# NASA TECHNICAL MEMORANDUM

NASA TM X-71664

NASA TM X-71664

(NASA-TM-X-71664) PRELIMINARY EVALUATION OF TURBOFAN CYCLE PARAMETERS AND ACOUSTICAL SUPPRESSION ON THE NOISE AND DIRECT OPERATING COST OF A COMMERCIAL MACH 0.85 TRANSPORT (NASA) 48 p HC $3.75 CSCL 20A G3/07

N75-19244

Unclas
13390

# PRELIMINARY EVALUATION OF TURBOFAN CYCLE PARAMETERS AND ACOUSTICAL SUPPRESSION ON THE NOISE AND DIRECT OPERATING COST OF A COMMERCIAL MACH 0.85 TRANSPORT

by J. D. Eisenberg
Lewis Research Center
Cleveland, Ohio 44135
February 1975

This information is being published in preliminary form in order to expedite its early release.

E-8239

ABSTRACT

A study was made of the effects of turbofan cycle parameters and the use of acoustic noise suppression material to quiet 200 passenger, Mach 0.85 trijets having design ranges of 2778, 4630, and 9260 kilometers (1500, 2500, and 5000 n. mi.). Aircraft gross weight and direct operating cost, which varied with amount of suppression and cycle selection, are presented as functions of both EPNdB traded and 90 EPNdB contour footprint area. Noise levels 10.9 EPNdB below FAR 36 requirements result in a 5 percent increase in DOC for an aircraft designed for a range of 9260 kilometers (5000 n. mi.). An aircraft designed for a 2778 kilometer (1500 n. mi.) range would have an EPNdB level 14 below FAR 36 for this same economic penalty. In this range of noise level, fan-machinery noise is the principal source.

# PRELIMINARY EVALUATION OF TURBOFAN CYCLE PARAMETERS AND ACOUSTICAL SUPPRESSION ON THE NOISE AND DIRECT OPERATING COST OF A COMMERCIAL MACH 0.85 TRANSPORT

by J. D. Eisenberg

Lewis Research Center

## SUMMARY

The purpose of this study was to determine the relative penalty in gross weight and direct operations cost associated with the use of acoustic suppression material and cycle selection for reducing the engine noise generated by turbofan powered commercial, subsonic, transport aircraft. The study aircraft were all 200 passenger CTOL trijets cruising at a Mach number of 0.85 and designed for ranges of 2778, 4630, and 9260 kilometers (1500, 2500, and 5000 n mi). The engines were somewhat advanced in design, having a 2600° F turbine inlet temperature. The fans were single stage.

Aircraft gross weight and direct operating cost, which varied with amount of suppression and cycle selection, are presented as functions of both EPNdB traded and 90 EPNdB contour footprint area. Noise levels 10.9 EPNdB below FAR 36 requirements resulted in a 5 percent increase in DOC for an aircraft designed for a range of 9260 kilometers (5000 n mi). An aircraft designed for a 2778 kilometer (1500 n mi) range would have an EPNdB level 14 below FAR 36 for this same economic penalty.

It was found that in this range of noise level the fan machinery noise is the principal source.

## INTRODUCTION

The current noise regulation (FAR Part 36) went into effect on December 1, 1969. For airplane gross weight above 272 154 kilograms (600 000 lb), allowable noise at the designated check points is 108 EPNdB. Allowable noise is less for lighter aircraft. Older long-range aircraft (such as the Boeing 707 and Douglas DC-8) exceed the requirements by several PNdB. The newer wide-body airplanes (Boeing 747, Douglas DC-10, and Lockheed L1011) meet or better these requirements.

Other noise evaluation studies have been made for advanced transport systems. The results are summarized in reference 1. The studies of reference 1, however, assumed a large future improvement in noise reduction techniques. The present study is confined to techniques that are presently available.

In reference 2 a study was made in which the engine cycles that were optimum (that is resulted in lowest TOGW for a given noise level) were determined for various sideline PNdB levels. In that study the turbine inlet temperature at sea-level-static conditions ($T_4$ SLS) was fixed at 1700 K (2600° F) and the best $T_4$ at cruise was determined. Full-coverage film cooling was assumed in the turbines.

That study showed the effects of noise suppression by means of acoustic suppression material on the takeoff gross weight (TOGW) of a 200-passenger, high-L/D, three-engine aircraft flying a range of 5556 kilometer (3000 n mi) at a cruise Mach number of 0.85. The cruise altitude was about 12 192 meters (40 000 ft). The base airframe L/D was 20 for that study. Some DOC results were presented. The present study branches out from the basic study of reference 2.

In the present study the basic L/D at cruise is set at 18, comparable to current aircraft, and lower and higher L/D's are examined. The aircraft range now varies from 2778 to 9260 kilometers (1500 to 5000 n mi). The airframe weight model is modified to cover the aircraft flying ranges other than 5556 kilometers (3000 n mi). The weight of suppression material, the thrust loss due to suppression material, and the fan machinery noise model have been updated to agree with more recent estimates. The method for computing fan jet noise is modified. Core or internal noise is accounted for in this study. Approach noise and takeoff noise are also taken into account in this study rather than limiting the study to sideline noise as in reference 2. Footprints are also computed here. Sensitivity studies of several parameters are also included.

The basic computer program used in this study is that developed for and utilized in the study of reference 2. The method of engine design is exactly the same in both studies (i.e., the thermodynamics including cooling, the sizing, and the weight estimation). The takeoff turbine inlet temperature is also the same for the major portion of this study (1700 K) (2600° F).

The aircraft configuration, the climb and descent characteristics, and the cruise conditions are the same. The aircraft in both studies is a 200-passenger trijet flying at Mach 0.85 at an altitude of about 12 192 meters (40 000 ft).

The mathematical models for the complete program are either based on technology that is currently available or on technology improvements that appear possible with current knowledge. However, the study is not based on a particular airframe or on a particular engine that is in existence at the present time. Furthermore, detailed design evaluations of the airframes or engines are beyond the scope of this study.

One basic aircraft configuration is used throughout with a constant 200-passenger payload. The ranges considered are 2778, 4630, and 9260 kilometers (1500, 2500, and 5000 n mi). The 2778 kilometer (1500 n mi) range has been assumed as the range of greatest interest. Turbofan engines each having a single stage fan, a 1700 K (2600° F) $T_{4,SLS}$, and utilizing full-coverage, film cooling of the turbine are assumed for the major portion of this study.

The noise sources considered are primary jet noise, secondary (fan) jet noise, fan machinery noise, and core (internal) noise.

The fan-machinery noise model is based on preliminary data from large scale fans with low-noise features. Therefore it may possibly be more advanced than the current state of the art.

Fan machinery noise is quieted by the use of acoustic suppression material. The weight of suppression, and thrust and SFC loss curves take into account the use of splitters in the more highly suppressed cases.

Although core machinery-noise suppression was investigated, it offered little or no improvement for the noise levels presented in this study. Only in cases of even lower noise levels would it become a method to be considered.

The engine noise is evaluated at the sideline and approach points. A flight path is chosen that should make takeoff noise equal to sideline noise in PNdB. The takeoff-point noise is difficult to determine accurately since exact aerodynamics are required.

Since the engine noise is made up of several sources, a choice of the combination of fan pressure ratio, bypass ratio, and amount of suppression that results in the lowest direct operating cost (DOC) for a given noise level must be made.

Payload and range are held constant in this study, and engine and aircraft size and weight are allowed to vary. Noise levels are presented both as EPNdB values and as footprint areas for a given EPNdB level. The penalties associated with quieting the engines are in terms of DOC.

For each of the three ranges considered in this study the datum case is one in which engines typical of engines used by current, wide-body jet aircraft ($T_{4STL}$ = 1478 K) (2200° F) are used. The base core for each range using the advanced cycles of this study generate the same noise as the datum case. All noise reduction effects are then evaluated using the advanced cycles.

The most important results of this study are those of economic penalty due to quieting engines. However, the improvement of DOC by using advanced cycles is also a result.

This study is confined to under-the-wing engines using acoustical material to quiet noise. Other concepts such as over-the-wing engines and sonic inlets are not considered. Airframe noise, a possible factor at low noise levels is also ignored.

# METHOD OF ANALYSIS

## General Approach

The basic mission program designs the aircraft, determines the engine weight and aircraft weight, computes the fuel, calculates the noise, and then computes the DOC. The aircraft design and weight portion of the program is iterative in nature. The engine parameters are inputs. Therefore, two series of computer runs are required for each case. The first series insures that takeoff thrust-to-weight ratio is correct. The second series determines which cycles give the lowest DOC for a given noise level.

## Aircraft

Aircraft configuration. - Figure 1 depicts the basic aircraft configuration, a conceptual advanced 200 passenger trijet. Due to the method of computation the study results would not change if the placement of engines was changed to one under each wing.

It has been assumed that the weight for each passenger, including baggage, is 200 pounds. This results in a 40 000 pound payload which is held constant throughout the study.

Airframe weight. - Figure 2 presents a relation for airframe weight as a function of the fraction of fixed plus payload weight. In determining this relation, data for a large number of transport aircraft were plotted, and the line shown in figure 2 was determined from a best fit of these data. Several of these current aircraft are shown in figure 2.

The relation is

$$WAF = 0.109\ (TOGW) + 0.47308\ (TOGW - W_{F,tot}) \qquad (1)$$

where TOGW is takeoff gross weight and $W_{F,tot}$ is total fuel weight.

Lift-drag ratio. - The basic value of cruise lift to drag ratio $(L/D)_{cr}$ used for this airframe is 18, which is typical of current jet transport aircraft (ref. 3). The drag of the engine nacelles is also added to yield the total L/D for the aircraft.

At the cruise Mach number of 0.85 changes in wave drag are very small and may be ignored.

Basic values of $(L/D)_{cr}$ of 16 and 20 are also used for comparison purposes.

Fuel weight. - The total fuel weight is made up of four parts. Using $W_F$ to represent a fuel weight

$$W_{F,tot} = W_{F,climb} + W_{F,descent} + W_{F,cruise} + W_{F,reserve}$$

As in reference 2, the climb, descent, and reserve fuel were approximated by:

$$W_{F,climb} = (TOGW/386\ 000)20\ 000 \tag{2}$$

$$W_{F,descent} = (TOGW/386\ 000)2000 \tag{3}$$

$$W_{F,reserve} = 0.18\ (W_{F,tot}) \tag{4}$$

or

$$W_{F,reserve} = 0.2195\ (W_{F,climb} + W_{F,descent} + W_{F,cruise}) \tag{5}$$

The weight of the cruise fuel is computed in an iterative process in conjunction with the computation of takeoff gross weight (TOGW) which follows.

Aircraft gross weight. - Within the program the following method is used to compute the aircraft gross weight and the actual weight of fuel consumed. Two basic equations are used. The first is a form of the Breguet cruise range equation.

$$e^{\left\{\frac{(R - R_{cd})(sfc)}{[(L/D)_{cr}](M_{cr})(c_s)}\right\}} = \frac{(TOGW - W_{F,climb})}{(TOGW - W_{F,climb} - W_{F,cruise})} \tag{6}$$

The symbol $e$ is the Naperian logarithmic base. The other symbols are defined in the table of symbols. $R_{cd}$ is the sum of the climb and descent ranges, 648.2 kilometers (350 n mi). The right hand numerator represents the aircraft weight at the start of cruise. The right hand denominator is the aircraft weight at the end of cruise. The sfc is discussed in the engine section.

The second equation is simply a summation of weights.

$$TOGW = WAF + WENG + WINST + WPAY + W_{F,tot} \tag{7}$$

Two weights in equation (7) have not yet been mentioned. These are the bare engine weights, WENG, and the engine installation weights, WINST. These parameters are discussed in the engine section of this report.

The process of computation is an iterative one. Initially the $(L/D)_{cr}$, the fuel required, the weight of bare engines, engine installation weight, airframe weight, and TOGW are not known. Thus a series of recomputations are required until all weights are consistent with one another.

## Engines

Engine description. - The engines used in this study are all turbofan engines with single stage fans. Two engine cycles were considered: a baseline cycle typical of those used in current wide-body aircraft, and an advanced cycle with increased turbine inlet temperature and using advanced methods of cooling. Fan machinery noise suppression is inserted in the form of acoustic liners and acoustically treated splitter rings. Core noise suppression is added as an acoustic liner to the core nozzle. Separate exhaust flows are assumed. A sketch of the study engine installation configuration showing fan-machinery suppression and core suppression is shown in figure 3.

The baseline cycle had a takeoff fan pressure ratio of 1.6 and a rotor turbine inlet temperature of 1478 K (2200° F). The advanced engine cycle had a design compressor pressure ratio of 15 and a turbine inlet temperature of 1700 K (2600° F) at takeoff. A fan pressure ratio at takeoff of 1.6 was used in all advanced engine cases. The reason for this will be discussed later.

With the fixed fan pressure ratio and compressor pressure ratio the bypass ratio is varied. It is increased as lower noise goals are desired. Once an engine has a bypass ratio of 5 or 6, small increases in bypass ratio greatly reduce the primary jet velocity and thus the primary jet noise.

Since the sea level $T_4$ is fixed at 1700 K (2600° F) for standard day operation, a temperature somewhat lower than 1700 K (2600° F) occurs at altitude. This is due to the fact that full power is not required at cruise. Compressor discharge air is bled off and used for turbine cooling in the engine model. Full-coverage film cooling is assumed, with cooling requirements estimated according to the methods discussed in references 2 and 4. The details of the method will not be repeated here.

For this study a relation between corrected fan-tip speed and FPR was assumed in order to use the simplified method for turbine cooling as presented in references 2 and 4. The bulk metal temperature of the turbine blades was fixed at 1172 K (1650° F) for the rotors and at 1366 K (2000° F) for the vanes for the $T_{4SLS}$ = 1700 K (2600° F) engines. For current-type high-bypass engines with $T_{4SLS}$ = 1478 K (2200° F) the bulk metal temperatures were varied to make the chargeable bleed about 7 percent of the primary air flow (more in line with the bleed values in existing engines).

In the computations all the engines in this study are designed at cruise, and therefore takeoff operation is an off-design case. To compute these off-design conditions a component-matching computer program (ref. 6) was used. This program uses component maps in the matching procedures. Fixed nozzle geometry was assumed throughout this study.

Pertinent cruise design-point efficiencies and pressure loss data used for the advanced engine are presented in table I.

In order to make the noise computation at takeoff similar for all aircraft of this study, all aircraft are required to have an altitude of 460 meters (1500 ft) at the 6.48 kilometer (3.5 n mi) measuring point. Information in reference 2 was used to establish the sea-level-static thrust-to-weight ratio necessary to just achieve this altitude for every aircraft in this study. This was used to size the engines. The value of aircraft thrust-to-weight ratio was about 0.32 for the BPR considered in this study.

Engine weight and size. - The engine weight and engine dimensions were determined by the method described in reference 5. This method is parametric in nature.

The parameters on which the engine weights are based are turbine inlet temperature at takeoff, cruise Mach number, engine bypass ratio at takeoff, design life, duct length, total weight of airflow at takeoff, total engine pressure ratio, and year of design. The life is either "long" or "short." Cruise engines require a long life. Duct length is "long" or "short." This length parameter is a very weak one, causing only small changes in weight. A long duct was used. The year 1973 was chosen for the technology level.

After a review of the engine installation weights of a number of current aircraft, a typical installation weight of 3.13 times engine corrected airflow was chosen. This weight accounts for such items as inlet nacelle, exhaust nozzle, and other additional items.

The parameters on which the engine size is based are for the most part those used for engine weight. There are some differences, however. The turbine inlet temperature is not used, and the additional parameters are Mach number at the fan face, inlet guide vanes (yes or no), fan pressure ratio, hub to tip ratio, and fan efficiency. The engine size is required to determine the nacelle size for the computation of nacelle drag.

Noise models. - Four noise sources are considered: primary jet, secondary (fan) jet, fan machinery noise, and core or internal noise.

Primary jet noise is computed by the Society of Automotive Engineers (SAE) method of references 7 and 8. The core noise relation is based on work done by the General Electric Company and given to the author by David Latham. The resulting curve-fit relation is as follows:

$$PNL_{core} = 84 + 10\left[\log_{10}\left(\frac{\text{Weight rate gas flow}}{K_1}\right)\right] \qquad (8)$$

where

$$K_1 = 57.606$$

for weight in kilograms or

$$K_1 = 127$$

for weight in pounds. Equation (8) is for the 460 meter (0.25 n mi) sideline measuring point. Standard techniques were used to adjust the noise for other distances and reduced lower at approach. Its use is limited to the type of engine used in this study.

The fan jet noise is computed by the Sanders method which is presented in reference 9. The fan machinery noise is assumed to follow the relation depicted in figure 4 where PNdB level is plotted as a function of FPR.

The curve presented in figure 4 is based on information in reference 10. The sharp rise at 1.6 FPR is a reflection of the appearance of multiple pure tones. In actuality there is a band of FPR where the multiple pure tones have an effect. For simplicity a single point is used.

Noise suppression models. - The models of suppression weight and suppression-caused losses in thrust and SFC are based on data developed by the General Electric Company and the V/STOL and Noise Division at the NASA Lewis Research Center. These curves are based on both experimental and computed data of acoustic lining type suppression and the incorporation of inlet and exit splitters where required. The curves are presented in the following two figures.

Figure 5. - Weight of suppression against reduction in fan-machinery noise, and weight of suppression against reduction in core noise.

Figure 6. - Fraction of thrust and SFC loss against reduction in fan machinery noise or core noise.

The actual weights of suppression vary with the square of the diameter of the flow path.

Noise computation. - The noise is computed at two of the three FAR-36 measuring points. One point is the approach point. This is located 1.852 kilometers (1 n mi) from the threshold of the runway. On a typical glide path the aircraft is 112.78 meters (370 ft) above the ground. A typical L/D is chosen of 5.5. This then determines the approach power setting. However, a maximum engine cutback of 34 percent of takeoff thrust is set in order to insure proper engine response in the event of a go-around.

Noise is also computed at the FAR-36 sideline point. Here the aircraft is at an altitude where shielding and ground attenuation is not present once the measurement is made at a perpendicular distance of 460 meters (1500 ft) from the centerline of the runway (0.25 n mi).

The third FAR 36 measuring point is directly under the aircraft flight path 6.48 kilometers (3.5 n mi) from the start of takeoff roll. Here the aircraft is positioned at a 460 meter (1500 ft) altitude by choosing the proper aircraft thrust to weight ratio.

Since the power setting and the distance to the observer are the same as at sideline, the PNdB value is equal to that at sideline assuming no cutback. No computation is made for this specific measuring point.

PNdB values were corrected to EPNdB using figure 7. This figure was originally transmitted in an informal communication from the General Electric Company. Preliminary calculations verified its worth for the computations of this study.

Footprints for given EPNdB levels are computed from the noise values at the three FAR 36 measuring points. These calculations were made by John F. Groeneweg and Eugene A. Krejsa of the NASA Lewis V/STOL and Noise Division, using an approximate method based on the noise footprint areas of current aircraft.

## Direct Operating Cost Computation

Direct operating cost (DOC) was computed for the optimum engine cycles at each noise goal using the 1967 ATA domestic formula. An optimum engine cycle is one that gives minimum TOGW and DOC for a given noise level. Because of uncertainties in costs at this preliminary stage, only relative DOC has any merit. In this study, airframes were assumed to cost $158.73 per kilogram ($72 per lb) (based on current airplanes). Acoustic suppression materials for fan and core noise was assumed to cost the same per pound as the airframe. Engine price was assumed to be a function of sea-level-static corrected airflow and was computed as follows (ref. 2).

$$C_{eng} = 1.2\times10^{6}\left[\frac{\left(W_a\sqrt{\theta_1/\delta_1}\right)_{SLS}}{K_2}\right]^{0.35}$$

$C_{eng}$ is the cost in dollars. $K_2$ is a reference constant.

$K_2 = 589.67$ for weight of airflow in kilograms

$K_2 = 1300$ for weight of airflow in pounds

The other symbols are defined in the table of symbols. This cost 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.

## Calculations

Cycles used. - The engine cycles used in the noise tradeoff studies all have a 1700 $K_{SLS}$ (2600° $F_{SLS}$) $T_4$. The same turbine cooling bleed model is used for all of them (full-coverage film cooling). The compressor pressure ratio is always 15.

In this study three parameters are not given fixed values. The fan pressure ratio, bypass ratio, and amount of suppression are examined during this study. For any noise level their values are set so that noise levels may be achieved for the lowest DOC.

All of these 1700 K (2600° F) $T_{4,SLS}$ cycles used in the tradeoff studies are referred to in this report as advanced cycles, since they are somewhat more advanced than those of engines flying today.

In order to determine a base case for each of the three ranges, mission computations were made using an engine cycle and amount of suppression used by current wide-body jet aircraft. The $T_{4,SLS}$ is 1478 K (2200° F). Only lining noise suppression for fan machinery noise is used. The lining suppression for the fan gives approximately a 7 PNdB reduction. The turbine-cooling bleeds are about 7 percent, typical of those of the current wide-body jets. These base cycles are called current cycles in this report.

Note that cycle is referred to here rather than engine, for in the calculation procedure the actual aircraft is designed for each case of interest. Thus each aircraft of this study has a different thrust requirement, and thus a different size engine. Then, although the cycle may be the same for two cases, if, for example, the range were different for these two cases the actual engines would differ in size.

Initially for the 200 passenger payload and for each of three ranges 2778, 4630, 9269 kilometer (1500, 2500, and 5000 n mi) airplanes were designed using the current-type engine cycles. The noise at the FAR 36 measuring points was determined in terms of EPNdB as previously mentioned. The DOC is also computed. For each range this is the base case, representative of current-technology aircraft engines, with current noise levels.

Then these same calculations are made using the advanced (2600° F $T_{4,SLS}$) engine cycles. Variations in suppression and bypass ratio (BPR) are made using these engines for the 2770, 4630, and 9260 kilometer (1500, 2500, and 5000 n mi) ranges until the noise generated by these advanced cycle engines (measured at the FAR 36 points) closely approximates the noise generated by the current-type cycle engines for the respective ranges. The EPNdB (traded) is exactly the same for both the current and advanced cycles. The combination of engine parameters that gives the minimum DOC and meets the current cycle noise is used.

Each of these base cases then becomes a datum. When further modifications are made to reduce the noise below current noise levels, the resulting penalties in DOC may be compared to the respective datum.

As these cycles are quieted, the BPR is increased slightly so that the difference in PNdB between fan machinery noise and primary jet noise is about the same for these quieted cycles as for the base advanced cycle. It had been found in preliminary calculations that this gave essentially optimum noise-DOC results without the necessity of rerunning total optimization studies for each noise level.

In figure 8, which is from reference 2, the effect on TOGW as a function of FPR is plotted for various noise goals. The minimum TOGW points represent the best FPR. This information is acceptable for this study on a gross level. These curves indicate a cruise FPR of from 1.75 to 1.70 for engines yielding noise levels from 10 to 20 PNdB below FAR 36. Referring to figure 9, it is seen that at a takeoff FPR of 1.5 to 1.6 there is a sharp rise in fan machinery noise due to a jump in multiple-pure-tone noise.

For computational purposes it is assumed that the point at which a subsonic fan can no longer be used is at a 1.6 sea-level-static FPR. This choice may be slightly optimistic, but it should not affect the trends of this study.

Sensitivity studies showed that for all noise levels equal to or less than the noise levels of wide-body aircraft flying today that a takeoff fan pressure ratio just below the jump in noise was the point resulting in both minimum TOGW and minimum DOC. Therefore the takeoff FPR's of all advanced cycles were the same 1.599. The cruise FPR's varied between 1.709 and 1.760, depending on the BPR and cruise turbine inlet temperature.

With the FPR at takeoff the same in all cases, it is then only necessary to find the optimum combination of BPR and suppression for any noise level desired.

Cases investigated. - Using the methods described above the following noise cases are examined. For the 2778 kilometer (1500 n mi) range, the case just matching the EPNdB (traded) of the current engine, FAR-36-10 traded, FAR-36-15 traded and three high suppression cases are examined, two of which have core noise suppression. The first three cycles are then examined at 4630 and 9260 kilometers (2500 and 5000 n mi). Slight adjustments in fan suppression have been made to meet the FAR 36-10 traded and the FAR 36-15 traded goals for the 4630 kilometer (2500 n mi) case. A similar adjustment is made for the FAR 36-10 case at 9260 kilometers (5000 n mi). However, the FAR 36-15 case at 9260 kilometers (5000 n mi) is modified to a FAR 36-14 case. Exceptionally large changes in suppression are required in this case to get to FAR 36-15.

A table of these cycles is presented in the RESULTS AND DISCUSSION section.

Footprint calculations for all of these cycles were at 90 EPNdB.

## RESULTS AND DISCUSSION

The results are divided into three distinct sections. The first set presents the cycles that were chosen for the base case and the other noise levels examined. Some of the noise levels have associated with them large increases in DOC. Their presentation on the curves is not meant to indicate their acceptability from a cost standpoint.

The second set of results consists of the relative increase in DOC (economic penalties) as a function of noise level in EPNdB, or of footprint area for a given noise level in EPNdB.

The third set of results are sensitivity variations. There are two purposes in presenting these curves. One is to indicate the effects on the results of this study should actual noise values differ from these computed values. The second purpose is to show the results of possible improvements in the state of the art in noise suppression and source reduction.

### Cycle Selection

Table II(a) presents the noise levels generated by aircraft with current cycle engines flying three given ranges with all other mission ground rules those of this study.

Table II(b) presents the base, or -1, cases using the advanced cycle engines. These aircraft produce the same noise levels in EPNdB at the FAR 36 measuring points as the noise values listed in table II(a). The increase in noise with increase in range is due entirely to the fact that the longer range aircraft are heavier, and thus more thrust and, therefore, larger engines are required. Using the TOGW of the -1 case for each range the required FAR 36 noise value for each range is determined (table II(b)).

Table III(a) to (c) present the cycles that resulted from this study. The -1 cycle for each range is the base cycle. The bypass ratios are higher with these advanced cycles than the 4 to 6 bypass ratios of current cycles. This is due to the higher $T_{4,SLS}$ of the advanced cycles. A greater BPR is required to reduce the primary jet velocity, and thus the primary jet noise, down to those values of current engines.

The -2 and -3 airplanes are for 10 and 15 EPNdB, respectively, below the required FAR 36 value (table II(b)) for the 2778 kilometer (1500 n mi) and 4630 kilometer (2500 n mi) ranges, and for 10 and 14 EPNdB, respectively, below this value for the 9260 kilometer (5000 n mi) range.

For the 2778 kilometer (1500 n mi) and 4630 kilometer (2500 n mi) ranges additional fan machinery suppression was added and BPR increased even more. Finally a point was reached just above the noise level at which core noise would become a significant factor. These are presented as the 1500-4 and 2500-4 cases.

At this point cycles using various combinations of additional fan machinery noise suppression and core noise suppression were examined. In these cases with core suppression, engine performance deteriorated even further and engine weight rose with little reduction in noise level. Case 1500-5 is an example of such a cycle.

## Direct Operating Cost

Figure 9 presents the DOC penalty in percent as a function of noise level in traded EPNdB for the three ranges examined. The current technology engines are noted on the figure. Each current technology point is connected by a dashed line to the respective -1 point, the advanced technology engine-cycle aircraft that has the same respective noise level.

As would be expected, an advanced engine cycle with a better SFC results in a lower DOC in each case. Relative to current engines the advanced engines offer about a 2 to 6 percent reduction in DOC for the ranges considered. The improvement increases with increasing range.

The advantage of advanced cycles can be taken in another way, as a reduction in noise level for the same DOC. For a 2778 kilometer (1500 n mi) range the improvement in noise is 3.3 EPNdB. It decreases to 2.9 EPNdB for a 9260 kilometer (5000 n mi) range.

Further noise decreases entail DOC increases. It is beyond the scope of this study to determine what if any increase in DOC can be tolerated. However, as an example, the noise improvement that can be achieved for a 5 percent ΔDOC value is examined. For the 2778 kilometer (1500 n mi) range aircraft the traded EPNdB is 90. Comparing this value with those values in the box on figure 9, it is seen that this is 14 EPNdB below FAR 36 requirements. As the range increases, the improvement in noise for the 5 percent DOC penalty becomes smaller. At a range of 9260 kilometers (5000 n mi) the noise level is 96.1 EPNdB or 10.9 EPNdB below FAR 36. Thus for a given penalty in DOC much greater improvements can be made for short-range aircraft.

It should be noted that each of these curves has a knee, a point at which noise level decreases very little but DOC rises very sharply with the suppression technology postulated in this study. The knee occurs at higher noise levels as the aircraft range increases. Therefore, as the range increases, not only is the absolute noise level higher, but also substantial noise reductions become less feasible.

Thus, an airplane having a range of 5000 miles cannot be quieted much below the FAR 36 value minus 10 EPNdB with the suppression technology in this study. The shorter range airplanes on the other hand may be quieted much below the FAR 36 values. In the case of the 2778 kilometer (1500 n mi) range, more than 17 EPNdB below the FAR 36 value was achieved (table III(a)). However, at noise levels below FAR 36 minus 13 EPNdB the slope of the curve begins to increase very rapidly.

## Noise Footprints

Another manner in which the noise level may be shown is by footprint. In figure 10 contours of 90 EPNdB noise level are plotted. The area within them is that area in which the population will be exposed to a noise level equal to or greater than the noise level of the contour.

Figures 10(a) to (c) present noise contours for the 2778, 4630, and 9260 kilometer (1500, 2500, and 5000 n mi) range, respectively, all for 90 EPNdB contours. The highly suppressed case of 1500-5 has a footprint boundary that is less than 304.8 meters (1000 ft) from the centerline of the runway on the sides and less than 3048 meters (10 000 ft) from the ends of the runway at the extreme ends. Thus the greatest portion of the area may well be within the bounds of the airport. Less suppressed cases result in the inclusion of large areas, that could well be populated, within the 90 EPNdB contours.

Figure 11 depicts the economic penalty associated with these footprint area reductions, expressed as the difference in DOC in percent as a function of the area in kilometers and statute square miles enclosed by the 90 EPNdB contour. Note that the pattern is quite similar to that of the traded EPNdB in figure 9. For the 2778 kilometer (1500 n mi) range the areas can be reduced by about a factor of two by suppression quieting while for the 9630 kilometer (5000 n mi) range a reduction in area of only about one third appears feasible. Thus, footprints seem to tell the same story as traded EPNdB, namely that losses associated with suppression become very high with the addition of splitters and that both the absolute noise levels are higher and the possible percent reduction in noise is lower with longer range aircraft.

It should be noted here that DOC may not be a total measure of economic impact. For example, three methods being used or suggested for alleviating the noise problems are curfews, operational restrictions, and the acquisition of large areas of land around airports. Since low-area noise footprints have associated with them large increases in DOC, the economic choice may be between the cost of flight limitations or the purchase of land areas and the DOC increase associated with quieting the aircraft. Such an economic evaluation is beyond the scope of this study, however.

## Sensitivity Variations

The sensitivity study has several aims. One is to determine if a change in engine cycle parameters would change the results to any major degree. Another is to determine what the effects of small (±10 percent) errors in suppression weight, engine losses due to suppression, and level of unsuppressed fan-machinery noise are on the results of the study. Also an aim of this sensitivity study is to determine if a small change in L/D would change the results to any major degree. The effect of noise level on calculated footprint area is also desired.

In addition the results of this sensitivity study can be used to ascertain the effect that a major improvement in suppression techniques or fan-machinery noise level would have on the DOC against noise level situation. A further use of the noise footprint data is to determine the area within footprint contours other than the 90 EPNdB contour.

Figure 12 is a plot of difference in DOC in percent as a function of noise for the 2778 kilometer (1500 n mi) case. One curve is for an aircraft using the advanced cycles of this study. The second curve is for an aircraft using a current-technology cycle. Note that the difference in DOC is almost constant over the range of noise levels considered. Thus, should highly suppressed engines be built based on current engines, the penalty resulting would closely parallel the penalties incurred by advanced engines. Therefore, the trends of the study are valid for aircraft using engines with lower $T_{4,SLS}$ than the advanced engine of this study.

Figure 13 is a plot of difference in DOC in percent against noise level in EPNdB for a 2778 kilometer (1500 n mi) range. Here curves are shown for cases with reduced losses in engine performance. Note that for DOC increases of as much as 10 percent and thrust loss changes of as much as 15 percent, less than 1 EPNdB difference in noise level exists for a given DOC increase. Figure 14 is a similar plot except that the curves are for various levels of suppression weight. Again for DOC increases up to 10 percent, a 15 percent change in suppression weight results in less than a 1 EPNdB noise level difference.

The fact that moderate differences in thrust losses and suppression weight losses cause very little difference in traded EPNdB suggests that the original optimization study of reference 2 (see fig. 8) is approximately valid for a range of suppression thrust and weight penalties.

It must be noted here that although small percentage reductions from the penalty models chosen for this study result in only small DOC changes, similarly large reductions would result in large DOC improvements. For example, the solid line labeled 50 percent in figure 13 represents a thrust loss that is only 50 percent that of the basic study. The dashed line represents the same improvement in thrust loss and a similar 50 percent improvement in weight of suppression treatment. Looking at an EPNdB level of 86, the DOC penalty with the level of technology of this study is 25 percent. With only 50 percent of the original thrust loss the penalty in DOC is 13.5 percent. If, in addition, the weight of suppression treatment is half of the original the penalty in DOC is less than 7 percent. Thus new technology that might greatly reduce suppression weight and thrust losses caused by suppression would be of great benefit.

Figure 15 shows the effect of variations in fan source noise. In this case the changes are substantial. For example, a 3 EPNdB change at a traded noise level of 90 EPNdB results in a $4\frac{1}{2}$ percent improvement in DOC. This points up the fact that at noise levels below FAR 36 requirements the noise source is mainly the machinery noise of the fan.

Since fan machinery noise changes result in large DOC changes for a given level of noise, it is of great importance that very exact prediction methods be developed for the determination of this noise source. A situation where uncertainty could possibly cause a large error in noise computation is presented in figure 4. The dashed area is one of uncertainty as to the exact noise level. Such areas of uncertainty require clarification.

Figure 16 is a plot of difference in DOC plotted against noise level in EPNdB for three base airframe L/D's, 16, 18, and 20, respectively. In this figure, however, the relative increase in DOC is normalized to the -1 case for each L/D. Here for a DOC increase of 10 percent there is only about 1/2 EPNdB noise difference. Thus the trends of this study may be applied to an aircraft of different L/D.

Figures 17(a) to (c) are plots of area within the contour plotted against noise level contour for the several aircraft used in this study. These curves can be used to determine the area enclosed by a noise level contour other than 90 EPNdB. Also, however, these curves can be used to show how extremely sensitive the area is to changes in noise source.

For example in figure 17(c) the 90 EPNdB contour of the 5000-1 case encloses an area of 4.8 square miles. If an accumulation of source errors resulted in the noise being 2 EPNdB higher, the 90 EPNdB contour would enclose the area of the present 88 EPNdB contour, that is, 6.6 square miles. This is nearly a 40 percent increase in area. Thus, determining the area enclosed within a given contour, which would be indicative of population exposed to noise levels equal to or greater than that contour, is most difficult to do with great accuracy. It appears, then, that although footprint areas would be the best criteria for evaluating noise problems, the large area errors resulting from small errors in noise level reduces the value of these footprints considerably.

## CONCLUDING REMARKS

A study was made of a family of CTOL, Mach 0.85, 200 passenger aircraft flying various ranges in order to determine the tradeoff between lower noise level and higher DOC using current noise and suppression technology. The cycle bypass ratio was varied and noise suppression for both fan and core noise was added to reduce the aircraft engine-generated noise level. Each aircraft was powered by three turbofan engines having a turbine inlet temperature of 1700 K (2600° F). The fans were single stage with about a 1.7 fan pressure ratio at cruise. The compressor pressure ratio was 15. Advanced full coverage film cooling of the turbine was assumed.

The results were computed both as increase in direct operating cost as a function of traded noise level in EPNdB and increase in direct operating cost as a function of area within the 90 EPNdB contour of a noise footprint.

1. Noise levels of 10 EPNdB traded below FAR 36 requirements seem reasonable with aircraft flying ranges up to 9260 kilometers (5000 n mi). Somewhat greater reductions appear reasonable for shorter range aircraft. Of course the determination of a reasonable DOC penalty is somewhat subjective. It is in part dependent on the feelings of the nation as to what constitutes a desirable noise level. This determination is beyond the scope of this study.

2. Advanced technology engines with lower SFC make two possibilities available. The current noise levels may be maintained at a lower DOC, or somewhat lower noise levels may be attained at current DOC levels.

3. With a given level of engine technology all reductions in noise result in increased direct operating cost. If the engines are suppressed to the point that EPNdB levels much lower than 10 EPNdB below the FAR 36 requirements are achieved, high DOC penalties are incurred with the technology postulated in this study. For a total economic picture, however, DOC would have to be compared with the costs of other suggested solutions to the noise problem, such as operating limitations and land acquisition. This is beyond the scope of this study.

4. The amount of noise reduction possible is reduced and the absolute noise level is increased as the design range increases.

5. At the noise levels examined in this study fan machinery noise predominates. With quieting of this noise by means of linings and splitters, at some point there is a knee in the curve of DOC against suppression. Beyond this knee small noise reductions result in large DOC increases. Quieting, then, is only a possible solution slightly past the knee of the curve. On the other hand, technology improvements either in fan machinery source noise or suppression technology that can move the knee to lower noise levels would be of great assistance.

6. Sensitivity studies indicate that the results of this report are valid for cases with current engine cycles as well as advanced cycles, different aircraft L/D's, and with moderate variations in thrust loss and weight increases due to suppression. If, however, the technology

were available to make very large decreases in thrust losses and suppression weight, similarly large improvements in DOC would result.

Variations in fan machinery source noise cause noticeable variations in the results. This points up the fact that the principal noise source at the range of noise levels examined is the fan machinery noise.

7. Footprint areas for a given noise level are greatly reduced by small reductions in generated EPNdB. But, however, this also means that small errors in EPNdB computation will result in large differences in area. Thus the absolute footprint area, although it could best determine number of people exposed to noise greater than some given level, is the most difficult noise criteria to ascertain.

Although the absolute size of a footprint is difficult to ascertain, footprints may be used to show the relative effect of noise suppression.

Note that airframe noise, which could be a contributing factor at low engine noise levels, was not considered in this study.

## REFERENCES


1. Antl, Robert J.: The Effect of Noise Constraints on Engine Cycle Optimization for Long-Haul Transports. AIAA Paper 73-1292, Nov. 1973.

2. Kraft, Gerald A.: Optimization of Engines for a Commercial Mach 0.85 Transport using Advanced Cooling Methods. NASA TM X-68173, 1972.

3. Whitlow, John B., Jr.; and Kraft, Gerald A.: Optimization of Engines for Commercial Air Transports Designed for Cruise Speeds Ranging from Mach 0.90 to 0.98. NASA TM X-67906, 1971.

4. Kraft, Gerald A.; and Whitlow, John B., Jr.: Optimization of Engines for a Commercial Mach 0.98 Transport Using Advanced Turbine Cooling Methods. NASA TM X-68031, 1972.

5. Gerend, Robert P.; and Roundhill, John P.: Correlation of Gas Turbine Engine Weights and Dimensions. AIAA Paper 70-669, June 1970.

6. Koenig, Robert W.; and Fishbach, Laurence H.: GENENG: A Program for Calculating Design and Off-Design Performance for Turbojet and Turbofan Engines. NASA TN D-6552, 1972.

7. Jet Noise Prediction. Aerospace Information Report 876, SAE, July 10, 1965.

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

9. Minner, Gene L; and Feiler, Charles E.: Low-Speed Jet Noise from a 1.83-Meter (6 Ft) Fan for Turbofan Engines. NASA TN D-6314, 1971.

10. Feiler, C. E.; and Conrad, E. W.: Noise from Turbomachinery. AIAA Paper 73-815, Aug. 1973.

# APPENDIX - SYMBOLS

| | |
|---|---|
| BPR | engine bypass ratio |
| $C_{eng}$ | cost of engine, dollars |
| $c_s$ | speed of sound in air, km/hr (n mi/hr) |
| DOC | direct operating cost, cents per seat km (cents per seat s mi) |
| EPNdB | effective perceived noise, dB |
| e | Naperian base |
| FPR | fan pressure ratio |
| $K_1$ | constant used in noise computations, 57.606 if weight flow in kilograms, 127 if weight flow in pounds |
| $K_2$ | constant used in engine cost computations, 589.67 if weight flow in kilograms, 1300 if weight flow in pounds |
| L/D | aircraft lift to drag ratio |
| M | Mach number |
| PNdB | perceived noise, dB |
| $PNL_{core}$ | perceived noise level of internal noise generated by core, PNdB |
| R | total aircraft range, km (n mi) |
| $R_{cd}$ | sum of climb and descent ranges, km (n mi) |
| sfc | specific fuel consumption, N-hr/kg (1/hr) |
| $T_4$ | turbine inlet temperature, K ($^{o}$F) |
| TOGW | aircraft takeoff gross weight, kg (lb) |
| $W_a$ | weight rate of engine airflow, kg/sec (lb/sec) |
| WAF | weight of airframe, kg (lb) |
| WENG | weight of all engines, kg (lb) |
| $W_{F,climb}$ | fuel to climb to cruise altitude, kg (lb) |
| $W_{F,cruise}$ | fuel used during cruise portion of flight, kg (lb) |

$W_{F,descent}$ fuel to descent from cruise altitude and land, kg (lb)

$W_{F,reserve}$ reserve fuel, kg (lb)

$W_{F,tot}$ total mission fuel, kg (lb)

WINST weight of all engine installations, kg (lb)

WPAY weight of payload, kg (lb)

$\delta$ pressure parameter, actual pressure divided by standard sea-level-static pressure

$\theta$ temperature parameter, actual temperature divided by standard sea-level-static temperature

Subscripts:

cr cruise

SLS at sea-level-static conditions

TABLE I. - BASIC ENGINE DATA

| | |
|---|---|
| Compressor adiabatic efficiency . . . . . . . . . . . . . . | 0.86 |
| Combustor efficiency. . . . . . . . . . . . . . . . . . . . | .99 |
| Inner turbine adiabatic efficiency. . . . . . . . . . . . . | .89 |
| Outer turbine adiabatic efficiency. . . . . . . . . . . . . | .88 |
| 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 |
| Fan design adiabatic efficiency (FPR = 1.7) . . . . . . . . | .838 |

TABLE II. - AIRCRAFT NOISE LEVELS

(a) Noise of trijets using cycles typical of current engines

| Range | | Noise in EPNdB | | |
|---|---|---|---|---|
| km | n mi | Sideline | Approach | Traded |
| 2778 | 1500 | 91.5 | 98.3 | 96.3 |
| 4630 | 2500 | 92.2 | 98.9 | 96.9 |
| 9260 | 5000 | 94.7 | 101.4 | 99.4 |

(b) FAR 36 noise level requirements for aircraft using advanced cycles generating noise at current levels

| Aircraft code number | Range | | TOGW, lb | Required EPNdB (nearest EPNdB) |
|---|---|---|---|---|
| | km | n mi | | |
| 1500-1 | 2778 | 1500 | 154 000 | 104 |
| 2500-1 | 4630 | 2500 | 182 000 | 105 |
| 5000-1 | 9260 | 5000 | 908 000 | 107 |

TABLE III. - ENGINE CONFIGURATIONS

(a) 2778 km range (1500 n mi)

| | Code number | | | | |
|---|---|---|---|---|---|
| | 1500-1 Current noise | 1500-2 | 1500-3 | 1500-4 | 1500-5 |
| Takeoff | | | | | |
| BPR | 8.5 | 8.6 | 8.7 | 9.1 | 9.1 |
| FPR | 1.60 | 1.60 | 1.60 | 1.60 | 1.60 |
| Approach | | | | | |
| BPR | 9.5 | 9.6 | 9.7 | 10.0 | 10.0 |
| FPR | 1.28 | 1.28 | 1.27 | 1.23 | 1.23 |
| Cruise | | | | | |
| BPR | 8.6 | 8.7 | 8.8 | 8.9 | 8.9 |
| FPR | 1.71 | 1.71 | 1.72 | 1.76 | 1.76 |
| Suppression | | | | | |
| Fan (PNL) | 6.8 | 9.2 | 15.1 | 18.0 | 19.1 |
| Core (PNL) | 0 | 0 | 0 | 0 | 3 |
| Type of treatment | Lining | Lining and splitters or nacelle extension | | | Like -4 plus core supp. |
| TOGW (kg) | 69.81 | 70.90 | 78.20 | 88.63 | $94.94\times10^3$ |
| (lb) | 153.9 | 156.3 | 172.4 | 195.4 | $209.3\times10^3$ |
| Percent relative DOC | -2.2 | -0.7 | 8.0 | 20.3 | 27.7 |
| Sideline EPNdB | 91.7 | 89.7 | 86.2 | 85.3 | 83.6 |
| Approach EPNdB | 98.3 | 96.0 | 91.0 | 88.3 | 87.4 |
| Traded EPNdB | 96.3 | 94.0 | 89.0 | 86.8 | 85.5 |
| Relative to FAR 36 | -7.7 | -10 | -15 | -17.2 | -18.5 |

TABLE III. - Continued. ENGINE CONFIGURATIONS

(b) 4630 km range (2500 n mi)

| | Code number | | | |
|---|---|---|---|---|
| | 2500-1 Current noise | 2500-2 | 2500-3 | 2500-4 |
| Takeoff | | | | |
| BPR | 8.5 | 8.6 | 8.7 | 9.1 |
| FPR | 1.60 | 1.60 | 1.60 | 1.60 |
| Approach | | | | |
| BPR | 9.5 | 9.6 | 9.7 | 10.0 |
| FPR | 1.28 | 1.28 | 1.27 | 1.23 |
| Cruise | | | | |
| BPR | 8.6 | 8.7 | 8.8 | 8.9 |
| FPR | 1.71 | 1.71 | 1.72 | 1.76 |
| Fan suppression (PNL) | 6.8 | 8.9 | 14.7 | 18.0 |
| Type of treatment | Lining | Lining and splitters or nacelle extension | | |
| TOGW (kg) | 82.64 | 84.19 | 95.93 | $117.8\times10^3$ |
| (lb) | 182.2 | 185.6 | 211.5 | $259.8\times10^3$ |
| Percent relative DOC | -2.9 | -1.5 | 9.6 | 29.4 |
| Sideline EPNdB | 92.4 | 90.7 | 87.1 | 86.6 |
| Approach EPNdB | 98.9 | 97.0 | 92.0 | 89.4 |
| Traded EPNdB | 96.9 | 95.0 | 90.0 | 88.0 |
| Relative to FAR 36 | -8.1 | -10 | -15 | -17 |

TABLE III. - Concluded. ENGINE CONFIGURATIONS

(c) 9260 km range (5000 n mi)

| | Code number | | |
|---|---|---|---|
| | 5000-1 Current noise | 5000-2 | 5000-3 |
| Takeoff | | | |
| BPR | 8.5 | 8.6 | 8.7 |
| FPR | 1.60 | 1.60 | 1.60 |
| Approach | | | |
| BPR | 9.5 | 9.6 | 9.7 |
| FPR | 1.28 | 1.28 | 1.27 |
| Cruise | | | |
| BPR | 8.6 | 8.7 | 8.8 |
| FPR | 1.71 | 1.71 | 1.72 |
| Fan suppression (PNL) | 6.7 | 9.3 | 16.6 |
| Type of treatment | Lining | Lining and splitters or nacelle extension | |
| TOGW (kg) | 139.8 | 147.5 | $274.7\times10^3$ |
| (lb) | 308.1 | 325.2 | $605.7\times10^3$ |
| Percent relative DOC | -6.5 | -2.5 | 58.4 |
| Sideline EPNdB | 94.7 | 85.2 | 91.0 |
| Approach EPNdB | 101.4 | 99.0 | 95.0 |
| Traded EPNdB | 99.4 | 97.0 | 93.0 |
| Relative to FAR 36 | -7.6 | -10 | -14 |

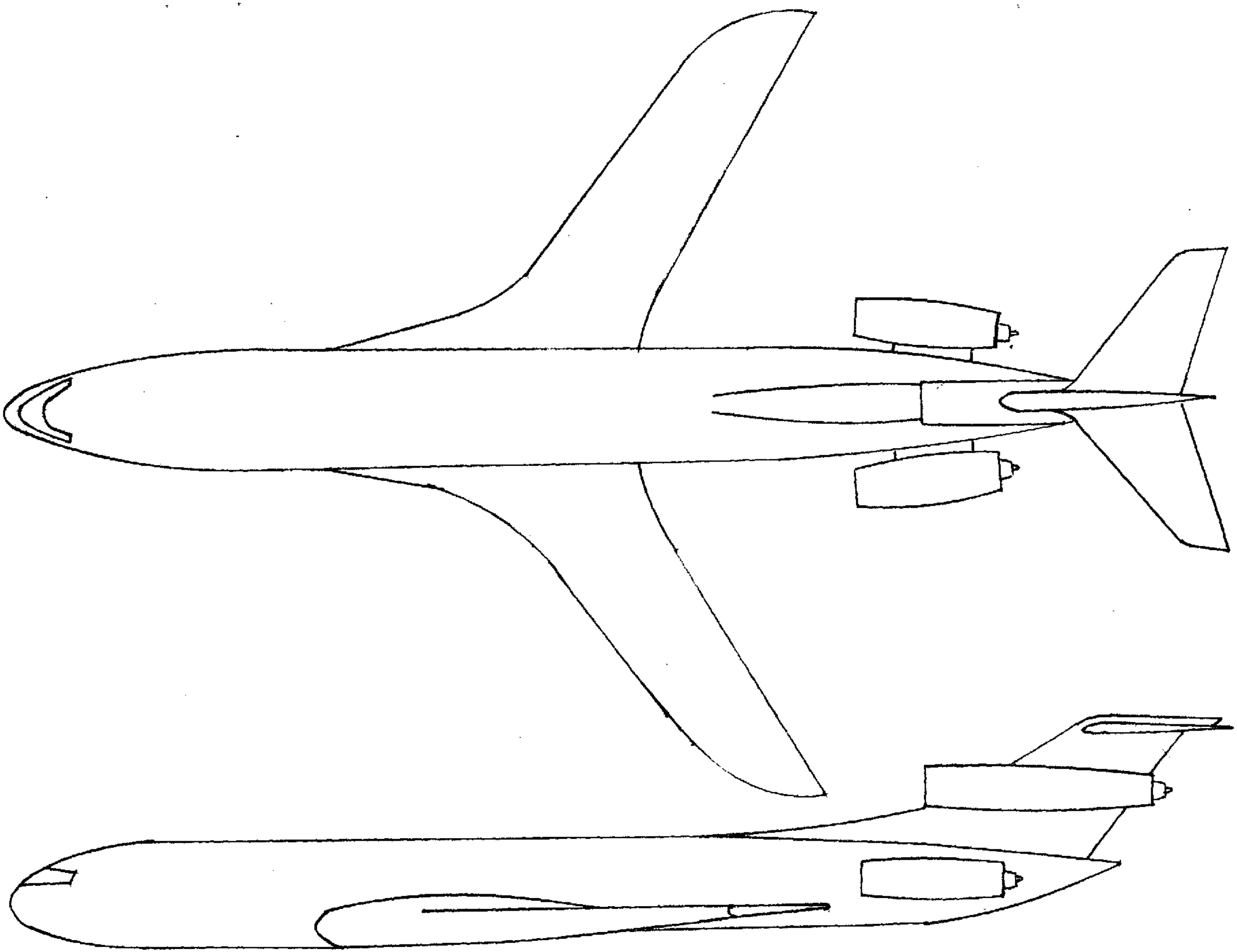


FIGURE 1. - SKETCH OF CONCEPTUAL ADVANCED MACH 0.85 TRI-JET AIRCRAFT

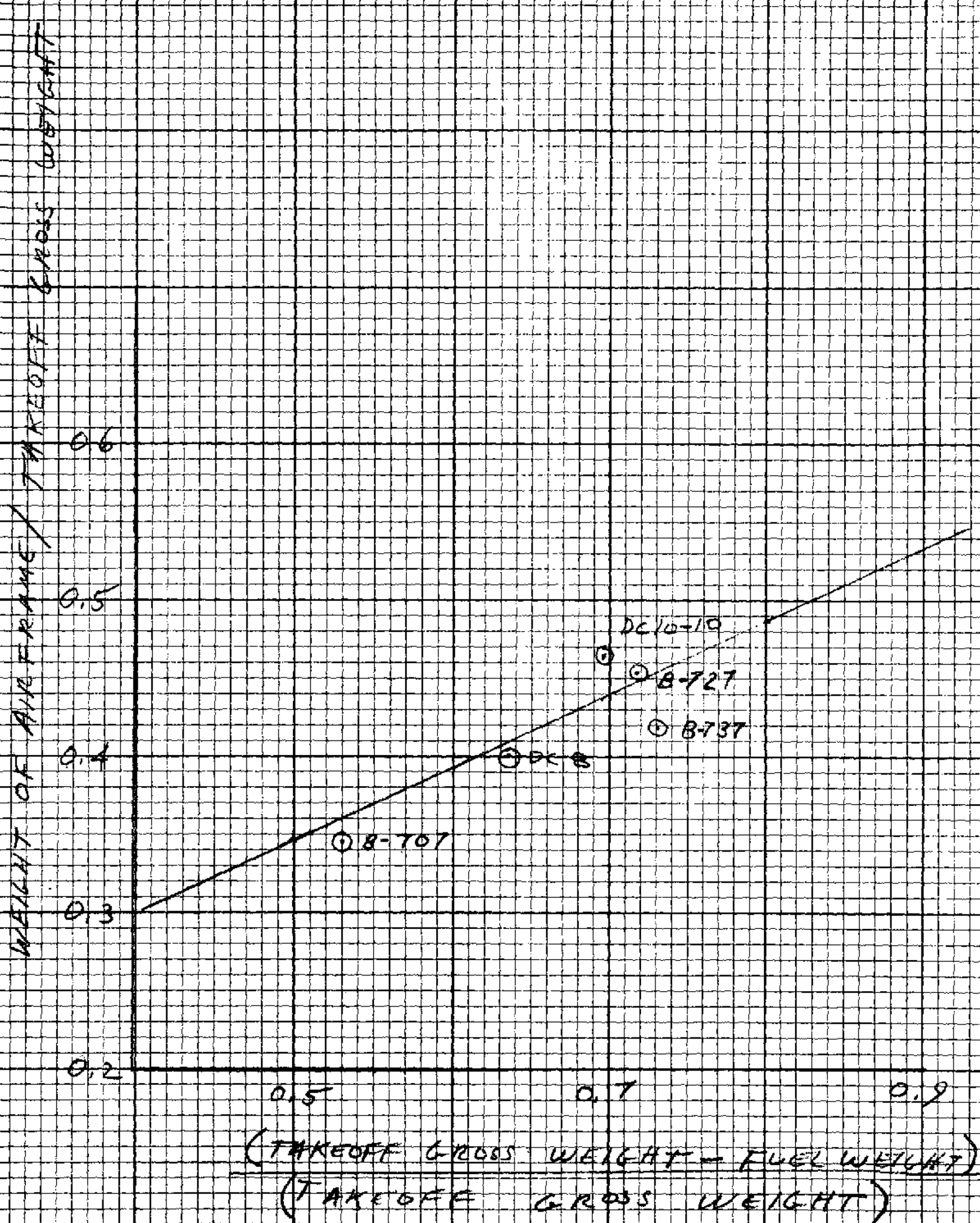



FIGURE 2 - RELATIONSHIP FOR DETERMINATION OF AIRFRAME WEIGHT

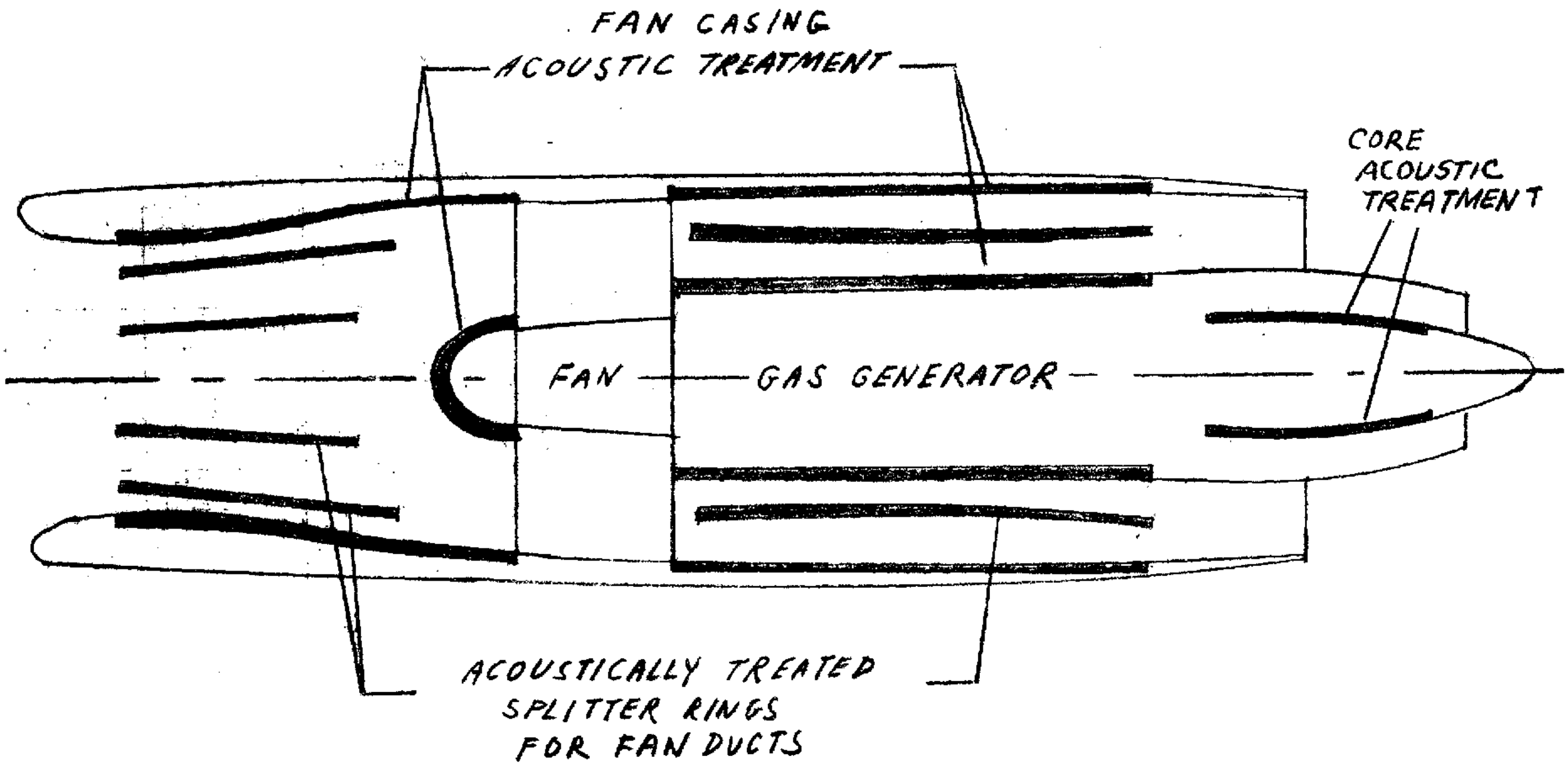



FIGURE 3 - SKETCH OF TURBOFAN ENGINE MODEL WITH ACOUSTIC TREATMENT

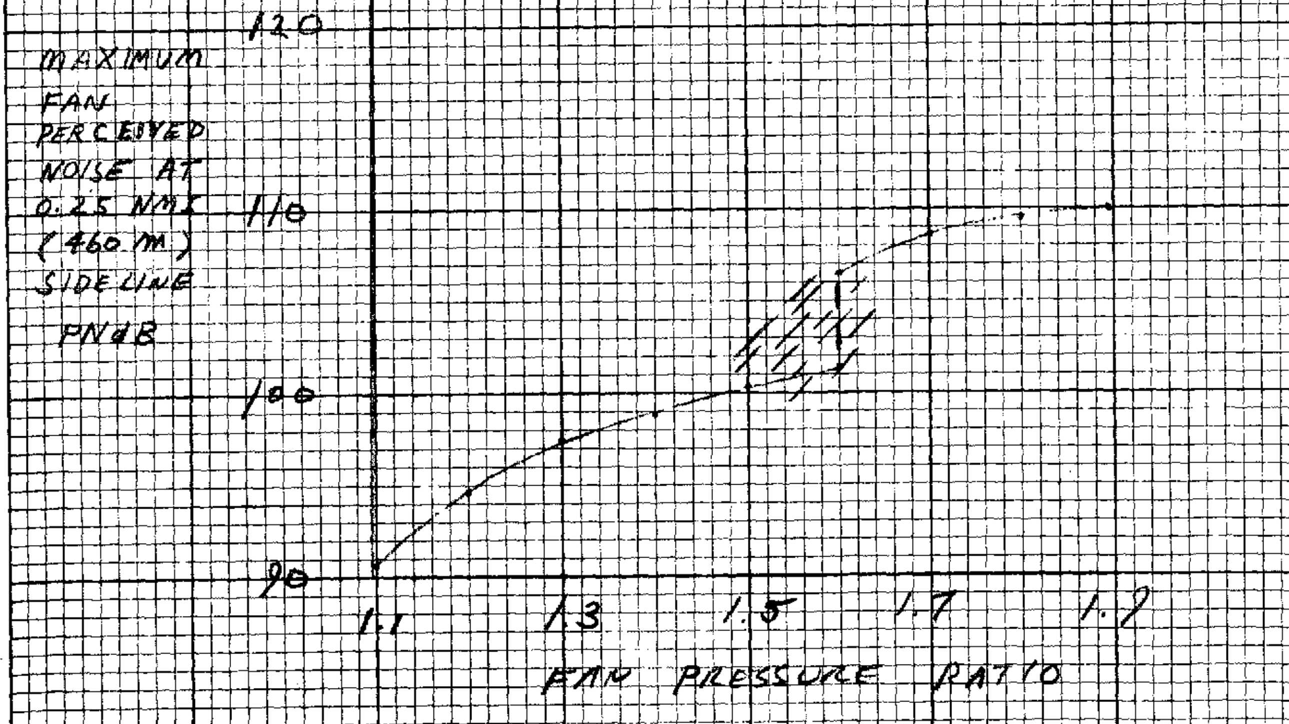



FIGURE 4 - PRESCRIBED VARIATION OF UNSUPPRESSED FAN MACHINERY NOISE WITH FAN PRESSURE RATIO FOR SINGLE STAGE FANS. MAXIMUM NOISE AT 460 m (1500 FT) SIDELINE. $FN_{SLS}$ = 50 70 97 N. (114 000 LB.)

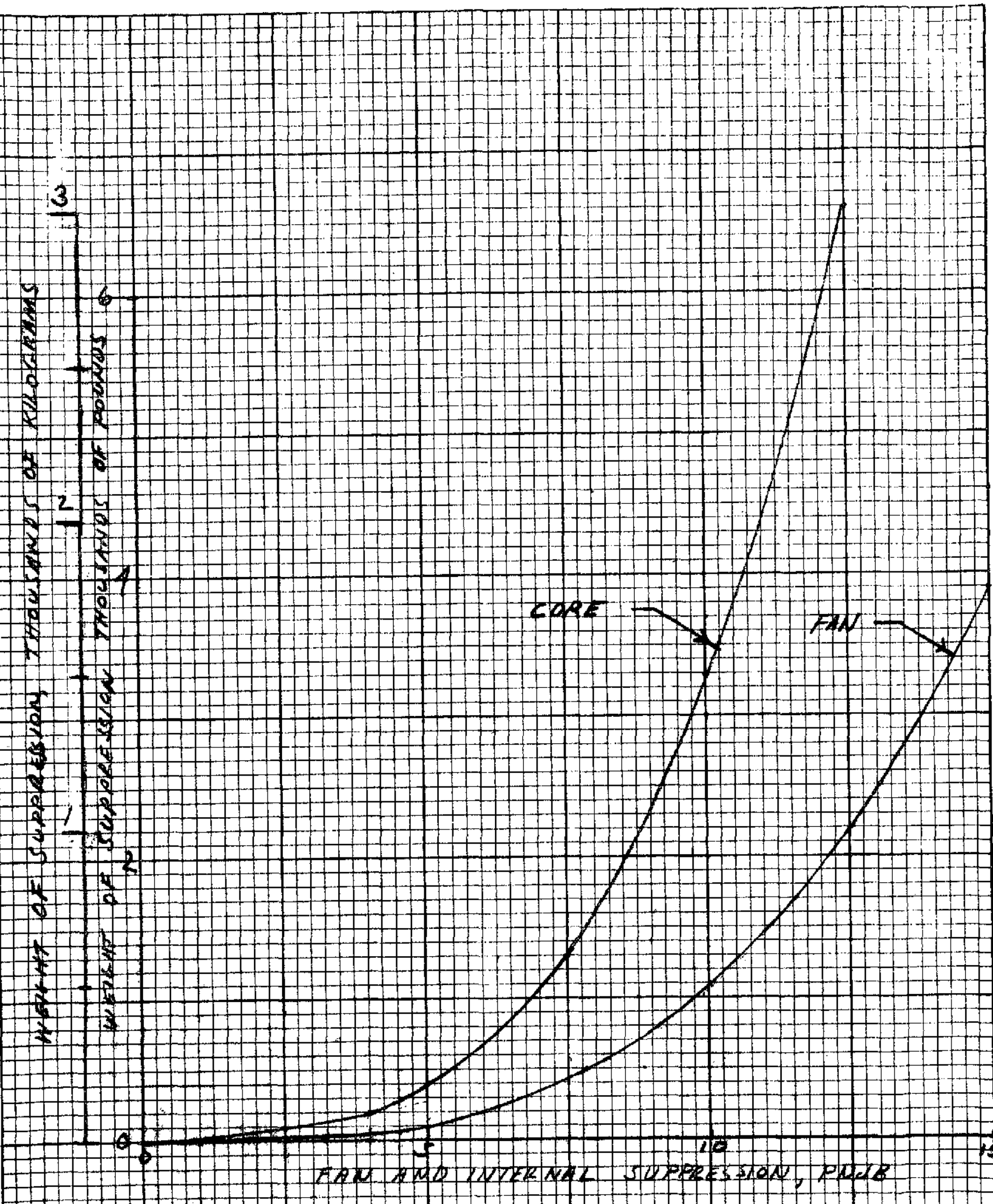



FIGURE 5 – WEIGHT OF FAN AND CORE SUPPRESSION AS A FUNCTION OF PNdB SUPPRESSION ASSUMING THAT EXTERNAL DIAMETER OF EACH FLOW PATH IS 2.032 METERS (80 INCHES). CORE MATERIAL DESIGNED FOR HIGH TEMPERATURES.

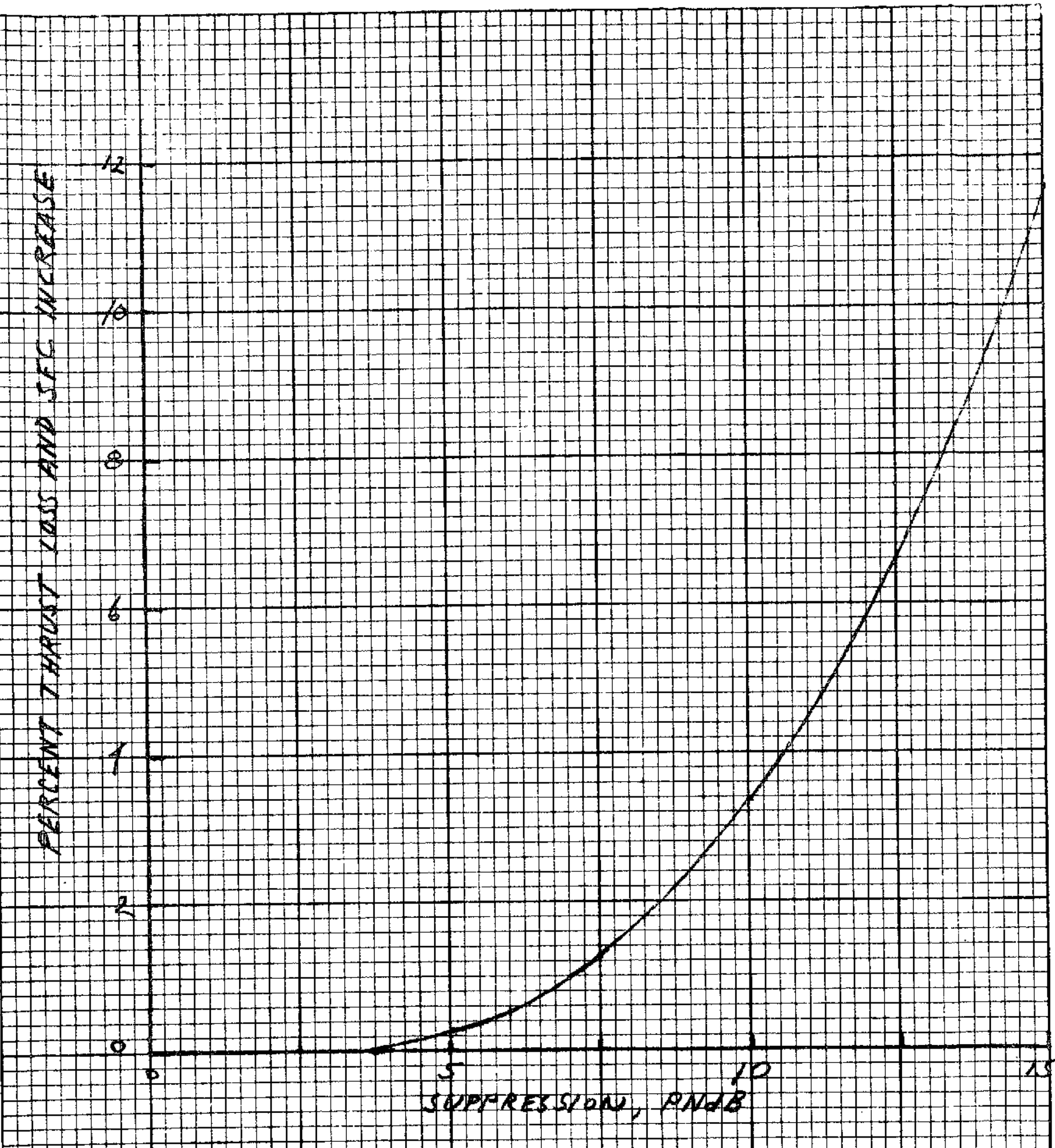



FIGURE 6 - THRUST AND SFC PENALTY AS A FUNCTION OF SUPPRESSION

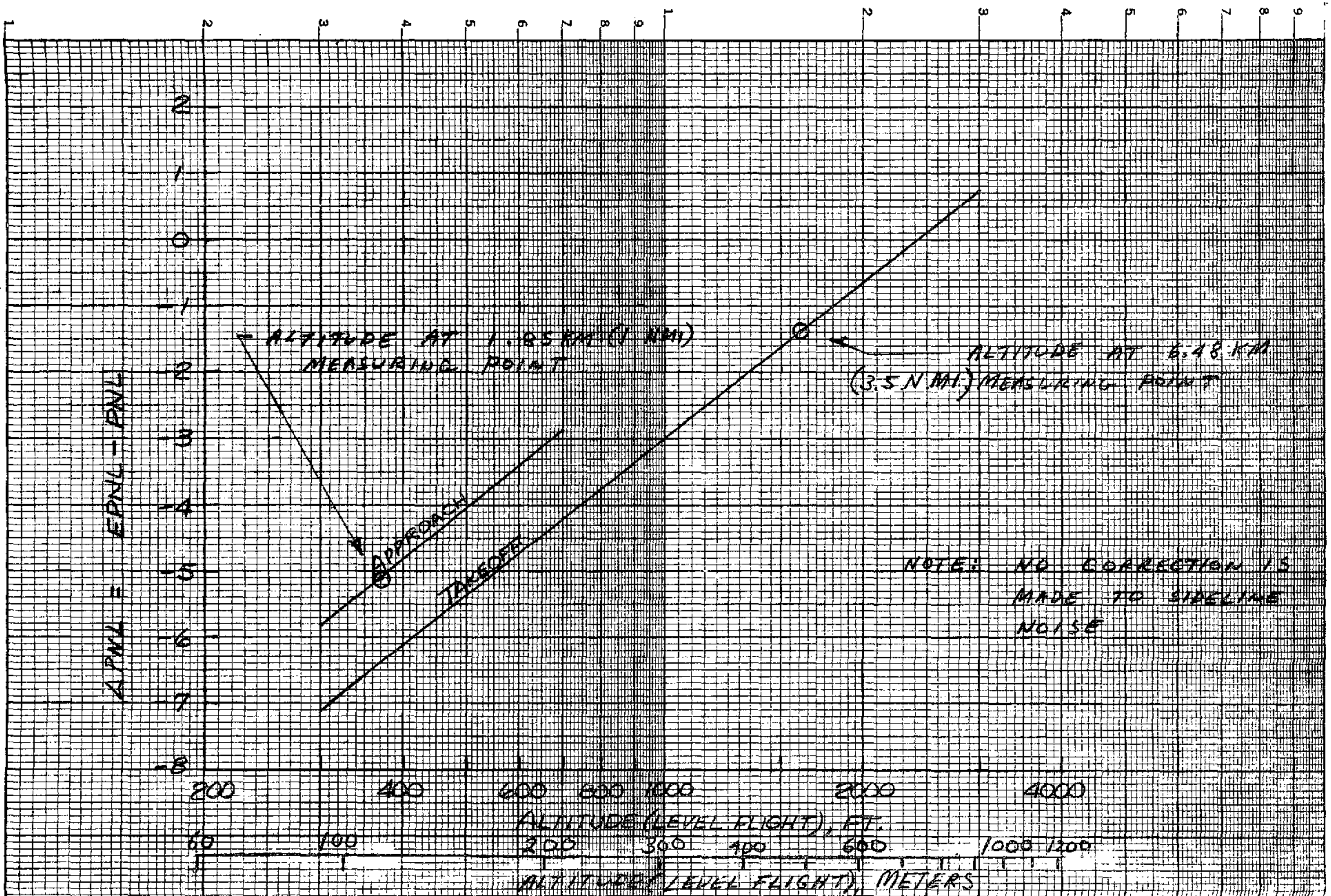



FIGURE 7 - APPROXIMATE CONVERSION FROM PNdB TO EPNdB

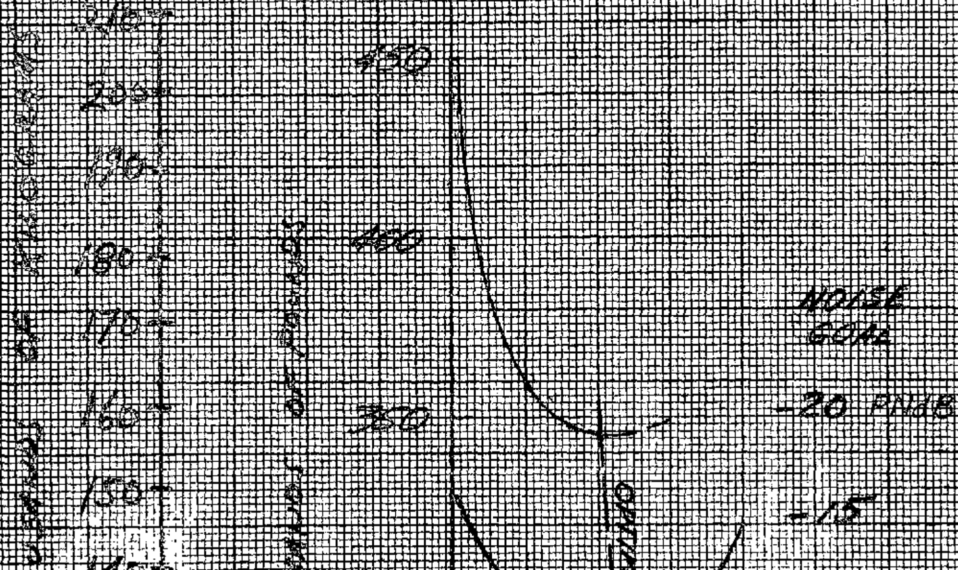



FIGURE 8. OPTIMUM TOGW VERSUS FPR cr FOR SEVERAL NOISE GOALS. FROM REF. 1. 200 PASSENGERS, 5556 KM (3000 N. MI.) RANGE, M = 0.85

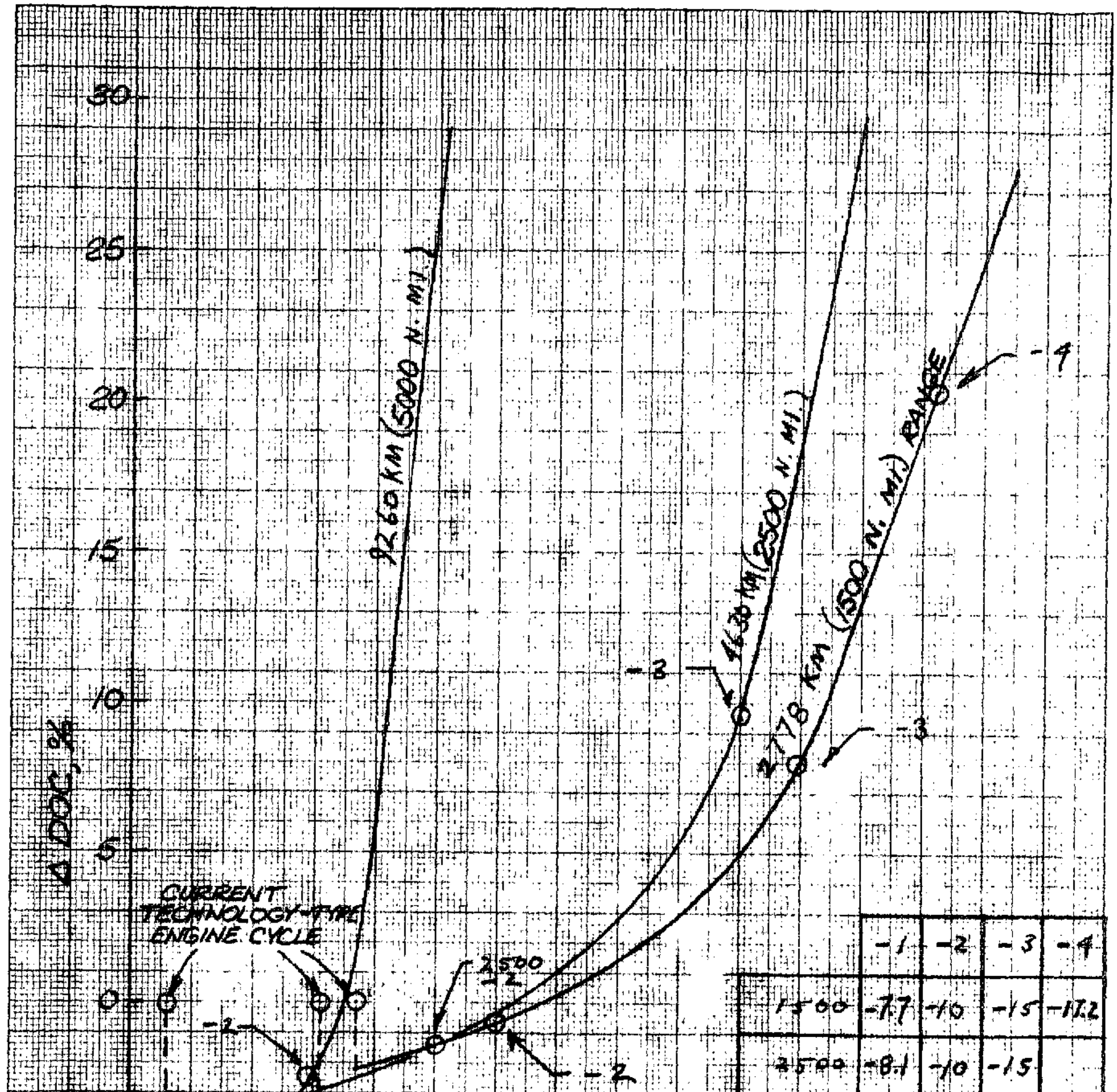



FIGURE 9 - DOC-NOISE TRADEOFF FOR 3-ENGINE CTOL
200 PASSENGERS, M=0.85

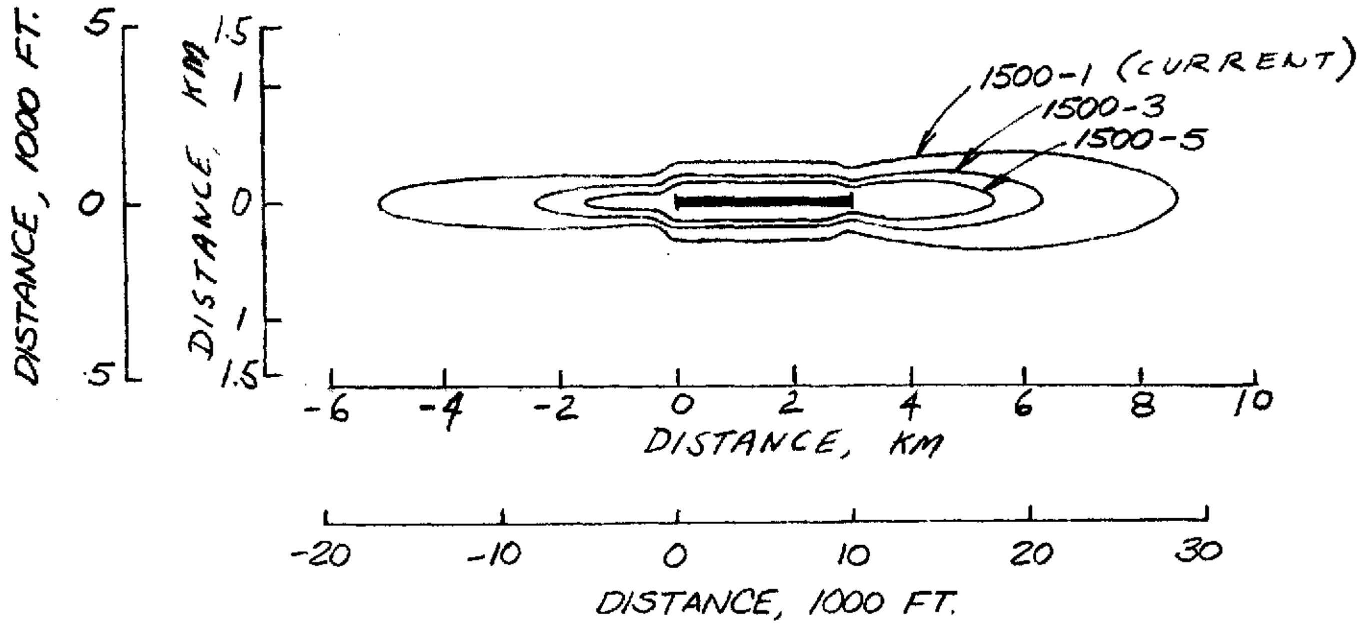



FIGURE 10a. – CONTOURS OF 90 EPNdB FOR 1500 N.MI. RANGE.

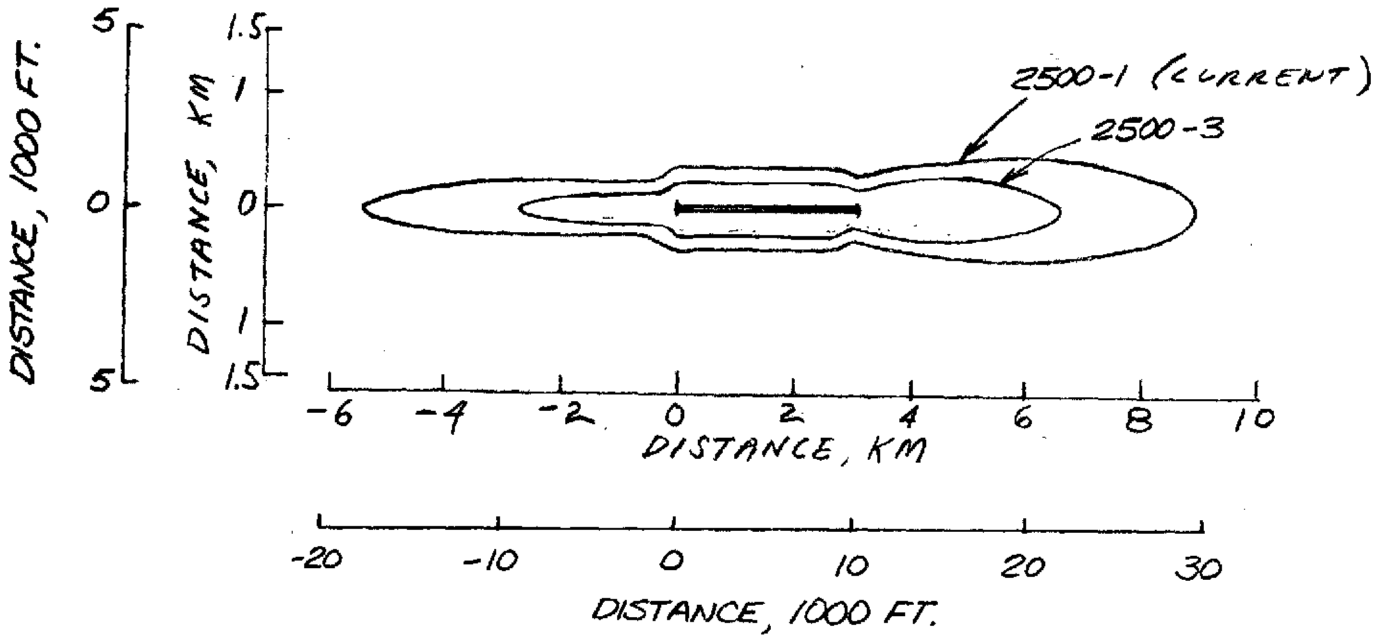



FIGURE 10 b. – CONTOURS OF 90 EPNdB FOR 2500 N.MI. RANGE.

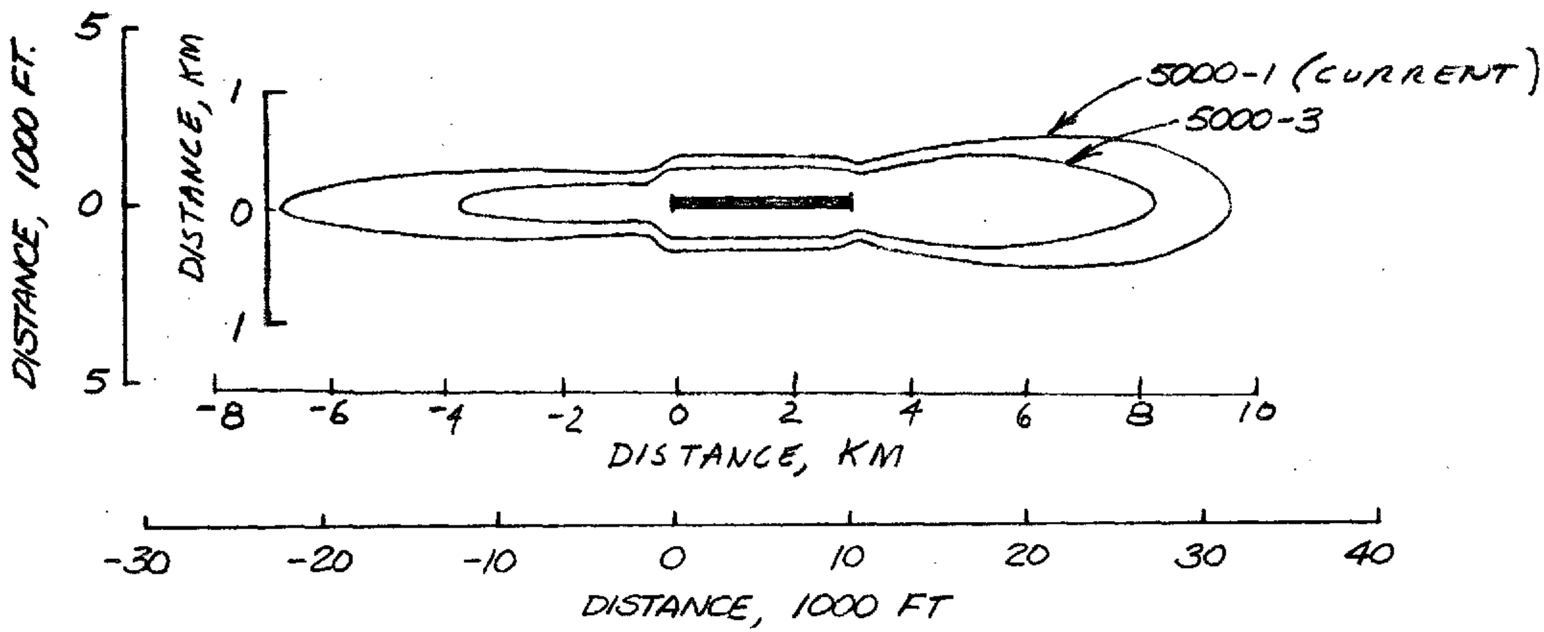



FIGURE 10c. – CONTOURS OF 90 EPNdB FOR 5000 N.MI. RANGE.

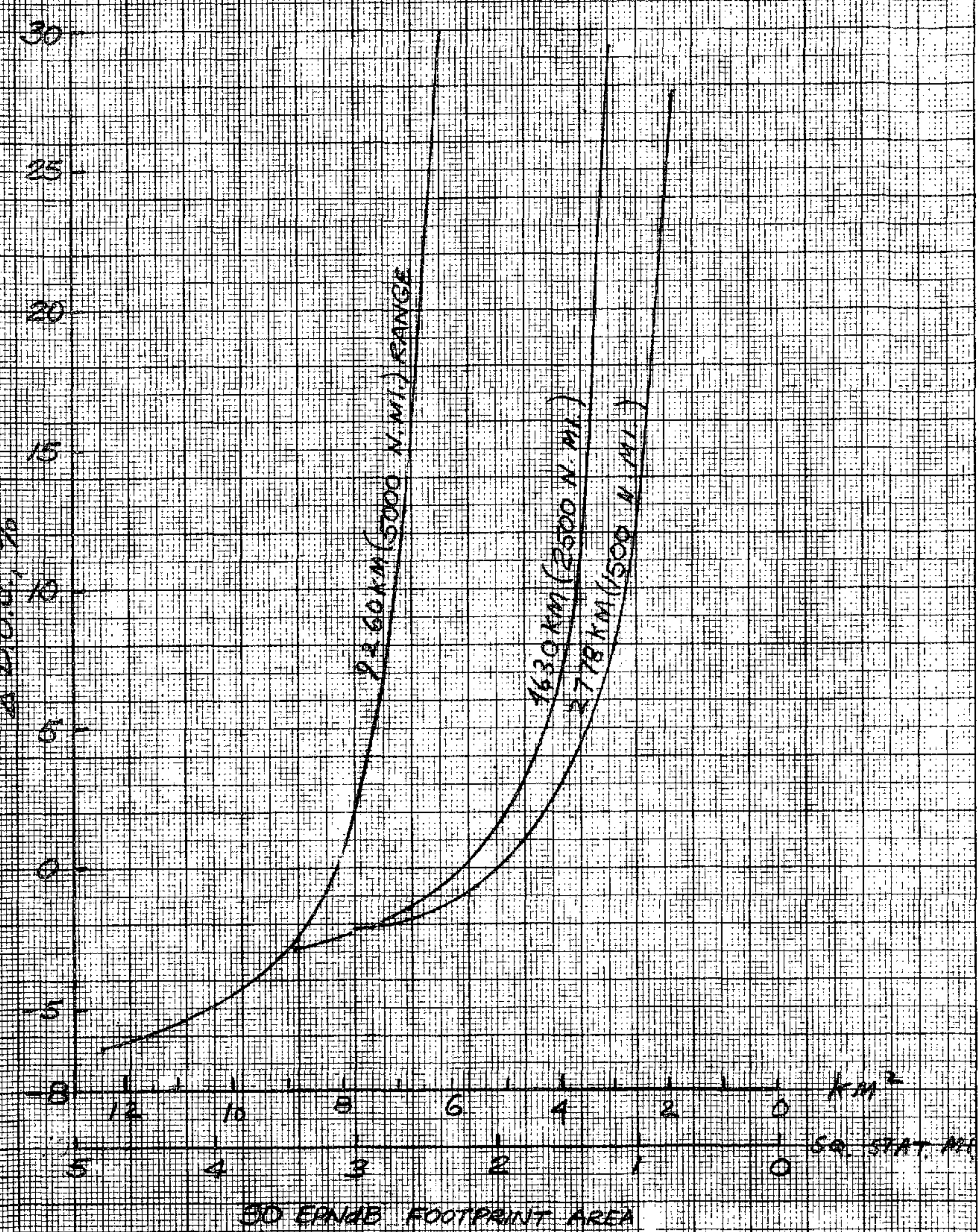



FIGURE 11 - VARIATION OF D.O.C. WITH FOOTPRINT AREA.

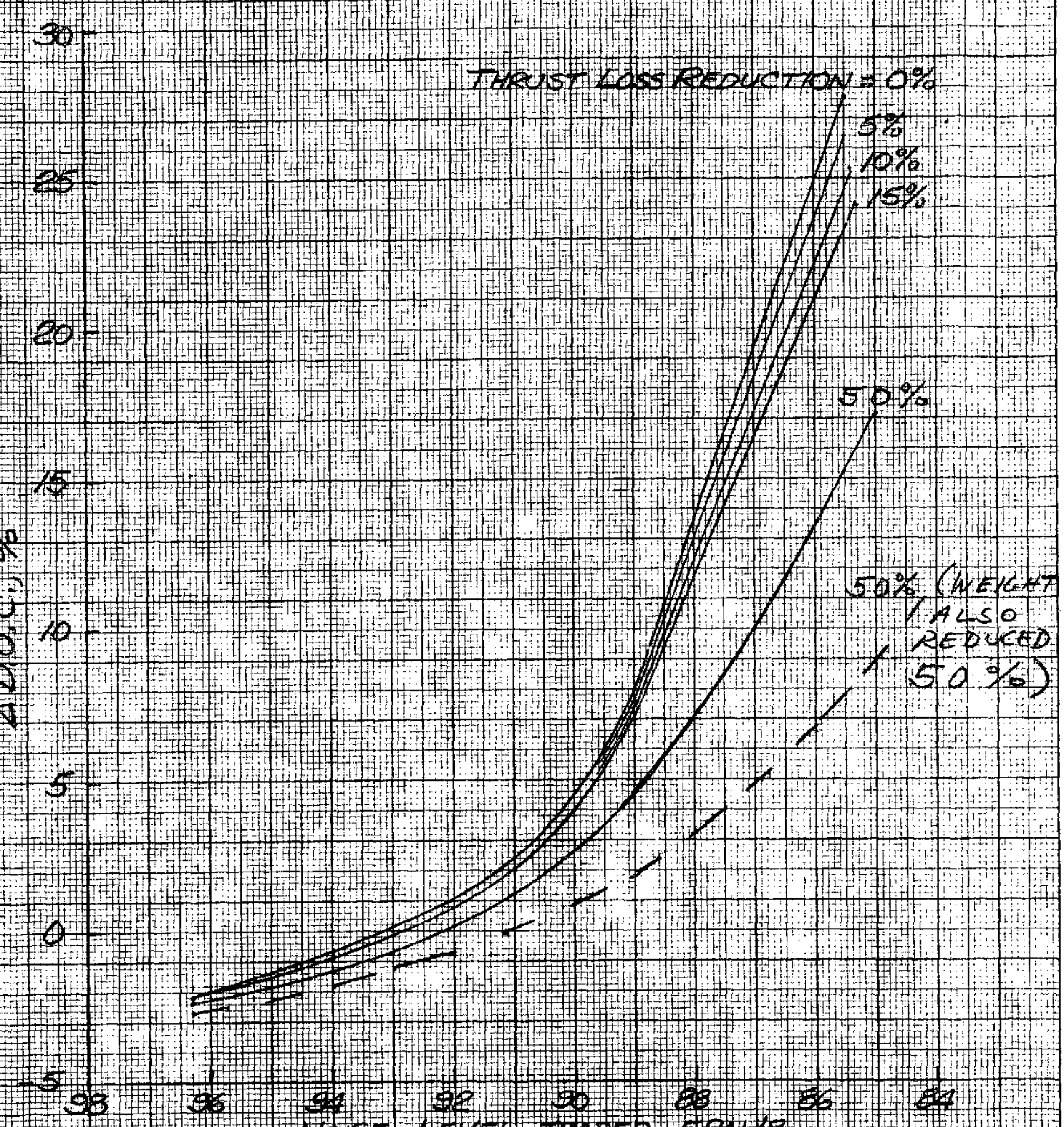



FIGURE 13 - EFFECT OF REDUCED THRUST LOSS ON D.O.C.
(2 778 KM RANGE) (1500 NMI RANGE)

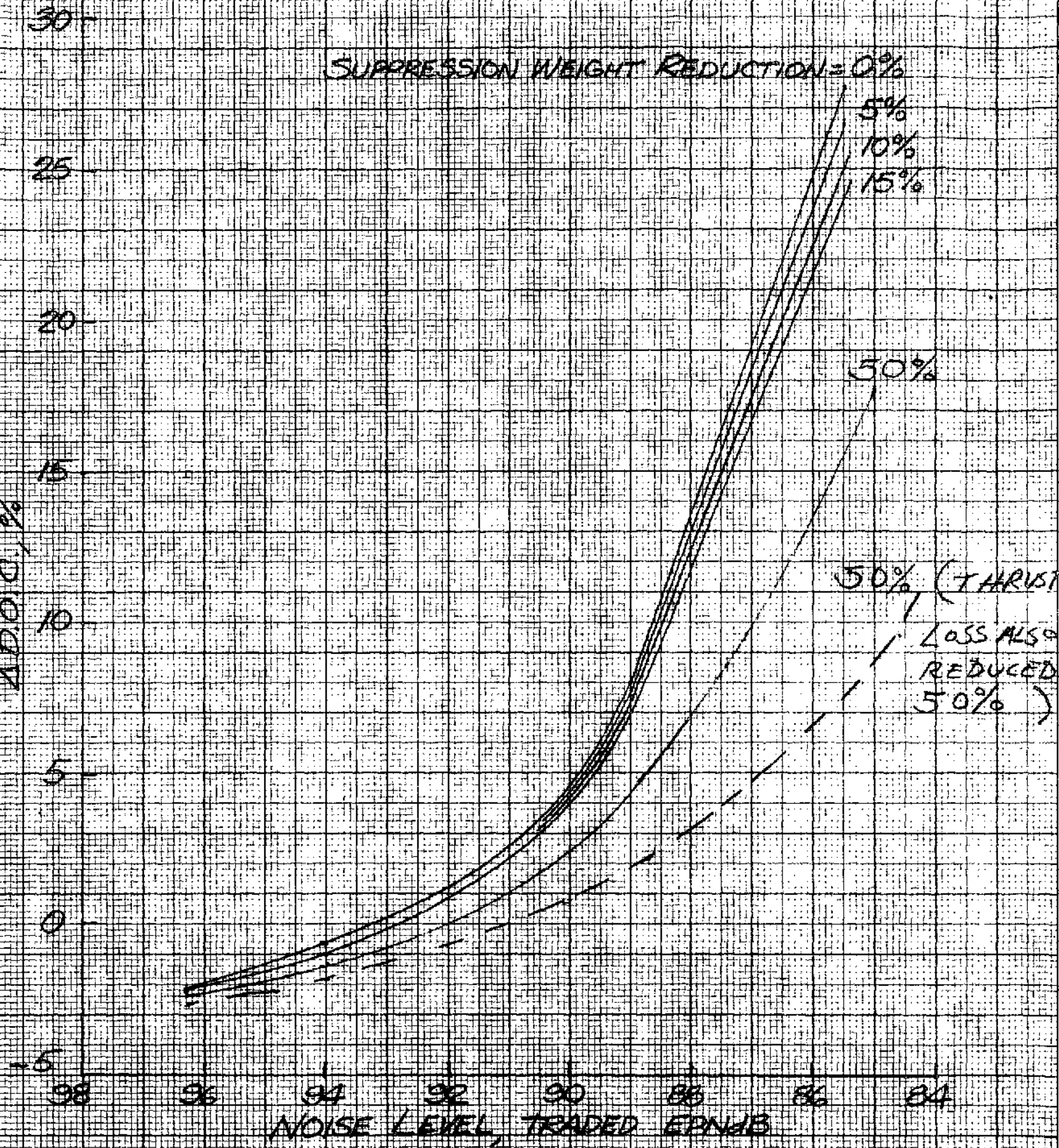



FIGURE 14 - EFFECT OF REDUCED SUPPRESSION WEIGHT ON D.O.C.
(2778 KM RANGE) (1500 N. MI. RANGE)

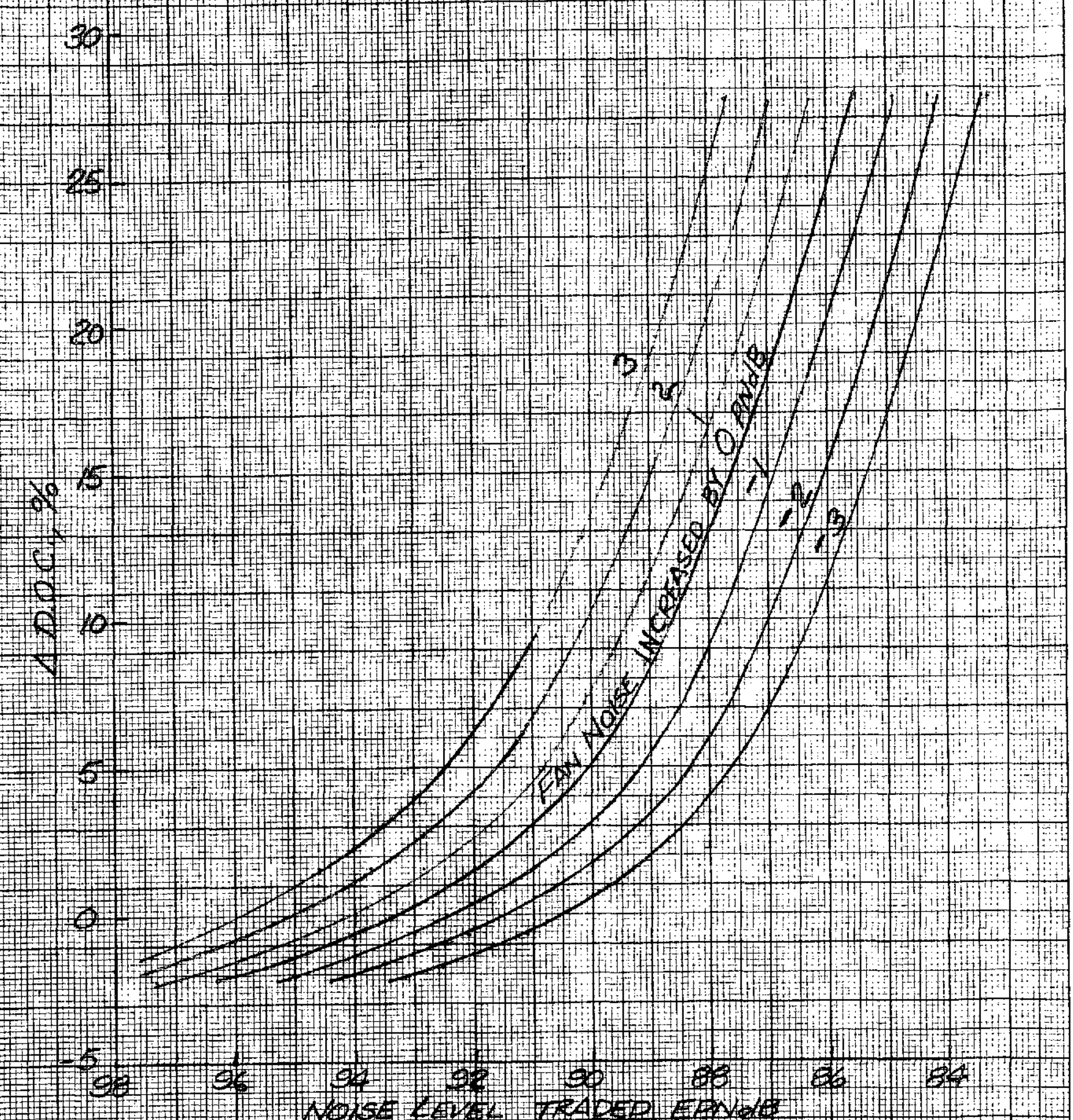



FIGURE 45 – EFFECT OF REDUCED FAN NOISE ON D.O.C.
(2778 KM RANGE) (1500 N.M.I. RANGE)

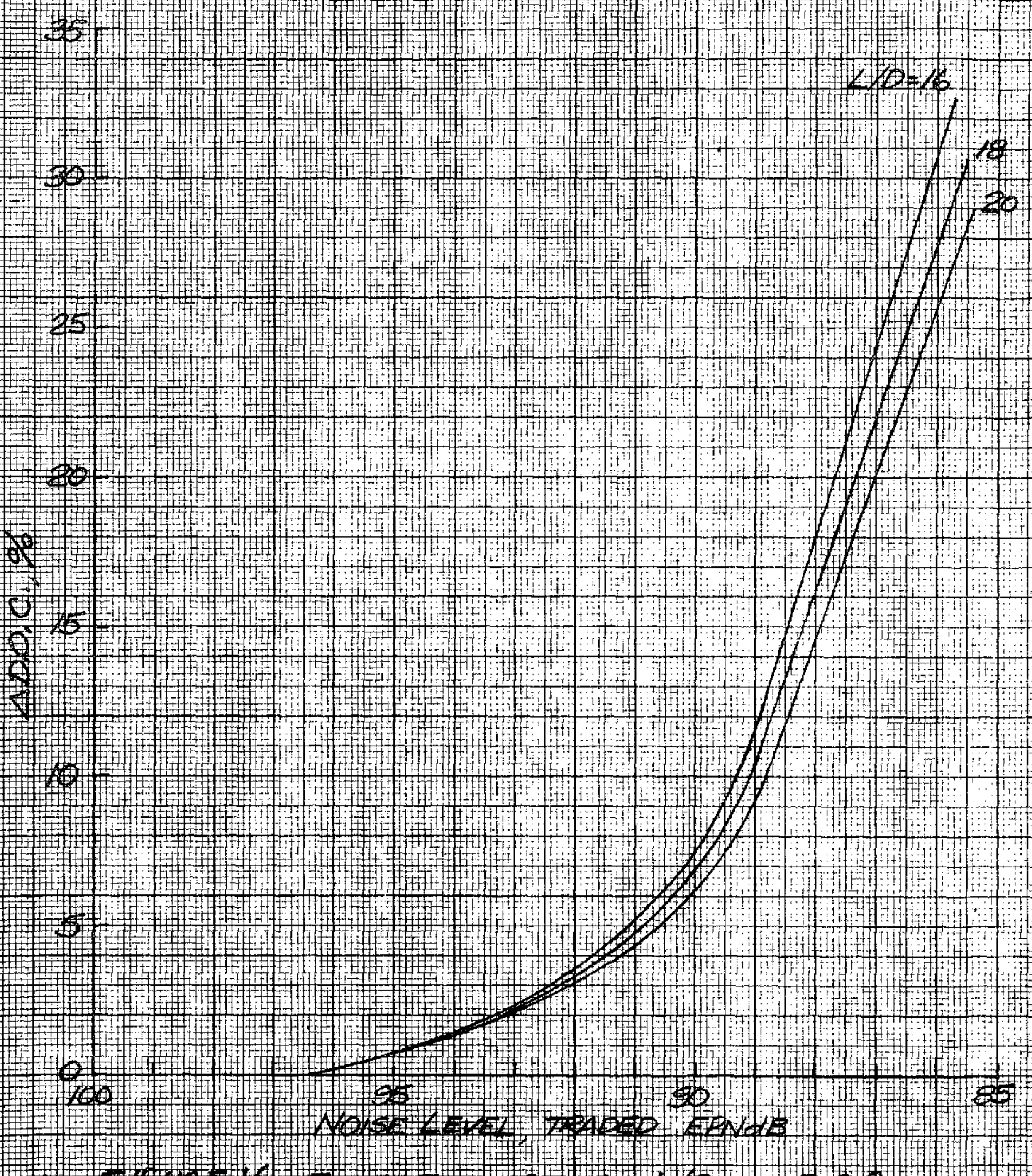
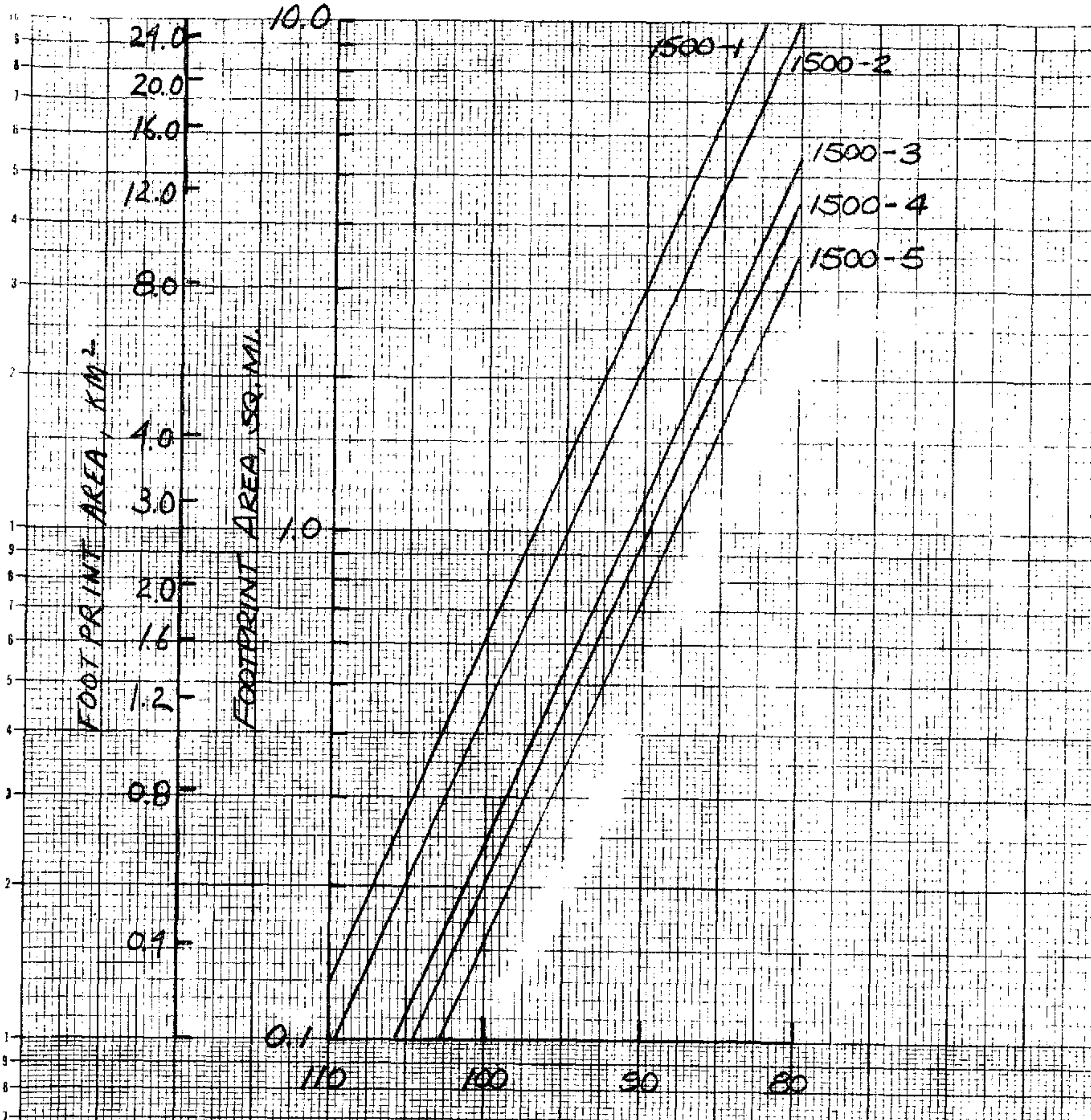
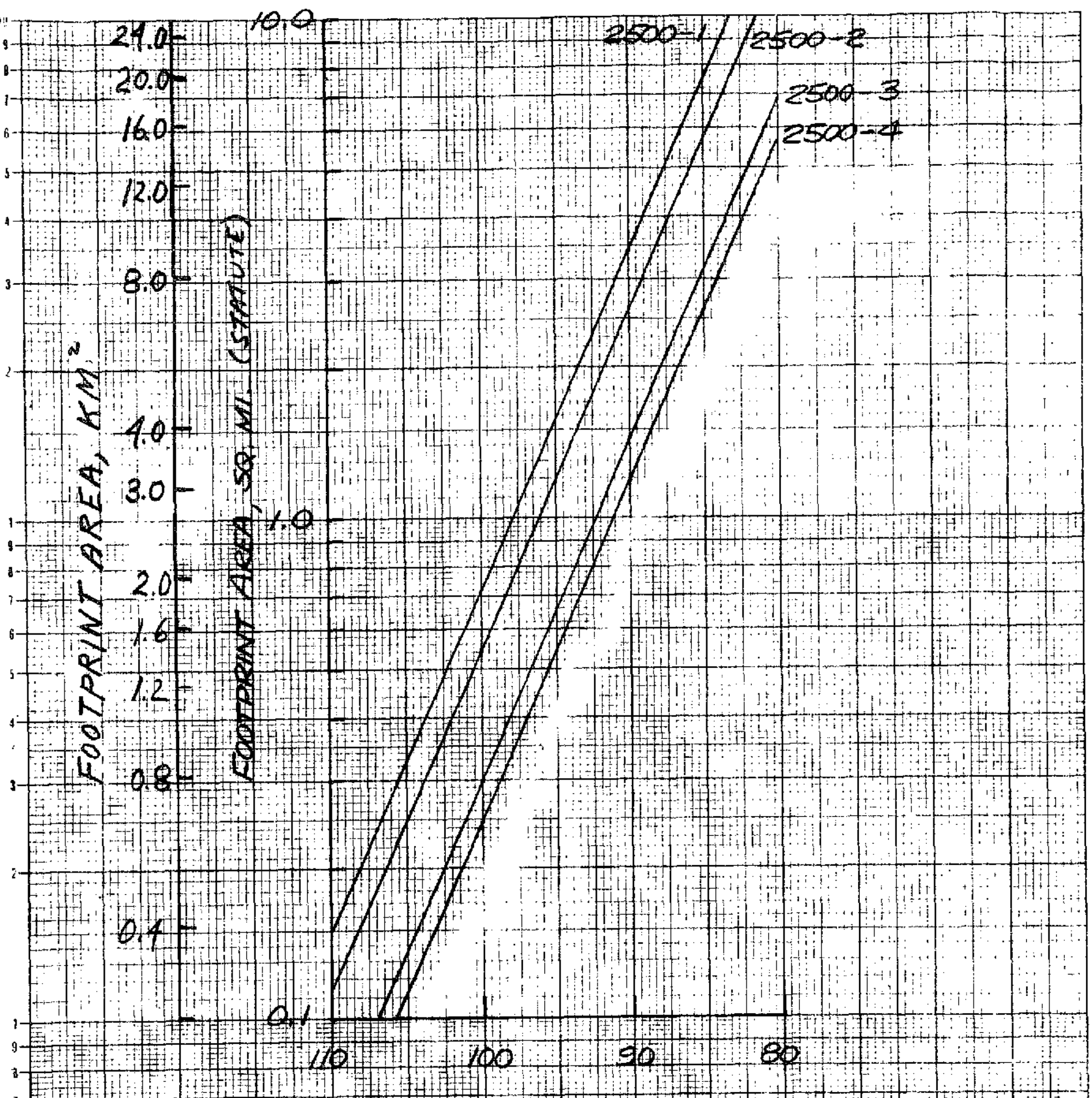



FIGURE 16 - EFFECT OF CRUISE L/D ON D.O.C.
(2778 KM RANGE) (1500 N. MI. RANGE)



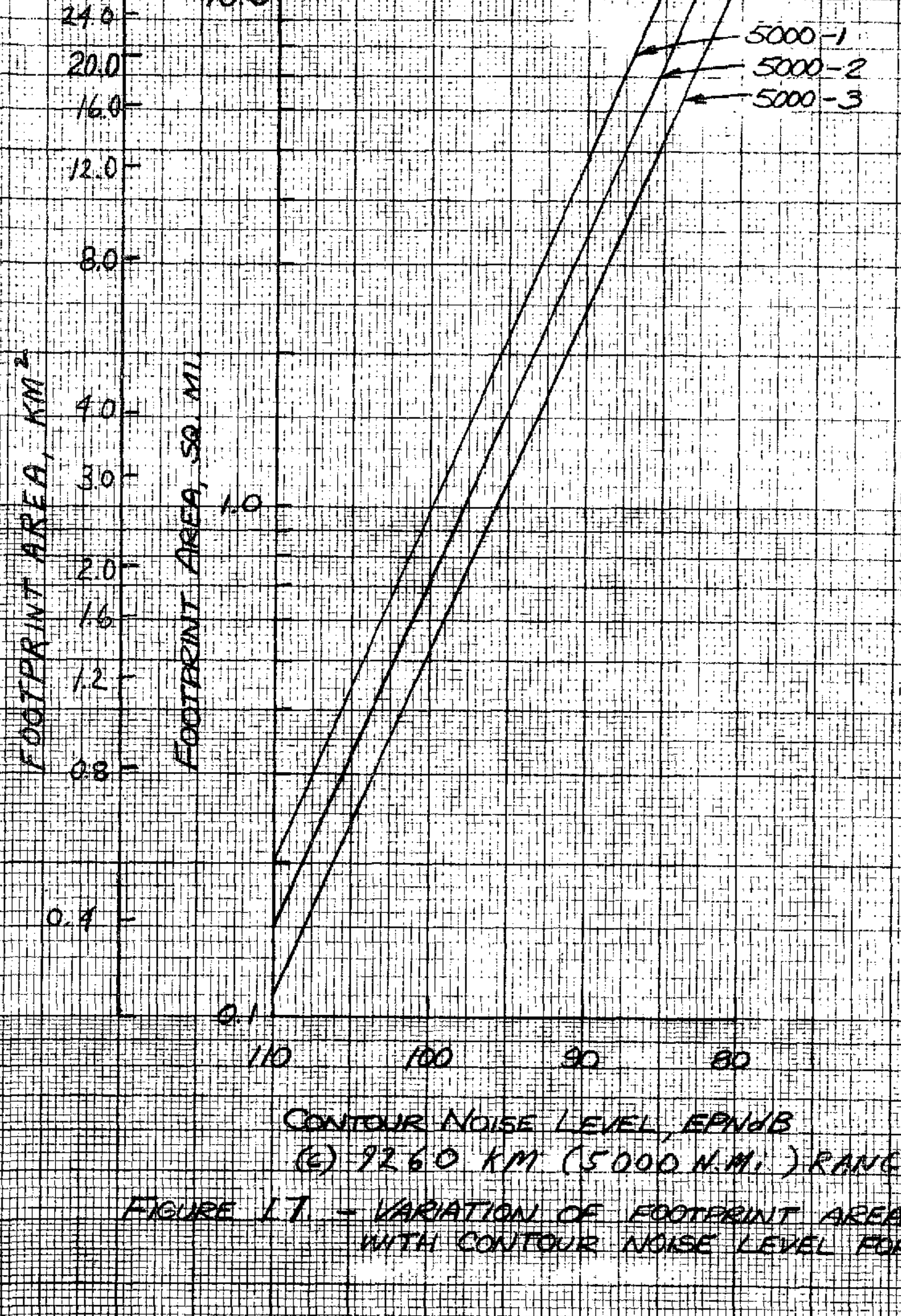

(a) 2778 KM (1500 N.MI.) RANGE

FIGURE 17. - VARIATION OF FOOTPRINT AREA WITH CONTOUR NOISE LEVEL FOR




(b) 4230 KM (2500 N.MI.) RANGE

FIGURE 1.7 – VARIATION OF FOOTPRINT AREA WITH CONTOUR NOISE LEVEL FOR




(c) 9260 KM (5000 N.MI.) RANGE

FIGURE 17 - VARIATION OF FOOTPRINT AREA
WITH CONTOUR NOISE LEVEL FOR