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PRELIMINARY STUDY OF ADVANCED TURBOFANS FOR LOW ENERGY CONSUMPTION

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ABSTRACT

This analysis determines the effect of higher overall engine pressure ratios (OPR's), bypass ratios (BPR's), and turbine rotor-inlet temperature on a Mach-0.85 transport having a range of 5556 km (3000 nmi) and carrying a payload of 18144 kg (40 000 lbs-200 passengers). Sideline noises (jet plus fan) of between 91 and 106 EPNdB (FAR36) are considered. Takeoff gross weight (TOGW), fuel consumption (kg/pass. km) and direct operating cost (DOC) are used as the figures of merit. Based on predicted 1985 levels of engine technology and a noise goal of 96 EPNdB, the higher-OPR engine results in an airplane that is 18 percent lighter in terms of TOGW, uses 22.3 percent less fuel, and has a 14.7 percent lower DOC than a comparable airplane powered by a current turbofan. Cooling the compressor bleed air and lowering the cruise Mach number appear attractive in terms of further improving the figures of merit.

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SUMMARY

The present analysis determines the effect of higher overall engine pressure ratios (OPR's), bypass ratios (BPR's) and turbine rotor-inlet temperatures on a Mach-0.85 transport having a range of 5556 km (3000 nmi) and carrying a payload of 18144 kg (40 000 lb-200 passengers). OPR's of 30, 35, and 40 are considered. For each OPR, three fan pressure ratios (FPR's) 1.5, 1.6, and 1.7 are studied. Turbine rotor-inlet temperatures as high as 1922 K (3460° R) are considered. Sideline noises (jet plus fan) of between 91 and 106 EPNdB (FAR 36) are investigated. To achieve the lower noise, a maximum of 20 PNdB of turbomachinery noise suppression is assumed. Takeoff gross weight (TOGW), fuel consumption (kg/pass. km), and direct operating cost (DOC) are used as the figures of merit. The results are compared with those achieved with a comparable airplane powered by current turbofans. The sensitivity of the figures of merit to predicted **1985 levels of engine technology is determined.** The effects of cooling the compressor bleed air (for turbine cooling), and reducing the cruise Mach number on the various figures of merit are determined.

Compared with a current separate-flow turbofan (FPR_{cr} = 1.69, OPR_{cr} = 28, BPR_{cr} = 6, T_{4SL} = 1489 K (2680° R)), a higher OPR engine (FPR_{cr} = 1.6, OPR_{cr} = 40, BPR_{cr} = 10.4, T_{4SL} = 1783 K (3210° R) using a more advanced turbine cooling scheme (full-coverage film) results in a 6 percent reduction in cruise SFC. This is the optimum engine for a noise goal of 96 EPNdB. Based on predicted 1985 technology, this engine results in an airplane that is 18 percent lighter in terms of TOGW, uses 22.3 percent less fuel, and has a 14.7 percent lower DOC. Cooling the compressor bleed flow results in a 3 percent reduction in cruise SFC. Reducing the cruise Mach number from 0.85 to about 0.78 appears attractive in terms of reduced TOGW and fuel consumption.

INTRODUCTION

Because of present and future shortages of fossil fuels, the oil-dependent industries must work at reducing their present rate of consumption. Only in this way can we conserve the world supply of crude oil. To this end studies are now being conducted in the aviation industry and by government agencies to reduce the fuel consumption of the turbofan engine. This engine powers most of today's commercial transports.

The development of the turbofan engine over the past 10 years is indicated in figure 1 (ref. 1). During this time period engine specific fuel consumption (SFC) has been reduced by 25 percent (fig. 1(a)). This decrease in SFC resulted mostly from advances in compressor blade loading, air-cooled turbine technology, and improved materials to name a few. These advances in technology permitted the sea-level turbine temperature (T_{4SL}) to be increased from 1200 K (1700°F) to 1622 K (2460° F) (fig. 1(b)). During this same period engine overall pressure ratio (OPR) has increased from 15 to 30 (fig. 1(c)). Engine bypass ratio (BPR) has increased from approximately 1.0 (fig. 1(d)) in 1964 to about 6 in 1974. These trends are likely to continue.

Reference 2 indicates that an additional 15 percent improvement in cruise SFC may be possible by designing the turbofan to operate at still higher BPR's, OPR's, and T_4's. Other approaches being considered to conserve fuel include variable-area turbines, variable-area nozzles, and cycle modifications such as intercooling and regeneration.

The present study considers the effect of higher BPR's, OPR's, and T_4's on the performance of a separate-flow-turbofan in terms of vehicle takeoff gross weight (TOGW), fuel used per passenger km (nmi) and direct operating cost (DOC). Airplane range was fixed at 5556 km (3000 nmi) for a payload of 18144 kg (40 000 lb) (200 passengers). The vehicle cruises at Mach-0.85 at an initial altitude of 12.19 km (40 000 ft). BPR's as high as 13, OPR's as high as 40, and T_4's as high as 1922 K (3460°R) are considered. The results are compared with those obtained with current engines based on 1973 engine technology. Noise goals as low as FAR36-15 (91 EPNdB) are considered using a maximum of 20 PNdB of turbomachinery suppression. The sensitivity of airplane TOGW, fuel used per passenger km (nmi) and DOC to cruise Mach number and predicted 1985 engine technology is determined.

ANALYSIS

The vehicle used in the present study is a three-engine, turbofan-powered airplane (fig. 2) having a range of 5556 km (3000 nmi) and a payload of 18144 kg (40 000 lb) (200 passengers). It cruises at Mach-0.85 at an initial altitude of 12192 m (40 000 ft). Noise goals of between FAR36 (106 EPNdB) and FAR36-15 are considered. TOGW, fuel used per passenger km (nmi) and DOC are used as the figures of merit.

Reference TOGW and Airframe Weight

The ground rules used in this study pertaining to the airframe with which to match the various parametric engines are the same as those used in references 3 and 4 for the Advanced Technology Transport (ATT) using a supercritical wing and an aluminum structure. The variation in airframe weight with TOGW is shown in figure 3. Total range is calculated by the following equation.

$$R = 648.2 + \frac{(L/D)_{cr} M_{cr} C_s}{SFC} \ln \frac{W_{start\ cr}}{W_{end\ cr}}, \text{ km}$$

$$R = 350 + \frac{(L/D)_{cr} M_{cr} C_s}{SFC} \ln \frac{W_{start\ cr}}{W_{end\ cr}}, \text{ nmi}$$

The 648.2 km (350 nmi) term represents the climb range (370.4 km - 200 nmi) plus the letdown range (277.8 km - 150 nmi). Other terms on the right side of the equation represent the range for a Brequet cruise.

Fuel for climb and letdown was estimated by the following equations.

$$\text{Fuel climb} = \frac{TOGW}{175086} \times 9072, \text{ kg}$$

$$(\text{Fuel climb} = \frac{TOGW}{386000} \times 20\ 000, \text{ lbs})$$

$$\text{Fuel letdown} = \frac{TOGW}{175086} \times 907.2, \text{ kg}$$

$$(\text{Fuel letdown} = \frac{TOGW}{386000} \times 2000, \text{ lbs})$$

These values are again based on reference 3 for an airplane having a TOGW of 175086 kg (386 000 lb). The 9072 (20 000) and 907.2 kg (2000 lbs) represent the fuel assumed for climb and letdown of that airplane. The reserve fuel is assumed to be 18 percent of the total fuel load. The payload consists of 200 passengers or 18144 kg (40 000 lb).

Engines

The figures of merit (TOGW, fuel used per passenger km (nmi), and DOC) used in this study are influenced not only by engine cycle parameters (OPR, BPR, and T_4), but also engine weight and component efficiencies. These last two technologies are being advanced continually. For the present study which considers the effect of higher

BPR's, OPR's, and T_4's on the performance of a separate flow-turbofan, current-technology levels of engine weight and component efficiencies are used. However, the effects of engine weight and component efficiencies on the figures of merit are also determined for the optimum engine based on predicted 1985 levels of technology.

Diameter and weight.- Engine diameter and base engine weight are calculated by the procedure of reference 5. Included in the weight of the base engine are the effects of BPR, OPR, and T_4. This procedure results in an uninstalled thrust-weight ratio of 6.3 (when the year is input as 1973 in ref. 5) versus 6 for a current high BRR engine now in service.

In addition to the weight of the base engine, each engine is assumed to have an installation weight of 1.42 kg/sec (3.13 lb/sec) times the corrected total airflow at takeoff. This weight is based on empirical data for existing high BPR engines used in wide-body commercial transports. The 1985 goal in terms of engine weight is a 20 percent improvement in installed engine weight. This was accomplished in the present study by substituting the year 1985 into the equations of reference 5 and using the same installation factor.

Suppression.- Acoustic lining and splitters were assumed for the inlet and duct walls to reduce the fan machinery noise. Different amounts of treatment are required to achieve different amounts of suppression. A sketch of a high BPR, separate-flow turbofan engine with acoustical treatment is shown in figure 4. A maximum of 20 PNdB of suppression is assumed for the present study. The actual suppression configuration varied from linings only for 5 PNdB of suppression to linings plus three inlet and two duct splitter rings for 20 PNdB. Performance losses and weight penalties associated with various amounts of suppression are indicated in figure 5. The dashed curves represent current estimates by General Electric and the VTOL and Noise Division at the Lewis Research Center. The solid curves are from reference 3 and are based on initial ATT study results. Since fan noise (discussed later) is of the order of 106 EPNdB (FAR36), then approximately 15 PNdB of suppression would be required to achieve FAR36-15. At these noise levels, the penalties associated with the dashed data would probably be prohibitive. Therefore, for the present study, the more optimistic data of reference 3 is used. Front-end noise may be better handled by means of a sonic inlet. Based on reference 6, 20 PNdB of suppression may be achieved by this means. However, a sonic inlet will not reduce noise generated from the rear of the engine. The suppression weight penalty was scaled with engine diameter for other size engines.

Performance and sizing.- Engine performance calculations were made for each of the two-spool, separate-flow turbofan engines considered in the study. For each of the three overall pressure ratios evaluated (30, 35, 40), three fan pressure ratios (1.5, 1.6, 1.7) were considered. As in reference 3, single-stage fans were assumed. The study considers bypass ratios as high as 13. The engines were operated off-design at takeoff with T_4 equal to 1784 K (3210° R) and sized for a $(F/WG)_{SLS}$ of 0.319. The temperature required at cruise (for T = D) was always found to be at least 150° less than T_4 at takeoff, which is desirable for engine durability. A range of cruise or design turbine rotor-inlet temperatures of from 1422 K (2560° R) to 1922 K (3460° R) was investigated to assure that cruise SFC was not penalized by this sizing process. The value of $(F/WG)_{SLS}$ is based on the thrust lapse data and the schedule of S.L.S. thrust-TOGW ratios presented in reference 3 for high bypass ratio engines.

The design fan and compressor efficiencies used in the study are shown in figures 6(a) and (b), respectively. Also indicated are efficiencies for a current high bypass ratio turbofan. Other design parameters are listed in table I. Based on reference 7, current annular combustors have efficiencies near 100 percent and pressure losses of 4 percent. The turbine efficiencies are based on reference 8 for current cruise engines. An inlet pressure recovery of 0.98 is used in the study. Since completing the study the author has learned that current recoveries for the wide-body jets are approaching 1.0. However, this will not affect the relative comparisons presented in this study between the current and advanced turbofans. The other design point parameters are representative of current cruise engines.

All off-design performance was calculated with a component matching computer program called GENENG (ref. 9). This program uses component maps in the matching procedure. In matching the components, the nozzle exhaust areas remain fixed at the design point. No customer bleeds or horsepower extraction was considered.

Cooling.- Turbine cooling requirements are based on the procedure given in reference 4 using full-coverage film cooling. A brief outline of the procedure is given here. To determine the total cooling requirements, the number of turbine stages must be known. For the present study, the high-pressure turbine is assumed to consist of one stage. This may be slightly optimistic. Based on current turbine stage work factors for high-pressure turbines and the variations in turbine work required for the OPR's considered, a two-stage turbine may be required. However, turbines having higher stage work factors are currently being investigated. A booster stage would also decrease the work required from the high-pressure turbine.

The present cycle calculations use T_4, turbine-rotor inlet temperature as an independent variable. Therefore, cooling air for the high pressure stator was not included. Any stator cooling air is included in the combustor airflow and is not calculated. The number of low pressure turbine stages is calculated using the equation from reference 4 (based on a current turbine work factor of 2.5).

$$\text{Number of stages} = \frac{9660(1 + \text{BPR})(P_6/P_1)DH_{5,6}}{[1 + FA_4(1 - \text{BLEED}_{total})]V^2_{fan-tip}\sqrt{T_6/T_1}}$$

where

FA_4 is the fuel-air ratio at the turbine rotor-inlet station

P_6/P_1 is the total pressure at the low-pressure turbine exit station/ total pressure at the fan face station, lb/ft^2

T_6/T_1 is the total temperature ratio, °F

$DH_{5,6}$ is the change in enthalpy between the high pressure turbine exit station and the low pressure turbine exit station, BTU/lb

and BLEED_{total} is the total cooling bleed for both turbines plus shroud and wall cooling expressed as a fraction of compressor exit airflow. These terms are determined from the cycle calculations. The schedule of corrected fan-tip speed ($V_{fan-tip}$) used in the study is shown in figure 7 (ref. 4). The curve is a linear approximation tangent to the curve in reference 10 for a fan blade loading of 0.3 (current technology) at a fan-tip speed of 1900 ft/sec. This procedure gives good results when compared with more elaborate methods of estimating the number of stages.

Knowing the number of stages, and the enthalpy and temperature drop across each stage from cycle calculations, and the temperature of the cooling air, the cooling bleed for a particular stage can be calculated using the bleed flow schedule in reference 11.

This schedule is based on laboratory tests of full-coverage film cooled vanes tested in Allison's high temperature cascade rig. The resultant cooling bleed requirements for similar engine conditions are lower than with current cooling methods such as convection-impingement film cooling. The blades are of advanced design using advanced fabrication techniques. Bulk metal temperatures of 1172 K (2110° R) and 1367 K (2460° R) are assumed for the rotor blades and the stator vanes, respectively. These temperatures are lower than for advanced blades using advanced materials with convection cooling due to oxidation problems associated with the coolant flow passages (ref. 12).

Noise Calculations and Constraints

For airplanes of interest in this study (TOGW 90718 **kg** 200 000 lbs)-136 077 kg (300 000 lb) Federal Air Regulations, Part 36 (FAR36) specifies a noise goal of approximately 106 EPNdB for sideline and approach and 102.5 EPNdB at takeoff conditions. Based on the results of references 3 and 4, noise calculations were made only for the sideline noise. As in reference 3, the airplanes in this study are always at an altitude of 457 m (1500 ft) at a point 6.49 km (3.5 nmi) from the start of takeoff roll (takeoff noise point). Since the power is allowed to be reduced, a noise problem at this condition is not likely.

The approach noise, as found in reference 4, is no more severe than the sideline noise. This is especially true if a two-segment approach is used. The sideline noise corresponds to the noise measured on the ground after liftoff at a sideline distance of 0.463 km (0.25 nmi) for the airplane used in this study. The point of maximum noise would be after the aircraft reaches an altitude where ground attenuation and engine masking is greatly diminished. The aircraft Mach number was assumed to be 0.3 and the altitude 168.6 m (553 ft).

Total perceived noise has a number of components, jet noise (from the two jet streams), fan noise, and core noise (compressor, combustor, turbine). For the noise goals considered in this study, core noise would have a minor effect on the total noise. Therefore, it is not considered. Jet noise is calculated by the methods of references 13 and 14. Fan turbomachinery noise is considered to be a function of FPR as shown in figure 8 as well as thrust and distance. This curve is from reference 3 and is based on data from reference 15. It is a composite curve representing a low speed fan with few (if any) multiple pure tones (MPT's) at a FPR of 1.5, and a high-speed fan with MPT's at a FPR of 1.9. The band of accuracy on this curve is expected to be ± 2 PNdB. A spectral distribution for fan machinery noise was assumed based on reference 16 and shown in reference 4. The total perceived noise is obtained by adding the machinery noise and the jet noise by octaves as described in reference 13. These results are in terms of EPNdB. This adjustment appears to be minor and thus was not accounted for in the study.

Lift-Drag Ratio

As in reference 3, a L/D of 20 is used for the reference airplane. This value includes the drag of three 80 inch diameter nacelles. The drag (friction) for one of these nacelles is shown in figure 9. The curve for other size engines agrees with those in use by engine and airframe manufacturers. Using this curve, the **reference L/D is adjusted for other engine nacelle diameters.**

Direct Operating Cost

Direct operating cost (DOC) was calculated for each engine at each noise goal using the 1967 ATA domestic formula. Engine maintenance costs, however, were based on the short-form equations of reference 17. Airframe cost was assumed to be \$158.7/kg (\$72/lb) (based on current airplanes). Turbomachinery noise suppression material was assumed to cost the same per pound as the airframe. Engine price was taken to be a function of the sea-level static corrected airflow and computed as follows

$$C_{eng} = 1.2x10 \left[\frac{(Wa\sqrt{\theta}/\delta)_{SLS}}{1300} \right]^{.35}$$

This cost is based on empirical data and adjusted to reflect the cost of a turbofan used in a wide-body trijet. No attempt was made in this preliminary analysis to account for differences in engine design. However, engine cost was perturbed to determine the sensitivity of DOC to the higher cost of a high BPR, high OPR turbofan. The nominal fuel cost was \$79.3/m^3 (30¢/gal).

RESULTS AND DISCUSSION

An advanced engine designed for low energy consumption is likely to have design parameters different from current engines for two reasons.

First the design parameters may change because of the optimization criteria - minimum fuel usage rather than minimum DOC. Second, advanced technology will permit higher turbine temperatures (T_4) which will require higher OPR's and different design values of FPR and BPR. As the turbine temperature and the OPR increase, the emission and cooling problems become more difficult. The already difficult cooling problems may be aggravated even more because of the possibility of higher temperature cooling air. In addition the number of turbine stages increases along with engine length, and weight. Also hub and tip losses cause rear stage efficiency to decrease. Therefore, for the present study, engine OPR was limited to 40.

Effect of Turbofan Design Parameters on Cruise SFC

The effect on cruise SFC of operating a separate-flow turbofan at a higher T_4, OPR, and BPR is indicated in figure 10. This figure compares the cruise SFC of a current turbofan with that of an advanced engine at Mach-0.85 and 12192 m (40 000 ft). Increasing the OPR from 28 to 40, the BPR from 6 to 11 and the turbine rotor-inlet temperature from 1367 K (2460° R) to 1644 K (2960° R) results in a 9 percent decrease in the cruise SFC.

The effect of rotor-inlet temperature (T_4) on cruise SFC (Mach 0.85 and 12192 m (40 000 ft)) is indicated in figure 11 for an engine having an OPR of 40. For a given temperature the cruise SFC varies only slightly with BPR, figure 1(a).

This is due to the fact that the fan pressure ratio was optimized for each BPR. For each temperature curve, the optimum FPR decreases as the BPR increases. The optimum BPR increases with T_4.

For an engine having an OPR of 40, the optimum cruise T_4 is 1617 K (2910° R), figure 11(b). The performance indicated in figures 10 and 11 for the high OPR engines is based on the coolant bleed flow schedule of reference 4 and T_{4cr}. Based on the optimum level of T_{4cr} and the data of reference 3, the turbine rotor-inlet temperature at takeoff was fixed at 1783 K (3210° R). Based on this higher value of T_4, a coolant bleed flow greater than the 4 percent used for a T_4 of 1617 K (2910° R) will be required. Thus the performance at cruise will be penalized (discussed later) unless the bleed flow can be varied or the bleed air is cooled. The bleed air could be cooled by passing the compressor bleed air through a heat-exchanger located in the fan stream.

The effect of reducing the temperature of the compressor bleed air on the required coolant flow is indicated in figure 12 for a particular engine. Based on the compressor discharge temperature (844 K (1520° R)), and the higher turbine-rotor inlet temperature at takeoff 1783 K (3210° R), a bleed of almost 8 percent is required to cool the turbines using full-coverage film cooling. Cooling the bleed air from 844 K (1520° R) to 583 K (1050° R) reduces the required bleed from 8 to 4.2 percent. The bleed temperature could also be reduced by extracting the air at some intermediate point in the compressor.

A brief study of the heat exchanger approach is summarized in figure 13. For a fan-air heat exchanger having an effectiveness of 0.85, 0.275 percent of the duct air would be required to cool the compressor exit air to 583 K (1050° R). Based on reference 18, an effectiveness of 0.85 appears reasonable for a rotary storage-type heat exchanger. A matrix about 18 inches in diameter and 6 inches thick would be required. The weight of a heat exchanger of this type is estimated to be about 68 (150) to 90.7 kg (200 lb). A major development problem would be seals to handle the high pressure ratios.

The effect of various coolant bleed flows on the cruise performance of a particular turbofan engine is indicated in figure 14. As indicated previously, with a heat exchanger, a coolant bleed flow equal to 4.2 percent of the compressor discharge air is required. Using the compressor discharge air directly, a bleed of approximately 8 percent is required based on T_{4SL}. As a result the SFC at cruise is about 3 percent greater. With convection cooling rather than full-coverage film, the required bleed is about 12 percent (ref. 12), and the cruise SFC is 7.5 percent greater. For the remainder of the study, the compressor bleed flows are based on using uncooled compressor exit air and a takeoff T_4 of 1783 K (3210° R). At FAR36-10 noise levels the engine cycle parameters would have to be reoptimized if the compressor bleed flow is cooled. This is due to the fact that the core jet noise increases as the amount of bleed flow is reduced. Therefore to attain FAR36-10 noise levels, the turbomachinery noise must be suppressed even more. Thus unless the engine is reoptimized the gains in SFC achieved by cooling the compressor bleed air (fig. 14) are lost to greater suppression penalties (fig. 5).

Effect of Turbofan Design Parameters on Takeoff Gross Weight

The effect on vehicle takeoff gross weight (TOGW) of engine OPR, and BPR for noise goals as low as FAR36-15 is indicated in figure 15 for a T_{4SLS} of 1783 K (3210° R) and fan pressure ratios (FPR's) of 1.5 (15(a)), 1.6 (15(b)), and 1.7 (15(c)). For all three FPR's and OPR's, TOGW increases rapidly as the noise goal is reduced for a given BPR. This is due to the increased performance and weight penalties associated with the increased turbomachinery suppression (fig. 5). Thus for a FPR of 1.6 (fig. 15(b)) and an OPR of 40 TOGW increases rapidly for a BPR of 9 as the noise goal is decreased. Higher BPR's are required to minimize these penalties. By increasing the BPR, the jet and the fan noise are decreased as is the cruise SFC (fig. 10). Therefore, lower noise goals can be attained without drastic increases in TOGW. But BPR can be increased just so far for each FPR and OPR. Otherwise the pressure in the aft-end of the engine is less than ambient after the turbine work is extracted. The optimum BPR, for a given noise goal, decreases as the FPR is increased. For a noise goal of 96 EPNdB, the optimum BPR decreases from 12.5 for a fan pressure ratio of 1.5 (fig. 15(a)) to about 9 for a FPR of 1.7 (fig. 15(c)).

To maintain a given fan-tip speed as BPR is increased with no reduction gear, the turbine RPM must be decreased. This increases the number of turbine stages for a given work factor. With a gear-driven fan the RPM of the turbine can be increased and the reverse is true. The Quiet Clean STOL Experimental Engine (QCSEE) does have a gear-driven fan. This engine has a BPR of about 12, but a lower fan tip speed (950 fps). Turbines having higher stage work factors are being studied (ref. 8). However, these turbines presently have lower efficiencies. With the present fan tip speeds and higher turbine-stage-work factors, a gear may not be required. For this preliminary study no gear is assumed, and the consequent impact of more turbine stages on cooling bleed is accounted for.

Figure 16 compares the best of the high OPR (advance) engines with a current engine in terms of airplane TOGW. For a noise goal of 96 EPNdB the current turbofan (FPR_{cr} 1.69, OPR_{cr} 28, T_{4SL} 1488 K (2680° R), BPR 6) requires a vehicle having a TOGW of 263500 pounds. This is based on current engine weights, and current cooling schemes (7 percent bleed). A more advanced cooling scheme, full-coverage film, reduces the cooling bleed to 2.5 percent and the TOGW by 3.5 percent. Increasing the OPR, BPR and T_4 reduces the TOGW by an additional 4.5 percent or by 7 percent compared with the current engine. The optimum FPR for this noise goal (96 EPNdB) is 1.6.

As the noise goal is reduced for the current engine, the core jet noise becomes the predominate noise source. With current cooling schemes, the higher bleed flow reduces this noise source. Thus a lower TOGW is achieved for a given noise goal than when full-coverage film cooling is used. In other words, with a more advanced cooling scheme the cycle parameters for the current engine are nonoptimum.

For a noise goal of 96 EPNdB, the optimum BPR and OPR in terms of TOGW are indicated in figure 17 for the advanced engine. For an OPR of 40, the optimum BPR is 10.3 (fig. 17(a)). The optimum OPR for a BPR of 10.4 is 40 (fig. 17(b)).

At present, emission problems are tougher at the higher pressure ratio. Thus an OPR lower than the optimum may be attractive. This will depend on the state of emission technology at the time an engine is selected.

Effect of Turbofan Design Parameters on Fuel Consumption

The next three figures indicate the effect of various engine parameters on the fuel used in terms of kg/pass. km (lb/pass. nmi) for the assumed mission. The trends in these figures (18-20) are similar to those of figures 15-17 for TOGW. This is not surprising since the engine parameters resulting in the minimum TOGW for a given noise goal also result in the minimum cruise SFC or close to it. For noise goals between 91 and 106 EPNdB, an OPR of 40 results in the lowest fuel consumption for the three fan pressure ratios considered 1.5 (fig. 18(a)), 1.6 (fig. 18(b)) and 1.7 (fig. 18(c)). Again for a noise goal of 96 EPNdB, the optimum BPR decreases from 12.5 to 9 as the FPR increases from 1.5 to 1.7.

The fuel saved by increasing engine OPR and BPR relative to a current engine is shown in figure 19. Based on the current turbine cooling requirement, the fuel used by the current low OPR engine amounts to 0.0246 kg/pass. km (0.1005 lb/pass. nmi). This is for a noise goal of 96 EPNdB. With a more advanced turbine cooling scheme, full-coverage film, the fuel consumption of the current engine can be reduced by 5 percent. Increasing the engine OPR and BPR results in an additional 5 percent savings in fuel. Compared with the current engine using the current turbine cooling scheme, the total fuel saved due to increasing the OPR and BPR to 40 and 10.4 amounts to 10 percent. Thus a 6 percent decrease in the uninstalled cruise SFC results in a 10 percent savings in fuel. A similar savings in fuel is achieved with the advanced engines at other noise goals. Considering that about 57 million tons of jet fuel are used annually (ref. 19-21), this represents a sizeable savings. Relaxing the noise goal has a noticeable effect on the fuel used by all three engines. For example relaxing the noise goal from 91 (FAR36-15) to 101 EPNdB results in a 17 percent saving in fuel for the high OPR engine. Using the current suppressor penalties (dashed curves) of figure 5, the fuel saving would be even greater. Thus any improvement in suppressor performance or decrease in fan or jet noise (at the lower noise level) will have a significant effect on fuel consumption.

For an overall pressure ratio of 40, figure 20 indicates the effect of BPR (fig. 20(a)) and FPR (fig. 20(b)) on fuel consumption for a noise goal of 96 EPNdB. The rapid increase in fuel usage with lower BPR's for a given FPR is due in part to the higher cruise SFC of the related engine cycle (fig. 10). As a result TOGW increases. This in turn increases the amount of suppression required due to the increase in engine thrust required at takeoff. As a result SFC is penalized even more. Thus choosing the correct BPR at low noise goals is most important if one is to conserve fuel.

For a FPR of 1.6, the optimum BPR is 10.6 compared to about 11 for minimum SFC (fig. 10). Figure 20(b) indicates that for a noise goal of 96 EPNdB and an OPR of 40, the optimum FPR is 1.61.

Effect of Turbofan Design Parameters on DOC

The effect of engine OPR and BPR on DOC is indicated in figure 21 as a function of noise for a $T_{4_{SLS}}$ of 1783° K (3210° R) and FPR's of 1.5 (fig. 21(a)), 1.6 (fig. 21(b)), and 1.7 (fig. 21(c)). Fuel cost is based on a nominal value of \$79.3/m^3 (30¢/gal). The DOC trends are similar to those of figures 15 and 18 for airplane TOGW and fuel expanded (kg/pass. km) for the mission. At the lower noise goals, the lowest DOC for each FPR is achieved with a BPR corresponding closely with the minimum uninstalled cruise SFC of figure 10. As the noise goal is increased, the higher SFC of a lower BPR can be traded for a smaller and, therefore, lighter engine. In other words, fuel cost is traded for engine cost. At lower noise goals, an OPR of 40 is best for all three FPR's.

Lower DOC's are attained with the higher OPR and BPR engines than with current engines. For an engine having current values of FPR, OPR, BPR, T_4, and using the current turbine cooling scheme, the DOC is 0.665¢/seat KM (1.07¢/seat mi) for a noise goal of 96 EPNdB (fig. 22). Using full-coverage film cooling, the DOC is decreased by 3.5 percent. The higher OPR and BPR engine results in an additional 2.7 percent decrease in DOC for a total of 5.9 percent. A FPR of about 1.6 results in the lowest DOC for noise goals between 92.6 and 97.4 EPNdB. For a noise goal of 96 EPNdB, figure 23 indicates the optimum BPR (fig. 23(a)) and FPR (fig. 23(b)) are 10.7 and 1.62. However, DOC is not that sensitive to FPR. Thus based on TOGW (fig. 16), fuel consumption (fig. 18) and DOC (fig. 22), a single engine design is near optimum for all three engine criteria. Emission standards may require an engine OPR lower than the optimum.

The effect of fuel cost on DOC is shown in figure 24 for three engines based on a noise goal of 96 EPNdB. Increasing the fuel cost from \$79.3/m^3 (30¢/gal) to \$211/m^3 (80¢/gal) results in a 64.5 percent increase in DOC for a current engine. This increase is practically the same for the current engine with full-coverage film cooling and the higher OPR engine. Hence increasing engine OPR and BPR saves fuel but does little to minimize the impact on DOC of further fuel price increases. Reoptimization of the engine for the case of higher fuel cost will not change this situation. This is because the optimum engine based on minimum fuel usage is basically the same engine when optimized for minimum DOC.

Another way to save fuel is to decrease the cruise Mach number. Figure 25 shows the effect on TOGW (fig. 25(a)) and fuel consumption kg/pass. km (lb/pass. nmi) (fig. 25(b)) of decreasing the cruise Mach number from 0.85 to 0.78. For this figure the reference lift-drag ratio was corrected for Mach number and sweep angle effects according to reference 22. These lift-drag ratios were then adjusted to include the effects of higher aspect ratios indicated in reference 23. The resulting reference lift-drag ratio increased from 20 at Mach-0.85 to 21.8 at Mach 0.78. No change in vehicle operating weight empty (OWE) except that due to resizing was included. The present study indicates the optimum cruise Mach number to be 0.78 (fig. 25). Reference 21, which optimized the configuration characteristics for various cruise Mach numbers, indicates the optimum to be 0.8. In terms of the fuel used, kg/pass. km (lb/pass. nmi), figure 25(b) indicates about an 8 percent reduction due to reducing the cruise Mach number from 0.85 to 0.78. However, a more detailed look at the effect of cruise Mach number is required.

Sensitivity Study

Figure 26 reflects the sensitivity of vehicle TOGW, fuel used, and DOC to improvements in various engine components. The nominal engine has a FPR of 1.6, a OPR of 40, and a BPR of 10.35 for a noise goal of 96 EPNdB. The cruise Mach number is 0.85. Of the five parameters considered (fan and compressor efficiency, combustor pressure loss, nozzle velocity coefficient and engine weight), the effect of the nozzle velocity coefficient is most pronounced. Applying the five improvements indicated in figure 26 to the high OPR engine results in decreases in TOGW, fuel used (kg/pass. km) and DOC of 5.9, 9.3, and 5.7 percent, respectively.

However, based on 1985 component technology, all of the previous improvements will probably not be achieved. For example to reduce engine weight while increasing the core pressure ratio, blade loading is increased at the expense of possible increases in component efficiency. The improvements considered as reasonable goals for 1985 by individual component specialists on the Lewis staff are indicated in figure 27. The projected improvements are for fan efficiency, nozzle velocity coefficient, and engine weight. These three parameters affect the overall performance of all engines and, therefore, should not affect the engine optimization. Combined these three improvements result in a 11.9 percent decrease in TOGW, a 14.1 percent decrease in fuel used, and a 9.3 percent decrease in DOC. These percentages increase to 18, 22.3, and 14.7 when the 1985 technology high OPR engine is compared with the current engine (FPR_{cr} = 1.69, OPR_{cr} = 28, T_{4SL} = 1489 K (2680 R)).

For an engine of comparable size, a high OPR engine will probably cost more. This will increase the DOC of the advanced engine. Figure 28 indicates that a 20 percent increase in engine cost still yields a 11 percent decrease in DOC compared with the current engine.

CONCLUSIONS

This analysis determines the effect of higher overall engine pressure ratio (OPR's), bypass ratios (BPR's), and turbine rotor-inlet temperature on a Mach 0.85 turbofan transport. Vehicle takeoff gross weight (TOGW), fuel consumption (kg/pass. km), and DOC are used as the figures of merit. The airplane has a range of 5556 km (3000 nmi) and a payload of 18144 kg (40 000 lbs-200 passengers). Sideline noises (jet plus fan) of between 91 and 106 EPNdB (FAR36) are considered. To achieve the lower noise levels, a maximum of 20 PNdB of turbomachinery noise suppression is assumed.

Compared with a current separate-flow-turbofan (FPR_{cr} = 1.69, OPR_{cr} = 28, BPR_{cr} = 6, T_{4SL} = 1489 K (2680° R)), a higher OPR engine (FPR_{cr} = 1.6, OPR_{cr} = 40, BPR_{cr} = 10.4, T_{4SL} = 1783 K (3210° R) using a more advanced turbine cooling scheme (full-coverage film) results in a 6 percent reduction in cruise SFC. This is the optimum engine for a noise goal of 96 EPNdB. For a given noise goal, the optimum engine design is the same for the three figures of merit. Based on current engine weight, component technology and a noise goal of 96 EPNdB, the higher OPR engine results in an airplane that is 7 percent lighter in terms of TOGW, uses 10 percent less fuel and has a 5.9 percent lower DOC. Based on a predicted 1985 level of engine technology, the same reductions increase to 18, 22.3, and 14.7 percent. Cooling the compressor bleed air appears attractive as a means of reducing fuel consumption as it results in an additional 3 percent reduction in cruise SFC. Reducing the cruise Mach number from 0.85 to about 0.78 appears attractive in terms of reduced TOGW and fuel consumption.

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TABLE I.- ENGINE DESIGN PARAMETERS

FAN ADIABATIC EFFICIENCIES	SEE FIG 6(a)
COMPRESSOR ADIABATIC EFFICIENCIES	SEE FIG 6(b)
COMBUSTOR EFFICIENCY	.99
PRESSURE RATIO ACROSS COMBUSTOR	.96
INNER TURBINE ADIABATIC EFFICIENCY	.89
OUTER TURBINE ADIABATIC EFFICIENCY	.88
INLET PRESSURE RECOVERY	.98
FAN DUCT TOTAL PRESSURE RATIO	.94
EXHAUST NOZZLE VELOCITY COEFFICIENT (BOTH STREAMS)	.98

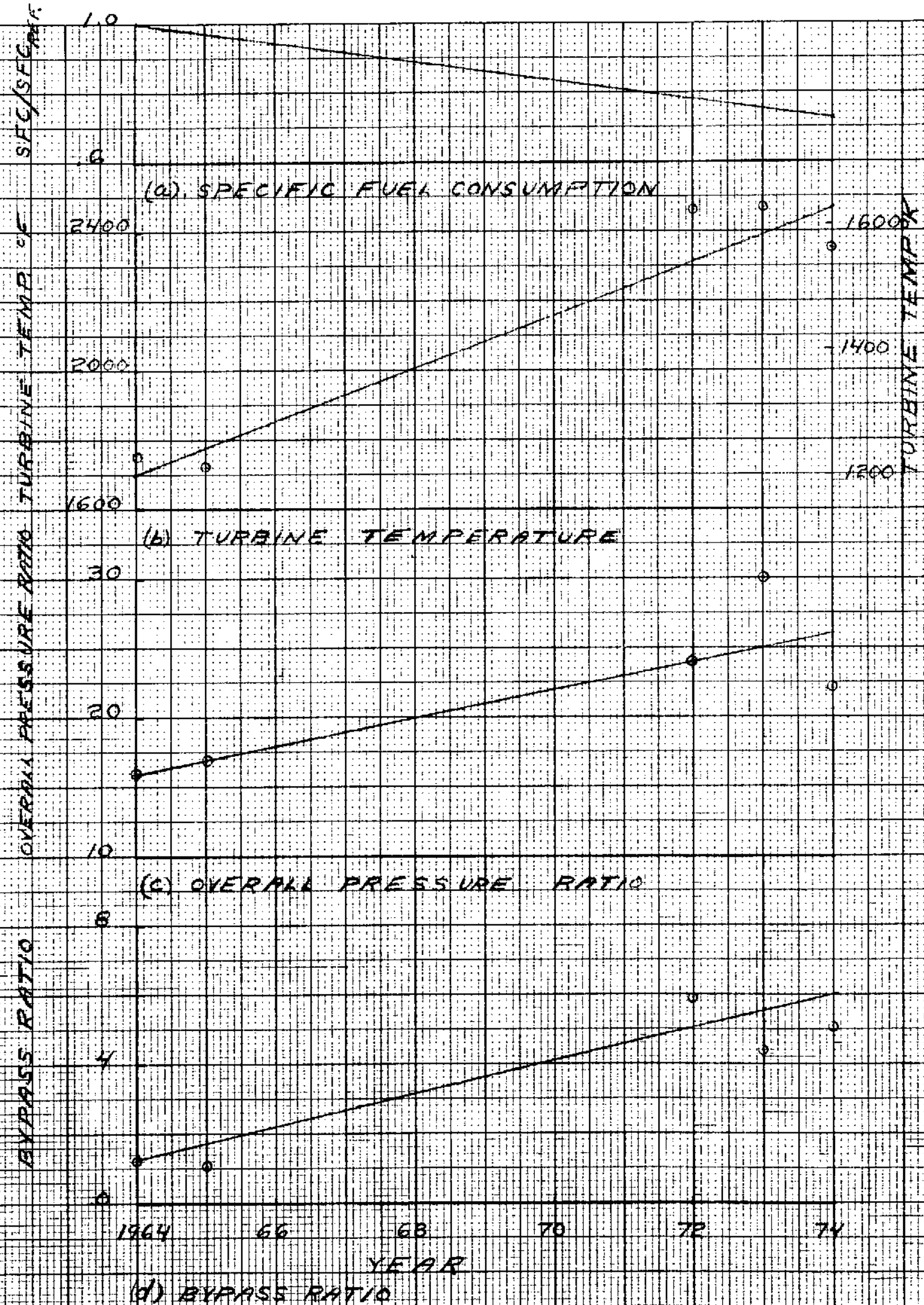


FIGURE 1. TRENDS IN TURBOFAN DEVELOPMENT

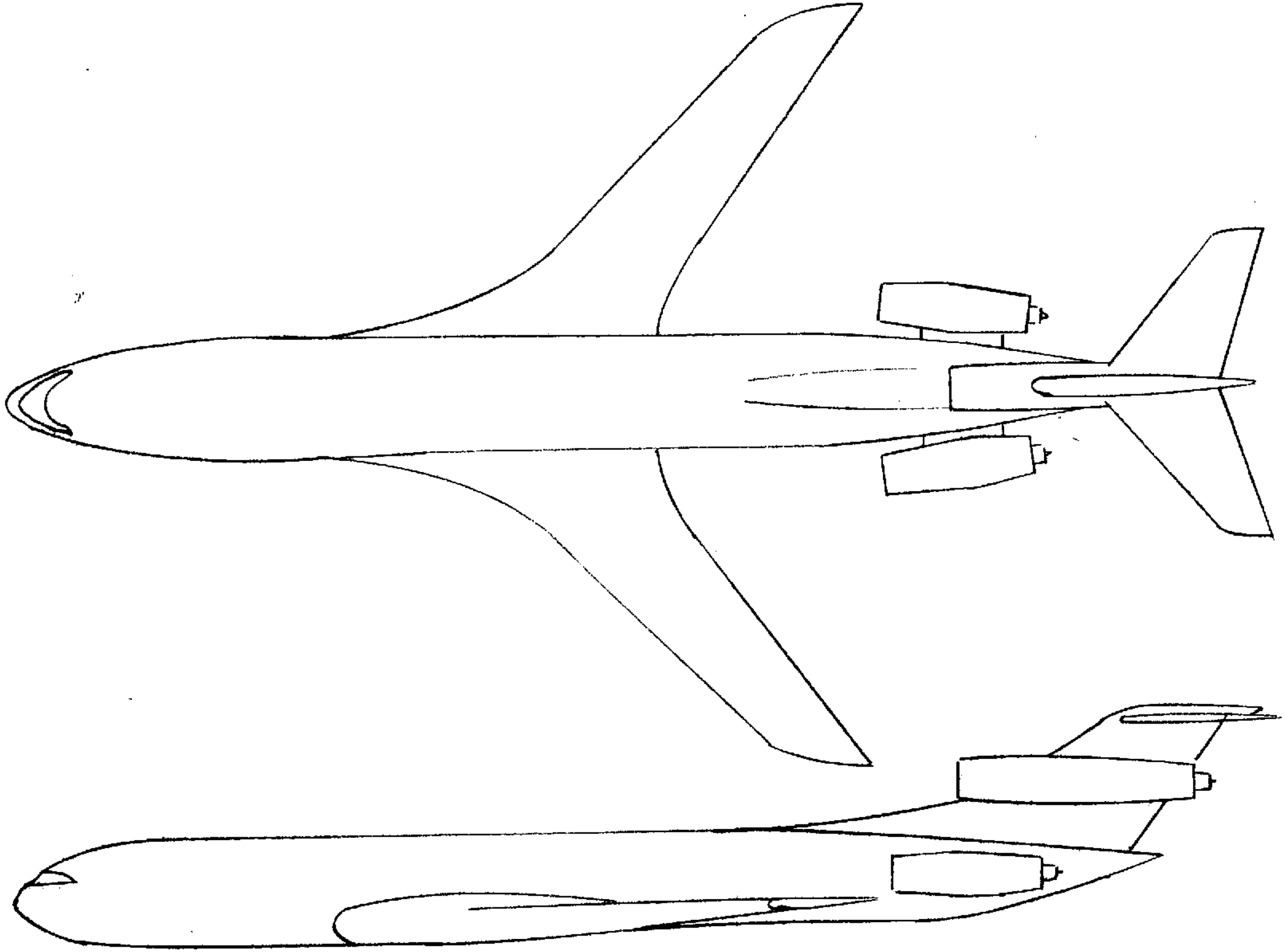


FIGURE 2.- SKETCH OF CONCEPTUAL ADVANCED TRI-JET TRANSPORT.

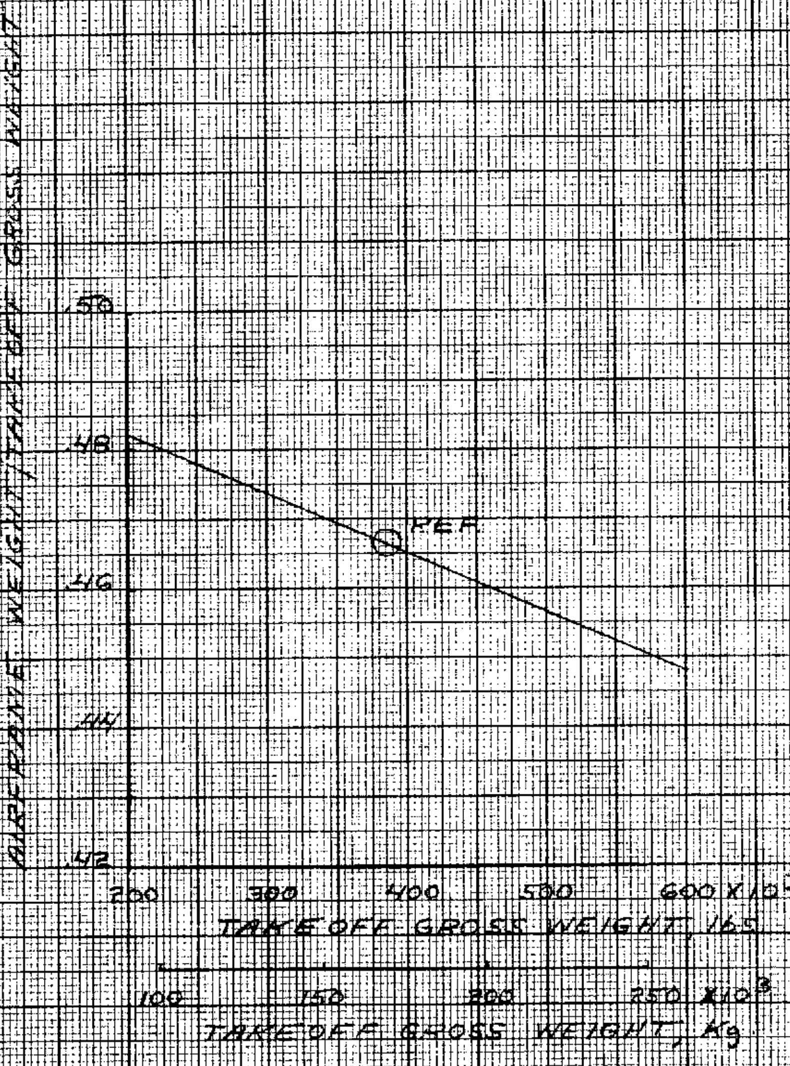


FIGURE 8. AIRFRAME WEIGHT FRACTION.
FUSELAGE DIMENSIONS FIXED,
TAKEOFF WING LOADING FIXED.

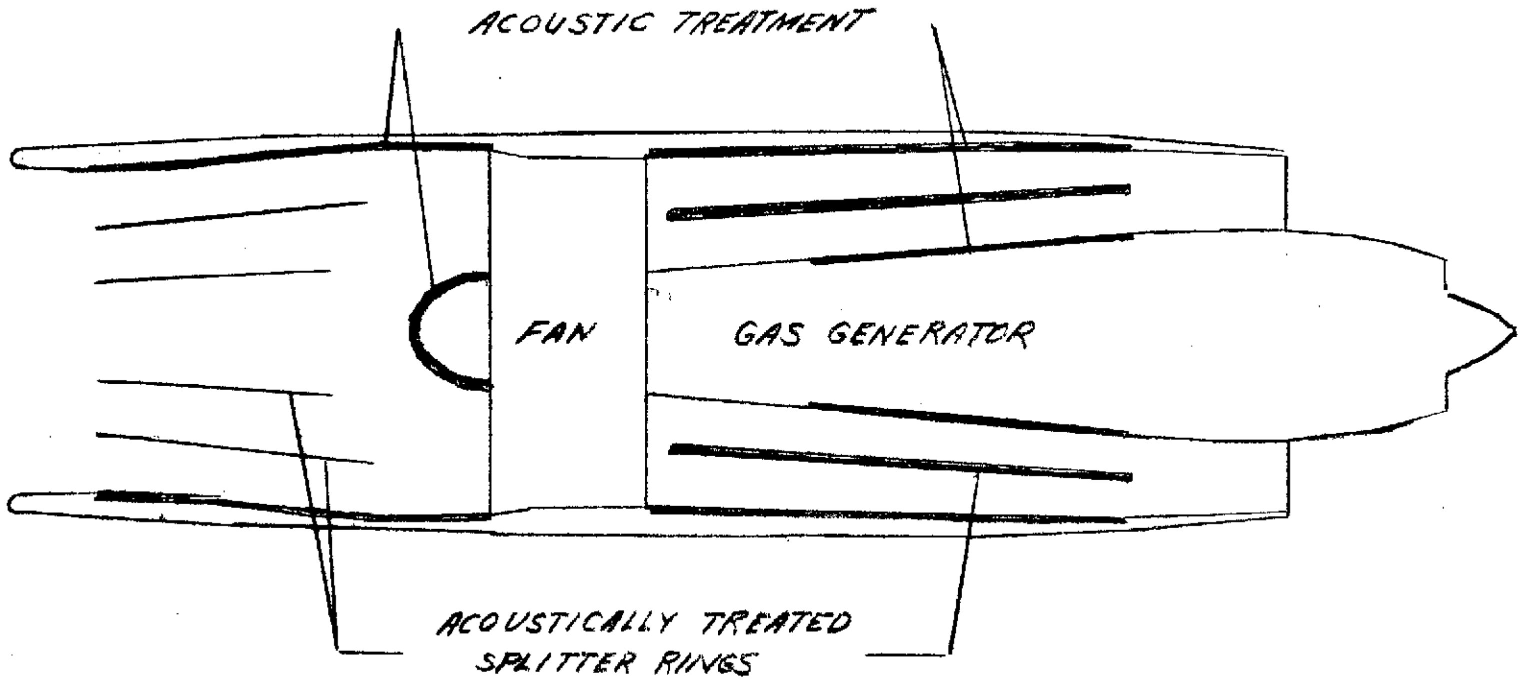
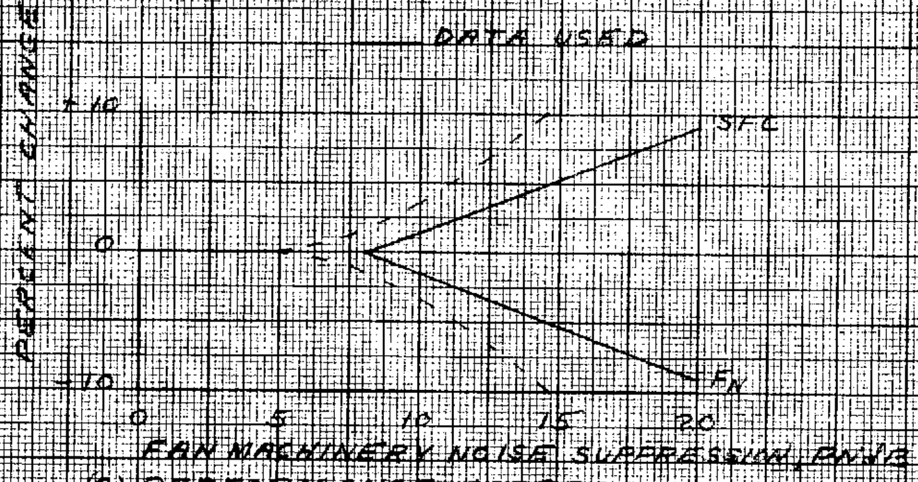


FIGURE 4.- SKETCH OF TURBOFAN ENGINE WITH ACOUSTIC TREATMENT



(a) PERFORMANCE LOSSES

(b) WEIGHT PENALTIES

FIGURE 5. - THRUST, SFC, AND WEIGHT PENALTIES VERSUS AMOUNT OF FAN MACHINERY NOISE SUPPRESSION, PNdB

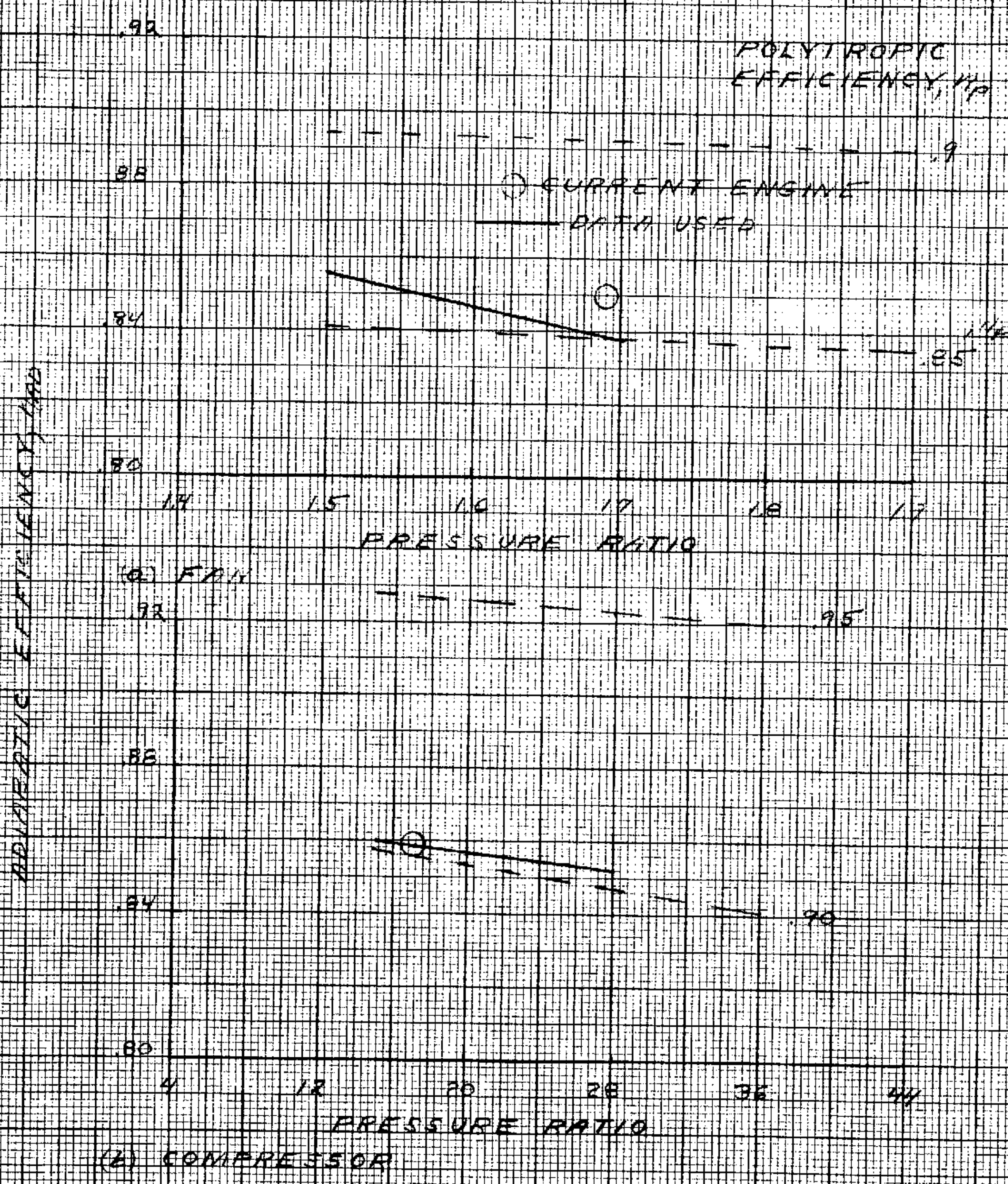


FIGURE 6 FAN AND COMPRESSOR ADIABATIC EFFICIENCY

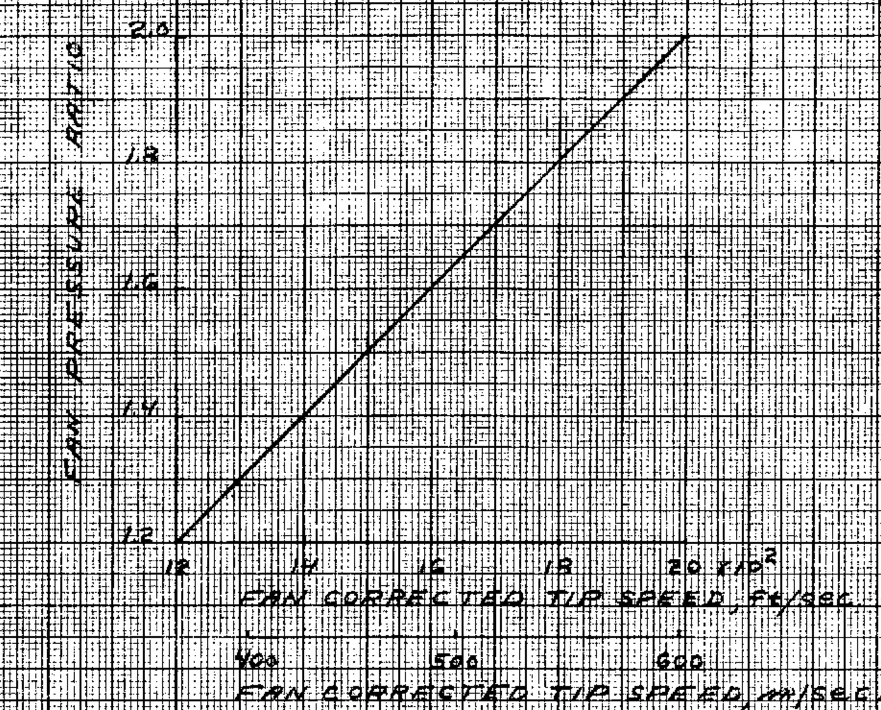


FIGURE 7. FAN TIP SPEED FOR ONE STAGE FANS

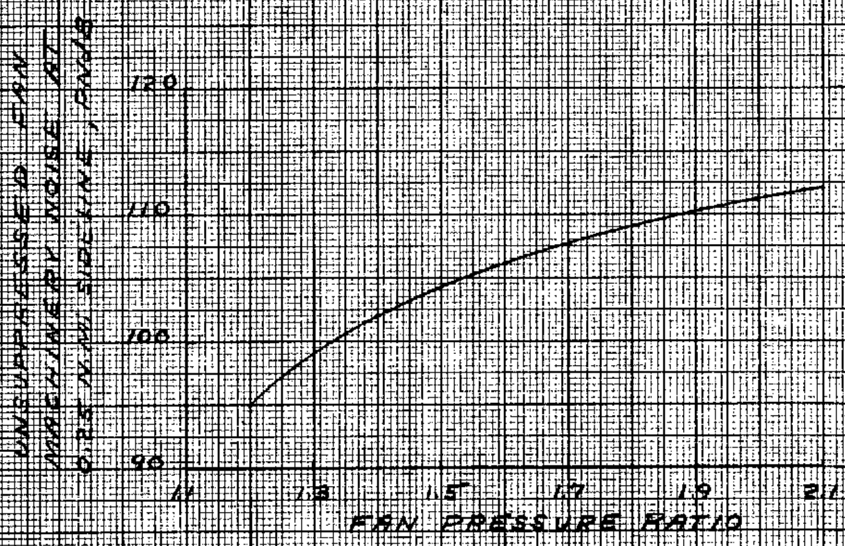


FIGURE 8: FAN MACHINERY NOISE VERSUS FAN PRESSURE RATIO FOR SINGLE STAGE FANS, $F_{n_{SLS}}$ = 11400 lbs (51710 Kg)

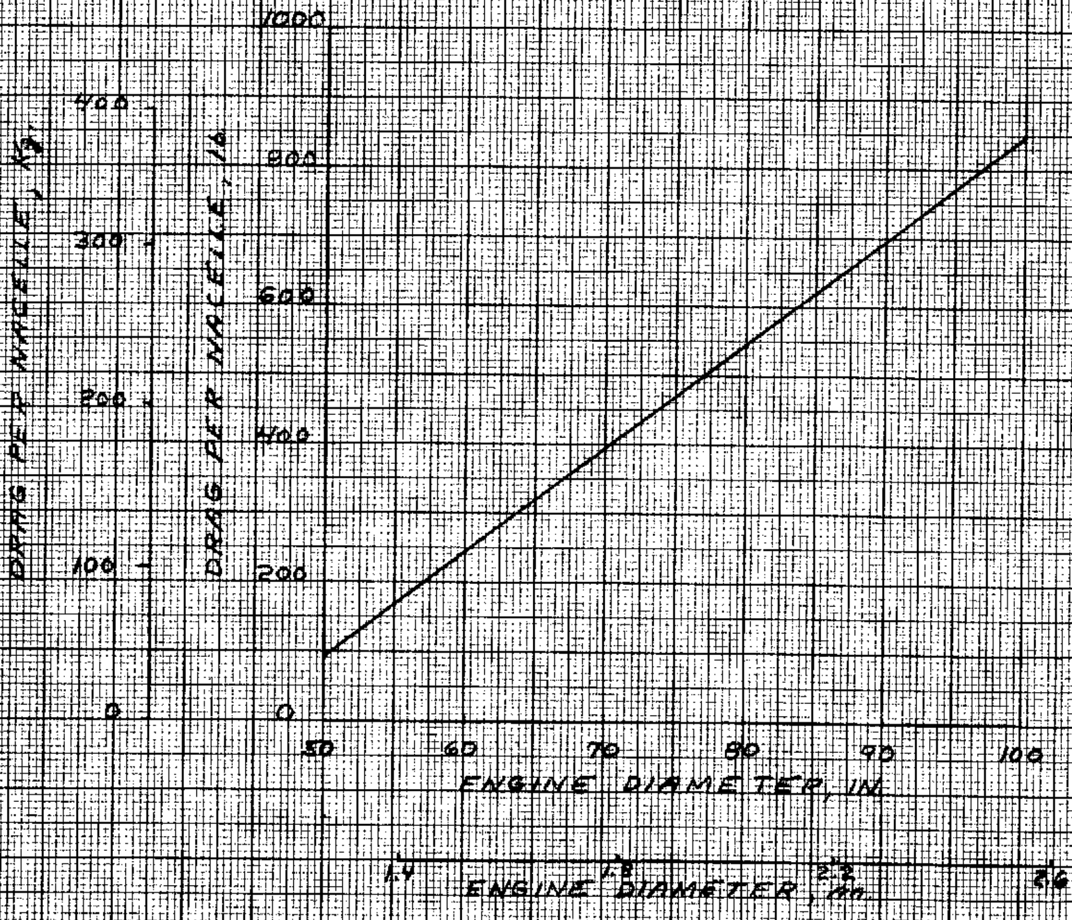


FIGURE 9.- NACELLE DRAG RELATED TO ENGINE MAXIMUM DIAMETER CRUISE MACH NUMBER = 0.85

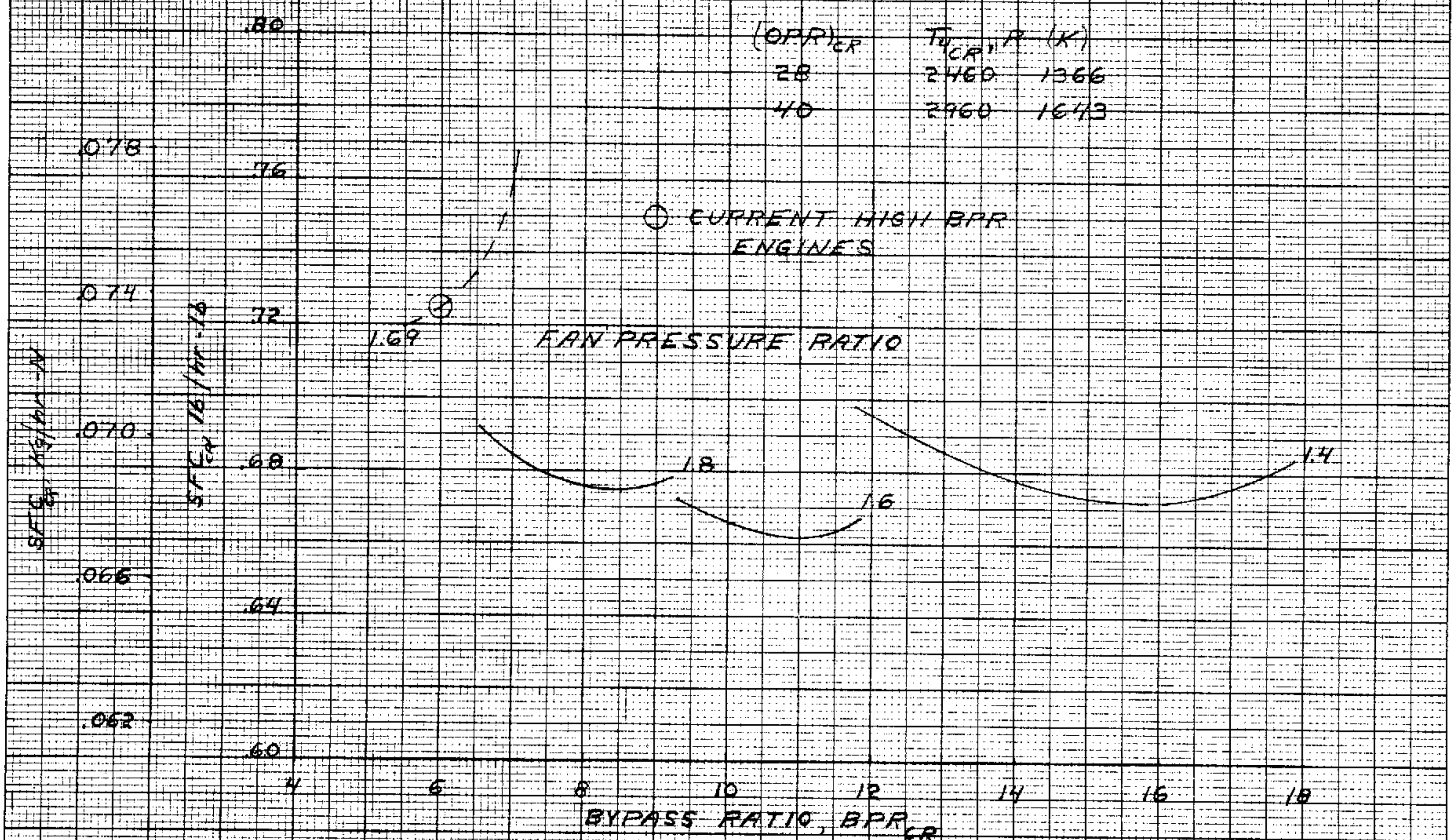
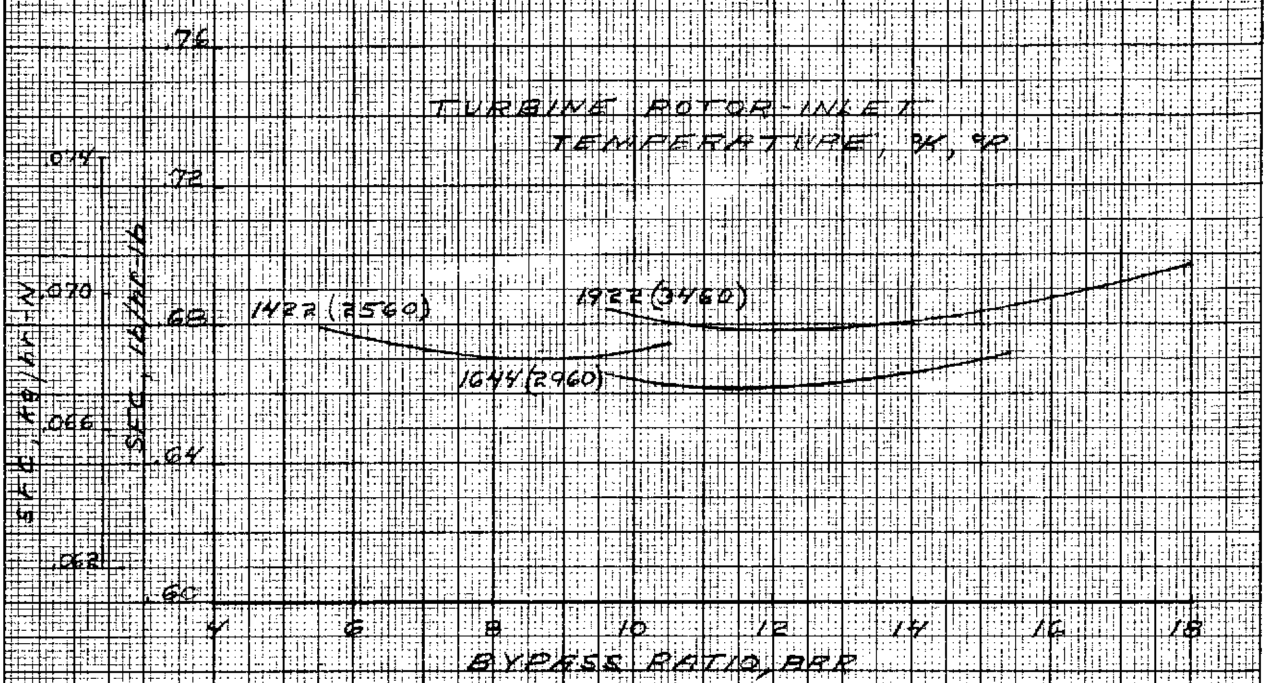
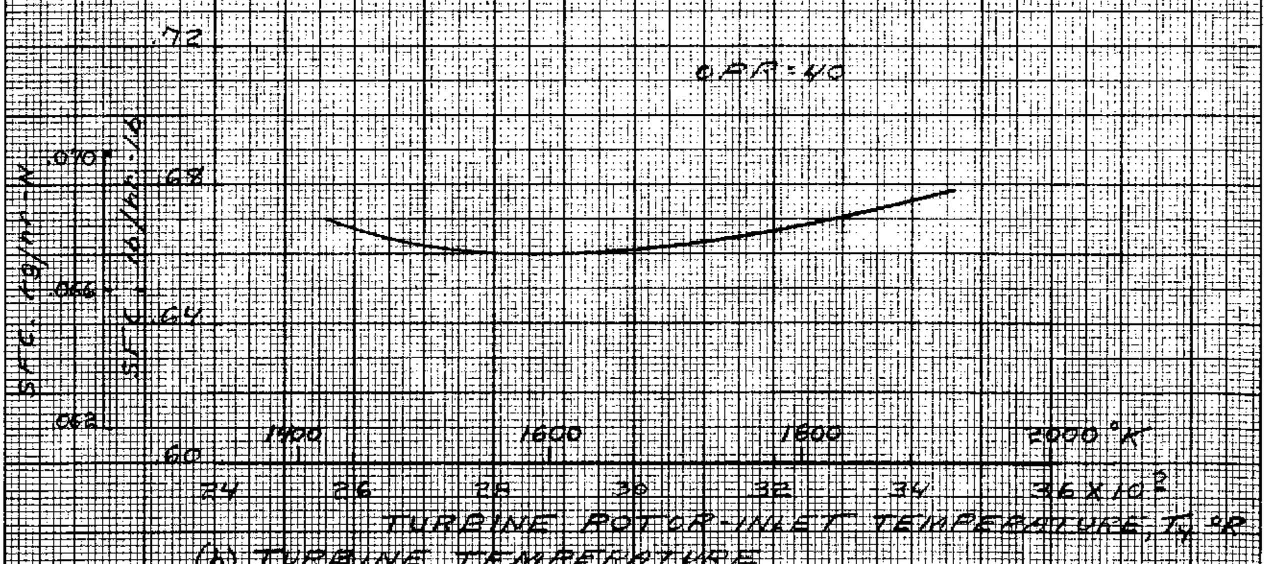


FIGURE 10 EFFECT OF HIGHER OVERALL PRESSURE RATIO AND TURBINE ROTOR-INLET TEMPERATURE ON THE PERFORMANCE OF A TUBOFAN ENGINE AT MACH .85 AND 40000 FT.



(a) BYPASS RATIO



(b) TURBINE TEMPERATURE

FIGURE 11 EFFECT OF CRUISE TURBINE ROTOR-INLET TEMPERATURE ON THE PERFORMANCE OF A HIGH OVERALL-PRESSURE RATIO TURBOFAN ENGINE AT MACH .85 AND 12 192 m (40000 FT.) COMPRESSOR BLEED = .042, OPTIMUM FPR

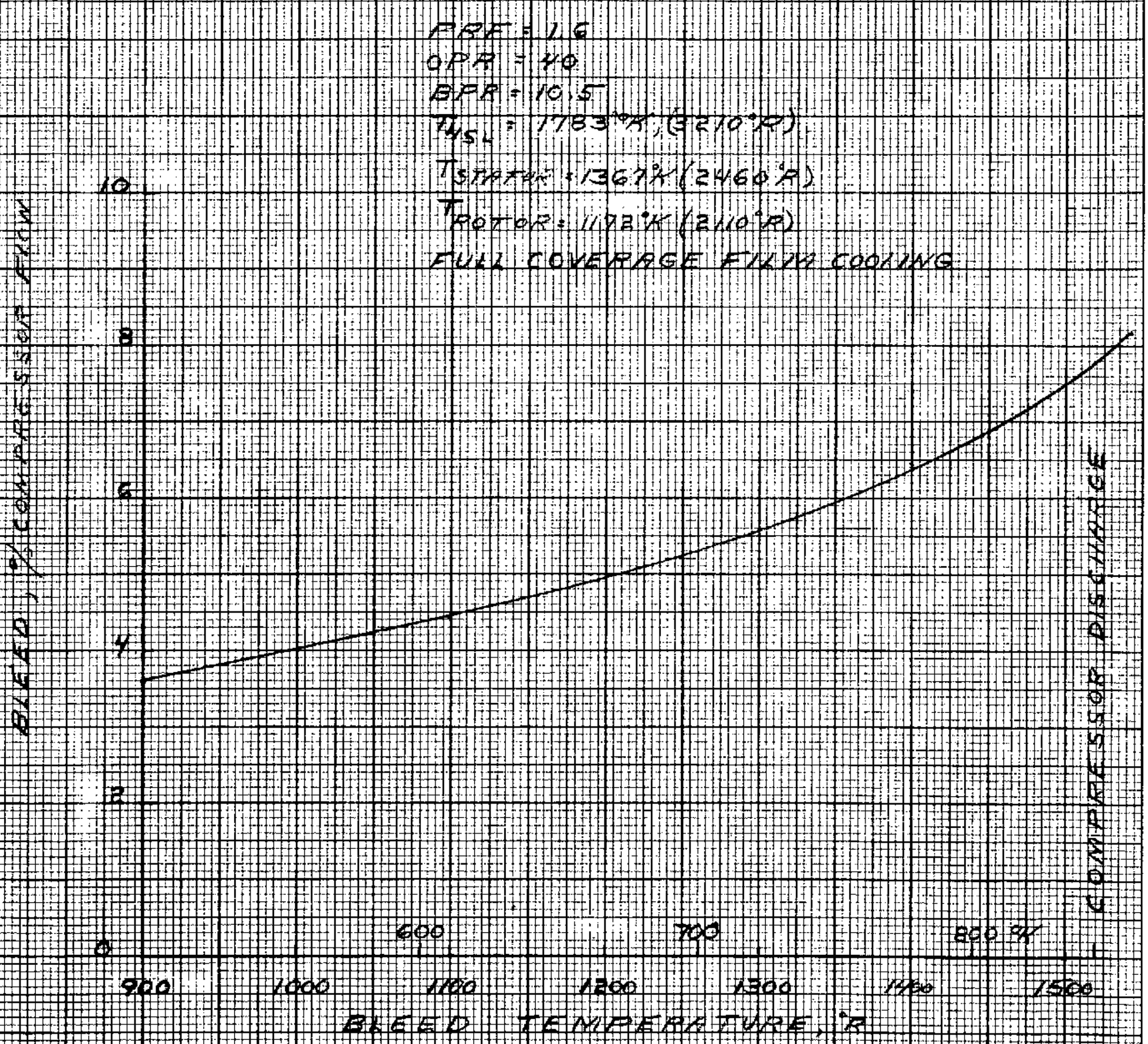


FIGURE 12. EFFECT OF COOLANT TEMPERATURE ON THE REQUIRED COOLANT FLOW.

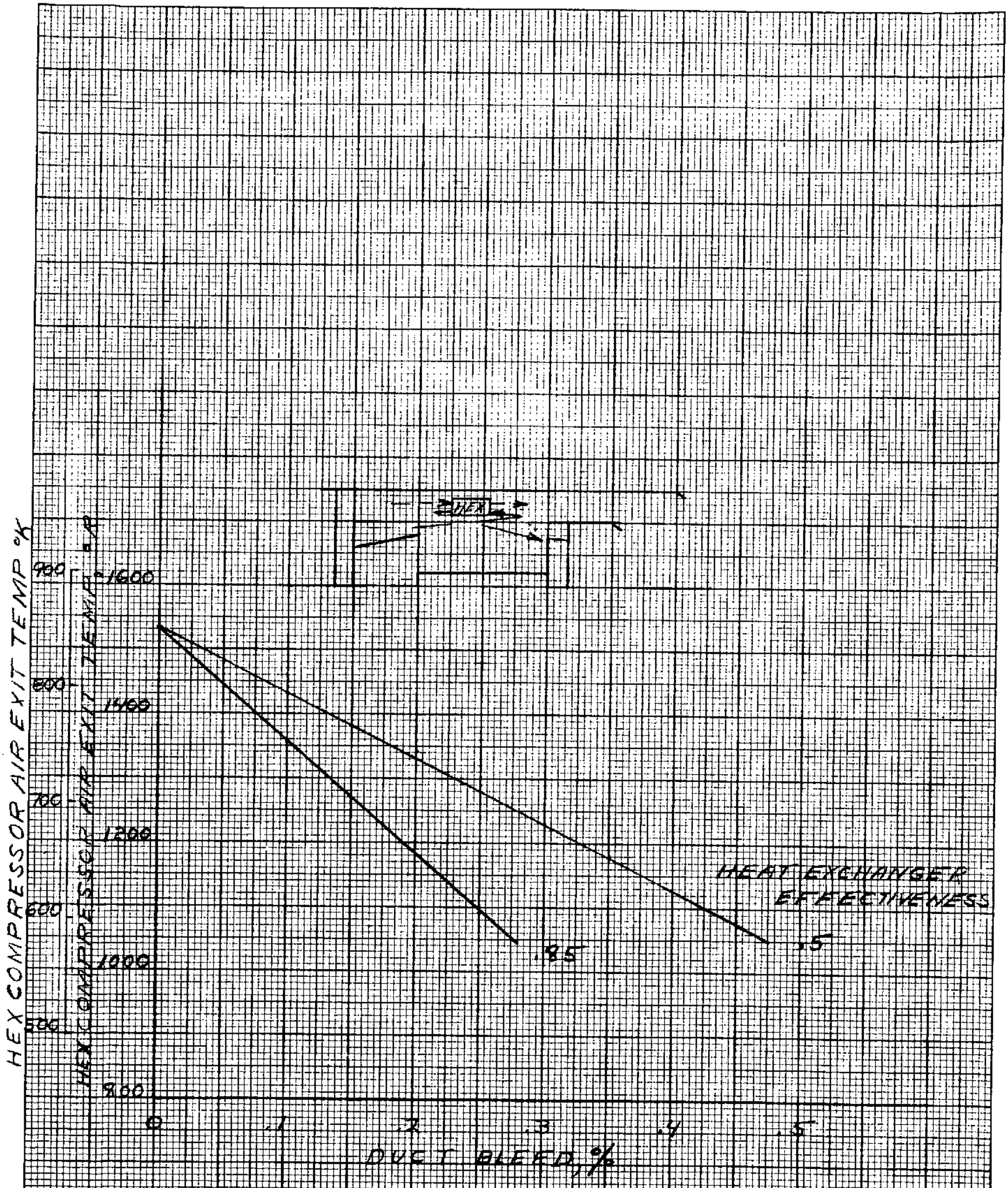


FIGURE 18 EFFECT OF VARIOUS DUCT BLEEDS ON THE COMPRESSOR BLEED AIR TEMPERATURE. PRF 1.6, OPR 40, BPR 10.5, T_{4SL} 1783°K (3210°R) COMPRESSOR BLEED = .042

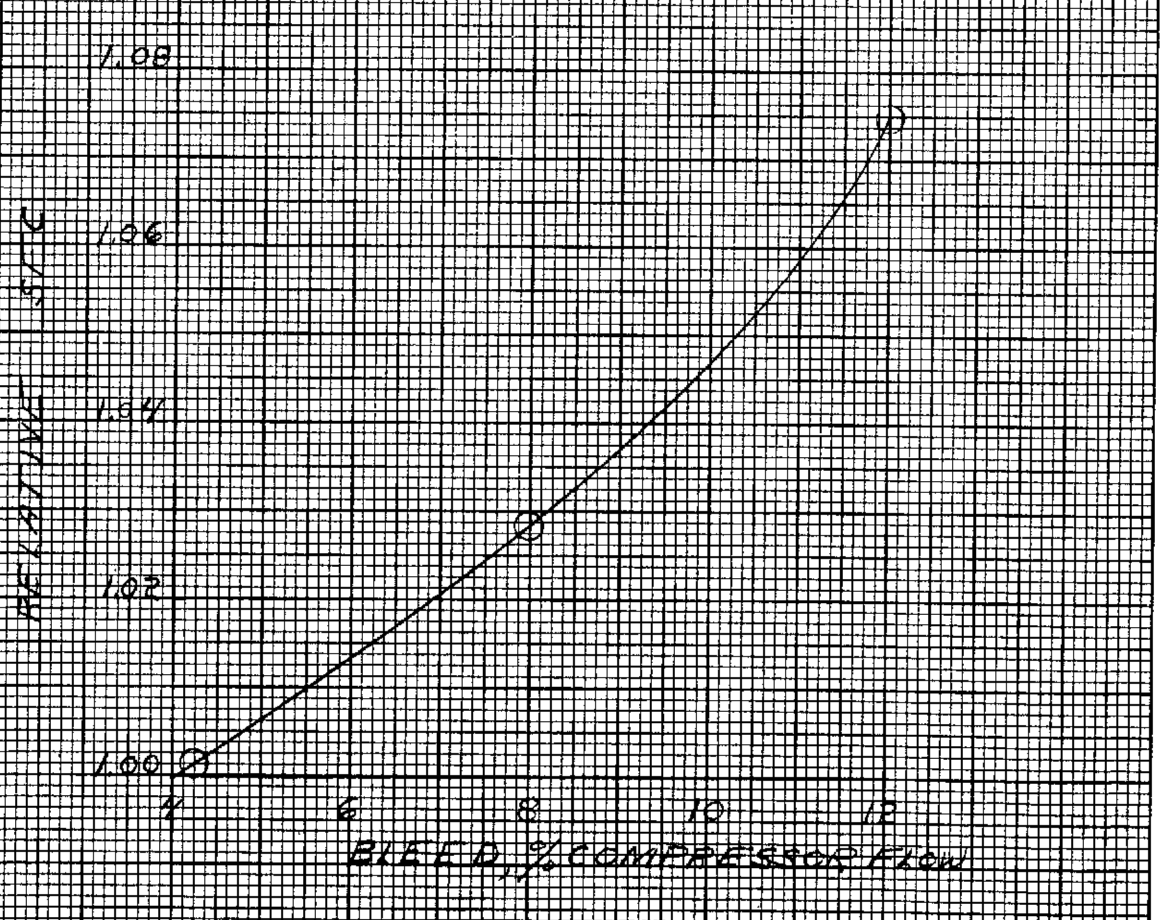
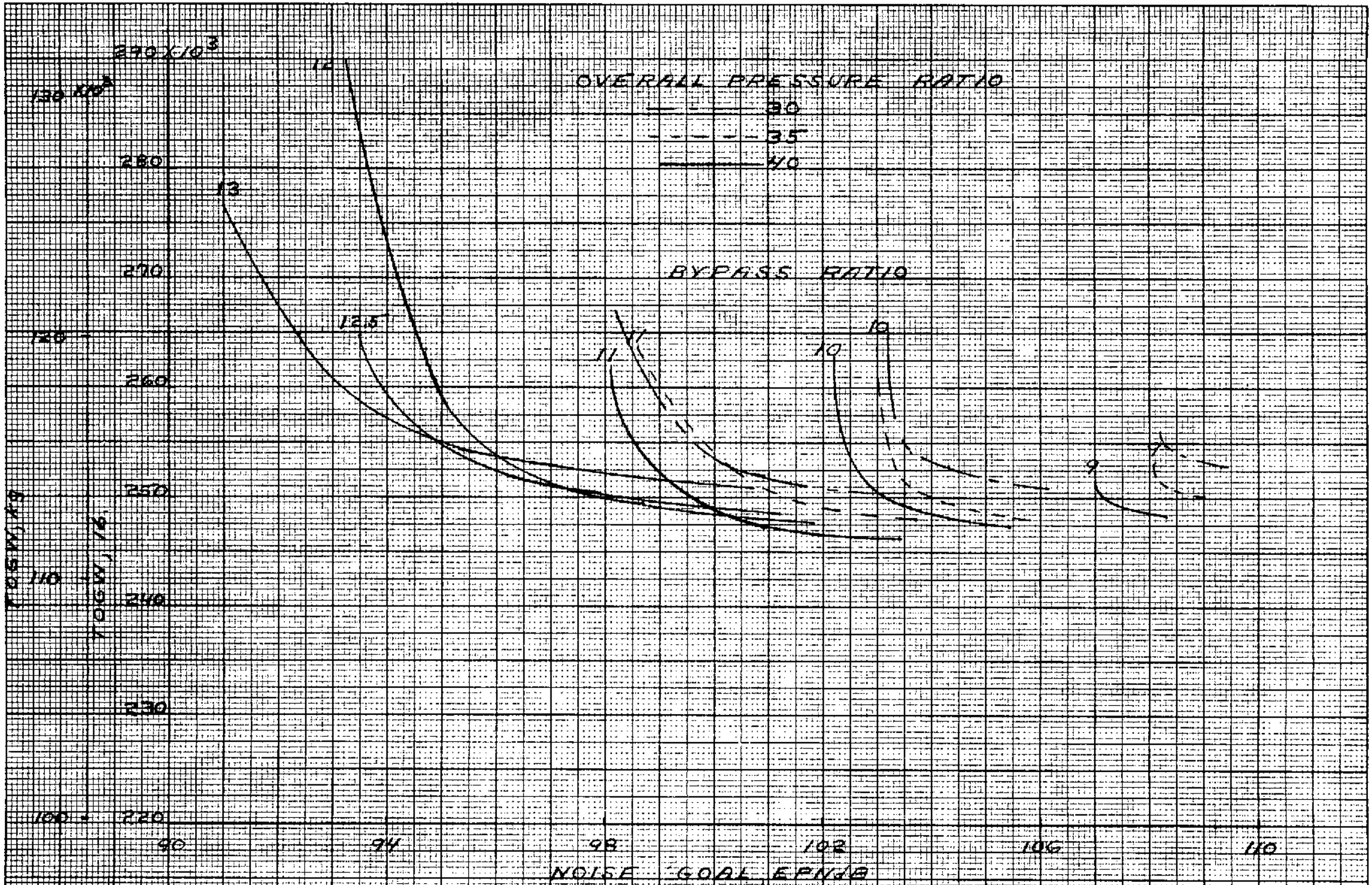
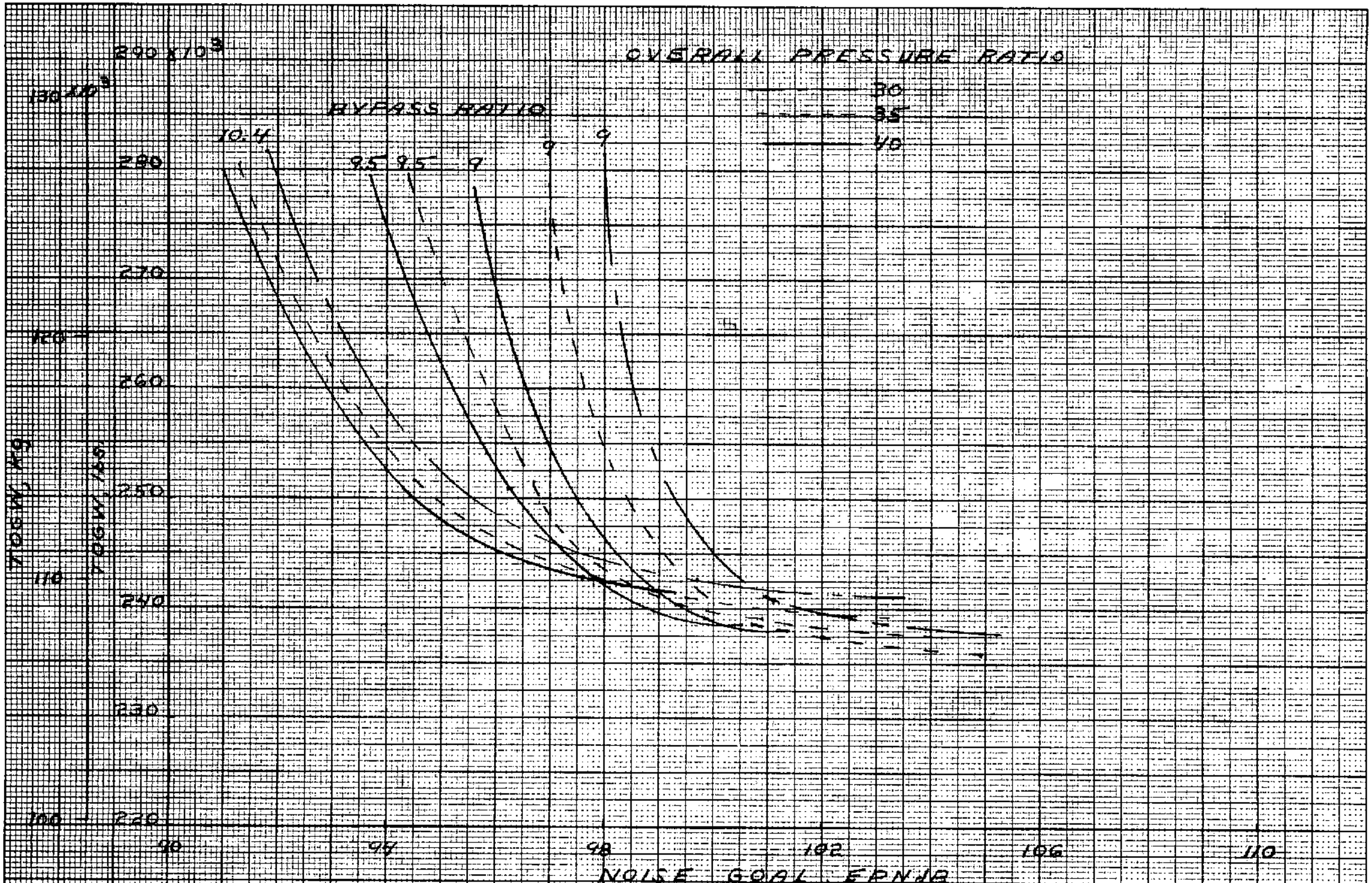


FIGURE 14. EFFECT OF COOLANT BLEED FLOW ON THE PERFORMANCE OF A TURBOFAN ENGINE. PRF=1.6, OPR=40, T_{i4} 1644K (2960°R) BPR=16.4, M=.85, 40000 ft. (12192 m)



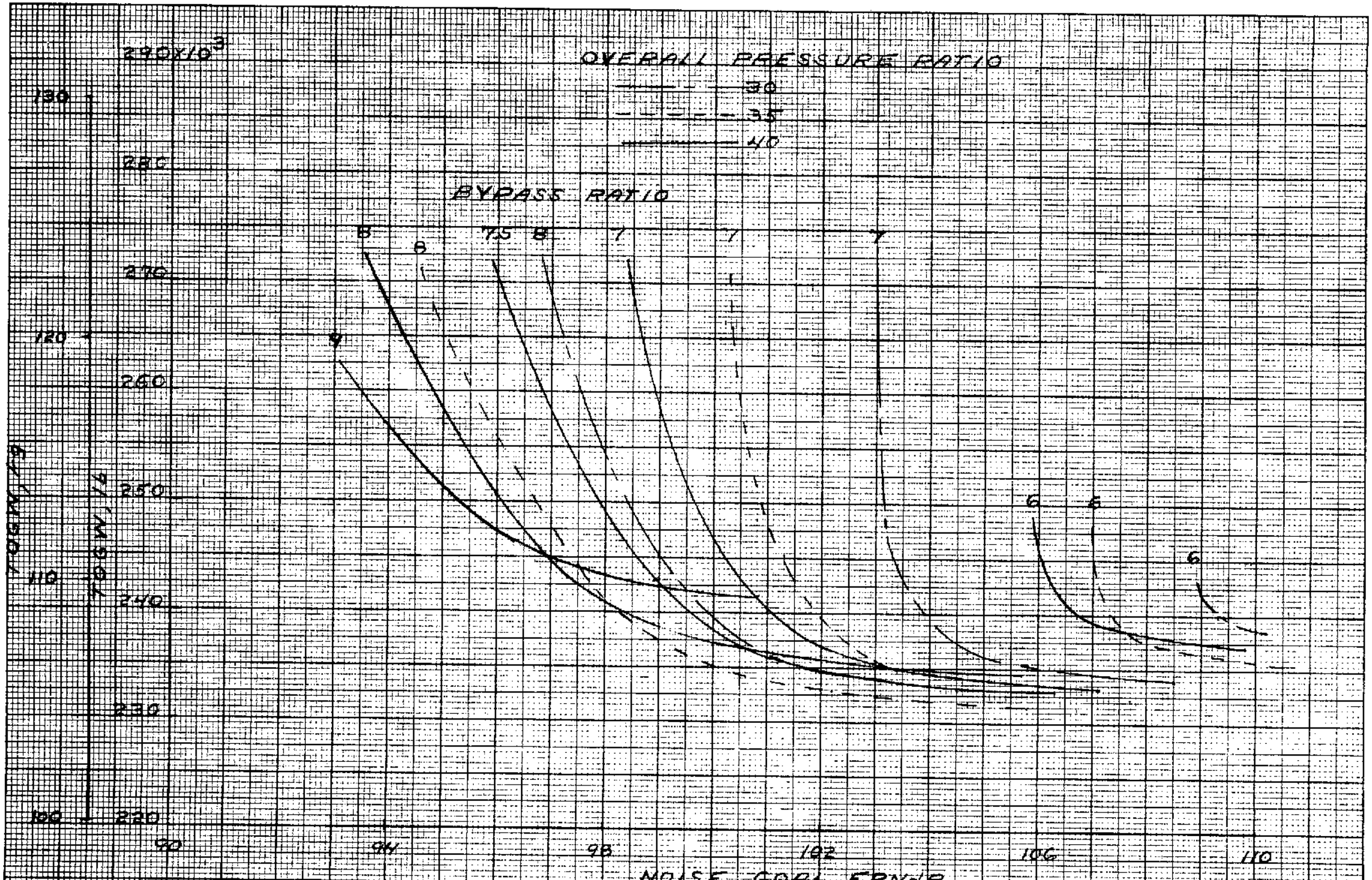
(a) FAN PRESSURE RATIO = 1.5

FIGURE 15 EFFECT OF VARIOUS ENGINE PARAMETERS ON VEHICLE TAKEOFF GROSS WEIGHT FOR VARIOUS NOISE GOALS $T_{4_{SLS}}$ = 3210 °R (1783 °K)



(b) FAN PRESSURE RATIO = 1.6

FIGURE 16 - CONT.



(C) FAN PRESSURE RATIO = 1.7

FIGURE 15.- CONCLUDED

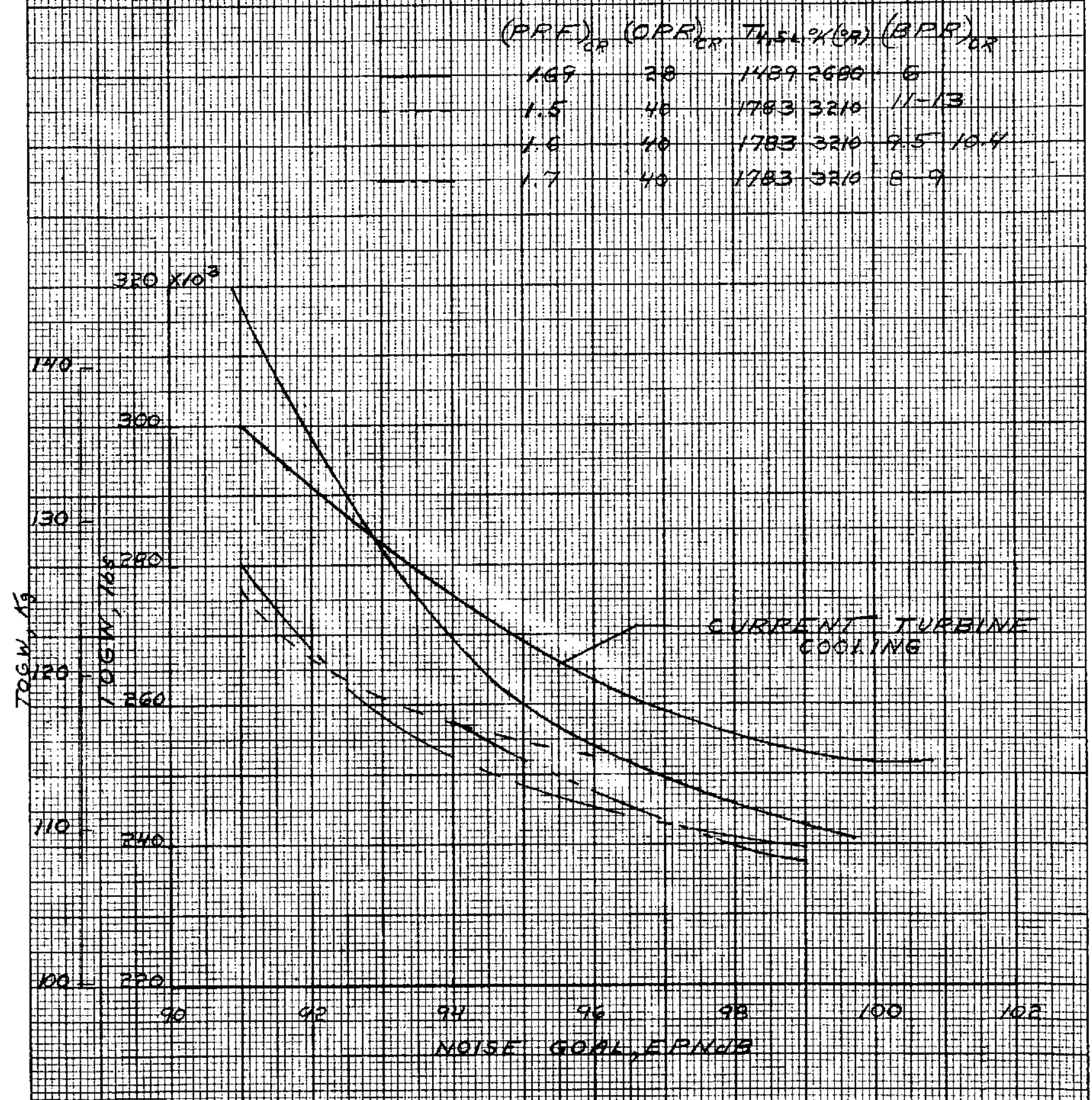


FIGURE 16 - EFFECT OF INCREASING ENGINE OVERALL PRESSURE RATIO AND BYPASS RATIO ON AIRPLANE TAKEOFF GROSS WEIGHT. FULL-COVERAGE FILM COOLING.

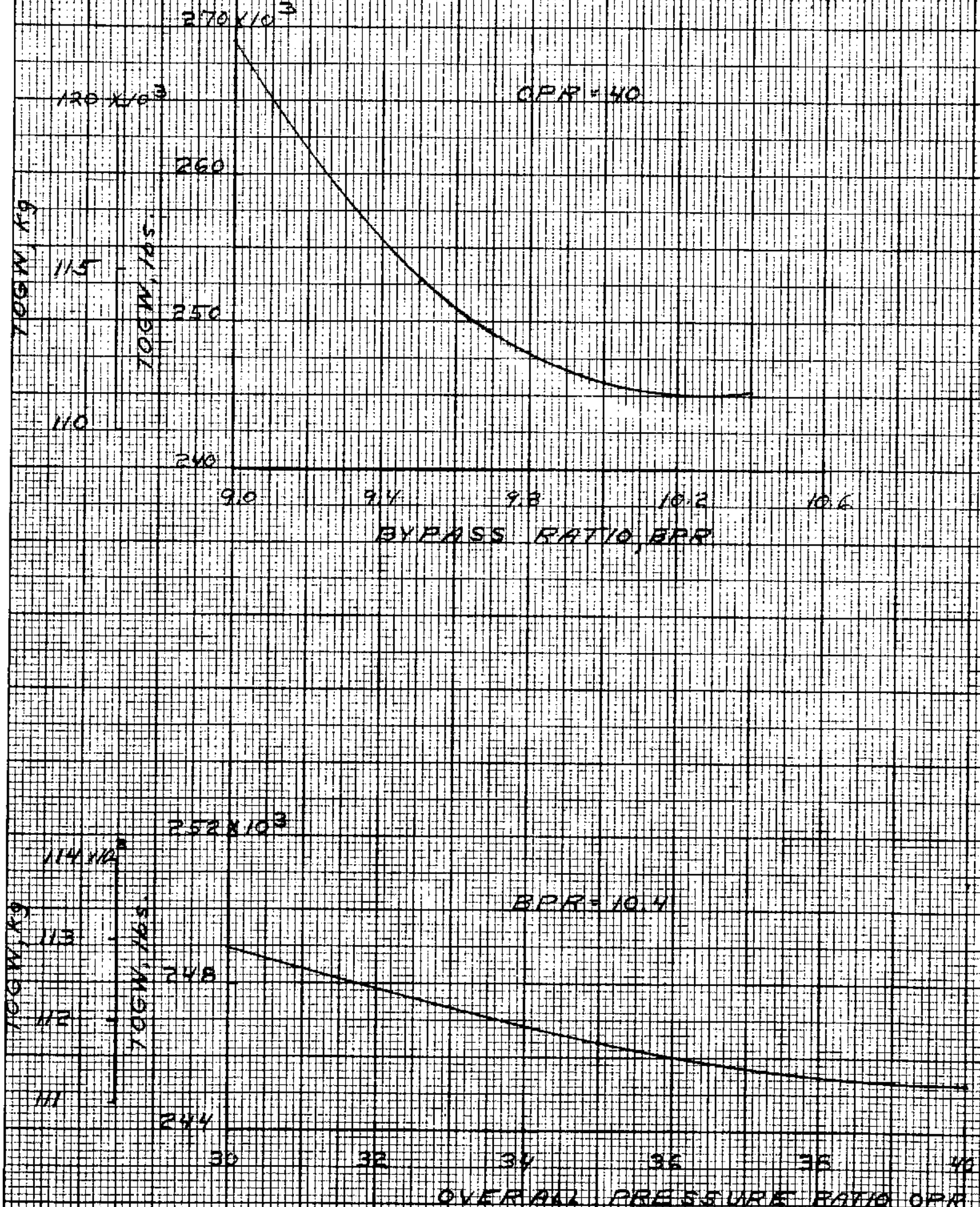
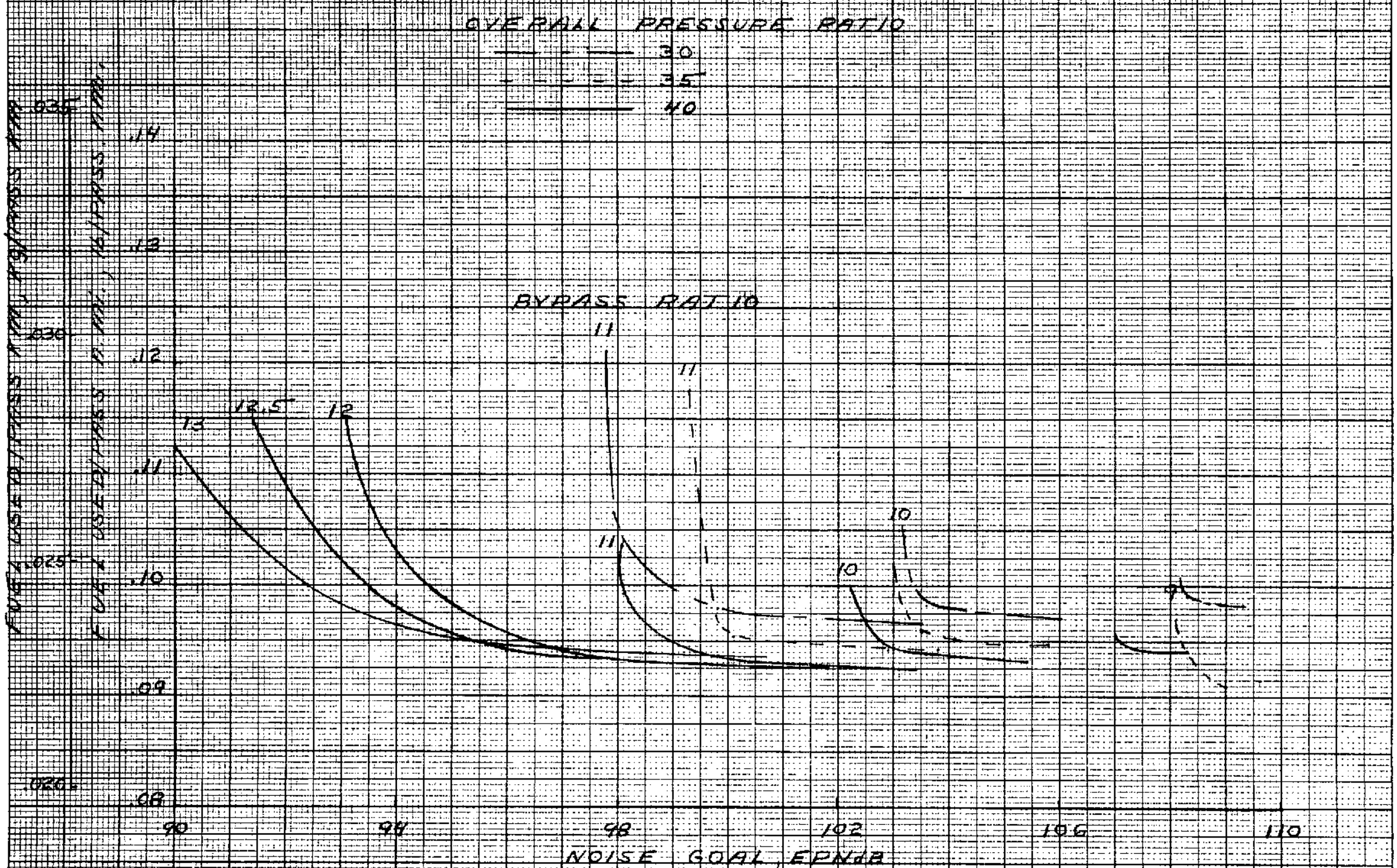
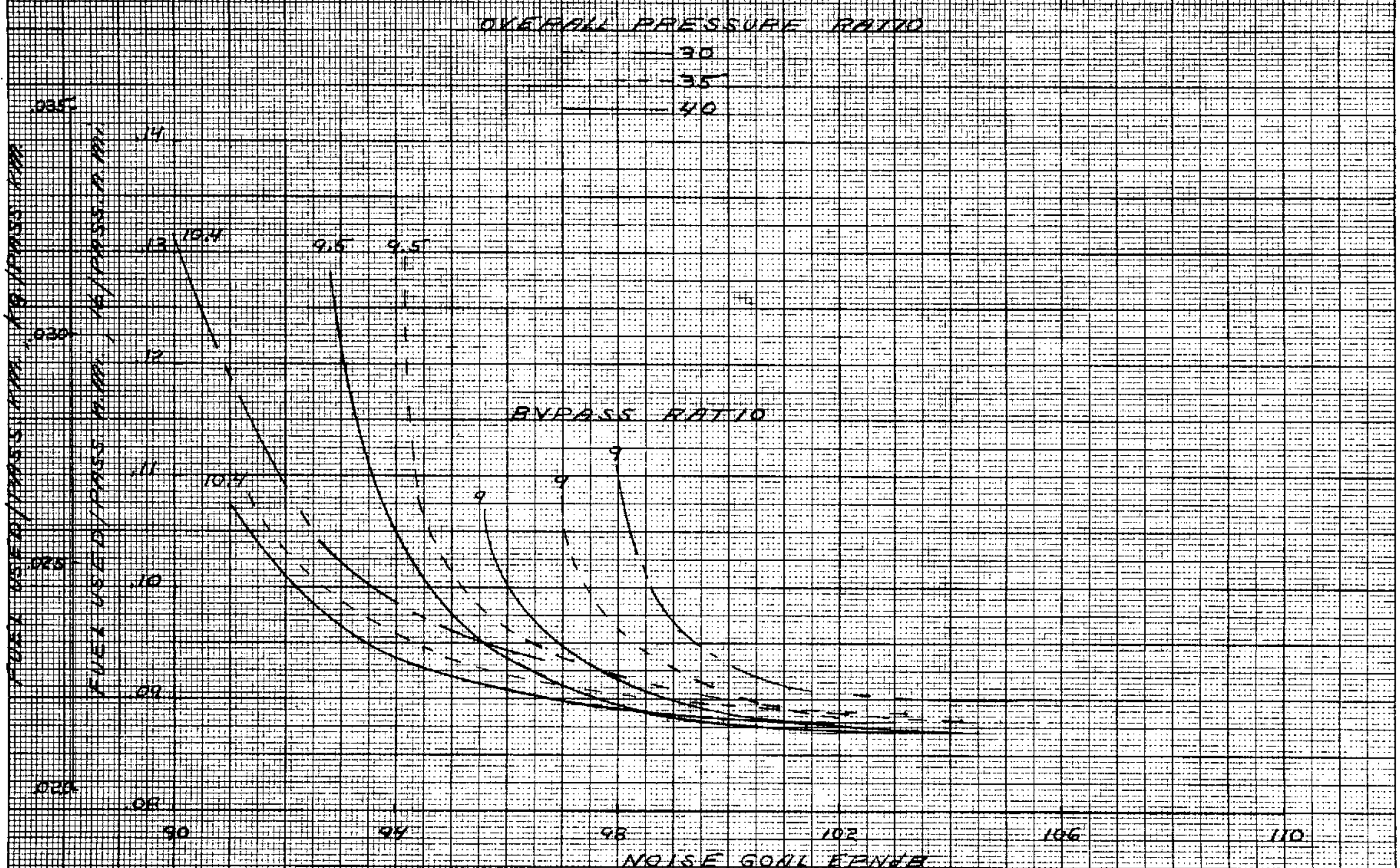


FIGURE 19 EFFECT OF ENGINE BYPASS RATIO AND OVERALL PRESSURE RATIO ON VEHICLE TAKEOFF GROSS WEIGHT FOR A NOISE GOAL OF 96EPNdB.
FPR=1.6



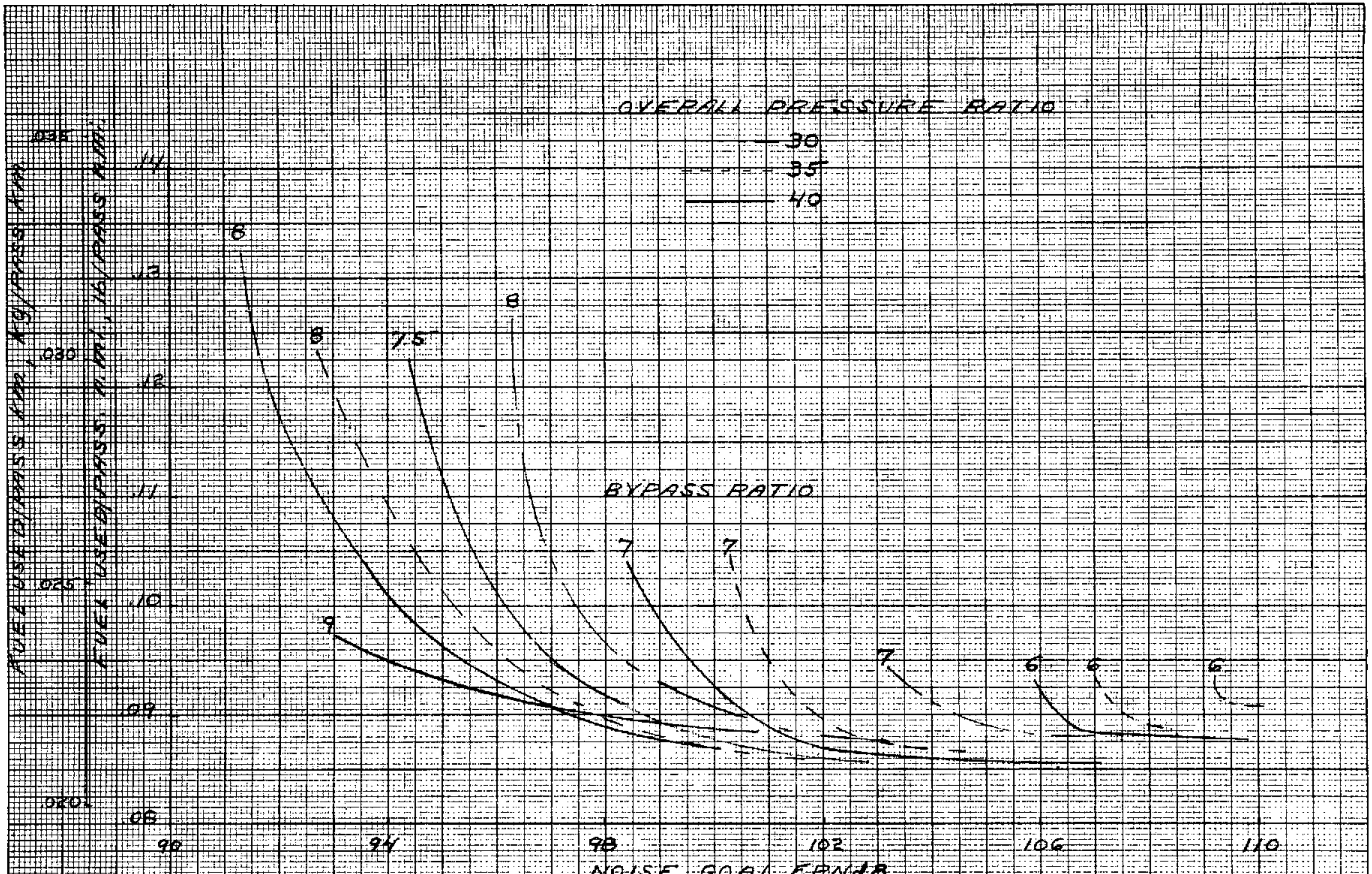
(a) FAN PRESSURE RATIO = 1.5

FIGURE 18.- EFFECT OF VARIOUS ENGINE PARAMETERS ON FUEL USED FOR VARIOUS NOISE GOALS $T_{4_{SLS}}$ = 1783°K (3210°R)



(b) FAN PRESSURE RATIO = 1.6

FIGURE 18 - CONT.



(C) FAN PRESSURE RATIO = 1.7

FIGURE 18.- CONCLUDED.

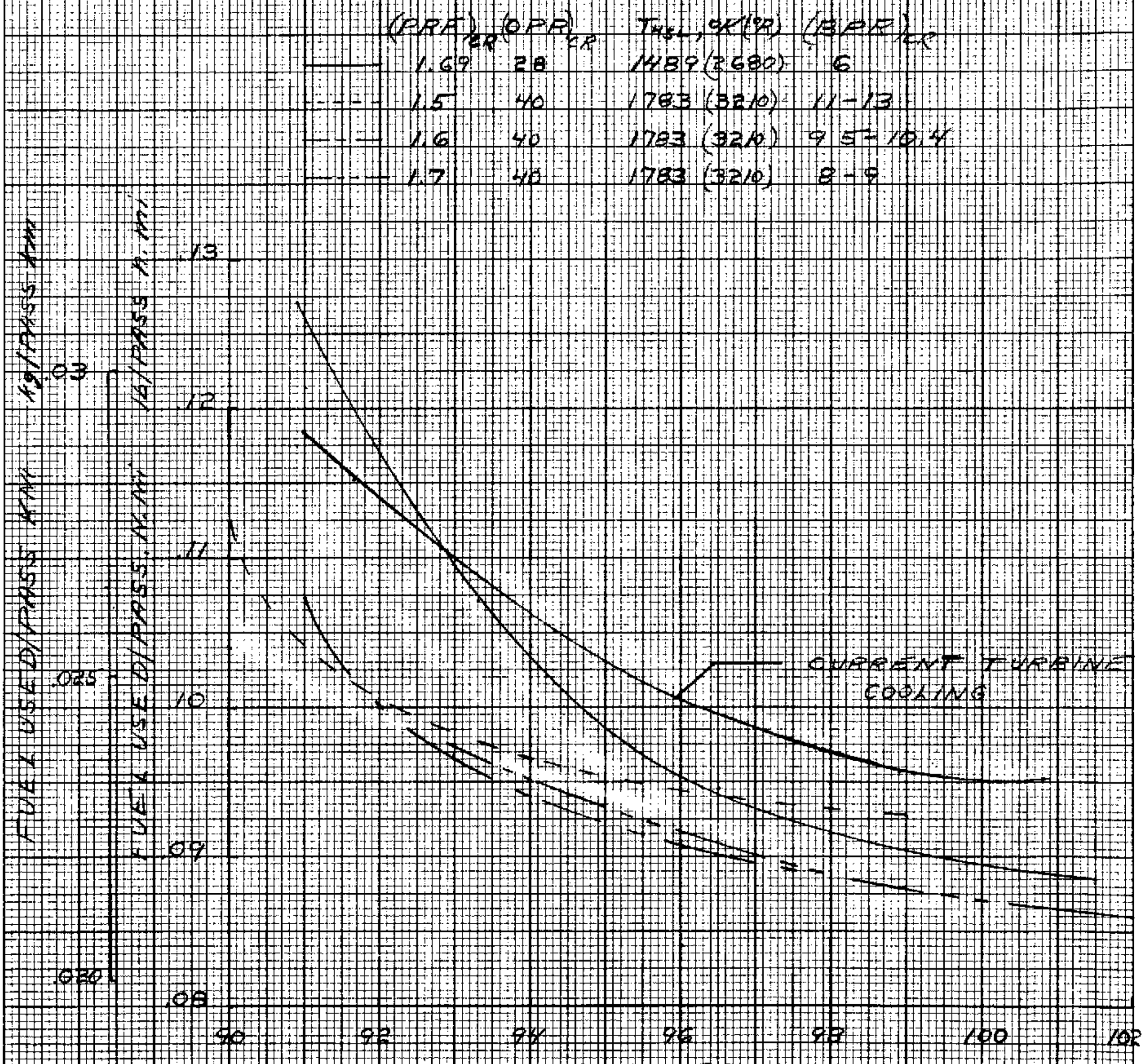


FIGURE 17- EFFECT OF INCREASING ENGINE OVERALL PRESSURE RATIO AND BYPASS RATIO ON FUEL USED PER PASSENGER N.MI. FULL-COVERAGE FILM COOLING

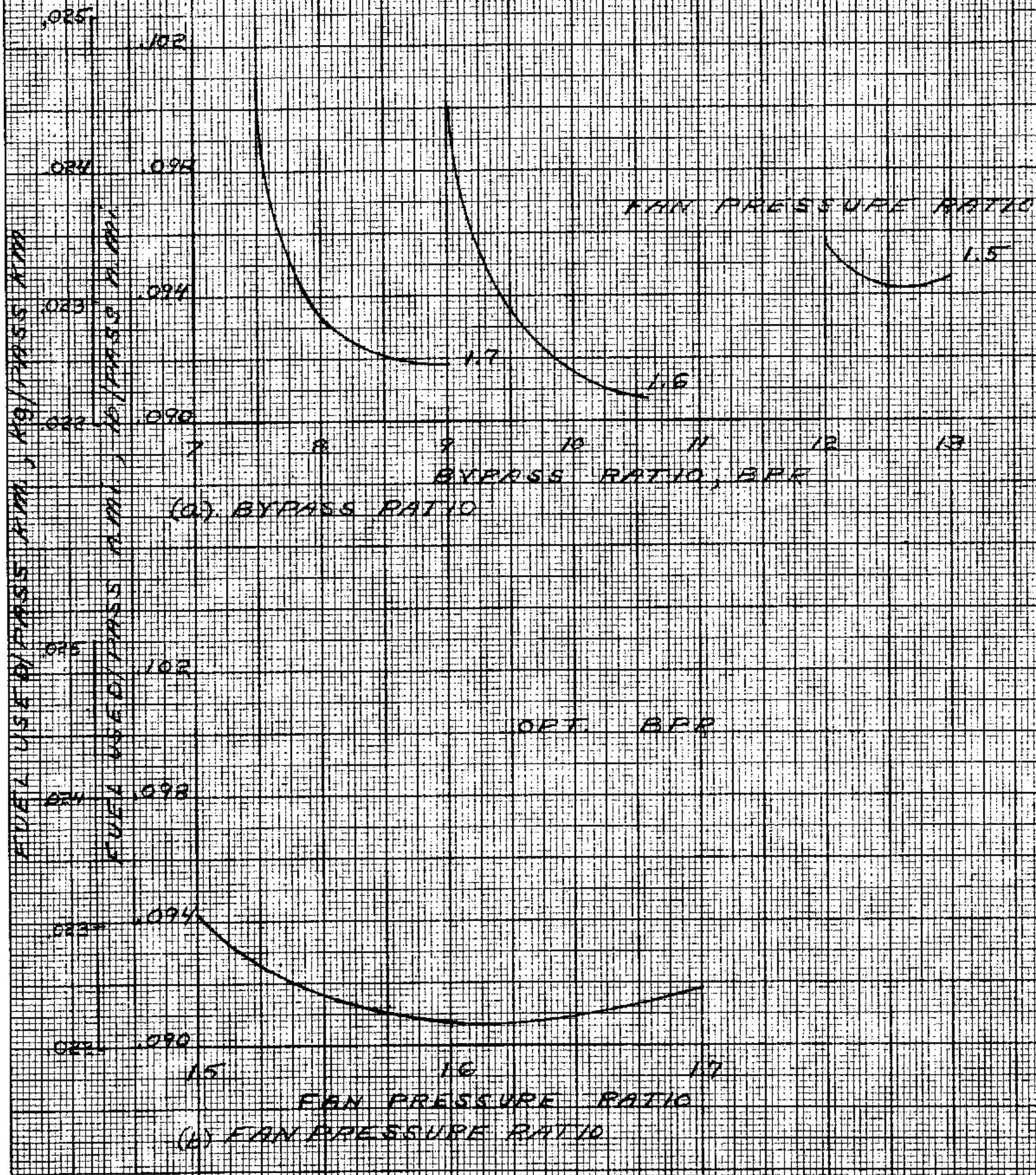
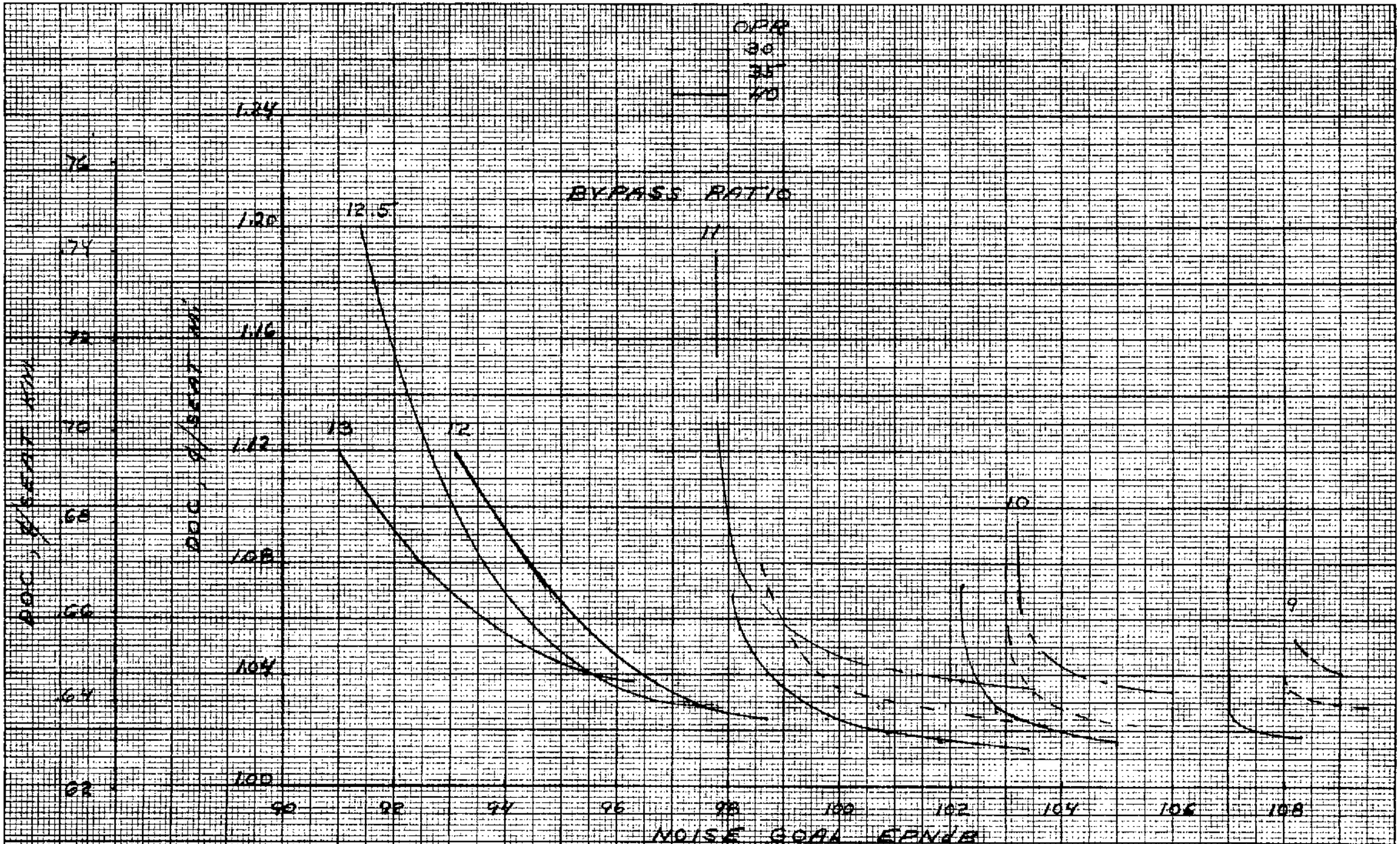
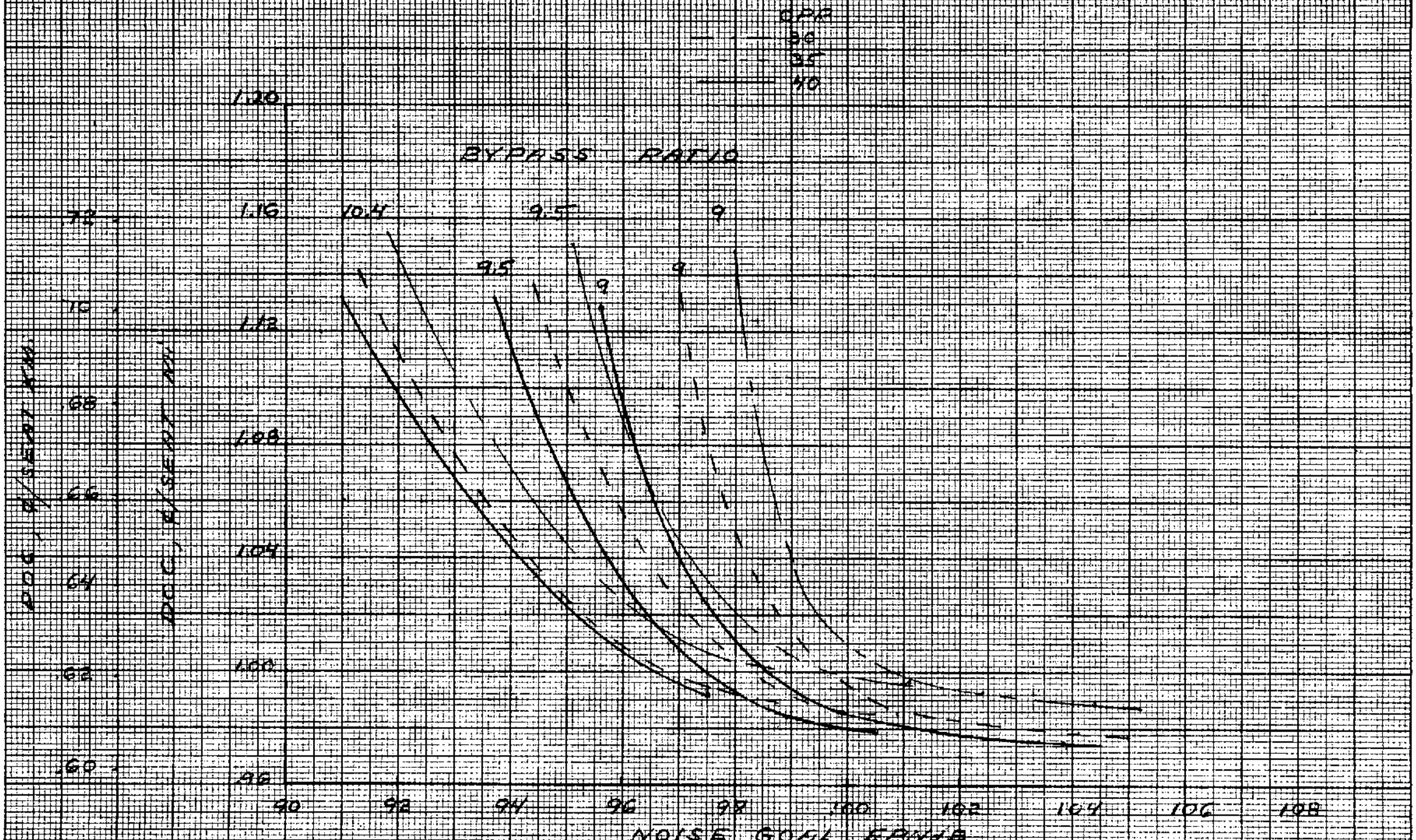


FIGURE 20.- EFFECT OF BYPASS RATIO AND FAN PRESSURE RATIO ON FUEL USED FOR A NOISE GOAL OF 96 EPNdB. OPR = 40 T_4 = 1783°K (3210°R)



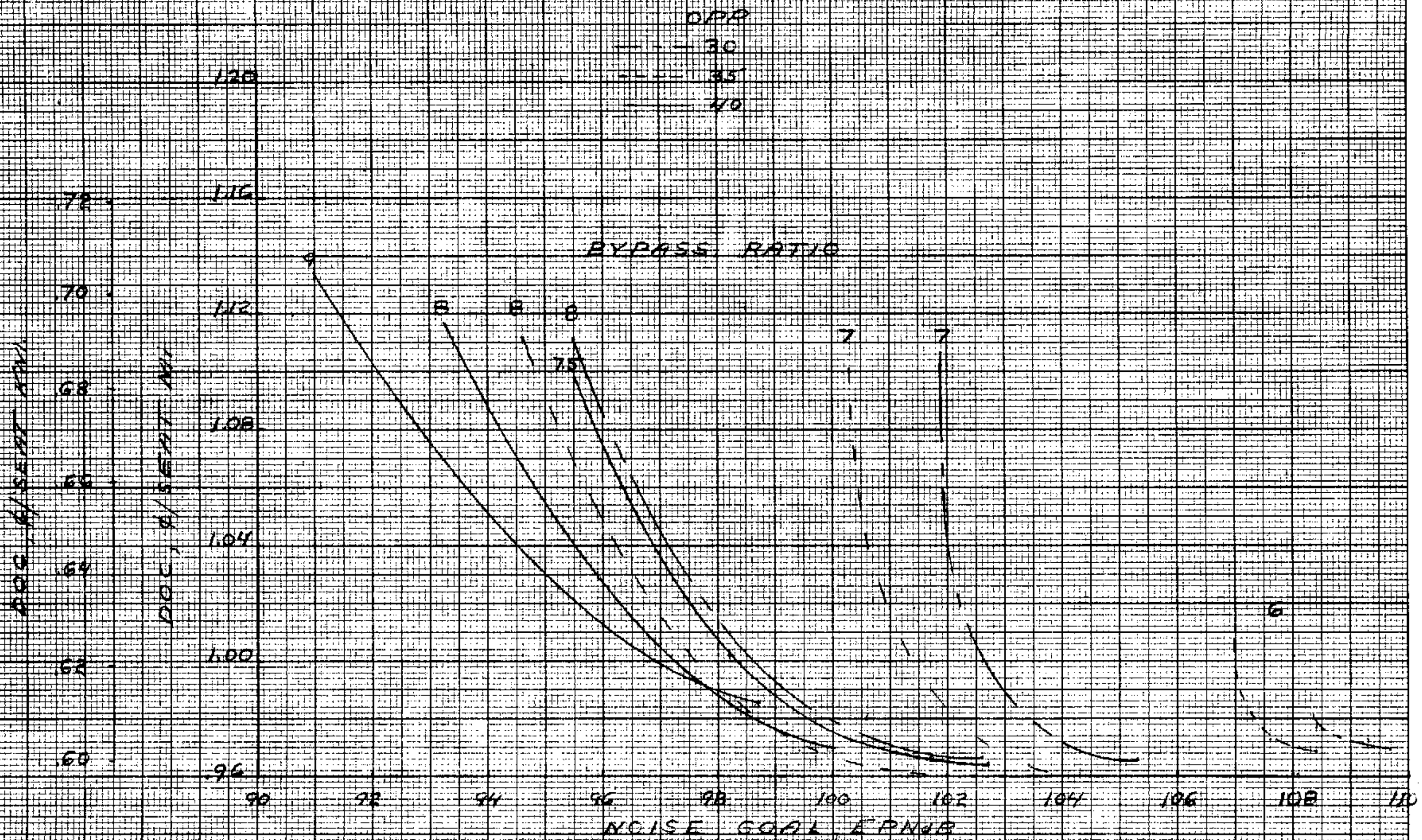
(a) FAN PRESSURE = 1.5

FIGURE 21. EFFECT OF VARIOUS ENGINE PARAMETERS ON AIRPLANE DIRECT OPERATING COST. T_{SL} = 1783K (3210R); FUEL COST 79.3¢/m³ (30¢/gal)



(b) FAN PRESSURE RATIO - 1.6

FIGURE 21.- CON'T



(c) FAN PRESSURE RATIO = 1.7

FIGURE 21.- CONCLUDED.

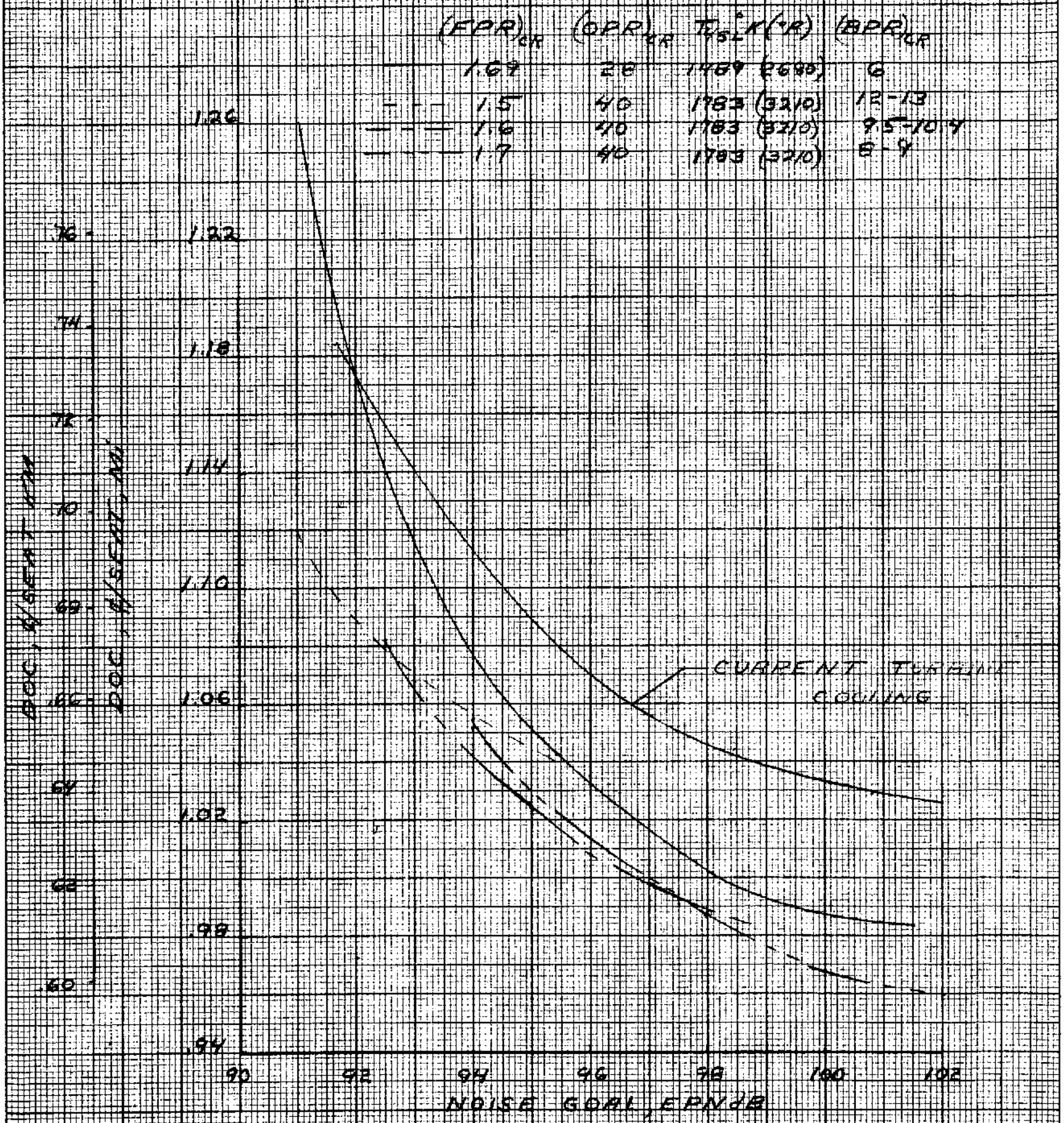


FIGURE 22 EFFECT OF INCREASING ENGINE OVERALL PRESSURE RATIO AND BYPASS RATIO ON AIRPLANE DIRECT OPERATING COST. FULL-COVERAGE FILM COOLING. FUEL COST 79 ¢/M³ (30 ¢/gal.)

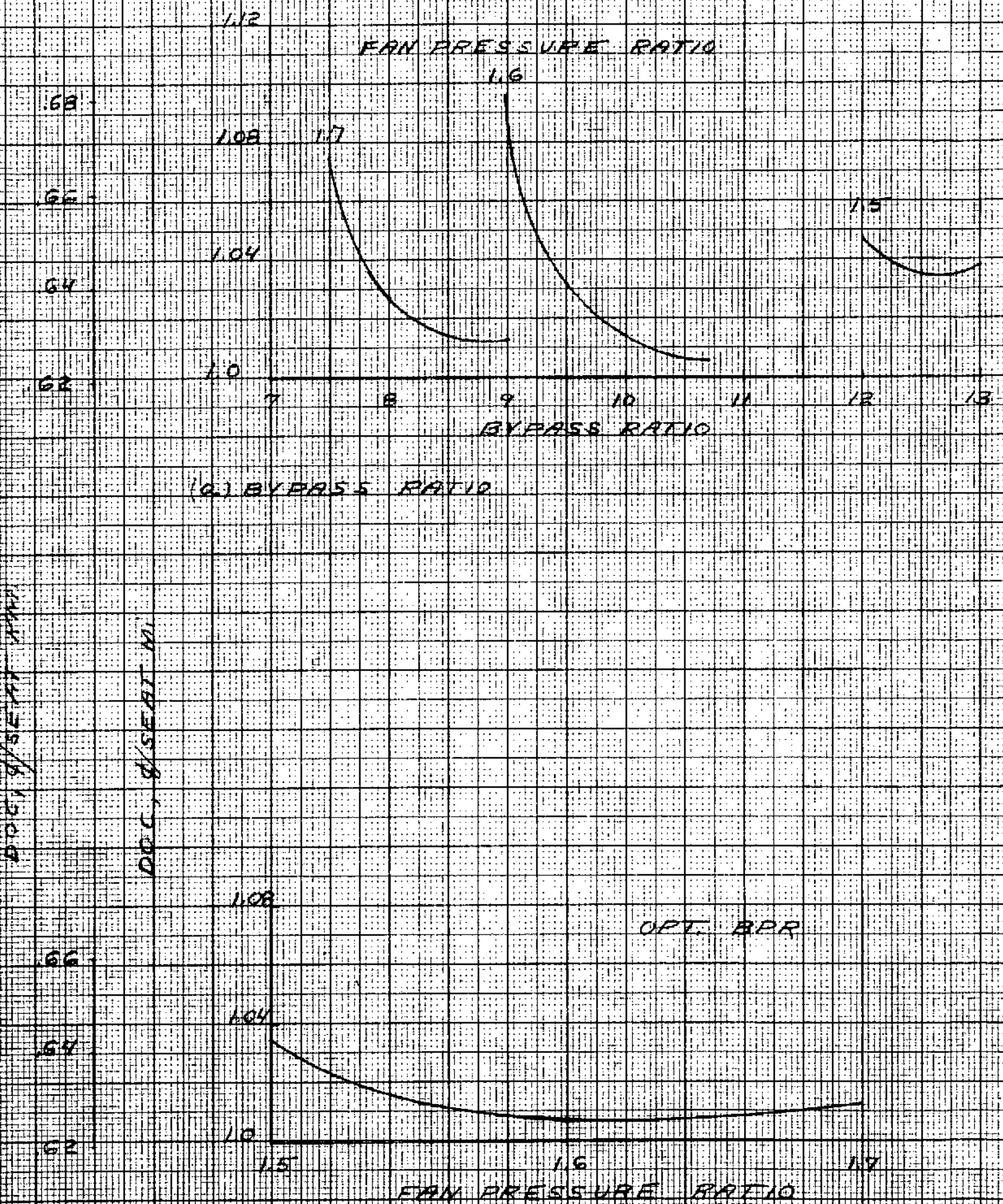


FIGURE 23. EFFECT OF BYPASS RATIO AND FAN PRESSURE RATIO ON DOC FOR A NOISE GOAL OF 96 EPNdB OPR=40 T_{4SC} = 1793°K (3210°R) FUEL COST 79.3 $/m³ (30¢/GAL)

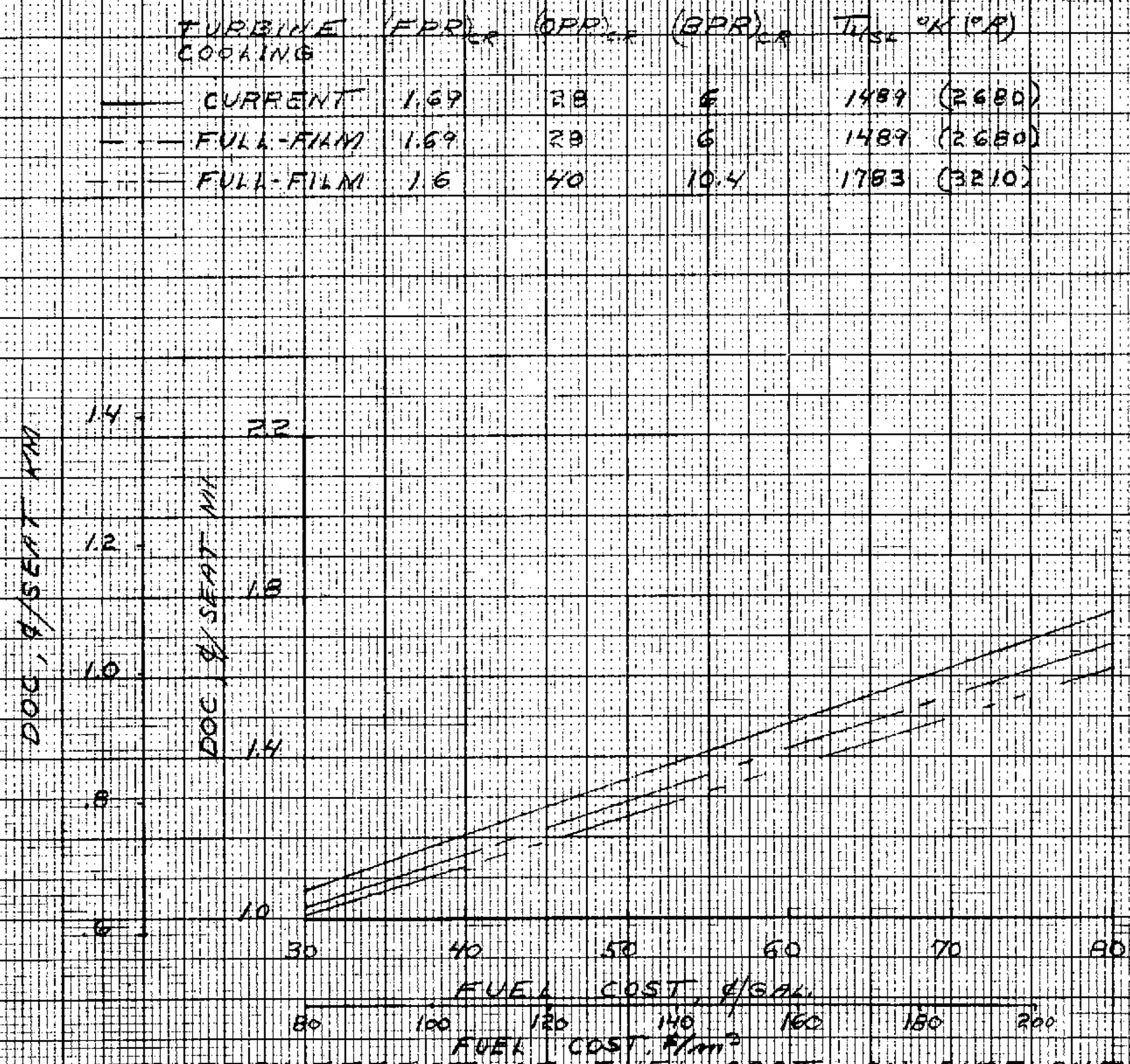


FIGURE 24-EFFECT OF FUEL COST ON AIRPLANE DIRECT OPERATING COST FOR VARIOUS ENGINES. 96 EPNdB

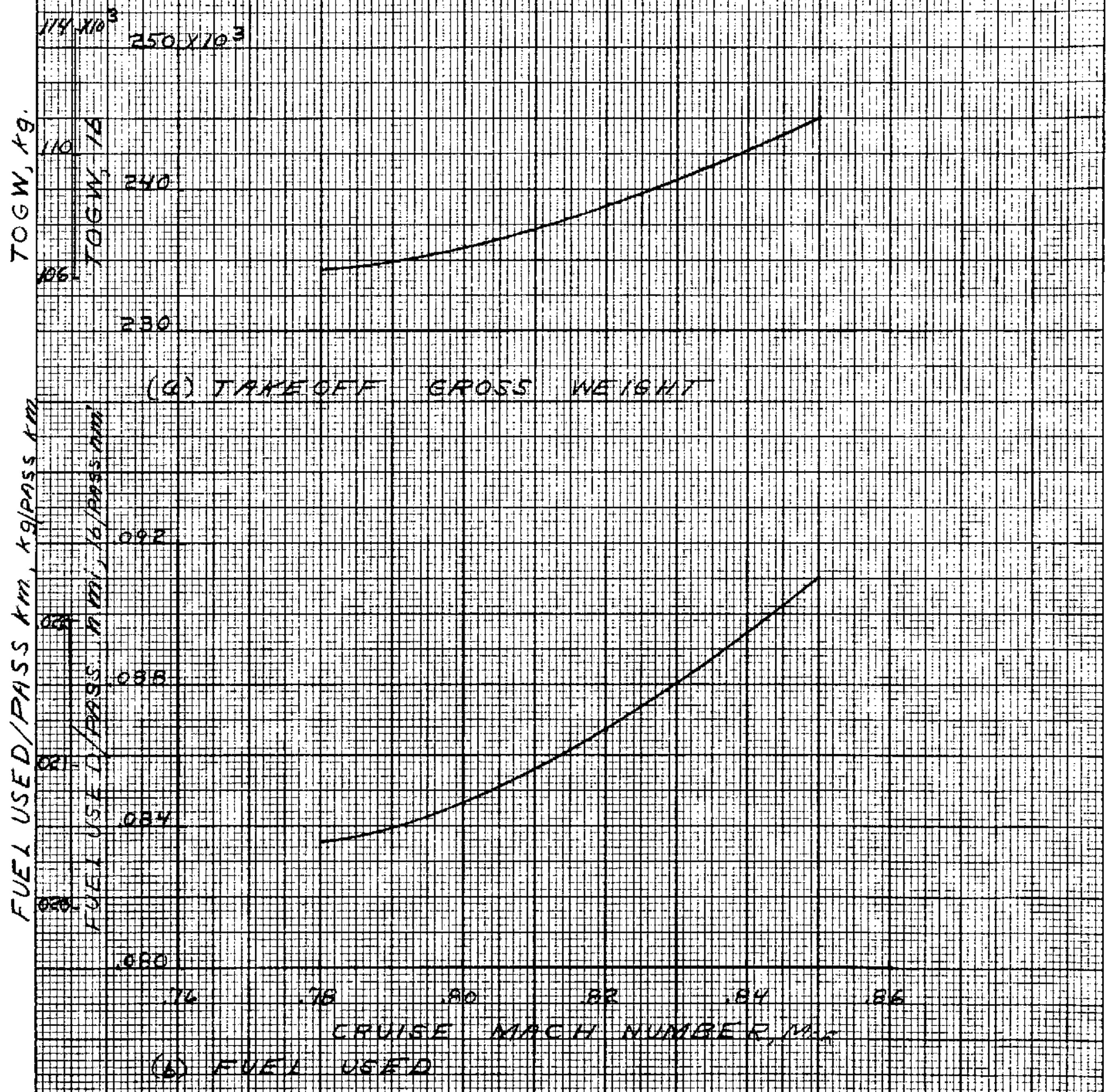


FIGURE 25 EFFECT OF CRUISE MACH NUMBER ON VEHICLE TOGW AND FUEL USED. FPR = 1.6, OPR = 40, BPR = 4.0, T_{t02} = 1783°K (3210°R) 96 EPNdB

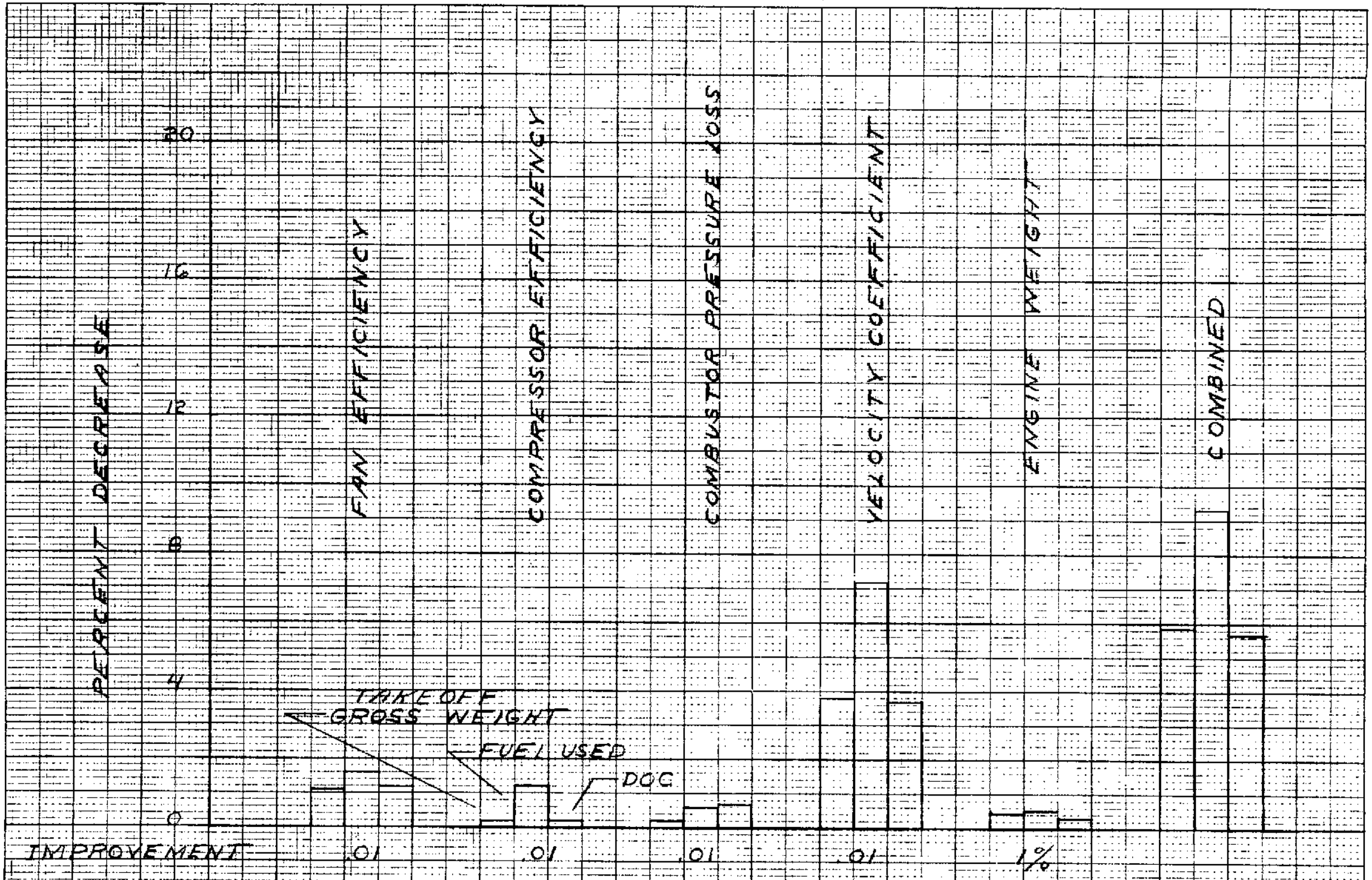


FIGURE 26 - SENSITIVITY OF AIRPLANE TAKEOFF GROSS WEIGHT, FUEL USED PER PASSENGER KM AND DOC TO VARIOUS ENGINE PARAMETERS. FPR = 1.6, CPR = 40, BPR 10.35, T_{t4} = 1783K (3210F), M = .85 96 EPNdB, FUEL COST = 77.3 $/m³ (30¢/gal)

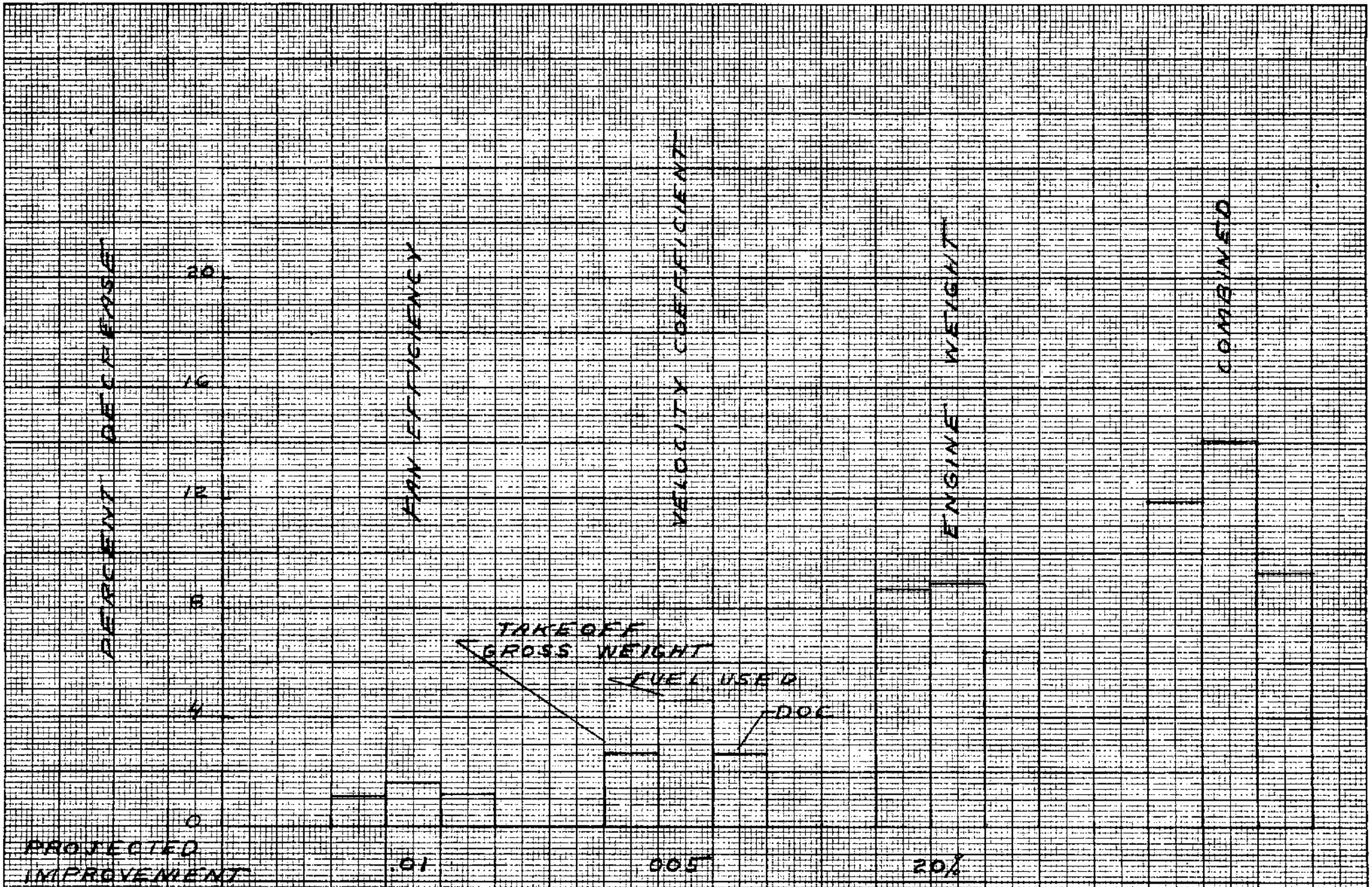


FIGURE 27 EFFECT OF PROJECTED IMPROVEMENT OF VARIOUS ENGINE COMPONENTS ON AIRPLANE TAKEOFF GROSS WEIGHT, FUEL USED PER PASSENGER Km, AND DOC. FPR 1.6 OPR 40 BPR 10.35, T_{4SL} 1783K (3210R), η_C .85, 96 EPNdB FUEL COST 7.9¢/l (30¢/gal.)

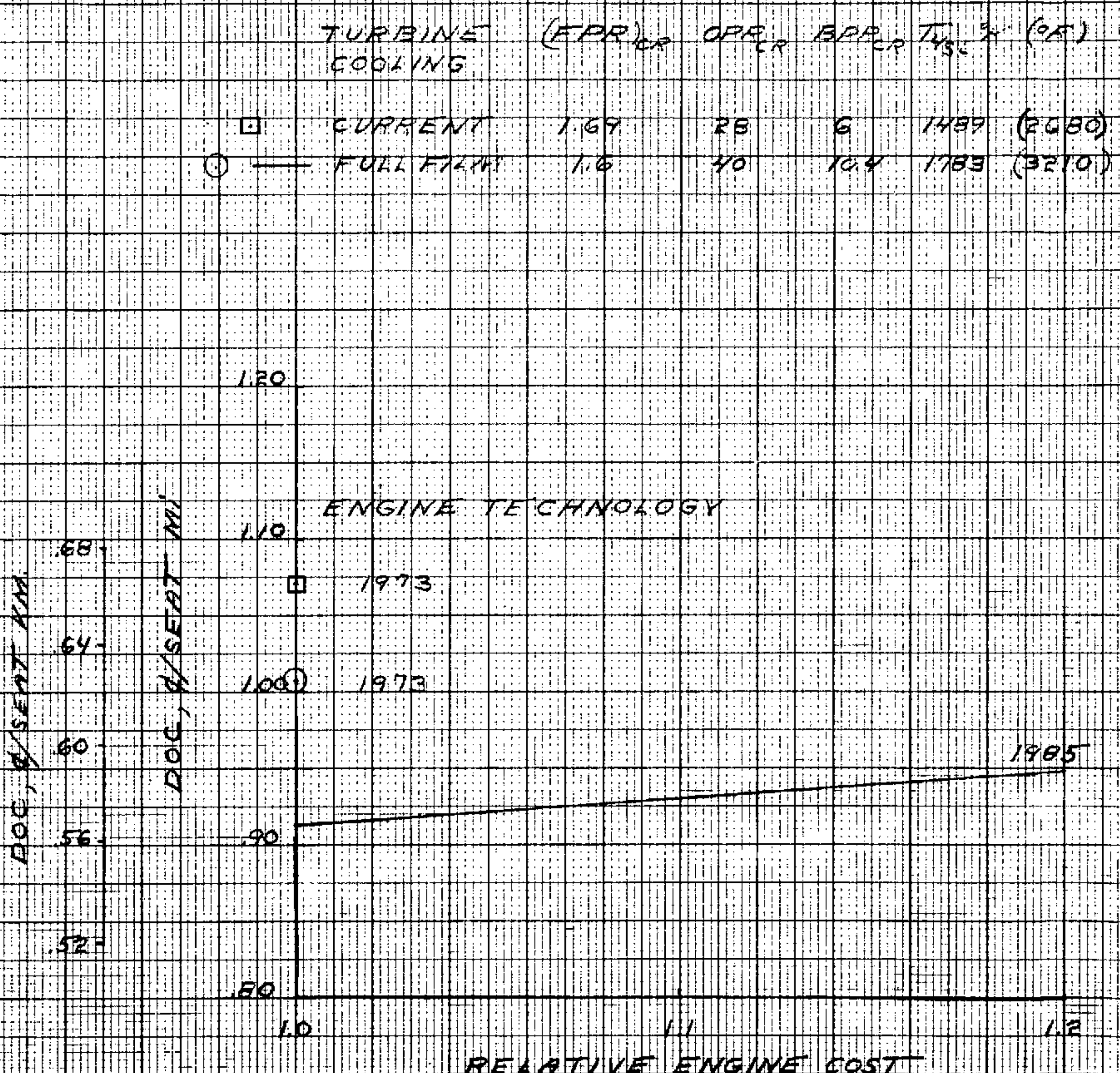


FIGURE 28 EFFECT OF ENGINE TECHNOLOGY AND COST ON AIRPLANE DIRECT OPERATING COST. 96 EPNdB FUEL COST 79.3 ¢/m³ (30¢/gal)