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OPTIMIZATION OF ENGINES FOR COMMERCIAL AIR TRANSPORTS DESIGNED FOR CRUISE SPEEDS RANGING FROM MACH 0.90 TO MACH 0.98

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ABSTRACT

A parametric study was made of a group of separate-flow-exhaust turbofan engines for advanced technology airplanes designed to carry 300 passengers over a transcontinental range. Cruise lift-drag ratios compatible with the supercritical wing were assumed. Combined jet and fan machinery perceived noise was calculated at both the sideline (lift-off) and approach measuring stations specified by FAR Part 36. Noise goals as low as 106 PNdB could be met with 20 PNdB of acoustic treatment with a two-stage fan having a pressure ratio of 2.25 at cruise. With this amount of suppression, a noise goal about 10 PNdB lower could be met with a single-stage fan having a pressure ratio of 1.70. The airplane figure of merit (range or gross weight) was compromised by the reduction in fan pressure ratio, however. Although these parameters were optimized by reducing cruise speed to about Mach 0.90, direct operating cost was minimized by designing for cruise at Mach 0.94. Noise goals as low as 96 PNdB can probably be met at what looks to be only a moderate economic penalty.

E-6515

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SUMMARY

A parametric study was made of a group of separate-flow-exhaust turbofan engines for use in advanced technology airplanes designed for cruise speeds ranging from Mach 0.90 to 0.98. The airplanes were sized to carry a payload of 300 passengers over a transcontinental range. Cruise lift-drag ratios compatible with the supercritical wing were assumed. A matrix of study engines with fan and compressor pressure ratios and bypass ratio as variables was studied. Engine weight was allowed to vary with bypass ratio, overall pressure ratio, and airflow. The engines were sized for cruise. Turbine rotor-inlet temperature was fixed at 2300° F at takeoff conditions, but was allowed to vary during cruise to optimize an airplane figure of merit (e.g., range or gross weight) while simultaneously observing takeoff and climb thrust constraints. Combined jet and fan machinery perceived noise levels were calculated for selected engines at both the sideline (lift-off) and approach measuring stations specified by FAR Part 36.

It was found that noise goals as low as 106 PNdB could be met with 20 PNdB of inlet and duct acoustic treatment with two-stage fans having a design (cruise) pressure ratio of 2.25. With the same amount of machinery noise suppression, it was found that a noise goal approximately 10 PNdB lower could be met with a single-stage fan having a design pressure ratio of 1.70. The airplane figure of merit was compromised by this reduction in fan pressure ratio, however, especially at cruise speeds approaching the Mach 0.98 upper limit considered here. The airplane figures of merit of range and gross weight were optimized by selection of a design cruise speed at the low end of the spectrum investigated. Direct operating cost, however, was minimized at a slightly higher cruise speed (about Mach 0.94). At this cruise speed, it was found that noise goals as low as 96 PNdB can be met at what appear to be only moderate economic penalties.

INTRODUCTION

The supercritical wing proposed by Whitcomb (ref. 1) offers the potential for delaying the transonic drag rise experienced by present-day subsonic jet transports as their flight speed approaches Mach 1. Transport airplanes using this wing could then cruise at somewhat higher speeds than in present commercial use with little or no penalty in lift-drag ratio (L/D). Alternatively, at lower cruise speeds (e.g., around

Mach 0.9) the advanced wing technology will permit less sweepback and/or more thickness, increased aspect ratio, etc. Such changes could result in higher cruise L/D or less wing weight for the same L/D. In this study in which design cruise speed was varied from a maximum of Mach 0.98 down to Mach 0.90, it was assumed that wing weight for any given takeoff gross weight would remain constant as design speed was reduced but L/D would increase. L/D's with this schedule are postulated at Mach 0.98 to be near that obtainable in practice now with the Boeing 747 cruising at Mach 0.86. At Mach 0.90 with advanced technology, L/D is postulated to be slightly above that obtained with the Boeing 707-320B designed to cruise at Mach 0.80.

Previous studies (refs. 2 and 3) have been made to define the optimum engine design parameters for a Mach 0.98 advanced technology transport. In these studies range was allowed to vary as the airplane figure of merit as different engines were installed in a fixed airframe of constant weight. Takeoff gross weight (TOGW) and payload were also fixed. In the first study (ref. 2), the engine characteristics were determined for an engine that would meet a noise goal of 106.5 PNdB at the sideline and approach measuring points specified by Federal Air Regulation Part 36. In the second study (ref. 3), the engine parameters required to meet noise goals as low as 86 PNdB were examined. In both of these studies, several simplifying assumptions were made (e.g., turbine rotor-inlet temperature T_4 at cruise was always 200° F lower than at takeoff and takeoff and cruise fan pressure ratio FPR, bypass ratio BPR, and compressor pressure ratio were the same).

In the present study, airplanes are considered for design speeds of Mach 0.90 and 0.94, as well as Mach 0.98. In the first part of the study, range is again used as the figure of merit for airplanes with fixed TOGW, airframe weight, and payload (as in refs. 2 and 3). As the engine design parameters were changed, both the specific fuel consumption (sfc) and engine weight (and, hence, fuel weight) changed, thus causing range to change. But range as a figure of merit does not reflect the importance of block time reductions afforded by higher cruise Mach numbers. Direct operating cost (DOC) as calculated by the standard ATA method (ref. 4) does, however, reflect the importance of block time in economic terms. Hence, DOC was calculated in this study for engines optimized to meet a range of noise goals as low as 86 PNdB. Changes in engine airflow, fuel weight, acoustic treatment weight, block time, and range caused DOC to vary as the engine design parameters were changed.

Ranges from 3000-plus miles to more than 4000 nautical miles were obtained in the first part of the study. A more meaningful comparison of airplanes is obtained if range is fixed and airplane TOGW is allowed to vary as required. This was done in the second part of this study (with range fixed at 3000 n. mi.). Airframe weight (i.e., OEW minus installed engine weight) was assumed to remain a constant percentage of the TOGW, based on data from reference 5. These TOGW calculations were made only for selected engines which were shown to be optimum at each noise level in the first part of the study. DOC was again calculated in much the same way as before except that in this part of the study airframe cost was assumed to vary with airframe weight.

In the present study, T_4 at takeoff was fixed at 2300° F because data from references 2 and 3 indicated that higher temperatures did not offer any appreciable benefits, especially when noise constraints were applied. The T_4 at cruise (the engine sizing condition), however, was allowed to vary from 2200° F downward as required to maximize the airplane figure of merit with the constraint that enough thrust must be available for takeoff. (In refs. 2 and 3, T_4 at cruise was arbitrarily assumed to be 200° F less than at takeoff.) Cruise T_4 in this study was not allowed to exceed 2200° F (i.e., takeoff and climb T_4 minus 100° F) so that some acceleration would still be available as cruise was approached. This restraint eliminated the possibility that infinite time to climb up to cruise might be required. As in the previous studies of references 2 and 3, time and range to climb up to cruise were assumed to remain constant in all cases. This assumption may be somewhat more inaccurate in this study since cruise Mach number and altitude now vary, but it is thought to be of only secondary importance to the overall mission time and range.

Another difference between this study and the studies of references 2 and 3 is that it is no longer accurate enough to assume that FPR, compressor pressure ratio, and BPR are the same at takeoff and the cruise design point. This occurs because of the different cruise Mach numbers (and, hence, altitudes) studied in this report and also the varying difference in T_4 between takeoff and cruise. Hence, a component-matching computer program was used to correct the cruise values of these parameters (together with corrected airflow) to the takeoff condition, as a function of cruise BPR.

In references 2 and 3, the estimated turbomachinery perceived noise was added antilogarithmically to the combined jet perceived noise of the fan and core exhausts, as calculated by the SAE standard method (refs. 6 and 7). It has since been discovered that this procedure underestimates the combined perceived noise by as much as 1.2 PNdB in the sideline calculation and 2.0 PNdB in the approach calculation. These maximum differences occur when the individual perceived noise levels of the fan turbomachinery and the combined jet streams are approximately equal. The procedure that was used in these previous studies is valid only when the spectral distribution of the noise sources to be combined is similar. Sound pressure level (SPL) for the combined jet streams, however, is usually at a peak in the second or third octave while fan machinery SPL peaks at a higher frequency (usually in the sixth octave). In this report, a fan machinery noise spectrum was assumed (i.e., SPL in dB as a function of frequency) and was added antilogarithmically at each octave to the combined SPL of the two jet streams. From this point on, the procedure for computing the total perceived noise was the same as indicated in reference 6 for jet noise calculations.

Climb calculations for range, time, fuel consumed, etc. were not made in this study, but were assumed to remain constant for all airplanes considered, except in the second part of the report where TOGW was allowed to vary. In this case, climb and letdown fuel were assumed to vary directly with TOGW. The aerodynamic data used in the mission calculations was a schedule of cruise L/D against design Mach number. These L/D's were assumed to be valid for a nominal engine pod diameter. As engine pod diameter was changed from the nominal value, airplane cruise L/D was adjusted to account for changes in nacelle friction drag. It was assumed that wave drag changes could be largely eliminated by re-area-ruling the airplane as the size of the engine pods changed. (This procedure is similar to that used in ref. 3 but is in contrast to that of the earlier ref. 2 study in which L/D was assumed to stay fixed regardless of pod dimensions.)

SYMBOLS

BPR	bypass ratio
C_{eng}	cost per engine, dollars
C_L	lift coefficient
c_s	speed of sound, knots (n mi/hr)
D	drag, lb
F_n	net thrust, lb
FPR	fan pressure ratio
L	lift, lb
M	Mach number
OEW	operating empty weight, lb
OPR	overall fan and compressor pressure ratio
P	total pressure, lb/ft^2
R	range, n mi
S_{wing}	wing planform area, ft^2
SPL	octave sound pressure level, dB
sfc	specific fuel consumption (lb fuel/hr)/lb thrust or hr^{-1}

T	total temperature, ^{o}F
TOGW	takeoff gross weight, lb
W_a	total airflow per engine, lb/sec
$W_{end\ cr}$	airplane gross weight at end of cruise, lb
W_{eng}	installed weight of three engines, lb
W_g	takeoff gross weight, lb
$W_{start\ cr}$	airplane gross weight at start of cruise, lb
δ	pressure parameter, P/2116
θ	temperature parameter, (T + 460)/519

Subscripts:

cr	cruise
sls	sea-level-static
1	fan inlet station
2	fan discharge or inner compressor inlet station
3	inner compressor discharge or burner inlet station
4	turbine rotor-inlet station

METHOD OF ANALYSIS

Selection of TOGW and Airframe Weight

In the first part of the study, as in references 2 and 3, it was desired to select a fixed airframe to hang parametric engines onto. Range was calculated as the airplane figure of merit, as indicated by the equation

$$R = 350 + \frac{(L/D)_{cr} M_{cr} c_s}{sfc} \ln \frac{W_{start\ cr}}{W_{end\ cr}}$$

The first term on the right side of the equation (i.e., 350 n mi) represents the climb plus letdown range assumed for all airplanes considered. The other term on the right side of the equation represents the range for a Breguet cruise.

First, it was necessary to select a reasonable TOGW and airframe weight that would provide a range of approximately 3000 nautical miles for a payload of 60 000 pounds (300 passengers at 200 lb each). M_{cr} was selected to be 0.98 with a corresponding $(L/D)_{cr}$ at 16.8. (The selection of L/D will be discussed later.) The speed of sound c_s in the stratosphere is 573.3 knots. A reasonable installed cruise sfc for a high BPR turbofan engine is in the vicinity of 0.7 pound of fuel per hour per pound of thrust. To evaluate the logarithm in the last term of the above equation, both the TOGW and the operating empty weight (OEW) are needed.

Figure 1 has been constructed from data points of reference 8 to show the OEW as a function of TOGW for existing turbofan-powered subsonic transports. In determining the TOGW and OEW combination that will satisfy the above equation when R is 3000 nautical miles, the airplane was assumed to lie on the curve for "wide-body trijets" (fig. 1). An iterative calculation is necessary to pick the right point off the curve to satisfy the above equation. In the equation, the numerator of the log term is simply the assumed TOGW minus the fuel consumed in climb up to cruise. 20 000 pounds of fuel is assumed to be used in takeoff and climb in this part of the study. The denominator of the log term is simply the sum of the OEW and the letdown and reserve fuel. Letdown fuel was assumed to be 2000 pounds in this part of the report. The reserve fuel was assumed to be 18 percent of the total fuel load. The total fuel load was obtained by subtracting the sum of the OEW and payload from the TOGW. After several iterations, it was found that a TOGW of 386 000 pounds and an OEW of 220 000 pounds satisfied these conditions.

After finding the correct TOGW and OEW, it was then necessary to subtract the installed engine weight from the OEW to find the airframe weight. Podded engines of existing weight technology were found to weigh about 13 300 pounds each when sized at 40 000 pounds sea-level-static thrust. By subtracting the weight of three of these engines from the OEW of 220 000 pounds, airframe weight was found to be 180 000 pounds. Airframe weight and TOGW were then fixed for the remainder of the first part of the study where range was used as the figure of merit as engine design parameters were varied. Range variations were obtained because of changes in cruise M, sfc, L/D, and fuel weight. Since engine weight changed as a function of the engine design parameters, total fuel load was also required to change since the sum of installed engine weight and fuel weight must remain constant. Cruise L/D varied not only with Mach number, but also was affected by engine diameter (to be discussed in greater detail later).

In the second part of this study, range was fixed at 3000 nautical miles and TOGW was allowed to vary as the figure of merit. Payload was held constant at 60 000 pounds (300 passengers), as in the first part of the study. The airframe weight was assumed to remain a constant percentage of the TOGW. According to data from reference 5, airframe weight will remain very nearly a constant fraction of the TOGW over a considerable range of TOGW when the size of large transports is scaled up or down. The airframe weight percentage used in the second part of the study was fixed at the 46.6-percent value obtained in the previously described iterative calculation of the first part of the study. This value is somewhat high in comparison with data presented in reference 5, which indicates that for current technology transports a value of 34 percent is appropriate. This difference probably occurred because we iterated to the vicinity of the left end of the "wide-body trijet" OEW-against-TOGW curve (fig. 1). OEW at this point on the curve appears to be somewhat high relative to that obtained if the curve labeled "narrow-body jets" were extended to a TOGW of 386 000 pounds. At any rate, it is reasonable to pick a high value of airframe weight fraction because of the higher cruise speeds to be considered in this report. Surface temperatures and pressures will be higher and area ruling will be more extensive than in current transports. In addition to airframe weight, the climb and letdown fuel weight assumptions were also scaled directly with TOGW.

A sketch of the concept of this study airplane is shown in figure 2. The engines are located at the rear to provide as clean a wing as possible in order to achieve a high cruise L/D. A sketch of a typical high-BPR, separate-flow-exhaust turbofan engine installation follows in figure 3. Note the acoustic lining in the inlet and duct walls for the reduction of fan turbomachinery noise. In addition, an inlet splitter ring concentric with the centerbody and outer wall is shown with sound deadening material. More than one splitter ring may be required in some installations. Acoustically treated radial struts in the duct may also be required in some installations, depending on turbomachinery noise reduction requirements and duct dimensions.

Lift-Drag Ratio

The schedule of cruise L/D against Mach number used in this study is shown as the solid curve in figure 4. This curve is representative of airplanes with the nominal-size engines (i.e., 80-in. diam). These L/D ratios are adjusted by means of the nacelle drag curves shown in figure 5 when engine diameters are other than 80 inches.

The L/D schedule for advanced technology transports (solid curve, fig. 4) was obtained by drawing a curve through the two circled adjusted data points. These data points were obtained from preliminary model test data at NASA-Langley. The raw wind tunnel model test data was corrected to full-scale and adjusted for the estimated effect of nominal engines by Langley. Although the two raw data points were obtained by two different design teams, they have been adjusted for comparison on the same basis. The solid curve through these points represents an estimate of the cruise L/D that can be obtained at various M_{cr}'s (ranging from 0.90 to 0.98) when the airplane configuration is reoptimized with regard to wing sweepback, thickness-to-chord ratio, aspect ratio, etc. at each M_{cr}. It is interesting to note the similarity in the shape of this curve for advanced transports to that for existing transports (broken curve through two triangular data points, fig. 4). The triangular data point at $M_{cr} = 0.80$ represents the Boeing 707-320B and the one at $M_{cr} = 0.86$ represents the Boeing 747. For the same level of cruise L/D, we are postulating a Mach number advance of almost 0.13, when compared with existing commercial transports. At Mach 0.86, which is the approximate upper limit in cruise speed for existing transports, the use of advanced technology is postulated to increase L/D from 16.6 to about 20.

As already mentioned, the cruise L/D schedule for advanced airplanes (fig. 4) was drawn for 300-passenger airplanes with a nominal engine diameter of 80 inches. When other engine sizes are used, a new nacelle drag must be read from one of the curves of figure 5 and compared with that obtained for a diameter of 80 inches. The difference multiplied by the number of engines (three for these airplanes) represents the change in airplane drag from some reference level obtained with the nominal engines. The nominal initial cruise drag was obtained by dividing the airplane weight at the start of cruise by the nominal L/D read from figure 4. This drag was then adjusted by the difference just computed and divided into the initial cruise weight to obtain the actual cruise L/D. The nacelle drag curves of figure 5 agree with those in use by the engine and airframe manufacturers. By far the greatest part of this nacelle drag is due to friction. It is assumed that when nacelle size is changed, increases in wave drag can be area-ruled out by reconfiguring the fuselage and tail in the vicinity of the nacelles.

The only aerodynamic data available at the time of this study was the cruise L/D schedule already presented. No low-speed or climb aerodynamics was available. The lack of such data is probably not too important to the overall mission calculations (e.g., total range, TOGW, etc.), however, since only a small part of the mission, time-wise and range-wise, was conducted at other than the cruise condition. However, to determine the approach thrust to be used in the noise computations, an approach L/D of 5.5 was assumed to occur at a speed of 135 knots.

Engines

Cycle calculations were made for the two-spool turbofan engines of this study for cruise fan pressure ratios of 1.70 and 2.25. The FPR of 1.70 is approximately the maximum achievable with a single stage. Single-stage fans are desirable from a machinery noise standpoint since experimental data (ref. 9) indicate that multistaging at any given FPR increases the perceived noise about 8 PNdB. Higher FPR's are desirable, however, because they improve the airplane figure of merit (refs. 2,3). Cruise FPR's higher than 2.25 were not considered because data presented in reference 3 indicates that more than 20 PNdB of fan machinery noise suppression would be required to meet a 106 PNdB noise goal at the sideline and approach measuring stations. With techniques that are currently available, it is felt that a 15-PNdB reduction in fan turbomachinery noise can be realized with proper suppressor design and balance (ref. 9). A 20-PNdB reduction is thought to be a realistic, although somewhat optimistic, goal to strive for in the year 1978 - the assumed date of first flight of the airplanes in this study.

Cruise bypass ratios from 0.5 to 10 and overall cruise fan and compressor pressure ratios from 20 to 52 were considered. Turbine rotor-inlet-temperature T_4 was fixed at 2300° F during takeoff and climb up to cruise (as in ref. 3), but the corresponding cruise T_4 was allowed to vary downward from a maximum of 2200° F. Cruise T_4 was chosen at each design Mach number and FPR to maximize the range of the fixed-TOGW airplanes. If, however, the takeoff thrust-to-gross-weight ratio $(F_n/W_g)_{sls}$ fell below 0.24 (the level obtained with a fully loaded Boeing 727-200), the cruise T_4 was reduced from its range-optimum value, thus increasing the airflow required to overcome the drag encountered during cruise. Greater airflow was thus provided at takeoff, too, with a consequent thrust improvement since takeoff T_4 was fixed. As previously mentioned, cruise T_4's greater than 2200° F were not considered because some acceleration margin in climb was needed immediately before cruise so that time and range up to cruise could be held to reasonable values.

Range of the fixed-TOGW airplanes was generally improved at all cruise Mach numbers by increasing the cruise T_4 to the limit of 2200° F. Unfortunately, takeoff thrust was not always sufficient with T_4 at the limit - especially for the lower design cruise Mach numbers. For the single-stage-fan engines with a design FPR of 1.70 at cruise, a cruise T_4 of 2200° F was satisfactory for design speeds of Mach 0.98 and 0.94, especially at the BPR's required for low jet noise. But at Mach 0.90, cruise T_4 had to be reduced to 2100° F to have sufficient thrust for takeoff with T_4 at 2300° F. (Initial cruise altitude, an important consideration in determining thrust lapse rate, was selected to provide a dynamic pressure of 264 lb/ft^2.) For cruise FPR's of 2.25, a cruise T_4 of 2200° F was acceptable for cruise at Mach 0.98, but to obtain sufficient takeoff thrust when M_{cr} was 0.94 it was necessary to lower the cruise T_4 to 2070° F. For a design M_{cr} of 0.90, cruise T_4 was reduced to 1965° F. Turbine cooling bleed chargeable to the cycle for the high-pressure turbine was fixed at 7.5 percent of the core airflow, regardless of cruise temperature. (This is in agreement with the bleed schedule of ref. 3 for a takeoff T_4 of 2300° F.) It was assumed that no bleed was required for the low-pressure turbine.

All parametric engines in this study were designed for cruise and operated off-design at takeoff. Correction factors that could be applied to the design engine parameters to obtain their sea-level-static values were obtained by using a component-matching computer program (refs. 10 and 11) capable of determining off-design operating points. The correction factors (i.e., the sea-level-static value divided by the cruise value of the parameter) were plotted against cruise BPR for corrected airflow at the face of the fan, fan pressure ratio, compressor pressure ratio, and bypass ratio. These correction factors were found to be relatively insensitive to overall pressure ratio except near the maximum BPR at which the engines would run. The correction factors that were used for a cruise FPR of 1.70 are shown in figure 6(a-d). A separate curve was plotted for each M_{cr} and ΔT_4 (where $\Delta T_4 = T_{4_{sls}} - T_{4_{cr}}$) combination that was used. Similar curves are shown in figure 7(a-d) for a cruise FPR of 2.25. During the component-matching procedure at off-design conditions, it was assumed that there was no change in exhaust nozzle area.

One of the constraints to be examined in this report is the approach noise at one nautical mile from the runway threshold. Engine thrust was reduced to a low level commensurate with an assumed L/D of 5.5 at an approach speed of 135 knots (Mach 0.203). A typical approach weight for the 386 000-pound airplanes of the first part of the report was about 286 000 pounds. If it is assumed that the airplane angle of attack is 10° and the altitude is 370 feet (based on a 3° glide slope to the top of a 50-ft obstacle at the end of the runway), the net thrust required is about 12 000 pounds per engine. Further calculations show that the approach thrust requirement is reduced about 1000 pounds per engine for each 40 000-pound reduction in TOGW. Approach thrust is roughly equivalent, therefore, to about one-third of the takeoff thrust. To determine the engine operating parameters needed to calculate both the jet noise and the fan turbomachinery noise during approach, the turbofan component-matching computer program (refs. 10 and 11) was again used. This program uses scaled fan, compressor, and turbine maps in determining part-power operating conditions.

At each cruise design point, the component efficiencies, pressure losses, coefficients, etc. of reference 3 were used, as follows:

Fan adiabatic efficiency	0.88
Compressor adiabatic efficiency.	.89
Combustor efficiency	.99
Inner turbine adiabatic efficiency	.91
Outer turbine adiabatic efficiency	.90
Inlet pressure recovery.	.98
Pressure ratio across combustor.	.96
Total duct pressure ratio from fan discharge to nozzle	.94
Total core pressure ratio from low-pressure-turbine discharge to nozzle.	.98
Exhaust nozzle thrust coefficient (both streams)	.98

Uninstalled engine weight and dimensions were allowed to vary with the sea-level-static BPR, OPR, and total airflow, as described by Gerend and Roundhill (ref. 12). They have also correlated engine weight with the year of first flight. It was assumed that the engines of this study would first fly in the year 1978. The additional weight for installation (including inlet, nacelle, and nozzle) was assumed to be 3.13 times the total airflow at takeoff. This incremental installation weight is based on empirical data for existing high-BPR engines used in large commercial transports.

Noise Constraints

Noise calculations were made for two measuring points, both of which are specified in Federal Air Regulation Part 36. They were:

(1) Sideline noise measured on the ground at the angle of maximum noise immediately after lift-off on a 0.25-nautical-mile (1520-ft) sideline for three-engine airplanes (0.35-n mi sideline for four-engine airplanes).

(2) Approach noise, when the airplane is one nautical mile from the runway threshold, measured on the ground directly under the glide path at the angle of maximum noise. The airplanes of this study were assumed to be at an altitude of 370 feet at this measuring station.

For airplanes with TOGW's of interest, FAR Part 36 specifies a noise limit of 106 EPNdb for both of the above measurements. A third measurement specified by this regulation should be made at a point 3.5 nautical miles from the start of takeoff roll on the extended runway centerline. If the airplane altitude at this measuring point exceeds 1000 feet, the thrust may be reduced to that required for a 4 percent climb gradient or to maintain level flight with one engine out, whichever thrust is greater. The noise limit at this measuring station for the TOGW's considered here is 102-104 EPNdB. This noise measurement was ignored in this study because insufficient low-speed aerodynamic data were available to investigate the tradeoffs involved in minimizing noise at this point. The tradeoffs involved are between constant Mach number climb to maximum altitude and maximum acceleration to 1000 feet before thrust is reduced. For the three-engine airplanes which meet a sideline noise goal in this study, it is felt that little difficulty will be involved in meeting the 3.5-mile "takeoff" goal since the sideline noise is measured at 1520 feet. With four-engine airplanes, the 3.5-mile goal might be more difficult to meet, however, because the sideline measurement is specified at 2126 feet and is therefore easier to meet. The 3.5-mile measurement might thus be more of a constraint for four-engine airplanes.

Total perceived noise has two components - jet noise from the two jet streams and fan turbomachinery noise. Jet noise, measured in PNdB, was calculated by standard methods described by the Society of Automotive Engineers in references 6 and 7. Jet noise is primarily dependent on the exit velocities of the two flow streams, but is also affected by the gas flow rates and the flow areas. These variables were calculated at both Mach 0.23 (152 knots) after lift-off at full thrust and with thrust cut back to the level required during the 3° approach at Mach 0.203 (135 knots). It was assumed that the overall SPL curve of reference 6 plotted against relative jet velocity could be linearly extrapolated on a log scale to velocities below 1000 feet per second (as per data presented in ref. 9).

Fan turbomachinery noise, also measured in PNdB, is a function of many things - for example, spacing between stator and rotor, tip speed, number of stages, fan pressure ratio, thrust, and amount of nacelle acoustic treatment. In this study, it was assumed that the engines would be built with optimum stator-rotor spacing without any inlet guide vanes in order to minimize noise. Curves presented in reference 9 relate machinery perceived noise level to fan pressure ratio at a fixed thrust and distance for both one- and two-stage fans. These curves were scaled from a total airplane net thrust of 90 000 pounds and a measuring-point distance of 1000 feet to both the sideline and approach conditions of this report. In addition to logarithmic thrust and distance-squared scaling, extra air absorption due to a change in slant range (ref. 6) was included. The curves which result for the sideline condition are shown in figure 8(a) for a total airplane net thrust of 114 000 pounds. The curves which result for the approach condition are shown in figure 8(b) for a total airplane net thrust of 36 000 pounds. These thrust levels are typical for airplanes having a TOGW of 386 000 pounds, as was the case in the first part of the study where range was used as the figure of merit. But when range was reduced to 3000 nautical miles by reducing TOGW in the second part of the study, it was necessary to correct these turbomachinery noise readings (fig. 8) for the variation in thrust. The sideline noise correction is plotted against total thrust from three engines in figure 9(a). The approach fan turbomachinery noise correction is plotted against TOGW with total thrust as an auxiliary scale in figure 9(b).

In order to determine the total perceived noise from both the jets and the fan turbomachinery, it was necessary to add antilogarithmically the jet and machinery sound pressure levels (SPL) in each octave. (This procedure is described in ref. 6 for the addition of core and fan jet noise.) To do this, it was necessary to assume a spectral distribution of fan turbomachinery SPL as a function of frequency. Figure 10 shows octave SPL (in dB) at a distance of 200 feet that was assumed for all the fans considered in this study. This octave SPL was attenuated for the inverse-square distance effect and the extra-air-absorption effect at distances greater than 200 feet, as described in reference 6. The distance-squared effect is the same for all octaves, but the extra air absorption affects the higher octaves the most. The spectrum shown in figure 10 depicts data obtained from reference 13 for a TF39 fan modified for low noise. It was assumed that the spectral distribution would not change significantly with power setting or acoustic treatment.

To obtain the octave SPL of the fan machinery noise, the perceived noise level in PNdB was first obtained from the curves of figure 8. Corrections from figure 9 were then applied. The amount of attenuation from acoustic treatment, if any, was subtracted. Absolute numbers were then arbitrarily placed on the ordinate scale of figure 10 and the fan machinery perceived noise was computed by summing and manipulating the octave SPL's thus obtained, as described in reference 6. The calculation was repeated by sliding the arbitrary ordinate scale of figure 10 up or down as required in an iterative calculation until the fan perceived noise thus calculated equaled that read from the curves of figure 8 (as modified by fig. 9 and the application of acoustic treatment). After completing this computerized iteration, machinery octave SPL was added antilogarithmically to the combined jet SPL at each octave. Total perceived noise was obtained by summing and manipulating all the combined octave SPL's (as described in ref. 6).

The noise calculations made in this study are in units of PNdB. The FAR Part 36 requirements, however, are stated in terms of EPNdB. The EPNdB scale (where E stands for effective) is a modification of the PNdB scale where a correction is made to account for (1) subjective response to the maximum pure tone and (2) the duration of the noise (ref. 14) heard by the observer. These modifications to the PNdB scale were ignored in this study, since the amount of information known about the maximum tones and directivity of the noise from these parametric engines is rather limited. It is thought that the error introduced by ignoring these modifications is less than the error that might occur by making further assumptions about the noise sources. McPike (ref. 15) takes a similar position and states that the results would be similar using either unit.

In this study, attention was concentrated on designing cycles that would minimize the range or TOGW penalties that occur with up to 20 PNdB of turbomachinery acoustic treatment. Noise goals as low as 92.6 PNdB were obtained with this amount of acoustic treatment. As discussed in the previous section entitled "Engines," a 20-PNdB suppression of fan turbomachinery noise is thought to be a somewhat optimistic - although still realistic - goal to strive for at the time of first flight, postulated to be in 1978. As mentioned in reference 9, it is felt that a 15-PNdB suppression of turbomachinery noise can currently be realized with proper suppressor design. It was assumed somewhat optimistically in this study that no performance losses occurred as a result of the insertion of splitter rings in the inlet and radial splitters in the duct, together with wall lining in the inlet, duct, and nacelle. It is encouraging to note that tests of a 6-foot fan with acoustic treatment which included multiple splitter rings (ref. 16) did not reveal any fan performance losses due to the noise suppressors, within the experimental measurement error.

Duct and inlet wall treatment and an acoustically lined splitter ring inserted in the inlet were found in reference 17 to penalize the weight of a Pratt & Whitney JT3D engine about 370 pounds. Much of this weight penalty is undoubtedly due to structural modification since the lining material by itself is very light. This amount of treatment on the JT3D engines of a DC8 airplane lowered the approach noise about 11 PNdB. The addition of one splitter to the inlet of some of the high BPR engines of this study may not be as effective in reducing approach noise of these engines as it was for the low-BPR JT3D because of the larger inlet diameter-to-sound-wave-length ratio (ref. 18). It was estimated in this study that this type of inlet and duct treatment combined will reduce the fan machinery noise about 10 PNdB. A 15-PNdB reduction, the maximum demonstrated to date, can be attained only by the addition of more splitter rings in the inlet and probably the addition of radial splitters in the duct as well (ref. 19).

In both references 17 and 19, the weight penalties involved more than just treatment weight. There were structural changes to the engine as well. To separate the weight due to treatment and the weight due to structure is impossible from those references alone. However, reference 20 indicates that two splitter rings weigh 150 pounds. To achieve 10 PNdB suppression in a long duct engine, the inlet needs only one ring and the duct and inlet walls must be treated. In this report it was assumed that this could be done for 150 pounds on a 53-inch-diameter engine. Of this, 75 pounds was attributed to the single splitter and the other 75 pounds to the treatment of the duct and inlet walls. When 15 PNdB was required in this study, it was assumed that the extra inlet ring and additional duct treatment weigh 75 pounds for a 53-inch-diameter engine. Since most of the treatment weight is applied near the periphery of the engine, treatment weight was scaled directly with maximum engine diameter in this study. The airplane operating-empty-weight penalty due to turbomachinery noise suppression used in this study is plotted as a straight line (fig. 11) through the origin and these two points at 10 and 15 PNdB of suppression. Engine diameter was adjusted for this plot from 53 inches to the nominal 80-inch size more compatible with high-BPR turbofans.

Cycle Optimization with Noise and Thrust Constraints

At each design FPR considered, once the relation between cruise and sea-level-static T_4 has been established, a "thumbprint" plot similar to the sketch of figure 12(a) can be made for a spectrum of design BPR's and OPR's. TOGW was fixed in the cycle optimization part of the study and total range was used as the airplane figure of merit. Contours of constant range are shown in the figure with $R_A > R_B > R_C > R_D$. A thrust limiting line (i.e., $(F_n/W_g)_{sls} = 0.24$) is shown below which a takeoff thrust will be unsatisfactory. Broken lines of constant sideline jet noise (for the combined fan and core streams) are also shown, with the lowest lines representing the highest noise levels. Four engine cycles (i.e., points A, B, C, and D) are selected from the "thumbprint" plot for further analysis with respect to total noise (i.e., jet plus fan turbomachinery) and the range penalty involved with acoustic treatment. (The range contours shown on the "thumbprint" plot were computed for no acoustic treatment penalty.) Engines A, B, C, and D were selected because they produce the maximum range that can be obtained at each of four selected levels of sideline jet noise (i.e., the jet noise curves are tangent to the range contours at these points).

A plot like figure 12(b) is next constructed to show the relation between total approach noise and total sideline noise for different levels of turbomachinery noise suppression. These noise levels were obtained by adding antilogarithmically, octave-by-octave, the machinery noise and the combined jet noise as described in the preceding section entitled "Noise Constraints." Calculations were made with 0, 10, 20, and 30 PNdB of turbomachinery noise suppression assumed. Lines of constant BPR are also shown in this sketch. A noise goal represented by point X is postulated such that approach and sideline noise are equal. By interpolation, it appears from figure 12(b) that the noise goal can be achieved with about 16 PNdB of turbomachinery noise suppression.

A plot like figure 12(c) is next constructed to show range as a function of total sideline noise at various levels of machinery noise suppression. The range obtained from the "thumbprint" plot is adjusted by means of figure 11 to account for the range penalty due to turbomachinery noise suppression in figure 12(c). If this plot is entered with the total sideline noise goal of figure 12(b), point X can be located at the intersection of this noise line with the curve representing 16 PNdB of suppression. Incidentally, for this particular sideline noise, figure 12(c) shows that the suppression can be increased from 16 to 20 PNdB with practically no range penalty. If it is, in fact, possible to obtain a suppression of 20 PNdB by the year 1978, it would be beneficial to increase the suppression to this level because the sketch of figure 12(b) shows that this will reduce the approach noise by what may be a significant amount.

Cost Estimation

Direct operating cost was computed for selected engines of interest by the standard ATA formula (ref. 4). Since neither range nor TOGW as figures of merit reflect the importance of block time changes with cruise Mach number, DOC probably serves as a better comparative index. It reflects the importance of these block time changes in economic terms. Uncertainties of airplane pricing at this preliminary stage of development make the computational accuracy of DOC in terms of absolute numbers somewhat doubtful. The relative merits of the airplanes studied can, however, be compared with some confidence on a DOC basis. In this study, airframes were assumed to cost \$72 per pound (based on data from ref. 5 for current airplanes). Acoustic suppression for turbomachinery noise was also assumed to cost \$72 per pound. Engine price was assumed to be a function of sea-level-static corrected airflow and is computed as

$$C_{eng} = 1.2\times10^6\left[\frac{(W_a\sqrt{\theta_1}/\delta_1)_{sls}}{1300}\right]^{0.35}$$

This cost variation with airflow is based on empirical data adjusted to reflect the typical cost of a high-BPR turbofan such as those used to power the new wide-body trijets. Later, the assumed airframe and engine costs were increased by 50 percent to see what the effect would be on both the overall level of DOC and the relative comparison of the various airplanes. In all of the DOC computations, the domestic economic ground rules of reference 4 were used.

RESULTS AND DISCUSSION

Cycle Optimization with Fixed TOGW and Variable Range

"Thumbprint" performance plots. - A "thumbprint" plot is shown in figure 13(a) for a series of engines designed to cruise at Mach 0.98 with a fan pressure ratio of 1.7. The cruise T_4 was arbitrarily chosen to be 200° F less than the takeoff T_4 everywhere on this plot. Notice that for the fixed TOGW of 386 000 pounds the range maximizes at 3340 nautical miles at a cruise BPR between 0.4 and 1.0. Optimum cruise OPR's lie between 36 and 44. Unfortunately, as the plot shows, there is not enough takeoff thrust and sideline jet noise is much too high at the peak range. To reduce the sideline jet noise to "floor" levels that are likely to be acceptable (i.e., below 106 PNdB), cruise BPR must be increased to a value of 5 or more with a range penalty of at least 100 miles. $(F_n/W_g)_{sls}$ is increased to values of 0.33 or more by so doing, whereas it is postulated that 0.24 will be sufficient. In other words, to achieve the levels of sideline jet noise that are required, airflow in excess of that required for adequate takeoff thrust is obtained when T_4 at cruise is reduced 200° F from the takeoff and climb setting.

If the cruise T_4 is raised 100° F, the engines will be smaller and the takeoff thrust level should be closer to the limiting line at sideline jet noise levels of interest. As can be seen in figure 13(b), this is indeed the result that was obtained when the cruise T_4 was raised to 2200° F (only 100° F less than the takeoff T_4). Not only did the maximum achievable range increase as cruise T_4 was increased, but the optimum BPR increased to the vicinity of 3. Thrust is adequate at this point because the $(F_n/W_g)_{sls}$ limiting line falls below the contour of maximum range. To obtain a sideline jet noise "floor" of 106 PNdB, the cruise BPR must be raised to about 5. A range penalty of only about 35 miles is involved by so doing when the cruise OPR is 40. If a jet noise "floor" of 96 PNdB is desired, BPR must be raised to 6, where the range penalty is about 65 miles. Although more than enough takeoff thrust is available, as discussed earlier it would be dangerous to raise the cruise T_4 still more because this would make climb acceleration very marginal as cruise is approached. Although the optimum cruise OPR appears to occur at a value of about 40 because of the lightweight engine technology assumed, lower values can be chosen without much range penalty. (It is possible that either compressor design considerations or nitrogen oxide pollution control might cause a design OPR of about 30 to be selected.)

For cruise at Mach 0.94 with a fan pressure ratio of 1.7, range maximizes near both the thrust limiting line and the sideline jet noise levels of interest (fig. 13(c)) when the cruise T_4 is raised to within 100° F of the takeoff T_4. Practically no range penalty is involved in meeting sideline jet noise levels of 96 PNdB. Less than a 40-mile penalty is involved in modifying the cycle to meet an 86-PNdB sideline jet noise level. It is interesting to note the maximum range attainable at Mach 0.94 is 575 nautical miles greater than that obtained at Mach 0.98, as may be seen by comparing figures 13(b) and (c). For a sideline jet noise "floor" of 96 PNdB, a 640-nautical-mile improvement can be obtained by designing for cruise at Mach 0.94 instead of Mach 0.98. Optimum BPR and OPR at these noise levels is about the same for either Mach number.

Figure 13(d) is plotted for cruise at Mach 0.90 with a fan pressure ratio of 1.7. In order to obtain sufficient takeoff thrust with engines sized for this cruise condition, it was necessary to reduce the cruise T_4 to 2100° F for a fixed takeoff T_4 of 2300° F. The maximum range island of 4194 nautical miles falls slightly below the limiting thrust line, but the range penalty involved in meeting the thrust limit is very slight. The sideline jet noise curve of 96 PNdB very nearly coincides with the thrust limiting curve. A further penalty of only about 40 miles is involved in increasing the BPR so that a sideline jet noise "floor" of 86 PNdB is met. By comparing figure 13(d) with figure 13(c), it may be seen that about 200 miles more range may be obtained when cruise speed is reduced from Mach 0.94 to Mach 0.90 with FPR fixed at 1.7.

A cruise fan pressure ratio of 2.25 is considered in the next three "thumbprint" plots (fig. 13(e-g)). A cruise speed of Mach 0.98 is considered first in figure 13(e). A variation of cruise T_4 with takeoff T_4 fixed at 2300° F showed that range was maximized by selecting a cruise T_4 of 2200° F. When the maximum range island of this "thumbprint" plot is compared with that for an FPR of 1.7 (fig. 13(b)), it is seen that an increase of 335 nautical miles is realized at the higher FPR. For the design parameters required to obtain a sideline jet noise level of 96 PNdB, a similar comparison shows a range increase of about 390 miles instead of 335 miles. At this higher FPR, the 96 PNdB sideline jet noise curve almost intersects the maximum range island. For the lower FPR (fig. 13(b)), however, there was a range penalty involved in obtaining a jet noise "floor" of 96 PNdB. It is also well to notice in comparing the two "thumbprints" that lower design BPR's are obtained at any given level of sideline jet noise as FPR is increased. This is because at any given BPR more specific work must be done by the turbine to drive the fan with the higher FPR. Thus, less energy is left in the gas downstream of the turbine and jet exhaust velocity (the most important jet noise variable) is reduced at the higher FPR.

A cruise speed of Mach 0.94 is considered next in figure 13(f) for a design FPR of 2.25. To have enough takeoff thrust with T_4 at 2300° F, it was necessary to reduce the cruise T_4 to 2070° F. The thrust limiting line almost touches the island of maximum range for this cruise T_4. Cruise OPR optimizes at a slightly lower value than in the previously discussed thumbprints. A sideline jet noise of about 99 PNdB is obtained at the thrust limiting line. By comparing these results with those of figure 13(e), it may be seen that a range improvement of more than 400 miles is obtained when cruise speed is reduced from Mach 0.98 to 0.94 at an FPR of 2.25. A range improvement of about 200 miles occurs when FPR is increased from 1.70 to 2.25 for cruise at Mach 0.94, as a comparison with the thumbprint of figure 13(c) will show.

In figure 13(g) a thumbprint plot is shown for a Mach 0.90 cruise with an FPR of 2.25. To increase the takeoff thrust to acceptable levels with T_4 at 2300° F, it was necessary to reduce the cruise T_4 to 1965° F. With this sizing criterion, it was necessary to move less than 100 miles away from the island of maximum range (4350 n mi) to reach the thrust limiting line. Lower cruise T_4's would have lowered the limiting $(F_n/W_g)_{sls}$ line relative to the maximum range island, but this island would have had a lower value. Hence, the range tradeoff is about equal but the selected T_4 gives a slightly lower sideline jet noise. A sideline jet noise of 98 PNdB is obtained at the intersection of the thrust limiting line and the line of optimum cruise OPR (i.e., OPR = 32). A comparison with the previous thumbprint (fig. 13(f)) shows that range can be increased by about 85 miles at the thrust limiting line by reducing the cruise speed from Mach 0.94 to 0.90 for a cruise FPR of 2.25. A comparison with the Mach 0.90 thumbprint for an FPR of 1.7 (fig. 13(d)) shows that raising the cruise FPR to 2.25 increases the range only about 90 miles at the optimum OPR on the thrust-limiting line. At the higher Mach numbers a greater range increase occurred over this rise in FPR. Hence, even without any consideration of fan machinery noise, the desirability of the higher FPR becomes less apparent as cruise speed is reduced.

Range penalty for reduction of combined jet and fan turbomachinery noise. - As previously discussed in "Method of Analysis" in connection with figure 12(a-c), optimum cycle points are next selected from the foregoing "thumbprints" in order to evaluate the range penalty that must be paid for different amounts of noise reduction. Figure 14(a) summarizes the results of this exercise for a cruise FPR of 1.70. Range with a penalty included for the weight of the turbomachinery noise suppressors is plotted against the total combined noise at either the sideline or the approach condition, whichever is greater. Three curves are shown - one for each of the cruise Mach numbers considered. The right-hand end of each curve represents the optimum cycle meeting the thrust constraint from one of the "thumbprint" plots. No acoustic suppression has been applied at these points and the ranges plotted here therefore agree with those from the corresponding thumbprints. At each of the three cruise speeds considered, it is seen from figure 14(a) that the optimum engines for this FPR can meet a noise goal of only about 114 PNdB. For the Mach 0.98 airplane unconstrained by noise, total noise is about the same at both the sideline and approach measuring stations. It is dominated by jet noise at the sideline condition and machinery noise at the approach condition. As cruise speed is reduced, approach noise exceeds sideline noise - by as much as 8 PNdB for the Mach 0.90 airplane.

As the noise goal is reduced by proceeding to the left in figure 14(a), the design BPR is increasing at the same time that turbomachinery acoustic treatment is being added. As the noise goal is reduced, the suppressed sideline and approach noise levels become equal at some point. This occurs almost immediately for the Mach 0.98 airplanes, but does not occur until a noise goal of 104 PNdB is reached for the Mach 0.94 airplanes. It occurs at a noise goal of 95 PNdB for the Mach 0.90 airplanes.

At the left-hand end of the curves, 27 to 30 PNdB of turbomachinery noise suppression is required. Also shown intersecting the three Mach number curves of figure 14(a) is a limiting line for 20 PNdB of turbomachinery noise suppression. As previously mentioned, 20 PNdB of fan machinery noise suppression is an optimistic goal to strive for, but one which hopefully can be met by the postulated year of first flight - 1978. Notice that with 20 PNdB suppression noise goals from 93 to 96 PNdB can be met at this design FPR.

Figure 14(b) shows the effect of various amounts of turbomachinery noise suppression for engines with a cruise FPR of 2.25. Again, the right-hand and points of the three curves represent the optimum cycle points without any suppression with the constraint that $(F_n/W_g)_{sls} \geqq 0.24$. With no suppression, it is seen that noise levels as high as 125 to 126 PNdB are obtained. Approach noise exceeded the sideline noise at all levels of suppression considered on this plot. With noise unsuppressed, the fan machinery noise exceeds the jet noise at both noise measuring stations regardless of design Mach number. As the amount of suppression is increased (i.e., proceeding to the left in fig. 14(b)), machinery noise eventually reaches the level of the jet noise. Unlike the case with an FPR of 1.70, however, BPR is not increased as the noise goal is reduced. It was found that with an FPR of 2.25 the range decreased as BPR was increased without a significant reduction in total noise. (Total noise was generally dominated by machinery noise, which is unaffected by BPR.) Hence, the best tradeoff was to keep the engine cycle parameters fixed as more machinery noise treatment was added.

The points at the left-hand end of the curves of figure 14(b) represent results that could be obtained if it were possible to suppress machinery noise by 30 PNdB. If we strive for a goal of 20 PNdB of suppression, the limiting line shows that goals of 106 to 108 PNdB of approach noise can be obtained, depending on design cruise Mach number. If the trades of FAR Part 36 are permitted, the goals that are met can be said to be 2 PNdB lower than these values since noise measured at the sideline station is more than 2 PNdB less than the approach noise. (With 20 PNdB of suppression, sideline noise is 6 to 7 PNdB less than approach noise.)

Results from figures 14(a) and (b) have been tabulated in table I to show how range is affected by higher design fan pressure ratio. The results are tabulated first for no noise constraint and then for noise goals of 106 and 96 PNdB with acoustic treatment. Data are shown for each of the three cruise speeds considered. No data are shown for cases where more than the assumed maximum limit of 20 PNdB of turbomachinery noise suppression was required to meet a given noise goal. It is apparent from the last column of the table that it becomes increasingly more desirable from the range standpoint to increase the design FPR as cruise speed is increased. At the low end of the cruise Mach number spectrum, lower design FPR's can be specified for lower noise with very little range penalty. (At the FPR of 1.70 the noise goal can be reduced from 106 to 96 PNdB with only a 40- to 66-mile range penalty, regardless of cruise speed.)

Results with 20 PNdB of turbomachinery noise suppression - In figure 15(a) range is plotted against cruise Mach number for noise goals of 106 and 96 PNdB. Data for the 106 PNdB curve was taken from figure 14(b) for the two-stage fans with an FPR of 2.25. Data for the 96 PNdB curve was taken from figure 14(a) for the single-stage fans with an FPR of 1.70. These noise goals were selected for further scrutiny because they can be achieved with approximately 20 PNdB of turbomachinery noise suppression at the FPR's under consideration. Lower noise goals at these FPR's would require more suppression than is likely to be achievable by the time the plane is postulated to be introduced. If curves for lower noise goals were to be plotted in figure 15(a) and still be compatible with the two curves shown, it would be necessary to obtain additional data for design FPR's lower than 1.7.

Figure 15(a) emphasizes the increase in range possible by reducing the cruise speed from Mach 0.98 to 0.90. The range improvement that is obtained by reducing speed is especially evident with the curve for the 96 PNdB noise goal. At this goal, the range can be increased by about 800 nautical miles by this reduction in cruise speed. If the speed reduction is halved to Mach 0.94, range can be increased by 600 miles over its value at Mach 0.98. The range improvement that can be obtained by these reductions in cruise speed is not quite as great at the higher noise goal of 106 PNdB. For this goal, a range increase of only 500 nautical miles was possible by decreasing the design cruise speed from Mach 0.98 to 0.90. If the speed reduction was halved to Mach 0.94 for this noise goal of 106 PNdB, 80 percent (400 n mi) of this range improvement can be retained.

It is also apparent from figure 15(a) that there is a range penalty involved in reducing the noise from 106 to 96 PNdB. This range penalty decreases from 400 nautical miles at Mach 0.98 to less than 100 miles at Mach 0.90. At Mach 0.94, there is a 200-mile range penalty involved when the cycle is optimized for 96 PNdB instead of 106 PNdB with 20 PNdB of machinery noise suppression.

In figure 15(b) the optimum cruise bypass ratios are shown as a function of cruise Mach number for noise goals of 106 and 96 PNdB. BPR optimizes in the vicinity of 4 at all values of M_{cr} for the 106 PNdB noise goal. For the 96 PNdB noise goal, BPR optimizes at about 6.

In figure 15(c) the optimum cruise overall compressor pressure ratios are shown to vary from 32 to 36 for the 106-PNdB noise goal. For the 96-PNdB noise goal the optimum OPR's are somewhat higher and vary from 36 to 41. As can be seen by referring to the "thumbprint" plots, however, OPR is not a strong optimum and can be reduced to the vicinity of 30 without any significant adverse effect on range. This reduction may be required to curtail nitrogen oxide emissions. OPR optimized at rather high values in this study because of the advances that were assumed to occur in engine weight technology by the year 1978. Higher OPR's, therefore, did not cause great increases in engine weight in this study. More conservative engine weight assumptions would have caused engine weight to rise faster with OPR, with the result that the optimum OPR's would have been lower.

In figure 15(d) it is shown that the takeoff thrust-to-gross-weight ratio increases from the minimum of 0.24 for the lower cruise speeds to values as high as 0.31 for a cruise speed of Mach 0.98 with a noise goal of 96 PNdB. It will be recalled that the cruise (design) T_4 was adjusted with the takeoff T_4 fixed to obtain an $(F_n/W_g)_{sls}$ of not less than 0.24. (The three-engine Boeing 727-200 has this value of $(F_n/W_g)_{sls}$ when fully loaded.) The fact that $(F_n/W_g)_{sls} > 0.24$ for the Mach 0.98 cruise cases reflects that the cruise T_4 has been adjusted upward to its maximum permissible value of 2200° F (i.e., 100° F less than the fixed takeoff T_4 of 2300° F). To have obtained values of $(F_n/W_g)_{sls}$ closer to 0.24 would have required raising the cruise T_4 beyond 2200° F, thus violating one of the study ground rules. Such a rise in cruise T_4 with takeoff T_4 held fixed would make the climb thrust too marginal as cruise is approached.

The cruise T_4's that optimized performance are plotted against Mach number in figure 16(e). For the 106-PNdB noise goal, it is seen that the cruise T_4 rises linearly from 1965° F at Mach 0.90 to 2200° F at Mach 0.98 when the takeoff T_4 is fixed at 2300° F. For the 96-PNdB noise goal, the cruise T_4 optimizes at 2100° F at Mach 0.90 and increases linearly to 2200° F at Mach 0.94 where it meets the aforementioned constraint for thrust margin. Beyond Mach 0.94 the cruise T_4 is restricted to 2200° F, although range would probably have improved if higher temperatures had been allowed.

Figure 15(f) shows the sea-level-static corrected airflow required for each of the optimized engines with airplane TOGW fixed at 386 000 pounds. For the engines optimized to meet the 106-PNdB noise goal, these airflows varied from 840 to 950 pounds per second. Airflows varying from 1030 to 1360 pounds per second were required to meet the 96-PNdB noise goal. The corresponding engine maximum diameters are shown in figure 15(g). For the optimum engines meeting the 106-PNdB goal, the maximum diameter is about 70 inches. To meet the 96-PNdB goal, the engine maximum diameters must be increased to 80 to 90 inches.

The next figure (fig. 15(h)) shows the variation of both sideline and approach noise with M_{cr} for the two noise goals under consideration. The solid curves represent sideline noise and the broken curves represent approach noise. The figure shows that at the nominal 106-PNdB goal, the approach noise ranges from 106 to 108 PNdB, depending on M_{cr}. The corresponding sideline noise varied from 100 to 102 PNdB. (As previously discussed, the ground rules of FAR Part 36 permit an excess of up to 2 PNdB at one measuring station if a corresponding reduction can be obtained at another measuring station.) For the 96-PNdB goal there was very little difference between the sideline and approach noises.

Direct operating cost. - DOC is shown plotted in figure 16(a) for the range-optimized engines with a cruise FPR of 1.70. The DOC points plotted in this figure correspond to the range points plotted in figure 14(a). Whereas range was maximized by choosing an M_{cr} of 0.90, figure 16(a) shows that the best DOC was obtained with an M_{cr} of 0.94. Although the range was less at Mach 0.94 than at Mach 0.90, the greater block speed at Mach 0.94 counteracts this effect in the DOC calculations.

Similar DOC results are shown in figure 16(b) for the range-optimized engines with a cruise FPR of 2.25. The DOC points plotted in this figure correspond to the range points plotted in figure 14(b). Here, again, DOC is best at a cruise Mach number of 0.94 while range was greatest at Mach 0.90. However, because the range penalty involved in increasing M_{cr} to 0.98 is not as great at the higher FPR, the DOC at Mach 0.98 is better than it is at Mach 0.90. With an FPR of 1.70, the reverse is true - that is, the DOC's at Mach 0.98 are worse than they are at Mach 0.90.

DOC data from figures 16(a) and (b) has been replotted against cruise Mach number in figure 17 for noise goals of 96 and 106 PNdB. These DOC curves are analogous to the range curves of figure 15(a). The curves of figure 17 show clearly that the best (i.e., lowest) DOC's are obtained at cruise speeds of about Mach 0.94. At Mach 0.94 the DOC increases by only 0.014 cent per seat-statute-mile when the noise goal is reduced from 106 to 96 PNdB. If the cruise speed is increased to Mach 0.98, the DOC increases by 0.023 cent per seat-mile at the 96-PNdB noise goal. At the 106-PNdB noise goal (where the FPR is higher), the economic penalty of increasing the cruise speed to Mach 0.98 is not nearly as great. Here, the increase in DOC is only 0.0065 cent per seat-statute-mile.

Calculation of TOGW for Previously Optimized Cycles When Range is Fixed

The engine cycles which were previously optimized on a range basis are reevaluated in terms of TOGW in this section of the report for a fixed range of 3000 nautical miles. The airframe weight was assumed to be a constant percentage of the TOGW in these calculations. The payload was again held constant at 300 passengers. Engine airflows, diameters, and weights were recomputed on the basis of the different thrust levels required at the lower TOGW's. (Since ranges greater than 3000 miles were obtained for the optimum cycles when TOGW was fixed at 386 000 pounds, the TOGW's calculated in this section will all be less than this amount.)

<u>TOGW penalty for reduction of combined jet and fan turbomachinery noise</u>. - Figure 18(a) shows how TOGW varies with noise goal at the three cruise speeds under consideration when the FPR is fixed at 1.70. This figure is analogous to figure 14(a), except that TOGW has been substituted for range as the ordinate. From figure 18(a), it appears that there is very little increase in TOGW when the noise goal is reduced at cruise speeds of Mach 0.90 to 0.94. But when cruise speed is increased to Mach 0.98, the increase in TOGW becomes more severe as noise goal is reduced.

Figure 18(b) shows the variation of TOGW with noise goal when cruise FPR is fixed at 2.25. This figure is analogous to figure 14(b) with TOGW substituted for range as the ordinate. It appears from figure 18(b) that there is very little increase in TOGW associated with reducing the noise goal for any of the design cruise speeds considered.

<u>Results with 20 PNdB of turbomachinery noise suppression</u>. - In figure 19(a) TOGW is plotted against cruise Mach number for noise goals of 106 and 96 PNdB. Data for the 106 PNdB curve was taken from figure 18(b) for the two-stage-fan engines with an FPR of 2.25. Data for the 96 PNdB curve was taken from figure 18(a) for the single-stage-fan engines with an FPR of 1.70. These noise goals were selected for further scrutiny because they can be attained with approximately 20 PNdB of turbomachinery noise suppression. Figure 19(a) is analogous to figure 15(a) with TOGW substituted for range as the ordinate. Figure 19(a) emphasizes the significant increase in TOGW that is required when cruise speed is increased from Mach 0.94 to 0.98. This increase is especially significant for the 96-PNdB noise curve. The figure shows that at the lower Mach numbers (up to $M_{cr} = 0.94$) there is only a modest rise in the TOGW requirement for a noise goal of 96 PNdB as opposed to 106 PNdB. At Mach 0.94 a TOGW of 267 000 pounds is required to meet a noise goal of 106 PNdB. A TOGW of 281 000 pounds is required to meet a noise goal of 96 PNdB at the same speed. Figures 15(b-e) show some of the characteristics of the optimum cycles which are independent of size. Figures 19(b-d) show the size-related characteristics for the engines used in the airplanes of figure 19(a).

Direct operating cost. - DOC is shown plotted in figure 20(a) for the optimum engines with a cruise FPR of 1.70 with range fixed at 3000 nautical miles. The DOC points plotted in this figure correspond to the TOGW points plotted in figure 18(a). The DOC penalty associated with increasing the cruise speed from Mach 0.90 to 0.94 is so slight that it could well be ignored. The penalty involved in raising the cruise speed to Mach 0.98, however, might be significant (just under 0.09 cent/seat-s-mi at a noise goal of 96 PNdB).

Similar results are shown in figure 20(b) for optimum engines with a cruise FPR of 2.25 with range fixed at 3000 miles. These DOC points correspond to the TOGW's plotted in figure 18(b). At this higher FPR there does appear to be some economic benefit to cruising at Mach 0.94 instead of Mach 0.90. Also, raising the cruise speed to Mach 0.98 is not quite as severe a penalty DOC-wise as it was at the lower FPR, relative to the DOC's obtained at the lower cruise speeds.

DOC data from figures 20(a) and (b) have been replotted against cruise Mach number as the solid curves in figure 21(a) for noise goals of 96 and 106 PNdB. These 3000-mile DOC curves are analogous to the TOGW curves of figure 19(a). For comparison, the DOC curves for a constant TOGW and variable range (fig. 17) have been replotted in figure 21(a) as the broken curves. By comparing the two sets of curves it is seen that the reduction in TOGW that was accomplished by fixing the range at 3000 nautical miles lowered the level of DOC generally and accentuated changes resulting from increments in cruise Mach number or noise goal reduction.

The large difference between the solid curves and the broken curves at Mach 0.94 and below results from the fact that TOGW was calculated to be more than 100 000 pounds less when range was fixed at 3000 miles. The reduced TOGW was partly due to the assumption that airframe weight fraction should remain constant for scaled similar airplanes. Actually, the airplanes were not entirely similar after fixing the range and reducing the TOGW because the number of passengers and, hence, fuselage dimensions were fixed. This nonsimilarity may cause the airframe weight fraction to increase slightly as TOGW is reduced. Airframe weight fraction should probably be increased an additional amount as range is reduced because of the greater number of takeoff and landing cycles in a shorter-haul operation in a given period of time. A strengthening of the structure would probably be required to provide fatigue life equivalent to that of the longer-range airplanes. Such considerations were ignored in this simplified analysis and contribute to what appears to be a wide displacement between the solid and broken curves of figure 21(a). The DOC's of both sets of curves, however, appear to minimize near the middle of the range of cruise speeds studied. For the fixed range of 3000 miles, the DOC actually minimized at Mach 0.94 for the 106-PNdB goal and Mach 0.92 for the 96-PNdB goal. But very little increase in DOC is introduced by raising the cruise speed to Mach 0.94 for the 96-PNdB noise goal and Mach 0.95 for the 106-PNdB noise goal. At these speeds, DOC is increased by only about 0.02 cent per seat-statute-mile when the noise goal is reduced from 106 to 96 PNdB. This does not seem to be a very large economic penalty to pay for a 10 PNdB reduction in noise. If the cruise speed is increased to Mach 0.98, the DOC increases by about 0.08 cent per seat-mile at the 96 PNdB noise goal, relative to its values for a Mach-0.94 cruise. At the 106-PNdB goal, the DOC rises by only about 0.03 cent per seat-mile when speed is increased to Mach 0.98.

The airplane prices obtained by the procedure discussed in the "Method of Analysis" ranged from $12 to 14 million for the optimum cases, depending on cruise speed. These prices were estimated on the basis of present-day airframe and engine costs, but may be somewhat low for advanced technology airplanes selling in 1978. Hence the DOC calculations were repeated with a 50 percent increase in airframe and engine costs assumed. The results are shown in figure 21(b) and show a slightly greater penalty for reducing the noise from 106 to 96 PNdB. The penalty for increasing the cruise speed to Mach 0.98 is also somewhat higher. The DOC at the "bucket" of the 106-PNdB curve rose from 0.484 to 0.602 cent per seat-mile because of the 50-percent rise in airplane price. At the 96-PNdB noise goal, the DOC rose from 0.504 to 0.631 cent per seat-mile at the "bucket" because of the increase in airplane price. These DOC's at the higher airplane prices are comparable to those obtained with the DC8-61 with 251 seats. The selling price of a DC8-61, however, was less than half that of the advanced technology airplanes. This indicates that the advanced technology airplanes operate more efficiently and by so doing tend to negate their initial cost disadvantage. At the same time, the advanced technology airplanes will be considerably more quiet.

DOC, of course, does not present the entire economic picture. It does not, for instance, show how load factor might be affected by the introduction of competing airplanes designed for higher cruise speeds. Hence, although the lowest DOC's occur at design speeds between Mach 0.92 and 0.94, load factor (and, therefore, profitability) could be adversely affected by the introduction of faster airplanes if block times are significantly reduced. For this reason, the block time difference between Mach 0.98 and 0.94 airplanes has been plotted against total range in figure 22. The block time difference is 11.5 minutes for the range considered in this study (i.e., 3000 n mi). It is unknown whether such a time difference would prove to be too much of a competitive disadvantage for the Mach 0.94 airplanes if they were threatened with competition from airplanes designed for Mach 0.98. Actually, a range of 3000 nautical miles is more than would normally be encountered on domestic United States routes. The range from New York to San Francisco (2235 n mi) might more typically represent a long-range domestic flight. The block time difference between Mach 0.94 and 0.98 at this range is only about 8.3 minutes. When block times are considered, however, it does seem worthwhile to increase the design speed to a point just to the right of the "bucket" of the DOC curves of figures 21(a) and (b) since so little penalty in DOC is involved by so doing. With this criterion, a good cruise speed selection might be Mach 0.95 for the 106 PNdB noise goal and Mach 0.94 for the 96 PNdB noise goal.

CONCLUDING REMARKS

A parametric study was made of a group of separate-flow-exhaust turbofan engines for use in advanced technology airplanes designed for cruise speeds ranging from Mach 0.90 to 0.98. Initial cruise altitudes ranged from 36 449 feet at Mach 0.90 to 40 000 feet at Mach 0.98. A schedule of cruise lift-drag ratio against Mach number compatible with airplanes using the Whitcomb supercritical wing was chosen. All airplanes in this study embodied area-ruled fuselages capable of seating 300 passengers. Three aft-mounted engines of advanced, lightweight technology were used for all the study airplanes. Combined jet and fan machinery noise calculations were made for selected cycles at both the sideline and approach measuring stations specified by FAR Part 36. Varying amounts of acoustic treatment were applied to the inlet, duct, and nacelle to obtain different levels of turbomachinery noise.

The engine parameters of bypass ratio, compressor pressure ratio, cruise turbine rotor-inlet temperature, and airflow were optimized at cruise fan pressure ratios of 1.70 and 2.25. The takeoff turbine rotor-inlet temperature was fixed at 2300° F. The FPR of 1.70 is a conservative upper limit of pressure ratio for a single-stage fan. Single-stage fans are desirable from a machinery noise standpoint since experimental data indicate that multi-staging at any given FPR increases the perceived noise about 8 PNdB. Higher FPR's are desirable, however, because they improve the airplane figure of merit. FPR's higher than 2.25 were not considered because of the greater difficulty of suppressing fan machinery noise to a given level.

It was found that approach noise for the acoustically untreated engines varied from 114 to 126 PNdB. Sideline noise for these engines varied from 104 to 115 PNdB. FAR Part 36 requires that these noise levels be 106 EPNdB or less for the takeoff gross weights considered here. (In this report, the PNdB scale is used instead of the EPNdB scale to simplify the calculations; the error introduced by so doing is probably less than that which would be introduced by making further assumptions required about directivity and maximum pure tones that are needed for the EPNdB calculation.) The machinery noise was the prime offender for most of these untreated engines - the exception being the noise of the low-FPR engines designed for $M_{cr} \geqq 0.94$, measured at the sideline station. Obviously, then, acoustic treatment of the inlet-duct-nacelle combination and/or cycle modification is required to bring the noise under control.

For the optimized engines with a design FPR of 2.25, the jet noise "floor" was so low that cycle modifications were not required to reduce the noise level to 106 PNdB. About 20 PNdB of acoustic treatment (i.e., the addition of concentric acoustically lined inlet splitter rings and wall lining for the inlet, duct, and nacelle) was required. For the single-stage fans (FPR_{cr} = 1.70), however, cycle modifications were required in many cases, at the same time that turbomachinery acoustic treatment was applied, in order to optimize the cycle at each noise level.

With 20 PNdB of turbomachinery acoustic treatment, noise goals of 92 to 96 PNdB can be met with the lower FPR, depending on the M_{cr} which is chosen. (20 PNdB of turbomachinery noise suppression requires some advancement of technology; to date, the maximum demonstrated suppression is 15 PNdB.)

Cruise bypass ratio optimized at about 4 for the engines having an FPR of 2.25. Overall fan and compressor pressure ratio ranged from 32 to 36 over the spectrum of cruise speeds considered here. Optimum cruise bypass ratio for the single-stage fan engines (FPR_{cr} = 1.70) ranged from 4 to 6, depending on cruise speed and amount of suppression. For 20 PNdB of suppression, BPR optimized at about 6, regardless of cruise speed. For 20 PNdB of suppression, the overall fan and compressor pressure ratio optimized over a range from 36 to 41, depending on cruise speed. Overall pressure ratio, however, does not strongly influence the airplane figure of merit (e.g., TOGW or DOC) and can be reduced to levels of 25-30 without significant adverse effect. (Control of nitrogen oxide emissions is likely to be easier at these lower pressure ratios.)

When range was fixed at 3000 nautical miles, TOGW minimized at a cruise speed of Mach 0.92 for an FPR of 2.25 and Mach 0.90 for an FPR of 1.70. The TOGW minimized at 262 000 pounds for the suppressed two-stage fans meeting the 106-PNdB noise goal and at 268 000 pounds for the suppressed single-stage fans meeting the 96-PNdB goal. Direct operating cost, however, minimizes at a slightly higher Mach number than TOGW because of the beneficial effect of the lower block time obtained at higher cruise speeds. DOC minimized at Mach 0.94 for an FPR of 2.25 and Mach 0.92 for an FPR of 1.70. Only a very slight increase in DOC is incurred by raising the cruise speed to Mach 0.95 for an FPR of 2.25 and Mach 0.94 for an FPR of 1.70. With airplane costs based on those of existing airplanes of the same weight, DOC was computed to be in the vicinity of 0.5 cent per seat-statute-mile for these optimum engines with 20 PNdB of suppression. If a 50 percent rise in airplane cost is assumed, DOC's minimize at slightly more than 0.6 cent per seat-mile.

What appear to be significant DOC penalties are incurred by increasing the design cruise speeds to Mach 0.98. For a cruise speed increase from Mach 0.94 to 0.98, a block time saving of about 11.5 minutes can be realized over a 3000-nautical-mile range. For a typical American transcontinental range, the block time saving would only be about 8 minutes. It is unknown whether block time savings of this amount would warrant increasing the cruise speed to Mach 0.98.

Only slight TOGW and DOC increases were encountered in the vicinity of Mach 0.94 when noise was reduced by 10 PNdB by switching from the two-stage to the single-stage fan engines with a higher bypass ratio. TOGW increased about 10 000 pounds. The DOC increased by only 0.03 cent per seat-statute-mile. These penalties seem to be a small price to pay for noise reductions of this magnitude. For noise levels below 92 to 96 PNdB, design FPR's lower than 1.70 are probably desirable, but were not considered in the present study.

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TABLE I. - EFFECT OF DESIGN FAN PRESSURE RATIO AND CRUISE SPEED ON RANGE OF ACOUSTICALLY-TREATED* OPTIMUM AIRPLANES

M_{cr}	Noise goal, PNDB	R @ FPR = 1.7, n mi	R @ FPR = 2.25, n mi	$\Delta R = R_{FPR=2.25} - R_{FPR=1.7}$, n mi
0.90	None	4175	4245	70
	106	4145	4180	35
	96	4102	----	---
0.94	None	3985	4175	190
	106	3950	4115	165
	96	3910	----	---
0.98	None	3410	3740	330
	106	3346	3680	334
	96	3280	----	---

*Acoustic treatment limited to an assumed maximum of 20 PNDB.

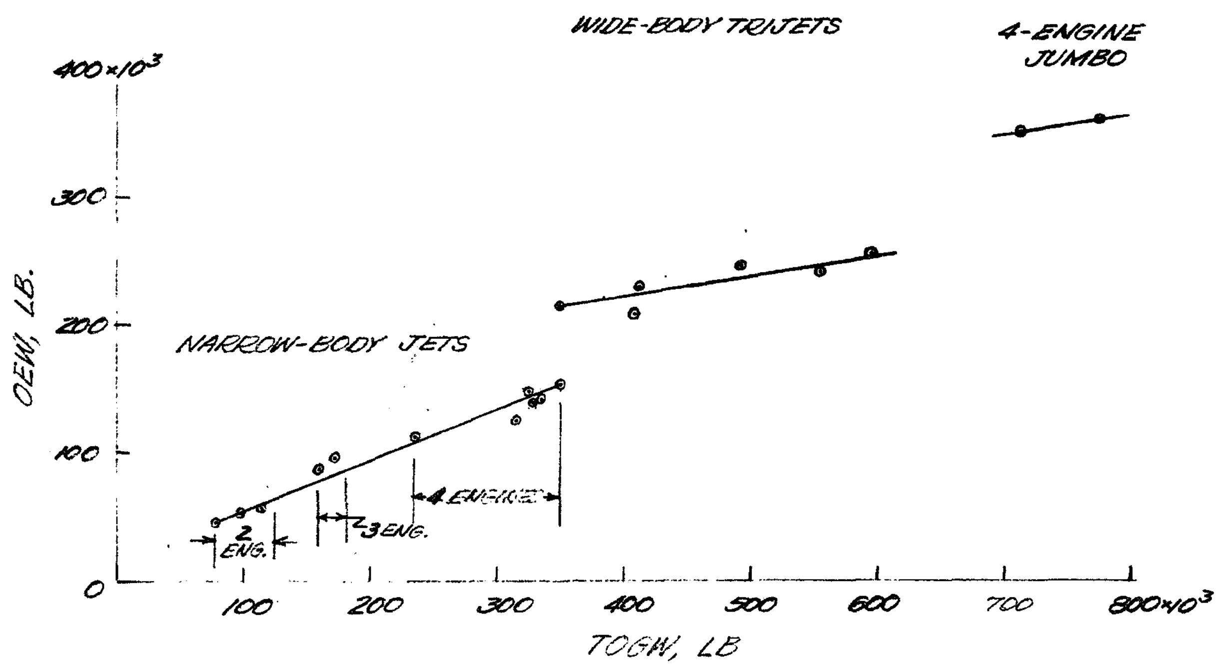


FIGURE 1. – WEIGHTS OF TURBOFAN-POWERED SUBSONIC TRANSPORTS. (DATA FROM REF. 8)

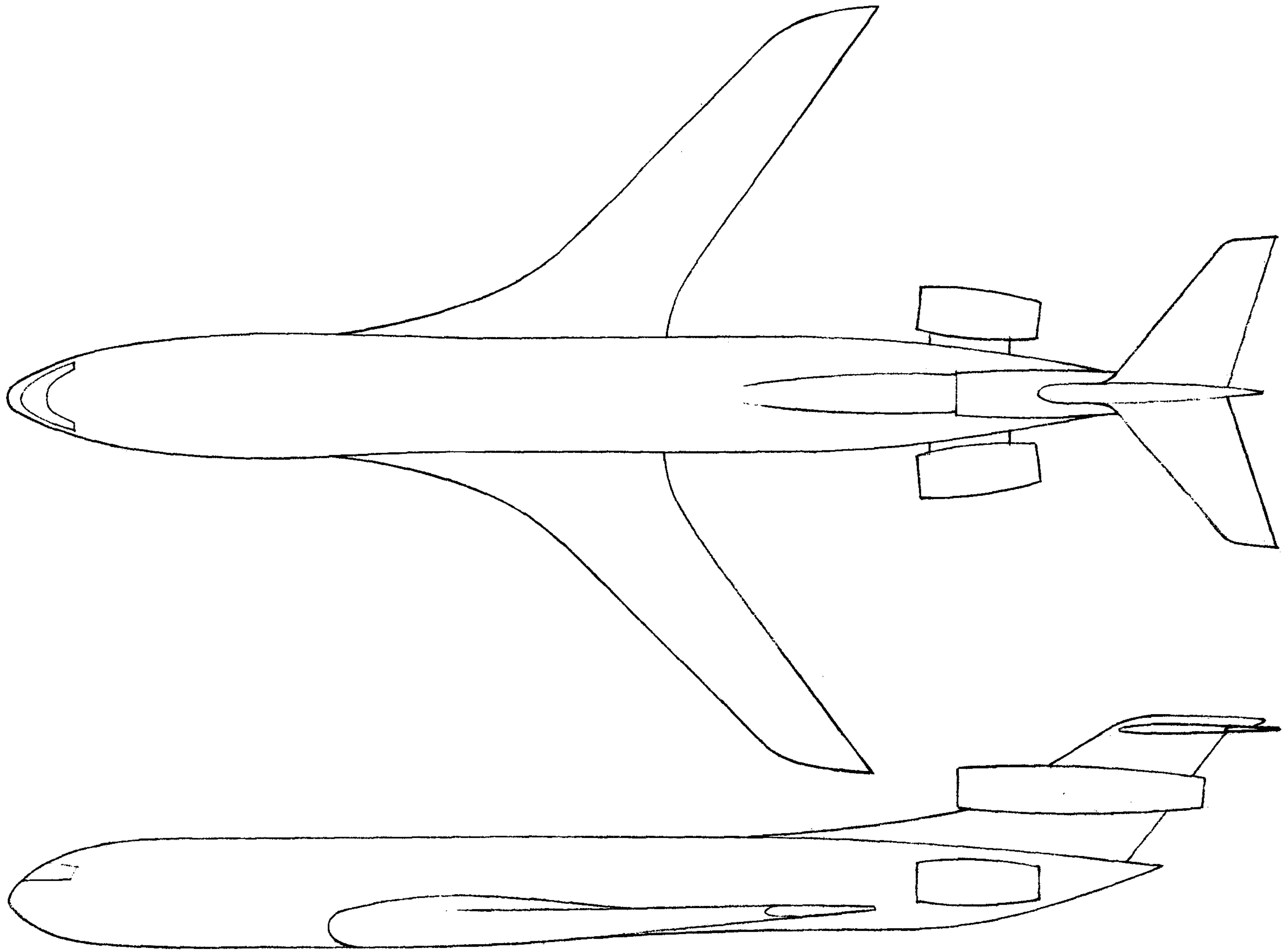


FIGURE 2.- SKETCH OF CONCEPTUAL ADVANCED TRI-JET TRANSPORT.

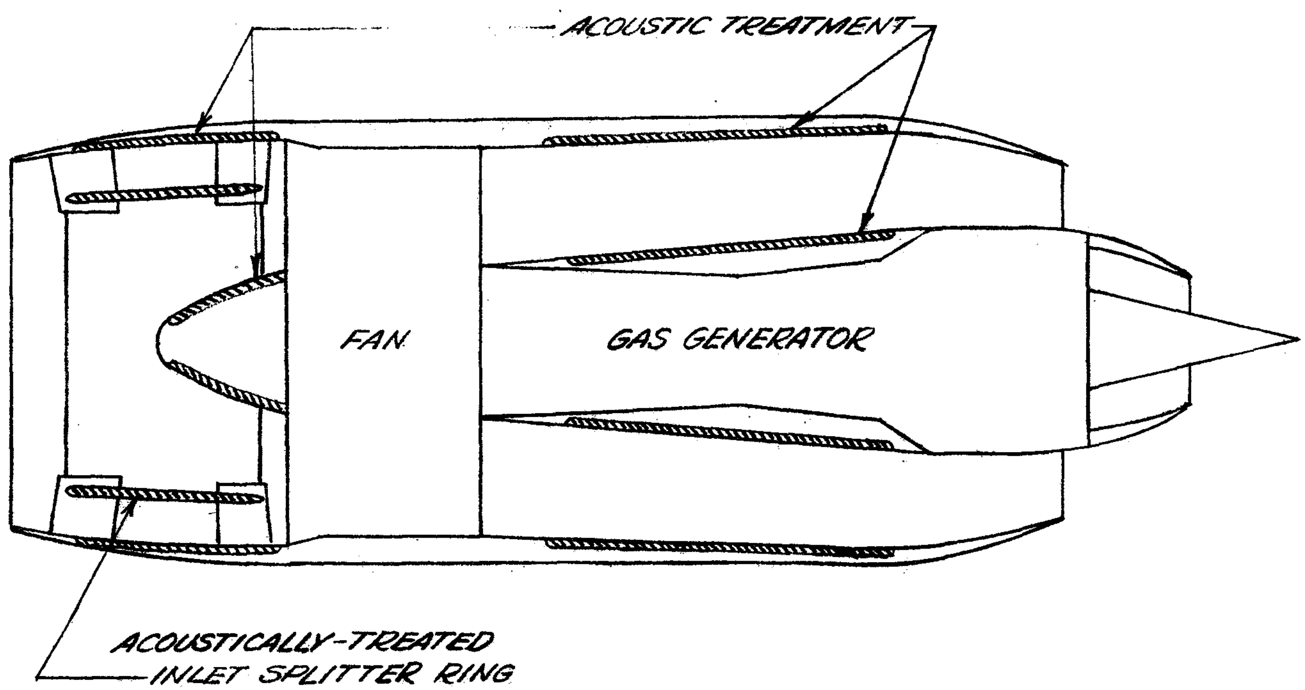


FIGURE 3. – SKETCH OF TURBOFAN ENGINE INSTALLATION WITH ACOUSTIC TREATMENT.

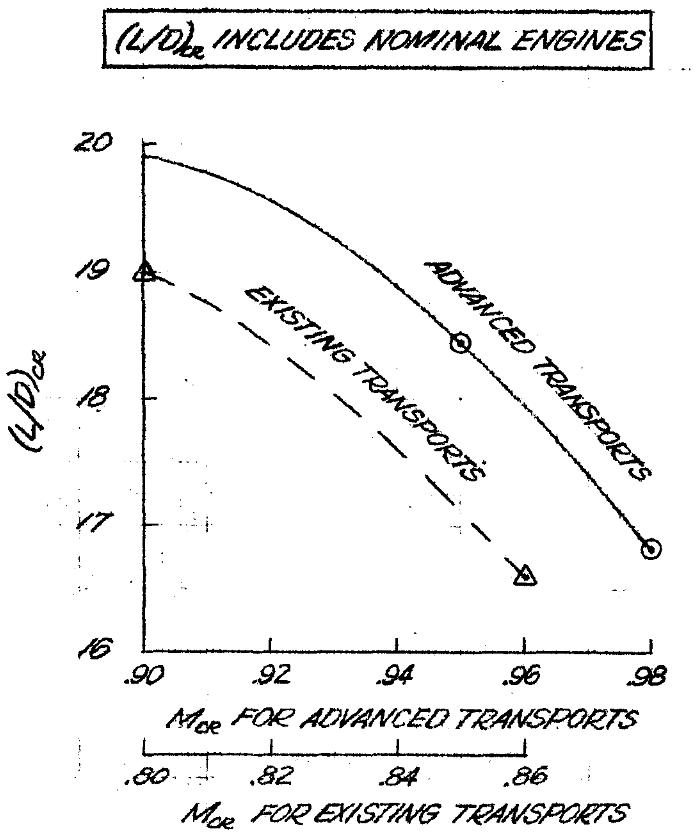


FIGURE 4.— SCHEDULE OF AIRPLANE LIFT-DRAG RATIO AS A FUNCTION OF CRUISE MACH NUMBER; NOMINAL 80-IN. DIAMETER ENGINES INCLUDED WITH ADVANCED TECHNOLOGY TRANSPORTS.

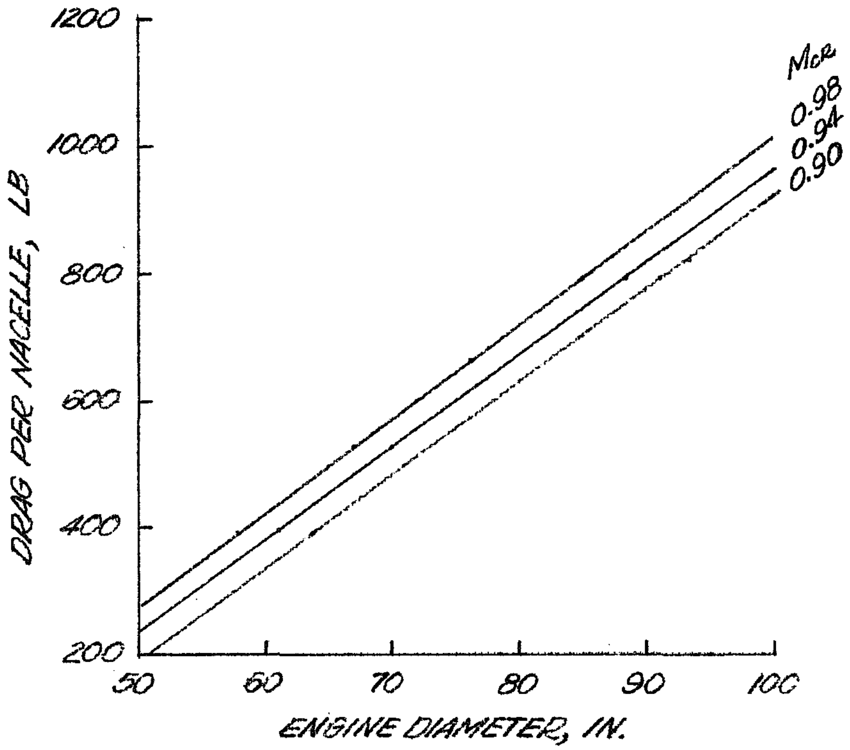
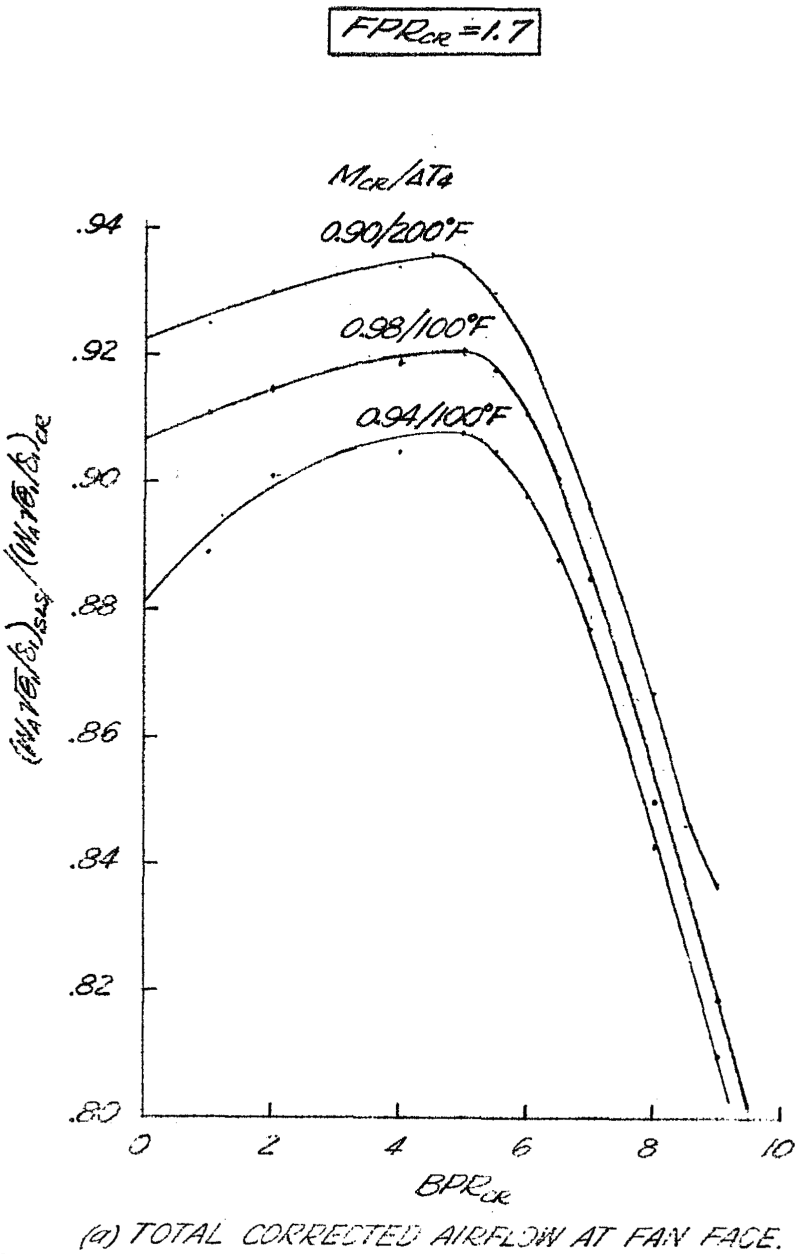
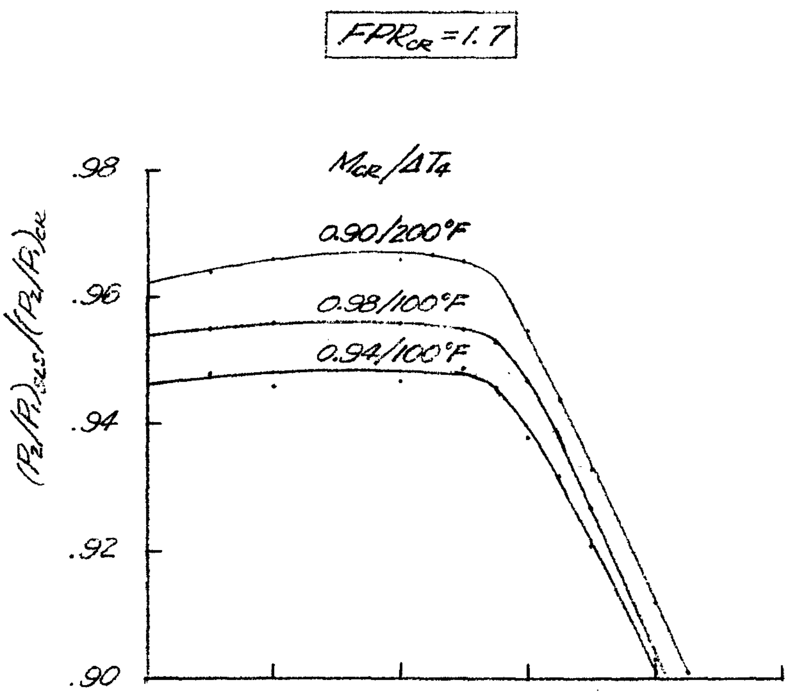


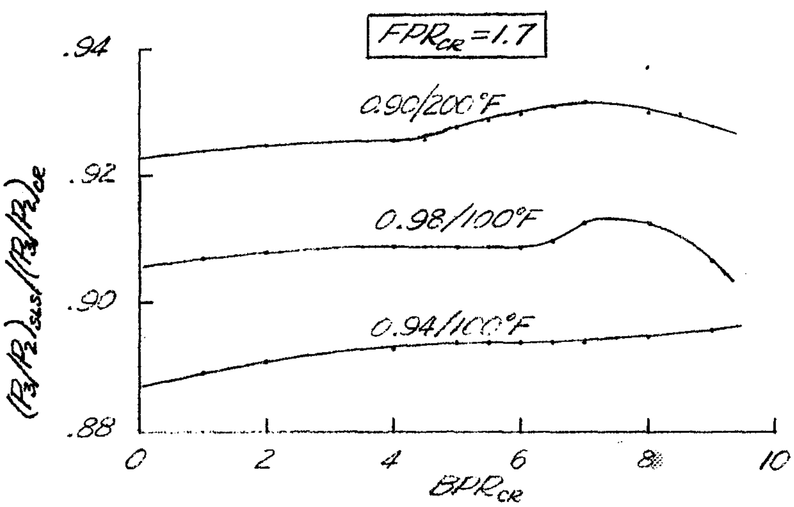
FIGURE 5.— NACELLE DRAG RELATED TO ENGINE MAXIMUM DIAMETER AND CRUISE MACH NUMBER.



(a) TOTAL CORRECTED AIRFLOW AT FAN FACE.
FIGURE 6.– FACTORS FOR CORRECTING CRUISE ENGINE PARAMETERS TO SEA-LEVEL-STATIC CONDITION. CRUISE FAN PRESSURE RATIO, 1.70.



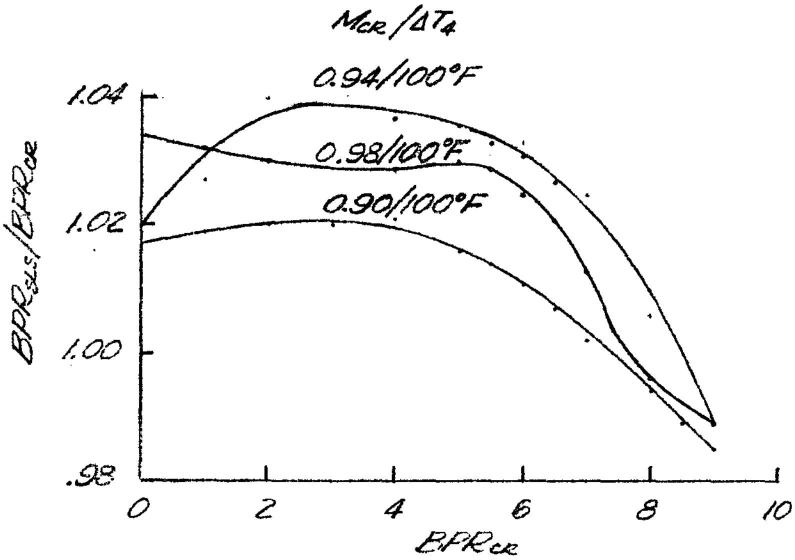
(b) FAN PRESSURE RATIO.



(C) INNER-COMPRESSOR PRESSURE RATIO.

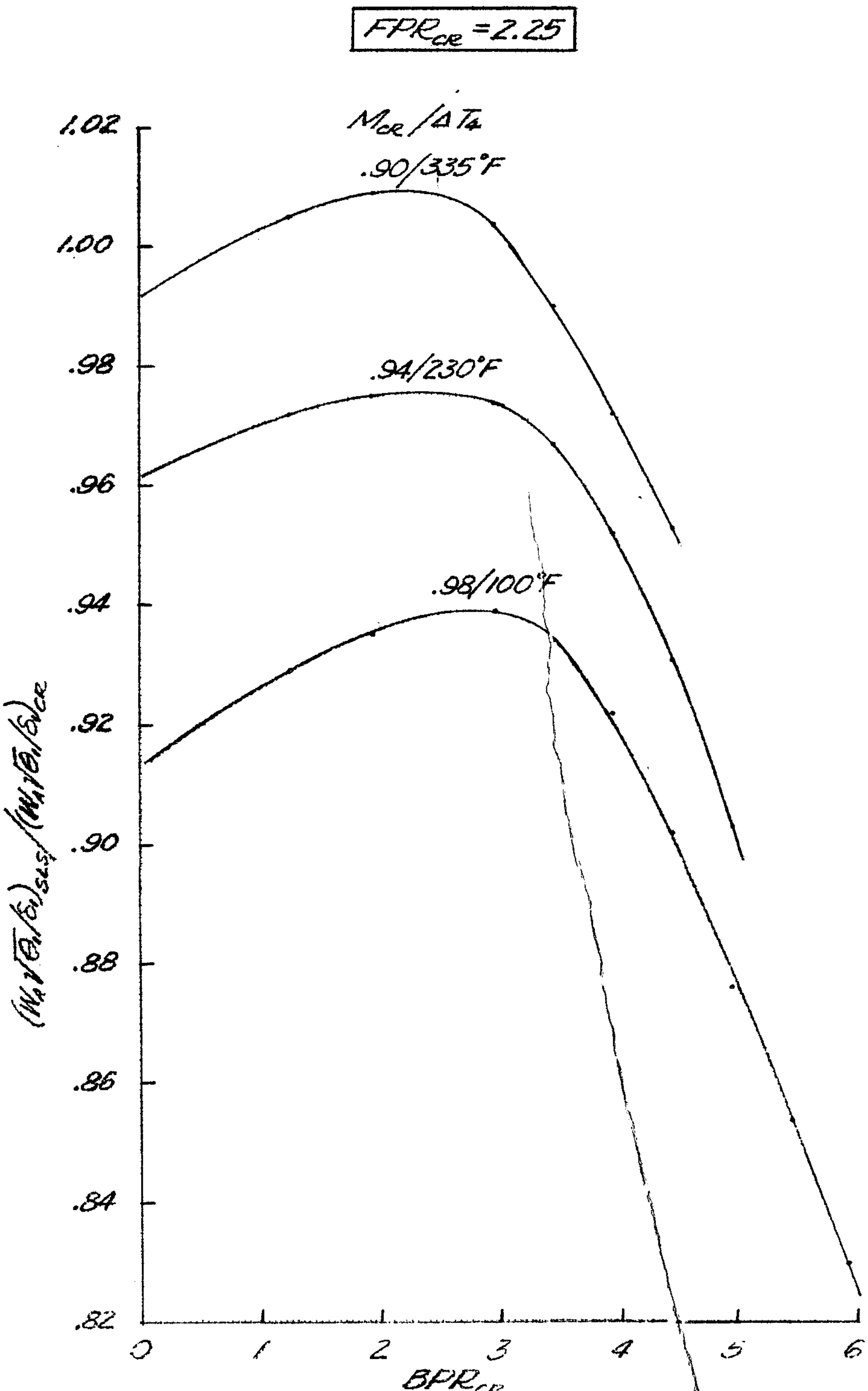
FIGURE 6. – CONTINUED.

$\boxed{FPR_{CR} = 1.7}$



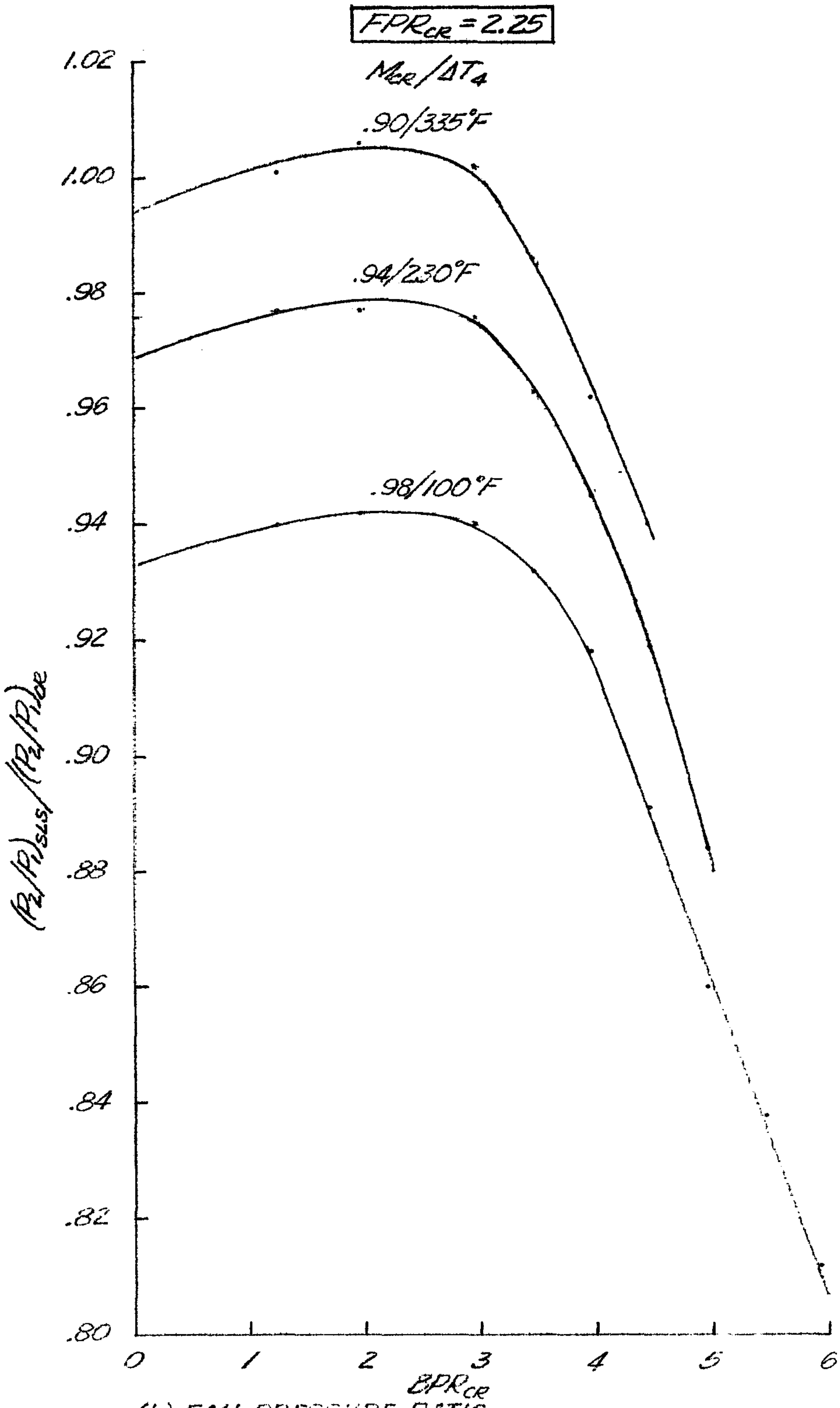
(d) BYPASS RATIO

FIGURE 6.—CONCLUDED.

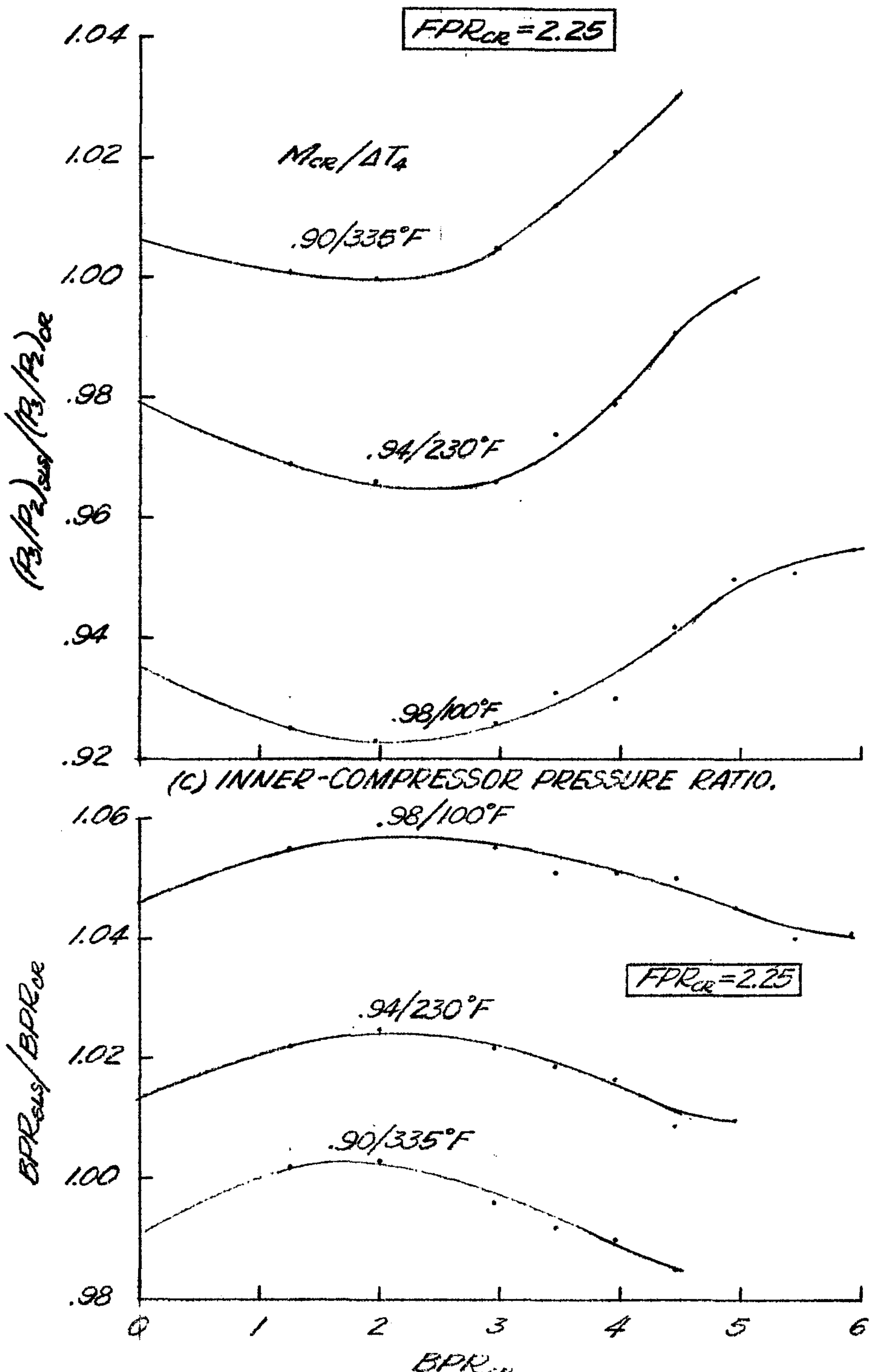


(a) TOTAL CORRECTED AIRFLOW AT FAN FACE.

FIGURE 7. – FACTORS FOR CORRECTING CRUISE ENGINE PARAMETERS TO SEA-LEVEL-STATIC CONDITION. CRUISE FPR, 2.25.



(b) FAN PRESSURE RATIO.
FIGURE 7. – CONTINUED.



(d) BYPASS RATIO

FIGURE 7. – CONCLUDED.

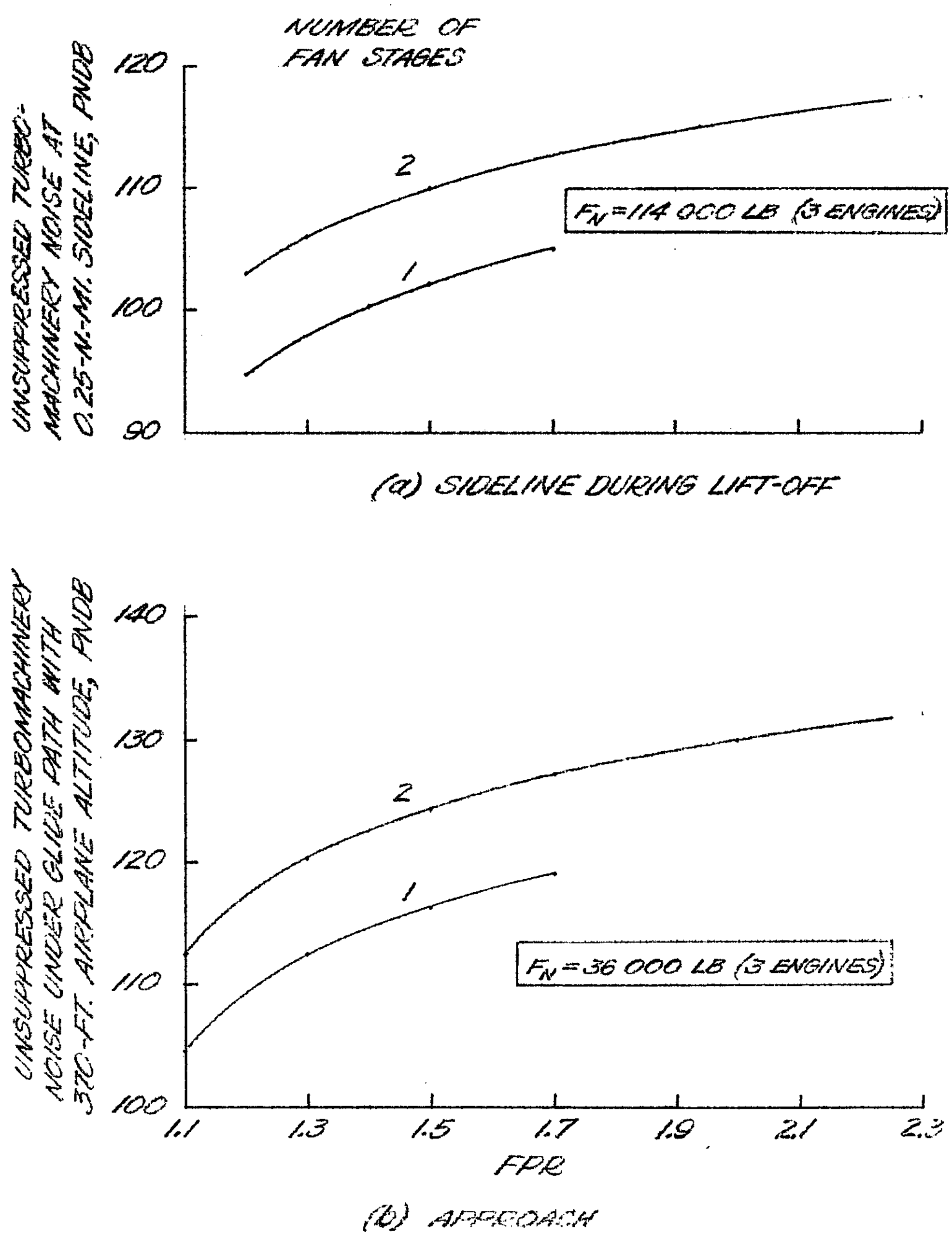
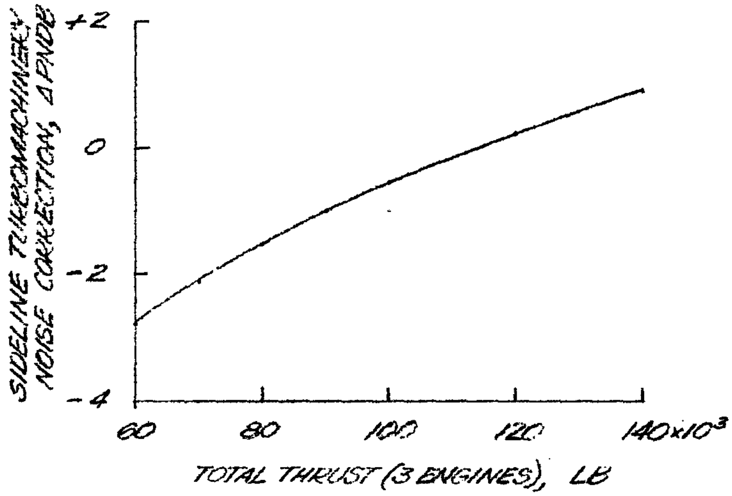
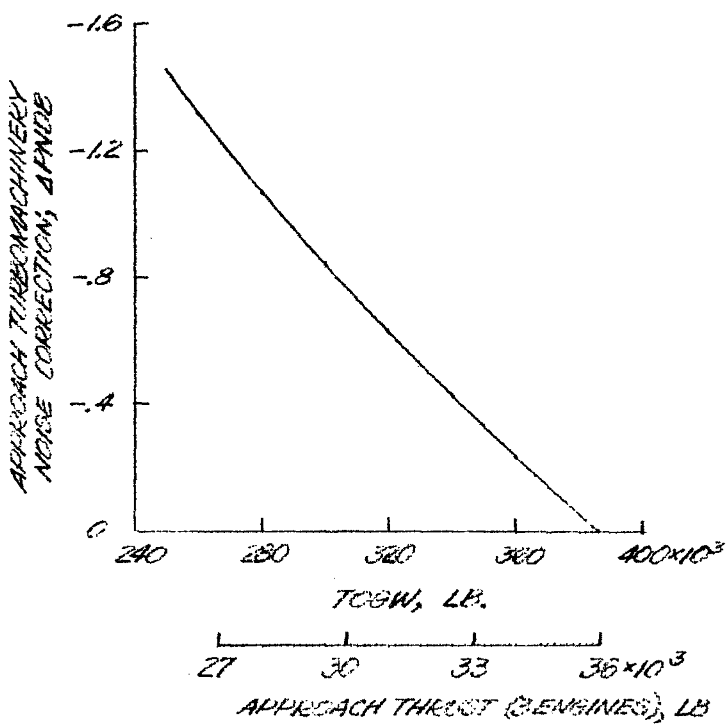


FIGURE 8. – FAN TURBOMACHINERY NOISE AT FIXED DISTANCES AND THRUSTS FOR BOTH ONE- AND TWO-STAGE FANS.



(a) SIDELINE



(b) APPROACH

FIGURE 9. - TURBOMACHINERY NOISE CORRECTIONS TO BE APPLIED TO DATA OF FIGURE 8 AS THRUST IS CHANGED FROM REFERENCE VALUE.

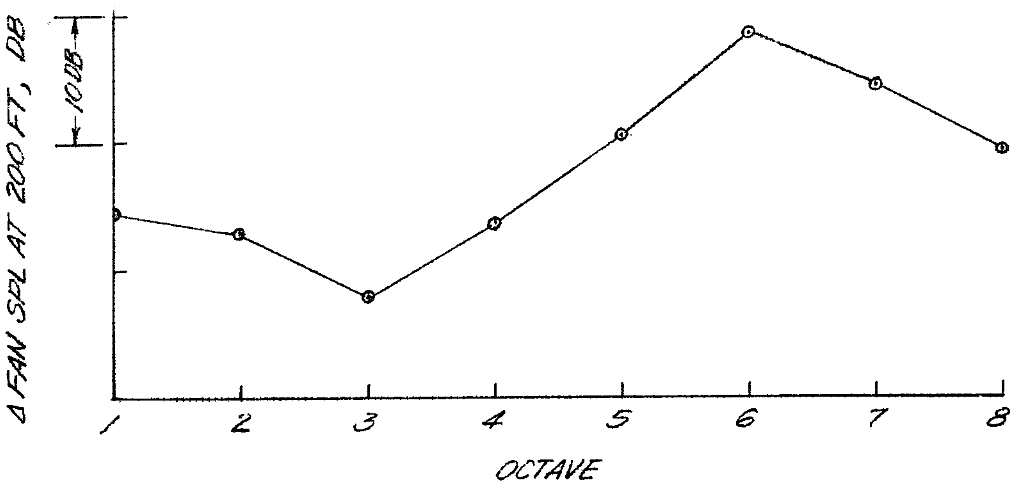


FIGURE 10.– OCTAVE SOUND PRESSURE LEVEL AT 200 FT FOR FAN TURBOMACHINERY.

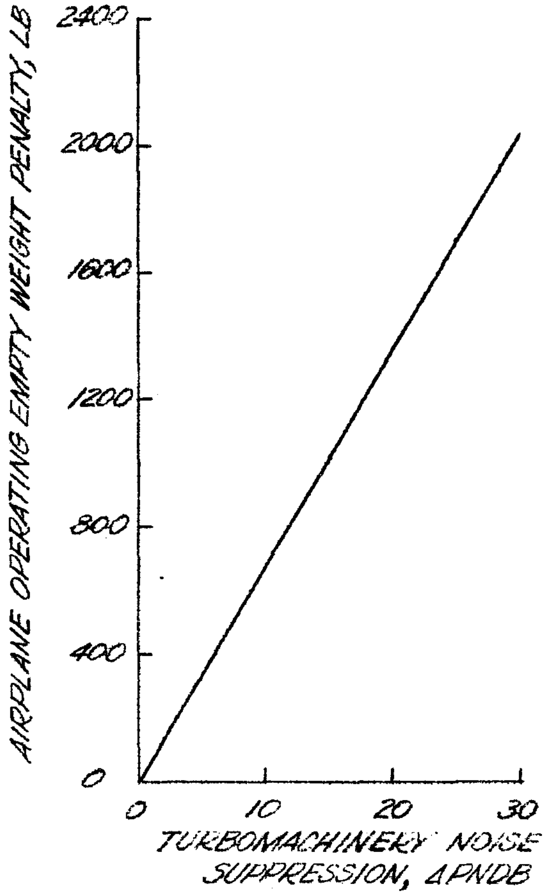
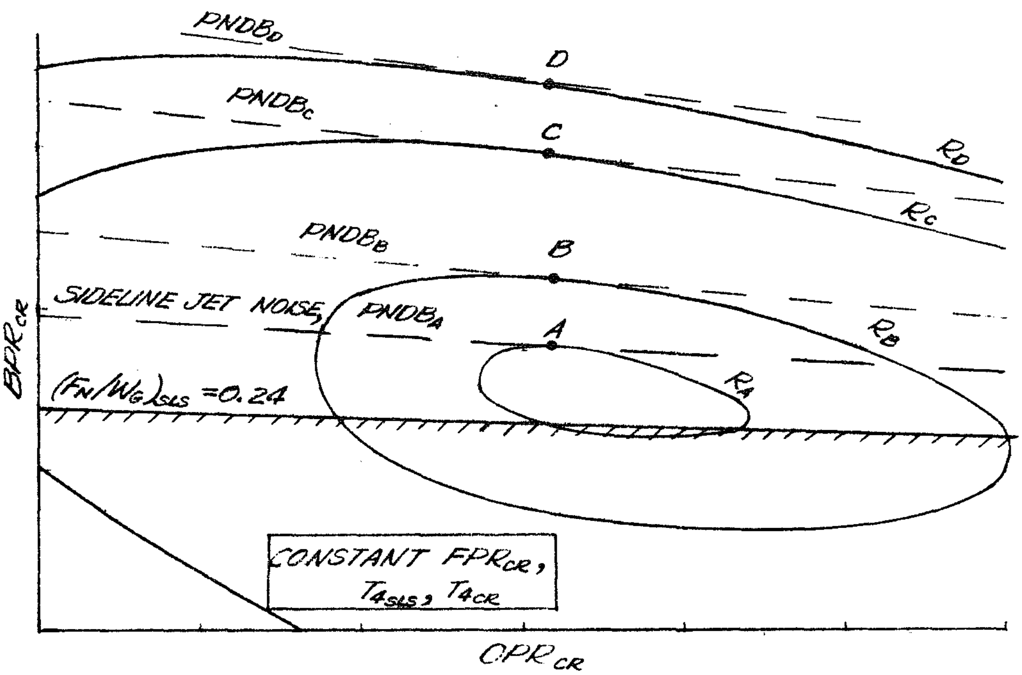
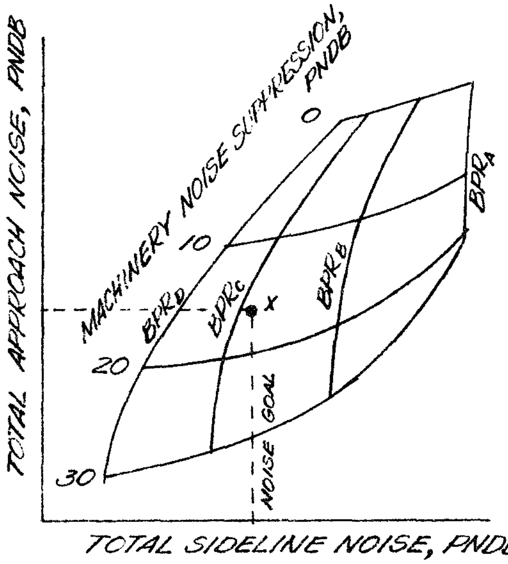


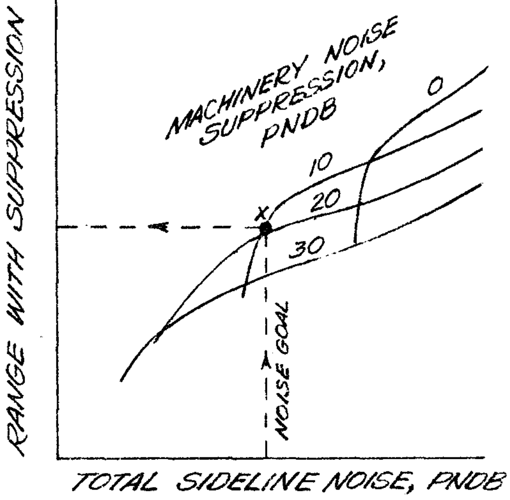
FIGURE 11. – AIRPLANE OPERATING-EMPTY-WEIGHT PENALTY RELATED TO FAN TURBOMACHINERY NOISE SUPPRESSION FOR A THREE-ENGINE AIRPLANE WITH NOMINAL 80-IN. DIAMETER ENGINES.



(a) "THUMBPRINT" PERFORMANCE PLOT. NO NOISE SUPPRESSION.

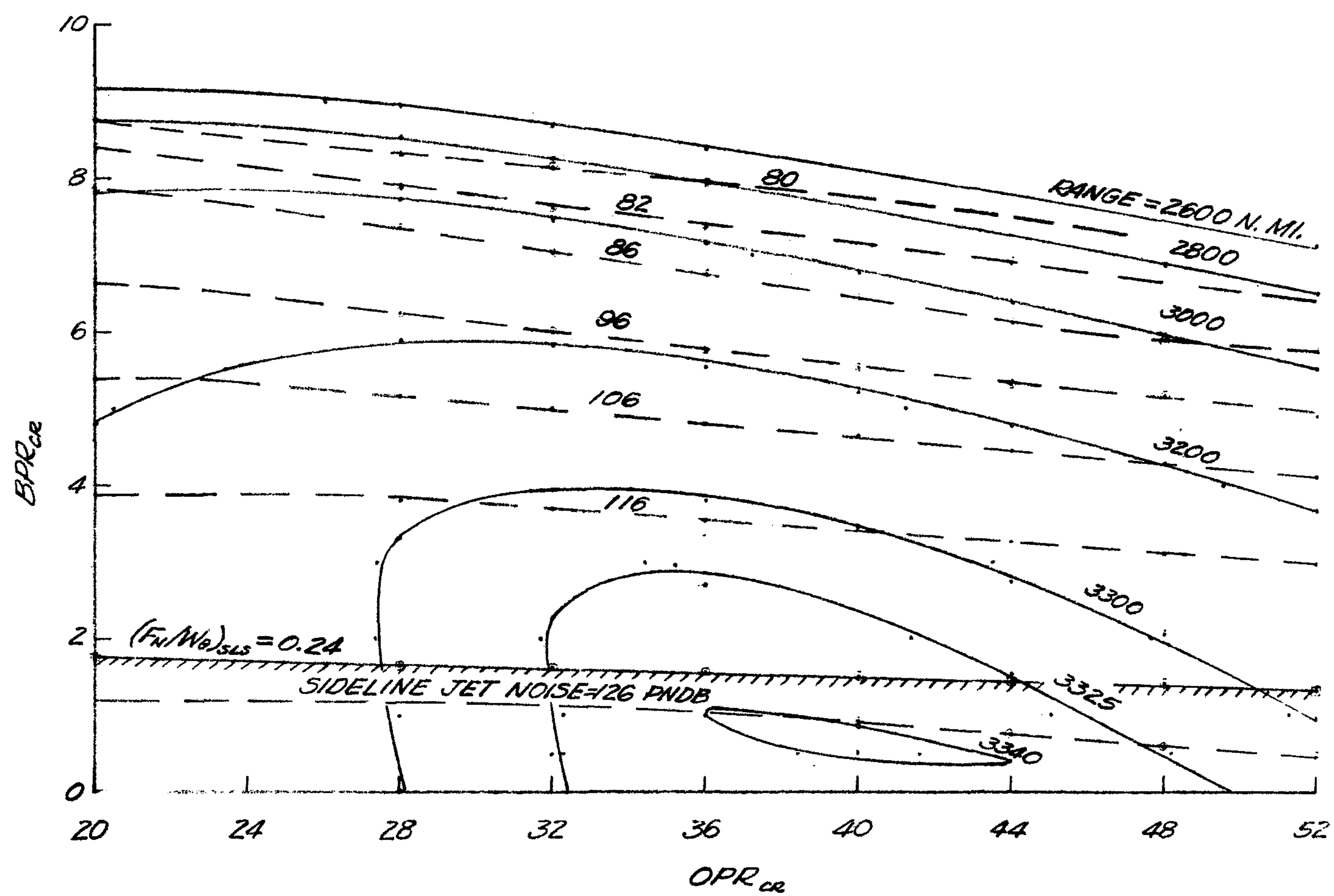


(b) TOTAL SIDELINE AND APPROACH NOISE RELATED TO AMOUNT OF FAN TURBOMACHINERY NOISE SUPPRESSION.



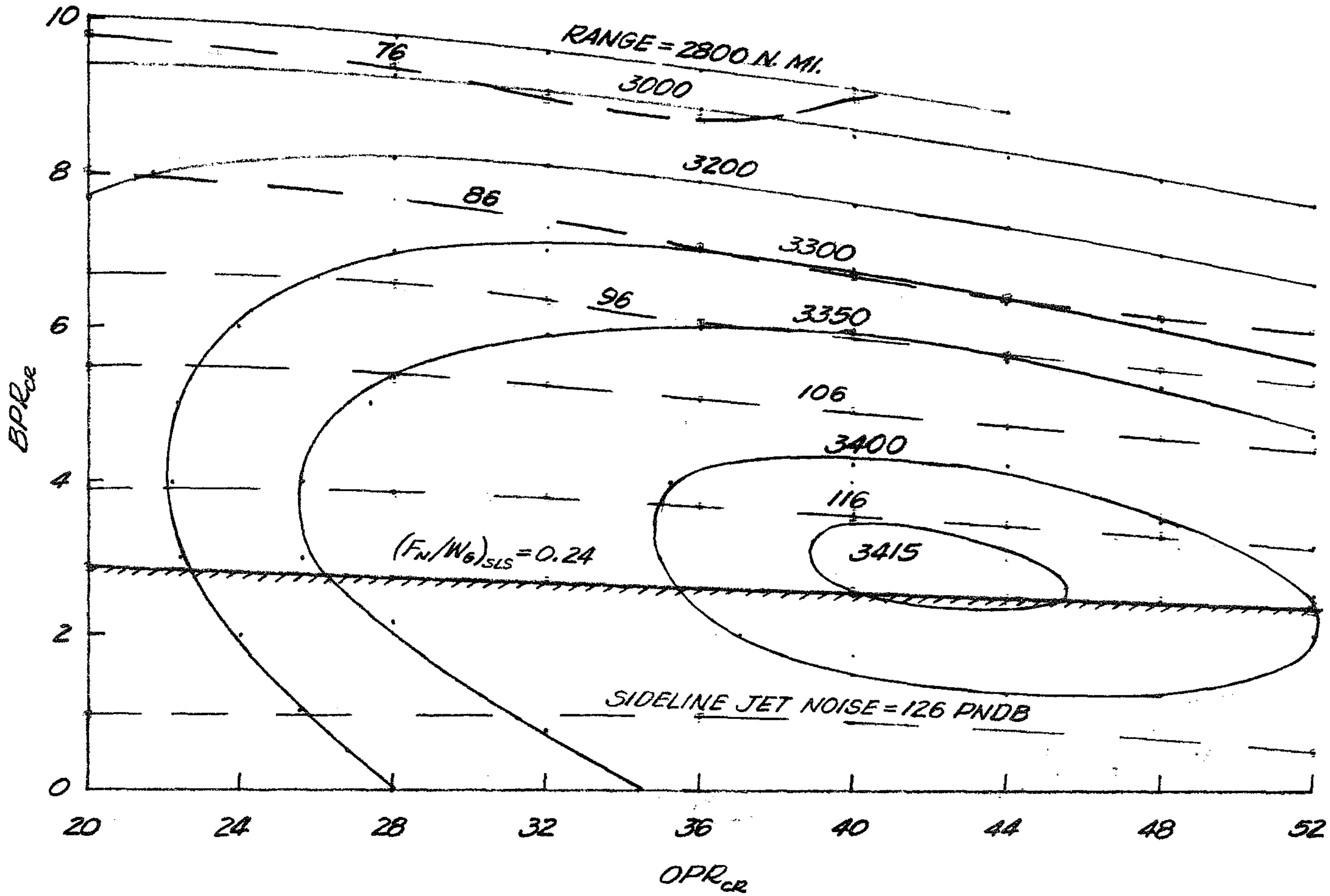
(c) RANGE WITH ACOUSTIC TREATMENT RELATED TO NOISE AND AMOUNT OF SUPPRESSION.

FIGURE 12.—ILLUSTRATION OF METHOD USED TO SELECT ENGINE PARAMETERS THAT MAXIMIZE RANGE FOR A GIVEN NOISE GOAL AND TAKEOFF THRUST CONSTRAINT. CONSTANT TOGW, PAYLOAD, FPR_{CR}, $T_{4_{SLS}}$, $T_{4_{CR}}$.



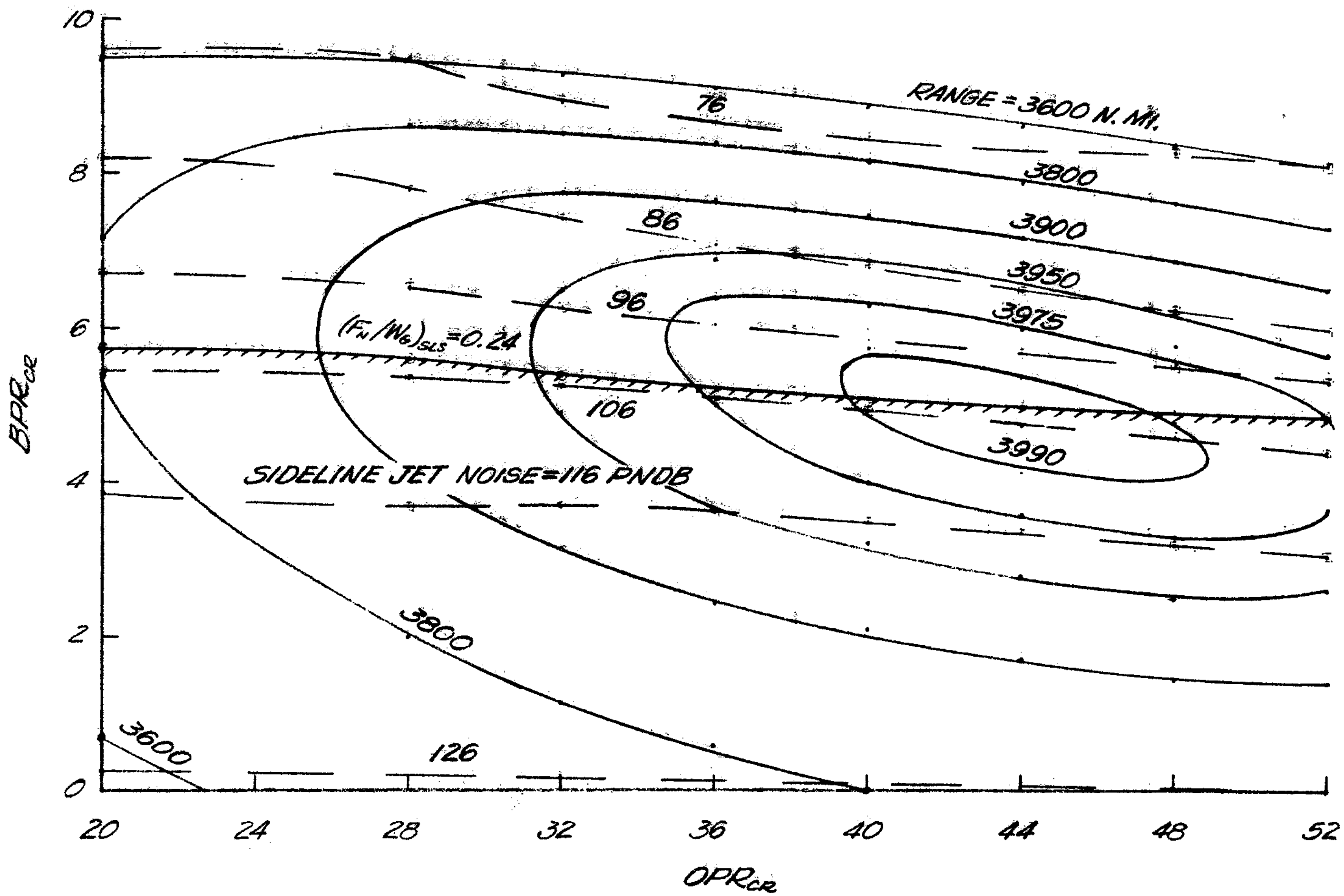
(a) CRUISE AT MACH 0.98 WITH FPR OF 1.70 AND T_4 OF 2100°F.

FIGURE 13.



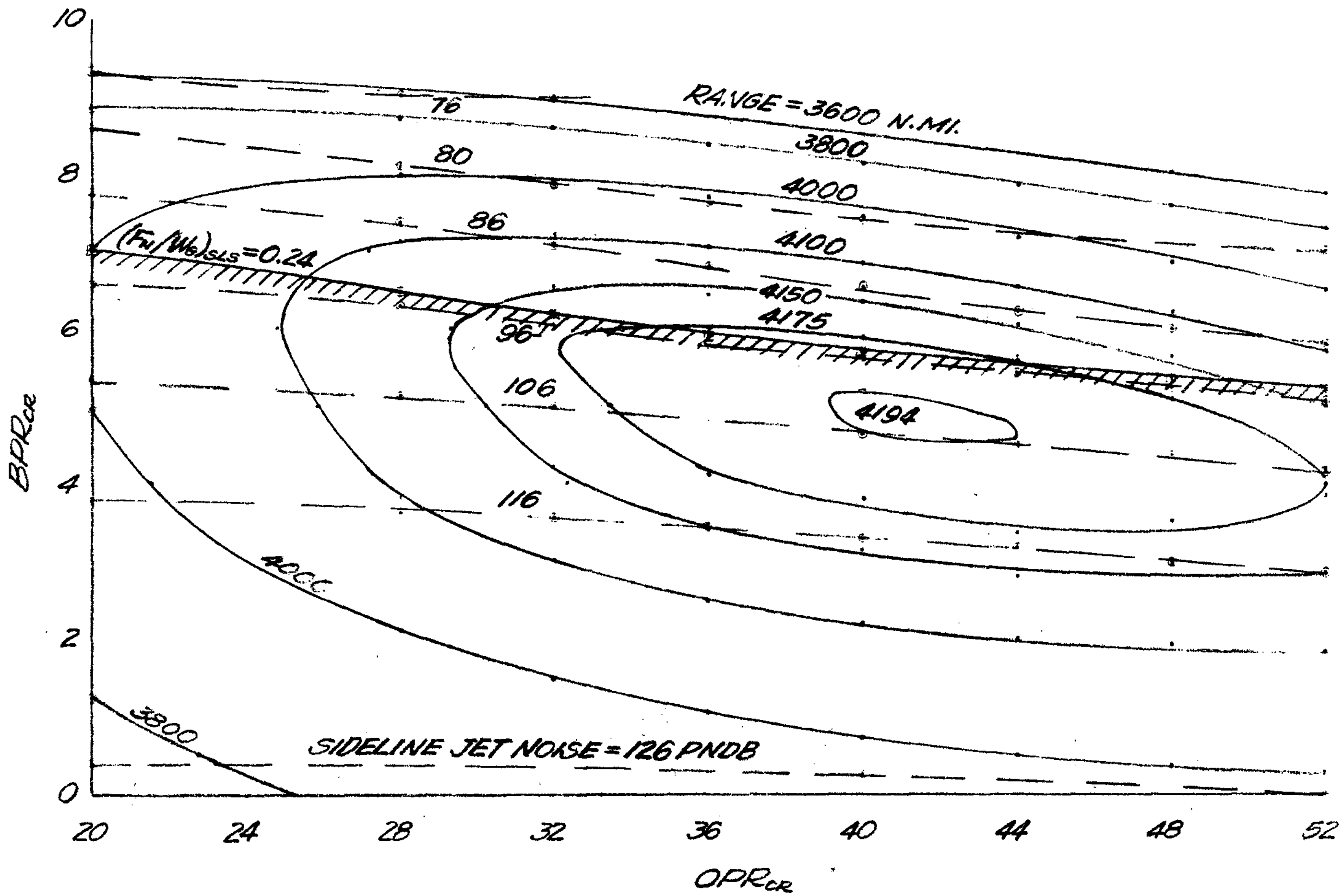
(b) CRUISE AT MACH 0.98 WITH FPR OF 1.70 AND T_4 OF 2200°F.

FIGURE 13. – "THUMBPRINT" PERFORMANCE PLOTS. NO NOISE SUPPRESSION. TAKEOFF GROSS WEIGHT, 386 000 LB; PAYLOAD, 300 PASSENGERS. $T_{4_{SLS}}$, 2300°F.



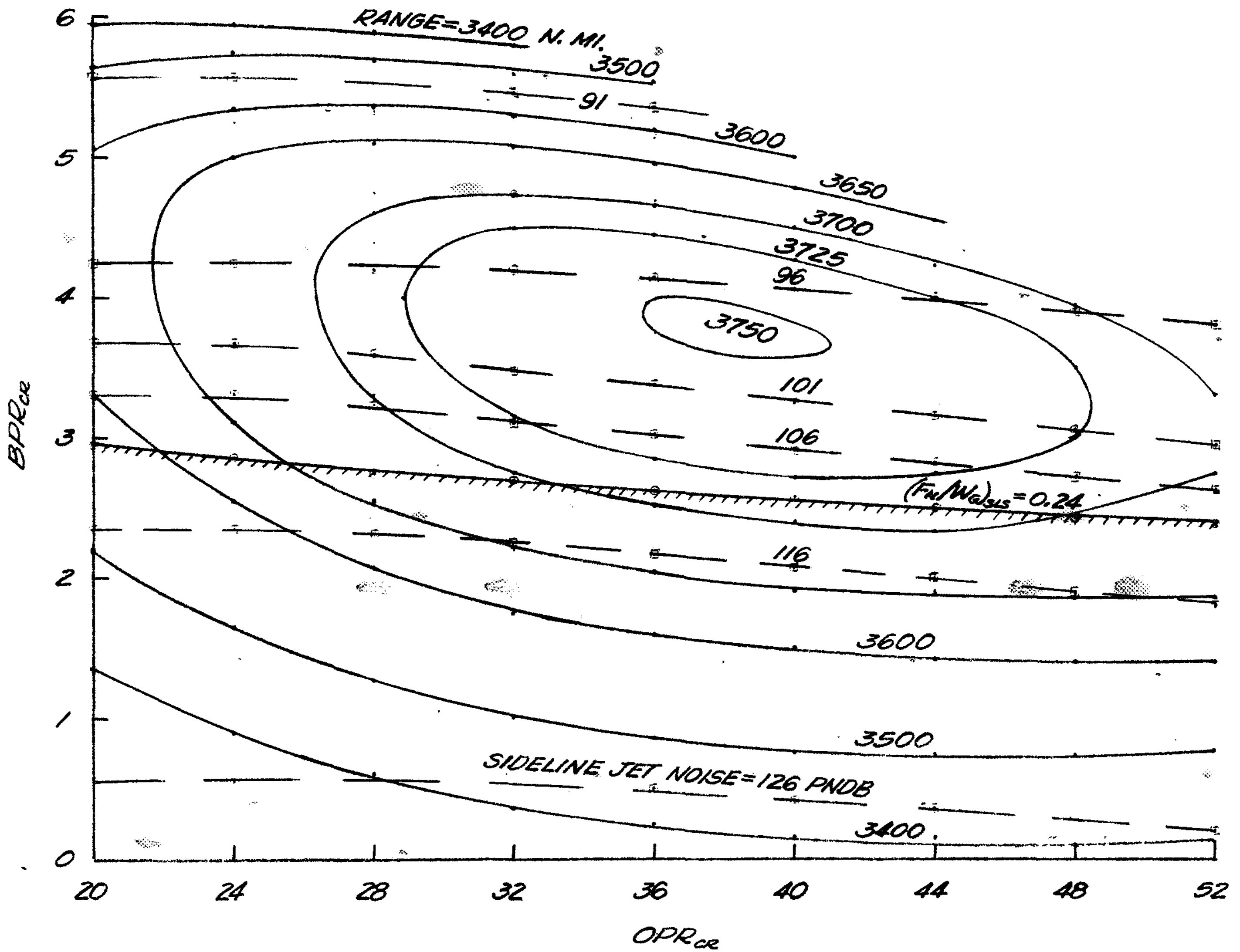
(c) CRUISE AT MACH 0.94 WITH FPR OF 1.70 AND T_4 OF 2200°F.

FIGURE 13. - CONTINUED.



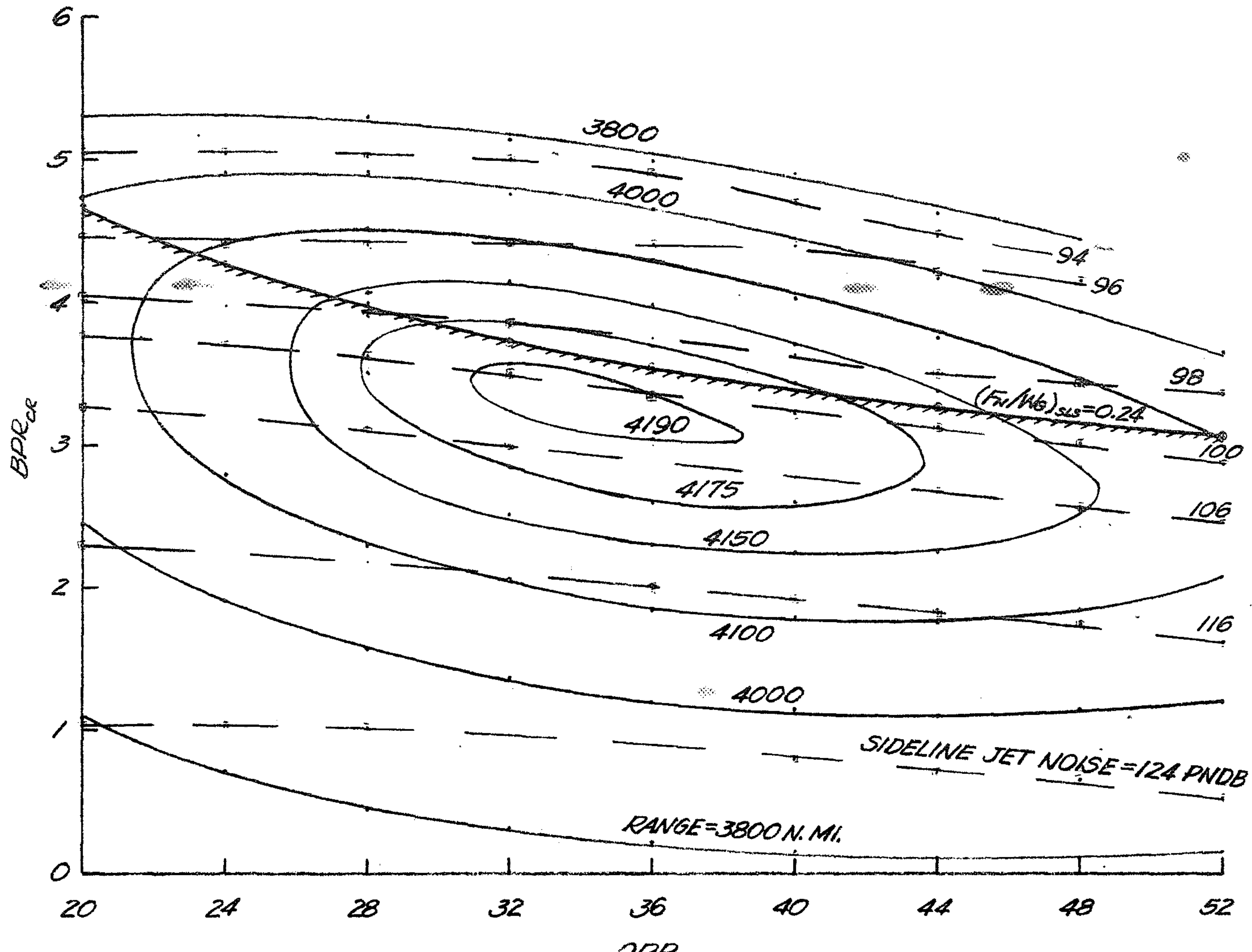
(d) CRUISE AT MACH 0.90 WITH FPR OF 1.70 AND T_4 OF 2100°F.

FIGURE 13. — CONTINUED.



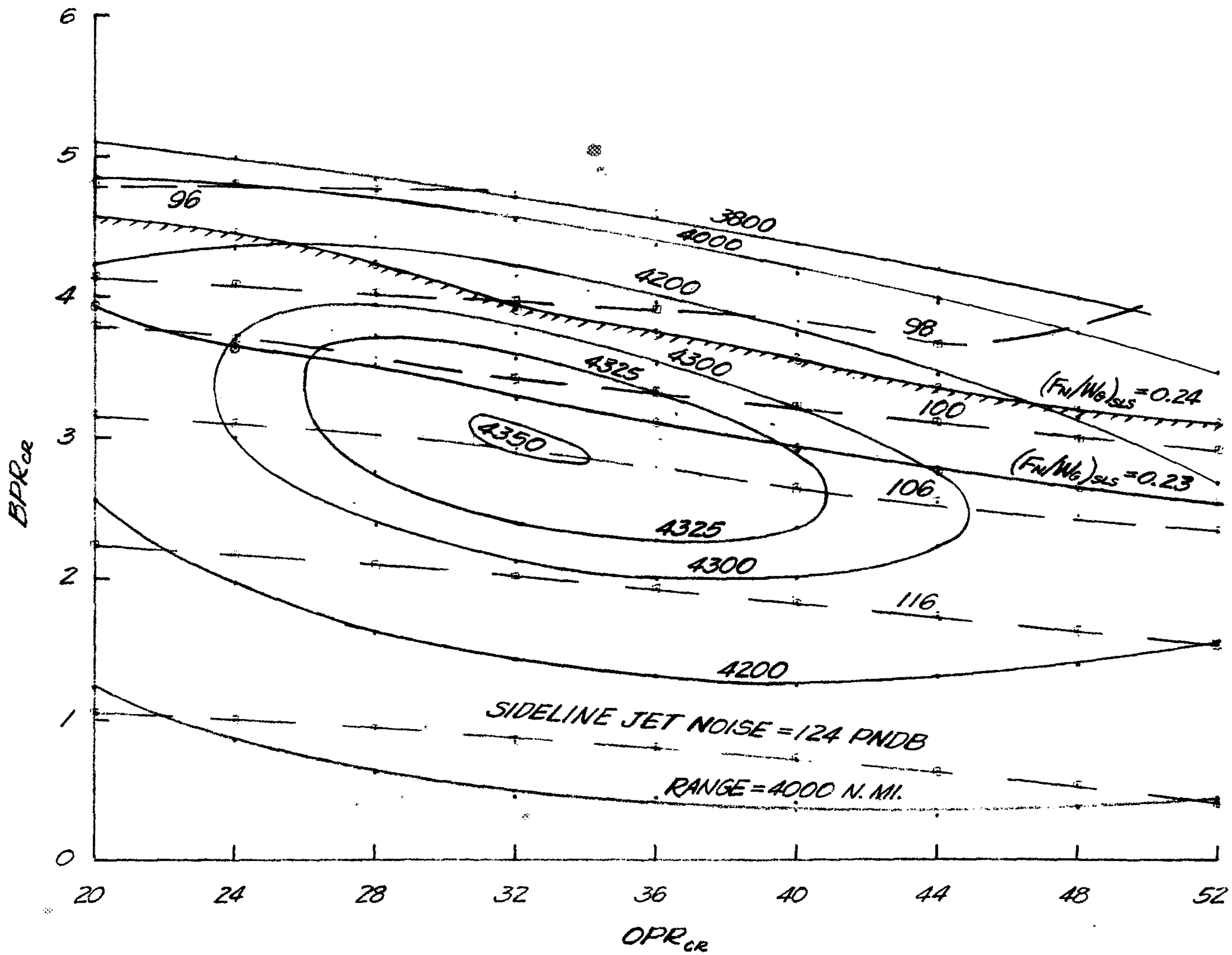
(e) CRUISE AT MACH 0.98 WITH FPR OF 2.25 AND T_4 OF 2200°F.

FIGURE 13. - CONTINUED.



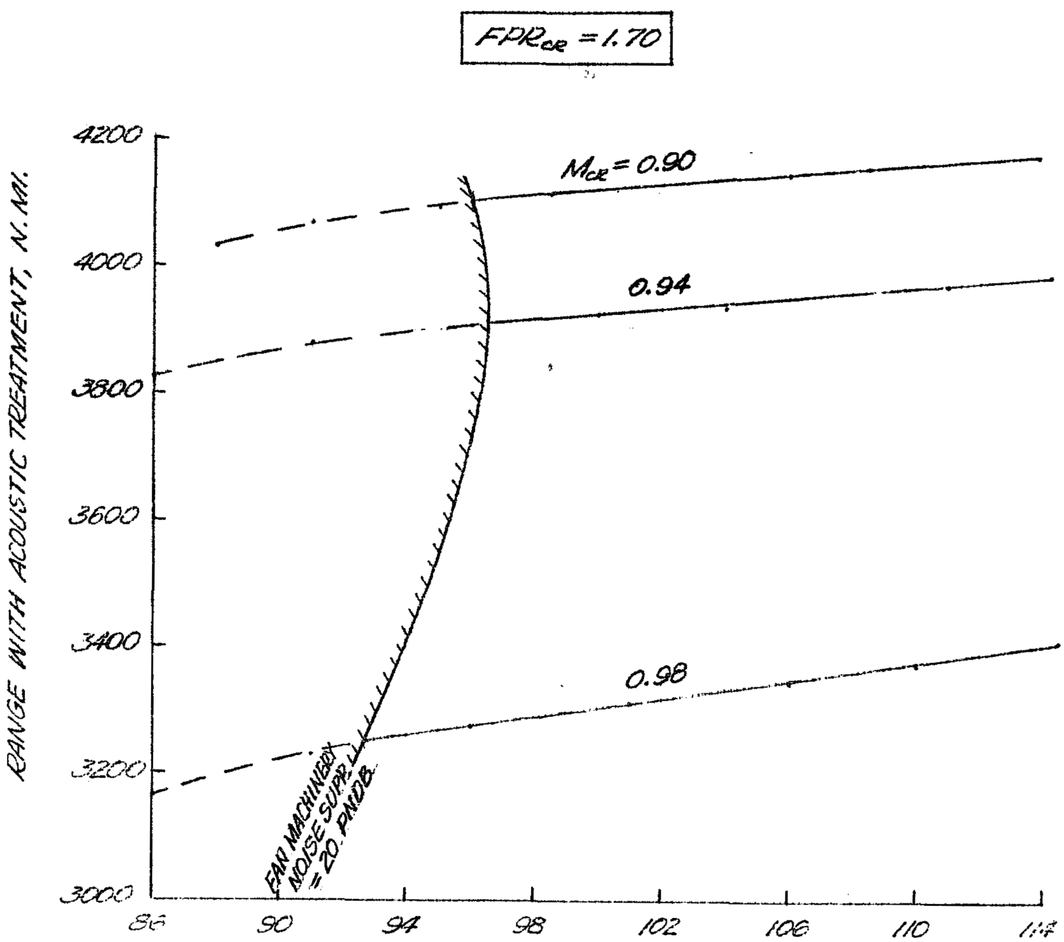
(f) CRUISE AT MACH 0.94 WITH FPR OF 2.25 AND T_4 OF 2070°F.

FIGURE 13. — CONTINUED.



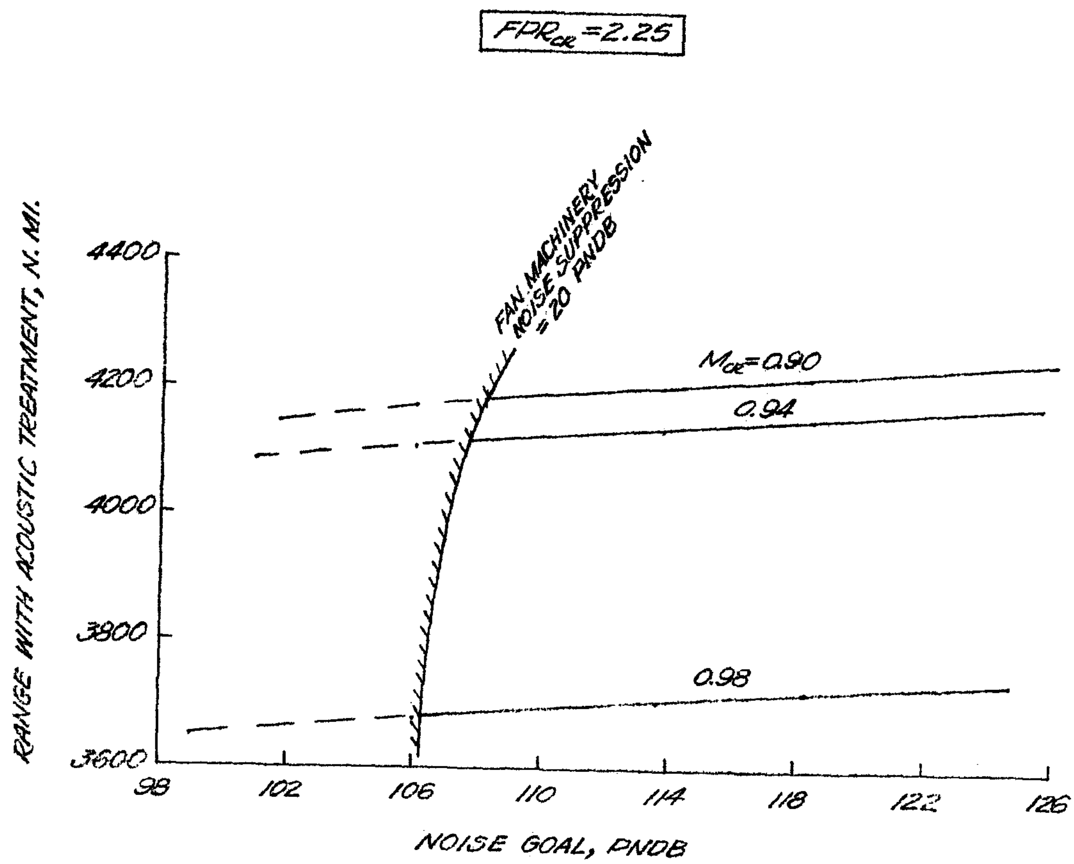
(g) CRUISE AT MACH 0.90 WITH FPR OF 2.25 AND T_4 OF 1965°F.

FIGURE 13. — CONCLUDED.



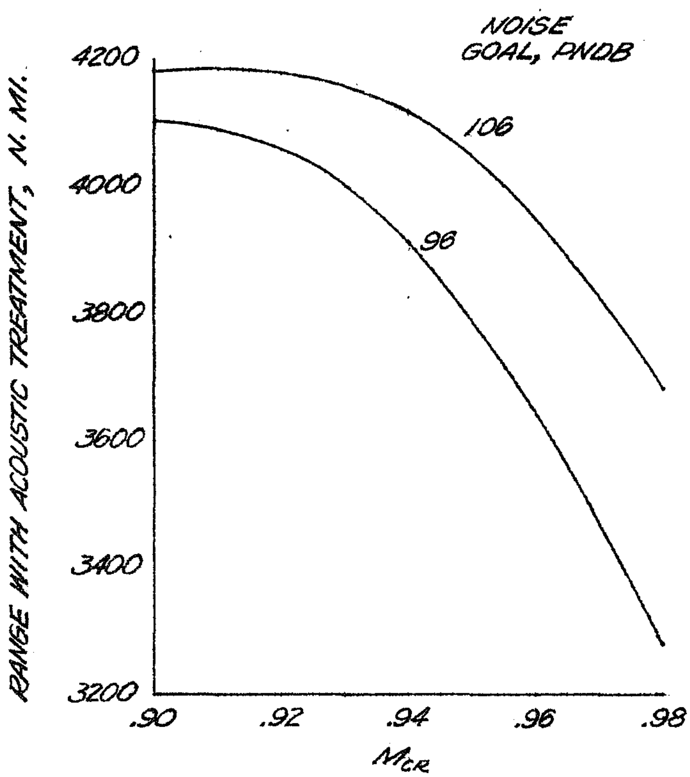
(a) CRUISE FAN PRESSURE RATIO, 1.70.

FIGURE 14.



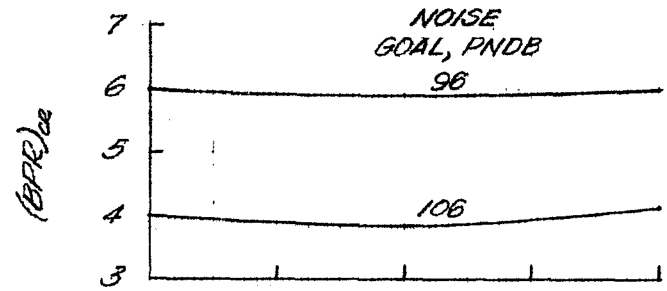
(b) CRUISE FAN PRESSURE RATIO, 2.25.

FIGURE 14. – RANGE OF ACOUSTICALLY-TREATED OPTIMUM AIRPLANES AS A FUNCTION OF DESIRED NOISE GOAL FOR VARIOUS DESIGN CRUISE MACH NUMBERS. TAKEOFF GROSS WEIGHT, 386 000 LB; PAYLOAD, 300 PASSENGERS. $T_{4_{SLS}}$, 2300°F.

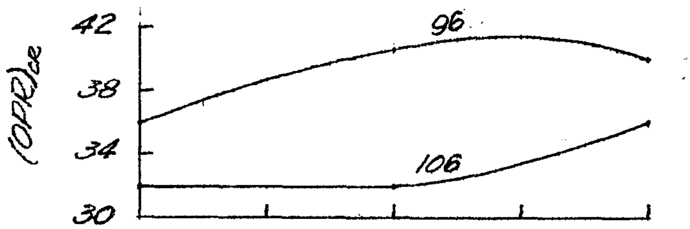


(a) TOTAL RANGE WITH ACOUSTIC TREATMENT.

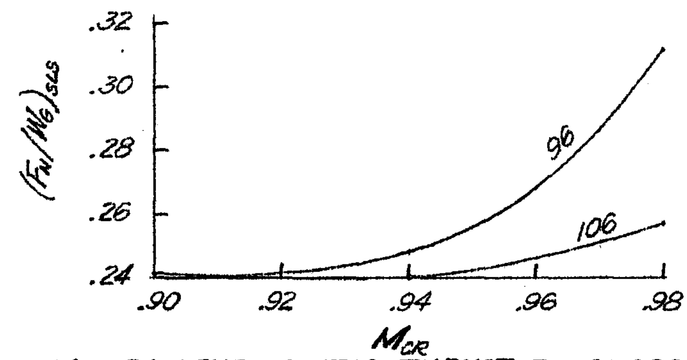
FIGURE 15. – CHARACTERISTICS OF RANGE-OPTIMIZED CYCLES RELATED TO DESIGN CRUISE MACH NUMBER AT NOISE GOALS OF 106 AND 96 PNDB. TAKEOFF GROSS WEIGHT, 386 000 LB; PAYLOAD, 300 PASSENGERS; $T_{4_{SLS}}$, 2300°F.



(b) CRUISE BYPASS RATIO



(c) CRUISE OVERALL FAN AND COMPRESSOR PRESSURE RATIO.



(d) SEA-LEVEL-STATIC THRUST-TO-GROSS-WEIGHT RATIO.

FIGURE 15.– CONTINUED.

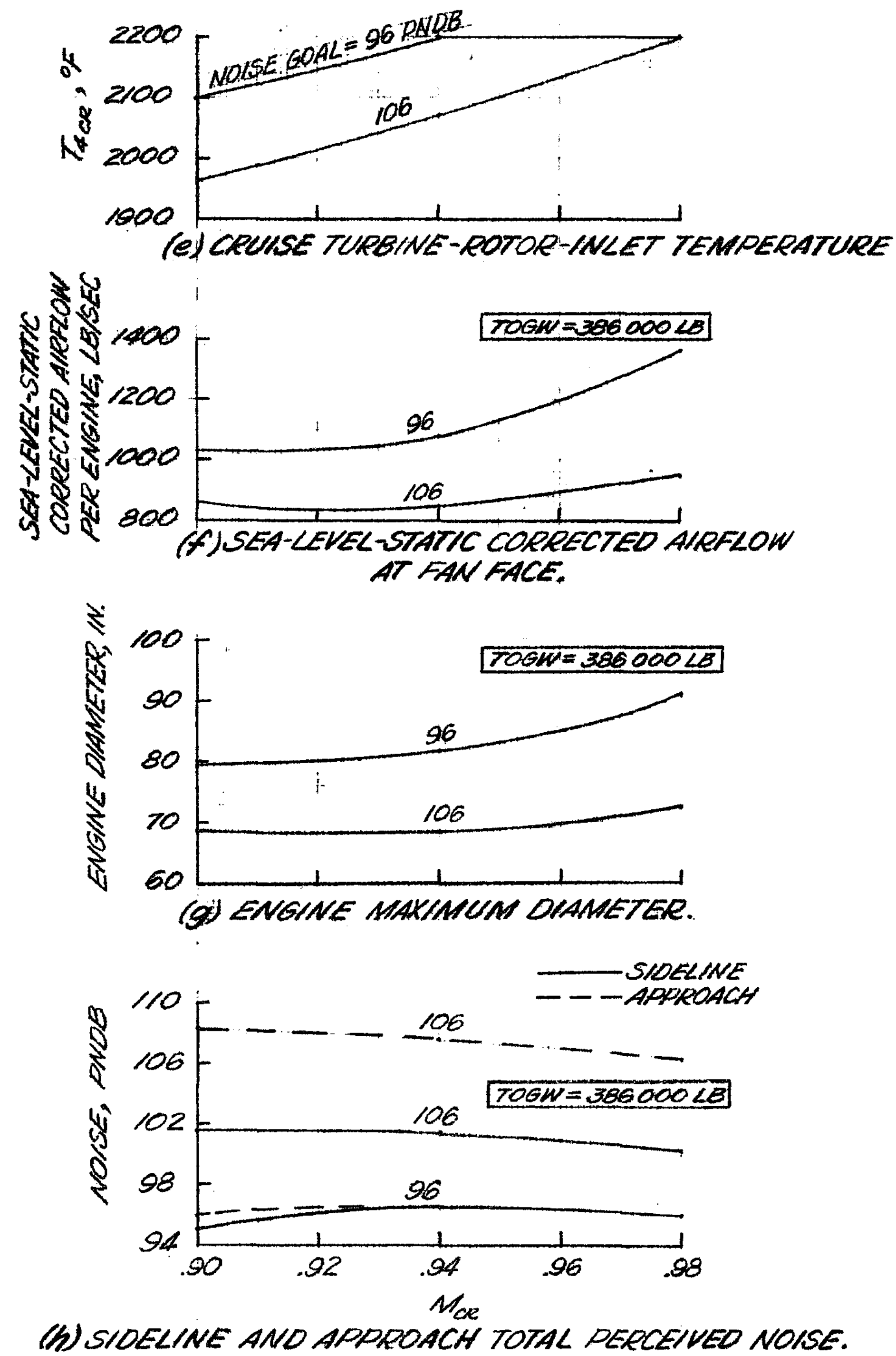
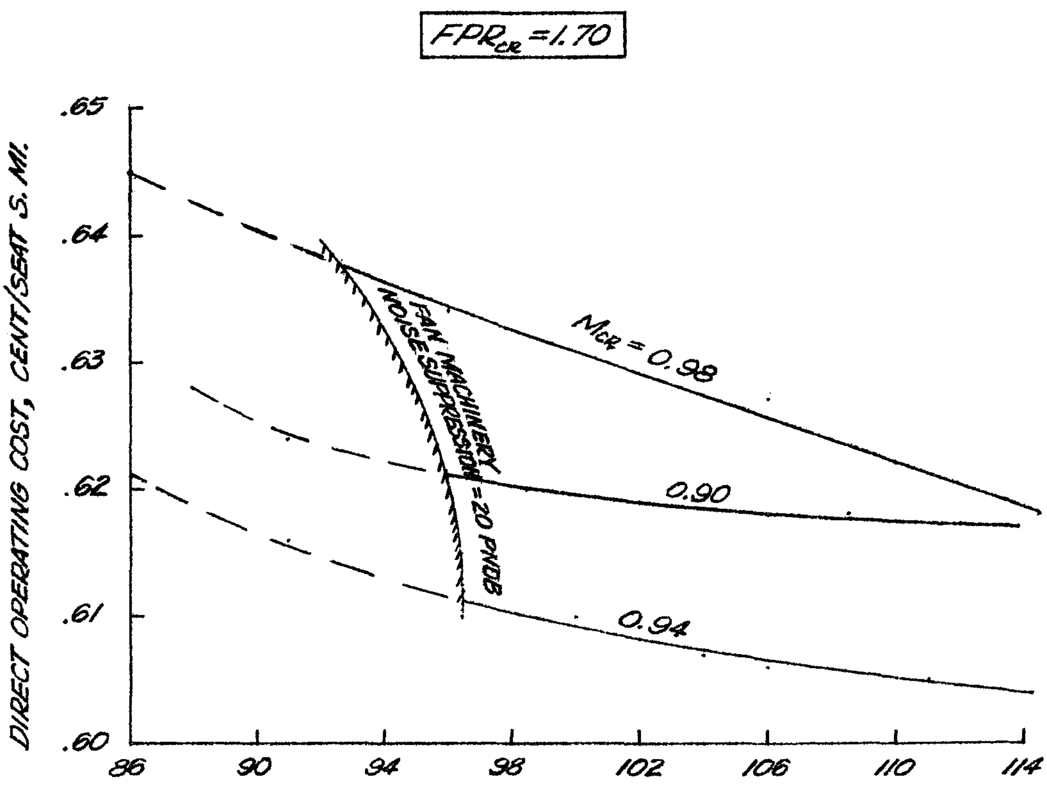
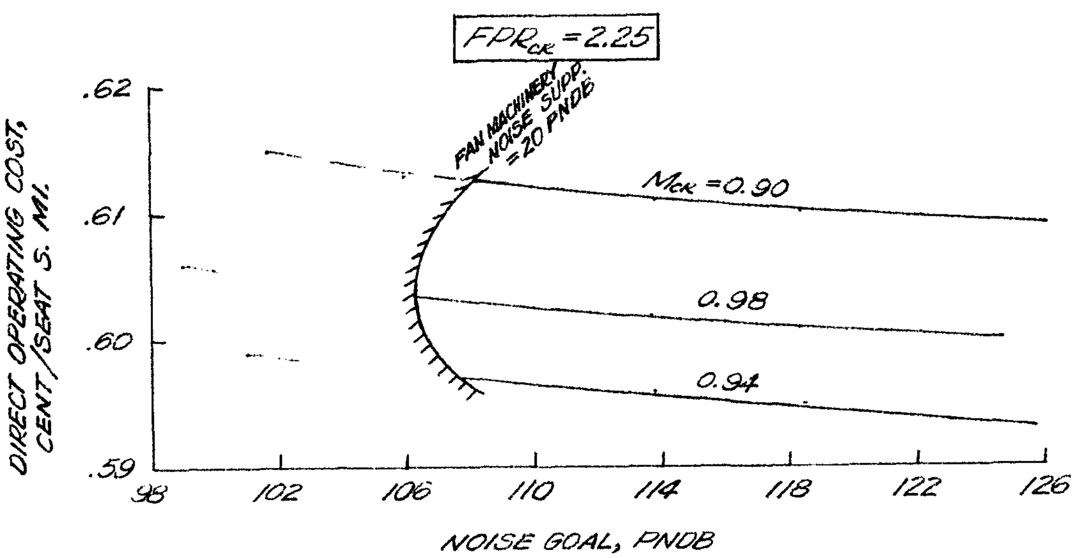


FIGURE 15. - CONCLUDED.



(a) CRUISE FAN PRESSURE RATIO, 1.70.

FIGURE 16



(b) CRUISE FAN PRESSURE RATIO, 2.25.

FIGURE 16. - DIRECT OPERATING COST OF ACOUSTICALLY-TREATED OPTIMUM AIRPLANES RELATED TO DESIRED NOISE GOAL FOR VARIOUS DESIGN CRUISE MACH NUMBERS. TAKEOFF GROSS WEIGHT, 386 000 LB; PAYLOAD, 300 PASSENGERS; $T_{4_{SLS}}$, 2300° F.

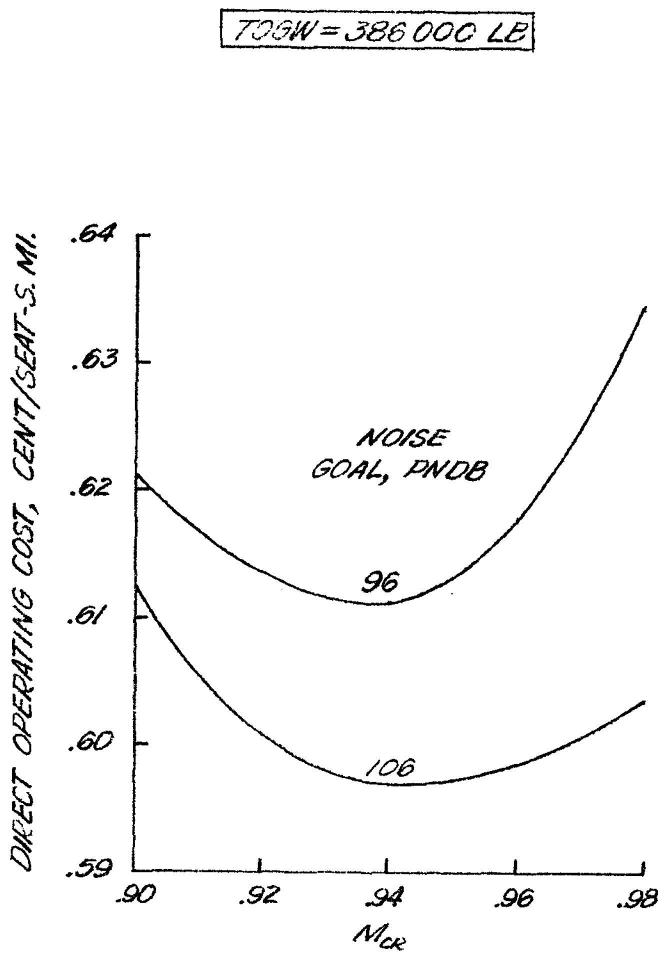
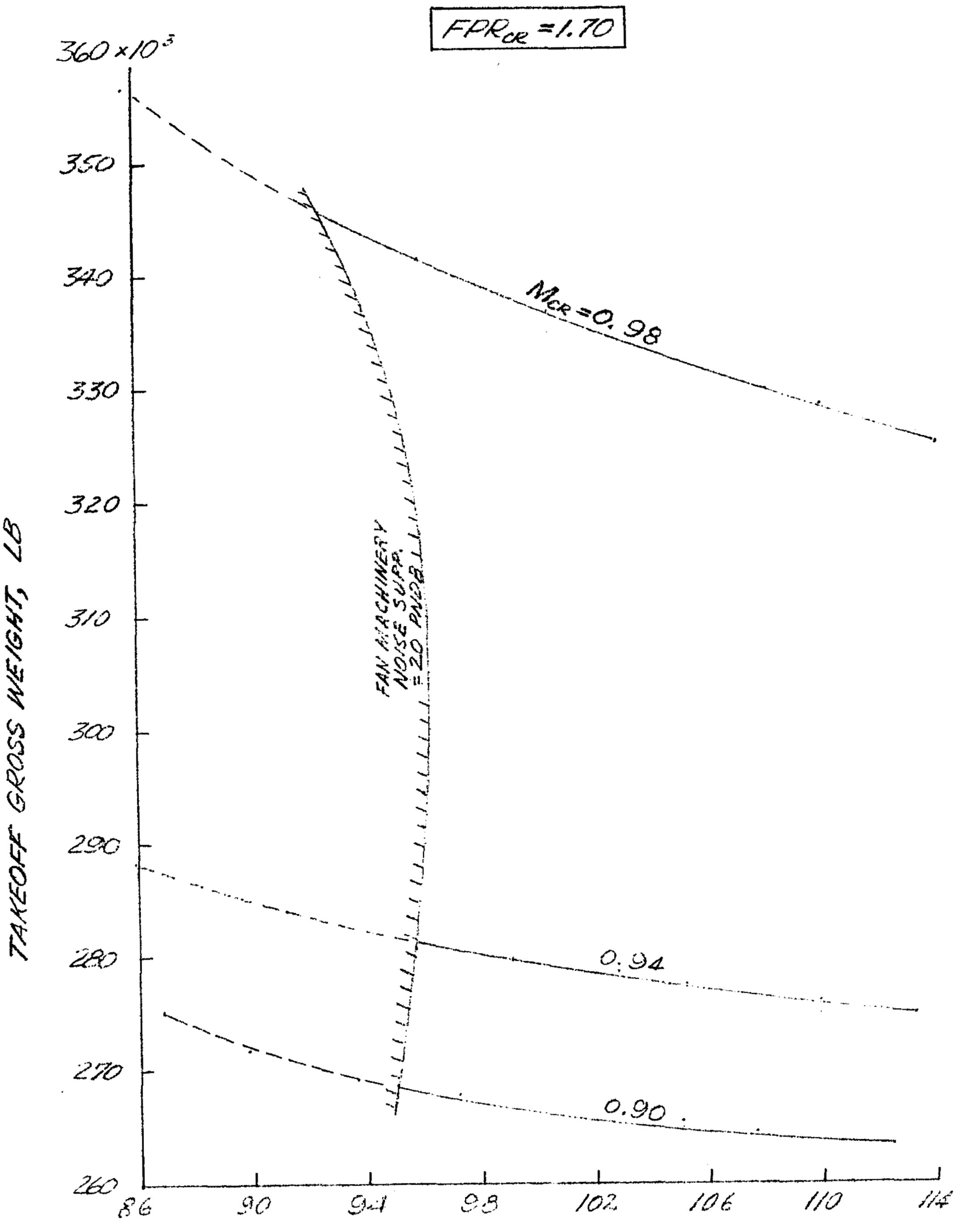
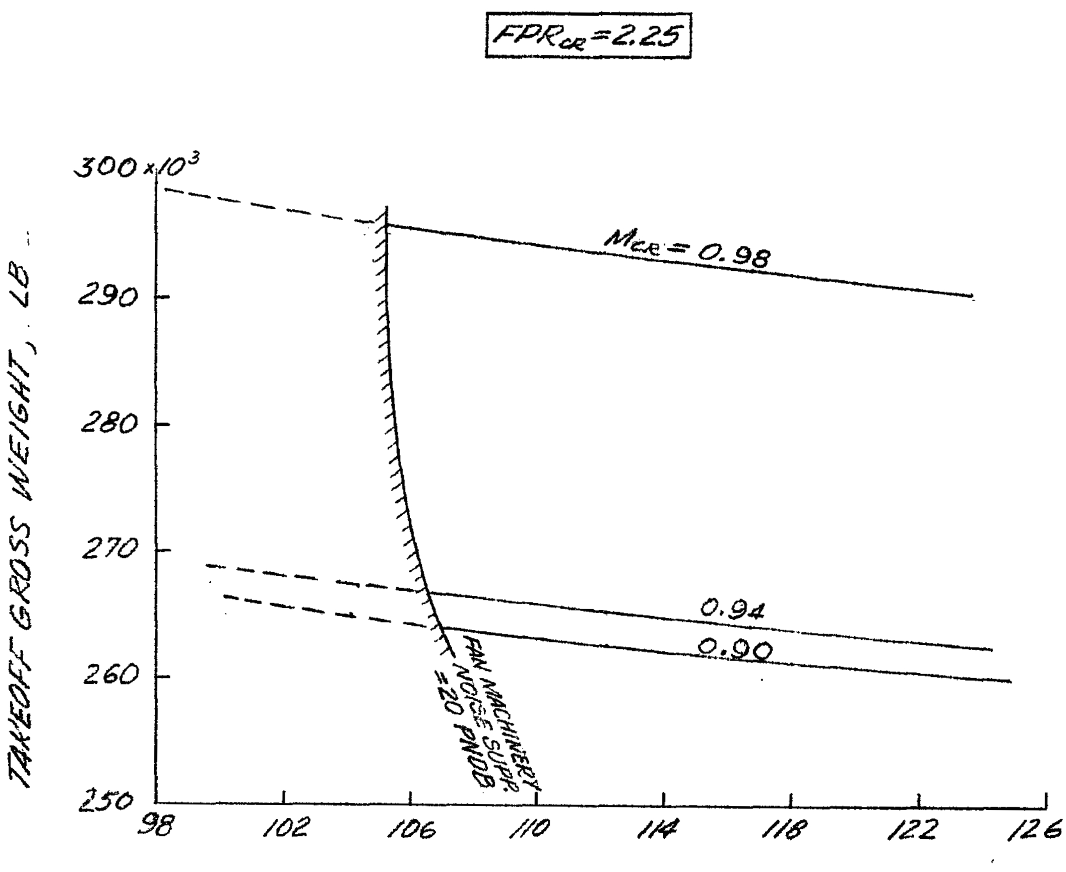


FIGURE 17. - DIRECT OPERATING COST OF RANGE-OPTIMIZED CYCLES RELATED TO DESIGN CRUISE MACH NUMBER AT NOISE GOALS OF 106 AND 96 PNDB. TAKEOFF GROSS WEIGHT, 386 000 LB; PAYLOAD, 300 PASSENGERS. $T_{4_{SLS}}$, 2300°F.



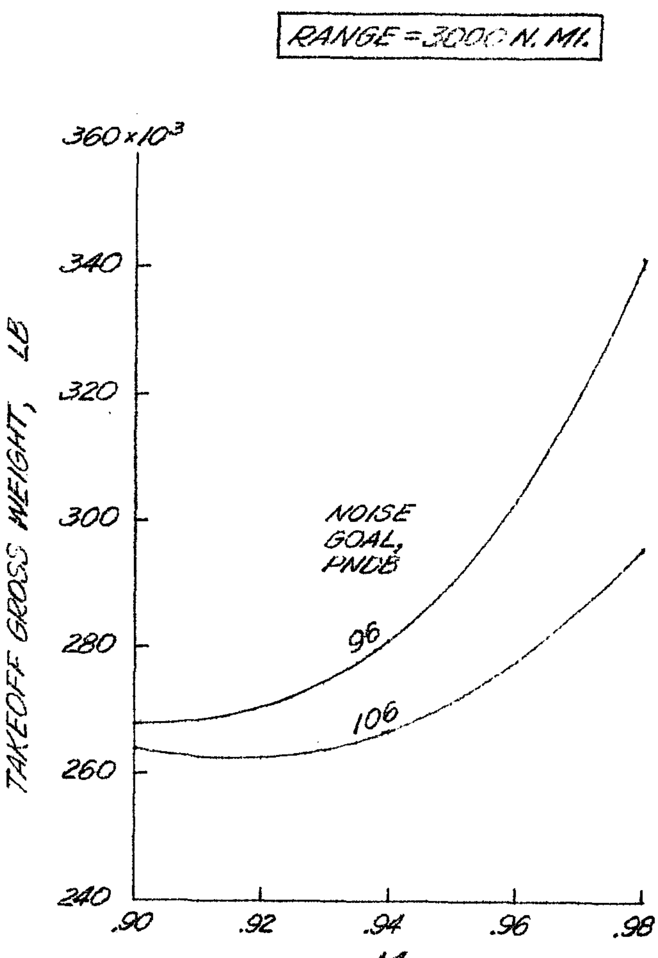
(a) CRUISE FAN PRESSURE RATIO, 1.70.

FIGURE 18.



(b) CRUISE FAN PRESSURE RATIO, 2.25.

FIGURE 18. - TAKEOFF GROSS WEIGHT OF OPTIMIZED AIRPLANES RELATED TO NOISE GOAL AT VARIOUS DESIGN CRUISE SPEEDS. TOTAL RANGE, 3000 N MI; PAYLOAD, 300 PASSENGERS. $T_{4_{SLS}}$, 2300°F.



(a) AIRPLANE TAKEOFF GROSS WEIGHT.

FIGURE 19. – CHARACTERISTICS OF OPTIMIZED CYCLES RELATED TO DESIGN CRUISE MACH NUMBER AT NOISE GOALS OF 106 AND 96 PNDB. TOTAL RANGE, 3000 N. MI.; PAYLOAD, 300 PASSENGERS; $T_{4_{SLS}}$, 2300°F.

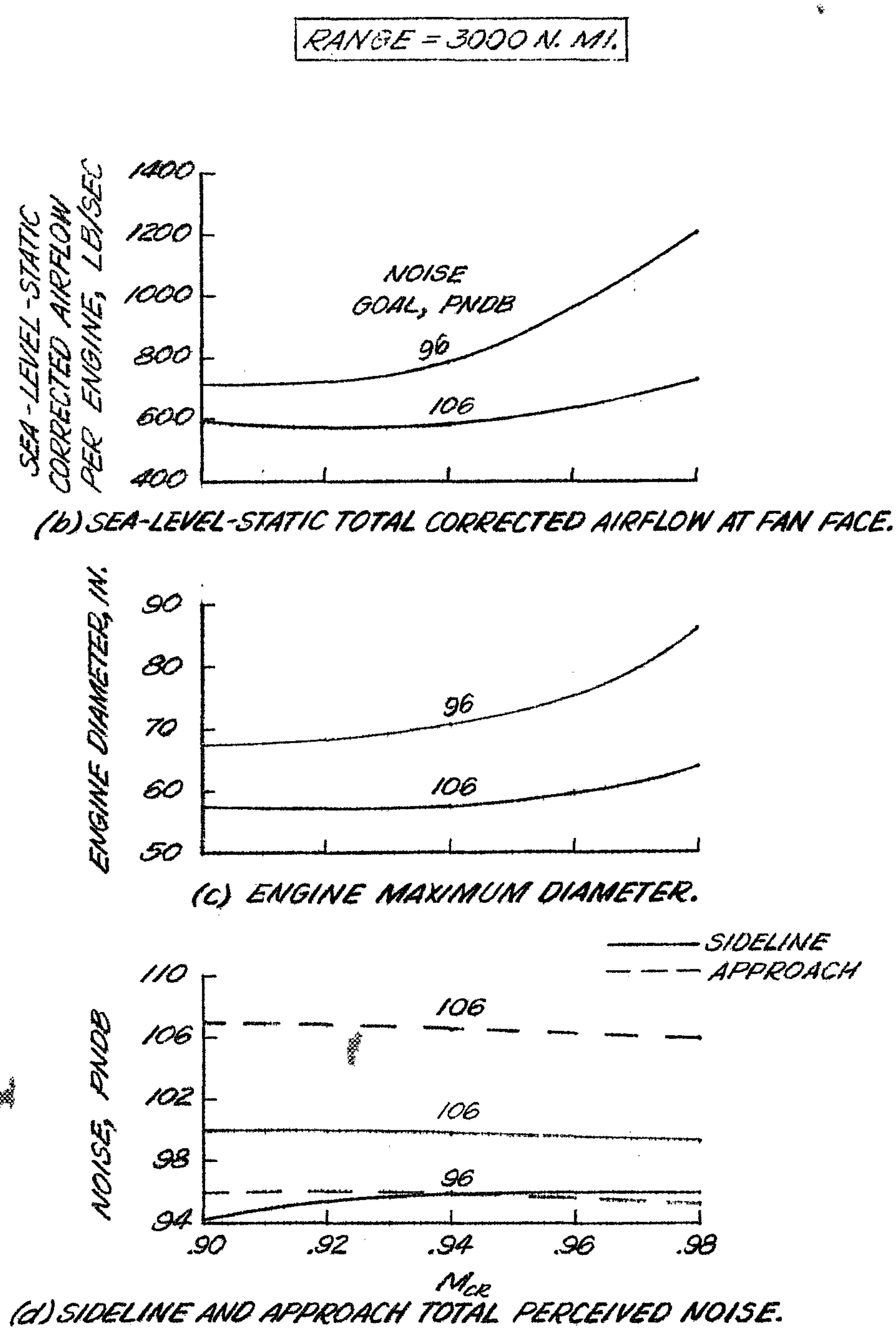
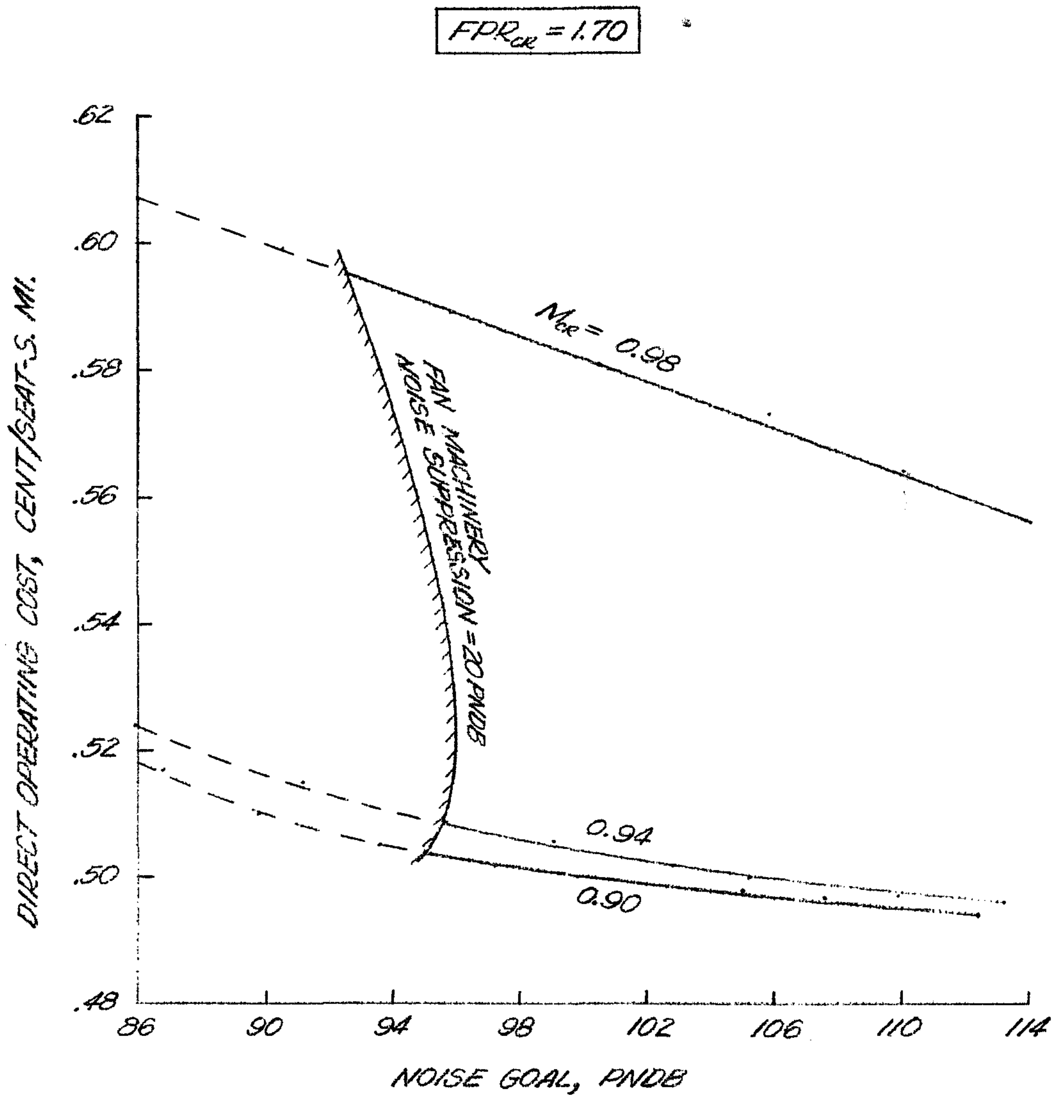
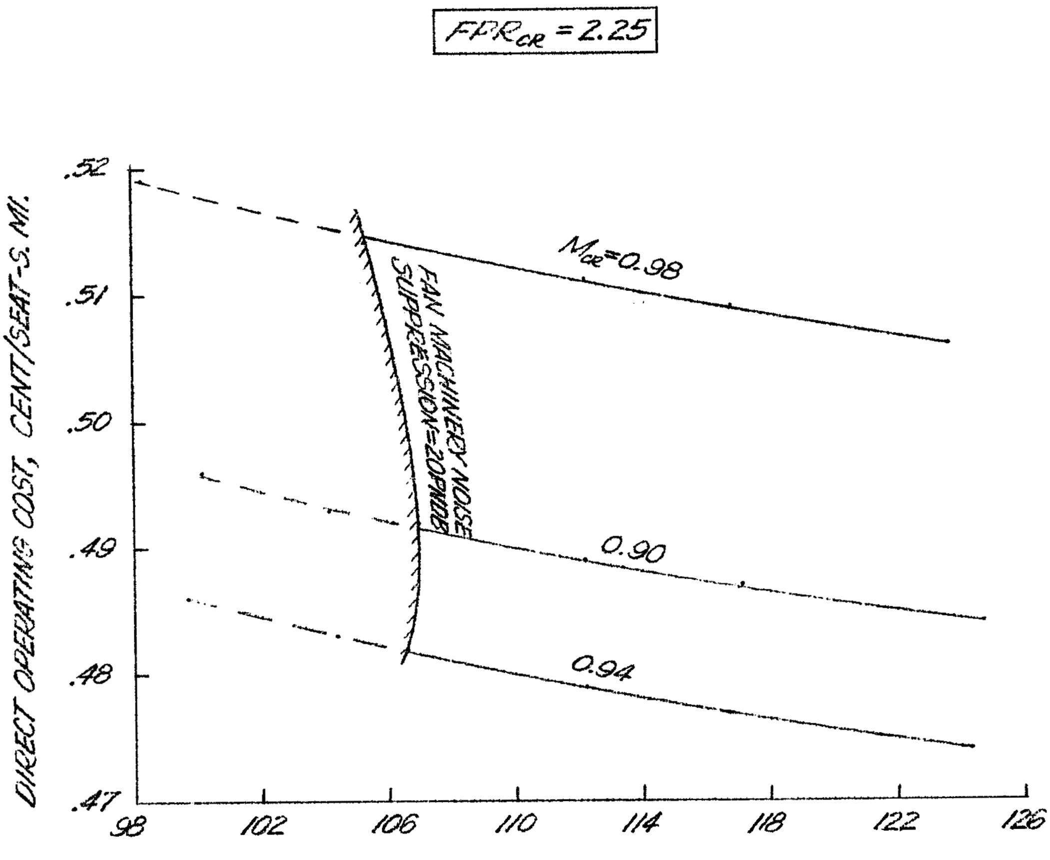


FIGURE 19. - CONCLUDED.



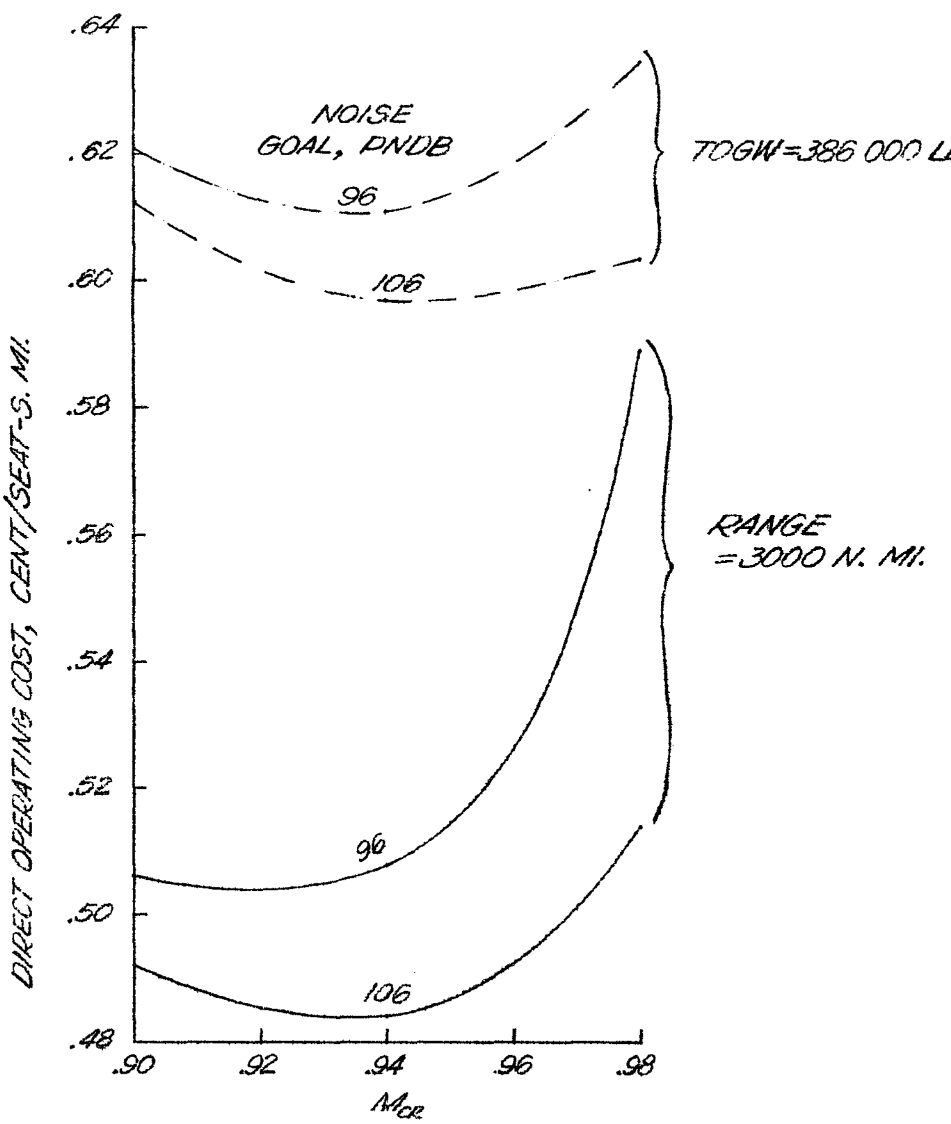
(a) CRUISE FAN PRESSURE RATIO, 1.70.

FIGURE 20



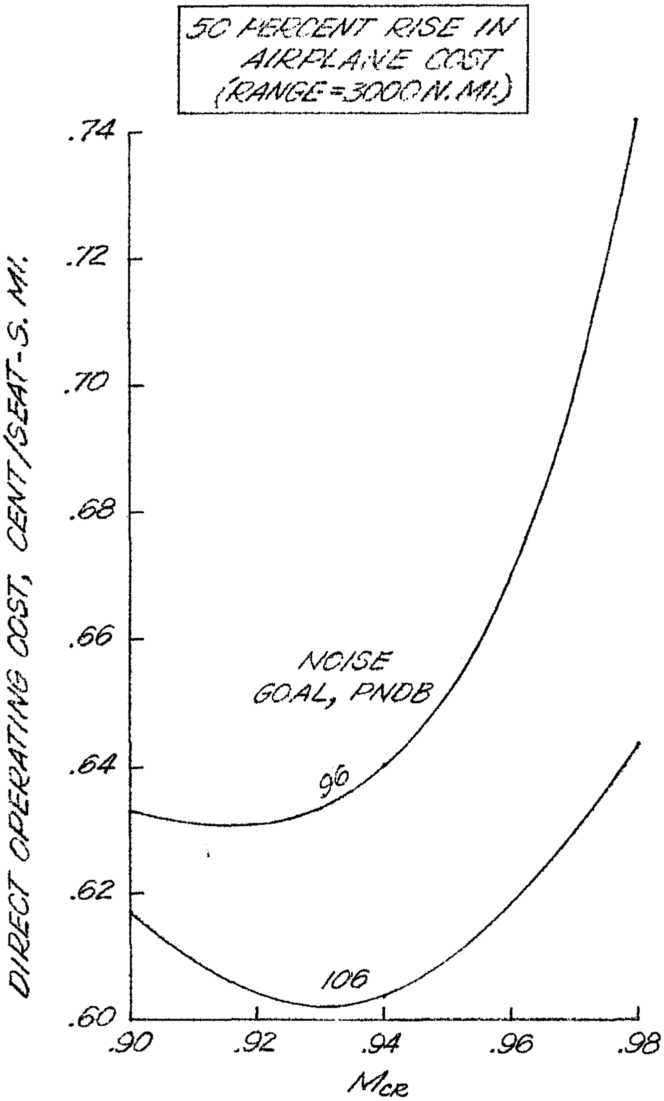
(b) CRUISE FAN PRESSURE RATIO, 2.25.

FIGURE 20. – DIRECT OPERATING COST OF OPTIMIZED AIRPLANES RELATED TO NOISE GOAL AT VARIOUS DESIGN CRUISE SPEEDS. TOTAL RANGE, 3000 N MI; PAYLOAD, 300 PASSENGERS; $T_{4_{SLS}}$, 2300°F.



(a) AIRPLANE COST ESTIMATES BASED ON CURRENT AIRPLANES.

FIGURE 21. – DIRECT OPERATING COST OF OPTIMIZED CYCLES RELATED TO DESIGN CRUISE MACH NUMBER AT NOISE GOALS OF 106 AND 96 PNDB. PAYLOAD, 300 PASSENGERS; $T_{4_{SLS}}$, 2300°F.



(b) AIRPLANE COST ESTIMATES RAISED 50 PERCENT; RANGE, 3000 N MI.

FIGURE 21.— CONCLUDED.

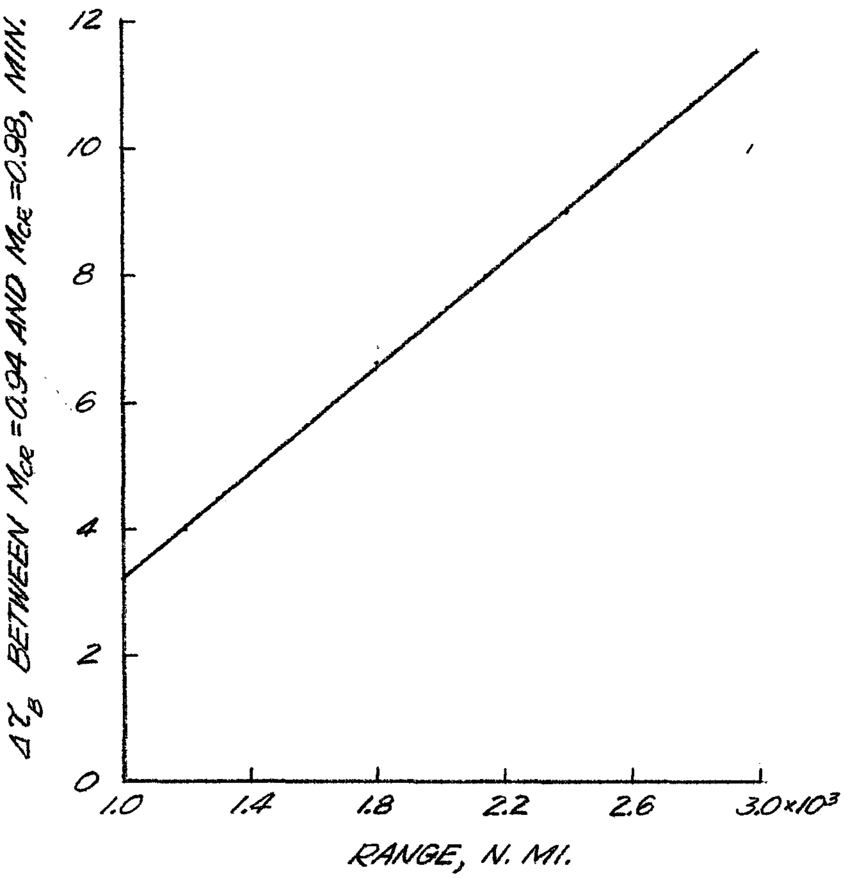


FIGURE 22.— BLOCK TIME DIFFERENCE BETWEEN CRUISE AT MACH 0.94 AND MACH 0.98 RELATED TO TOTAL RANGE.