (1300 lb) per engine weight penalty for a full sized engine of 409 kg/sec (900 lb/sec). The suppressor weight was scaled proportional to engine airflow in the aircraft sizing process.

Since the PW-LBE has no afterburner, sizing of the engine was performed differently than for the previous two engines, as shown in figure 22. The performance aircraft is not sized on the takeoff field length line. The performance aircraft is the appropriate size corresponding to a 1.52 m/sec (300 ft/min) rate of climb at cruise. Two additional configurations have been studied as shown with larger engine sizes to establish the cost noise trade. Climb profiles for the three takeoff procedures are in figure 23, for the performance aircraft. The altitudes over the flyover monitor are higher than previous engine cases, since the aircraft engine is slightly oversized for cruise rate-of-climb margin. Noise levels for the various climb paths as a function of inlet angle at the flyover monitor is shown in figure 24. Noise component breakdown is shown in figure 25. The prediction method for the suppressors does not permit a separation of the noise into jet mixing and shock components as in the previous cases. As was the case with the previous engines studied, the configurations with oversized engines were studied with different takeoff flap settings and throttle setting. The lowest traded takeoff noise levels were achieved for a derated thrust takeoff for 3810 m (12500 ft) field length and 20° flaps.

Noise levels at the three observer positions as a function of takeoff gross weight is shown in figure 26 for the three climb paths. Dramatic

reductions in flyover noise is achieved with cutback for oversized engines. The cost/noise trade is presented in figure 27. A modest degree of additional engine oversizing is required to meet 108 EPNdB traded noise levels.

No consideration has been given in this study to risk associated with the suppressor hardware performing to airline maintenance standards in the high temperature environment and no additional maintenance cost has been included in the economic calculations.

Analysis of the unsuppressed LBE engine has been included. The engine was studied in the same manner as the previous engines, including aircraft sizing, takeoff and landing performance, economics, and ANOPP noise analysis. Penalties associated with the mechanical suppressor were removed, i.e., thrust loss and suppressor weight.

The aircraft sizing chart for this engine is shown in figure 28. As was the case with the suppressed LBE, the "performance" aircraft is sized by cruise rate of climb limit of 300 feet per minute. The performance aircraft has a takeoff gross weight of 725,000 pounds compared to 738,000 pounds for the suppressed LBE aircraft. Analysis was conducted on two additional aircraft with oversized engines as indicated. The degree of engine oversizing was 14 percent and 35 percent.

Takeoff climb paths were generated for the three procedures previously studied, that is: $V_2 + 10$ knot without cutback, $V_2 + 10$ knot with cutback and acceleration with cutback. Oversized engines were analyzed for maximum power takeoffs and derated thrust takeoffs resulting in 12,500 foot field lengths, and 20- and 30-degree flap settings. The derated thrust takeoffs with 20° flaps provided the lowest average takeoff noise. Noise levels as a function of takeoff gross weight are shown in figures 29 and 30 for jet plus shock noise and jet noise only.

The cost and fuel sensitivity curves are shown in figure 31. Including uncontrolled shock cell noise increases the traded noise level by 1-2 EPNdB.

CONCLUSIONS AND RECOMMENDATIONS

A preliminary analytical study has been completed at the Langley Research Center to determine noise levels and direct operating costs for a Mach 2.7 design supersonic cruise concept. The study was based upon data generated in the SCR program to date which represents identified, but not proven technology. The noise levels generated were based on current FAR 36 noise certification procedures (constant flap setting and constant throttle setting prior to cutback over flyover monitor).

The results of the study indicate that the maximum performance airplanes which were sized for takeoff field length, have noise levels from 110 to 118 EPNdB. Engine oversizing of 14-24 percent relative to the minimum size engine needed to perform the mission would have traded noise levels of 108-114 EPNdB with up to 3 percent increase in direct operating cost. Further engine oversizing would provide negligible reductions in noise, but introduced even larger penalties in cost and fuel consumption.

The preliminary study results are not believed complete enough to determine what the optimal aircraft and engine combination would be to achieve any specified noise level for the particular aircraft mission, nor to establish precise tradeoff relationships among all the variables which must be considered. Additional studies, as a minimum those outlined below, are needed before definitive statements of feasible noise levels for future advanced design supersonic cruise aircraft can be made.

1. Determine the potential for noise reduction by incorporating advanced operating procedures for the various engine cycles.

2. Determine the practical limits for shock cell noise control.

3. Determine the feasibility of engine operation at very low power settings, required for decelerating approaches.

4. Determine the noise reduction and feasibility of incorporating simple mechanical suppressors on variable cycle engines.

5. Determine the cost/noise sensitivity to increasing fan size (varying bypass ratio), rather than scaling the entire engine as assumed in this study.

6. Provide an iteration with engine manufacturers to provide engine operating characteristics to maximize coannular noise benefit consistent with best aircraft operating conditions for low noise.

7. Conduct study of industry-generated aircraft concepts to determine uncertainties in noise and performance for different aircraft characteristics.

The above studies are important to the basic understanding of achievable noise levels and their design and cost implications. In addition, however, it must be recognized that additional empirical data is needed to refine both noise reduction features and other operating characteristics of all engine cycles under study. Data on variable cycle engine design parameters, coannular nozzle inverted flow noise reduction and advanced mechanical suppressors is urgently needed to reduce the present uncertainties in all studies of the type reported herein.

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SCAR

ADVANCED SUPERSONIC CRUISE AIRCRAFT CONFIGURATIONS

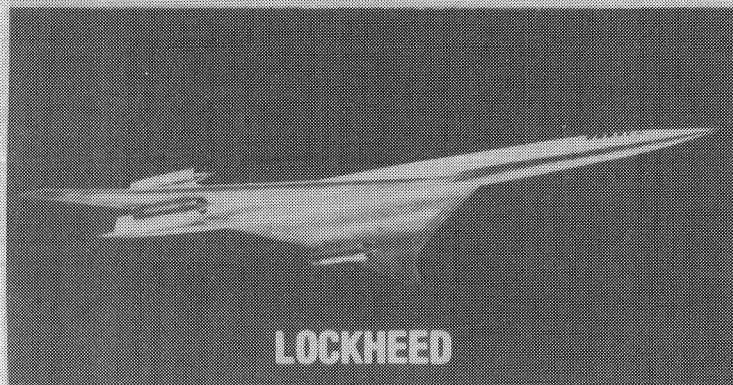
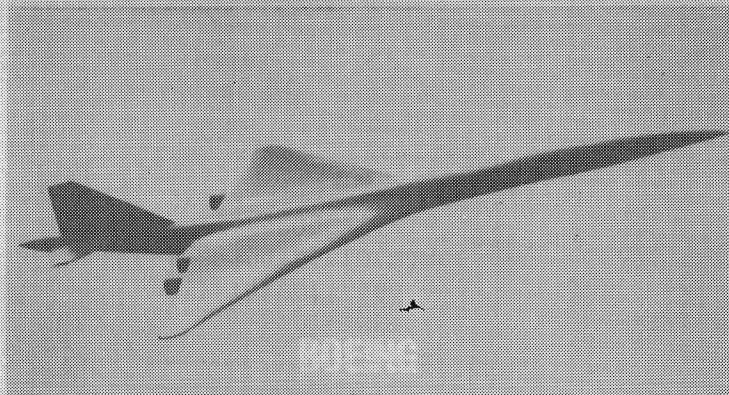


Figure 1. - Supersonic cruise concepts under study.

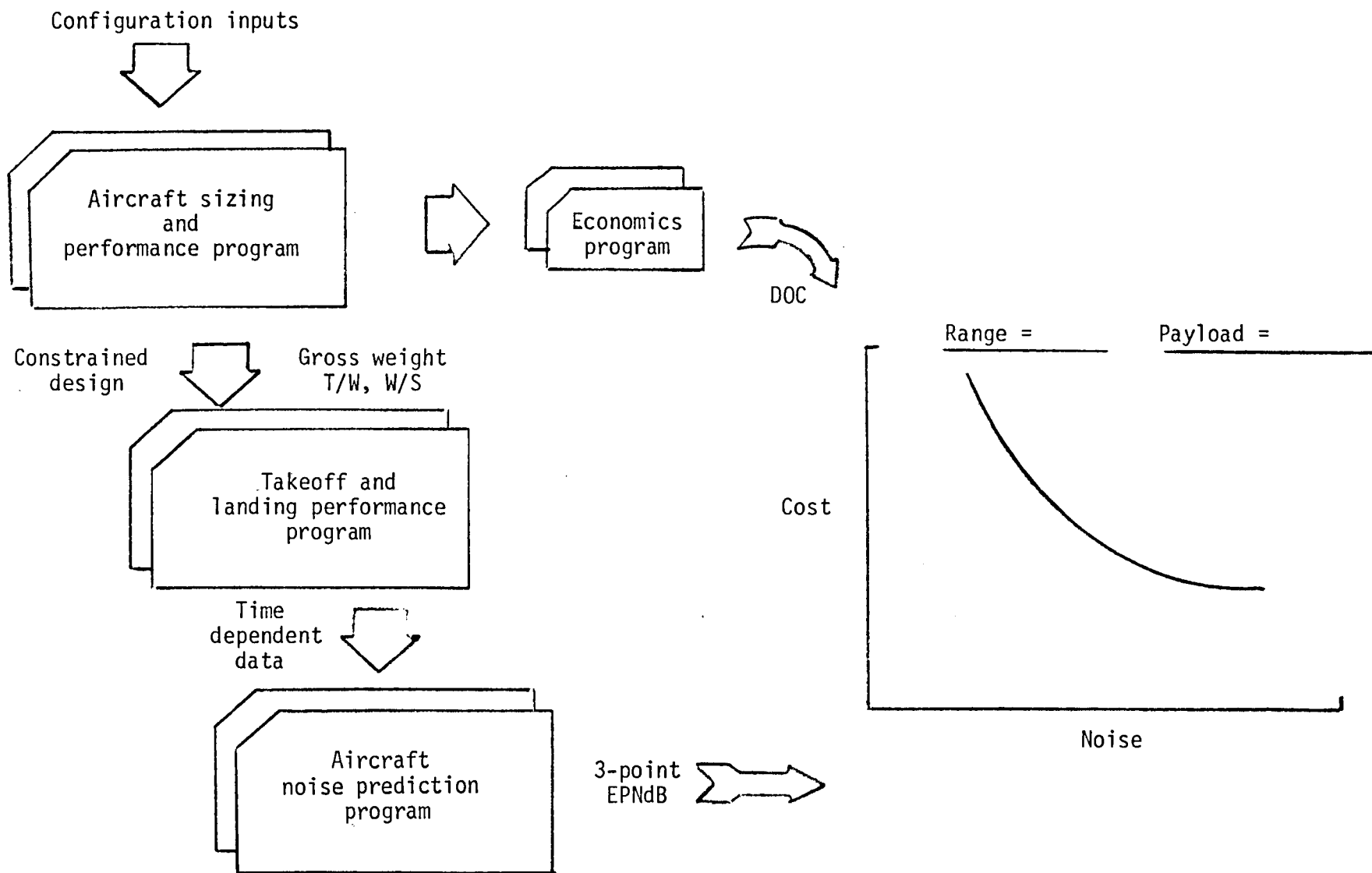


Figure 2. - Study approach.

NOTE: DIMENSIONS SHOWN IN METERS
WITH FEET IN PARENTHESIS

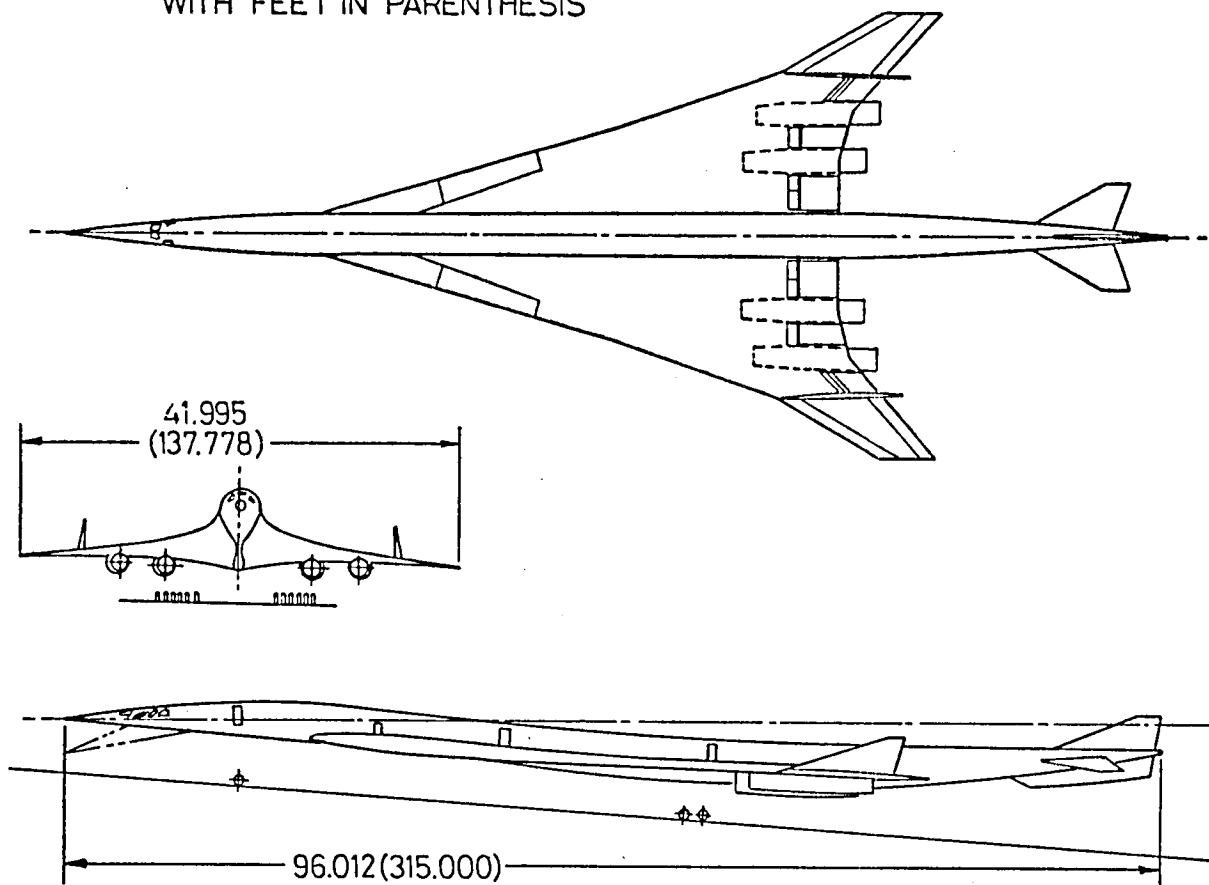


Figure 3. - General arrangement of the airplane.

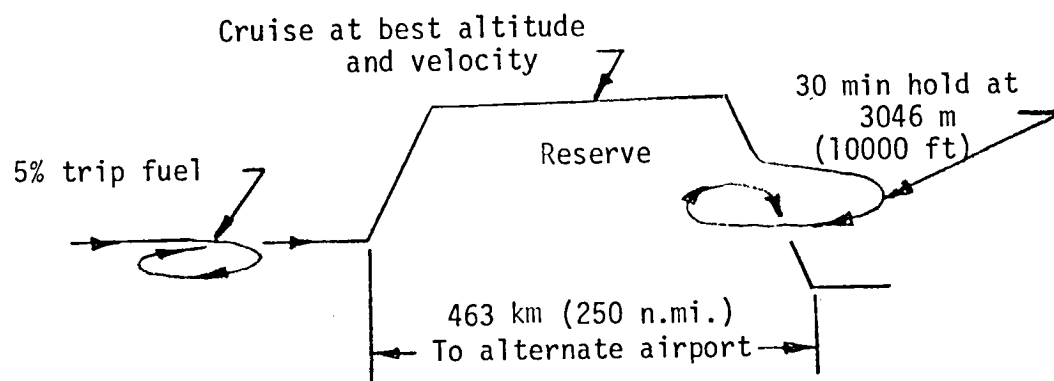
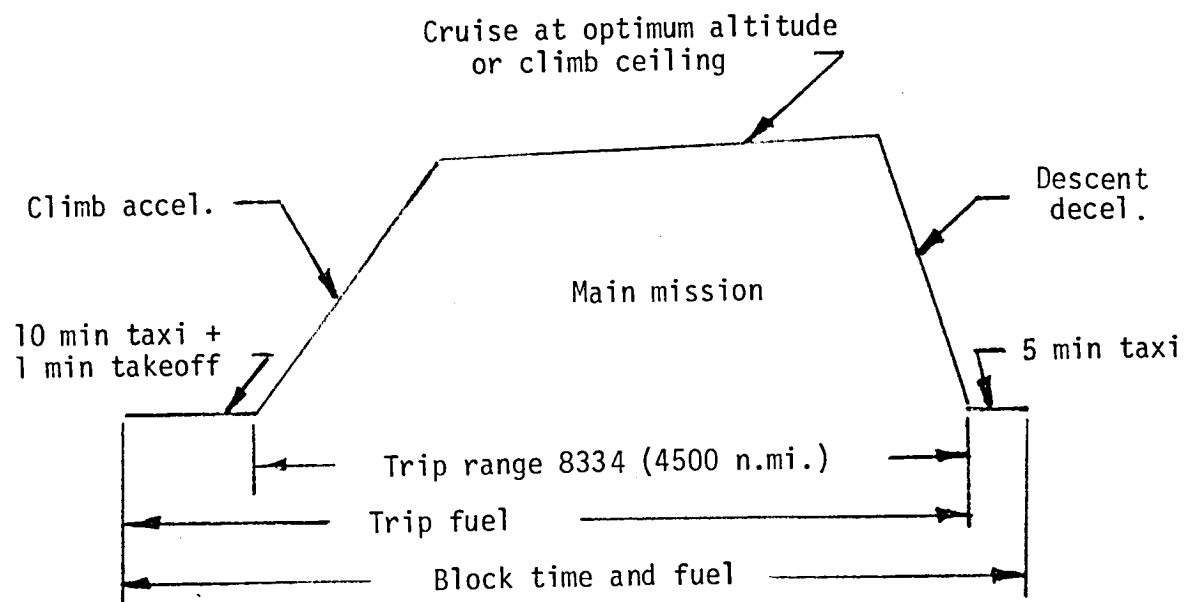


Figure 4. - Mission profile.

o Range = 8334 km (4500 n.mi.)

o 273 passengers

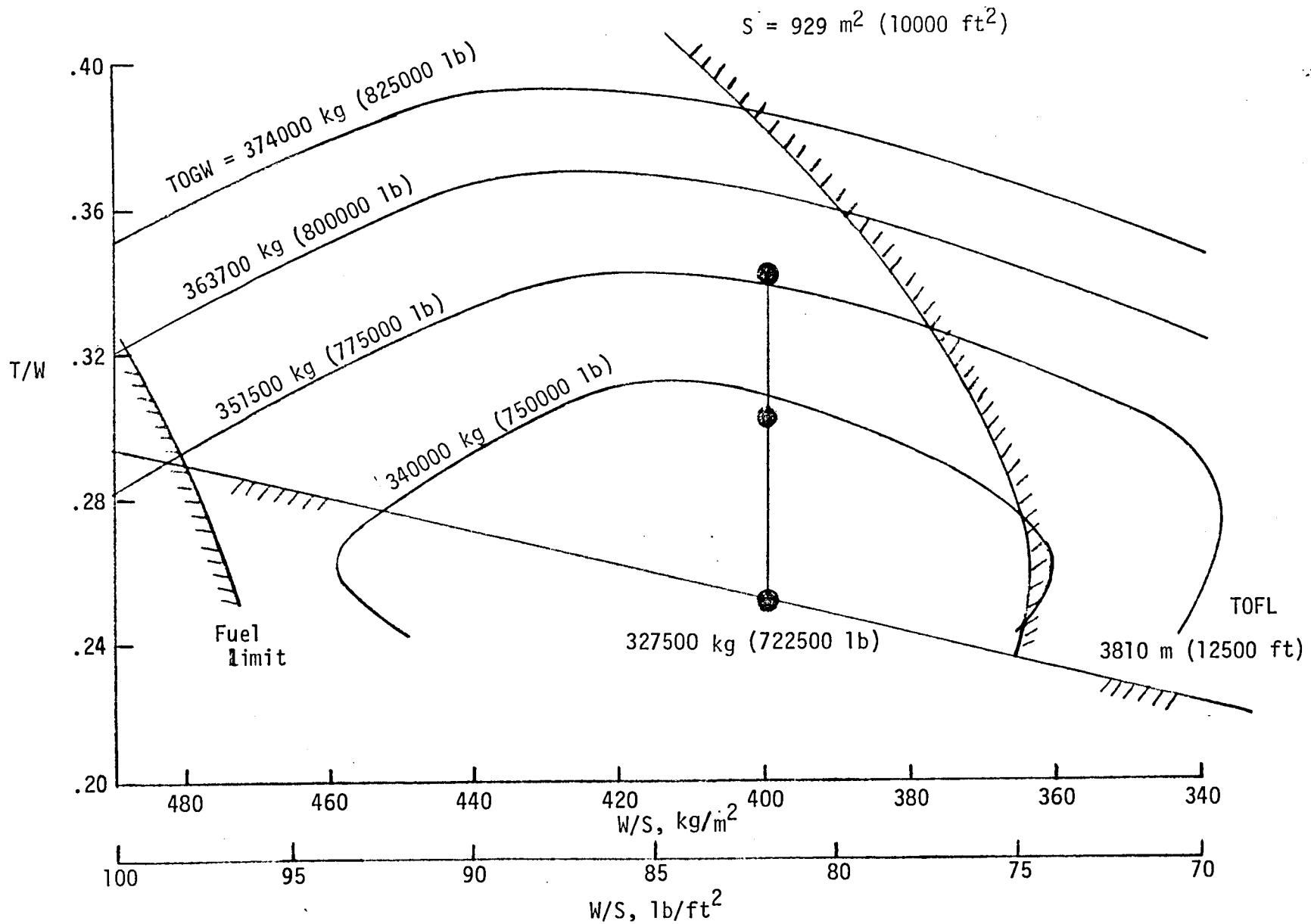


Figure 5. - Aircraft sizing chart for PW-VSCE engine.

- o Range = 8334 km (4500 n.mi.)
- o 273 passengers
- o TOFL = 3810 m (12500 ft)
- o Performance airplane
- o TOGW = 327700 kg (722500 lbs)

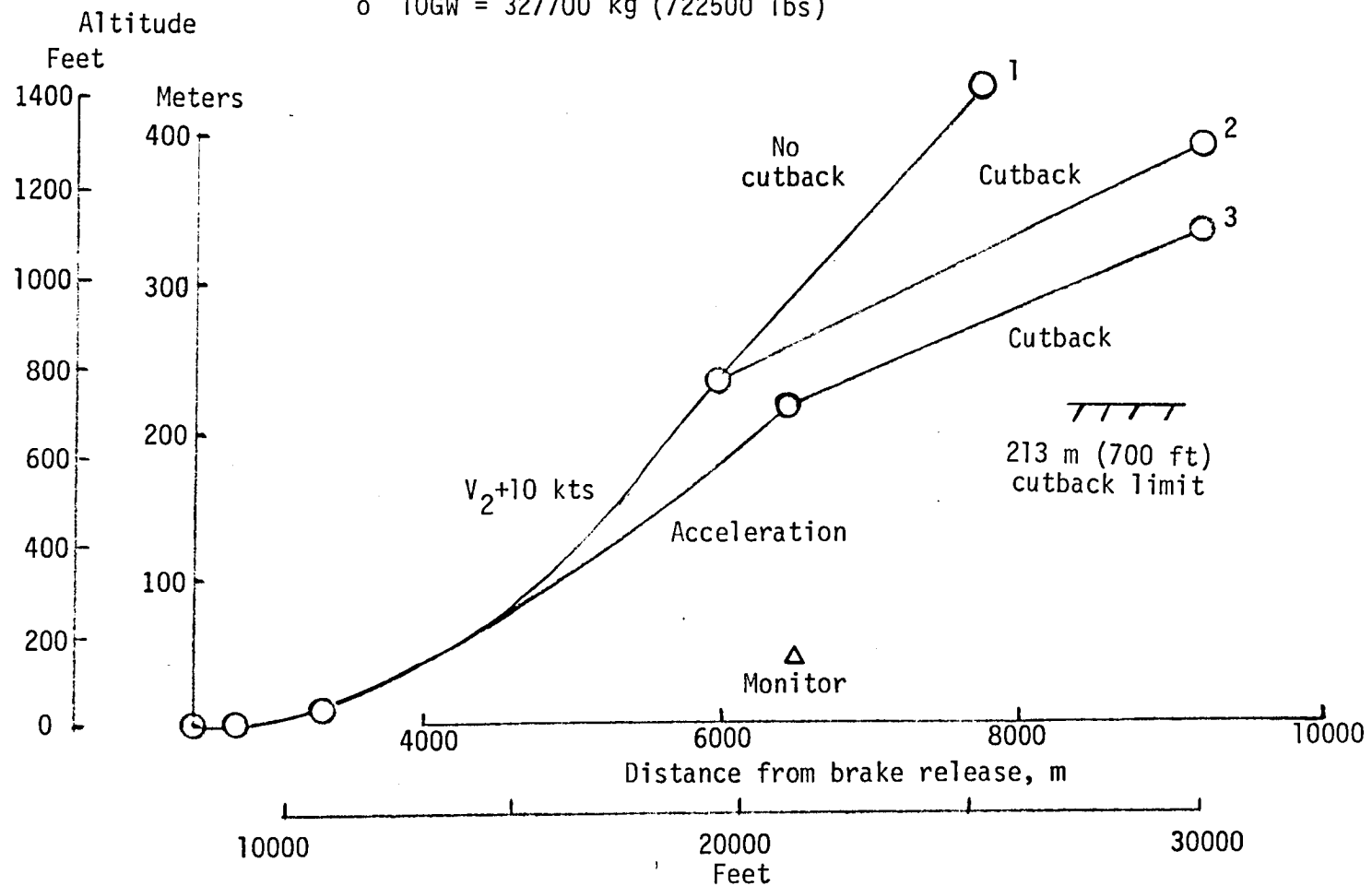


Figure 6. - Climb profiles - aircraft with PW VSCE engine.

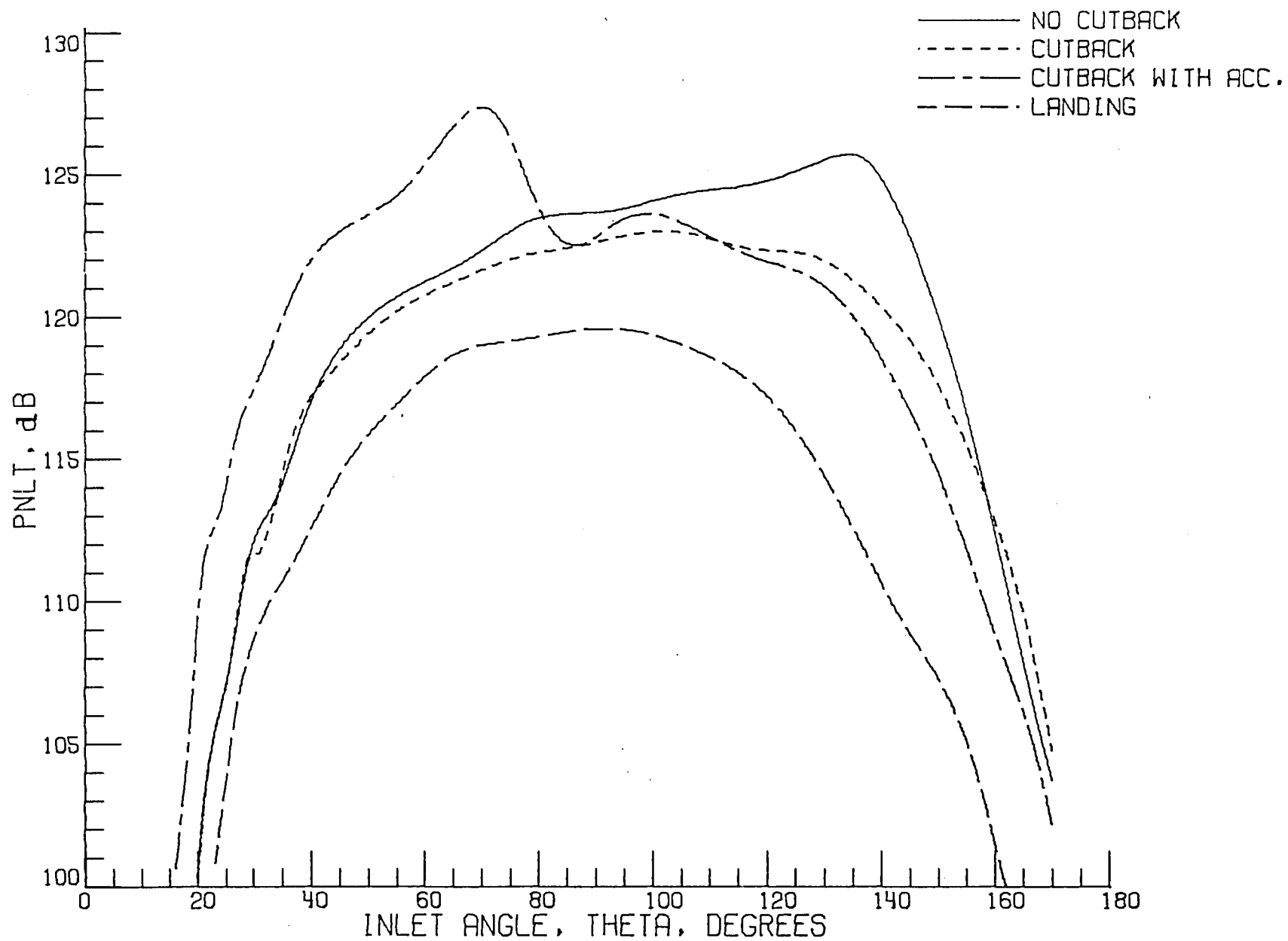


Figure 7.- Noise characteristics - performance aircraft with PW-VSCE engine.

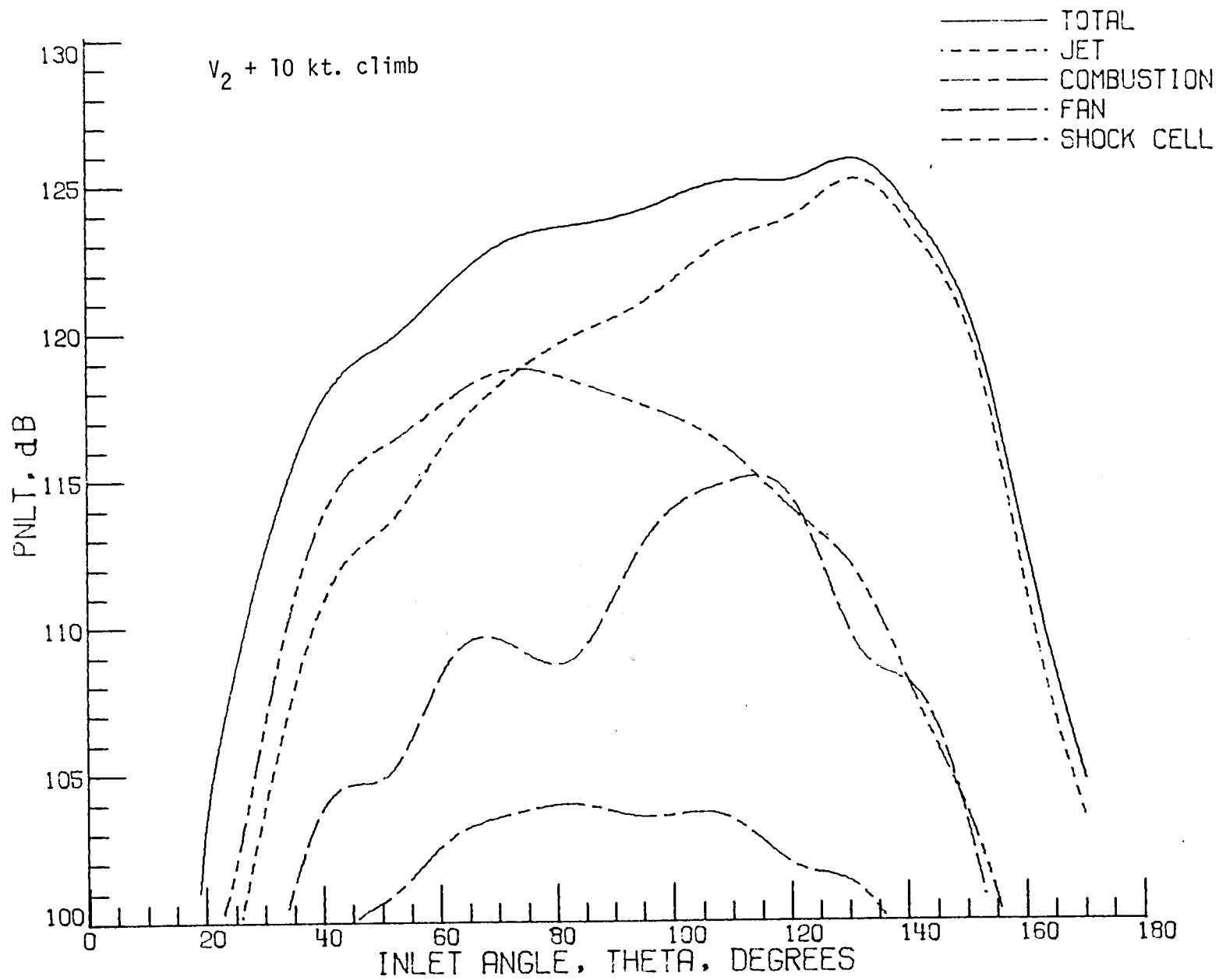


Figure 8.- Noise component breakdown - performance aircraft with PW-VSCE engine.

- o 8334 km (4500 n.mi.)
- o 273 passengers
- o Maximum power T.O. - 30° flaps
- o Jet and shock noise

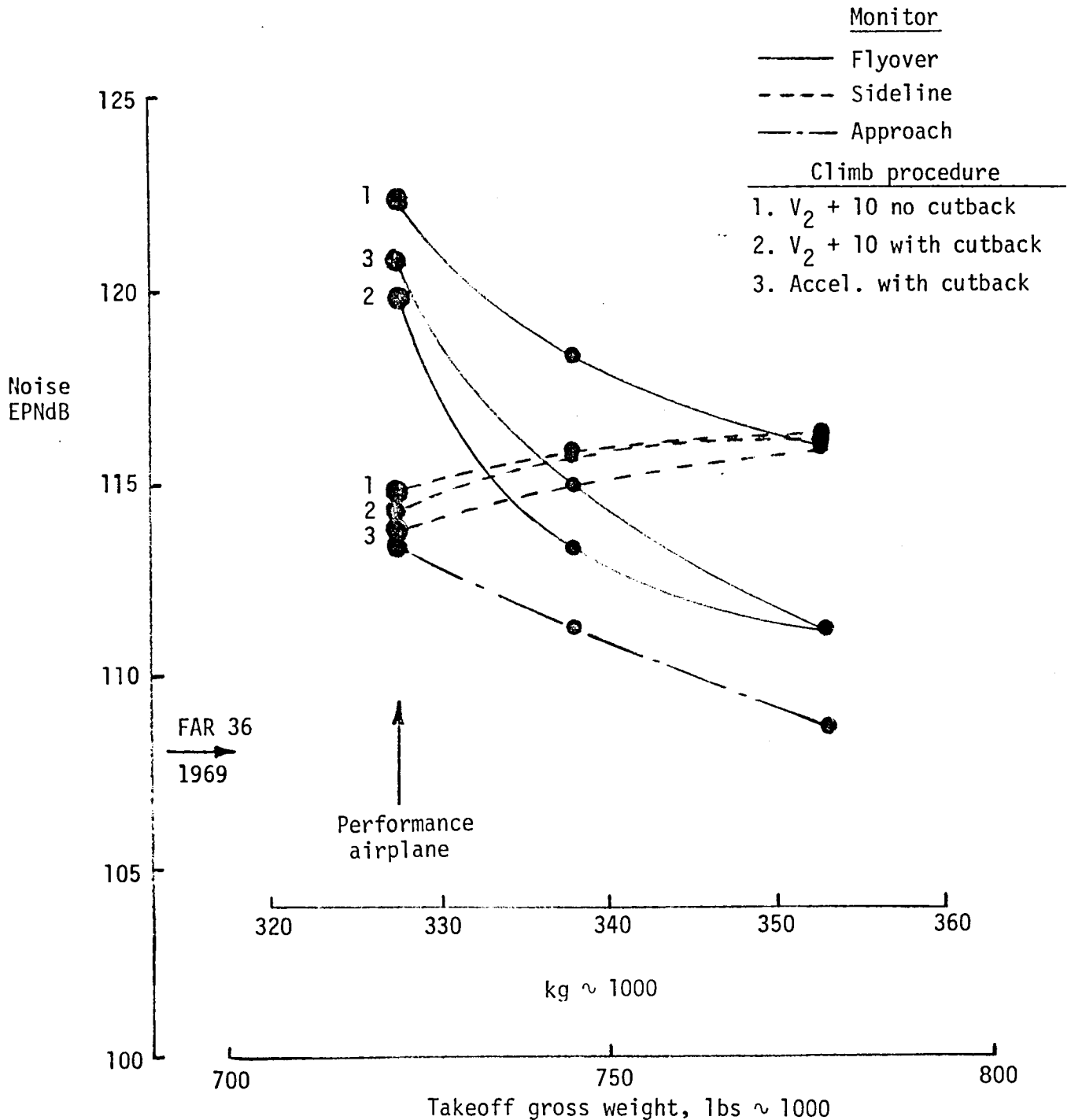
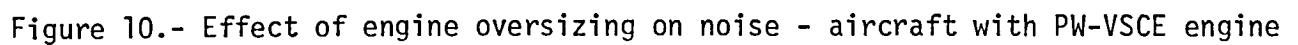


Figure 9. - Effect of engine oversizing on noise - aircraft with PW-VSCE engine.

- Monitor
- Flyover
- Sideline
- Approach
- Climb procedure
1. $V_2 + 10$ no cutback
 2. $V_2 + 10$ with cutback
 3. Accel. with cutback



- o Range = 8334 km (4500 n.mi.)
- o 273 passengers
- o Derated power for 3810 m (12500 ft)
- o Jet noise only

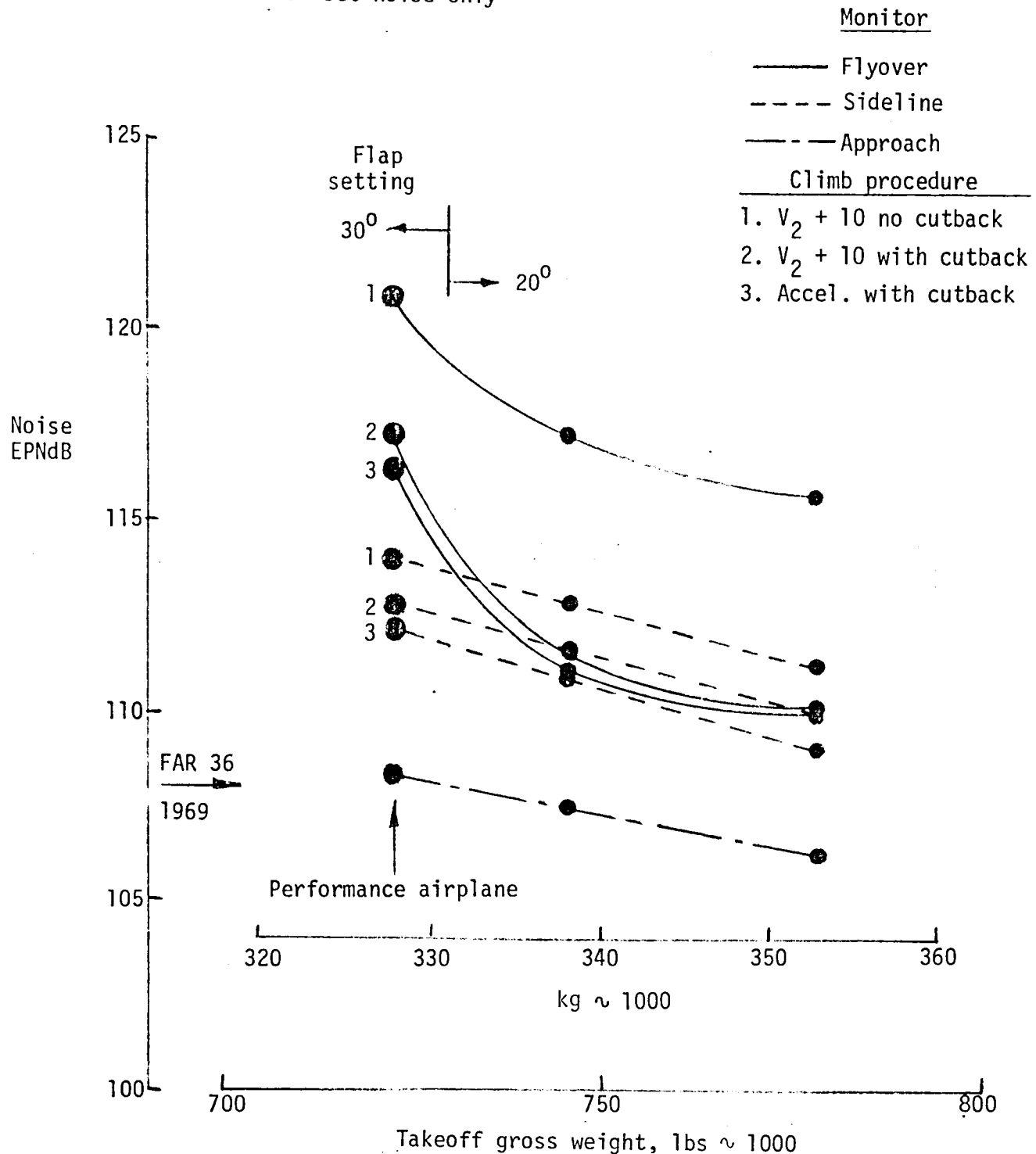


Figure 11. - Effect of engine oversizing on noise - aircraft with PW-VSCE engine.

- o Range = 8334 km (4500 n.mi.)
- o 273 passengers
- o TOFL = 3810 m (12500 ft)

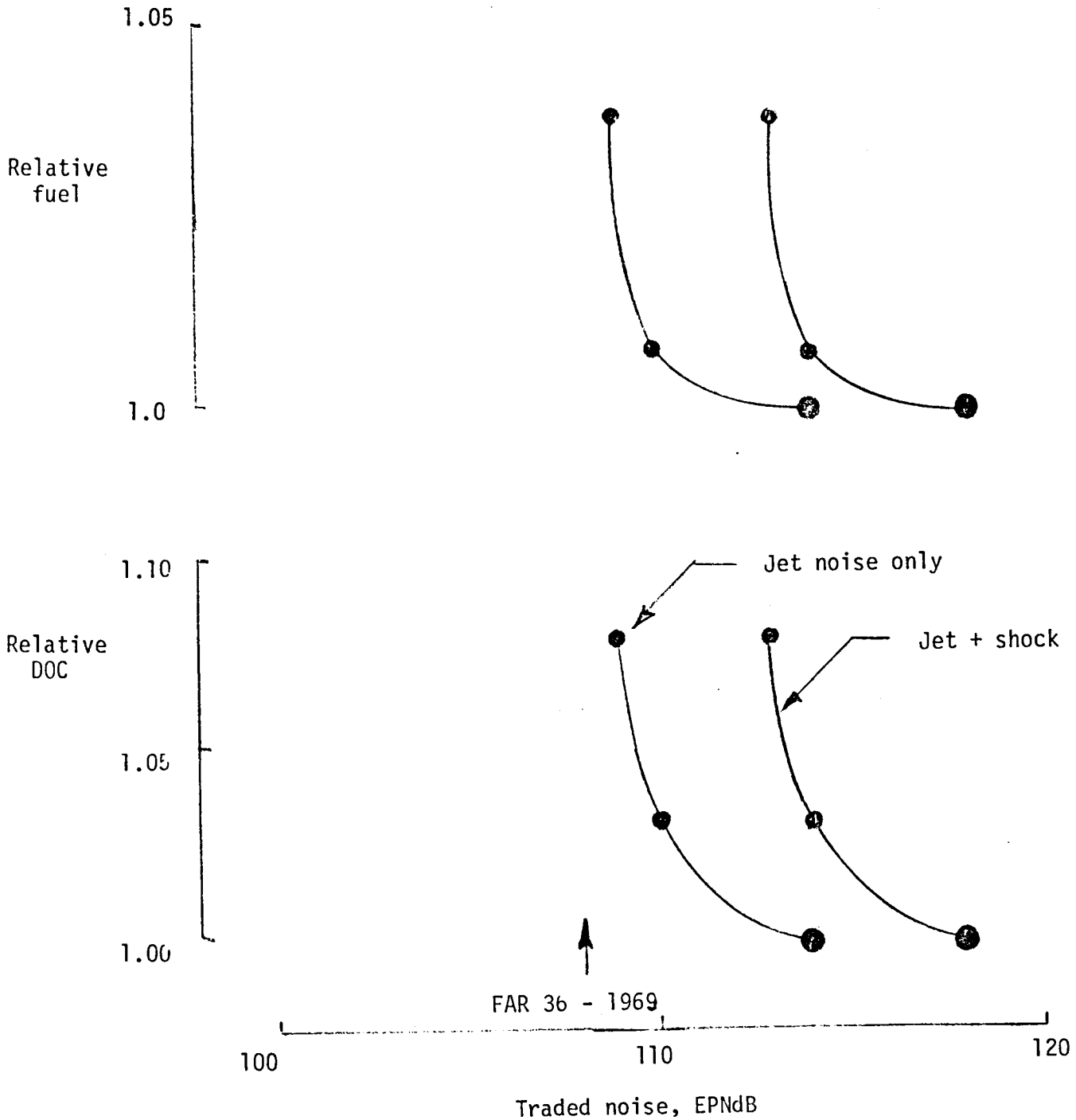


Figure 12. - Effect of traded noise level on cost and fuel - aircraft with PW-VSCE engine.

Max. power T.O. 30° flaps
 $V_2 + 10$ kt climb with cutback

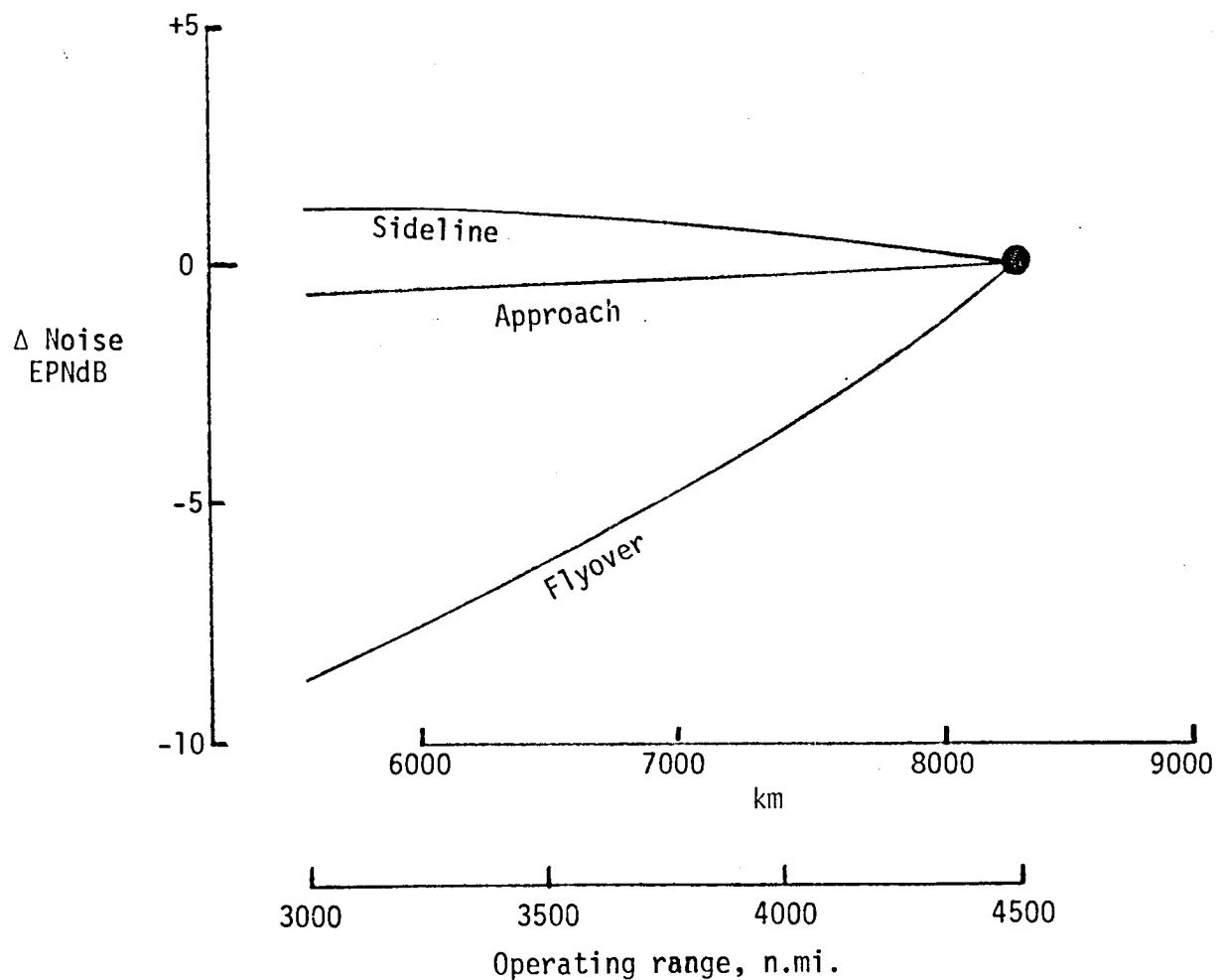


Figure 13.- Effect of operating range on noise - performance aircraft with PW-VSCE engine.

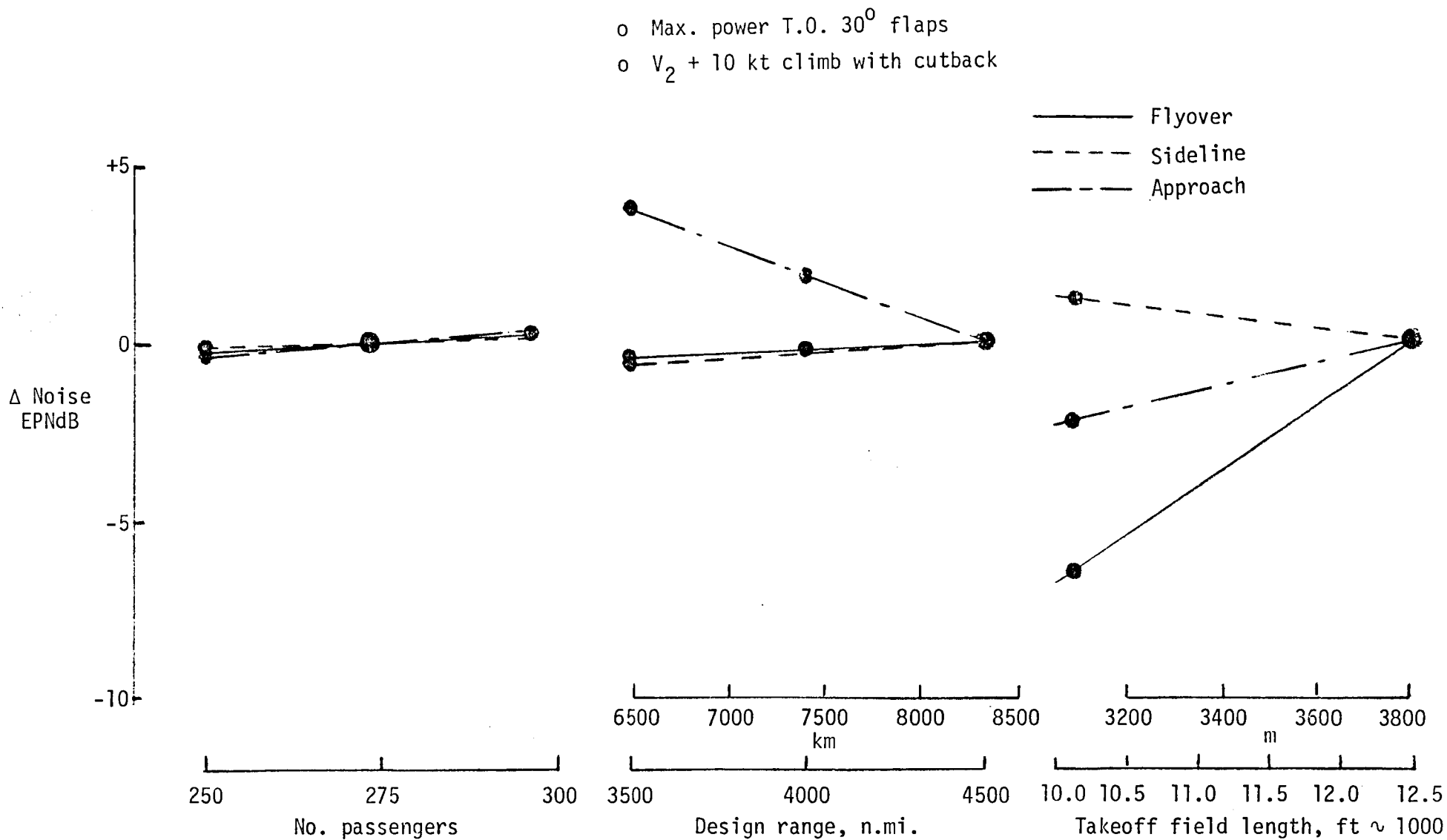


Figure 14. - Effect of design constraints on noise - aircraft with PW-VSCE engine.

- o Range = 8334 km (4500 n.mi.)
- o 273 passengers

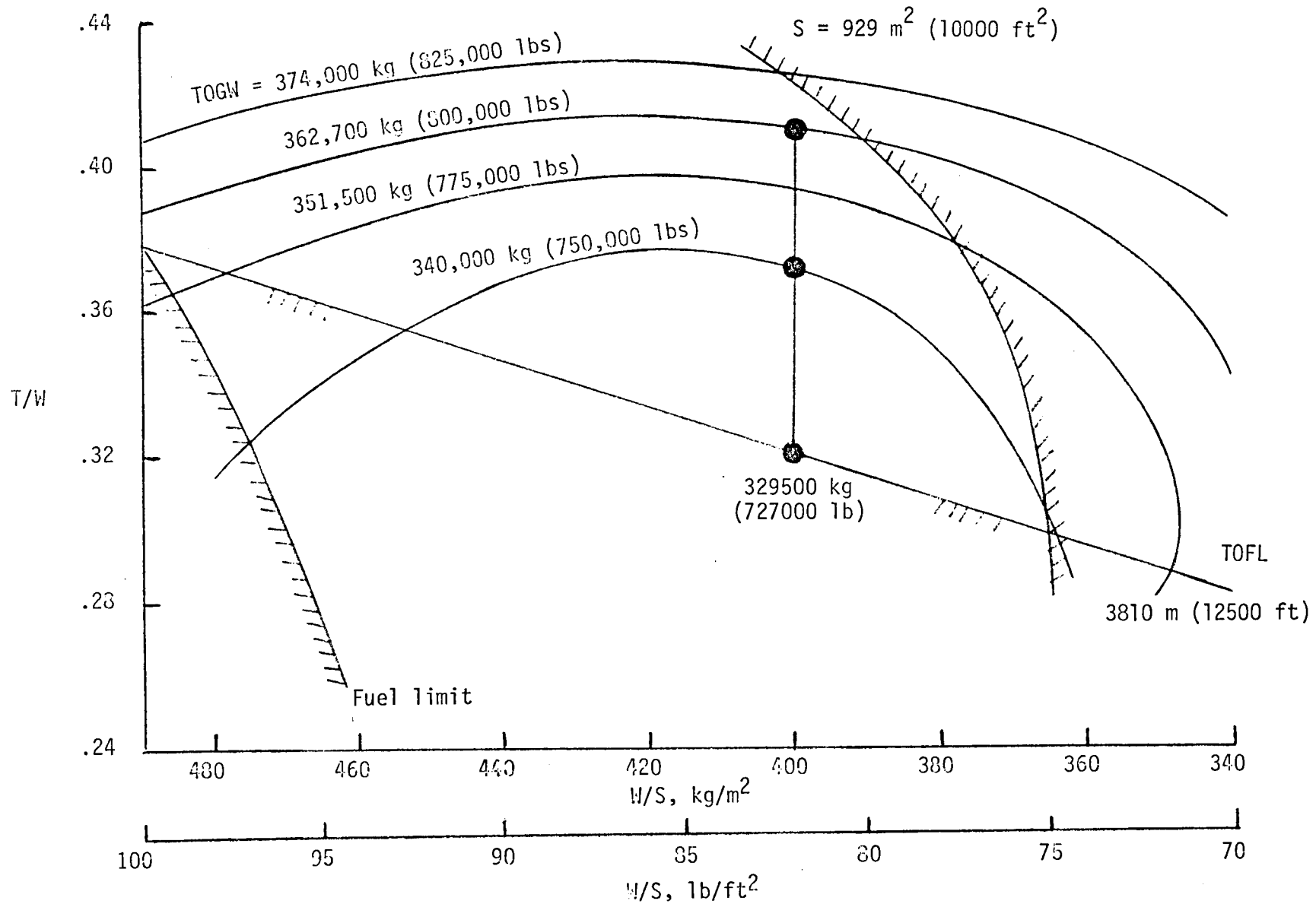


Figure 15.- Aircraft sizing chart for GE-DBE engine

- o Range = 8334 km (4500 n.mi.)
- o 273 passengers
- o TOFL = 3810 m (12500 ft)
- o Performance airplane
- o TOGW = 329500 kg (727000 lbs)

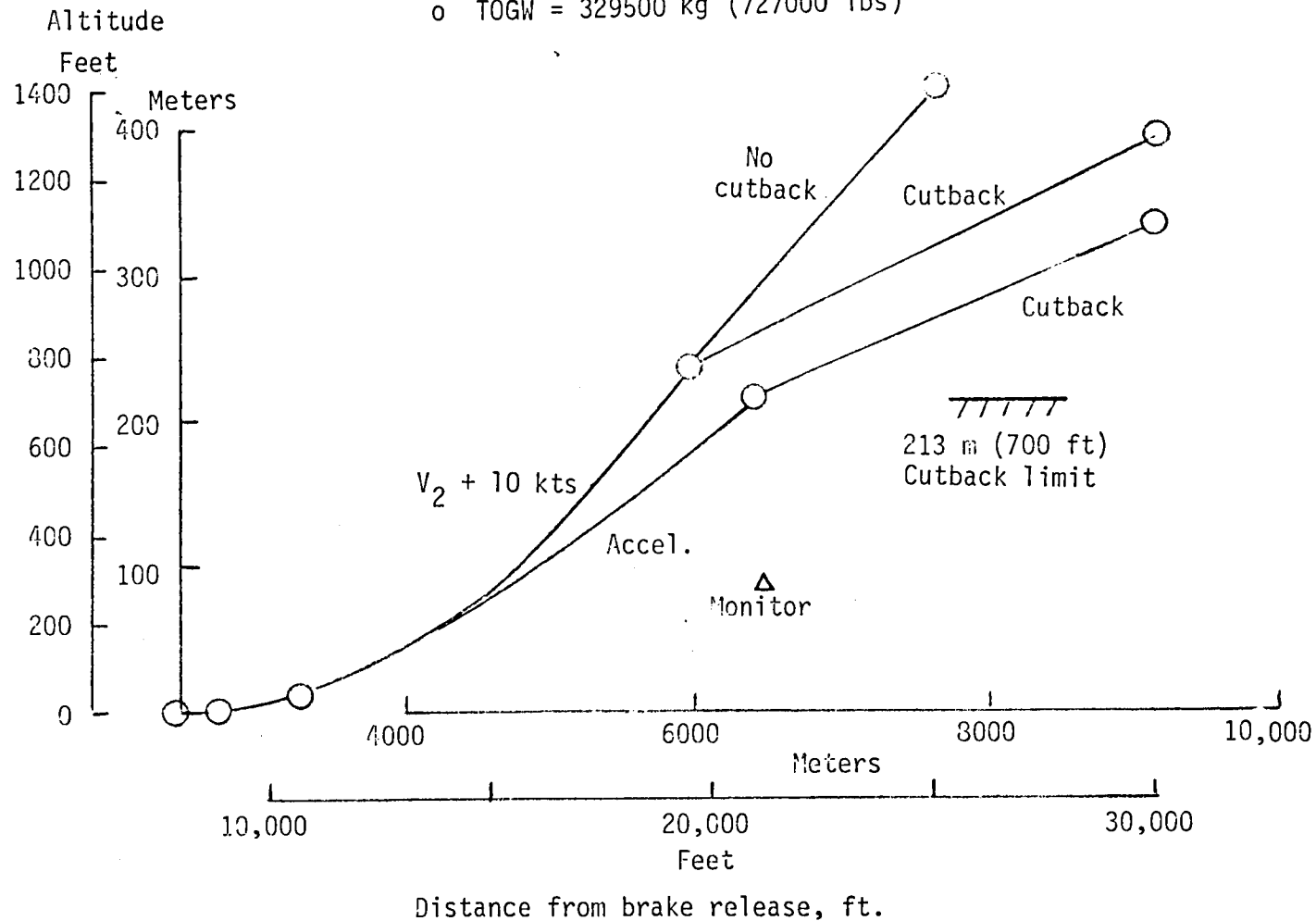


Figure 16.- Climb profiles - Aircraft with GE-DBE engine

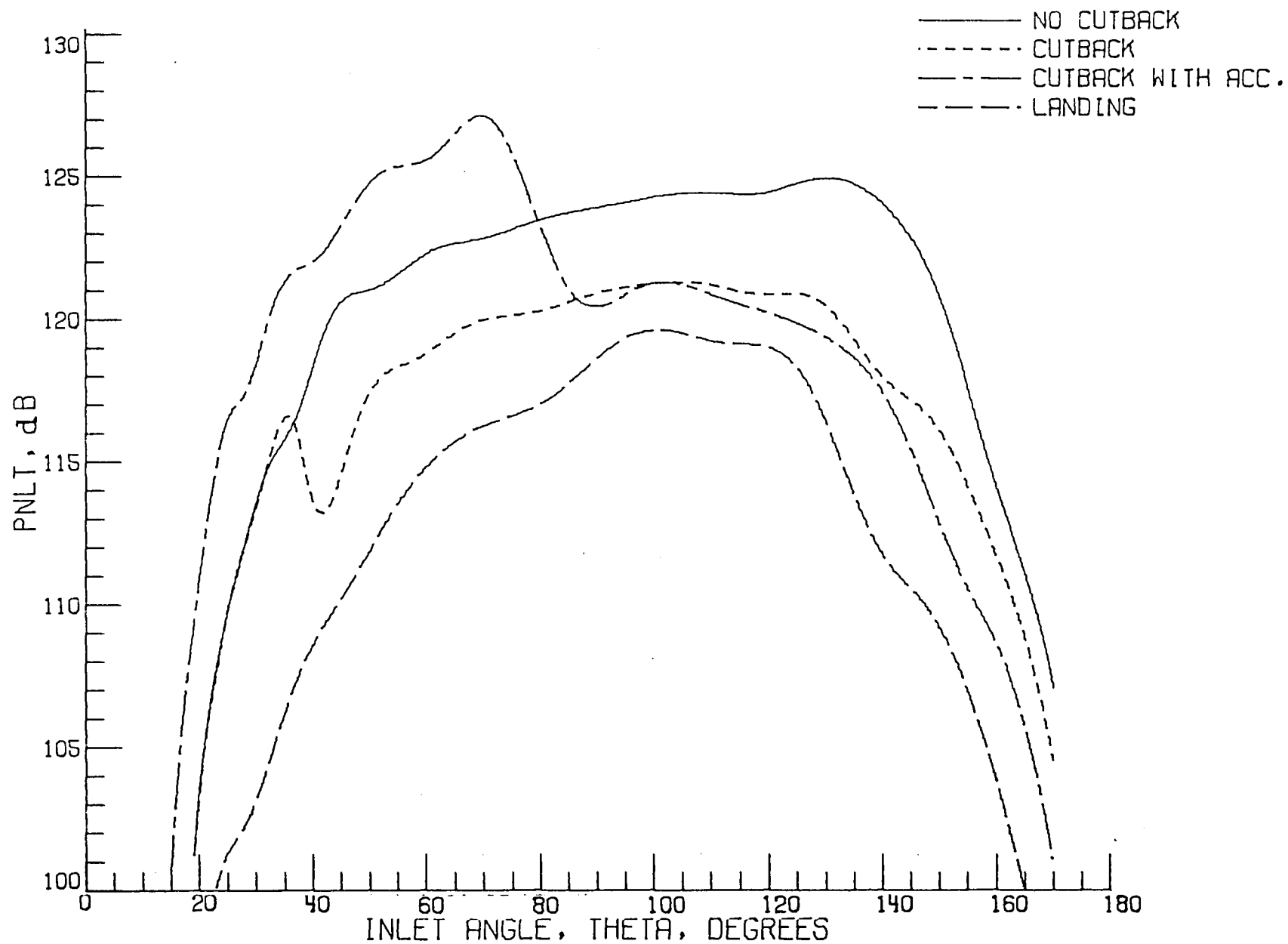


Figure 17.- Noise characteristics - performance aircraft with GE-DBE engine.

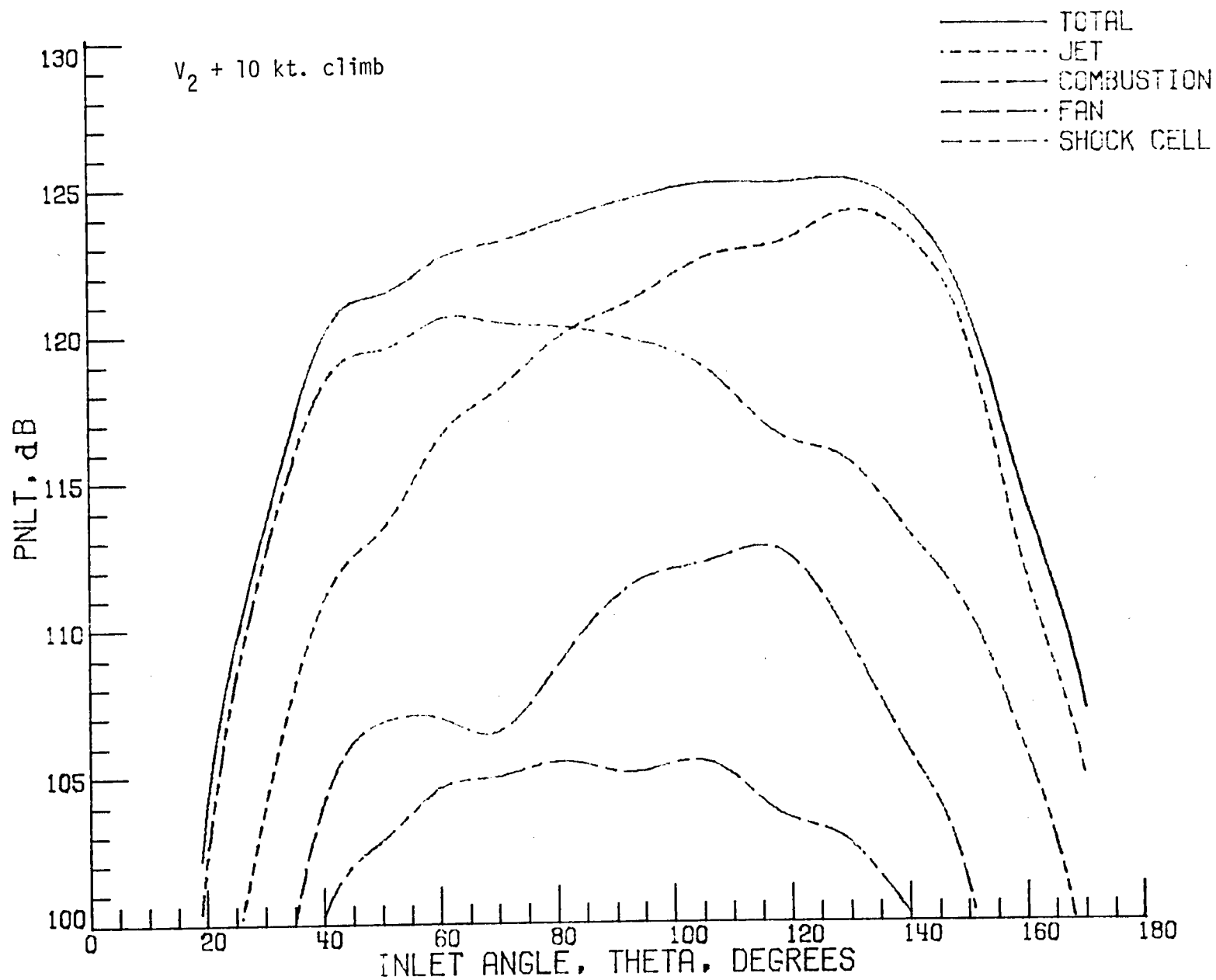


Figure 18.- Noise component breakdown - performance aircraft with GE-DBE engine.

- o Range = 8334 km (4500 n.mi.)
- o 273 passengers
- o Derated power for 3810 m (12500 ft)
- o Jet and shock noise

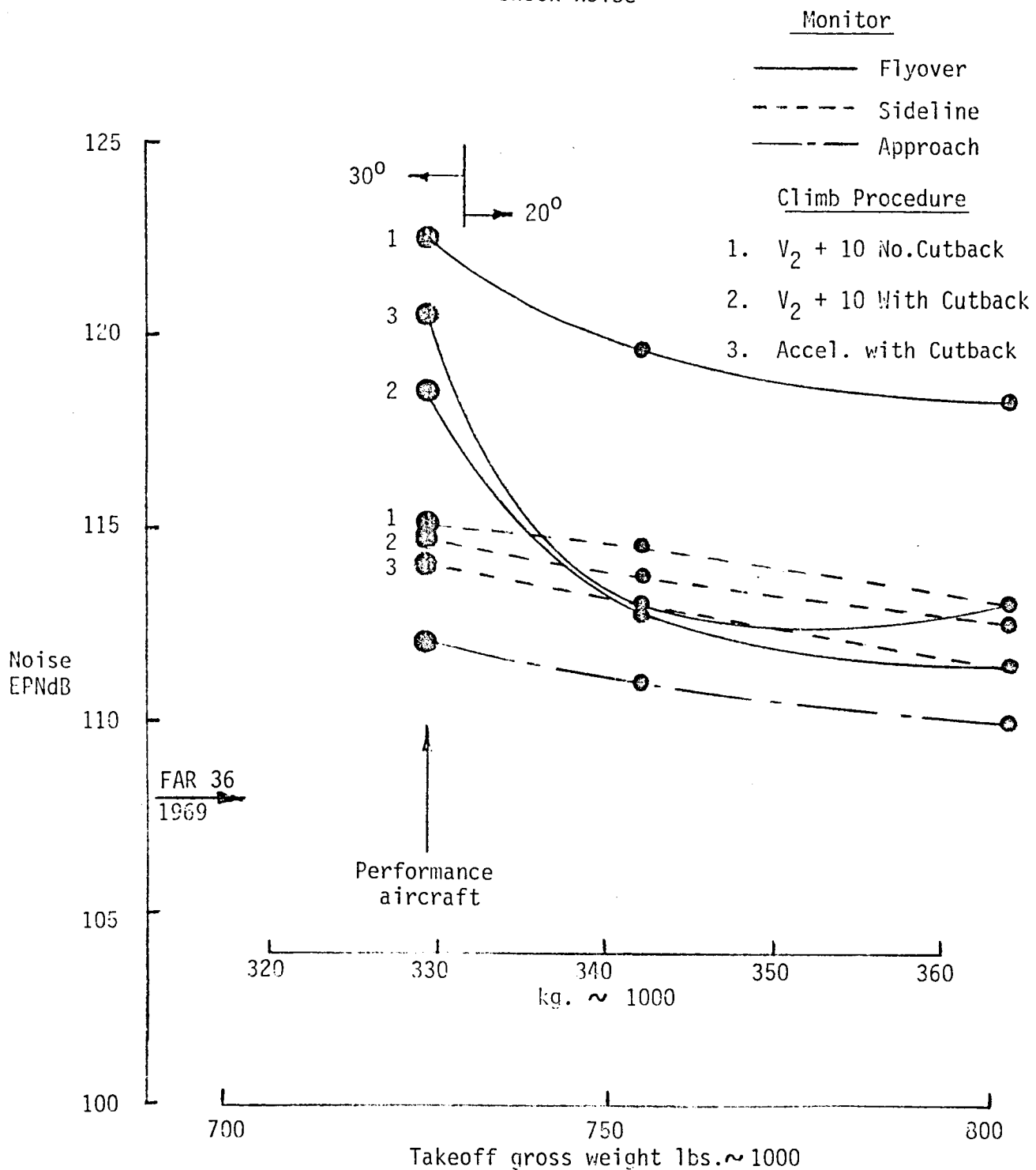


Figure 19.- Effect of engine oversizing on noise - Aircraft with GE-DBE engine.

- o Range = 8334 km (4500 n.mi.)
- o 273 passengers
- o Derated power for 3810 m (12500 ft)
- o Jet noise only

Monitor

- Flyover
- - - Sideline
- · - Approach

Climb Procedure

1. $V_2 + 10$ no cutback
2. $V_2 + 10$ with cutback
3. Accel. with cutback

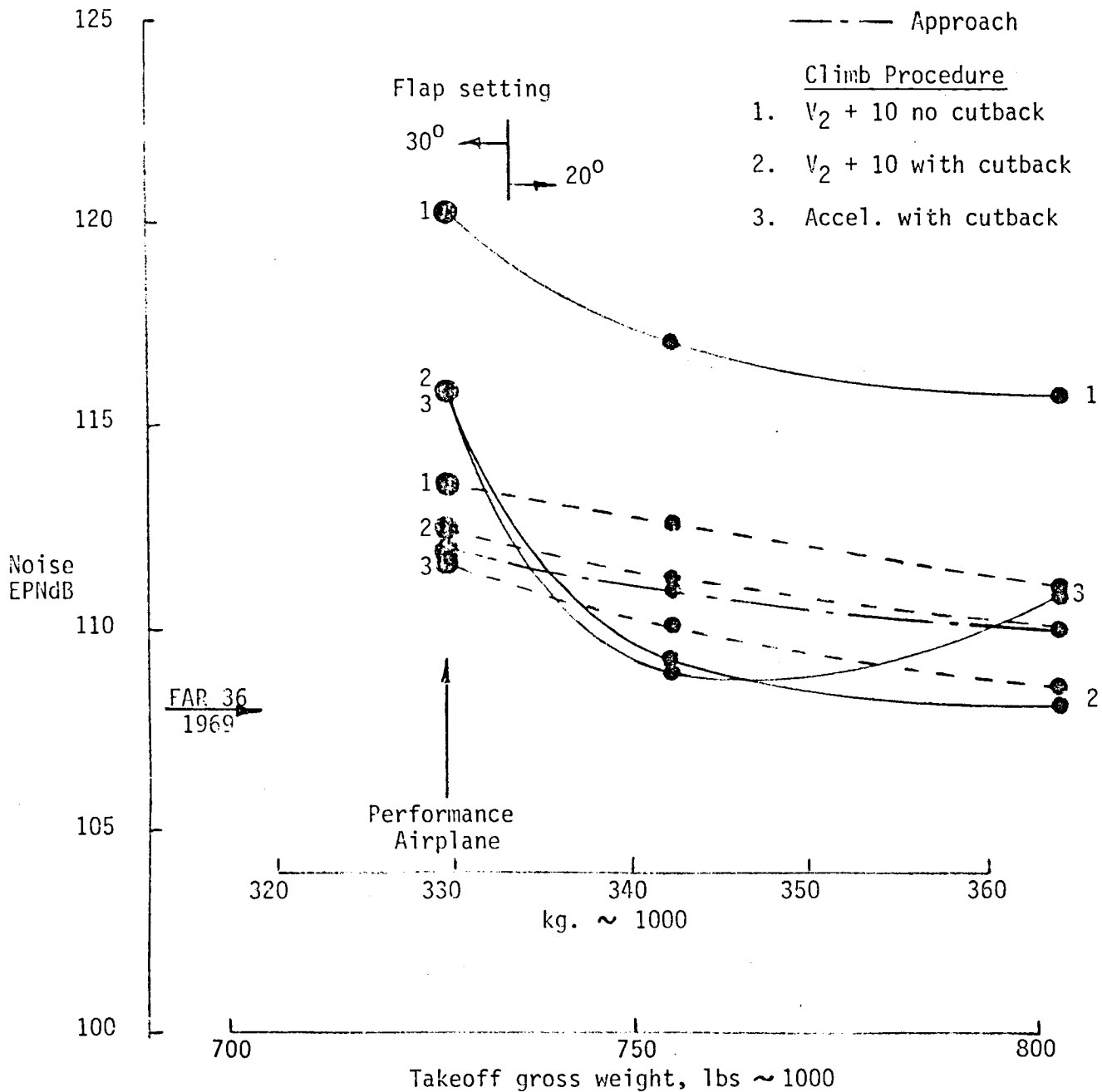


Figure 20.- Effect of engine oversizing on noise - Aircraft with GE-DRE engine.

- o Range = 8334 km (4500 n.mi.)
- o 273 passengers
- o TOFL = 3810 m (12500 ft)

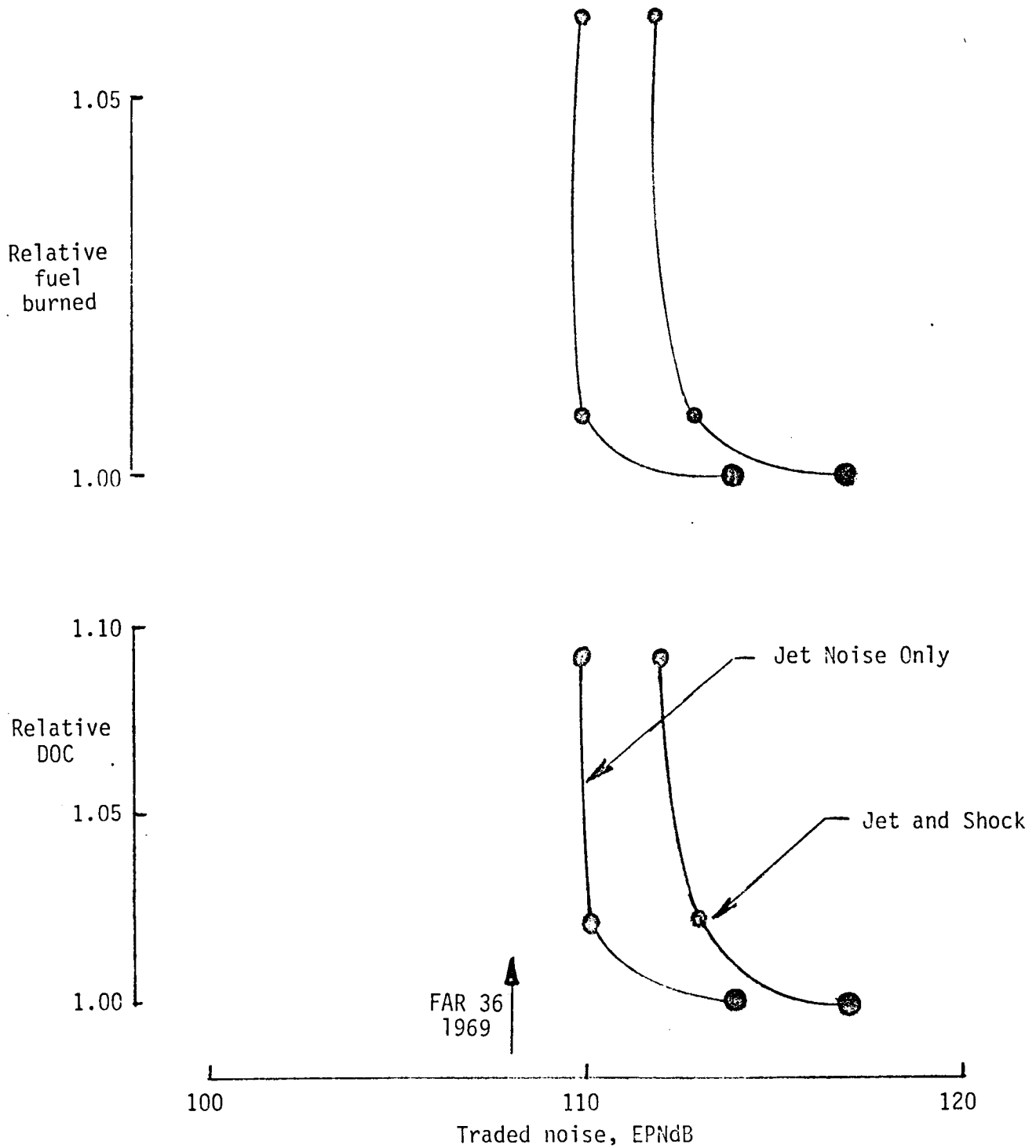


Figure 21.- Effect of traded noise on cost and fuel - Aircraft with GE-DBE engine.

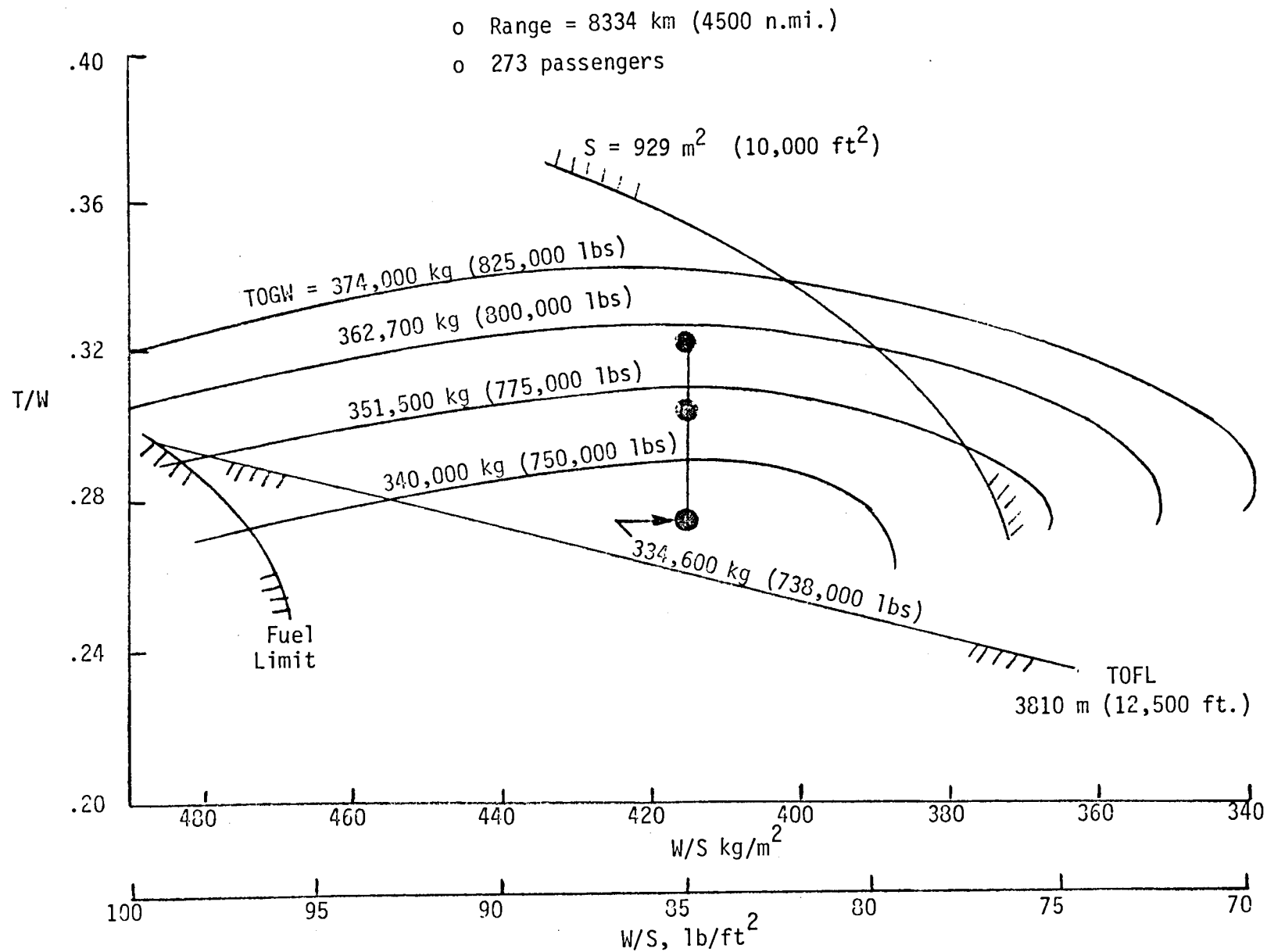


Figure 22.- Aircraft sizing chart for PW-LBE engine with mechanical suppressor

- o Range = 8334 km (4500 n.mi.)
- o 273 passengers
- o Performance aircraft
- o TOGW = 334600 (738000 lbs)

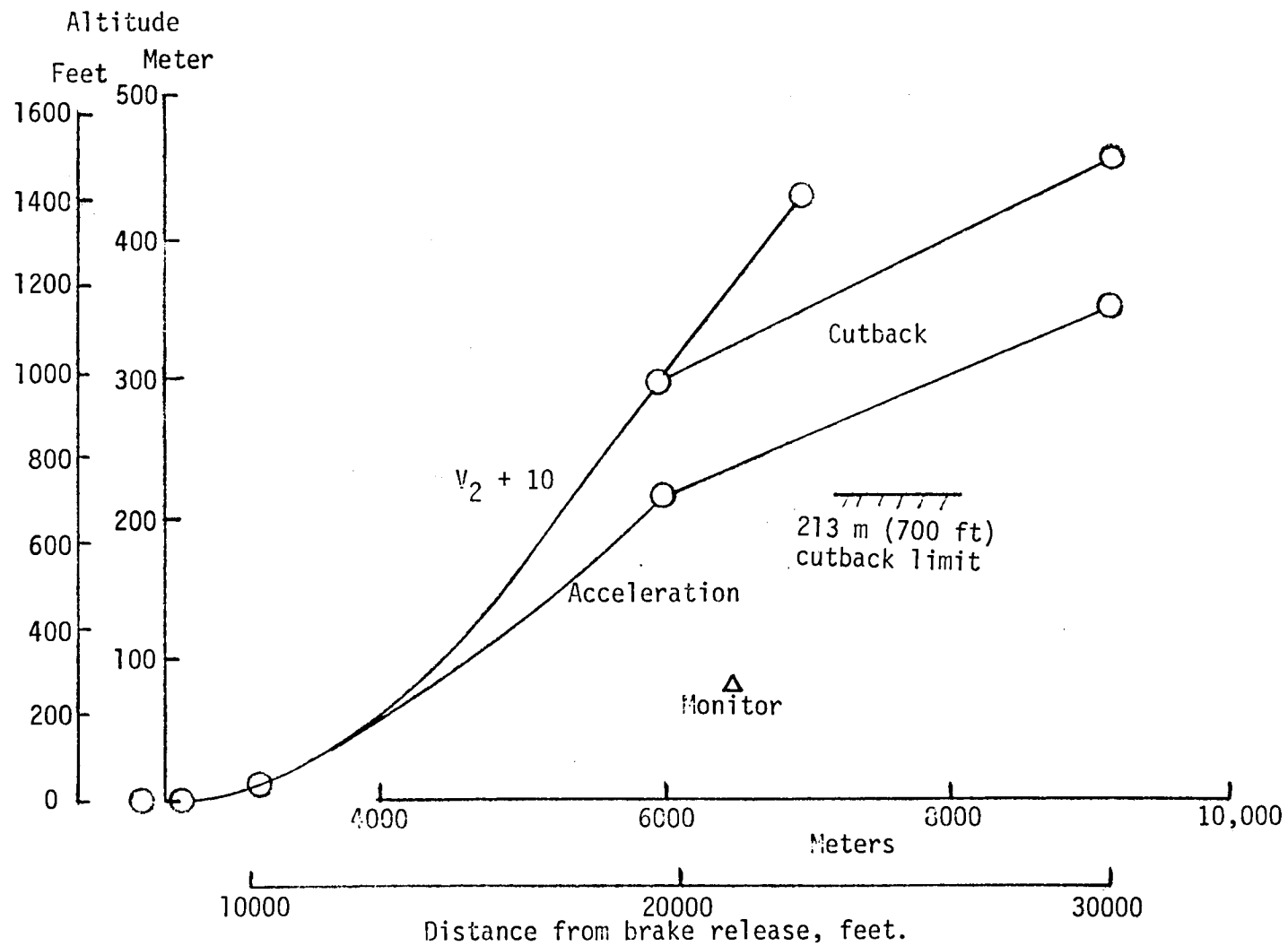


Figure 23.- Climb profiles - Aircraft with PW-LBE engine with mechanical suppressor

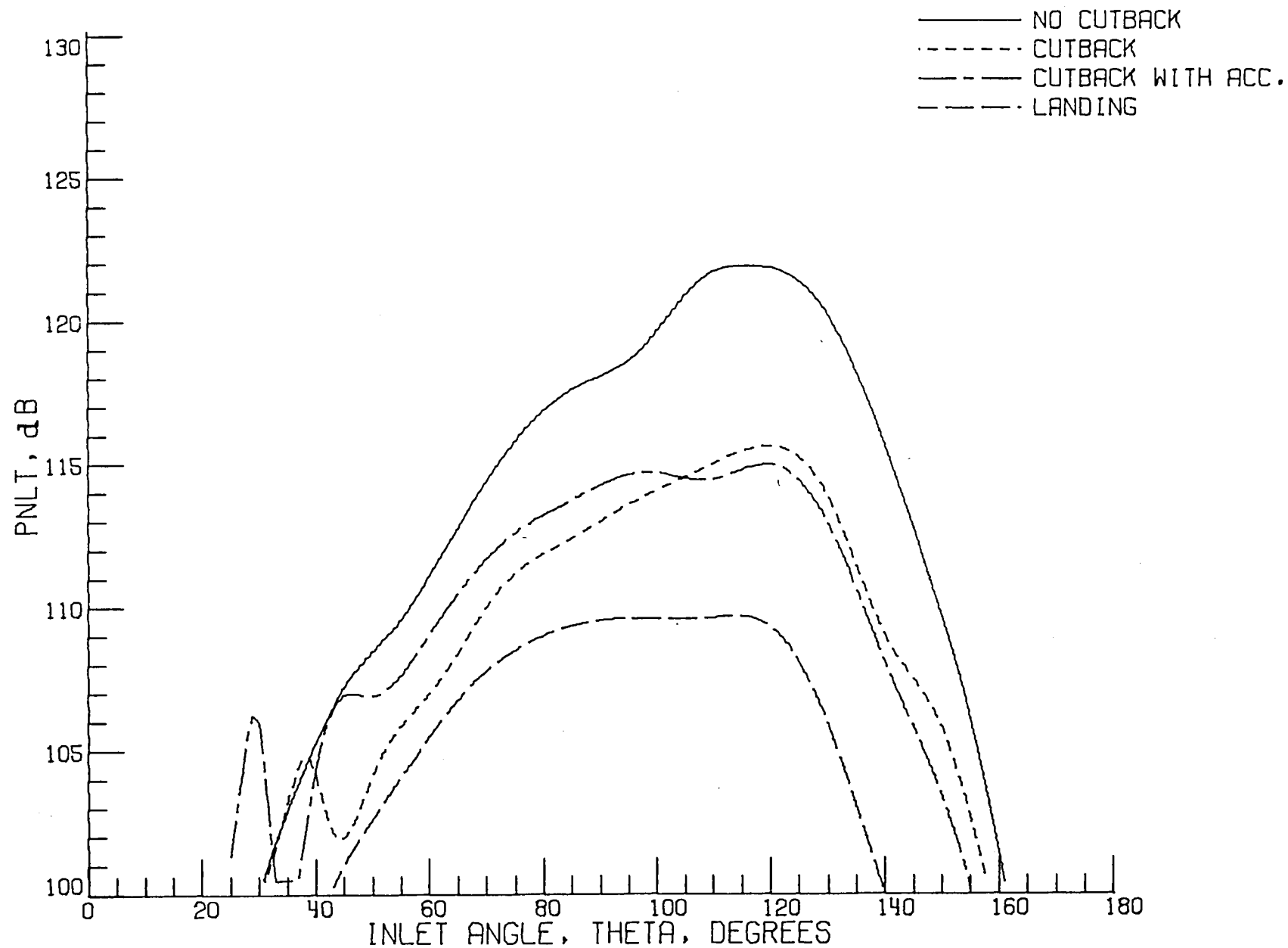


Figure 24.- Noise characteristics - performance aircraft with PW-LBE engine.

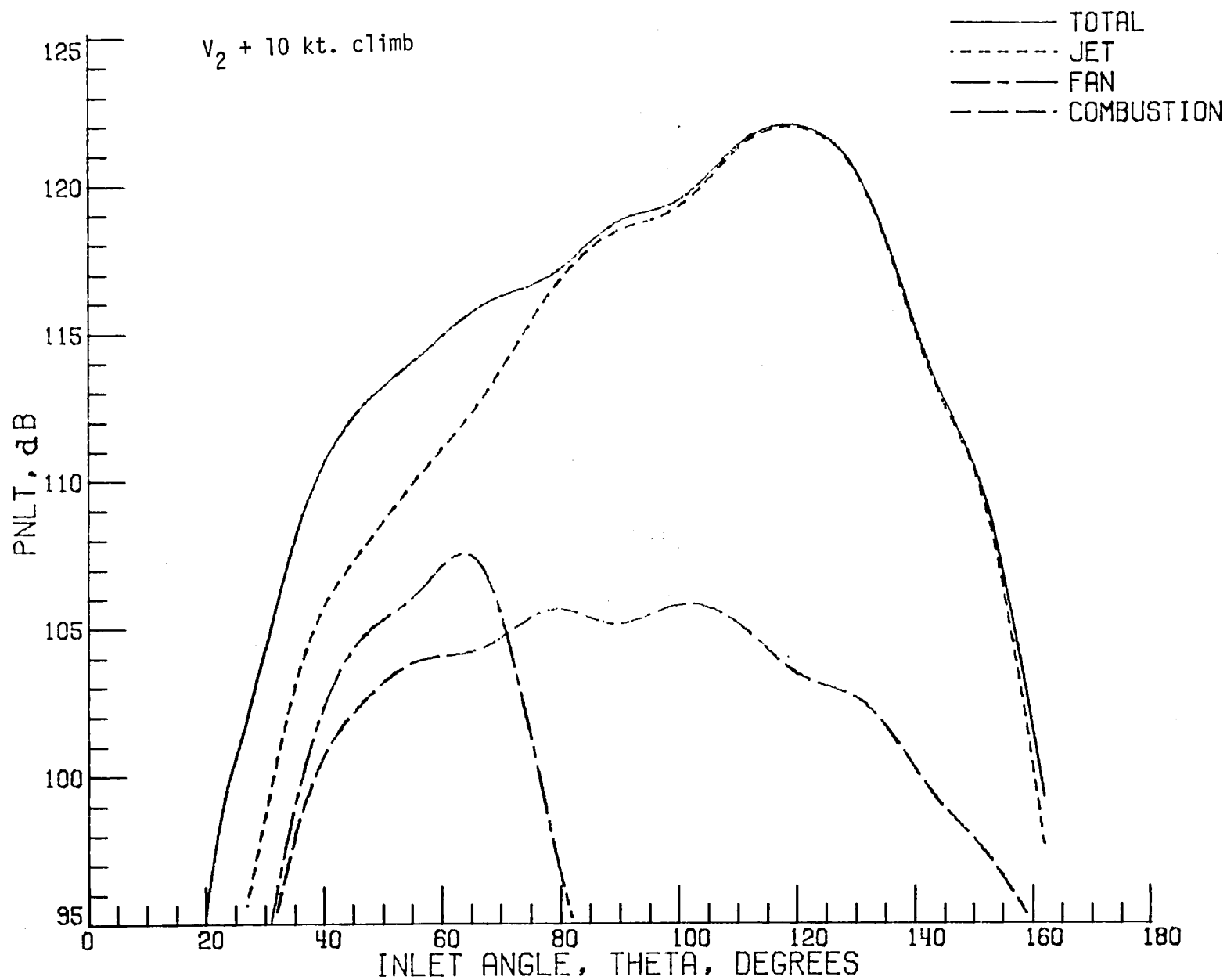


Figure 25.- Noise component breakdown - performance aircraft with PW-LBE engine.

- o Range = 8334 km (4500 n.mi.)
- o 273 passengers
- o Derated power for 3810 m (12500 ft)
- o Jet and shock noise

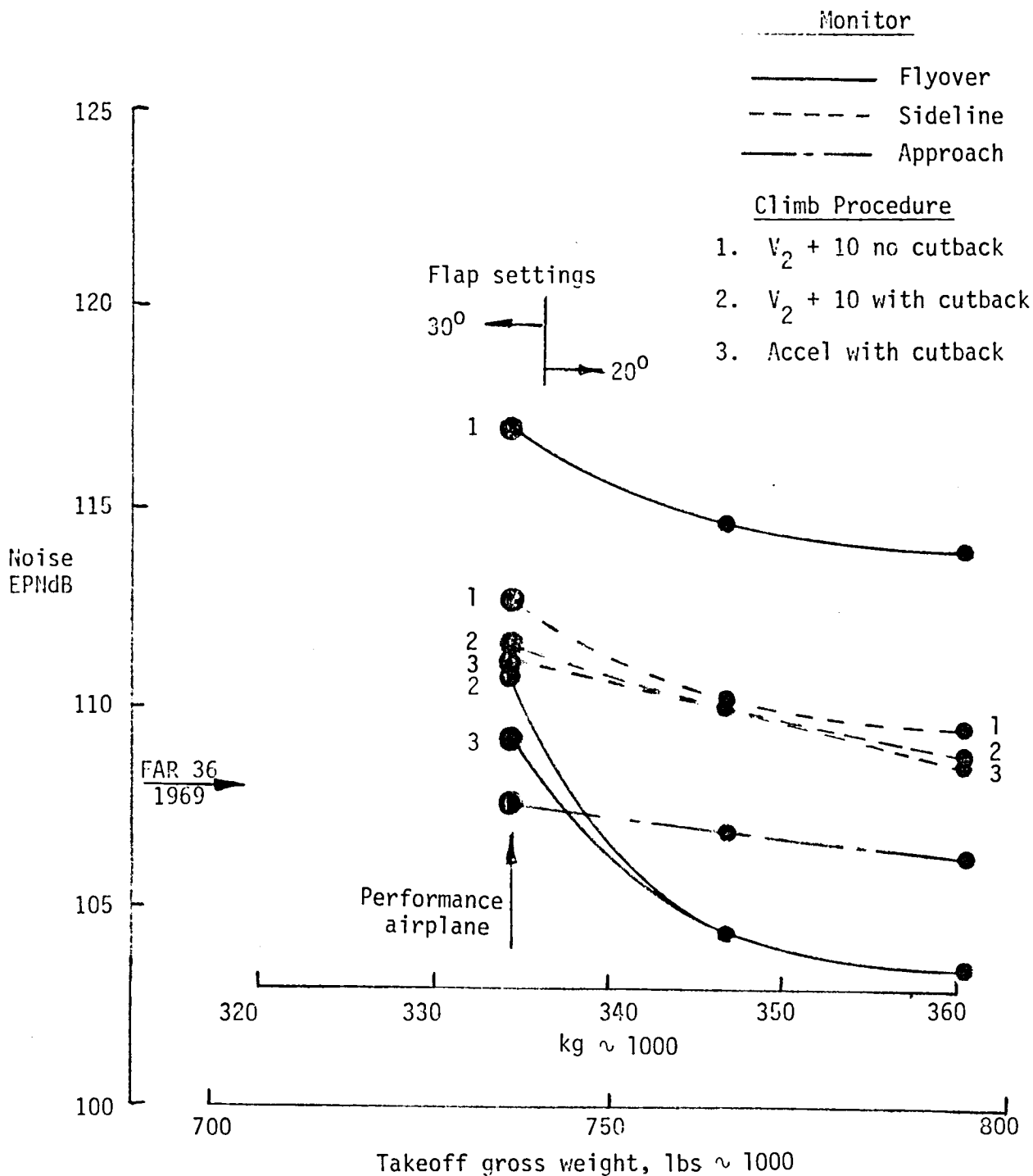


Figure 26.- Effect of engine oversizing on noise - Aircraft with PW-LBE engine with mechanical suppressor

- o Range = 8334 km (4500 n.mi.)
- o 273 passengers
- o TOFL = 3810 m (12500 ft)
- o Jet and shock noise

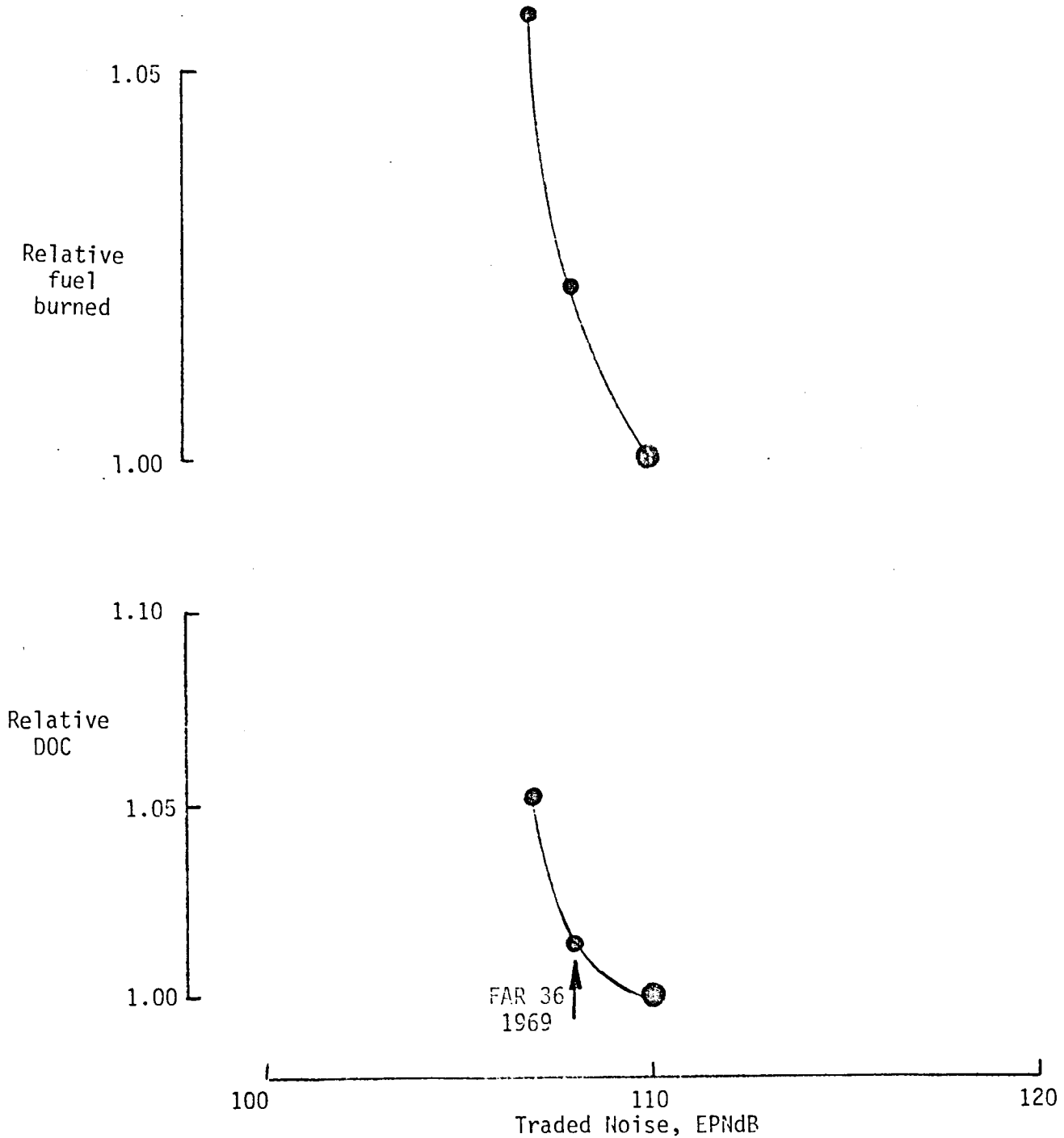


Figure 27.- Effect of Traded Noise on Cost and Fuel - Aircraft with PII-LBE mechanically suppressed engine.

0 Range = 8334 km (4500 n.mi.)

0 273 passengers

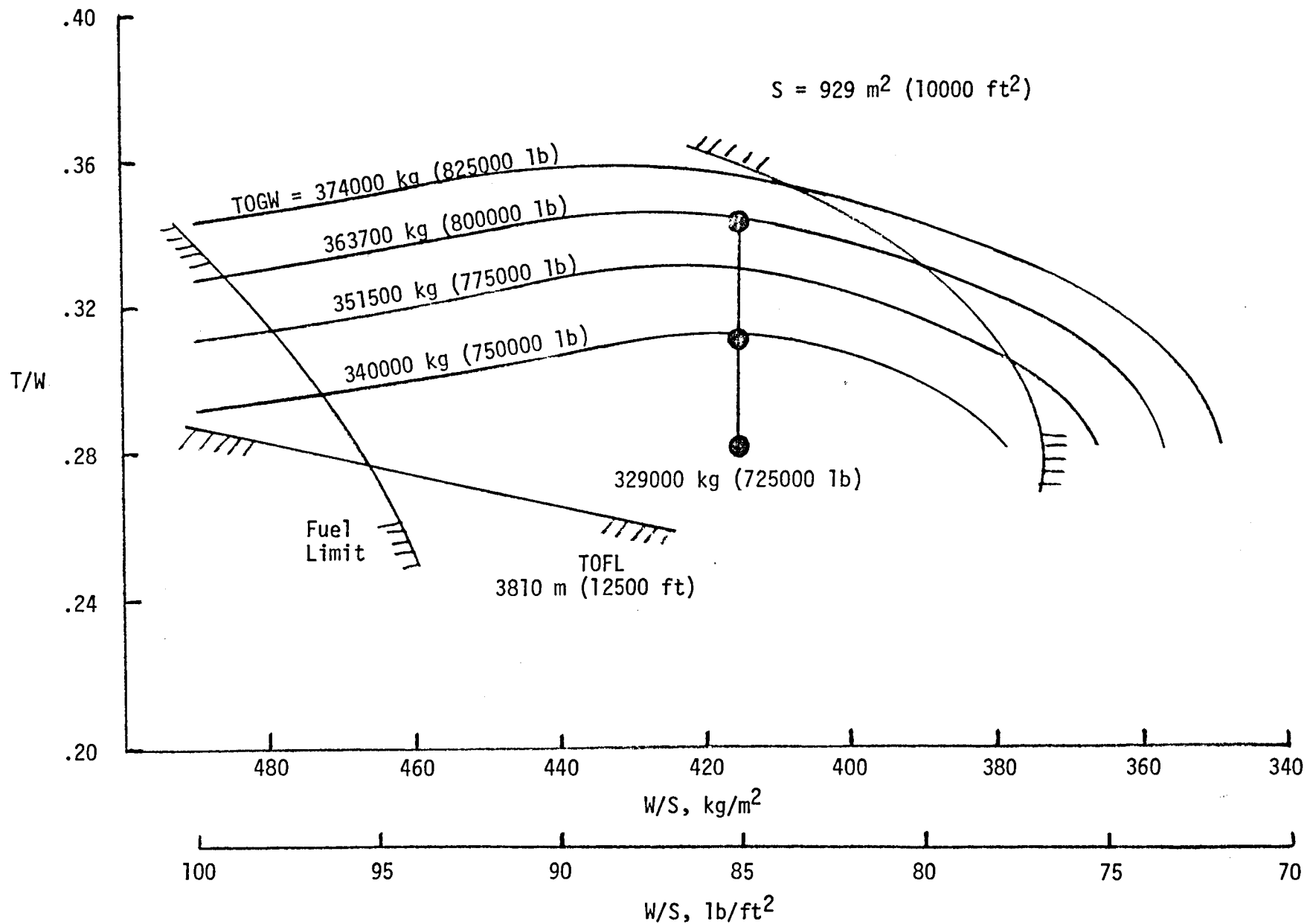


Figure 28.- Aircraft sizing chart for unsuppressed PW-LBE engine.

0 Range = 8334 km (4500 n.mi.)
 0 273 passengers
 0 Derated power to 3810 m (12500 ft)
 0 Jet and shock noise

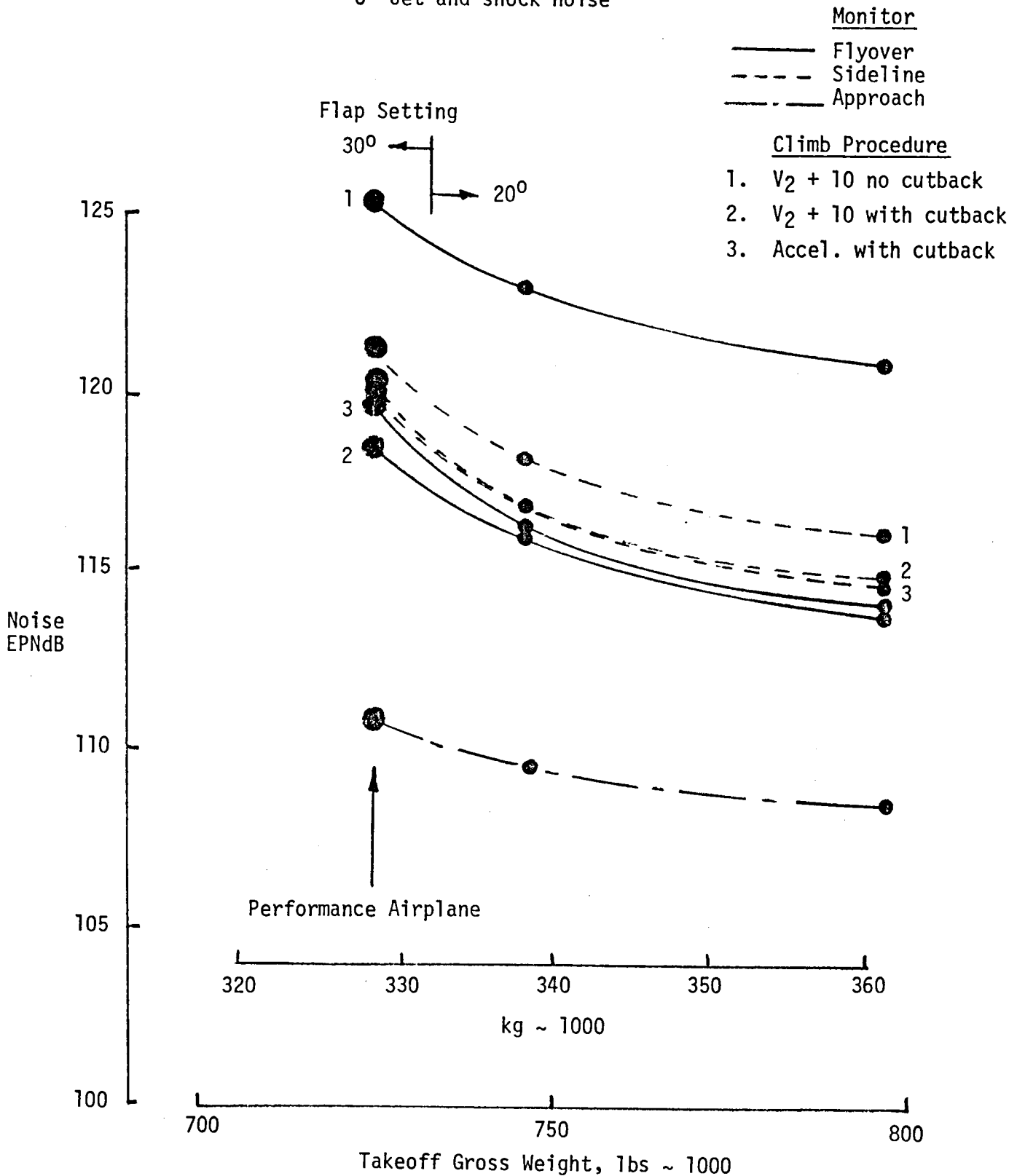


Figure 29.- Effect of engine oversizing on noise - aircraft with unsuppressed PW-LBE engine.

0 Range = 8334 km (4500 n.mi.)
 0 273 passengers
 0 Derated power for 3810 m (12500 ft)
 0 Jet noise only

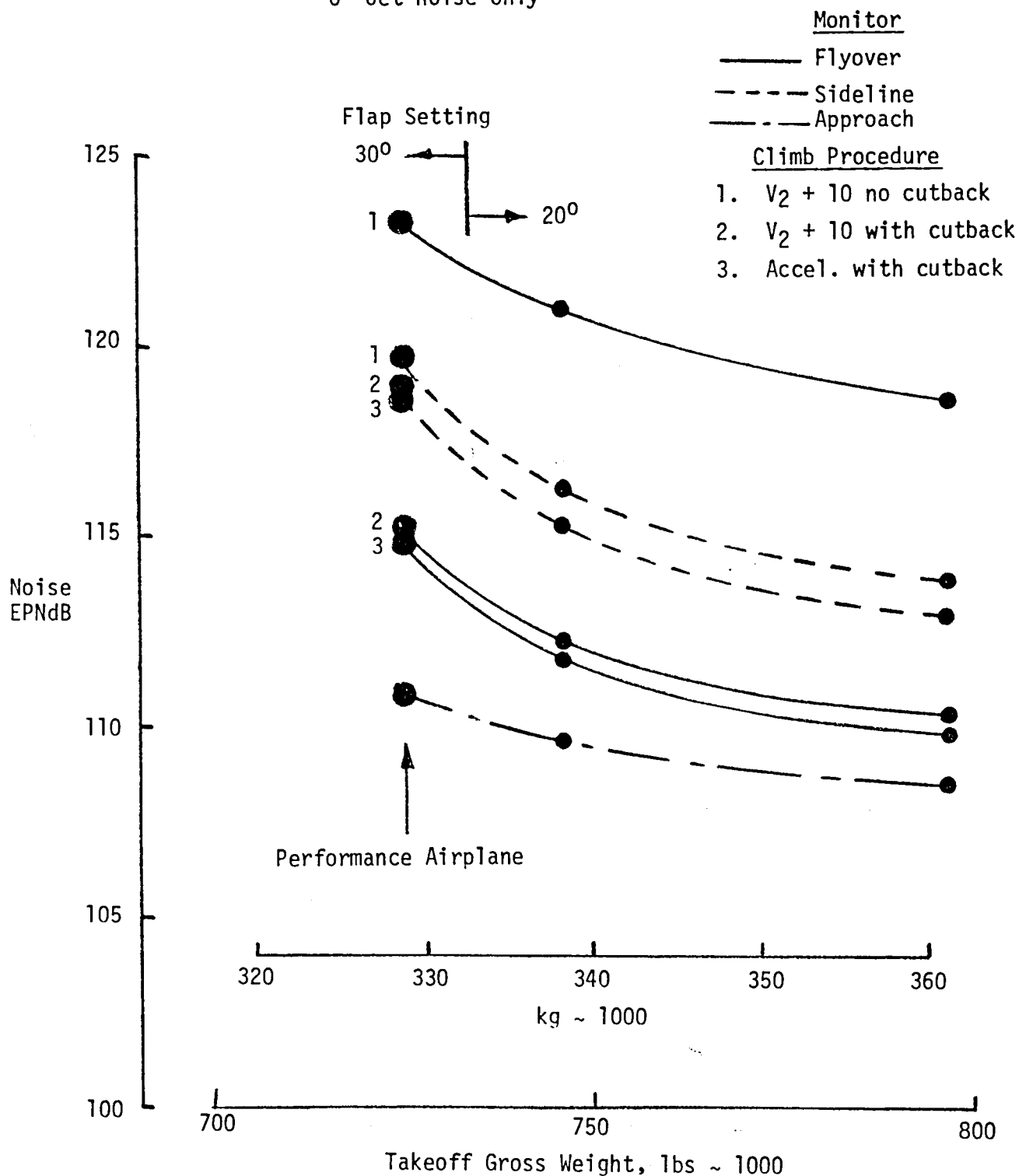


Figure 30.- Effect of engine oversizing on noise - aircraft with unsuppressed PW-LBE engine.

0 Range = 8334 km (4500 n.mi.)
 0 273 passengers
 0 TOFL = 3810 m (12500 ft)

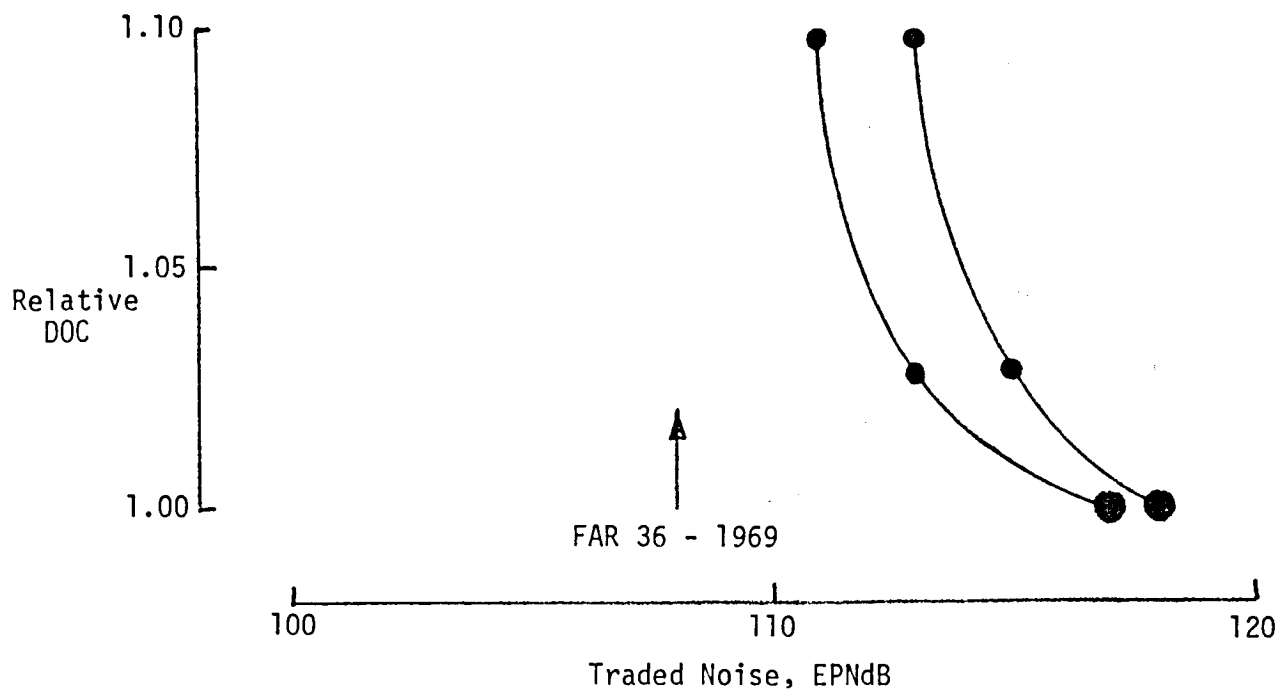
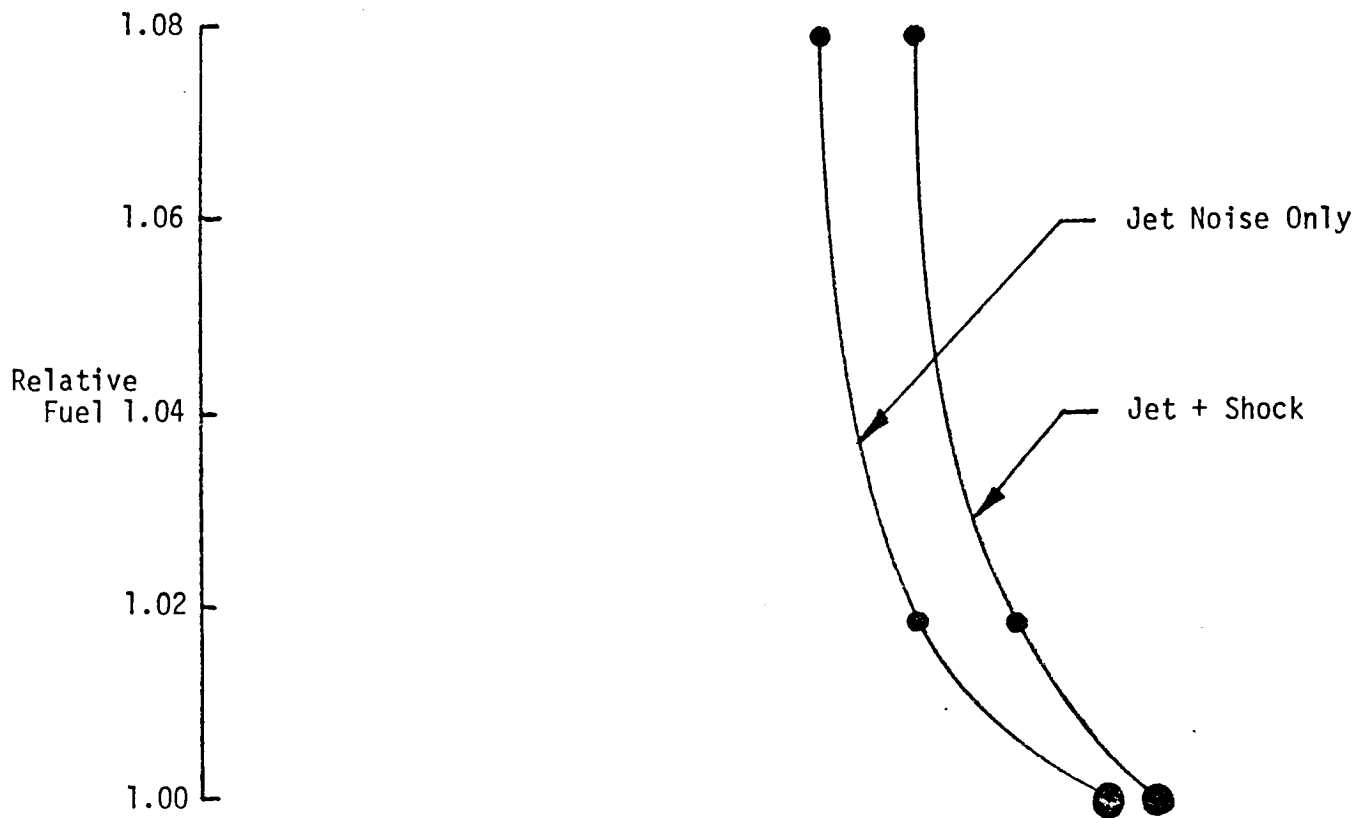


Figure 31.- Effect of trade ~ noise level on cost and fuel - aircraft with unsuppressed PW-LRE engine.

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16. Abstract A preliminary noise tradeoff study has been completed at the Langley Research Center for a Mach 2.7 design supersonic cruise concept. The study was based on the use of NASA computer codes in the areas of preliminary sizing and enroute performance, takeoff and landing performance, aircraft noise prediction, and economics. Aerodynamic configuration data were based on wind-tunnel model tests and related analyses. Aircraft structural characteristics and weight were based on advanced structural design methodologies, assuming conventional titanium technology. The most advanced noise prediction techniques available were used, and aircraft operating costs were estimated using accepted industry methods. The 4-engine cycles included in the study were based on assumed 1985 technology levels. Propulsion data was provided by Pratt and Whitney Aircraft and General Electric. Additional empirical data is needed to define both noise reduction features and other operating characteristics of all engine cycles under study. Data on VCE design parameters, coannular nozzle inverted flow noise reduction and advanced mechanical suppressors is urgently needed to reduce the present uncertainties in studies of this type.					
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