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16. Abstract

Sideline noise and takeoff field length were varied for two types of Mach 2.32 cruise airplane to determine their effect on engine cycle selection. One of these airplanes was the NASA/Langley-LTV arrow wing while the other was a Boeing modified delta-plus-tail derived from the earlier 2707-300 concept. Advanced variable cycle engines (VCE's) defined by both Pratt & Whitney and General Electric were considered. A more conventional advanced low-bypass turbofan engine was used as a baseline for comparison. Thrust, fuel flow, and weight margins were removed from all the engine data to obtain more consistent results. Mechanical jet noise suppressors were removed from those engine designs incorporating them. Appropriate exhaust nozzle modifications were assumed, where needed, to allow all engines to receive either an inherent co-annular or annular jet noise suppression benefit. All the VCE's out-performed the baseline engine by substantial margins in a design range comparison, regardless of airplane choice or takeoff restrictions. The choice among the three VCE's considered, however, depends on the field length, noise level, and airplane selected.

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SUMMARY

Sideline noise and takeoff field length were varied for two types of Mach 2.32 cruise airplane to determine how these factors affect the engine choice. Sideline noise levels of FAR 36 and FAR 36 - 5 EPNdB were considered at thrust levels commensurate with takeoff field lengths of both 12 000 feet (3658 m) and 10 500 feet (3200 m). One of the airplanes simulated in these mission studies was the NASA/Langley-LTV arrow wing while the other was a Boeing modified delta-plus-tail derived from the earlier 2707-300 concept. Three advanced variable cycle engines (VCE's) defined by both Pratt & Whitney and General Electric in NASA/Lewis contracted studies were considered. They were the P&WA VSCE 502B (an advanced duct burning turbofan), its derivative rear-valve VCE 112B, and the GE21/J9B1 double bypass engine. All of these engines may be viewed as VCE's because of valving or extensive flow modulation via variable components or novel control techniques. An advanced conventional engine, the P&WA LBE 405B mini-bypass turbojet, was also considered and used as a baseline against which VCE benefits were measured. Thrust, fuel flow, and weight margins, which differed between companies, were removed from the engine data to obtain more consistent results. Mechanical jet noise suppressors were removed from those engine designs incorporating them. Appropriate exhaust nozzle modifications were assumed, where needed, to allow all engines to receive either an inherent coannular or annular jet noise suppression benefit. All the VCE's out-performed the baseline engine by substantial margins in a design range comparison, regardless of airplane choice or takeoff restrictions. The choice among the VCE's, however, depends on the takeoff field length, noise level, and airplane selected.

INTRODUCTION

NASA began a Supersonic Cruise Airplane Research (SCAR) program in October, 1972. This program is not to be confused with the earlier SST program canceled in 1971 for technological, environmental, and financial reasons. The earlier program had as its aim the design and construction of a prototype airplane. The current SCAR program, on the other hand, is a technology program aimed at advancing those technologies that would be critical to the success of a supersonic cruise airplane should the United States ever decide to build one. No prototype airplane is to be built under this program.

The SCAR program encompasses both airframe and propulsion technologies. The airframe technologies, both aerodynamic and structural, are being coordinated by NASA/Langley Research Center. Most of this work has been accomplished through a series of contracts to major airplane companies, although a small in-house effort has been maintained. The propulsion program, coordinated by NASA/Lewis Research Center, has been accomplished in a similar manner, with most of the work done under contract by the two principal engine companies -- General Electric and Pratt & Whitney Aircraft.

Many types of engines, both conventional and unconventional, have been considered in the SCAR propulsion program. The philosophy was to start with a broad matrix of concepts and then to systematically sort out the best engines for further study. The propulsion study contracts have been divided into three phases, thus far. The results of the initial screening process are documented in the Phase I final reports of GE and P&WA (refs. 1, 2). The engines considered in the mission studies of this report were among those studied in the recently completed Phase II contracted work (refs. 3, 4). These Phase II engines are refined derivatives of some of the more promising engine cycles resulting from the Phase I initial screening process. Further refinement of the best engine cycles is continuing in Phase III contracts which are now under way.

In the mission studies of this report, takeoff field length and sideline noise restrictions were varied in two airplane configurations to determine how these factors affect the choice of an engine cycle. One of the airplanes considered was the NASA/Langley-LTV arrow-wing concept (ref. 5), which is highly efficient aerodynamically in the supersonic regime. It was specified as the reference to be used in the NASA/Lewis engine study contracts with the engine companies. Under NASA/Lewis contract # NAS3-16948, P&WA awarded a subcontract to Boeing to perform engine/airplane integration studies for several VCE concepts. The airplane Boeing used in these studies (ref. 4) was a modified delta-plus-tail derived from their earlier 2707-300 SST design. It is simpler structurally but has a poorer supersonic lift-drag ratio than the arrow-wing concept. The takeoff thrust requirements of the two airplanes are essentially the same because the higher available C_L at rotation for the Boeing airplane has been compensated for by a higher wing loading to save empty weight. For a given engine size, which is determined by this thrust and a sideline noise requirement, a variation in the cruise lift-drag ratio will affect the cruise throttle setting. If the cruise throttle setting is changed, the engine comparison may change, especially if there are any cross-overs among the throttle curves (i. e., curves of sfc against thrust), as there are for the candidate engines. For this reason, the Boeing airplane was chosen as representative of a more conservative design approach. The two airplanes used in this study are thought to represent two extremes of supersonic aerodynamics that might reasonably be expected. The Boeing airplane in this simulation is not the same as their most recent blended-body version. Although similar in planform and identical in operating empty weight, payload, and takeoff gross weight, the newer version has an improved supersonic cruise lift-drag ratio about mid-way between that of the two airplanes simulated in this study.

A reference airplane and certain common groundrules were specified to the engine companies for use in their own mission studies. Nevertheless, because of different calculation procedures, they obtained different results for the takeoff thrust required for the same field length as well as different jet noise levels for similar exhaust conditions. These differences lead to different apparent engine size requirements between contractors for the same specified conditions. The two companies have also used different inlet pressure recovery schedules and different engine weight and performance margins. These differences in margins reflect different management philosophies and are not indicative of the use of different levels of technology between companies. The same time-frame for engine development was specified to both contractors to minimize technology differences between them. Their materials selection and design techniques seem generally to represent similar levels of technology.

In the mission studies of this report, such inconsistencies were removed in the interest of obtaining a better comparison of the four selected Phase II engine cycle concepts defined by P&WA (contract # NAS3-16948) and GE (contract # NAS3-16950). Because of the removal of engine performance and weight margins, all the results of this study may be somewhat optimistic. Adjustments were also made to the engine data for the removal of mechanical jet noise suppressors in those designs incorporating them so that all engines considered could benefit from either an inherent annular or coannular suppression effect. On the other hand, there was no attempt made in this study to rematch any of the engine components or alter the internal design of the selected engines in any way.

In addition to the four engines considered in this report, there were several others considered by the engine companies in their Phase II studies. Examples of such engines are the P&WA front- and dual-valve series-parallel VCE's and the GE21/F12 Study B1 low-bypass augmented turbofan. These are not discussed herein for the sake of brevity and because the engine-company Phase II studies showed them to be significantly inferior to their prime offerings (the P&WA VSCE 502B and VCE 112B and the GE21/J9B1, respectively). The performance and weight of the P&WA LBE 405B baseline conventional engine chosen for this study are believed to be comparable to that of the GE21/F12B1 low-bypass augmented turbofan, and comments relative to the LBE 405B probably apply to this GE engine as well.

Exhaust nozzle modifications were assumed for the baseline P&WA LBE 405B mini-bypass turbojet engine so that, aside from VCE features, it would reflect approximately the same technology level and recent advancements that were included in the other concepts. The convergent-divergent nozzle with multi-element jet noise suppressor designed by P&WA was removed and a plug nozzle was substituted instead to provide the type of annular flow conducive to inherent suppression. The elimination of the mechanical suppressor saves weight and improves takeoff thrust. The preliminary finding of a significant annular flow jet noise reduction in a ventilated plug nozzle was recently made in static exhaust model tests by General Electric under NASA/Lewis SCAR technology contract # NAS3-18008. Likewise, the mechanical suppressor was removed from the GE21/J9 Study B1 double bypass engine, thereby eliminating some weight and a thrust penalty. This engine already incorporated a plug nozzle design. The P&WA VSCE 502B and its derivative rear-valved VCE 112B were originally designed by P&WA to take advantage of a coannular flow noise benefit without any mechanical suppressors. The significance of a coannular noise benefit was first identified by P&WA in static model testing under SCAR technology contract # NAS3-17866. In order for the maximum benefit to occur, substantial velocity differences must exist between the outer annular stream and the slower core stream. There is some doubt, however, that the VCE 112B in its present form can receive the full coannular noise benefit attributed to it. The velocity difference between its inner and outer exhaust streams is less than for the VSCE 502B and, furthermore, its core mass flow is much greater. It is possible, however, that a plug nozzle could be substituted for the C-D design, as was done with the LBE 405B in this study, to overcome these problems via an annular suppression benefit. When the core jet noise floor of a dual-flow exhaust is sufficiently low, as is the case with the VSCE 502B, the coannular suppression benefit is similar to that associated with mixed annular flow from a ventilated plug nozzle.

METHOD OF ANALYSIS

General

The sources of the data and the flow of the calculations used in the mission studies of this report are summarized in figure 1. Aerodynamic and weight data for the two airframes considered were supplied by NASA/Langley-LTV in one case and Boeing in the other. Engine performance and weight data were supplied by both General Electric and Pratt & Whitney for Phase II SCAR study engines. The engine data were then put on a comparable basis by eliminating thrust, fuel flow, and weight margins, which were different between the two companies. The performance of the GE engine was also adjusted for the better inlet pressure recovery schedule used in the other engines. Weight and performance adjustments were also made to the GE21/J9B1 and P&WA LBE 405B engines at this point to account for the removal of the multi-element mechanical jet noise suppressors. All the foregoing information, together with a fixed mission profile, was then fed into a flight performance computer program, which calculated the design range potential as a function of engine design airflow for the two fixed airplane designs.

The takeoff field length and sideline noise specifications were then applied to determine the engine sizing requirements for each airplane-engine combination. The takeoff thrust-to-gross-weight requirement was a function of the specified field length as well as the airplane wing loading and lift coefficient at the point of lift-off. For a specified level of sideline noise, a thrust per unit airflow is implied for a given engine type, and this, together with the calculated thrust-to-gross-weight ratio, was used to calcuate the engine design airflow (size). This size constraint was then applied to the previously generated curve of range against engine size.

A more detailed discussion of these methods, groundrules, and source data is contained in the sections which follow.

Mission

The flights simulated in this study were over a reference standard day + 14.4° F (+8° C) mission having a supersonic cruise at Mach 2.32. No subsonic cruise leg was used in the basic mission, but there were subsonic cruise elements in the reserve fuel calculation. This nominal mission is illustrated in figure 2. The takeoff gross weight, operating empty less propulsion system weight, and payload were fixed for each of the two types of airplanes considered. The range consumed in climb/acceleration (fig. 2) varied as a function of thrust margin and, to some extent, the rate of fuel consumption in each case. The climb/accel flight path used in all cases is shown in Mach number and altitude coordinates in figure 3. This placard is representative of those used in similar studies (e. g., ref. 5) but is not necessarily an optimum. The initial Mach 2.32 cruise altitude was a variable chosen to maximize the quotient of lift-drag ratio divided by sfc in a constant Breguet cruise. The cruise range varied as a function of several factors: namely, the fuel consumed up to cruise, the engine's cruise fuel flow characteristics, and the airplane weight at the end of cruise. The weight at the end of cruise is a function of the operating empty weight (and, therefore, propulsion system weight), as well as the reserve and descent fuel requirements. The reserve requirements are discussed in the next paragraph. A constant 213-nautical-mile (394-km) descent from the final cruise altitude at an estimated flight-idle fuel flow condition was assumed for all cases. Because of the variation in the range for both climb/acceleration and supersonic cruise, the total range for the nominal mission illustrated in figure 2 also varied. This total calculated range was the figure of merit used for comparison of the engines considered in this study.

A part of the total fuel load available was unused and held in reserve to fulfill the following additional requirements:

1) retain an enroute contingency fuel allowance equal to 5 percent of the mission fuel;

2) provide for a 260-nautical-mile (482-km) diversion to an alternate airport at Mach 0.9 at an optimum Breguet cruise altitude; and

3) provide for a 30-minute hold at Mach 0.45 at an altitude of 15 000 feet (4572 m).

These reserve groundrules are a simplified version of those specified by NASA/Lewis for use by P&WA and GE in their contracted mission analysis work. They are similar to those used in the Langley-LTV mission studies of reference 5 and the Boeing integration segment of reference 4, except that the 5-percent contingency fuel used here is that recommended by a Lockheed-TWA study (ref. 6). The Langley-LTV study used a 7-percent value previously recommended in a proposed FAR for the since-canceled U. S. SST, while the Boeing study used a value of 6 percent. The reserves of this study, therefore, are somewhat more optimistic than either of these other two studies.

Airframe

The major characteristics of the two airplanes considered in this study are summarized in table I. All of the tabulated characteristics remained fixed so that airplane total range, the overall figure of merit, varied with changes in engine weight and performance, including propulsion drag.

It is apparent from the operating empty less propulsion system weight item in table I that two different levels of structural weight technology are used in the two airplanes. These weights were extracted from reference 5 for the NASA/Langley-LTV arrow-wing airplane and from reference 4 for the Boeing modified delta-plus-tail configuration. These Boeing numbers agree also with those used for their more recent blended body configuration of similar planform. The Boeing airplane, however, should be a structurally simpler airplane to build, and thus might be expected to have a lower empty weight, especially since it has a smaller wing planform and a slightly lower takeoff gross weight. Table I shows, however, that the opposite is true. Such differences are not too unusual, considering that different design teams, different design philosophies, and different degrees of conservatism are represented. The range comparisons to be made should be among the engines as installed on a given airplane -- not between airplanes. The interest here in the airframe characteristics is to determine what effect they may have on engine rankings, but any comparisons made for that purpose should not be construed to indicate any preference for one airframe over the other.

The last item in table I, the allowable C_L at the point of lift-off, is important, together with the wing area, in determining the thrust needed for a given takeoff field length requirement. This thrust requirement, when coupled with a sideline noise specification (either FAR 36 or FAR 36 - 5 EPNdB in this study), sizes the engine. The field length and noise calculations will be discussed later in more detail.

The drag polars for these airplanes were assumed to be parabolic and could, therefore, be put in the form

$$C_D = C_{D_{min}} + (C_{D_i} / (C_L - C_{L_0})^2)(C_L - C_{L_0})^2 \quad (1)$$

Schedules of $C_{D_{min}}$, $C_{D_i}/(C_L - C_{L_0})^2$ and C_{L_0} against Mach number are shown in figure 4 for the two airframes under consideration. The $C_{D_{min}}$ schedule shown is for the altitude against Mach number schedule shown in figure 3 for climb/acceleration. Changes from this altitude schedule, as for example in the Mach 2.32 climb seeking an optimum Breguet cruise altitude, will cause a change in $C_{D_{min}}$ from the schedule shown in figure 4 because of Reynolds number and compressibility correction changes in the friction drag calculation. The $C_{D_{min}}$ schedules shown have been adjusted to include the drag of common nacelles -- that for four 900-pound-per-second (408-kg/sec) P&WA LBE 405B mini-bypass turbojet engines. A Boeing axisymmetric inlet was included in these nacelle drag estimates. The cowl lip diameter was based on the Mach 2.32 engine airflow requirement plus a 5.6-percent allowance for inlet bleed and leakage. The inlet length was assumed to be twice this diameter. Wave drag changes from changing pod dimensions were ignored in this study, due to the complexity of assessing the interference drag changes between the propulsion pods and the airframe. Only friction drag variations due to these dimensional variations were included in this simplified analysis.

Propulsion

Four types of promising engines were considered in this study. They are concepts defined by the engine companies under NASA/Lewis Phase II SCAR study contracts (i. e., contract # NAS3-16948 for P&WA and contract # NAS3-16950 for GE). The results of these contracted studies are reported in references 3 and 4. The engines considered in this report are the P&WA LBE 405B low bypass engine (a non-augmented mini-bypass turbojet), the P&WA VSCE 502B variable stream control engine (an advanced duct-burning turbofan), the P&WA VCE 112B variable cycle engine (a rear-valved derivative of the VSCE concept), and the GE21/J9 Study B1 double bypass VCE (a turbofan engine which has the capability to switch to a high-bypass mode at takeoff and subsonic cruise).

Some of the pertinent cycle design parameters of these engines, as well as their overall weights and dimensions, are shown in table II. The weights and dimensions have all been scaled for a 900-pound-per-second (408-kg/sec) nominal total airflow at the sea-level-static, standard day conditions. In the case of the GE21/J9 engine, the scaling has been to this size in the high-flow mode, which is the one normally used at takeoff for noise abatement. The low-flow mode airflow at this condition would be 740 pounds per second (336 kg/sec), as indicated in the table. It is indicative of the engine size used in the climb/acceleration and supersonic cruise mode. Two bypass ratios are also shown in the table for this engine. They represent the high and low flow conditions at sea-level-static, standard day conditions. The two fan pressure ratios shown for this engine represent, in the first case, the ratio across the front fan block, while the second number represents an overall fan pressure ratio across both fan blocks.

The combustor exit temperatures shown in table II are maximum values which, for the P&WA engines, do not occur at takeoff but either during climb/acceleration or at supersonic cruise. For these engines, takeoff will be at a temperature several hundred degrees below those indicated to obtain acceptable jet noise levels. In the case of the GE21/J9B1 double bypass engine, the takeoff combustor exit temperature is much closer to the indicated maximum because a greater turbine energy extraction in the high-flow mode keeps the jet velocity low. In the case of the P&WA VCE 112B engine, two combustor exit temperatures are shown. The first is for the core engine while the second is for the fan, or bypass, stream. This fan-stream heated air then passes through an aft turbine, where work is extracted when in the normal full-throttle mode of operation. A duct burner and an afterburner are used in the P&WA VSCE 502B and the GE21/J9B1, respectively, but no augmentation temperature is shown for them in table II because it is limited only by stoichiometry or nozzle cooling.

The engine weights shown in table II have been adjusted to reflect the elimination of weight margins that were included by the engine companies. These weight adjustments also reflect the elimination of the mechanical jet noise suppressors in the P&WA LBE 405B and the GE21/J9 Study B1 engines. In the case of the LBE 405B, the weight shown also reflects the substitution of a GE plug nozzle, scaled for size and with weight margin removed. This weight adjustment for conversion from the C-D to the plug nozzle turned out to be very small. The inlet weights were based on an estimation procedure supplied by Boeing for a translating centerbody axisymmetric configuration with a length-diameter ratio of 2. Since this ratio was fixed, the weight was a function of the inlet lip diameter which was sized to provide the engine airflow needed at Mach 2.32 plus 5.6 percent for inlet bleed. No weight penalty was assessed for the addition of auxiliary inlet doors for use with the GE21/J9B1 engine in the high-flow takeoff mode. The cowl weight estimating procedure used by Boeing in reference 4 was used in this study. Cowl weight was a function of the engine overall dimensions supplied by the companies. The mount and support weight was a function of the sum of the engine, inlet, and cowl weights, and was estimated on the basis of a procedure supplied by Boeing.

The engine performance data used in this study is shown in figure 5 for all four engines under consideration. Figure 5(a) shows the climb/acceleration performance in terms of full-throttle thrust and specific fuel consumption as a function of flight Mach number, for the altitude against Mach number schedule of figure 3. Discontinuities in these performance curves in the subsonic region generally represent changes in the augmentor setting of the augmented engines (i. e., all except the P&WA LBE 405B). The GE21/J9B1 data is shown with the afterburner unlit until Mach 0.95. It remained at the maximum setting from Mach 1 until supersonic cruise. The P&WA VSCE and VCE engines are shown with some augmentation at takeoff, but without any augmentation immediately afterwards. Duct burning is resumed for the VSCE 502B engine in the transonic region and modulated during the remainder of climb/acceleration to minimize the overall fuel consumption. For the VCE 112B, augmentation of the duct stream was resumed in increments, beginning at approximately Mach 0.6.

The supersonic cruise throttle curves are shown in figure 5(b). The minimum sfc for the GE21/J9B1 engine occurs at the maximum unaugmented throttle setting. This engine operates here in its low-flow mode which is equivalent to a sea-level-static corrected airflow (size) of 740 pounds per second (336 kg/sec), while the other engines are shown for a 900-pound-per-second (408-kg/sec) size. The rather steep rise in sfc for the GE engine beyond the maximum unaugmented throttle setting is the result of afterburning. The minimum sfc on the P&WA VSCE 502B curve occurs with some duct burning, however. All points on the curve for the P&WA VCE 112B were with the fan stream augmented with the rear valve in the cross-over position so that work was extracted from it by the aft turbine. In this mode, operation is similar to two turbojets in parallel. This similarity is displayed by the closeness of this curve to that for the P&WA LBE 405B, a mini-bypass turbojet.

Subsonic cruise throttle curves are shown in figures 5(c) and (d) for the cruise-to-alternate and hold conditions, respectively. All the engines are throttled back over the thrust spectrum shown. The P&WA LBE 405B suffers more in terms of sfc at these conditions because it has to be throttled back farther to reach the thrust levels of interest, due to its very low bypass ratio. The other three engines have very similar throttle characteristics at these subsonic cruise conditions.

All the performance data shown in figure 5 is installed performance with any thrust and fuel-flow margins that may have been included in engine company brochures removed. An adjustment has been included in the GE data also to include the inlet pressure recovery schedule common to all the other engines -- that of the Boeing Mach 2.4 axisymmetric inlet. No attempt was made, however, to reschedule the engine airflow to obtain a better match with the flow characteristics of this inlet. It should be recognized that a more detailed analysis might conclude that the use of a similar inlet by all the engine types is not appropriate. Installed engine performance included degradations due to nozzle boattail and/or afterbody drag and inlet spillage, bypass, and bleed drags. The installation performance decrement was computed by the engine companies for an isolated engine pod and incorporated here without adjustment.

Takeoff Thrust Requirement

Takeoff thrust levels commensurate with FAR field lengths of 12 000 feet (3658 m) and 10 500 feet (3200 m) were estimated for both airplane configurations considered in this study. The longer field length is one represented by Boeing as adequate for international supersonic cruise airplanes while the shorter more restrictive requirement is one specified by NASA/Lewis to the engine companies for use in their mission studies. The shorter 10 500-foot (3200-m) field length was also used as a maximum acceptable limit in the Langley-LTV mission studies (ref. 5). Such a criterion would give the airplane greater flexibility in that it could be accommodated by a larger number of the world's airports without off-loading fuel or payload. It is likely, however, that the design range would be penalized by a shorter field length requirement.

The FAR takeoff field length, which includes a safety margin for an engine-out as well as clearance of a 35-foot (11-m) obstacle at the end of the runway, becomes a rather complicated calculation. It is best handled for the purposes of this study on an empirical basis. The takeoff distance requirement can be shown theoretically (e. g., ref. 7) to be proportional to wing loading divided by the thrust-weight ratio, lift coefficient, and density ratio, all evaluated at lift-off, if second-order effects like thrust-drag ratio are ignored. This quotient is shown as the abscissa against which FAR field length is plotted in figure 6. The curve was obtained by fitting a straight line through the origin and a point represented by a distance of 12 000 feet (3658 m) evaluated for the abscissa parameters associated with the Boeing airplane. In addition to the gross weight, wing area, and C_L shown in table I for this airplane, a net thrust per engine of 44 500 pounds (198 000 N) was used together with the density ratio of 0.939 corresponding to the 1000-foot (305-m) altitude now used by Boeing in evaluating the thrust on a standard + 18°F (+10°C) day. The curve thus obtained (fig. 6) has a slope similar to that of an earlier unpublished curve supplied by Lockheed, when differences in altitude and ambient temperature are accounted for. The figure 6 curve is also similar to one shown in reference 7 for field length without any engine-out requirement, but with thrust evaluated at sea-level, standard-day conditions.

The curve of figure 6 was used to determine the takeoff thrust required for both airplane configurations at the two field lengths indicated on the figure by the dashed lines. In solving for the thrust loading at the two indicated values of the abscissa, the 0.939 density ratio for an altitude of 1000 feet (305 m) on a standard + 18°F (+ 10°C) day was used. The thrust-weight ratio thus obtained was consistent with Boeing's methodology. Since the engine company brochure data included performance at the Mach 0.3 lift-off speed at sea-level conditions instead of the 1000-foot (305-m) altitude, the thrust-weight ratios obtained from figure 6 were corrected to sea-level by multiplying by 1.0367 -- the ratio of the ambient pressures between sea level and altitude. The thrust-weight ratio required was the same for both configurations because the quotient of $(W_g/S)/C_{L_{TO}}$ appearing in the abscissa of figure 6 is the same for each one, based on the information appearing in table I. The actual levels of F_n, however, are different for the two airplanes at any given field length because the takeoff gross weights are slightly different.

Sideline Jet Noise Estimation

The sideline noise requirement together with the takeoff thrust requirement discussed in the preceding section determine the engine size needed. (In some cases for the unaugmented P&WA LBE 405B engine, climb/acceleration thrust margin over drag was inadequate with this takeoff sizing criterion, but it was presumed that this could be corrected by the addition of an afterburner at only a slight weight penalty.) The sideline measuring station is the one referred to in FAR 36 at 0.35 nautical miles (648 m) to the side of the takeoff flight path. The altitude of the airplane is defined as that which results in a maximum level of noise on this sideline, as determined by a trade-off between altitude attenuation and the gradual loss of both extra ground attenuation and fuselage masking of the multiple-engine effect.

The jet noise estimation procedure used in this study is based on data supplied by General Electric (top curve of fig. 7) for an unsuppressed mixed flow exhaust. Sideline noise from four engines was correlated against fully expanded jet velocity for a constant 61 000-pound (271 431-N) level of net thrust per engine at an airplane speed of Mach 0.3. The constant thrust implies that airflow (engine size) is constantly changing along the curve as velocity changes. The General Electric calculation procedure used in obtaining this curve was based on the classical SAE calculation procedure (refs. 8, 9) except that less noise reduction was attributed to the forward velocity of the airplane, based on new experimental evidence. The curve for coannular flow exhaust (second from top, fig. 7) was used for both the P&WA VSCE 502B and VCE 112B before applying coannular inherent suppression benefits. The velocity against which the total jet noise is correlated for this curve is that of the higher-speed outer annulus. This curve was derived from the top one by using the approximation from reference 8 that

$$\Delta N = 10 \log_{10}(\dot{W}_{by} / \dot{W}_{tot}) \qquad (2)$$

as applied to the VSCE 502B. This decrement is based on the presumption that the core flow is at such a low velocity, relative to that of the outer annulus, that it will make only an insignificant contribution to the total noise. This coannular exhaust curve was also used for the VCE 112B although the exhaust annular flow ratio that appears in equation (2) would be considerably different.

The upper curve of figure 7 was assumed to apply to both the P&WA LBE 405B and the GE21/J9B1 engines, even though the latter engine does not have a mixed-flow exhaust, strictly speaking. A small lower-velocity outer annulus surrounds the much larger, higher-velocity core exhaust. Good agreement with General Electric results was obtained, however, by using a mean effective exhaust velocity for the entire stream of the GE21/J9B1, as calculated from the familiar thrust equation

$$V_{j_{eff}} = \frac{1}{C_{fg}}\left(\frac{gF_n}{\dot{W}_8} + \frac{\dot{W}_0}{\dot{W}_8} V_0\right) \qquad (3)$$

The effective exhaust velocity thus calculated was the one used to determine noise from figure 7 for the double bypass engine. It was also used to calculate a real, rather than an effective, exhaust velocity for the P&WA LBE 405B mixed-flow exhaust engine for various thrust and airflow conditions.

A variation of equation (2) was used to adjust the noise level from the value read from figure 7 at the reference thrust level of 61 000 pounds (271 341 N) to the lower thrust levels of interest in this study. At any fixed level of jet velocity, the correlation

$$\Delta N = 10 \log_{10}(F_n / F_{n_{ref}}) \qquad (4)$$

was applied to the curves of figure 7 to account for the lower thrust and, hence, lower airflow.

As mentioned earlier, a noise benefit from coannular flow has been identified in static model tests, relative to that calculated by the SAE procedure. The bottom curve of figure 7 reflects initial estimates of this benefit, with data extrapolated to full-scale with a C-D ejector nozzle. A similar benefit was identified with a mixed-flow annular exhaust with a ventilated plug. These experimental results are reflected in the second from the bottom curve of figure 7. This curve was applied in this study to both the GE21/J9B1 double bypass VCE and the P&WA LBE 405B mini-bypass engine. In both cases, the mechanical multi-element suppressors were removed, as mentioned previously. In addition, a plug nozzle was substituted for the C-D version designed for the LBE 405B by P&WA, in order to obtain annular flow. A similar substitution could perhaps be made for the P&WA VCE 112B in the event that the coannular flow benefits are less than predicted for this engine, since the benefits assumed for it were actually based on experimental data obtained for exhaust conditions more similar to those of the VSCE 502B. The current P&WA Phase III studies are addressing the question of a plug nozzle for the VCE type of engine. To take full advantage of the annular noise reduction benefit with a plug, however, the VCE 112B cycle design parameters may need to be altered.

It is probable that the coannular flow noise benefit cannot cause the total jet noise of the combined flow streams to fall below the level of the core jet by itself. The core jet noise of the VCE 112B will be higher than that of the VSCE 502B for the same outer annulus jet velocity because of the VCE's higher core mass flow and jet velocity. The top curve of figure 7 can be adjusted downward to apply to the VCE 112B core jet by using a correction calculated by equation (2) with 0.744 substituted for the mass flow ratio (in this case, the ratio is the core flow at the exhaust station to the total flow). This gives an estimate of the core jet noise floor as a function of the velocity of the core jet. These estimates indicate that this floor would limit the coannular noise benefit to about half that shown in figure 7. The coannular noise benefits attributed in this study to the VCE 112B are, therefore, somewhat more optimistic than could be justified by a strict interpretation of the available coannular model test data or consideration of a possible core jet noise floor.

RESULTS AND DISCUSSION

NASA/Langley-LTV Airplane

The mission results in terms of total range for the NASA/Langley-LTV modified arrow-wing airplane concept are shown in figure 8, plotted against engine size. Results are plotted for all four engine types considered. In the case of the GE21/J9 Study B1 double bypass VCE, the abscissa refers to the high-mode airflow. In figure 8(a), the results are shown without any sizing constraints imposed. At the lowest engine sizes, the P&WA VCE 112B gives the best results, being slightly better than the P&WA VSCE 502B and considerably better than either the GE21/J9B1 or the P&WA LBE 405B. At small engine sizes, the supersonic cruise throttle setting must be high. Figure 5(b) showed that at high throttle settings, engines ranked on the basis of sfc, from best to worst, would be as follows: (1) P&WA LBE 405B, (2) P&WA VCE 112B, (3) P&WA VSCE 502B, and (4) GE21/J9B1. With the exception of the P&WA LBE 405B, this ranking holds true on the basis of range, also. The P&WA LBE 405B made a poor showing in the range comparison primarily because of its heavier weight and poorer subsonic cruise sfc. Its higher weight can be attributed to the greater percentage of more massive rotating machinery for a given total airflow as the bypass ratio is reduced to very small values. The poorer subsonic cruise sfc's used in the calculation of the reserve fuel load are due to the need to throttle back farther from the full-throttle condition to obtain the required low level of thrust.

As the engine sizes are increased somewhat from the lowest levels, the range obtained with the P&WA VSCE 502B begins to exceed that of the VCE 112B (fig. 8(a)). Lower supersonic cruise throttle settings are required with these larger sizes, and the sfc of the VSCE 502B becomes lower than that of the VCE 112B, as shown in figure 5(b). This explains the VSCE 502B's better range.

At still greater engine sizes, the range obtained with the GE21/J9B1 double bypass VCE becomes the highest, as its throttle setting approaches the maximum non-afterburning thrust condition where minimum sfc is obtained. Figure 5(b) shows that this sfc is lower than that obtained with any other engine. Table II also indicates that the podded weight for this engine will be the lowest of any of the engines when compared on the basis of equivalent high-mode nominal design airflow. These two factors combined produce the superior range results for large-size double bypass engines, as shown in figure 8(a).

Figure 8(b) shows how the engines compare when sized for the FAR 36 (108 EPNdB) sideline noise with the takeoff thrust required for a 12 000-foot (3658-m) FAR field length. At this condition, the P&WA VSCE 502B achieved the best range, being slightly better than the VCE 112B. Both engines had design airflow requirements approximating 800 pounds per second (363 kg/sec). Somewhat farther behind in the range comparison is the GE21/J9B1 engine, followed in last place by the P&WA LBE 405B engine. These latter two engines have size requirements of about 730 pounds per second (331 kg/sec). Their somewhat smaller size requirement relative to the two coannular flow engines is because the required level of thrust is obtained with essentially the total flow moving at the maximum velocity. In the coannular flow engines, a significant part of the flow moves at a lower velocity, thereby producing less total thrust for the same total airflow.

Figure 8(c) shows the engine comparison for the same FAR 36 noise level, but with a reduced 10 500-foot (3200-m) FAR takeoff field length. The engine sizes are, of course, larger than before at about 930 pounds per second (422 kg/sec) for the P&WA VSCE 502B and VCE 112B and about 850 pounds per second (386 kg/sec) for the GE21/J9B1 and the P&WA LBE 405B. The P&WA VSCE 502B and the GE21/J9B1 are almost tied for first place in the range comparison. The P&WA VCE 112B is somewhat worse, while the LBE 405B ranks as a poor last. Notice that because of the flatness of the range against size curve of the GE21/J9B1, its range is about the same whether the short or the long field length is specified at FAR 36. The range suffered for all the other engines as the field length was shortened.

Figure 8(d) shows the engine size constraints for a lower FAR 36 - 5 EPNdB (103 EPNdB) sideline noise at the longer field length of 12 000 feet (3658 m). The engine size requirements are just slightly higher than those shown in figure 8(c) for the higher noise level and the shorter field length. This difference is enough, however, for the GE21/J9B1 to take a slight range lead over the P&WA VSCE 502B. This occurs because the GE double bypass engine is still on the flat part of its range curve while the VSCE range is decreasing at an approximately constant rate as airflow is increased. At this lower noise level, the combustor exit temperature of the P&WA VSCE 502B engine was reduced approximately 100° F (55.5° C) from the nominal takeoff level used at the FAR 36 (108 EPNdB) sideline noise.

Some duct burning was used in conjunction with this lower core temperature to establish the correct exit velocity profile for maximum coannular benefit. No such option was available with the P&WA VCE 112B to preserve the optimum exit velocity profile at lower throttle settings. Only one schedule of exit velocity combinations was shown in the P&WA brochure for this engine as takeoff throttle setting was reduced. At the throttle setting for the correct outer annulus exit velocity for 103 EPNdB (from fig. 7), the brochure data indicates that only about half the velocity difference needed for the postulated coannular benefit is available. Since the two stream exit velocities are getting closer together as the noise is reduced to FAR 36 - 5 EPNdB, a size difference begins to appear in figure 8(d) between that required for this engine and the VSCE 502B, which had previously been about equal at FAR 36. The VCE 112B exit velocity profile is becoming more uniform, like that of the other two engines. Its size requirement, therefore, lies somewhere between the two extremes for coannular flow and mixed flow.

Figure 8(e) shows the engine sizing constraints applied for the shorter 10 500-foot (3200-m) FAR takeoff field length at the lower FAR 36 - 5 EPNdB noise level. This is the most severe sizing constraint considered in this study. As in the preceding case, there is a difference between the sizing requirement for the P&WA VSCE 502B and VCE 112B because the VCE 112B has a lower velocity difference between the two exhaust streams. The VSCE 502B's nominal airflow requirement is 1135 pounds per second (515 kg/sec) while the VCE 112B's is somewhat lower at 1095 pounds per second (497 kg/sec). Both the P&WA LBE 405B and the GE21/J9B1 have a size requirement of 1038 pounds per second (471 kg/sec). For this sizing constraint, the GE21/J9B1 double bypass engine is the best engine in terms of range, leading the second-place P&WA VSCE 502B by a significant margin. The P&WA VCE 112B ranks third, being slightly behind the VSCE 502B. The P&WA LBE 405B again ranks last by a considerable margin.

The preceding range comparisons for the NASA/Langley-LTV airplane are summarized in the bar graphs of figure 9. Figure 9(a) shows the comparisons at FAR 36 sideline noise, while figure 9(b) shows them at FAR 36 - 5 EPNdB. The shaded part of each bar represents the range for a 10 500-foot (3200-m) takeoff field length sizing requirement, while the total height of the bar represents the range obtained with engines sized for a 12 000-foot (3658-m) field length. Figure 9(a) shows that with the least stringent of the sizing constraints at FAR 36 sideline noise (i. e., at the longer field length) the P&WA VSCE 502B is the best choice. This same figure also shows, however, that the GE21/J9B1 double bypass VCE is the best choice for the shorter field length requirement. Figure 9(b) shows that for a sideline noise of FAR 35 - 5 EPNdB, the GE21/J9B1 engine is the best choice regardless of which field length requirement is chosen.

Boeing Airplane

The mission results for the Boeing airplane, a modified delta-plus-tail concept, are shown in figure 10. The results are shown in terms of range against engine size for each of the four engines. The figure 10(a) results are shown without any sizing constraints imposed. At small engine sizes, the P&WA VCE 112B maintains a greater range superiority over the second-place VSCE 502B than was the case with the NASA/Langley-LTV arrow-wing airplane, as a comparison with figure 8(a) will show. This is because the poorer supersonic cruise lift-drag ratio of the Boeing airplane demands a higher throttle setting at this condition. At small engine sizes, where the throttle settings for the NASA/Langley-LTV airplane were already to the right of the cross-over point of these two throttle curves (fig. 5(b)), a still higher throttle requirement in the Boeing airplane produces a further sfc improvement for the VCE 112B relative to the VSCE 502B. A further comparison of the results of figures 10(a) and 8(a) shows that the superiority of the GE21/J9B1 over the P&WA VSCE 502B at large airflows diminishes somewhat for the Boeing airplane. This is again because of its poorer supersonic cruise lift-drag ratio demanding a greater throttle setting for the GE21/J9B1 than the maximum unaugmented one where minimum sfc occurs. Slight increases in the supersonic cruise afterburning requirement for this engine cause it to very quickly lose its sfc advantage over the P&WA VSCE 502B, as figure 5(b) shows.

Figures 10(b) - (e) show the various sizing constraints applied to the Boeing airplane in the same sequence as they were considered for the NASA/Langley-LTV airplane in figures 8(b) - (e). The engine size requirements are similar for the two airplanes except that they are just slightly smaller for the Boeing airplane since its takeoff gross weight is slightly less (see table I). This difference in the size requirement as well as differences in the curves themselves may cause the ranking of the engines to change in some cases where the range comparison was close before in the NASA/Langley-LTV airplane.

As mentioned previously, the operating empty less podded propulsion system weights of the two airplanes were apparently calculated at substantially different technology levels. This is as might be expected from two different design teams using rather non-specific common technology guidelines. For this reason, range comparisons between airplane configurations are probably not valid. The only range comparisons which should be made are among engines installed in a common airframe.

A summary of the range comparisons made with the Boeing airplane appears in bar graph form in figure 11. (This figure is analogous to figure 9 for the NASA/Langley-LTV airplane.) Figure 11(a) shows the comparisons at FAR 36, while figure 11(b) shows them at FAR 36 - 5 EPNdB. Figure 11(a) shows that with the least stringent of the sizing constraints at FAR 36 sideline noise (i. e., at the longer field length), the P&WA VCE 112B is the best choice. This same figure also shows that for the shorter field length requirement there is no significant range difference among the three leading engines (i. e., the P&WA VSCE 502B and VCE 112B, and the GE21/J9B1). The relative position of the VCE 112B is better in these comparisons than it was in the other airplane comparison (fig. 9(a)), while the relative position of the GE21/J9B1 is worse. Figure 11(b) shows that for a sideline noise of FAR 36 - 5 EPNdB, there is no significant range difference among the same three engines in leading contention, when sized for the longer field length. In the earlier NASA/Langley-LTV comparison, the GE21/J9B1 was superior at these same conditions (fig. 9(b)). Figure 11(b) also shows that at the shorter field length and lower noise, the most severe of the sizing constraints considered, the GE21/J9B1 double bypass engine has a definite range superiority. This was also the case in the previous engine comparison with the other airplane (fig. 9(b)), except that the range superiority exhibited by the double bypass engine then was about twice as great as that found in this comparison.

The consideration of a possible core jet noise floor for the VCE 112B effectively eliminates this engine as a leading contender. It increases the airflow required for FAR 36 sideline noise by about 20 percent. The resulting range decrement was about 7 percent for the longer field length and 9 percent for the shorter one. These percentage decrements were about the same for either airplane configuration. The impact of the core jet noise floor on the FAR 36 - 5 EPNdB results was not estimated since the data furnished by P&WA for such low throttle settings indicated a core jet velocity higher than that of the annular stream - the opposite of the desired coannular velocity profile.

Re-inclusion of the weight and performance margins, which were removed in this study, could cause a further significant spread among the mission results of the three prime candidate engines. The margins which were included in the data furnished by the engine companies differ widely between the two companies. So to make a fair comparison, adjustments had to be made. In this study, the margins were entirely removed. It can be rightly argued that an engine design should have some margin built into it to account for tolerance build-up, etc., but for comparative purposes the margin requirements should be estimated on a consistent basis. The question is usually never resolved until engines are actually built and tested. Since an actual airplane will not be built as a part of the SCAR program, it is likely that the question of margins will hinder the direct comparison of engines for a supersonic cruise airplane for some time to come. Meanwhile, the above results with margins removed represent the best estimate of the potential of each engine concept.

CONCLUDING REMARKS

Sideline noise and takeoff field length were varied for two types of Mach 2.32 cruise airplane to determine how these factors affect the engine cycle selection. Sideline noise levels of FAR 36 (108 EPNdB) and FAR 36 - 5 EPNdB (103 EPNdB) were considered at thrust levels commensurate with takeoff field lengths of both 12 000 feet (3658 m) and 10 500 feet (3200 m). The two airplanes simulated in these studies were an advanced NASA/Langley-LTV arrow-wing design and a Boeing modified delta-wing with tail derived from the previously proposed 2707-300 SST, but without the blended body feature of their newest version. The takeoff thrust requirements of the two airplanes are about equal since differences in wing loading compensate for differences in lift coefficient available at the lift-off condition. The major airplane difference affecting the engine comparison is in the supersonic cruise lift-drag ratio, which is over 11 percent higher for the Langley-LTV airplane. This necessitates a different cruise throttle setting at a different sfc for engines sized by the same takeoff constraint. The empty weights are different, too, for these two configurations, but this difference does not significantly affect the engine comparison. It is, however, reflected in range differences between the two configurations which may not be real due to different structural weight analysis techniques used by the two design teams.

Three advanced variable cycle engines (VCE's) defined by both Pratt & Whitney and General Electric in NASA/Lewis contracted studies were considered herein. They were the P&WA VSCE 502B (an advanced duct burning turbofan), its derivative rear-valve VCE 112B, and the GE21/J9B1 double bypass engine. All of these engines may be viewed as VCE's because of valving or extensive flow modulation via variable components or novel control techniques. An advanced conventional engine, the P&WA LBE 405B mini-bypass turbojet, was also considered and used as a baseline against which VCE benefits were measured. All the VCE's out-performed the baseline engine by substantial margins in a design range comparison, regardless of airplane choice or takeoff restrictions. It is expected that similar results would have been obtained if the conventional baseline engine had been the GE21/F12B1 low-bypass augmented turbofan, a baseline engine used by General Electric in their Phase II study contract with NASA/Lewis. The choice among the three VCE's, however, depends on the takeoff field length and sideline noise restrictions as well as the airplane configuration selected. There is some doubt, though, that the VCE 112B in its present form can receive the full coannular noise suppression benefit attributed to it. For this reason, it represents a choice of somewhat higher risk among the leading engines.

For the least restrictive of the sizing criteria considered (i. e., 108 EPNdB sideline noise and a 12 000-ft or 3658-m takeoff field length), the P&WA VSCE 502B and VCE 112B engines become the prime candidates. The VSCE 502B is slightly better in the Langley-LTV airplane, while the rear-valve VCE 112B is slightly better in the Boeing airplane. As the takeoff engine sizing constraint is made more severe, the GE double bypass VCE significantly improves its relative position in the range comparison. At the most restrictive of the takeoff conditions considered in this study, the double bypass VCE was the best engine in both airplane range comparisons. Care must be exercized, however, in selecting the takeoff noise and field length criteria to be observed, so as not to specify a greater requirement than is absolutely necessary. Such over-specification unduly penalizes the range potential of the airplane. This can ultimately be translated into an economic penalty.

In three out of the four sizing cases considered, the airplane choice changed the preferred engine choice, based on design range as the sole figure of merit. In these cases, however, the range superiority was small -- never in excess of 100 nautical miles (185 km). In the actual engine selection process, though, other considerations such as initial cost, development risk, ease of maintenance, and reliability would be allowed to overshadow small increments of range superiority. Nevertheless, these results do show that the choice of airplane could influence the engine selection.

None of the engines considered had any weight or thrust penalties imposed for the use of mechanical jet noise suppressors. They were assumed to benefit from either annular or coannular flow suppression techniques recently discovered in static model testing of exhaust systems. This necessitated modifying the P&WA LBE 405B to incorporate a plug nozzle instead of the convergent-divergent system common to the P&WA engine designs. The VCE 112B noise results are predicated on the assumption that its coannular noise benefit related to the outer stream exit velocity will be the same as for the more conventional VSCE 502B. This assumption ignores the fact that the core jet noise of the VCE 112B will be significantly higher because of its greater mass flow and velocity relative to the VSCE 502B core jet, for the same outer stream velocity. The core jet noise level probably represents a floor below which no more coannular suppression benefit can be received. Unfortunately, experimental model test data are unavailable for the VCE 112B exhaust conditions. The estimated core jet noise floor for this engine would reduce the coannular noise benefit to about half that assumed. This would raise the engine sizing requirements by 20 percent at the FAR 36 sideline noise condition. The resultant range penalties of 7 to 9 percent are sufficient to eliminate the VCE 112B as a leading contender among the engines. It is possible, however, that a plug nozzle could be used with the VCE 112B in such a way as to benefit from the annular noise suppression assumed for the double bypass VCE and the LBE 405B mini-bypass turbojet. The current Phase III SCAR studies of P&WA are addressing, among other things, the question of using a plug nozzle in their VCE concept as well as any possible cycle changes that might make this concept more compatible with an annular flow exhaust scheme.

APPENDIX - SYMBOLS

C_D	drag coefficient
C_{f_g}	nozzle installed gross thrust coefficient
C_L	lift coefficient
C_{L_o}	C_L where $C_D = C_{D_{min}}$
$C_{L_{TO}}$	C_L at lift-off
F_n	installed net thrust, lb (N)
FAR	Federal Air Regulation
g	gravitational constant, 32.2 $(lb_m\text{-ft})/(lb_f\text{-sec}^2)$; $[1\ (kg\text{-m})/(N\text{-sec}^2)]$
N	noise, EPNdB
S	wing planform area, ft^2 (m^2)
sfc	installed specific fuel consumption, $(lb_m/hr)/lb_f$ $(kg/sec)/N$
$\dot{W}$	mass flow rate, lb/sec (kg/sec)
W_g	takeoff gross weight, lb (kg)
V	velocity, ft/sec (m/sec)
ρ	density of air, $slug/ft^3$ (kg/m^3)
ρ_o	standard-day density of air at sea-level, $slug/ft^3$ (kg/m^3)
σ	ρ/ρ_o, density ratio for air

Subscripts:

by	bypass stream
eff	effective
i	induced
j	jet exhaust
min	minimum
ref	reference
tot	total
∞	free-stream station
0	engine inlet station
8	engine exhaust station

REFERENCES

1. Szeliga, R.; and Allan, R. D.: Advanced Supersonic Technology Propulsion Study. (R74AEG330, General Electric Co.; NAS3-16950), NASA CR-143634, 1974.

2. Sabatella, J. A., ed.: Advanced Supersonic Propulsion Study. (PWA TM-4871, Pratt & Whitney Aircraft; NAS3-16948), NASA CR-134633, 1974.

3. Allan, R. D.: Advanced Supersonic Propulsion System; Phase II, Final Report. (General Electric Co.; NAS3-16950) NASA CR-134913, 1976.

4. Howlett, R. A.; et al.: Advanced Supersonic Propulsion Study Phase II, Final Report. (PWA-5312, Pratt & Whitney Aircraft; NAS3-16948), NASA CR-134904, 1975.

5. Advanced Supersonic Technology Concept Study Reference Characteristics. (LTV Aerospace Corp.; NAS1-10900), NASA CR-132374, 1973.

6. An Airline's View of Reserve Fuel Requirements for the Supersonic Transport. LR-26133, Lockheed-Calif. Co., 1973.

7. Corning, Gerald: Supersonic and Subsonic Airplane Design. 2nd ed., Edwards Bros., Inc., 1960.

8. Jet Noise Prediction. Aerospace Information Rept. 876, SAE, July 10, 1965.

9. Definitions and Procedures for Computing the Perceived Noise Level of Aircraft Noise. Aerospace Recommended Practice 865, SAE, Oct. 15, 1964.

TABLE I. - MAJOR AIRPLANE CHARACTERISTICS

Characteristic	Airplane	
	NASA/Langley-LTV	Boeing
Takeoff gross weight, lb (kg)	762 000 (345 637)	750 000 (340 194)
Number of passengers	292	273
Payload, lb (kg)	61 028 (27 682)	57 057 (25 881)
Reference wing area, ft^2 (m^2)	9969 (926)	7700 (715)
Operating empty less podded propulsion weight, lb (kg)	259 913 (117 897)	271 920 (123 343)
Lift-off C_L	0.55	0.70

TABLE II. - ENGINE CYCLE, WEIGHT, AND DIMENSIONAL CHARACTERISTICS

Characteristic	P&WA LBE 405B	P&WA VSCE 502B	P&WA VCE 112B	GE21/J9 Study B1
Fan pressure ratio	4.1	3.3	5.8	3.1/4.0
Bypass ratio	0.1	1.3	2.5	0.7/0.4
Overall pressure ratio	17	20	25	22.4
Max. combustor exit temperature, F (C)	2600 (1427)	2800 (1538)	2800/1900 (1538/1038)	2826 (1552)
Total corrected airflow, lb/sec (kg/sec)	900 (408)	900 (408)	900 (408)	900/740 (408/336)
Adjusted engine weight, including nozz./rev., lb (kg)	15 200 (6900)	13 085 (5940)	13 156 (5960)	13 250 (6010)
Max. engine diameter, in (m)	82.8 (2.10)	88 (2.23)	82 (2.08)	76.5 (1.94)
Length of engine, including nozz./rev., in (m)	345 (8.75)	266 (6.76)	305 (7.[illegible])	291 (7.39)
Inlet cowl lip diameter, in (m)	70.8 (1.80)	74.0 (1.88)	74.0 (1.88)	62.5 (1.59)
Weight of inlet, nacelle, mounts, lb (kg)	5760 (2610)	5640 (2560)	5930 (2690)	4440 (2015)
Total weight per pod, lb (kg)	20 960 (9510)	18 725 (8500)	19 086 (8650)	17 690 (8030)
Total pod length, in (m)	487 (12.4)	412 (10.5)	450 (11.4)	416 (10.6)

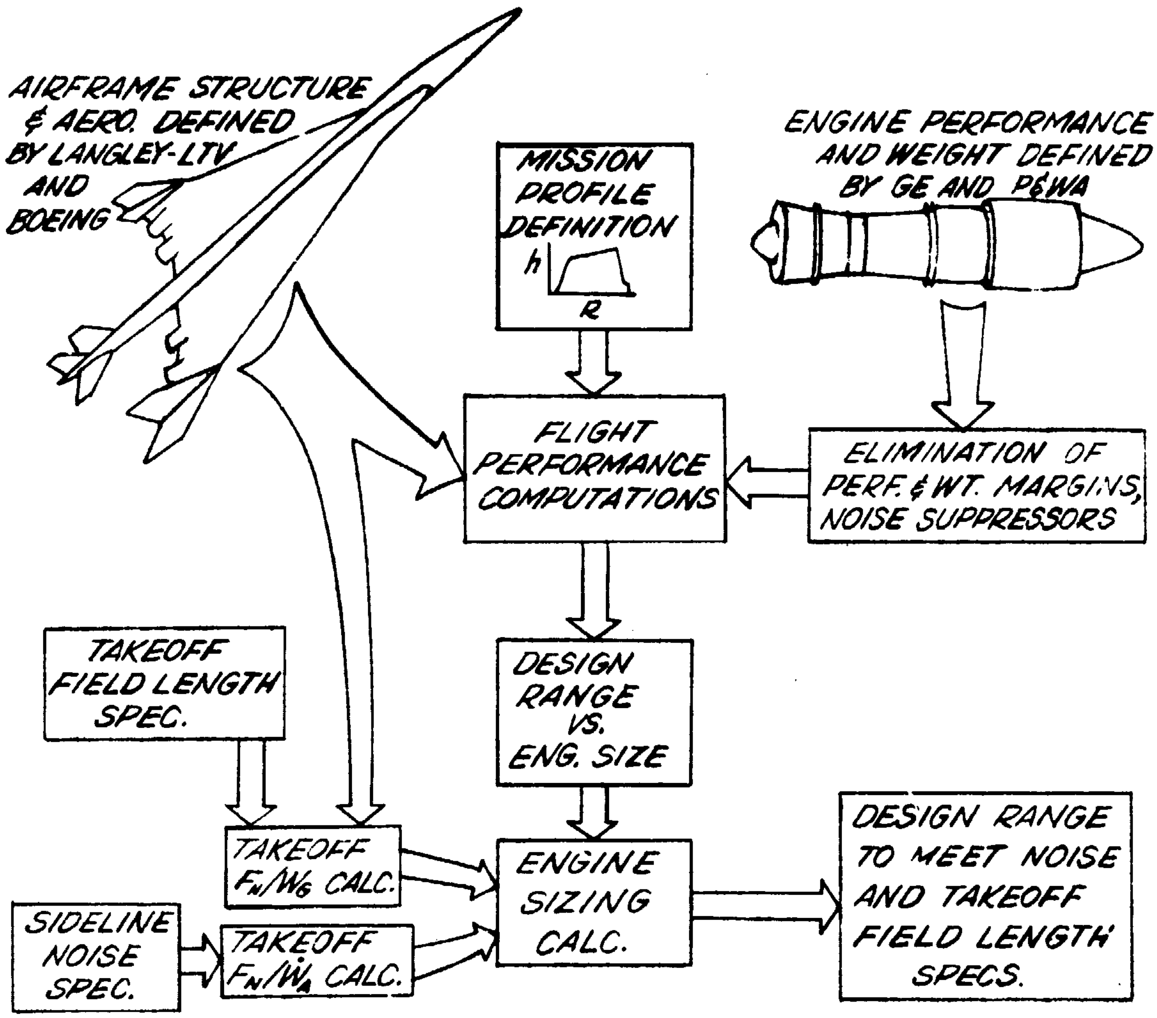

FIGURE 1. – CALCULATION FLOW CHART.

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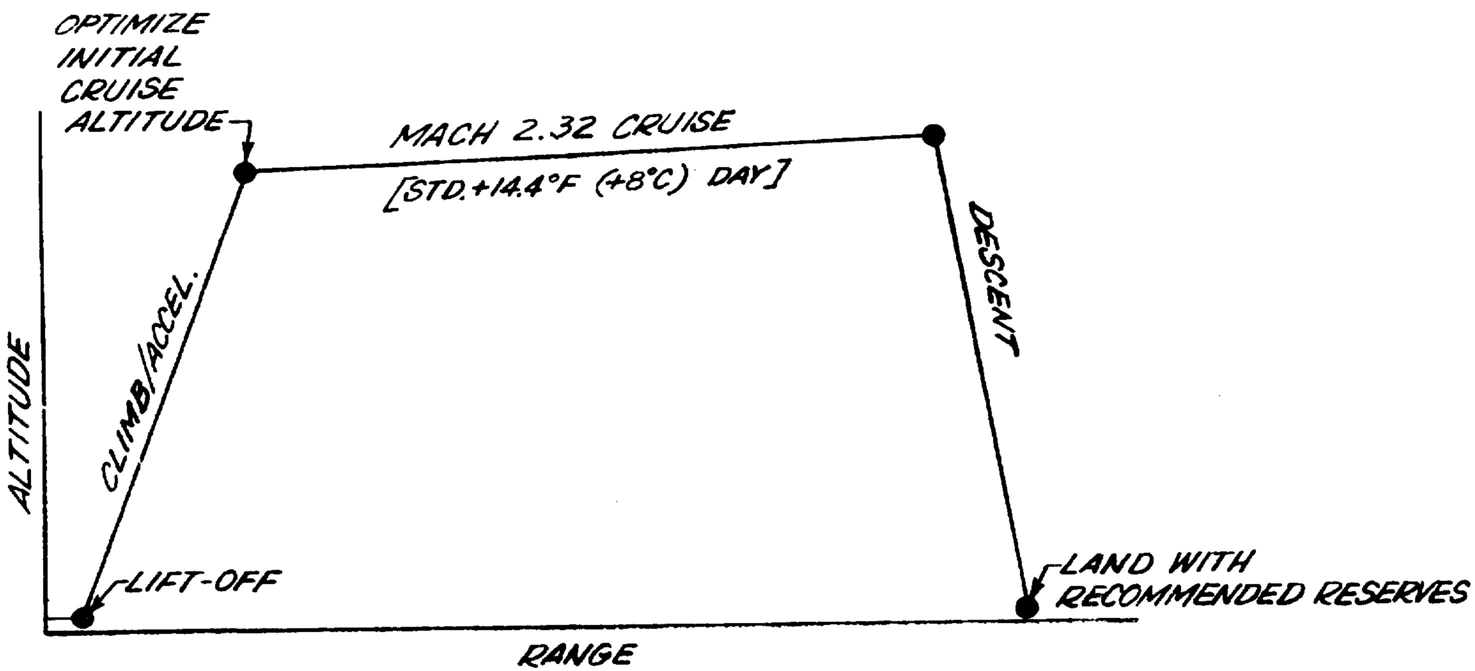


FIGURE 2. – REFERENCE MISSION DESCRIPTION.

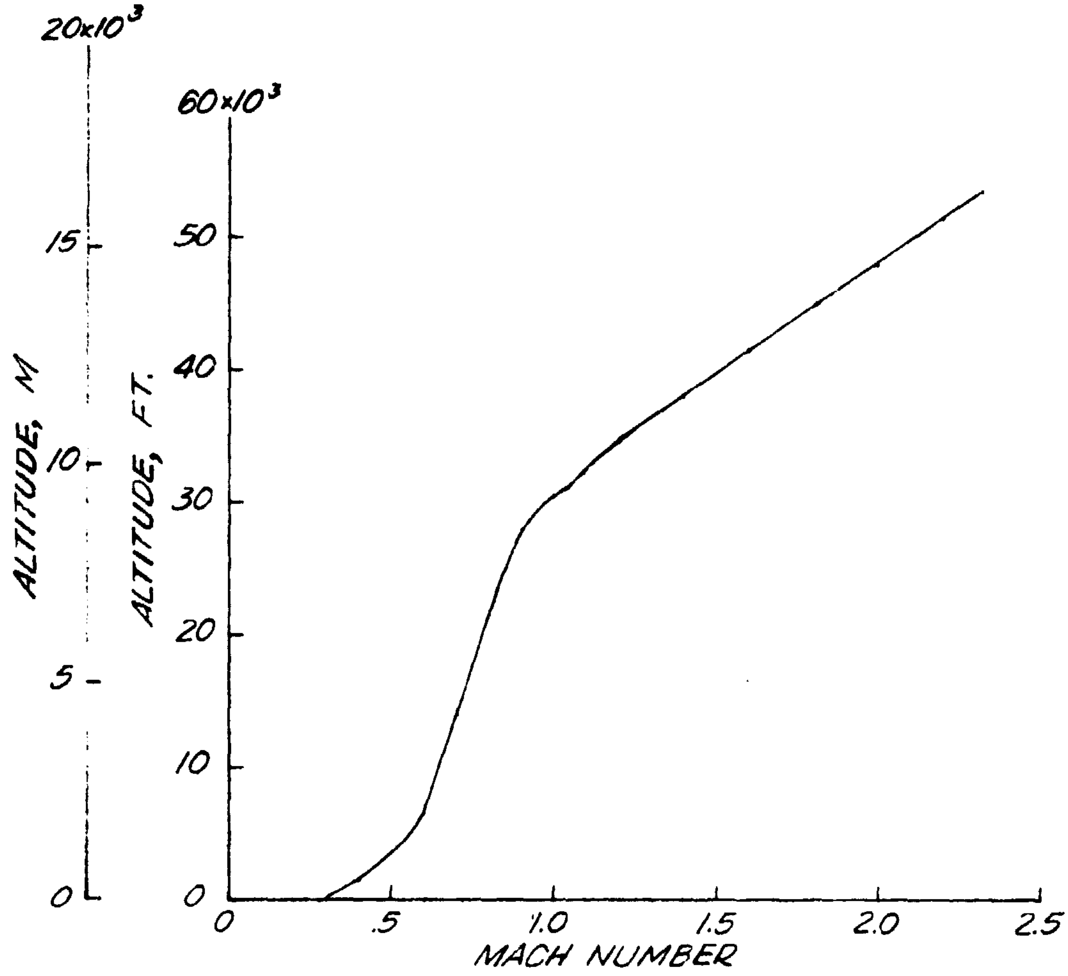


FIGURE 3. - FLIGHT PATH USED IN CLIMB/ACCELERATION.

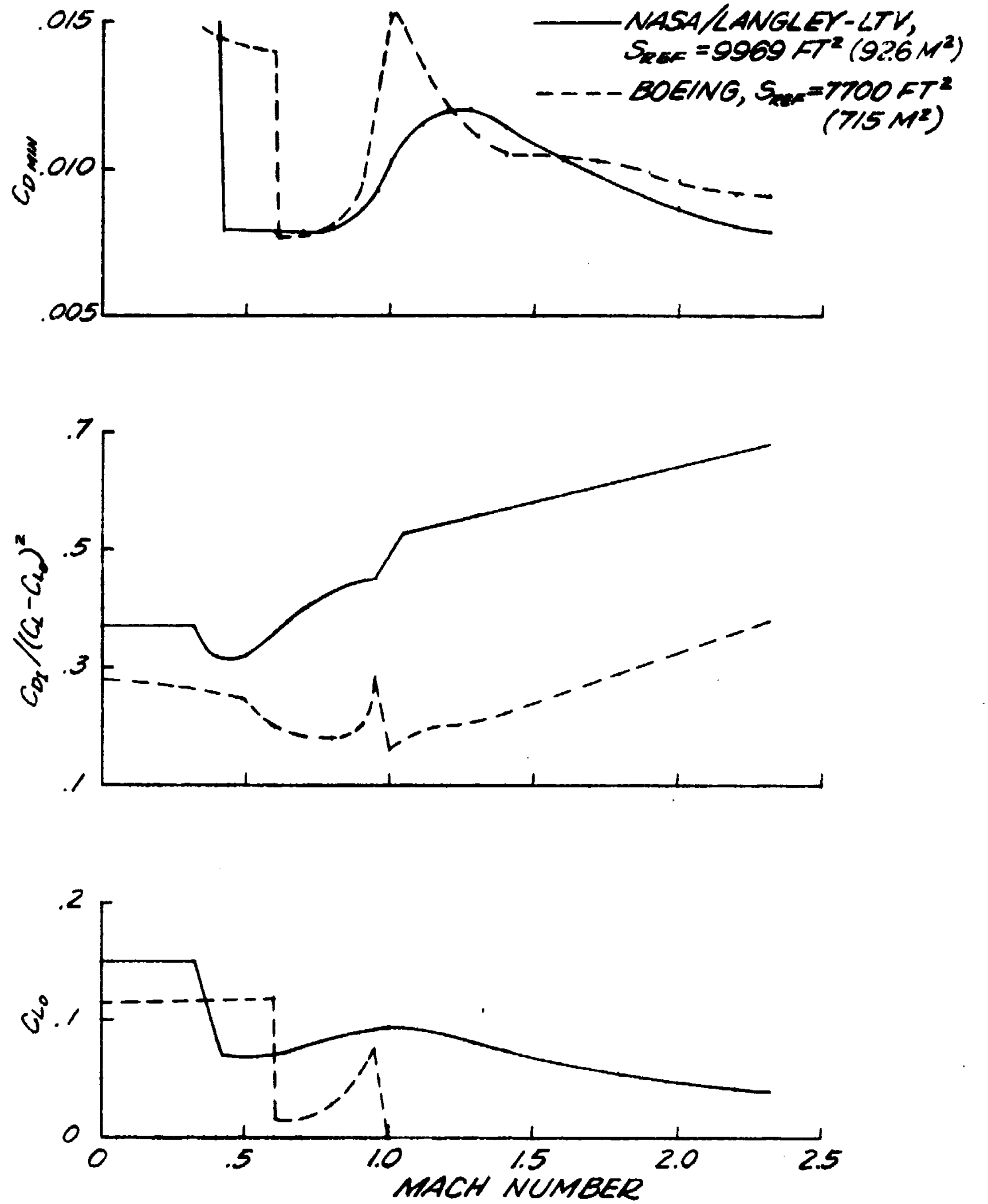
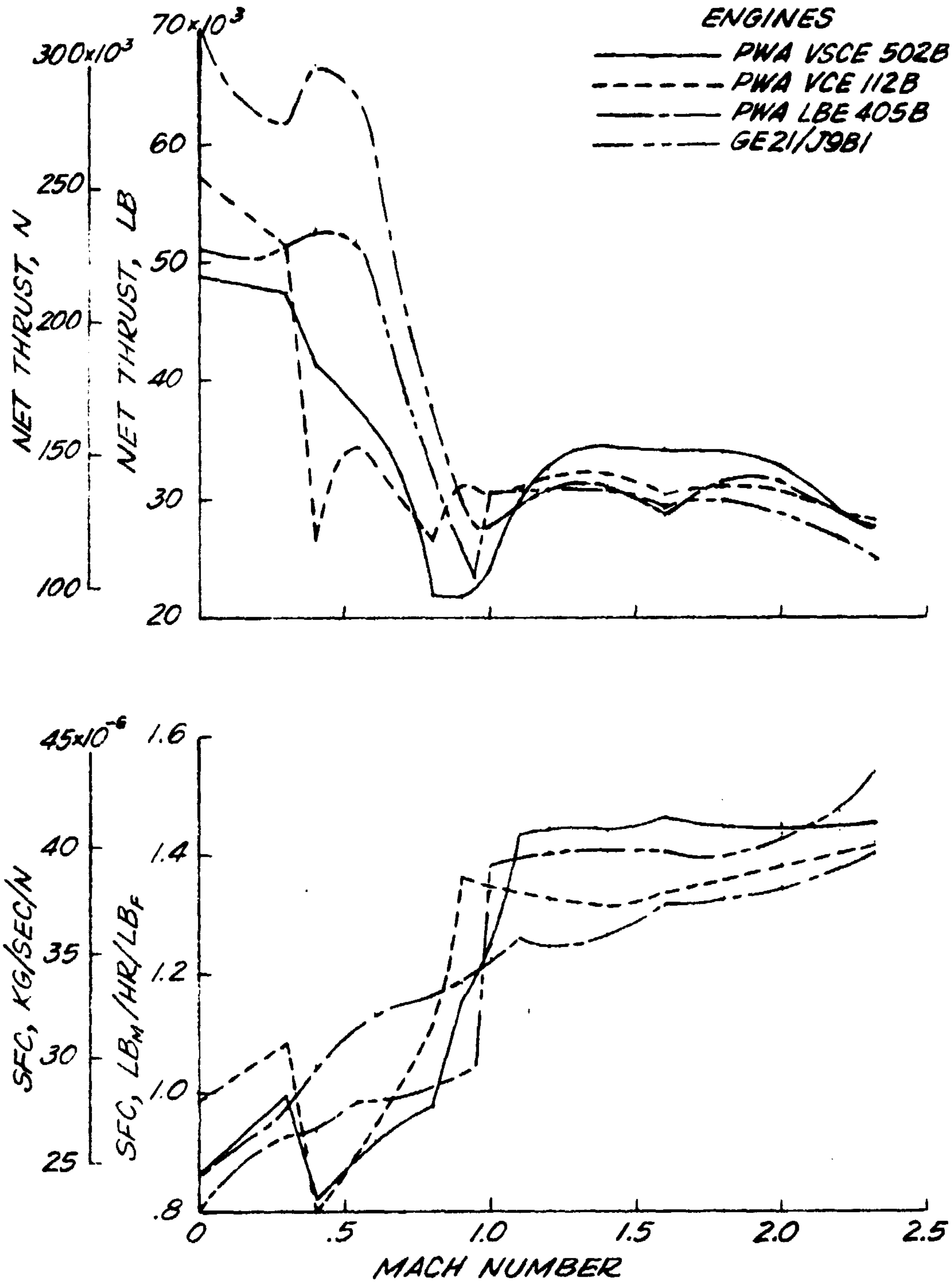
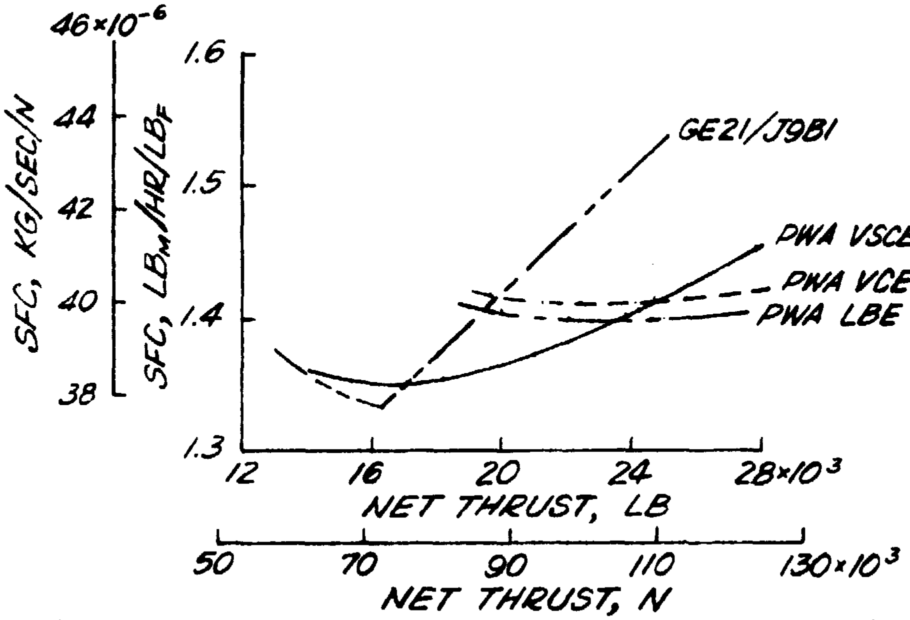


FIGURE 4.- COMPARISON OF AERODYNAMIC COEFFICIENTS USED TO SIMULATE THE TWO TYPES OF AIRPLANES CONSIDERED IN THIS STUDY. REFERENCE FLIGHT PATH. INCLUDES 900 LB/SEC (408 KG/SEC) SIZE P&WA LBE 405B NACELLES.

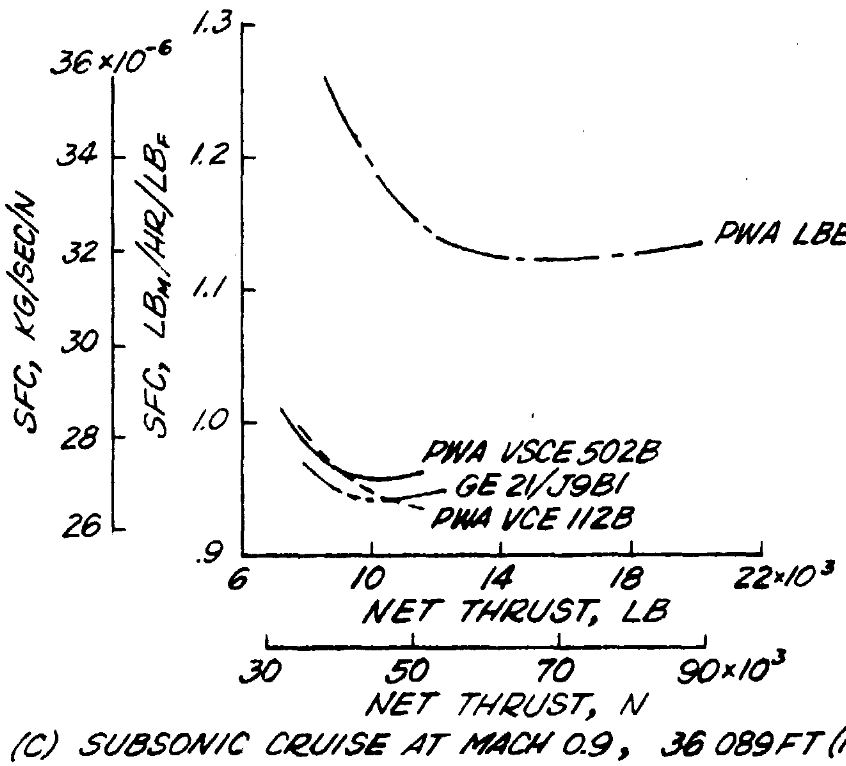


(A) CLIMB/ACCELERATION OVER REFERENCE FLIGHT PATH.

FIGURE 5.—INSTALLED ENGINE PERFORMANCE. STD. +14.4°F (48°C) DAY. THRUST AND FUEL FLOW MARGINS REMOVED. ADJUSTED FOR COMMON INLET RECOVERY. 900 LB/SEC (408 KG/SEC) SIZE.

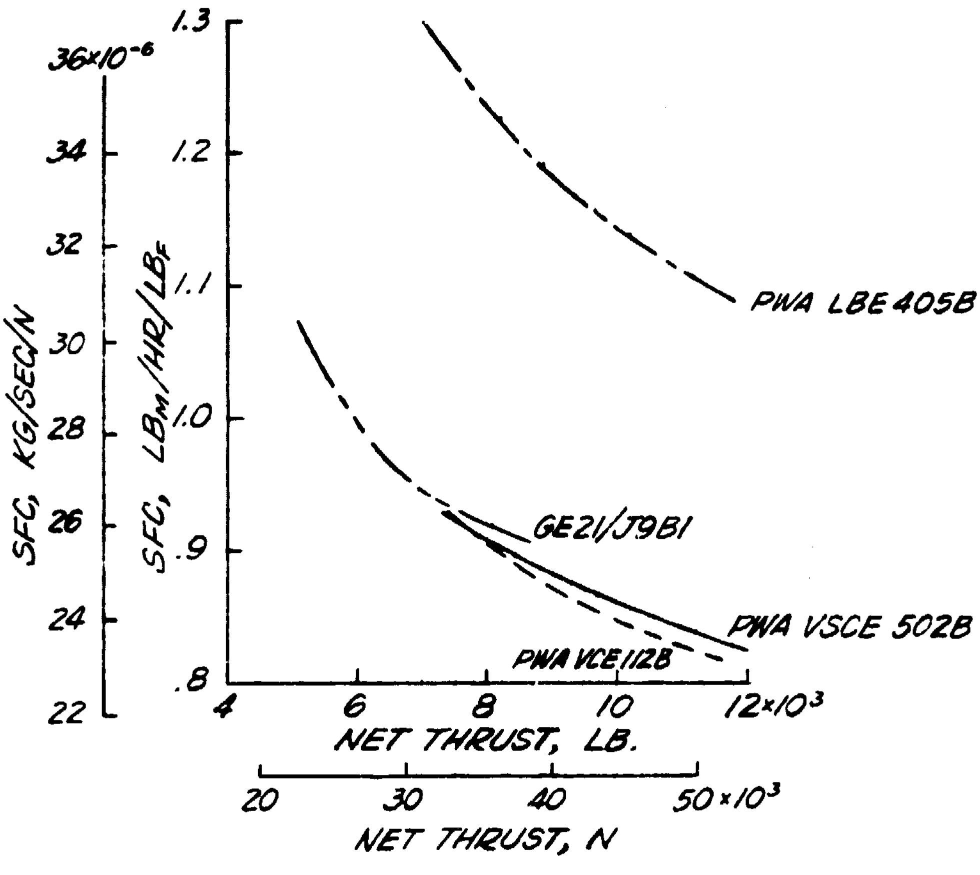


(B) SUPERSONIC CRUISE AT MACH 2.32, 53 400 FT (16 276 M).



(C) SUBSONIC CRUISE AT MACH 0.9, 36 089 FT (11 000 M).

FIGURE 5. – CONTINUED.



(D) HOLD AT MACH 0.45, 15000 FT (4572 M).

FIGURE 5. – CONCLUDED.

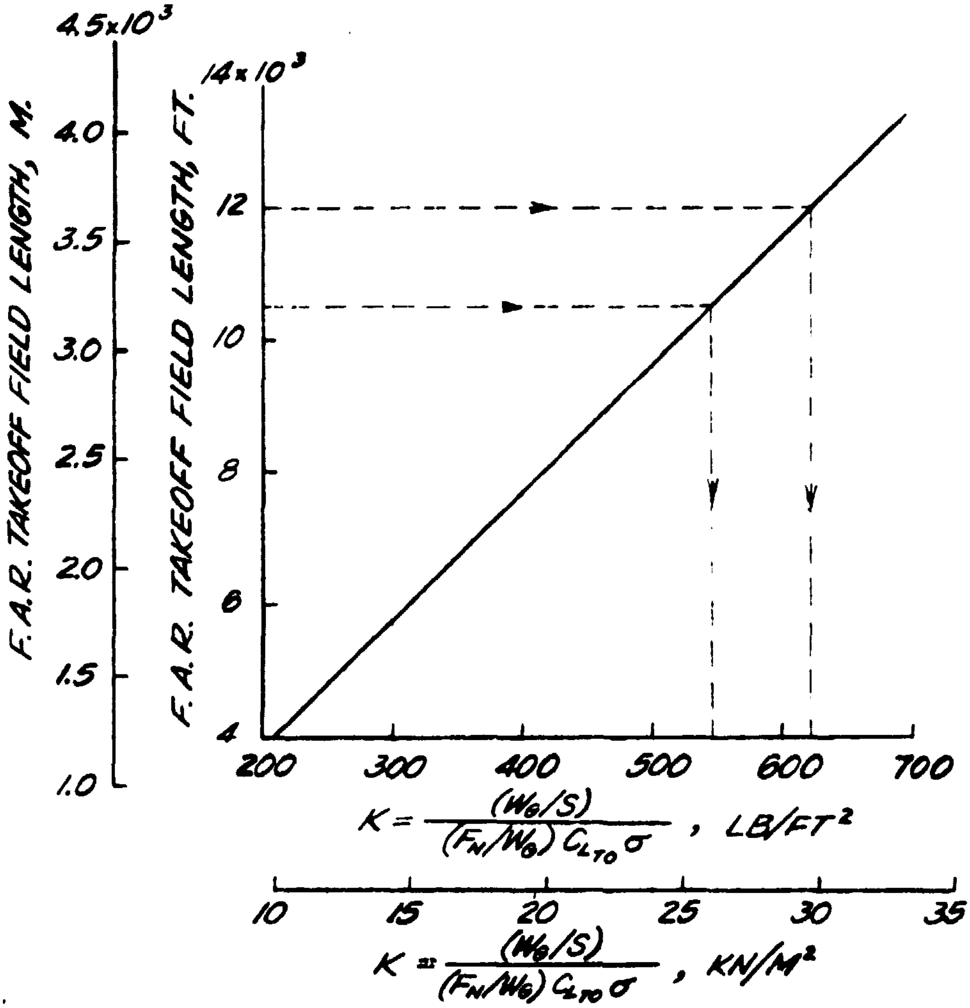


FIGURE 6. – F.A.R. TAKEOFF FIELD LENGTH RELATED TO SIGNIFICANT AIRPLANE PARAMETERS EVALUATED AT LIFT-OFF CONDITION. BASED ON EMPIRICAL DATA.

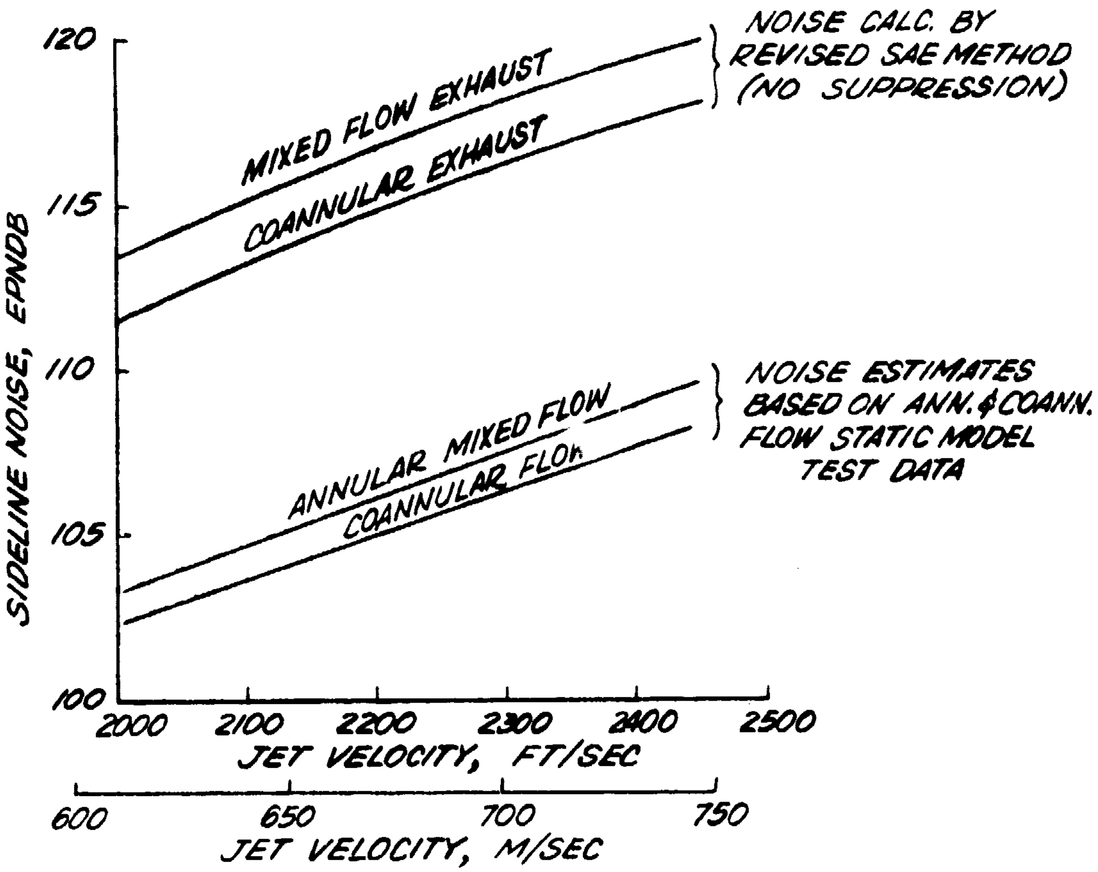
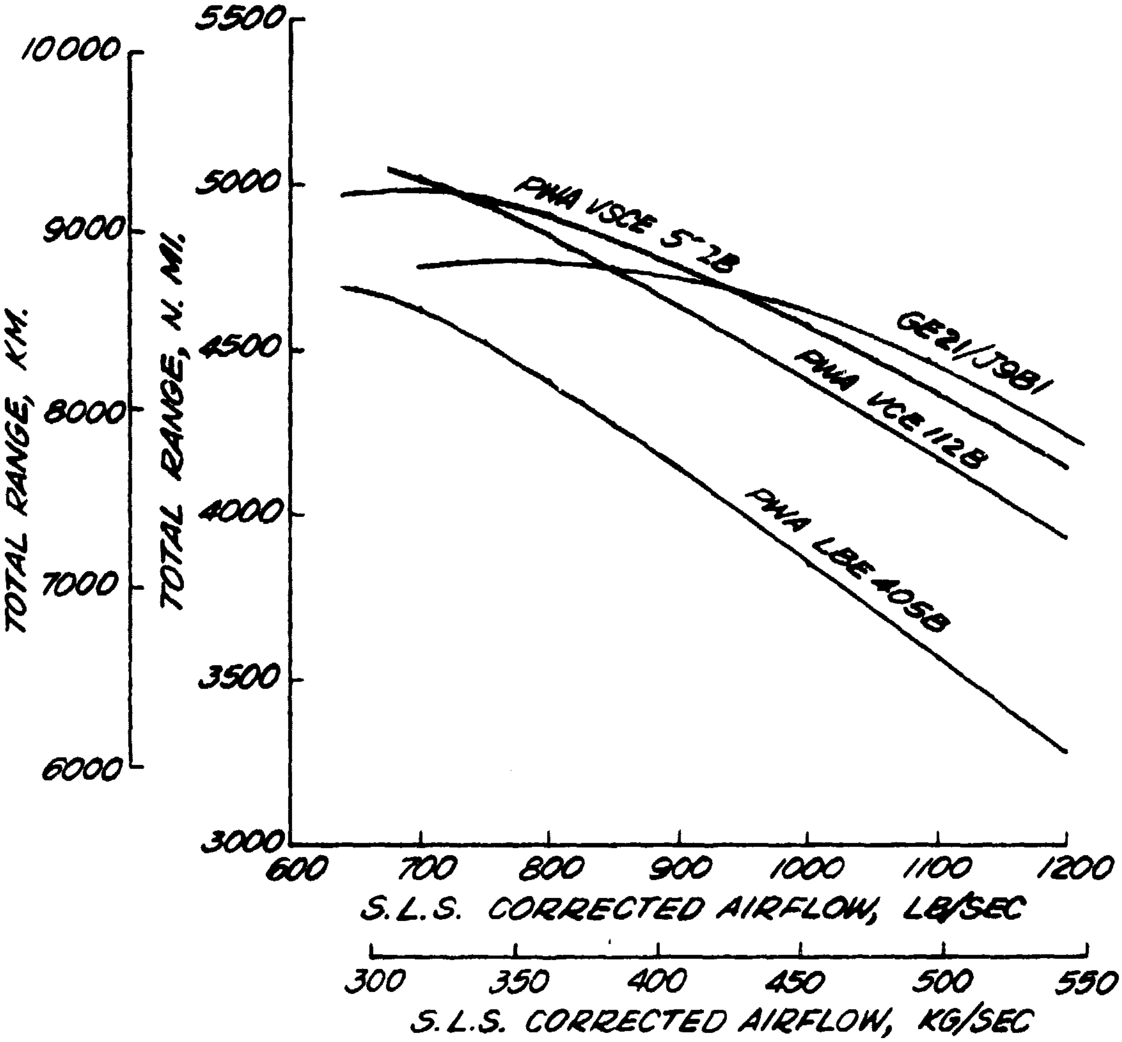
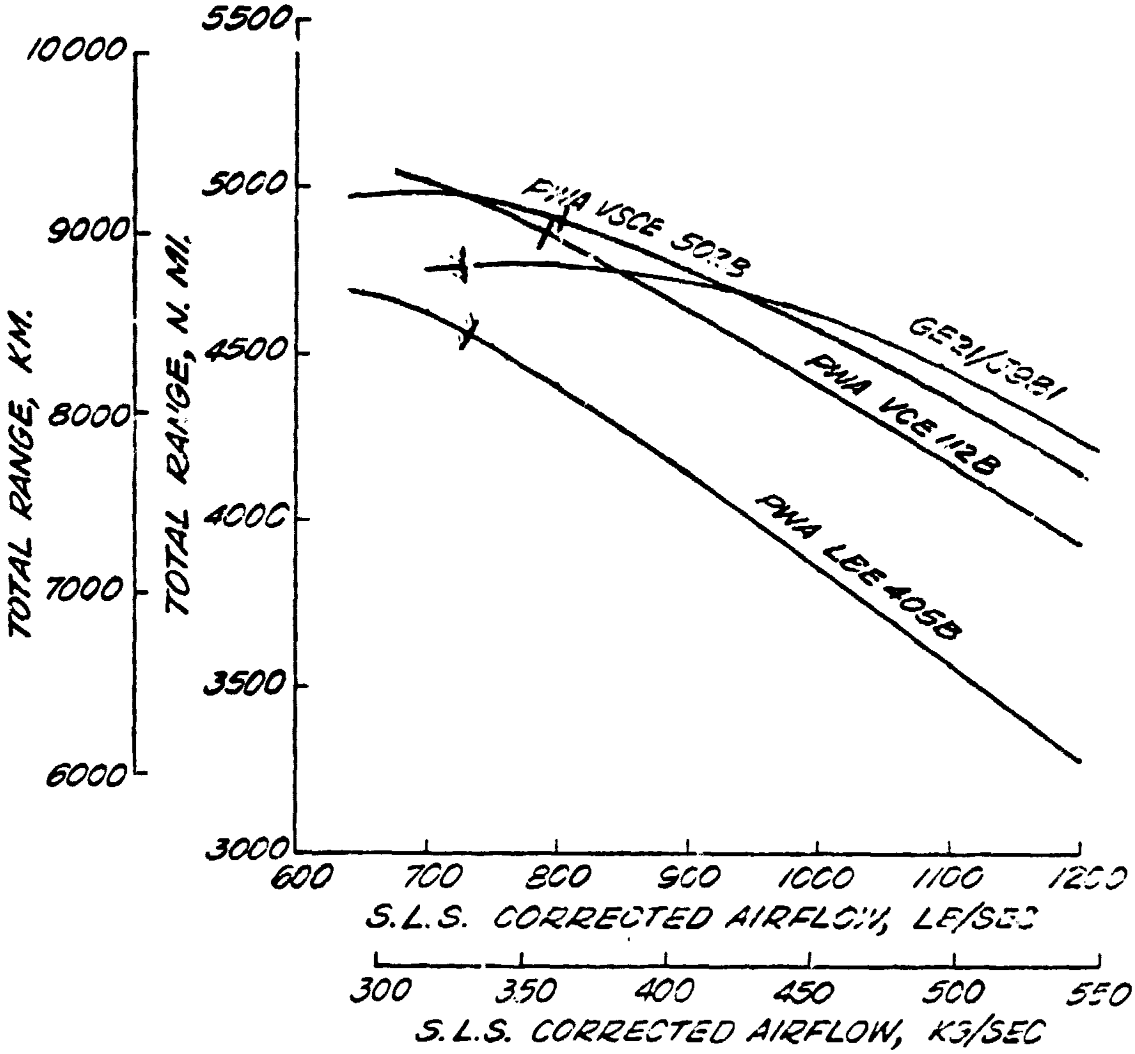


FIGURE 7.– AIRPLANE MAXIMUM SIDELINE JET NOISE RELATED TO ABSOLUTE JET VELOCITY AT MACH 0.3 AIRPLANE SPEED. NET THRUST, 61 000 LB (271 341 N) PER ENGINE. FOUR-ENGINE AIRPLANE. CORE FLOW IN COANNULAR EXHAUST (BPR = 1.3) ASSUMED TO MAKE NEGLIGIBLE CONTRIBUTION TO TOTAL NOISE, DUE TO ITS LOWER VELOCITY. NO MECHANICAL SUPPRESSORS.



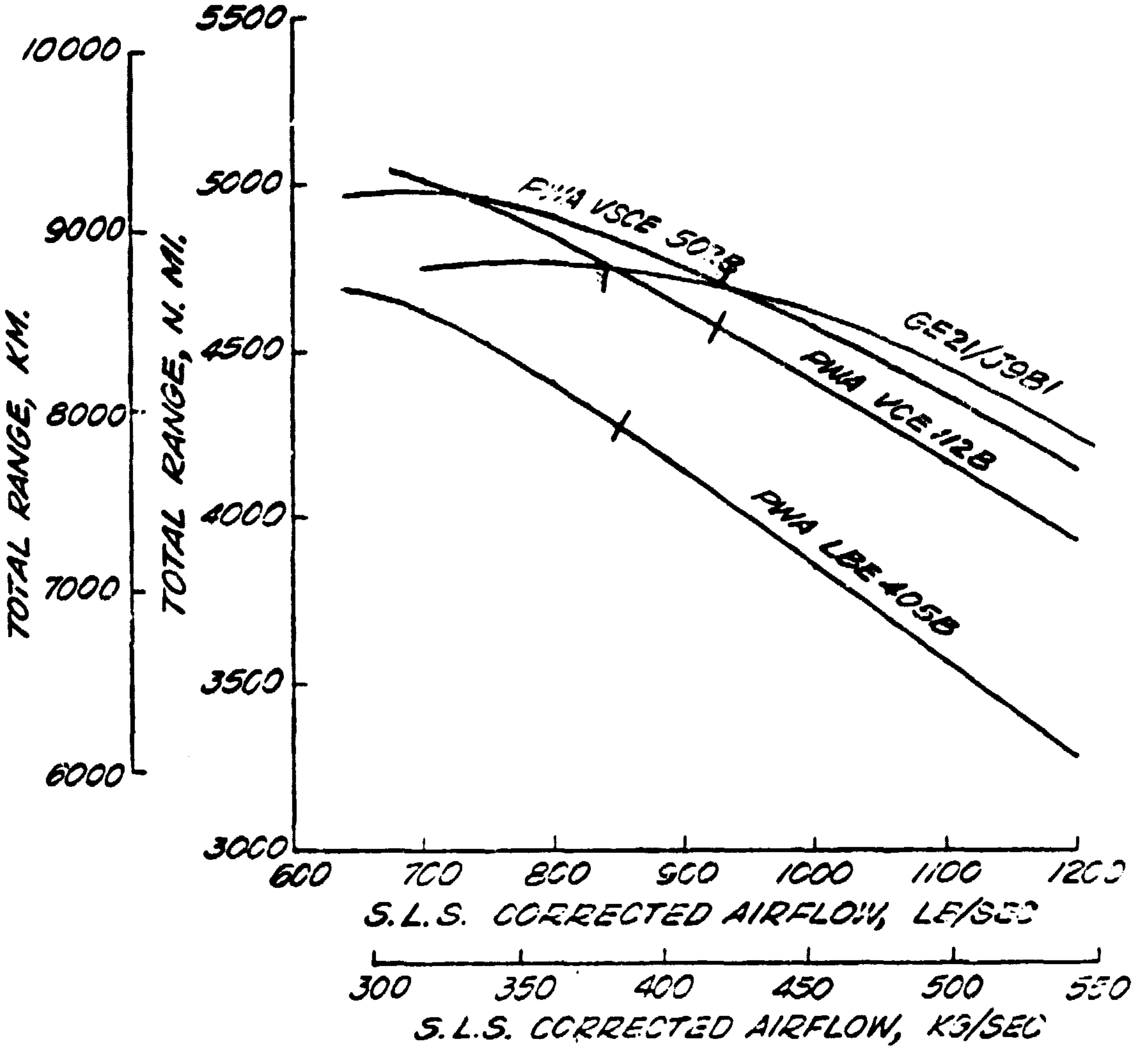
(A) NO SIZING CONSTRAINTS.

FIGURE 8. - EFFECT OF ENGINE SIZE ON RANGE FOR A NASA/LANGLEY-LTV MACH 2.32 AIRPLANE. TAKEOFF GROSS WEIGHT, 762 000 LB. (345 637 KG.). 292-PASSENGER PAYLOAD.



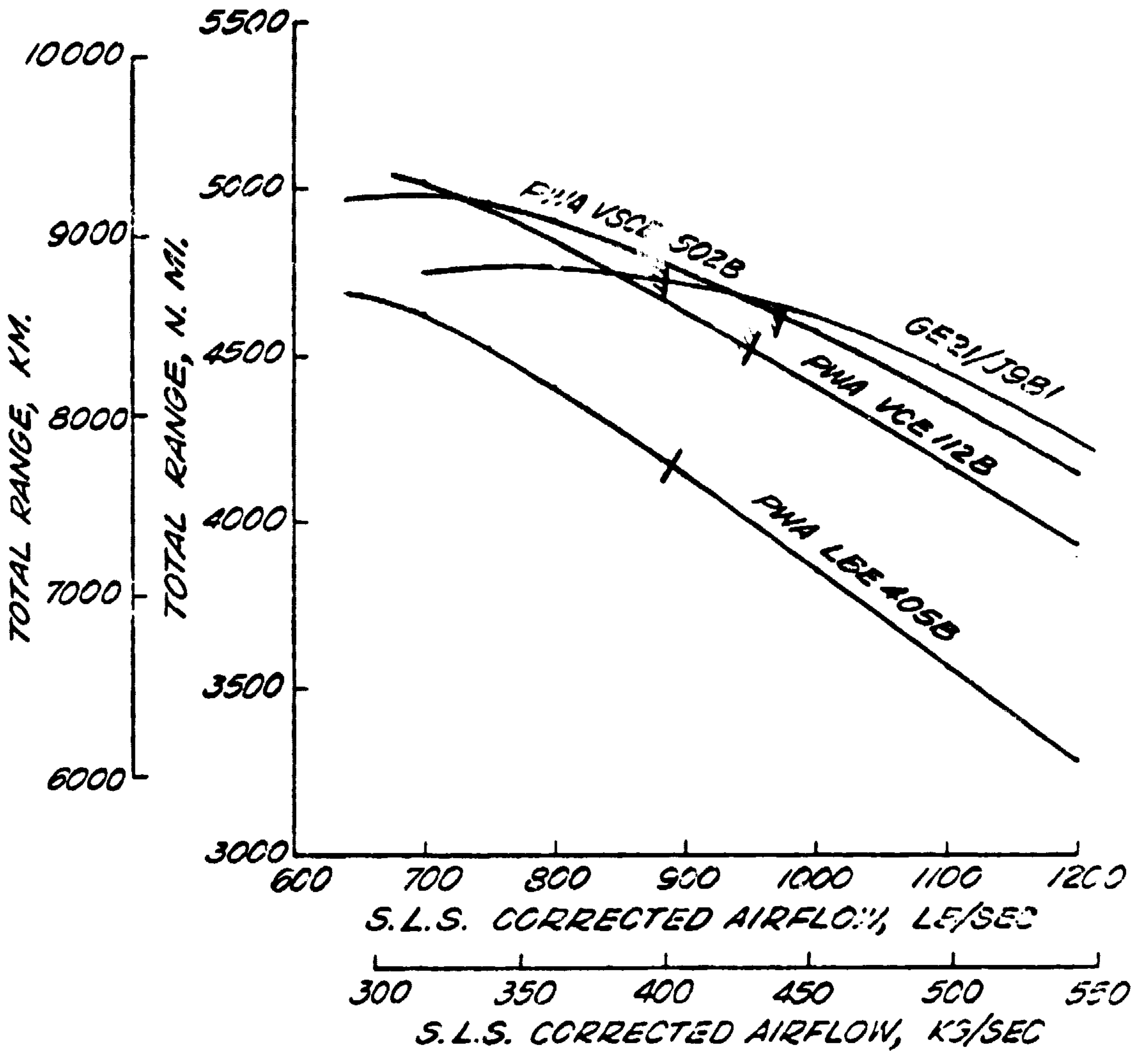
(B) CONSTRAINED FOR FAR 36 (108 EPNDB) SIDELINE NOISE WITH 12 000 FT (3658 M) F.A.R. TAKEOFF FIELD LENGTH.

FIGURE 8. – CONTINUED.



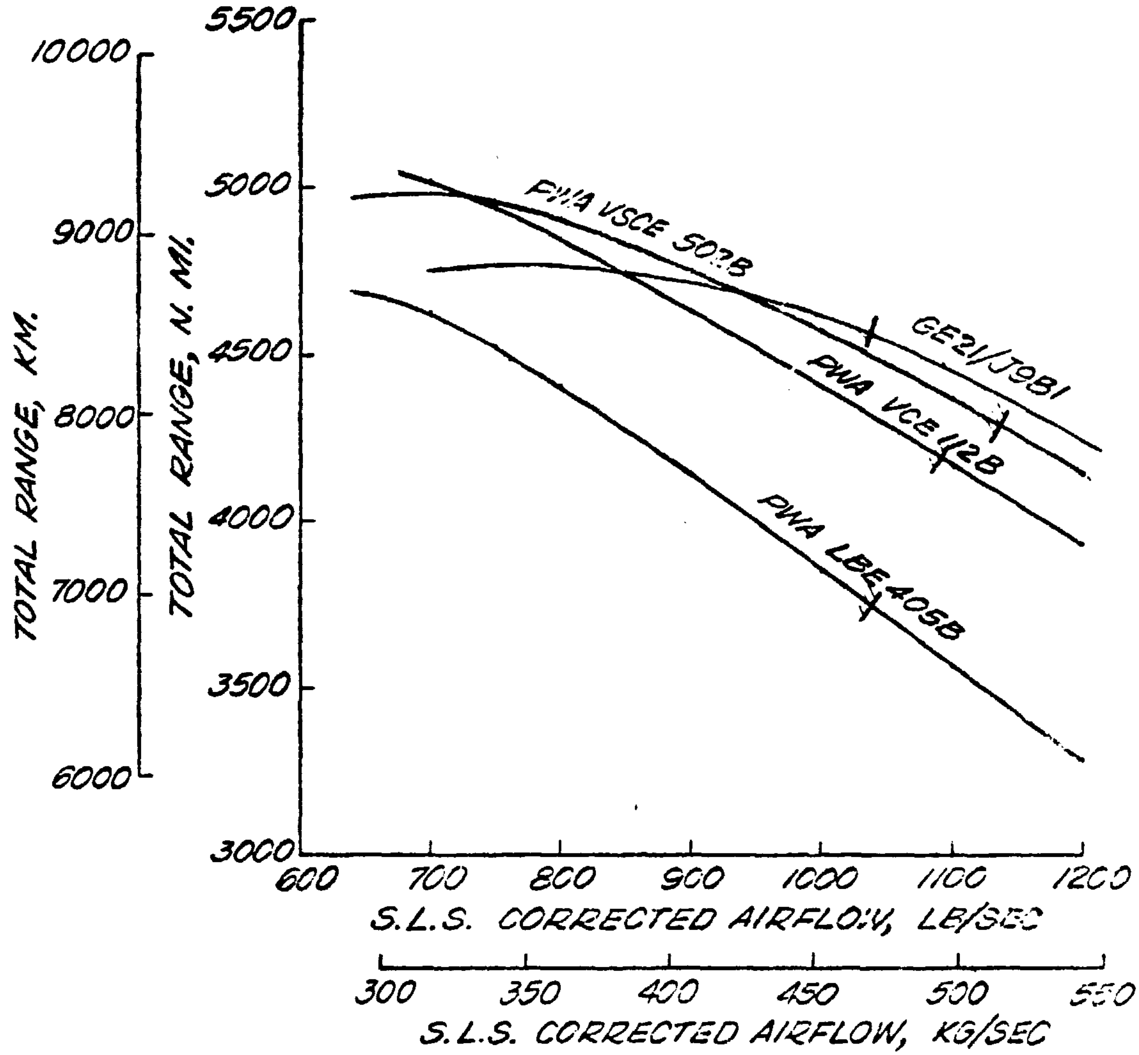
(C) CONSTRAINED FOR FAR 36 (108 EPNDB) SIDELINE NOISE WITH 10 500 FT (3200 M) F.A.R. TAKEOFF FIELD LENGTH.

FIGURE 8. – CONTINUED.



(D) CONSTRAINED FOR FAR 36-5 EPNDB (103 EPNDB) SIDELINE NOISE WITH 12 000 FT. (3658 M) F.A.R. TAKEOFF FIELD LENGTH.

FIGURE 8. – CONTINUED.



(E) CONSTRAINED FOR FAR36-5 EPNDB (103 EPNDB) SIDELINE NOISE WITH 10 500 FT (3200 M) F.A.R. TAKEOFF FIELD LENGTH.

FIGURE 8.– CONCLUDED.

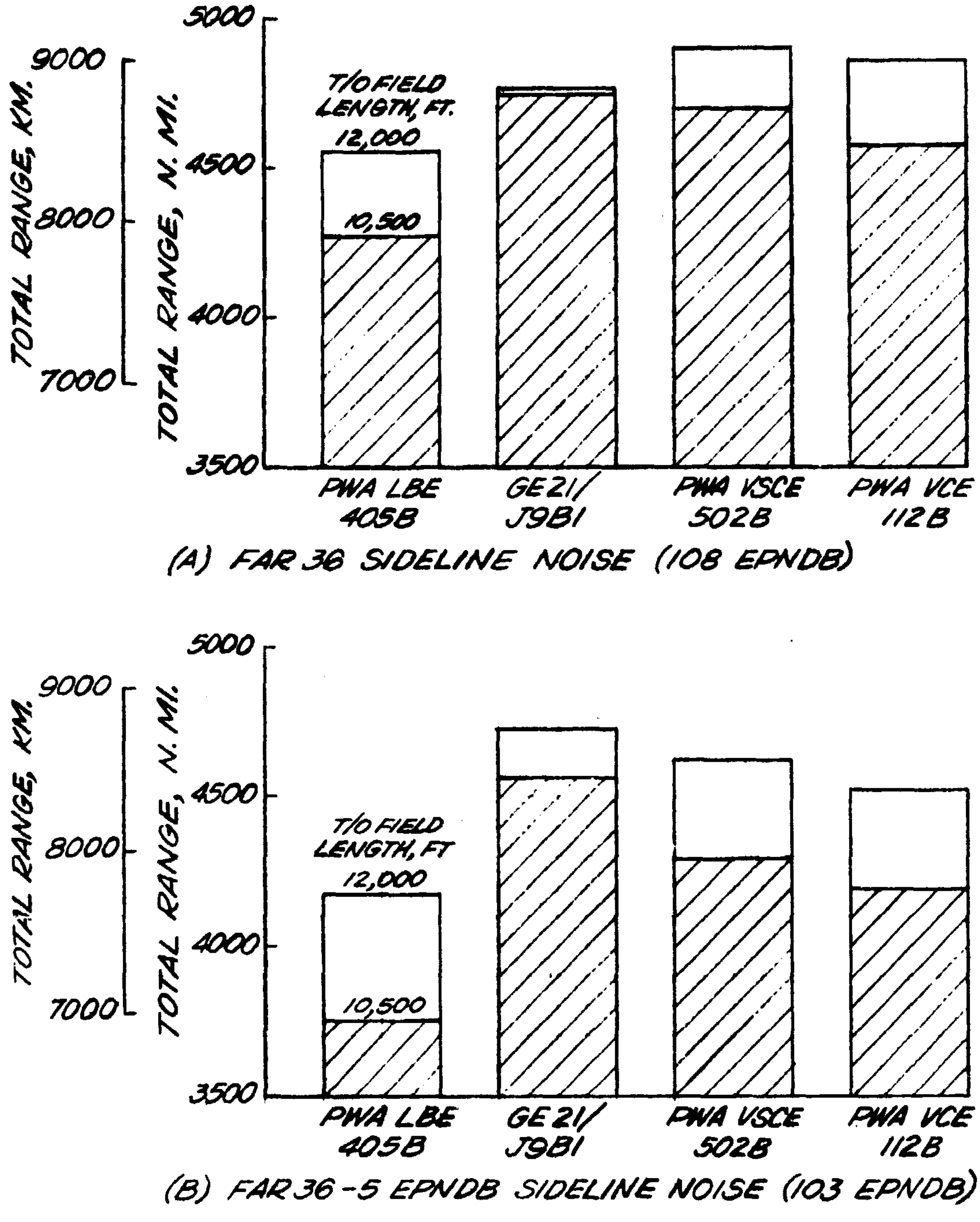
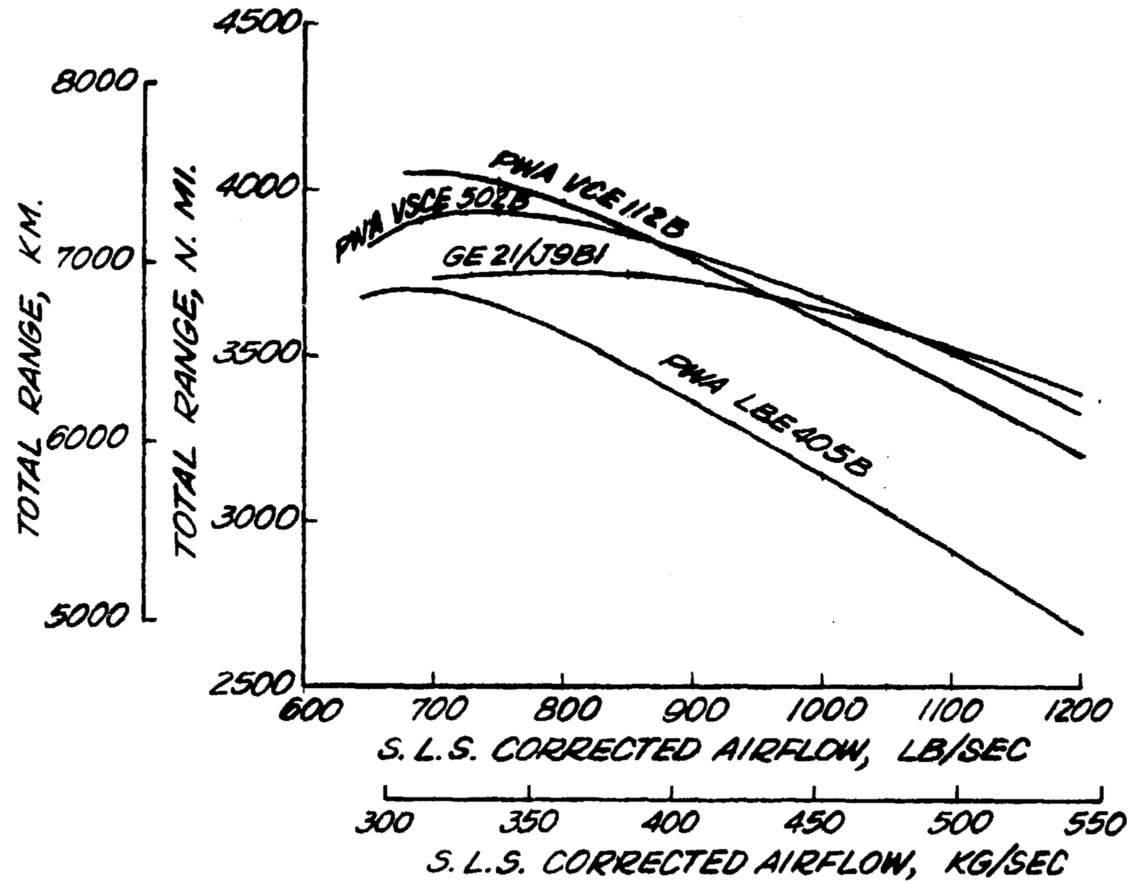
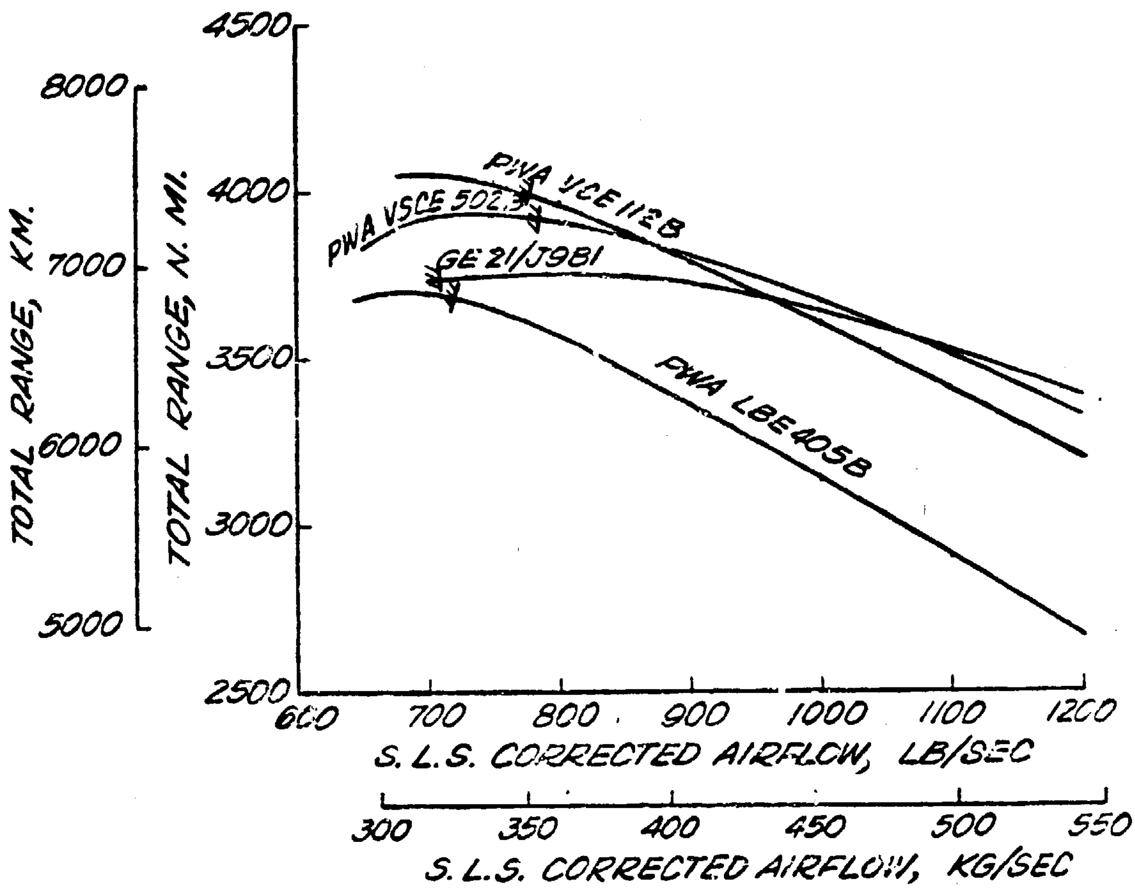


FIGURE 9. - EFFECT OF F.A.R. TAKEOFF FIELD LENGTH AND SIDELINE NOISE LEVEL ON RANGE OBTAINED WITH VARIOUS ENGINE TYPES INSTALLED IN THE NASA/LANGLEY-LTV MACH 2.32 AIRPLANE. TAKEOFF GROSS WEIGHT, 762 000 LB (345 637 KG). 292-PASSENGER PAYLOAD.



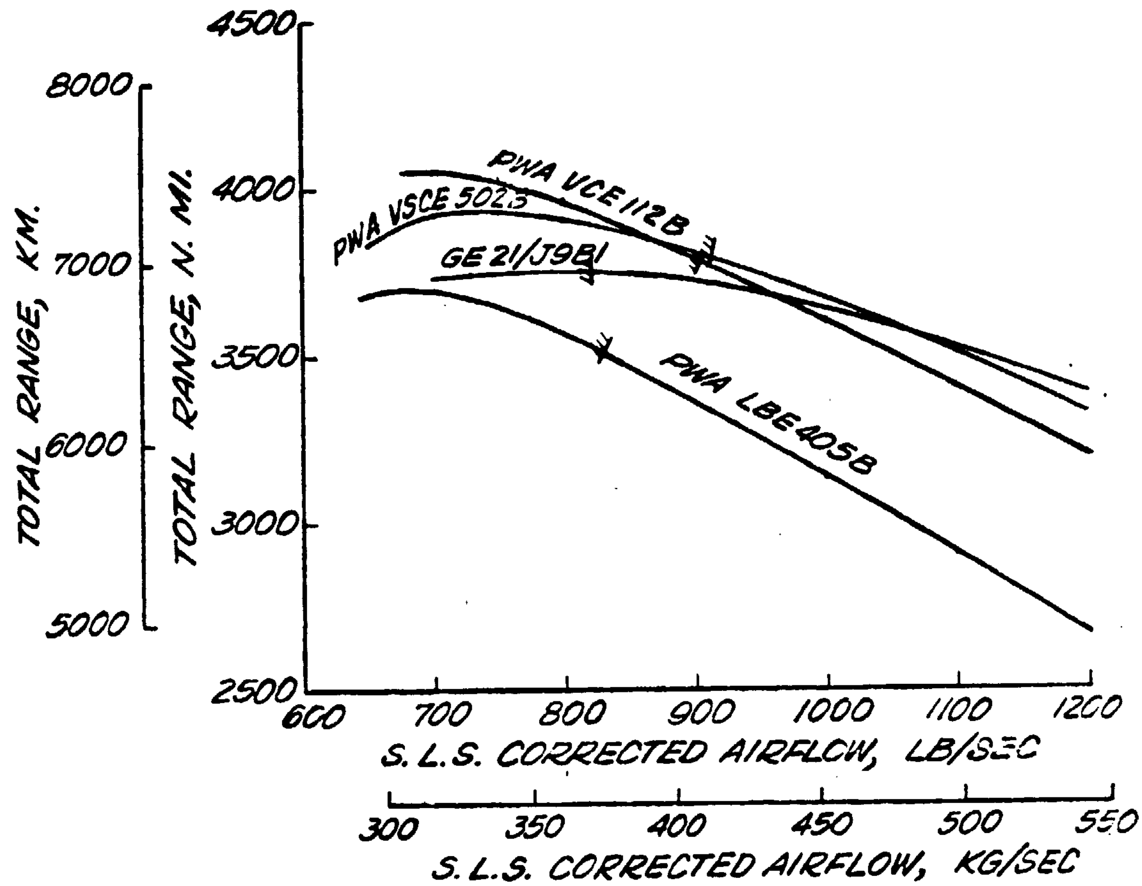
(A) NO SIZING CONSTRAINTS.

FIGURE 10. – EFFECT OF ENGINE SIZE ON RANGE FOR A BOEING MACH 2.32 AIRPLANE. TAKEOFF GROSS WEIGHT, 750 000 LB. (340 194 KG.). 273-PASSENGER PAYLOAD.



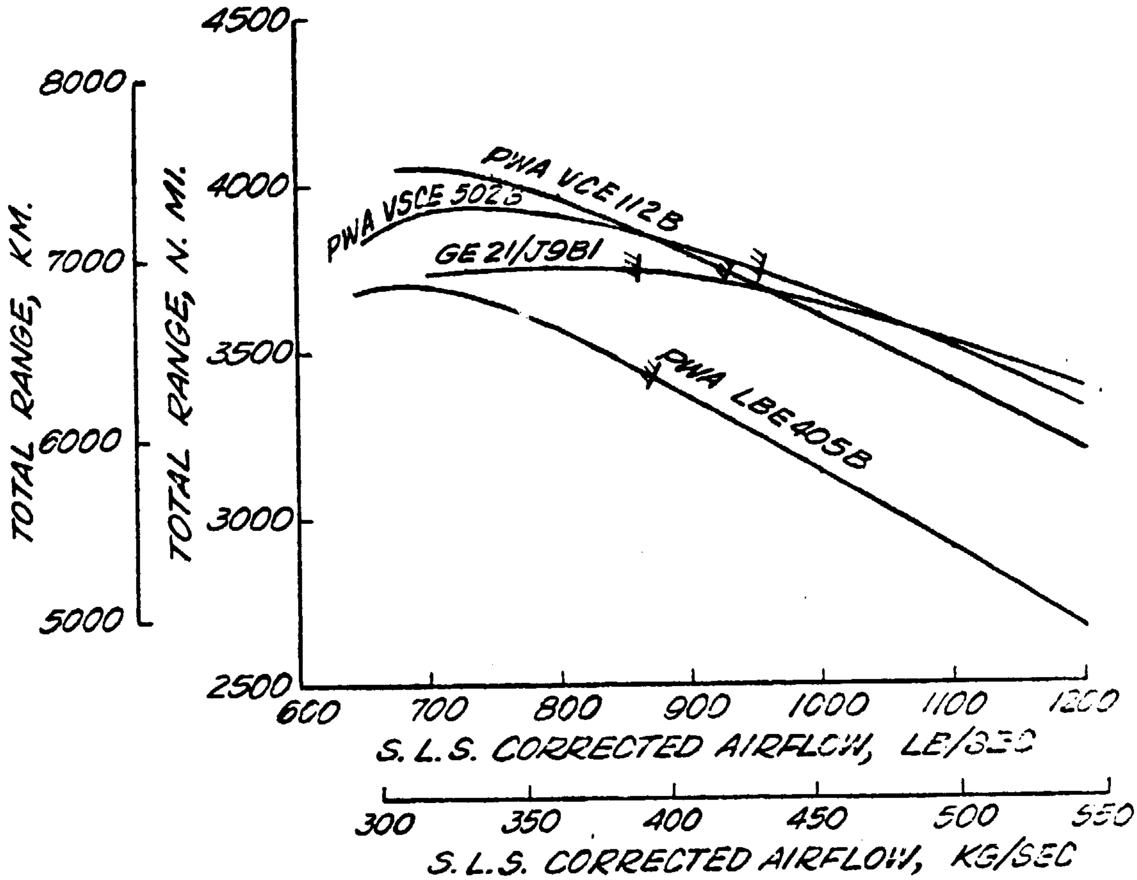
(B) CONSTRAINED FOR FAR 36 (108 EPNDB) SIDELINE NOISE WITH 12 000 FT (3658 M) F.A.R. TAKEOFF FIELD LENGTH.

FIGURE 10.- CONTINUED.



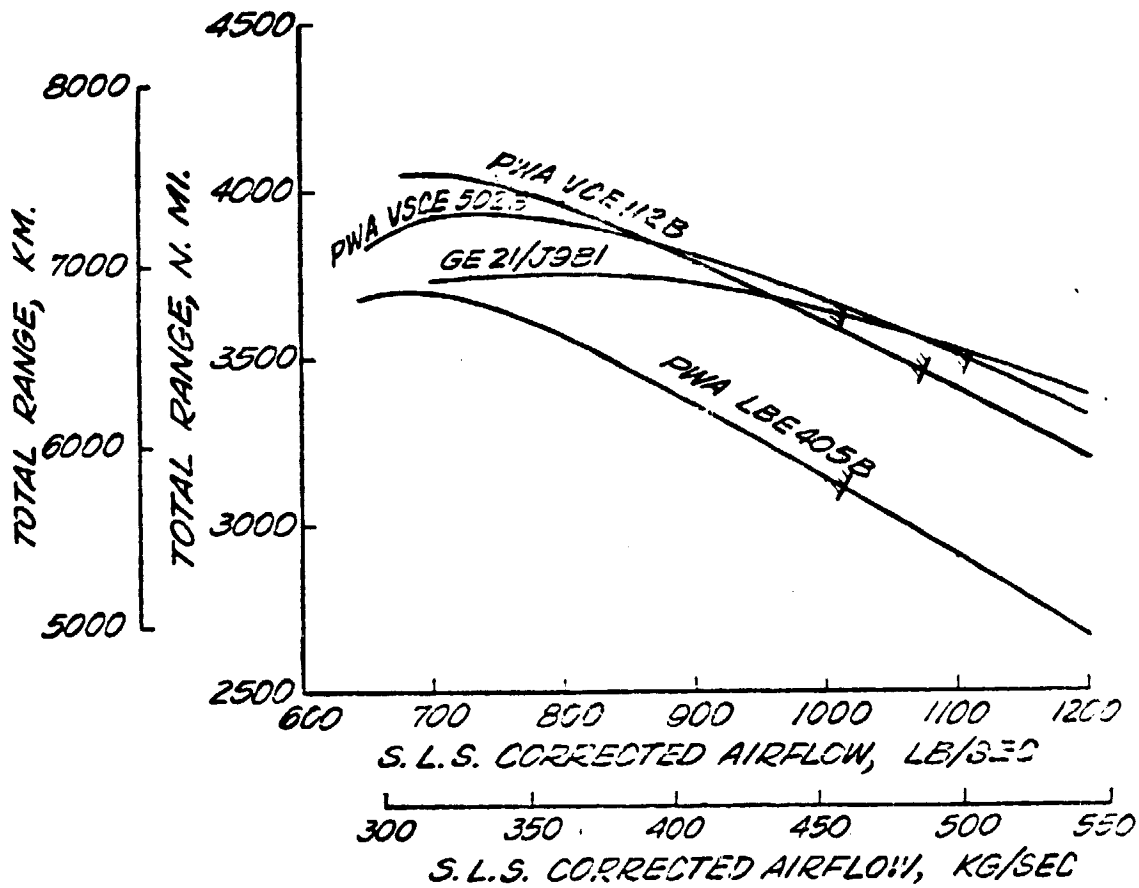
(C) CONSTRAINED FOR FAR 36 (108 EPNDB) SIDELINE NOISE WITH 10 500 FT (3200 M) F. A. R. TAKEOFF FIELD LENGTH.

FIGURE 10.- CONTINUED.



(D) CONSTRAINED FOR FAR36-5 EPNDB (103 EPNDB) SIDELINE NOISE WITH 12000 FT (3658 M) F.A.R. TAKEOFF FIELD LENGTH.

FIGURE 10. - CONTINUED.



(E) CONSTRAINED FOR FAR36-5 EPNDB (103 EPNDB) SIDELINE NOISE WITH 10 500 FT (3200 M) F.A.R. TAKEOFF FIELD LENGTH.

FIGURE 10.– CONCLUDED.

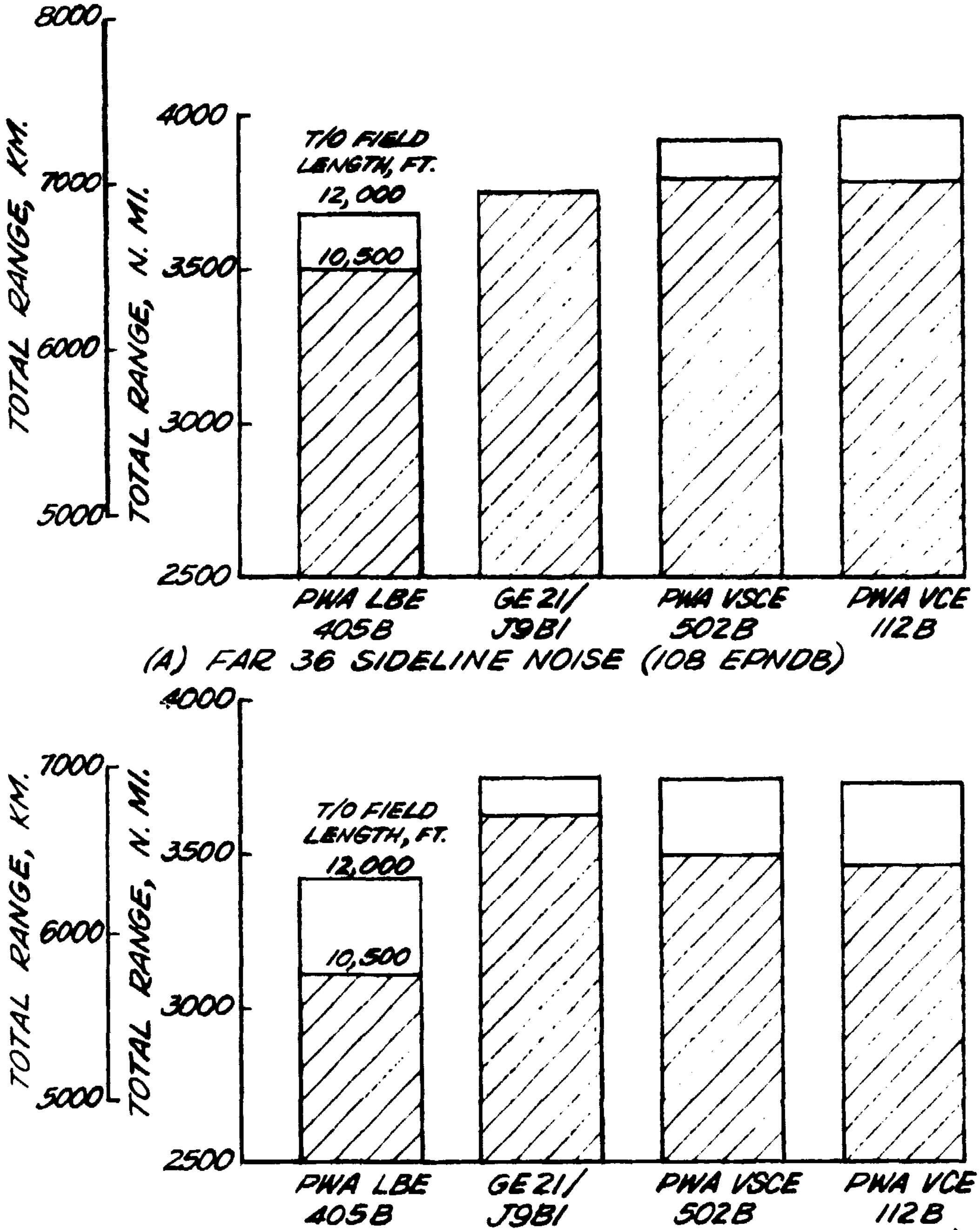


FIGURE 11. - EFFECT OF F.A.R. TAKEOFF FIELD LENGTH AND SIDELINE NOISE LEVEL ON RANGE OBTAINED WITH VARIOUS ENGINE TYPES INSTALLED IN THE BOEING MACH 2.32 AIRPLANE. TAKEOFF GROSS WT., 750 000 LB (340 194 KG.). 273-PASSENGER PAYLOAD.