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ADVANCED SUPERSONIC PROPULSION STUDY
FINAL REPORT

PRATT & WHITNEY AIRCRAFT DIVISION
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16. Abstract

A study was conducted to determine the promising propulsion systems for advanced supersonic transport application and to identify the critical propulsion technology requirements. The study showed that noise constraints have a major effect on the selection of the various engine types and cycle parameters. Several promising advanced propulsion systems were identified which showed the potential of achieving lower levels of sideline jet noise than the first generation supersonic transport systems. The non-afterburning turbojet engine, utilizing a very high level of jet suppression, showed the potential to achieve FAR 36 noise level. The duct-heating turbofan with a low level of jet suppression was the most attractive engine for noise levels from FAR 36 to FAR 36 minus 5 EPNdB, and some series/parallel variable cycle engines showed the potential of achieving noise levels down to FAR 36 minus 10 EPNdB with moderate additional penalty. The study also showed that an advanced supersonic commercial transport would benefit appreciably from advanced propulsion technology. However, an intensive research and development program must be undertaken to bring this technology to the state where it could be incorporated into development powerplants. The critical propulsion technology needed for a viable supersonic propulsion system and the required specific propulsion technology programs are outlined at the end of the report.

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ADVANCED SUPERSONIC PROPULSION STUDY
FINAL REPORT

OVERVIEW

The National Aeronautics and Space Administration is engaged in a study of the application of advanced technology to long-range, supersonic, commercial transport aircraft with emphasis on reduced noise and emissions and improved economics. As part of this overall effort, an advanced supersonic propulsion system technology study was conducted. The objective of the study was to determine promising propulsion systems based on advance technology and to identify technology programs necessary to provide a sound basis for design and development of a viable supersonic transport propulsion system. This information will be needed to permit sound judgement on an advanced supersonic transport if a decision is made to proceed with that project. A wide variety of conventional and unconventional propulsion systems were studied over a wide range of cycle variables. The conventional engines included the non-afterburning turbojet, the afterburning turbojet, the duct-heating turbofan, and the afterburning turbofan. The unconventional engines included variable cycle concepts of the series/parallel type, the augmented wing concept, the auxiliary engine concept, and the turbofan ramjet concept. Two component-technology levels were defined for purposes of engine definition: 1975 and 1980 technologies. This component technology is that which could generally be demonstrated in the respective time period and committed to an engine development program.

The study showed that noise constraints have a major impact on the selection of the various engine types and cycle parameters. Several promising advanced propulsion systems were identified as having the potential of achieving lower noise levels and emissions with better system economics than the first generation SST systems. The non-afterburning turbojet, utilizing a high level of jet suppression was a competitive engine around the FAR 36 noise level. The duct-heating turbofan with a low level of jet suppression was the most attractive engine for noise levels from FAR 36 to FAR 36 minus 5 EPNdB. The series/parallel variable cycle engine was competitive at FAR and FAR 36 minus 5 EPNdB and had the potential of achieving noise levels down to FAR 36 minus 10 EPNdB with additional moderate penalty. An additional study covering the complete integrated airframe/propulsion system is required before final selection of a propulsion system can be made.

The study also showed that an advanced supersonic commercial transport would benefit appreciably from the application of advanced propulsion technology. These benefits can be realized in terms of better overall system economics, lower noise levels, and reduced emissions. However, an intensive research and development program must be undertaken to bring the advanced propulsion technology to the state where it could be incorporated into a development powerplant. In addition to the environmental benefits of low emission primary burners and duct-heaters and advance jet noise suppressors, technologies with the greatest potential economic benefit were identified in the areas of aerodynamic loading and material improvements in turbines, fans, compressors, and burners. Also large potential gains are possible through improved design of the nozzle/suppressor/reverser for all the engines and unique components, such as a flow diverter valve, for the series/parallel variable cycle engines. Follow-on technology programs were formulated in Task VI for the most important technology items.

The application of hydrogen as a fuel for an advanced supersonic commercial transport was also studied. These studies included many cycles which were designed to take advantage of the unique properties of hydrogen and showed that the basic turbojet/turbofan cycles were still the best cycles for a hydrogen fueled, advanced supersonic transport application. Liquid hydrogen provides rapid and clean combustion and can readily be used in gas turbine engines without requiring development of any new technology. However, the economic advantages are extremely questionable in view of the high cost involved for both the fuel and the fuel distribution system.

INTRODUCTION

The National Aeronautics and Space Administration is engaged in a study of the application of advanced technology to long-range, supersonic, commercial transport aircraft with emphasis on reduced noise and emissions and improved economics. As part of this overall effort, an advanced supersonic propulsion system technology study was conducted under Contract NAS3-16948 by P&WA™. The objective of this study was to determine the promising propulsion systems based on advance technology and to identify the technology programs necessary to provide a sound basis for design and development of a viable supersonic transport propulsion system. This information will be needed to permit sound judgement on an advanced supersonic transport if a decision is made to proceed with that project.

The work under this contract, NAS3-16948, covered the areas of conventional and unconventional JP fueled engines, 1975 and 1980 component technology definitions, and the use of hydrogen fuel. The study was organized into six tasks planned to achieve the overall objectives. All six tasks have been completed and individual task reports have been prepared. This report summarizes the work performed in each task and presents the more important results.

- Task I - Parametric Study of Conventional Engines

  A study of conventional engines (non-afterburning and afterburning turbojets and duct-heating and afterburning turbofans) based on component technology available in 1975 for purposes of engine definition at that time.

- Task II - Variable Cycle Engine Study

  A study of variable cycle engines capable of varying their mode of operation in flight; based on 1975 technology.

- Task III - Advanced Technology Study of Conventional and Variable Cycle Engines

  Similar to Tasks I and II except based on 1980 technology.

- Task IV - Hydrogen Fueled Engines

  Conventional and unconventional engines using hydrogen fuel; based on 1980 technology.

- Task V - Refined Engine Study

  Refined study of promising Tasks I and II engines.

- Task VI - Technology Evaluation

  Identification of critical technology areas and formulation of required technology programs.

SUMMARY

The work under this contract covered the areas of conventional and unconventional JP fueled engines, 1975 and 1980 component technology definitions, and the use of hydrogen fuel for an advanced supersonic transport application. The study was organized into six Tasks planned to achieve the overall study program objectives. Tasks I, II and V concerned 1975 technology JP fueled engines. During Task I, a screening of conventional engine cycles was made to identify the most promising engine types for further study. During Task II, a screening of unconventional engine types was made to identify the most promising types for further study. More refined studies of the most promising Task I and II 1975 technology engines was conducted during Task V, and the bulk of the discussion and presentation of results are made in the Task V section.

The impact of 1980 engine component technology on system performance and economics was evaluated in Task III, and the technology items showing the greatest potential for system improvements were identified. During Task VI, technology development programs were formulated for the critical components identified in Task III. An investigation of the impact of hydrogen fuel on engine design and component development requirements was made during Task IV.

The results of each Task are summarized below.

TASK I: PARAMETRIC STUDY OF CONVENTIONAL ENGINES (1975 TECHNOLOGY)

The objective of Task I was to determine the most attractive conventional engine types and the desirable range of engine cycle parameters for a second generation supersonic transport designed to reduce noise and emissions below current levels. Assuming 1975 technology, a consistant set of parametric engines covering a wide range of cycle variables was defined for (1) non-afterburning (dry) turbojets, (2) afterburning (A/B) turbojets, (3) duct-heating (D/H) turbofans and (4) afterburning (A/B) turbofans. Cruise Mach numbers of 2.2, 2.7, and 3.2 were considered. Performance weight, cost, and dimensional data for most of the parametric engines were submitted by P&WA to airframe companies who under a contract to NASA-Langley were conducting parallel studies of advanced supersonic aircraft, including propulsion integration. To assist in the engine cycle selection process, P&WA calculated aircraft takeoff-gross-weight (TOWG), direct operating cost (DOC), and airline return-on-investment (ROI) for the complete matrix of engines studied, based on NASA airplane and mission definitions. The aircraft defined for the analysis was a modified arrow wing (SCAT 15F) configuration. The aircraft was sized to carry 236 passengers a total range of 4000 NM (7412 KM) including a 600 NM (1112 KM) subsonic leg.

The non-afterburning turbojet and the duct-heating turbofan were identified as the two most promising engine configurations (Figure 1S). The duct-heating turbofan had a significantly lower TOGW than any other engine for noise levels from FAR36 down to FAR36 minus 10 EPNdB.

The TOGW with turbojet engines was very sensitive to design noise level, and they required a high level of jet suppression in order to meet FAR36. Maximum combustor exit temperatures on the order of 2600°F to 2800°F (1427°C to 1538°C) and overall pressure ratios of 12:1 to 20:1 were found to offer best overall performance.

The duct-heating turbofans can meet a given noise objective with less jet noise suppression than the turbojets. Maximum combustor exit temperatures of 2600°F to 2800°F (1427°C to 1538°C) were also most attractive for the turbofans. Fan pressure ratios in the range of 2.5 to 4 gave best overall performance.

TASK II: VARIABLE CYCLE ENGINES (1975 TECHNOLOGY)

Whereas the Task I study concerned conventional engines for the supersonic transport, the Task II objective was to investigate unconventional (variable cycle) concepts for the same application, and identify the more promising ones for further study to determine their full potential. The engine technology time period (1975) as well as the systems analysis assumptions were consistent with those used in Task I.

The unconventional engine concepts studied in Task II were as follows:

- Series/Parallel Variable Bypass Engine (VBE).

  These are self-contained engines employing two or more fans or compressors with a flow diverter valve between them. The bypass ratio and total airflow of this type engine increases when switched from series to parallel modes.

- Augmented Wing Concept

  This system employs a low bypass ratio propulsion engine which has a valve for diverting flow into the wing ejector/flap system for suppressing jet noise during low noise operation.

- Auxiliary Engine Concept

  This concept employs an optimum main propulsion engine plus light-weight, low noise remote engines which are used for takeoff, landing, and possibly other subsonic flight conditions.

- Turbofan Ramjet

  This self-contained, variable cycle concept combines a high bypass ratio turbofan with an integral ramjet.

Engine performance, weight, cost, and dimensional data were sent to the Langley airframe contractors for evaluation. In addition, a P&WA evaluation was made as an aid to cycle optimization and for comparison of concepts. The variable bypass engine series/parallel concept was identified as one of the most promising of the variable cycles studied. A variable bypass engine series/parallel cycle, designated as VBE I was selected for further more refined analysis in Task V. A schematic of the VBE I type variable cycle is shown in Figure 2S. This engine employs two fans which could operate either in series or parallel, permitting a wide range of operation. When operating in the series mode at supersonic cruise, this series/parallel engine operates as a conventional low bypass ratio duct-heating turbofan, as shown in the lower half of the schematic. During parallel operation at takeoff and subsonic cruise when lower jet velocities are desired, a valve between the first and second fan diverts flow from the first fan into an auxiliary nozzle and brings ambient air into the second fan. One possible type of ducting arrangment for this type of engine is shown in Figure 3S. Retractable chutes (shown in the high bypass mode) bring auxiliary flow around the first fan and into the second fan. A second set of ducts discharges air from the first fan around the second fan into a retractable fan nozzle.

The P&WA evaluation also identified the augmented wing concept employing a low bypass ratio duct-heating turbofan engine as a supersonic transport propulsion system which might be capable of achieving low noise levels. However, proper evaluation of this concept requires careful analysis of the complete airplane/propulsion system to be certain that inherent penalties due to the ducting system are properly assessed. Further work on the augmented wing concept will require collaboration with an airframe company.

TASK III. ADVANCED TECHNOLOGY BENEFITS FOR CONVENTIONAL AND VARIABLE CYCLE ENGINES (1980 TECHNOLOGY)

Whereas the propulsion systems of Tasks I and II were based on 1975 technology, the Task III analysis was evaluated on a 1980 technology base. The intent of the Task III study was to evaluate those areas of advanced technology that indicate the greatest potential benefits to the noise, and economic characteristics of an advanced supersonic transport propulsion system. Based on these study results, technology programs were formulated in Task VI for the most critical technologies.

The major engine benefits realized in the Task III studies were in the areas of engine weight, where substantial improvements without loss in performance, noise, or emission characteristics were realized using 1980 technology. These benefits were in structural changes, materials advances, higher aerodynamic loadings, and fabrication improvements. A comparison of engine weights between 1975 technology and 1980 technology is shown in Figure 4S.

The impact on TOGW due to the improvement in individual engine components is shown in Figure 5S, where the top of the bar represent the 1975 TOGW result, and the bottom of the bar represents the 1980 TOGW result. Substantial potential benefits are shown for high-pressure turbine material and aerodynamic loading technology, composite fan materials for turbofan and variable bypass engines, low-emission augmentors for duct-heating turbofan and variable bypass engines, compressor aerodynamic loading for turbojet engines, and flow diverter valves for variable bypass engines. Application of 1980 technology did not significantly alter the relative comparison of engine types, as determined from Task I and II.

Schematic drawings showing the comparison between 1975 technology engines and selected 1980 technology engines is shown in Figure 6S for a non-afterburning turbojet, Figure 7S for a duct-heating turbofan, and Figure 8S for a series/parallel variable cycle engine. The 1980 technology engines show dramatic decreases in physical size for the same design airflow capacity.

TASK IV: HYDROGEN-FUELED ENGINES (1980 TECHNOLOGY)

During Task IV, a review was made of recent comprehensive in-house studies of supersonic propulsion systems for transport application. These studies included many cycles which were designed to take advantage of the unique properties of hydrogen, and showed that the basic turbojet/turbofan cycles were still the best for a hydrogen fueled supersonic transport. With this background, the 1980 technology engines from Task III were reexamined to determine how their design would be affected by the use of hydrogen fuel. Estimates of engine weight, size, performance, noise, emissions, and price were determined for selected engine cycles, based on the use of hydrogen fuel. In addition, any technology problems or differences associated with the use of hydrogen fuel in the engine and associated fuel systems were identified. Preliminary systems studies based on NASA defined aerodynamics and weights were also conducted.

Liquid hydrogen offers many potential advantages as a fuel for the engine of a supersonic transport. These advantages include a higher heating value, greater cooling capacity, improved burner blowout limits, improved thermal stability, and reduced emissions. The unique properties of hydrogen do have an impact on the engine design in several areas. The cryogenic property influences the engine fuel and control system, and material selection. The heat sink capacity infleunces the cooling system (e.g. turbine, burner, augmentor, controls, lubrication, etc.). And the combustor properties infleunce the combustor design. However, no technical barriers are forseen in using hydrogen fuel in gas turbine engines, and no new technology development is required. The use of hydrogen fuel in the supersonic transport did not affect the relative comparison of engines types as determined from previous tasks. However, the price of hydrogen fuel relative to JP fuel will have to be reduced signficantly from current projections if hydrogen fueled systems are to be economically competitive with JP fueled systems.

TASK V: REFINED CONVENTIONAL AND VARIABLE CYCLE ENGINE STUDY (1975 TECHNOLOGY)

The results of Tasks I and II were used as the basis for more refined evaluation of the most promising engines during Task V. Non-afterburning (dry) turbojets, duct-heating (D/H) turbofans, and series/parallel flow variable bypass engines (VBE) were identified during those Tasks as the propulsion systems of greatest interest for an advanced supersonic transport. During Task V, the effects of perturbations in the cycles of these propulsion systems were evaluated and both the engine definition and systems analysis models were refined. The ground rules for the systems and economic analysis were basically the same as those for Tasks

I and II; however, parametric variations of mission parameters were made in some cases to evaluate their impact on cycle selection. Performance, weight, and cost data for most of the Task V engines were submitted to the Langley airframe contractors for their systems studies.

Work done during previous tasks confirmed the fact that sideline and takeoff jet noise is the most critical noise problem of the supersonic transport. The jet noise problem is basically one of thrust/airflow which is proportional to relative jet velocity, the most important parameter affecting jet noise. For a given airplane and its takeoff thrust requirements, airflow size is a key parameter affecting jet noise. The larger the airflow size, the lower the jet noise if the engine is operated to just meet the required takeoff thrust. Oversizing the engines to reduce jet noise, however, results in TOGW penalties because of the increased engine weight on board the aircraft. An increase in the required takeoff thrust of an airplane, such as would be necessary with a shorter takeoff field length requirement, would result in an increase in sideline jet noise for a given airplane/engine combination because the engine would have to operate at a higher takeoff throttle setting resulting in higher relative jet velocities. This increased sideline jet noise due to increased takeoff thrust, however, may be accompanied by a reduction in takeoff (community) noise because the airplane will climb to a higher altitude over the takeoff noise measuring station. If the airplane/engine is sideline jet noise critical, then reduced thrust associated with longer field lengths will alleviate the problem. If the airplane/engine is takeoff noise critical, then increased thrust associated with shorter field lengths will alleviate the community noise problem at the expense of higher sideline jet noise.

From an engine/performance viewpoint, the best supersonic cruise performance is obtained with a turbojet or low bypass ratio turbofan. However, the supersonic cruise performance must be traded in the system evaluation against lower installed engine weight for a given airflow size, and better performance at subsonic flight conditions, which are achieved with higher bypass ratio turbofans.

Non-Afterburning Turbojets

The results of Task I indicated that a critical engine sizing condition for nonafterburning turbojets occurred at the end of supersonic acceleration for 2.7 Mn aircraft. High flowing the 2.7 Mn turbojet engine at supersonic conditions relative to the Task I airflow schedule was found to provide higher supersonic thrust, thereby alleviating the supersonic thrust to drag margin as a critical engine sizing constraint.

Since turbojet weight is relatively high for a given airflow size, the best TOGW of turbojet powered aircraft occurs at relatively small turbojet sizes, where the total installed engine weight can be kept to a reasonable fraction of the total airplane weight. These small turbojet airflow sizes result in high jet noise and, therefore, the turbojets require high levels of suppression to meet FAR 36 or lower jet noise levels. Practical suppressor mechanical and materials considerations will require that the exit gas temperature (EGT) be limited to the 1300°F–1500°F range when the suppressor is deployed. This exit gas temperature limit results in the engine size becoming critical at takeoff because the turbojets have to be throttled to meet this constraint, and then the engine size must be scaled up to meet the takeoff thrust requirement at the throttled operating condition. Thr turbojet engine overall pressure ratio can influence the turbojet thrust available when throttled to meet an exit gas temperature limit because OPR affects the engine nozzle exit pressure. With EGT limits as a constraint, the effect of OPR on turbojet system performance was reexamined, and it was found that the optimum OPR was between 15:1 and 18:1 for both 2.2 Mn and 2.7 Mn aircraft. It was also found that the use of variable turbine geometry did not result in an engine size advantage over the use of variable nozzle area alone when maintaining constant airflow during throttling.

Bypass turbojets ("leaky" turbojets or low bypass ratio turbofans) were also examined. The bypass flow of these engines provides cooling flow for the nozzle, and their weight is lower than that of a pure turbojet for a given airflow size. However, there is a significant loss in supersonic thrust with these engines resulting in a critical sizing condition even when the engines are high flowed supersonically. Based on preliminary results, when bypass turbojets are sized for adequate supersonic thrust, the installed bypass turbojet weight exceeds that of the pure turbojet, resulting in a TOGW penalty. Further study of these cycles may indicate ways to improve their performance.

Duct Heating Turbofans

One of the primary advantages of the duct heating turbofan over the turbojet is its lower engine weight for a given airflow size. In addition, the better subsonic performance of the turbofan results in reduced reserve fuel required for loiter and cruise to alternate airport as well as providing better range capability for subsonic cruise legs over populated land areas.

The duct heating turbofan can be used in relatively small airflow sizes, comparable to those of the turbojet, with low TOGW's resulting. But, just as in the case of the turbojet, the jet noise will be high and high suppression levels will be required. However, because the D/H turbofans have lower weight per pound of airflow, the relative airflow size can be increased with less penalty, and lower jet noise levels can be achieved. High fan pressure ratio (FPR>4)D/H turbofans provide higher thrust per pound of airflow than low fan pressure ratio turbofans. These high fan pressure ratio turbofans give the best results at the small airflow sizes where large amounts of suppression are required. Low fan pressure ratio cycles (FPR <3) may become thrust limited at non-augmented climb/cruise conditions in the small airflow sizes. They become attractive in the higher airflow sizes, under which conditions they need less suppression to achieve the same noise level as the turbojets and high FPR D/H turbofans.

The large number of possible cycle parameter combinations makes selection of an "optimum" D/H turbofan engine cycle more difficult than that of a turbojet. The jet noise distribution between the primary and duct streams of a turbofan affects the total jet noise perceived by an observer. Achieving minimum jet noise for a given airflow and thrust requires that the cycle parameters be properly selected. Noise/cycle studies show that a D/H turbofan with a jet suppressor deployed only in the duct stream can achieve noise levels very close to that achievable with both streams suppressed. In order to achieve best results when incorporating a jet suppressor on only one stream, the cycle parameters should be selected such that the noise of the suppressed stream dominates. Since the duct stream flows in the relatively narrow annular passage, very favorable conditions are presented for mixing with the adjacent ejector air introduced by the nozzle. The ejector air need only penetrate the duct flow because the primary stream jet noise can be designed to be well below that of the suppressed duct jet noise. All suppressed duct heating turbofans in this study utilized duct jet noise suppressors, and the engine cycle parameters and/or mode of operation was such that the total engine noise was essentially reduced by the amount of suppression in the duct stream.

Variable Bypass Engine

The series/parallel variable bypass engine has the potential of being designed as a low airflow size, high specific thrust cycle for good supersonic performance and being able to convert to a high airflow, low specific thrust cycle for low noise and good subsonic performance. These engines can be designed as turbojets or low bypass ratio duct heating turbofans in the series mode. The VBE I type series/parallel engine with a rotating fan splitter was selected from Task II studies for reevaluation in Task V. The VBE I engine is basically a high FPR low bypass ratio duct-heating turbofan in the series mode. In an airplane application, it has a relatively low series mode airflow size, comparable to that of a turbojet. This small airflow size reduces the installed weight to a reasonable fraction of the airplane weight. The requirement for a jet suppressor is eliminated (or at least minimized) by operating the engine in the parallel mode at takeoff, thereby increasing the engine airflow and reducing the average jet velocity. The sideline jet noise is usually the critical engine sizing condition for VBE I engines. The Task V study shows that there are further potential improvements in the series/parallel cycles to improve their noise characteristics, which can be incorporated as airflow size reductions and hence, improvements in the installed engine weight. The reduced airflow size of the variable cycle engines is necessary to compensate for the additional valve, fan, and nozzle weight over that of conventional engines.

Task II studies showed that the low series mode bypass ratio engines of the VBE I type provided the lowest TOGW systems. In Task V, the best series/parallel engine, VBE IA was reevaluated along with a lower bypass ratio version VBE IC. The lower bypass ratio version did improve the TOGW relative to VBE IA at noise levels around FAR 36, but did not provide any improvement around FAR 36 minus 10 noise levels.

Propulsion System Comparison

Aircraft thrust loading at lift-off was found to have a dramatic impact on the TOGW required to perform the prescribed mission for a given level of sideline noise. The lift-off thrust loading is an important parameter in the aircraft takeoff field length capability as well as its climb-out ability, which affects community noise. Thrust loading was treated as a parameter in the Task V studies. Figure 9S shows a summary engine comparison for 2.7 Mn aircraft. The curve on the left side of the figure is for a thrust loading of 0.245, and the curve on the right is for a thrust loading of 0.275. The effect of increasing the thrust loading (i.e. going to shorter field lengths) is to increase the TOGW penalty for any given sideline jet noise leve. The lowest TOGW systems were provided by duct-heating turbofans. The series/parallel variable bypass engines were competitive with the duct-heating turbofans over the range of noise levels from FAR 36 down to FAR 36 minus 10. Further refinements in engine matching/rating and inlet/nacelle design appear possible, which could provide further reductions in the TOGW of the series/parallel engines.

The noise level that could be achieved by the dry turbojet and the 4.1 FPR duct heating turbofan is highly dependent on the amount of suppression that could be achieved. With a suppressor capable of providing an assumed maximum suppression level of 18 PNdB, these engines could approach FAR 36 minus 5 sideline noise levels. However, if the maximum suppression capability of the assumed jet suppressor is only 10 PNdB, then these engines cannot meet FAR 36 with competitive TOGW's. For duct heating turbofans incorporating a constant 5 PNdB duct jet suppressor, a 3.3 FPR cycle provided the lowest TOGW at FAR 36 noise levels. At FAR 36 minus 5 PNdB and lower, a 2.5 FPR duct heating turbofan provided the lowest TOGW. The lower FPR engines have an advantage of lower installed engine weight for a given airflow size as well as a jet noise advantage because of reduced stream density. However, the non-augmented subsonic cruise thrust becomes a limiting engine sizing condition with low FPR cycles and small engine airflow sizes. Further study may lead to a way around this problem. Typical noise footprint contours were calculated for the non-afterburning turbojet and the duct heating turbofan. Takeoff noise footprints for a non-afterburning turbojet are shown in Figure 10S. The area of the 90 EPNdB takeoff contour was greatly increased when the turbojet engine was cutback to reduce the noise level at the takeoff noise measuring station. This was due to the reduction in suppression capability of the turbojet suppressor that occurred when the engine was cutback in power and the exhaust jet velocity was reduced. Note that with the 0.245 thrust loading assumed for this footprint calculation, the turbojet could not meet the FAR 36 takeoff noise limit. The noise contour area of the duct-heating turbofan did not encounter the large increase in area during cutback because the engine was not dependent on large amounts of jet suppression, as was the turbojet engine. In contrast, as the same thrust loading, the duct heating turbofan contour area was greatly reduced (Figure 11S) while, at the same time, meeting the FAR 36 noise level at the takeoff flyover noise measuring station.

Figure 12S compares the approach noise contour area with the takeoff noise contour area for a duct-heating turbofan incorporating only wall acoustic treatment for attenuation of fan noise. For engines sized to meet FAR 36 sideline noise levels, the single segment approach noise level also meets FAR 36. With a two segment 6°/3° approach, the approach noise level decreases by only 3 EPNdB, but the approach noise contour area is reduced to half that of the single segment approach contour area. When the duct-heating turbofans are sized for FAR 36 minus 5 EPNdB sideline noise, the takeoff contour noise area is reduced to half the area compared to the FAR 36 case. The approach noise level is not significantly reduced when the engine is sized for reduced sideline jet noise because the turbofan is fan noise dominant on approach, requiring additional duct acoustic treatment for reduction in fan noise, which will result in a significant TOGW penalty. Note, however, that the area of the approach noise contour is small compared to the takeoff noise contour, indicating that the biggest payoff in total footprint area reductions can be achieved by decreasing the takeoff lobe area of the noise footprint.

TASK VI: TECHNOLOGY REQUIREMENTS

One of the primary objectives of the AST Propulsion System Study was to identify the engine-related technologies which have the greatest potential for improving the environmental and economic characteristics of an advanced supersonic commercial transport. Work done during previous Tasks has shown that advanced propulsion technology has the potential for significant improvements in the environmental and economic areas; however, in order to realize these improvements, component research-and-development programs must be undertaken.

Based on results from Tasks I, II, III and V, seven advanced technologies are recommended for follow-on work. Component technology programs have been formulated in order to initiate an orderly development of these technologies. The recommended technology items for which technology development programs have been formulated are listed below:

1. Jet Noise Suppressor Integrated with Nozzle/Reverser Systems for Duct-Heating Turbofan and Variable Cycle Engines.

2. A Low Noise, Clean Duct-Heater for Turbofan and Variable Cycle Engines.

3. An Annular Inverter Valve (AIV) for Variable Cycle Engines.

4. Directionally Solidified Eulectric Material and Coating for Turbine Blades.

5. Ceramics for Turbine Vanes.

6. High Temperature Composite Fan Blades.

7. A Full-Authority Electronic Control Systems.

Additional technology requirements have been identified, but the programs can be deferred until progress has been made in one or more of the following areas: selection of the AST airframe/propulsion system configuration, further studies to determine specific technology requirements, and/or completion of related programs currently in progress.

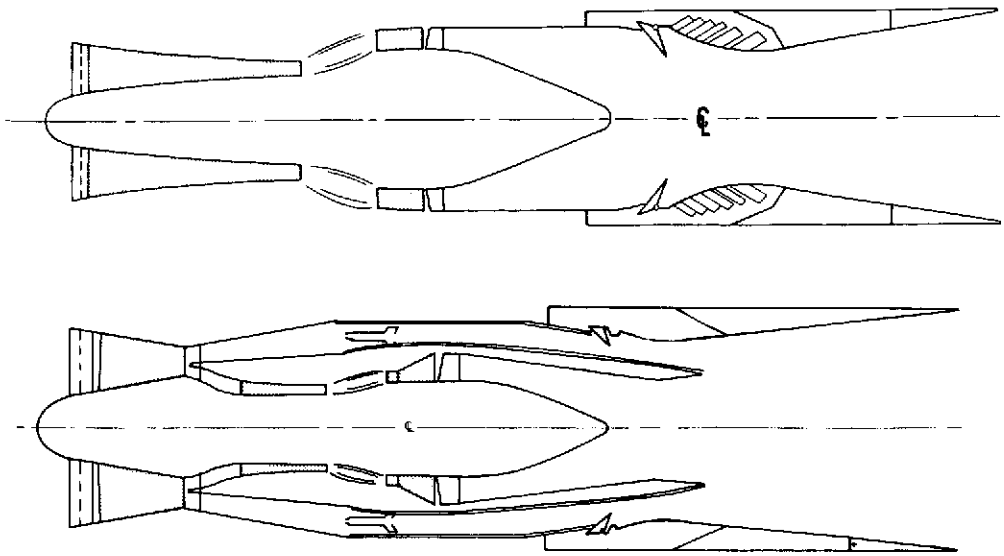


Figure 1S Schematics of Non-Afterburning Turbojet (top) and Duct-Heating Turbofan (bottom) Engines

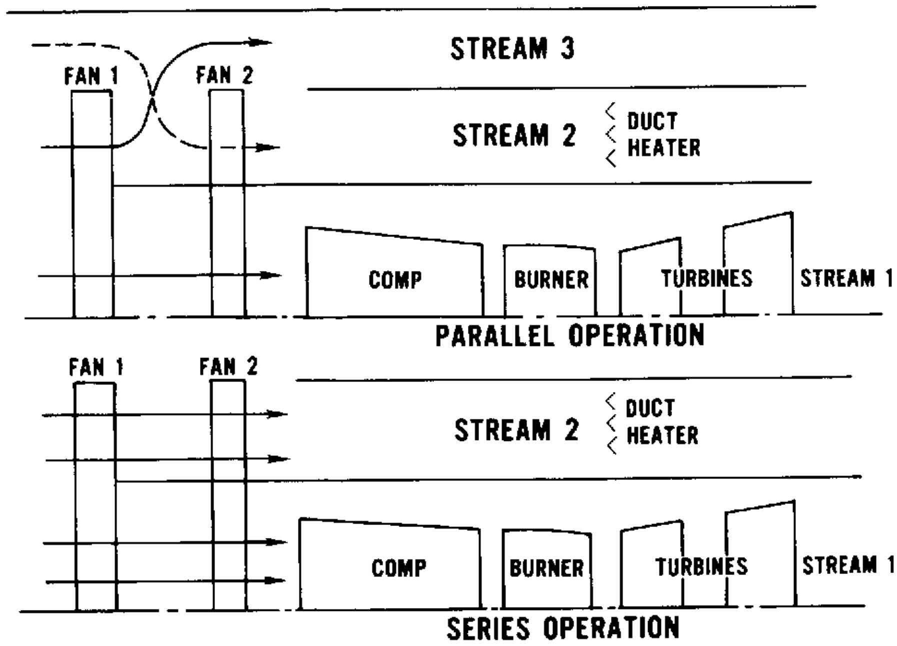


Figure 2S Schematic of Series/Parallel Fan Variable Cycle Engine With Splitter (VBE I)

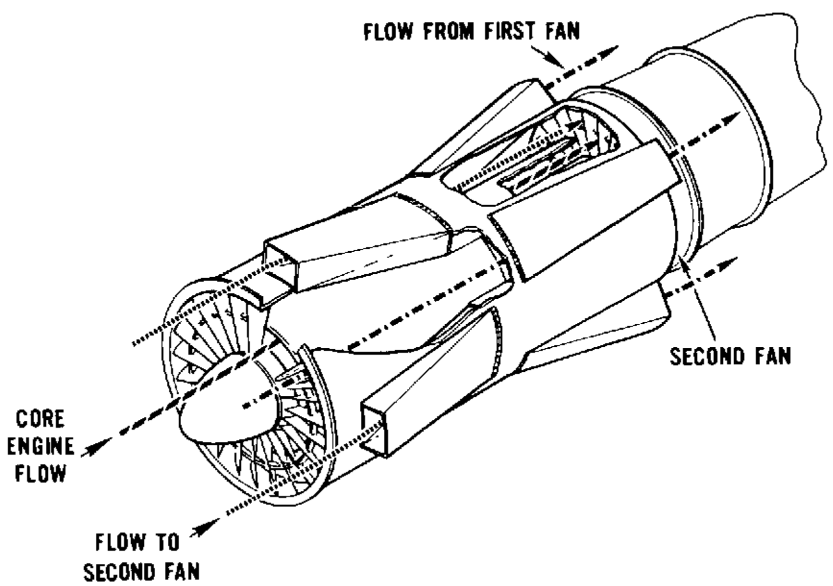


Figure 3S Typical Ducting Arrangement for Series/Parallel Variable Cycle Engine - Ducts Shown in Takeoff Position

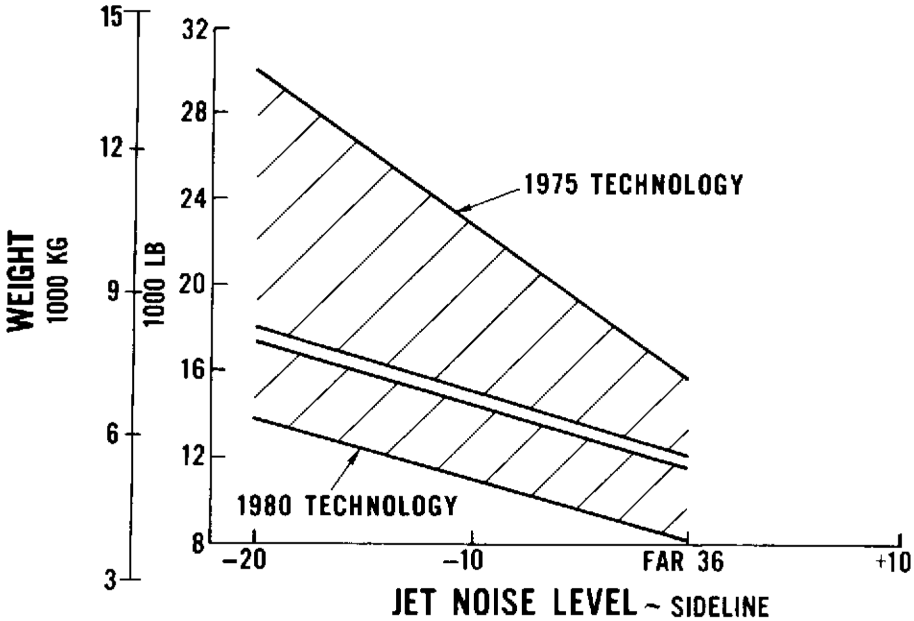


Figure 4S   Effect of Advanced Engine Technology on Engine Weight

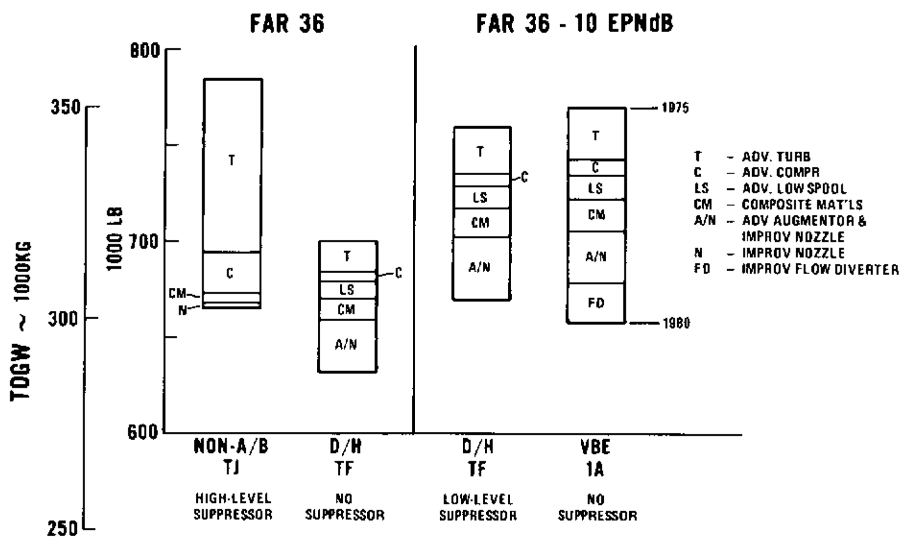


Figure 5S   Effect of Engine Component Technology on TOGW

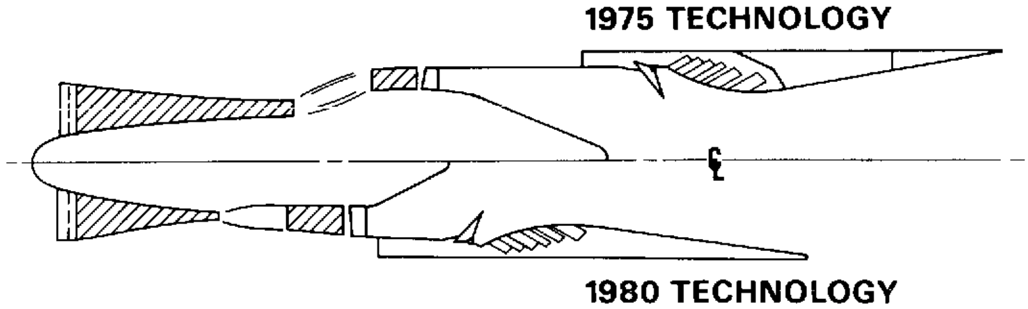


Figure 6S Effect of 1980 Engine Technology on Turbojet Engine Design

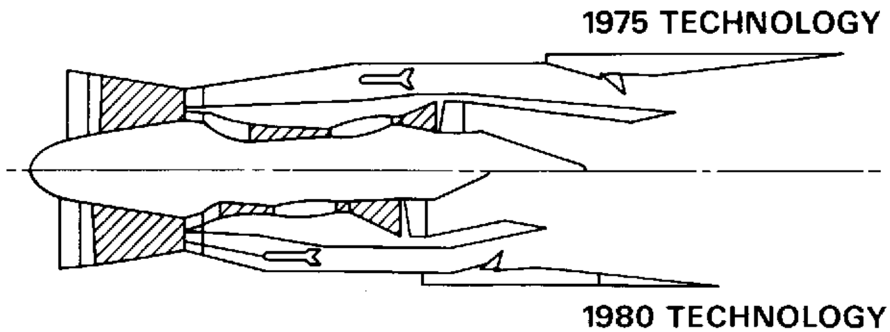


Figure 7S Effect of 1980 Engine Technology on Duct Heating Turbofan Engine Design

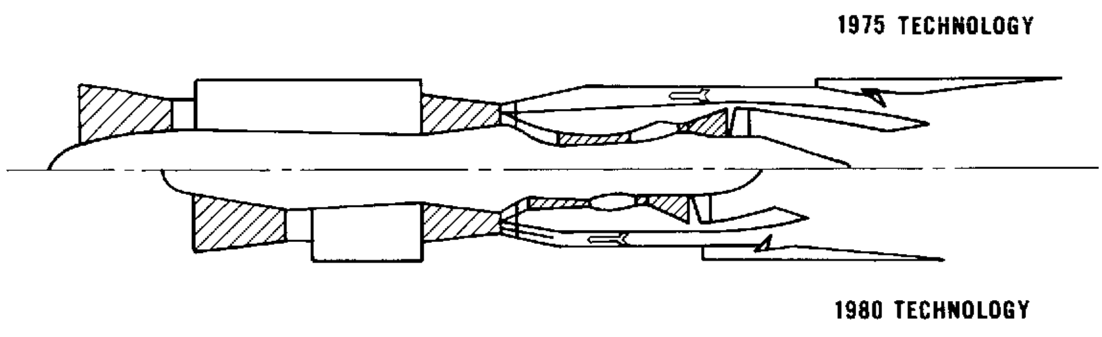


Figure 8S Effect of 1980 Engine Technology on Series/Parallel Variable Bypass Cycle Engine Design

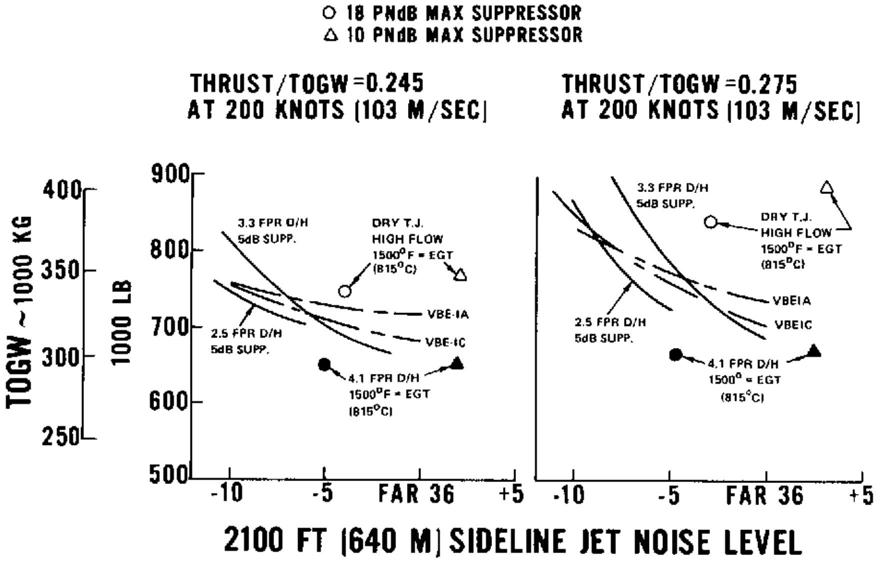


Figure 9S TOGW Comparison for Mach 2.65 (Hot Day) Nominal Mission

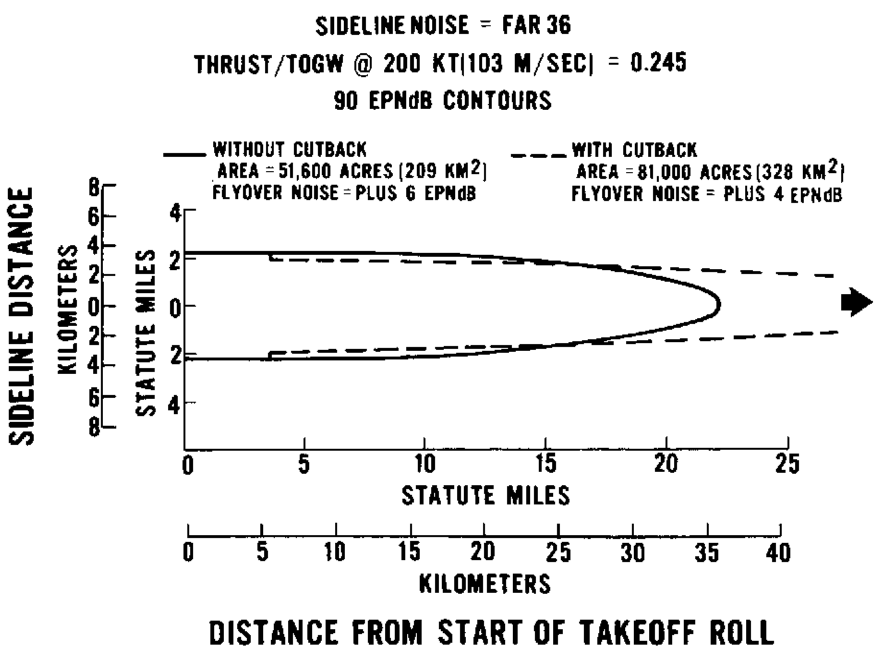


Figure 10S Non-Afterburning Turbojet Takeoff Noise Contour Plot

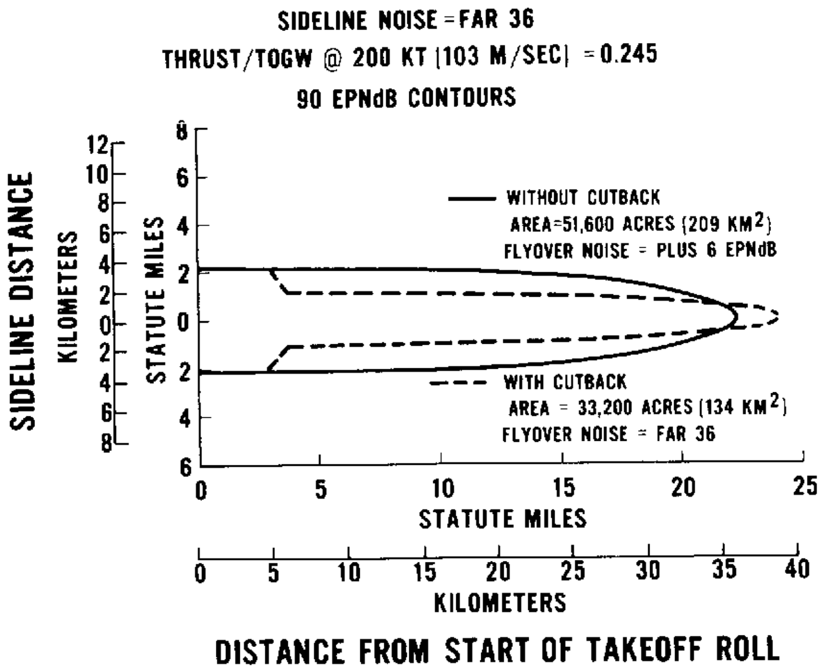


Figure 11S Duct-Heating Turbofan Takeoff Noise Contour Plot

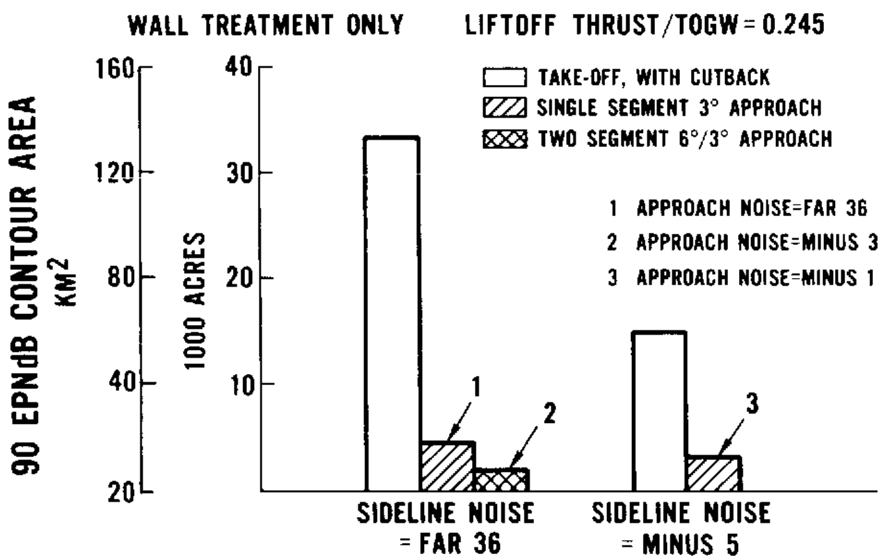


Figure 12S Duct-Heating Turbofan Contour Area Summary

TASK I

PARAMETRIC STUDY OF CONVENTIONAL ENGINES
(1975 Technology)

INTRODUCTION (TASK I)

The objective of Task I, a parametric study of conventional engines, was to determine the most attractive engine types and the desirable range of engine cycle parameters for a Mach 2.2, a 2.7, and 3.2 long-range, commercial supersonic transport designed to reduce noise and emissions below current levels. To accomplish the Task I objective, a consistent set of parametric engines was defined which covered a range of cycle variables for several types of engines. A conceptual design of each engine was made which included component definition, configuration arrangement, performance estimates, material selection, and weight and price estimates. Data for most of the parametric engines were submitted by P&WA to airframe companies who under a contract to NASA-Langley were conducting parallel studies of advanced supersonic aircraft, including propulsion integration. The data were provided to permit the airframe companies to determine the most attractive propulsion system. To assist in the engine cycle selection process, P&WA also calculated aircraft takeoff-gross-weight (TOGW), direct-operating cost (DOC), and airline return-on-investment (ROI) for the complete matrix of engines studied in Task I based on NASA airplane aerodynamics and mission definition.

Four conventional engine types were evaluated:

1) non-afterburning (dry) turbojets
2) afterburning (A/B) turbojets
3) duct-heating (D/H) turbofans
4) afterburning (A/B) turbofans

Cycle parameters for best overall performance were determined for each of the engine types at sideline noise levels from FAR 36 down to FAR 36 minus 10 EPNdB. A 1975 level of technology, contractually specified, was assumed for the engine definitions. This level of technology is that which would be expected to be demonstratable in the 1975 time period. Exceptions to this definition were made for a few items such as the upper range of turbine temperatures and the assumed jet noise suppression characteristics.

Extensive use of engine variable geometry was assumed for these studies, including variable geometry fans, compressors, turbines, and exhaust nozzles. Follow-on preliminary design and overall system studies are required to determine the full benefit of each of these variable geometry features.

SUMMARY (TASK I)

A matrix of approximately 50 parametric conventional propulsion systems was evaluated for application in a long range, advanced supersonic, commercial transport. The parametric family of engines incorporated 1975 technology and included afterburning and non-afterburning turbojets and afterburning and duct-heating turbofans. The non-afterburning turbojet and the duct-heating turbofan were identified as the two most promising engine configurations. The duct-heating turbofan had a significantly lower TOGW than any other engine for noise levels from FAR 36 down to FAR 36 minus 10 EPNdB. The penalty associated with FAR 36 minus 10 EPNdB sideline noise levels may be understated for the Task I engines because the estimated airplane thrust loading may be too low – the effect of thrust loading on cycle selection and noise level is explored in Task V.

The TOGW with turbojet engines was very sensitive to design noise level, and the turbojets required a high level of jet suppression in order to meet FAR 36. Maximum combustor exit temperatures on the order of 2600°F to 2800°F (1427°C to 1538°C) were found to offer the best overall level of performance. An overall pressure ratio of 12 was found to be attractive for Mn = 2.7 cruise speeds, while higher values of overall pressure ratio (15 to 20) were found to be better at Mn = 2.2.

The afterburning turbojets were inferior to the non-afterburning turbojets. The higher thrust-specific-fuel-consumption (TSFC) at supersonic cruise of the afterburning turbojets was only partially offset by a smaller and lighter weight engine. The afterburning turbojets also required higher jet suppression levels to achieve even the same noise level as the non-afterburning turbojets which themselves required high jet-suppression.

The duct-heating turbofans were best when a modest amount (~5 PNdB) of duct jet suppression was incorporated. Maximum combustor exit temperatures of 2600°F to 2800°F (1427°C to 1538°C) were also most attractive for the turbofans. A fan pressure ratio of about 3 appears to be the optimum for noise levels around FAR 36 and about 2.5 at FAR 36 minus 5 EPNdB. The afterburning turbofans were significantly worse than the duct-heating turbofans due to their higher TSFC at cruise.

The results of the Task I study were used during Task V as the basis for a more detailed analysis of the non-afterburning turbojet and the duct-heating turbofan engines. The results presented in the Task V portion of this report, therefore, represent a more refined and realistic evaluation of these cycles.

PARAMETRIC ENGINE EVALUATION (TASK I)

Component technology and configuration definitions were prepared for all major components of the engine for the range of engine cycles selected (shown in Table I). The definitions were based on 1975 technology and reflect experience obtained from other analytical and design studies. For each parametric cycle, the components were combined in a compatible manner that observed operational, design, and material limitations. From the engine definition; performance, noise, emissions, weight, price, and installation dimensions were determined for a matrix of approximately 50 parametric engines. This procedure was considered to be the most accurate and adaptable technique for defining a matrix of engines in a consistent manner. Consistency was emphasized because an objective of Task I was to compare a wide range of engines on a relative basis and to select the most promising of these for more detailed evaluation during Task V.

TABLE I
RANGE OF CYCLE PARAMETERS

Bypass ratio	0 to 6.6
Fan pressure ratio	1.7 to 4.8
Cycle pressure ratio	5 to 20
Hot day climb combustor outlet temperature	2000°F to 3000°F (1093°C to 1050°C)
Takeoff combustor outlet temperature	function of TO noise
Augmentor temperature	up to 3500°F (up to 1930°C)
Cruise flight Mach number	2.2; 2.7; 3.2

The component and material technology utilized for the parametric study was of a level that was expected to be demonstratable by 1975. After demonstration, this technology could be committed to a six to eight year engine development program, leading to certification by approximately 1985. The technology level and certification dates are approximate in that the range of cycle temperatures covered in this study (e.g., the 3000°F (1649°C) combustor-exit-temperature) are somewhat beyond 1975 technology for commercial engines. To avoid penalizing the high temperature end of the range, turbine cooling technology was applied that is more advanced than 1975.

Four basic types of engines were defined in the parametric study:

1) non-afterburning turbojets
2) afterburning turbojets
3) duct-heating turbofans
4) afterburning turbofans

The turbojet engines were defined as single-spool configurations because of the relatively low overall-pressure-ratio range being evaluated. All of the turbofan engines were twin-spool configurations with the compression section consisting of a fan and a high-pressure compressor. Low-pressure compressors were not necessary on the low-speed spool because of the range of overall-pressure-ratios and relatively high fan-pressure-ratios required for SST application. Typical schematics of these engines are shown in Figure 1.

Component Definition

A brief description of each major engine component used in the parametric engine definition of this study is presented in the following paragraphs.

Fan

The fans were defined to cover a range of fan pressure ratios from 1.5 to 5.0. The fans were variable geometry fans with from one to five stages. The variable geometry consisted of variable camber inlet-guide-vanes and exit-guide-vanes for good subsonic and supersonic cruise efficiency characteristics. The variable camber feature was obtained with variable trailing-edge-flaps on the inlet-guide-vanes and variable leading-edge-flaps on the exit-guide-vanes.

The fan aerodynamic loading reflected a surge margin of approximately 15 percent. The airfoil contours were multiple-circular-arc designs. All fan rotors had single partspan shrouds and moderately high aspect ratio blades to provide a favorable compromise between fan efficiency, weight, and cost. A 50 percent axial spacing between each row of airfoils was utilized to reduce fan rotor noise. A reduction in noise was obtained because this spacing allows the wakes from upstream airfoils to weaken by attenuation before striking the next row of airfoils. Further study is required to determine the correct balance between axial spacing between rows and the level of acoustic treatment applied to the fan. In order to obtain a high pressure ratio per stage with minimum weight and cost penalties, all of the fans were constant mean diameter configurations.

Turbofan Compressor

High-pressure compressors with pressure ratios up to 8.5 were defined for the turbofan engines. This pressure ratio range was sufficient to achieve the 5 to 15 range of overall pressure ratios under consideration in the parametric study. The turbofan compressors were variable-geometry, axial-flow configurations with advanced commercial engine aerodynamic loadings.

The corrected tip-speed of the compressor was established from the diameter of the compressor inlet and from the speed of the high-pressure rotor which was limited by stress considerations of the high-pressure turbine. The number of stages required was then determined for the design compressor pressure ratio. Turbine stress considerations that limited the speed of the high-pressure rotor are discussed in more detail in the turbine section.

The compressor inlet-guide-vanes and several rows of front stators utilized variable geometry for good efficiency and stability characteristics at subsonic and supersonic flight conditions. The compressor was defined as a constant mean-diameter configuration to represent an optimum combination of aerodynamic loading, weight, cost, and elevation match with the fan and burner.

Turbojet Compressors

The compressors for the turbojet engines were variable-geometry, single-spool configurations that provided a range of pressure ratios from 5 to 20. In order to provide good efficiency and stability characteristics at subsonic and supersonic flight conditions, the inlet-guide-vane and the front stators were variable. These compressors were defined with constant mean diameters to represent an optimum combination of aerodynamic loading, weight, diameter, and cost.

The compressor inlet diameter and rotor speed, limited by turbine stress considerations, established the compressor corrected tip-speed. The number of stages required was then determined for the design pressure ratio. The turbine stress considerations that limited the rotor speed are discussed in more detail in the turbine section.

Primary Burner

The primary burner was an advanced design burner that minimized emissions while providing high efficiency and stability. The design featured a piloted premix-burner with two fuel-zones which reduced both high and low power emissions. One zone, a piloted premix zone, was designed for low power operation and functioned throughout the entire operating range. The other zone, the main premix zone, was designed for high power operation. Control of the fuel-air mixture level and uniformity was accomplished by staging fuel flow between the pilot and main premixing passages. Provision for water injection could have been added to this design to reduce NO_2 emission levels even further than those obtained; however, water provisions were not included in this initial definition. A further discussion of the burner is presented in the section on emissions.

High Pressure Turbine

The single-spool turbojet engines utilized a two-stage turbine, and the twin-spool turbofan engines utilized a single-stage, high-pressure turbine. A single-stage turbine design could have been applied to the turbojets but not without a considerable penalty in diameter size and performance.

A limiting blade pull-stress set the maximum rotor-speed. The design rotor-speed was determined for each engine from the ratio of maximum-rotor-speed to design-rotor-speed. The design rotor speed set the compressor corrected-tip-speed and, consequently, determined the number of compressor stages required, as discussed in the compressor section.

The exit annulus area was set by a design exit axial Mach number of 0.56 for the turbofan engines and 0.40 for the turbojet engines. The difference in exit Mach number was a result of the variable throat area of the primary nozzle which increased the turbine exit Mach number for the single-spool turbojet engines but did not affect the high-pressure turbine exit Mach number for the twin-spool turbofan engines. Consequently, the exit annulus area for the turbojet engine turbine was designed for a lower flow per unit area which resulted in an increased annulus area. When combined with the stress limitation, there was a more severe restriction on the speed of the rotor for the single-spool turbojets than on the speed of the high-pressure rotor of the turbofan engines.

The total air requirements for cooling the turbine, including all secondary cooling and leakage airflow, were set as functions of the maximum exit-temperature of the combustor and the maximum exit-temperature of compressor which was the source of cooling air for the turbine. The 1st-stage turbine airfoils employed either impingement or transpiration cooling schemes, depending on the turbine inlet temperature level. The remaining stages were either uncooled or employed convection cooling, depending on the local gas temperature. Transpiration cooling (multihole film cooling) is an advanced type of cooling which is beyond 1975 technology; it was included, however, to avoid a large cooling air penalty for the higher end of the combustor exit temperature range – from 2600°F to 3000°F (1427°C to 1538°C).

Turbofan Engine Low-Pressure Turbine

The rotor speed of the low-pressure turbine was set by the requirements of the fan corrected tip-speed, except where a maximum low-pressure turbine blade pull-stress was exceeded. In such cases the fan corrected tip-speed was reduced, as discussed in the fan section. The rim diameter of the high-pressure turbine established the rim diameter of the inlet to the low-pressure turbine, and the rim wheel speed was determined from the rim diameter and the design low-pressure spool rotor speed.

Engine Support and Installation Features

The engine mounts were located at the turbine case and the intermediate case; the intermediate case was the thrust mount. A three-bearing arrangement, one thrust bearing and two roller bearings, was defined for the single-spool turbojet engines. The high-pressure spool of the turbofan engines consisted of the same three-bearing arrangement. In addition, a three-bearing arrangement was defined for the low-pressure spool, again consisting of one thrust-bearing and two roller-bearings, making a total of six main-shaft bearings. The engine gearbox and accessories were located externally as a maintenance feature.

Augmentor

The types of augmentors studied were turbojet afterburners, commonflow turbofan afterburners, and turbofan duct heaters. These augmentors were designed to minimize emissions while maintaining good stability and performance characteristics. The afterburners for the turbojet and turbofan engines were of conventional design with "V" gutter flameholders which did not require pilots because of the relatively high augmentor inlet temperatures. These afterburners were staged for good performance at maximum power and cruise conditions. The combustion length was varied as a function of the augmentor inlet temperature which affected the degree of fuel vaporization.

The turbofan duct heaters were ram induction type burners which required pilots because of the low fan-duct-temperatures at the augmentor inlet. The duct heaters were also staged for good performance at maximum power and cruise conditions. The combustion length of all duct heaters was approximately the same since the inlet temperatures of all the duct heaters were low.

Nozzle/Reverser/Suppressor

Two types of suppressor concepts were considered in Task I. The first type was assumed to be a highly effective tube-type suppressor which was incorporated into all single-stream engines (i.e., turbojets and afterburner turbofans). The second type was assumed to provide a modest amount of suppression and was incorporated into the duct heater turbofans.

The nozzle/suppressor/reverser used with the single-stream engines is shown schematically in Figure 2. The suppressor concept features a multi-tube type suppressor that is stowable in the nozzle shroud and operates in conjunction with an ejector to reduce engine jet noise with minimum thrust loss. A translating shroud provides ejector air to improve performance at low flight-Mach-numbers. Variable throat area provides inlet airflow scheduling capability, and variable exit area allows nozzle operation at optimum area ratio to provide good performance over a range of nozzle pressure ratios. An integrated thrust-reverser works in conjunction with the translating shroud during reverse thrust operation.

When the jet noise suppressor is deployed, tubes break up the engine exhaust to promote mixing with auxiliary air brought in by the ejector. The mixing of the engine exhaust with auxiliary air inside the nozzle lowers the jet velocity at the nozzle exit, resulting in reduced jet noise. The mass flow addition of the ejector air helps to minimize the thrust losses resulting from the multi-tube nozzle. Highly optimistic performance characteristics were purposely assumed for this suppressor (Figure 3) in order to determine if turbojets can be competitive for advanced SST application.

The nozzle/reverser for the duct-heating turbofan was similar to that previously described except that the suppressor was simplified. The duct-heating turbofan, through cycle selection, had flexibility which permitted the distribution of the jet noise between the primary and duct streams to be set such that the duct-stream noise dominated and the primary-stream noise kept below the noise level goal. The jet suppressor design was simplified by incorporating it only in the duct-stream; penetration of the primary stream by ejector air was not, therefore, necessary. Although the multi-tube type suppressor could have been incorporated effectively into the duct-heating turbofan, it was found that these engines required much less suppression than the turbojets; therefore, a much simpler suppressor design was practical, with an attendant reduction in weight and performance penalties. With the relatively narrow passage height of the duct stream, mixing of the ejector and fan air can be more readily accomplished.

Engine Material

Materials were defined and selected for each engine component. Selections were based on considerations of proper balance between cost and weight, assuming the 1975 level of technology.

The materials for the fan section and intermediate case, which are exposed to low to intermediate temperature levels, were titanium which allows for light weight and high strength. Blades, vanes, disks, inlet-guide-vane assemblies, cases, containment struts, and seals were all of titanium.

Steel, titanium, and nickel alloy materials were selected for the turbojet and turbofan compressors. The material was changed from steel or titanium to nickel alloys at the stages where air temperature precluded the use of steel or titanium. The material for blades, drum, and case was changed from titanium to nickel alloy, and the material for the stators was changed from steel to nickel alloy. For fire-safety reasons, steel vanes were selected to preclude the occurrence of a titanium-on-titanium rub in the event of a rotor stator axial shift failure.

The primary materials for the burner, including the liner and case, were nickel base alloys.

All turbine materials were nickel base alloys; the high-pressure turbine airfoils were also coated.

The augmentor and nozzles were of steel and titanium construction except for the augmentor liner which utilized a cobalt base alloy.

Whenever possible, honeycomb construction was employed in cases and ducts to reduce weight. A cost-weight trade study is required to substantiate this choice of case construction.

Engine Performance

The engine parametric studies were concerned with matching engine cycles to provide the best performance during climb, subsonic cruise, and supersonic cruise. Variable geometries were employed for the fan, compressor, and nozzle to provide maximum installed-engine-performance. The following combustor-exit-temperature (CET) schedules were used at the engine rating points:

STANDARD DAY CET, °F (°C)			STANDARD +8°C DAY CET, °F (°C)		
Takeoff	Climb	Cruise	Takeoff	Climb	Cruise
2000(1093)	1900(1038)	1800 (982)	2090 (1143)	1985 (1085)	1880 (1026)
2600 (1427)	2500 (1371)	2400 (1316)	2710 (1488)	2605 (1429)	2500 (1371)
2800 (1538)	2700 (1482)	2600 (1427)	2920 (1604)	2815 (1546)	2710 (1488)
3000 (1649)	2900 (1593)	2800 (1538)	3125 (1718)'	3020 (1660)	2920 (1604)

Because noise considerations are extremely important in achieving a viable supersonic transport, a major effort was devoted to minimizing sideline jet-noise and approach fan-noise. Fan, compressor, and nozzle variable geometries were used to maximize airflow and reduce fan/compressor pressure ratios, thereby reducing jet and fan noises to the lowest practical levels.

Airflow Schedules

Typically, fixed geometry turbojets, nonmixed flow turbofans, and mixed flow turbofans have different matching characteristics as inlet conditions to an engine are changed. To provide a common base for evaluating the parametric engines in Task 1, a common schedule for inlet airflow was used for all cycles. Dry and afterburning single-spool turbojets utilized variable nozzle-geometry to follow the airflow schedule during supersonic climb and cruise operation. To improve engine performance, compressor and/or turbine variable geometries were also assumed. For the unmixed-flow duct-heating turbofans, variable areas for the primary and duct nozzles were used to follow this airflow schedule and maximize engine performance during supersonic climb and cruise operation. Variable fan-geometry was used to improve performance of these engines during supersonic climb and cruise operation, and variable nozzle geometry was utilized to follow the required airflow schedule. The airflow schedules are shown in Figure 4.

Turbojet Matching

Typical compressor operating lines are summarized in Figure 5 for the single-spool, dry and afterburning turbojets during takeoff; subsonic cruise, 35000 ft (10,688 m) - 0.95 Mn; and supersonic climb to the 2.65 Mn supersonic cruise condition.

During takeoff operation, sideline noise constraint may require that the engine operate at reduced power. To minimize jet noise, it is desirable to pass as much flow through the engine as possible. For the single-spool turbojets, this was accomplished by opening the nozzle throat area as combustor temperature was reduced, thereby reducing compressor overall pressure ratio (OPR) while maintaining engine corrected airflow (WAT2) constant. This airflow was held constant until a turbine exit Mach number limit was reached. Further throttling was done at a constant jet area.

During subsonic cruise operation, the turbojets operated at 40 to 60 percent of maximum climb power. Performance studies showed that throttling the engine to maintain constant airflow produced better installed performance than achieved if the engine was throttled at constant nozzle area.

During supersonic climb, variable nozzle geometry was used to follow the inlet airflow schedule, as previously described.

During supersonic cruise operation, dry turbojets operate at 90 to 95 percent of maximum climb thrust. Engine throttling at this condition was also accomplished by opening the nozzle throat area to maintain constant airflow.

Duct-Heating Turbofan Matching

The fan operating lines for duct-heating turbofans are presented in Figure 6 for takeoff (sideline), subsonic cruise, and supersonic climb operations. To reduce both the fan and jet noises during takeoff and approach operations, the duct-heating turbofans were throttled by opening the duct and primary nozzle to maintain constant airflow while reducing the pressure ratio of the fan.

During subsonic cruise operation, duct-heating turbofans were to operate at 70 to 80 percent of nonaugmented, maximum-climb power. Throttling of the duct-heating turbofans was accomplished by varying the primary nozzle to maintain constant airflow (with a slight increase in the pressure ratio of the fan) until a turbine exit Mach number limit was reached. Further throttling was performed at constant nozzle areas and decreasing airflow.

During supersonic climb operation, both duct and primary nozzle areas were varied to achieve the desired airflow schedule and maximum performance. These variations in area were set to insure that the duct heater inlet Mach number and the turbine exit Mach number limits were not exceeded.

Afterburning Turbofan Matching

Typical fan operating lines for afterburning turbofans are shown in Figure 7 for takeoff (sideline), subsonic cruise, and climb from Mn 0.95 to Mn 2.65.

The nozzle throat area was opened during throttling at takeoff to hold airflow constant. This procedure provided reductions in both fan and jet generated noises while maximizing engine thrust. The procedure was also followed during approach to reduce noise and the acoustic treatment required.

During climb operation, the nozzle area was varied to obtain the desired airflow schedule. The maximum increase in nozzle area during climb was set to maintain the augmentor inlet Mach number within limits established for stable operation.

Emissions

The difficulty in designing a low emissions main burner that satisfies established requirements of a flight worthy combustor becomes evident when the required operating range for low emissions is compared to the axial flame temperature distribution within the burner (see Figure 8). Substantial NO_2 production occurs at temperatures in excess of 3200°F (1760°C), and substantial retardation of the reaction converting CO to CO_2 occurs at temperatures below 2900°F (1593°C). Hence, to provide low emissions, operation within a very narrow temperature range throughout the burner is required. In practical burner designs, the axial flame temperature varies considerably over the length of the burner. The primary zone is normally designed with an optimum fuel-air ratio at maximum power in order to provide good stability at low power. The secondary or dilution zone introduces the excess air and produces the desired exit temperature from the combustor. The net result is an axial temperature profile in the burner which starts at the combustor inlet and rises rapidly to approximately 4000°F (2204°C) and then decreases to the turbine inlet temperature level. At high power operation NO_2 is produced in the high temperature region in the front end of the burner. At low power operation the axial temperature distribution is similar to high power operation, but the temperature level in the burner is much lower. Although only small quantities of NO_2 are produced at the lower temperature, the rapid quenching in the secondary zone results in excessive CO. A simple redistribution of airflow in the burner results only in trading high NO_2 for high CO, with the probable compromise in stability and ignition characteristics. Completely new concepts of combustor design are needed to satisfy both emission and established combustor requirements.

The pilot zone of the burner in this study was a separate burner stage that provided good relight characteristics and reduced CO and total-hydrocarbon (THC) emissions at low power (ground idle) operation. The premix feature reduced primary zone residence time and thereby lowered NO_2 and smoke emissions at high power as well as reducing burner length. The advanced liner cooling system reduced the level of secondary dilution air required so that a lean fuel-air ratio in the primary combustion zone would be obtained to reduce peak temperatures and lower NO_2 levels.

Estimates of NO_2 emission levels for the AST engine at sea-level takeoff and supersonic cruise conditions, exhibited a substantial decrease relative to current subsonic transport engines (shown in Figure 9 as a function of the thrust augmentation ratio). Variations in NO_2 emission levels at the takeoff condition are a result of power setting restrictions to reduce sideline jet noise. The dry turbojet was sufficiently throttled to meet the AST NO_2 goals. The afterburning turbojet and the afterburning turbofan, both of which are nonaugmented at this condition, are at higher power settings with increased NO_2 levels. The duct-heating turbofan engine exhibited a lower NO_2 emission level than the afterburning turbofan as a result of the augmentation dilution effect. Limited augmentor data indicate that a negligible amount of NO_2 is produced in the augmentor, resulting in dilution of the NO_2 index by increasing fuel flow with augmentation. It should be noted that the dilution of the NO_2 index is not a reduction in the absolute pounds of NO_2 produced but rather the division of the relatively constant value of NO_2 by more pounds of fuel. It should also be pointed out that insufficient data are available to accurately predict the emissions with the augmentors lit.

CO and THC emission goals could be met by all engines, with the possible exception of a dry turbojet. The concept of a staged, premixed burner with the first stage optimized for idle operation, used throughout these studies, provided high burner efficiency at low power. This design concept satisfied most cycles sized in the conventional manner at sea-level takeoff. For the sea-level takeoff operating point, the temperatures and pressures entering the burner were appreciably above ambient conditions. Emission trends resulting from studies indicate that at decreasing temperatures the CO index increases rapidly in spite of a relatively constant efficiency achieved by the staged burner. This is probably a combined result of lower flame temperatures and more rapid quenching of the CO to CO_2 reaction with cooler air. Oversizing the turbojet at sea-level takeoff for sideline noise restrictions resulted in idle operation at significantly lower inlet temperatures and pressures and lower flame temperatures than when sized in the conventional manner. Therefore, in spite of the low power stage being optimized for ground idle operation, the significantly lower inlet temperatures, pressures and flame temperatures made it difficult to achieve the required CO index.

All the parametric engines met the smoke goal at sea-level takeoff. This was basically due to the relatively high combustor exit temperatures under consideration in the parametric study. Increasing combustor exit temperatures reduced smoke because the corresponding higher peak flame temperatures provided increased carbon oxidation. In addition, the advanced burner design employed had a higher density of fuel-injection sites, providing more uniform fuel-air mixtures which reduced carbon formation.

SYSTEMS ANALYSIS (TASK I)

The performance of a complete engine-pod propulsion system was calculated, including the effects of inlet drag (i.e., spillage, bypass, and bleed) and isolated external nacelle drag. The propulsion system was then "flown" over a complete mission profile in a SCAT 15F type aircraft, the characteristics of which were defined by NASA and are summarized below:

Wing Type	Modified Arrow Wing
Design Cruise Mach Numbers	2.2, 2.7, & 3.2
Total Range	4000 NM (7412 km) including
	600 NM (1112 km) Subsonic Leg*
Number of Passengers	236
Noise Requirements	FAR 36 and less
	FAR Field Length $\leqslant$ 12,400 ft (3779m)
	STD + 15°C
Thrust-to-Drag Ratio	[FN/D] $\geqslant$ 1.2 ~ STD + 8°C

*The 600 NM subsonic leg included the subsonic climb range.

For augmented engines, the level of augmentation was optimized as a function of Mach number and engine size. Subsonic and supersonic cruise altitudes were optimized for maximum range. The reserve subsonic cruise to alternate leg of the mission was performed at 35,000 ft. (10,680M) in all cases. Engine airflow size was treated in most cases as a parameter. The liftoff thrust loading required to satisfy the field length criteria was estimated to be 0.245. The power setting required to satisfy the field length criteria was calculated for each airflow size, which permitted the sideline noise to be calculated.

The DOC (direct operating cost) was calculated using the 1967 ATA (Air Transport Association) model, updated to 1972 dollars. The IOC (indirect operating cost) was calculated using the 1970 Lockheed California model. The airline ROI (return on investment) is the airline's net revenue from the aircraft divided by the initial investment. The design cruise Mach number affects not only the airframe and engine cost but also the productivity and utilization which can only be determined from a detailed route simulation which was beyond the scope of this study. Therefore, economic comparisons between aircraft systems with differing cruise Mach numbers should be viewed with caution.

The analytical procedure utilized was good for evaluating and comparing the various engines. However, because of the broad scope of the Task I study, the effects of some of the assumptions could not be explored. The reduced scope of the Task V study made it practical to investigate the sensitivity of the results to variations in key parameters and assumptions. The Task V results, therefore, should be referred to for a more realistic comparison of the non-afterburning turbojet and the duct-heating turbofan.

For example, the effect of thrust loading (FN/TOGW) was explored in Task V and found to have a significant effect on the penalty associated with low levels of sideline jet noise. Higher values of FN/TOGW increased the slope (and level) of curves of TOGW vs sideline noise. FN/TOGW is a highly airplane oriented parameter requiring accurate knowledge of the low speed aerodynamics which was not available during the program.

Turbojet Engines

It was determined early in the study that neither dry (nonaugmented) or afterburning turbojets could achieve the desired noise levels without a very effective jet noise suppressor. The problem of defining an aircraft to meet FAR 36 noise levels with an unsuppressed dry turbojet is illustrated in Figure 10. As airflow (and therefore engine size) increased, lower takeoff power settings were permitted and lower sideline noise resulted. However, the takeoff gross weight required to accomplish the mission increased rapidly because of the increases in engine weight.

The suppressed (based on a high level of suppression) and unsuppressed sideline jet noise vs. liftoff thrust (power setting) for a typical dry turbojet is presented in Figure 11. The engine was throttled at constant airflow (design level) down to the level indicated (broken line) by increasing nozzle jet area. Below this level, the airflow was decreased with decreasing thrust to prevent a choking condition in the turbine. Constant airflow throttling provided the lowest jet noise for a given level of thrust. For the unsuppressed engine, a given noise level was achieved through a combination of throttling and engine scaling to meet the thrust requirement. The flat portion of the suppressed curve – about 104 EPNdB between 50,000 lb and 60,000 lb (222,000 N and 267,000 N) thrust – is the result of decreasing the amount of suppression at the same rate as the engine noise decreased with decreasing jet velocity. If the level of noise was to be reduced below 104 EPNdB, a significant increase in engine size would have been required, severely penalizing the aircraft.

The results of the evaluation of the suppressed dry turbojet are presented in Figure 12. As airflow size was increased, TOGW increased and the unsuppressed noise level decreased. However, because of the characteristic flat section in the curve of suppressed noise vs. thrust at partpower, the sideline noise stayed essentially constant as airflow size was increased. The lowest TOGW and highest ROI system was the one with the lowest airflow size consistent with the minimum thrust/drag margin.

The overall pressure ratio of the turbojets was varied at a constant level of CET and sideline noise, and the results are shown in Figures 13 and 14 for the 2.7 Mn nonaugmented and afterburning turbojets, respectively. In both cases, the best overall pressure ratio was about 12 to 1. Similarly, combustor exit temperature was varied at constant overall pressure ratio and sideline noise level. These results are shown in Figures 15 and 16. For the dry turbojet, the optimum CET is somewhat higher than for the augmented turbojet; however, CET = 2800°F (1538°C) was close to optimum for both engines.

Turbofan Engines

Overall pressure ratio and combustor exit temperature were also evaluated for the turbofan engine. Figures 17 and 18 show that the best overall pressure ratio was about 15 for both the duct-heating and afterburning turbofan engines. Figures 19 and 20 show that the optimum CET was about 2800°F (1538°C) for both types of turbofan engines.

The effects of fan-pressure-ratio/bypass-ratio were also evaluated for the turbofan engines. The TOGW for the afterburning turbofan is shown in Figure 21 as functions of sideline noise level and of fan-pressure-ratio/bypass-ratio. TOGW increased as noise was reduced because larger engine sizes were required. The results for a duct-heating turbofan are shown in Figure 22. A very significant TOGW reduction is shown for the duct-heating turbofan with the 5 PNdB duct jet suppressor (This suppression level was assumed constant for all jet velocities).

Comparison of Engine Types

A summary of TOGW results is presented in Figure 23 for the best engine of each type. The duct-heating turbofan engine provided the lowest TOGW for the three cruise Mach numbers evaluated at any given noise level. There was a trend toward higher TOGW with higher Mach numbers.

The installed supersonic cruise performance is shown in Figure 24 for the best engine at each type for the 2.7 Mn case. The thrust levels shown are for the base size, 900 lb/sec (408 kg/sec), for all engines, but the indicated operating points are in their correct relative position for the scaled engine size. All of the augmented engines are shown at cruise with partial augmentation.

The installed subsonic cruise performance for the best engine of each type is shown in Figure 25. The thrust levels shown are for the base size, 900 lb/sec (408 kg/sec), for all engines, but the indicated operating points are in their correct relative position for the scaled engine size. The turbofan engines had significantly lower cruise TSFC's relative to the turbojets.

Approach Noise

In all of the discussions so far, only sideline jet noise has been addressed. The approach noise problem with the 3.3 FPR duct-heating turbofan is illustrated in Figure 26. The approach noise shown for the fan aft and fan inlet is hardwall source noise calculated at the appropriate power setting of an aircraft engine system sized to meet the indicated sideline noise. The "desired total" line is simply an approach noise level equal to the sideline noise. In all cases, the jet noise on approach was well below the "desired total" level. In order to meet the FAR 36 noise level, 13 PNdB and 10 PNdB noise increments had to be attenuated from the fan aft and fan inlet noises, respectively. These levels of attenuation were consistent with wall treatment in the fan duct and inlet for the geometry of this duct-heating turbofan. For FAR 36 minus 10 EPNdB, however, 23 PNdB and 19 PNdB noise increments had to be attenuated from the fan aft and fan inlet, respectively. A choked inlet could probably have provided the required inlet suppression, but the 23 PNdB fan aft attenuation may not have been possible with any reasonable treatment configuration.

The TOGW penalty associated with meeting the approach noise level is presented in Figure 27. The lower curve, labeled "sideline jet noise", shows the aircraft gross weight with the best duct-heating turbofans sized to meet the sideline noise level indicated on the abscissa. When sufficient acoustic treatment was installed such that the approach noise level was equal to the sideline noise, the system TOGW increased to the level indicated on the upper curve. There was little penalty for approach noise treatment at FAR 36 noise levels, but the penalty became large as the approach noise level approached FAR 36 minus 10 EPNdB.

TASK II

VARIABLE-CYCLE ENGINES
(1975 Technology)

INTRODUCTION (TASK II)

One of the most challenging technical problems facing the next generation of supersonic transports is the achievement of both low noise and good supersonic performance. Low noise is generally obtained with low specific thrust cycles while good supersonic performance is generally associated with high specific thrust cycles. Although the supersonic transport requires efficient operation at supersonic speed, there is also a requirement for efficient operation at subsonic speeds for flight over land and to minimize the reserve fuel carried. These diverse propulsion requirements provide a strong incentive to investigate the merits of a variable cycle engine concept which has the potential of providing an optimum cycle at both supersonic and subsonic flight conditions as well as low sideline noise at takeoff. The objective of Task II was to investigate variable cycle concepts for the supersonic transport application. Several concepts for achieving this objective were evaluated. Some of these concepts were for self-contained engines while others employed main propulsion engines with remote components or engines. The engine technology time period (1975) as well as the systems analysis assumptions were consistent with those used in the Task I studies of conventional engines.

The concepts studied in Task II were as follows:

- Series/Parallel Variable Bypass Engines (VBE)

  These are self-contained engines employing two or more fans or compressors with a flow diverter valve between them. The bypass ratio and total airflow of this type of engine increases when switched from series to parallel modes.

- Augmented Wing Concept

  This system employs a low bypass ratio propulsion engine which has a valve for diverting flow into the wing ejector/flap system for suppressing the jet noise during low noise operation.

- Auxiliary Engine Concept

  This concept employs an optimum main propulsion engine plus light-weight, low noise remote engines which are used for takeoff, landing, and possibly other subsonic flight conditions.

- Turbofan Ramjet

  This self-contained, variable cycle concept combines a high bypass ratio turbofan with an integral ramjet.

In general, the performance and weight of variable cycle engines were more difficult to estimate accurately than conventional cycles during the conceptual design phase. This was true because analysis of the variable cycle engines required that available knowledge be extended beyond the bounds of normal experience. Further, many of the benefits of the variable cycle engines could only be realized by a careful integration of the propulsion system and the airframe where the inlet, nozzle, and installation can be selected to optimize the performance of the total airplane. The goal of Task II was to identify a few of the more promising variable cycle concepts for further study to determine their full potential compared to conventional cycles.

SUMMARY (TASK II)

A range of variable cycle concepts were investigated for application in an advanced supersonic transport. These variable cycle engines were based on 1975 technology and included several types of series/parallel concepts, the augmented wing concept, the auxiliary engine concept, and the turbofan ramjet concept. Engine performance, weight, and dimensional data were sent to the Langley airframe-contractors for evaluation. In addition, a P&WA evaluation was made as an aid to cycle optimization and comparison of concepts. The variable bypass engine series/parallel concept was identified as one of the most promising of the variable cycles studied, having the potential of achieving lower noise levels than conventional engines. A variable bypass engine series/parallel cycle, designated as VBE 1, was selected for further work in Task V. Additional investigations of the variable bypass engine series/parallel concepts in both Task II and Task V indicated that there is probably more that can be done to improve the overall performance of these variable cycle engines through cycle optimization and engine matching at key flight conditions.

The P&WA evaluation also showed the augmented wing concept employing a low bypass ratio duct-heating turbofan engine as a propulsion system which might be capable of achieving low noise levels for the supersonic transport. However, proper evaluation of this concept requires careful analysis of the complete airplane/propulsion system to be certain that inherent penalties due to the ducting system are properly assessed. Further work on the augmented wing concept will require collaboration with an airframe company.

As in Task I, the penalty associated with sideline noise levels in the range of FAR 36 minus 10 EPNdB may be understated for the engines in Task II because the estimated airplane thrust loading may be too low –the effect of thrust loading on cycle selection and noise level is evaluated in Task V.

ENGINE DESCRIPTION (TASK II)

Series/Parallel Concepts

One approach to the variable cycle engine concept is to utilize two fans or compressors which could operate either in series or parallel, permitting a wide airflow range of operation. A schematic of an engine employing two fans is shown in Figure 28. When operating in a series mode at supersonic cruise, this series/parallel engine operates as a conventional low bypass ratio duct-heating turbofan, as shown in the lower half of the schematic. During parallel operation at takeoff and subsonic cruise when lower jet velocities are desired, a valve between the first and second fan diverts flow from the first fan into an auxiliary nozzle and brings ambient air from an auxiliary inlet into the second fan. This results in greater total airflow, lower jet velocities, and lower jet noise.

One possible type of ducting arrangement for the series/parallel variable cycle engine is shown in Figure 29. Retractable chutes (shown in the high bypass mode) bring auxiliary flow around the first fan and into the second fan. A second set of ducts discharge air from the first fan around the second fan into a retractable fan nozzle. Other variations of this ducting concept are possible as well as completely different valve concepts. For example, the airflow for the second fan could be supplied by the same inlet as the first fan, and the first fan exit flow could be mixed with the flow from the second fan and discharged through a common nozzle.

The initial definition of the series/parallel concept, shown in Figure 30, assumed that a full 360 degrees would be available for inlet chutes. A preliminary installation study of the diverter concept was conducted to determine the effect of the proximity of the wing undersurface on the axisymmetric nature of the fan and flow diverter flowpath. A result of this investigation is shown in Figure 31. This concept has the same characteristics and moving elments as the preceding concept except that the back chutes are now stationary and have cover flaps which fair in with the nacelle surface for series operation. To avoid interference between the wing undersurface and the opened chutes, the 90-degree segment in the 12 o'clock region does not contain any chutes. This dead region requires a fairing that directs the fully annular flow from the first fan to and around the 90-degree segment of blockage. The top view shows this fairing.

An alternate installation arrangement is shown in Figure 32 with an internal annular feed for the front chutes. The position shown in this drawing is the parallel mode with flow from the internal annulus ducted directly to the second fan assembly. Flow from the first fan is ducted to a separate set of auxiliary nozzles located over the second fan. The shading indicates the three separate flowpaths for parallel operation. The primary (inner) stream is unaffected by the position of the flow diverter. The second (middle) stream, coming from the first fan, is ducted to stationary chutes which then lead to the auxiliary nozzles. As shown in the back view, these stationary chutes and nozzles are configured to avoid impingement of the exit air on the wing undersurface. In this plane, a no-flow segment of approximately 90 degrees is required to accomplish this. The third stream starts with the annulus over the front fan and feeds flow into the second fan. To go to the series mode, shown in Figure 33, two sets of moving elements are actuated simultaneously. The front set of chutes is moved inward to fill the annulus behind the front fan, and the flaps over the auxiliary nozzles are closed. With these changes, all flow from the first fan is ducted through the movable chutes, around the stationary chutes in the back half of the diverter, and into the full annulus leading to the second fan. In this mode, all the air from the first fan flows directly to the second fan.

The possible problem areas with the series/parallel engine concepts that will require design and development are:

1. The transition effect on the engine components and control system when the diverter chutes are in an intermediate position,

2. Distortion from the diverter chutes possibly causing fan and engine instability, and

3. Integration of the engine with the airframe.

The design of the flow diverter valve system itself will, of course, require a design and development effort if maximum performance and minimum weight are to be achieved.

Several variations of the series/parallel type cycle were studied in Task II. These variations were grouped by types (designated VBE I through VBE V) and are described in subsequent paragraphs. The types are grouped according to the number of valves, whether all of the front fan flow or only the outer fan flow is diverted, and whether the diverted flow is from a fan or a compressor. Within each group, some cycle perturbations were included, as shown in Table II.

In order to provide a common base for evaluating these engines, the engines were matched to the same series mode airflow schedule as the inlet airflow schedule of Task I. Even though auxiliary inlets are shown in the engine schematics, from a performance viewpoint it was assumed that the main inlet could pass the large airflow increase in subsonic parallel mode operation without an increase in capture area or a degradation in pressure recovery. Parallel mode operation then corresponds to large values of the inlet mass flow ratio parameter and results in a reduction in inlet spillage drag.

TABLE II

SERIES/PARALLEL CYCLES

	BYPASS RATIO AT TAKEOFF	BYPASS RATIO AT CRUISE
VBE IA	2.45	1.5
VBE IB	4.10	2.95
VBE IIA	5.00	1.75
VBE IIB	6.65	3.20
VBE IIIA	3.35	1.50
VBE IVA	1.8	0
VBE VA	3.3	0

VBE I – Series/Parallel Turbofan With Splitter

The schematic referred to in the previous section (Figure 28) represents a series/parallel, two-fan turbofan with a splitter behind the first fan. In the low (series) mode, this engine is a conventional low bypass ratio, duct-heating turbofan. In the high (parallel) mode, this engine is a moderate bypass ratio turbofan with a lower fan pressure ratio. Only the outer front fan flow is diverted in the parallel mode. The inner front fan flow passes through both fans and on through the gas generator. The purpose of this arrangement is that the gas generator remains supercharged by the front fan in both modes of operation. The result is that, in the parallel mode, greater thrust and better TSFC's are possible with this cycle than one in which all of the first fan flow is diverted. For VBE I, duct heating is done only in stream 2. Streams 1 and 2 have variable area convergent-divergent nozzles, while stream 3 has an auxiliary variable area convergent nozzle which is used only during parallel operation.

Two cycle variations with different design (series) bypass ratios were evaluated: the low bypass ratio VBE IA and the moderate bypass ratio VBE IB. A cycle characteristic summary of these engines is shown in Table III. Large increases in total airflow and substantial decreases in jet velocity occurred with both cycles when switching from series to parallel mode of operation. VBE IB, with its higher design bypass ratio, had a larger increase in airflow and a greater decrease in jet velocity; however, its thrust was also less than that of VBE IA. The noise characteristics for both engines are shown in Figure 34. The substantial reduction in jet noise for parallel operation should be noted. Also, VBE IA and VBE IB had essentially equal noise in the parallel mode for any given thrust level above 40,000 lb (178,000 N), which is the region of interest. Engine matching to minimize noise and optimize performance at all key operating conditions was difficult with any of these series/parallel concepts. Further work could probably improve the noise and performance of these engines.

TABLE III

VBE I CYCLE CHARACTERISTICS
(SEA LEVEL STATIC – STANDARD DAY OPERATION)
MAXIMUM NON-AUGMENTED THRUST

CYCLE	VBE IA		VBE IB	
MODE OF OPERATION	SERIES	PARALLEL	SERIES	PARALLEL
Corrected Airflow, lb/sec	900	1350	900	1470
(kg/sec)	(408)	(612)	(408)	(667)
Bypass Ratio	1.5	2.45	2.5	4.1
Fan Pressure Ratio (each fan)	2.0	2.4	1.7	1.95
Cycle Pressure Ratio	15.0	16.5	15.0	16.5
Combustor Temperature, ^{o}F	2800	2800	2800	2800
(^{o}C)	(1538)	(1538)	(1538)	(1538)
Net thrust, lb	46,000	52,500	38,500	45,000
(N)	(204,608)	(233,520)	(171,248)	(200,160)
Relative Stream 1 Area	Base	+24%	Base	+30%
Jet Velocities, ft/sec (m/sec)				
Stream 1	1870 (570)	1570 (479)	1670 (509)	1270 (387)
Stream 2	1710 (520)	1230 (375)	1395 (425)	1000 (305)
Stream 3	—	1270 (387)	–	1030 (314)

VBE II – Series/Parallel Turbofan Without Splitters

A schematic of a series/parallel, two-fan turbofan, variable cycle without a splitter behind the first fan is presented in Figure 35. This cycle is a low bypass ratio duct heating turbofan in the series mode and a high bypass ratio, low overall pressure ratio turbofan in the parallel mode. This cycle differs from VBE I in that the valve diverts all of the first fan flow around the second fan in the parallel mode. This reduces the overall pressure ratio because the front fan is no longer pressurizing the gas generator flow and results in reduced thrust in the parallel mode.

Two cycles were evaluated for VBE II: a low design bypass ratio (VBE IIA) and a moderate design bypass ratio (VBE IIB). The characteristics of these cycles are summarized in Table IV. It can be noted that the increase in airflow from series to parallel modes was not as great as in the VBE I type even though all of the first fan flow was diverted. This was a result of the loss in gas generator flow which reduced the turbine work capability and prevented matching the engine at the higher total airflow.

The sideline noise characteristics of VBE IIA is shown in Figure 36. The loss in thrust due to desupercharging in the parallel mode is readily apparent.

TABLE IV

VBE II CYCLE CHARACTERISTICS
SEA LEVEL STATIC – STANDARD DAY OPERATION
MAXIMUM NON-AUGMENTED THRUST

CYCLE	VBE IIA		VBE IIB	
MODE OF OPERATION	SERIES	PARALLEL	SERIES	PARALLEL
Total Inlet Corrected Flow, lb/sec (kg/sec)	900 (408)	1125 (510)	900 (408)	1240 (562)
Bypass Ratio	1.5	5.0	2.5	6.65
Fan Pressure Ratio (each fan)	2.0	1.75	1.7	1.6
Cycle Pressure Ratio	15.0	7.6	15.0	9.3
Combustor Temperature, °F (°C)	2800 (1538)	2800 (1538)	2800 (1538)	2800 (1538)
Net Thrust, lb (N)	46,000 (204,608)	30,000 (133,440)	38,500 (171,248)	30,000 (133,440)
Relative Stream 1 Area	Base	Base	Base	Base
Jet Velocities, ft/sec (m/sec)				
Stream 1	1870 (570)	1010 (308)	1670 (509)	1070 (326)
Stream 2	1710 (521)	910 (277)	1400 (427)	800 (244)
Stream 3	– – –	900 (274)	– – –	800 (244)

VBE III – Series/Parallel, Three-Fan Turbofan With Splitter

A schematic of a series/parallel, three-fan variable cycle with a splitter behind the first fan is presented in Figure 37. In the series mode, this engine is a low bypass ratio duct-heating turbofan. During parallel operation, a valve between the second and third fan diverts the outer fan duct flow at the exit of the second fan into the auxiliary nozzle of stream 3, and brings ambient air from an auxiliary inlet into the third fan (stream 2). Another valve between the first and second fan diverts the outer fan duct flow of the first fan into the auxiliary nozzle of stream 4, and brings ambient air from an auxiliary inlet into the second fan (stream 3).

The purpose of this configuration is to increase the total airflow in the parallel mode even further than the VBE I type and to achieve even greater noise reductions. This is accomplished at the expense of increased weight and length due to the addition of a second valve. Table V lists the cycle characteristics of VBE IIIA in both modes. Figure 38 compares the sideline noise level of both VBE I and VBE III variable cycle engines. VBE IIIA has significantly lower noise at all thrust levels.

TABLE V

VBE IIIA CYCLE CHARACTERISTICS
[SEA LEVEL STATIC – STANDARD DAY OPERATION]
MAXIMUM NON-AUGMENTED THRUST

MODE OF OPERATION	SERIES	PARALLEL
Correction Airflow, lb/sec (kg/sec)	900 (408)	1800 (816)
Bypass Ratio	1.5	3.35
Fan Pressure Ratio (each fan)	1.6	2.0
Cycle Pressure Ratio	15.0	17.5
Combustor Temperature, °F (°C)	2800 (1538)	2800 (1538)
Net Thrust, lb (N)	46,000 (204,608)	61,000 (271,328)
Relative Stream 1 Area	Base	+30%
Jet Velocity, ft/sec		
Stream 1	1870 (570)	1550 (472)
Stream 2	1710 (521)	1060 (323)
Stream 3	–	1080 (329)
Stream 4	–	1060 (323)

VBE/IV — Series/Parallel Turbojet/Turbofan

Figure 39 shows a single-valve, two-compressor, series/parallel variable cycle engine which is a twin spool turbojet in the series mode and a low bypass ratio turbofan in the parallel mode. During parallel operation, a valve between the first and second compressor diverts all of the flow from the first compressor into the auxiliary nozzle of stream 2 and brings ambient air from the auxiliary inlet into the second compressor (stream 1). Augmenting is done only in stream 1 which has a variable-area, convergent-divergent nozzle. Stream 2 has an auxiliary variable-area, convergent nozzle which is used only during parallel operation.

In order to minimize jet noise in the turbofan mode with minimum performance loss, a study was conducted to determine the pressure ratios of the two compressors in the conventional turbojet (series) mode. As the pressure ratio of compressor 1 increases, the bypass ratio increases in the turbofan mode. However, there is also more desupercharging of compressor 2, which results in a significant decrease in thrust. The cycle characteristics shown in Table VI were found to give the best balance between noise reduction and thrust loss. The sideline noise for VBE IV is shown in Figure 40. Significant reductions in jet noise were produced with the VBE IV concept in parallel mode, but there was also a significant thrust loss.

TABLE VI

VBE IVA CYCLE CHARACTERISTICS
SEA LEVEL STATIC – STANDARD DAY OPERATION
MAXIMUM NON-AUGMENTED THRUST

	SERIES	PARALLEL
Relative Nozzle Area, Stream No. 1	Base	40%
Total Inlet Corrected Flow lb/sec (kg/sec)	900 (408)	1390 (630)
Bypass Ratio (2/1)	0	1.78
Pressure Ratio (Compressor No. 1)	3.0	2.94
Pressure Ratio (Compressor No. 2)	5.0	8.28
Overall Pressure Ratio	15.0	8.28
Combustor Exit Temperature, °F (°C)	2800 (1538)	2800 (1538)
Total Net Thrust, lb (N)	77,900 (346,499)	59,600 (265,101)
Nozzle Jet Velocity (Stream No. 1) ft/sec (m/sec)	2950 (900)	1580 (482)
Nozzle Jet Velocity (Stream No. 2) ft/sec (m/sec)		1430 (436)

VBE V – Series/Parallel, Three-Compressor Turbojet/Turbofan

A schematic of a series/parallel, three-compressor variable cycle is presented in Figure 41. This cycle is similar to VBE IV except that it has a second valve splitting the low compressor so that additional airflow is available in the turbofan mode. The cycle is a turbojet in the series mode and a three-stream, high bypass ratio, low overall pressure ratio turbofan in the parallel mode. Augmenting is done only in stream 1 which has a variable-area, convergent-divergent nozzle. Streams 2 and 3 have auxiliary, variable-area, convergent nozzles which are used only in parallel operation.

Like the two-compressor VBE IV, the three-compressor VBE V experiences desupercharging when operating in the parallel mode. The pressure ratios of the compressors were selected to provide the best balance of thrust loss and noise reduction for parallel mode operation. Table VII presents the cycle characteristics for VBE VA, and Figure 42 presents the sideline jet noise characteristics for VBE IVA and VBE VA.

TABLE VII

VBE VA CYCLE CHARACTERISTICS
SEA LEVEL STATIC – STANDARD DAY OPERATION
MAXIMUM NON-AUGMENTED THRUST

	SERIES	PARALLEL
Relative Nozzle Area (Stream No 1)	Base	+40%
Total Inlet Corrected Flow, lb/sec (kg/sec)	900 (408)	1642 (745)
Bypass Ratio (2 + 3/1)	0	3.31
Pressure Ratio		
Compressor No. 1	2.3	2.01
Compressor No. 2	1.9	1.94
Compressor No. 3	3.3	6.21
Overall Pressure Ratio	15.0	6.21
Combustor Exit Temperature, F(°C)	2800 (1538)	2800 (1538)
Total Net Thrust, lb (N)	78,200 (347,834)	51,800 (230,406)
Nozzle Jet Velocity, ft/sec (m/sec)		
Stream # 1	2955 (900)	1220 (372)
Stream # 2		1040 (317)
Stream # 3		1070 (326)

Augmented Wing Concept

Studies by NASA and the Boeing Company have shown that the augmented wing (ejector flap) can be a very effective jet noise suppressor for STOL aircraft. Since the supersonic transport has a jet noise problem, the augmented wing concept was considered as a candidate for this application. The augmented wing concept permits the use of a low bypass ratio, conventional duct-heating turbofan for climb and supersonic cruise operation while still achieving low noise during takeoff and landing by utilizing the wing flap/ejector system as a remote jet noise suppressor.

As shown in Figure 43, the basic elements of this concept are the duct-heating turbofan engine, ducting to carry fan air to the wing manifold, and the wind flap/ejector system. A valve system diverts flow from the engine fan duct to the wing duct manifold. During takeoff the engine is operated in the augmented wing mode with no flow passing through the fan duct of the engine. The jet and source noise from the fan are suppressed in the wing flap/ejector system. If the primary jet noise dominates, the primary jet velocity can be reduced by opening the primary nozzle jet area, which will maintain the total airflow and fan pressure ratio nearly constant while significantly reducing the primary stream jet noise.

For Task II studies, the augmented wing engine was operated as a conventional duct-heating turbofan during climb and all cruises. During approach to landing, the engine was operated in the augmented wing mode for quiet operation.

Two duct-heating turbofans were evaluated for the augmented wing concept. These cycles were identical to the Task I engines with the same fan pressure ratio. The only difference in the Task I and Task II engines was the valve and ducting necessary for the augmented wing operation. The cycle characteristics of these two engines are listed in Table VIII.

TABLE VIII

AUGMENTED WING DUCT-HEATING TURBOFAN
CYCLE CHARACTERISTICS
SEA LEVEL STATIC

Fan Pressure Ratio	3.3	4.8
Bypass Ratio	2.1	1.3
Cycle Pressure Ratio	15	15
Combustor Exit Temperature, °F (°C)	2800 (1538)	2800 (1538)

The diverter valve, scroll, duct system, and flap/ejector jet noise suppressor are items that would require technology development beyond that required by the basic duct-heating turbofan engine. Potential problem areas include transition effects when switching duct flow, thrust reversing, and engine/airplane integration with consideration for ducting and valve system.

Auxiliary Engine Concept

The auxiliary engine concept utilizes separate, remote turbofans in combination with the primary propulsion engines whose size and cycle would be selected for optimum performance. During takeoff and approach, the primary engines would be throttled back until their noise is below the goal level. The additional thrust required would be provided by low noise, light weight, remote turbofans which would be retracted into the fuselage when not in use.

Optimum sized duct-heating turbofans were used in this study as the primary propulsion engines. The remote auxiliary turbofan was a 10 bypass ratio, 1.25 fan pressure ratio engine with a 10:1 thrust/weight ratio. These cycle characteristics were selected on the basis of low noise, weight, emissions, and price. Because of the short duration of operation of the remote engines, fuel consumption characteristics were traded for low weight. A schematic for the remote turbofan is shown in Figure 44.

In addition to the development of the main propulsion system, technology is required to develop the light weight, low noise, low cost auxiliary engines. Integration of these auxiliary engines into the airframe is probably the biggest potential problem area.

Turbofan Ramjet Concept

This variable cycle scheme uses a high bypass ratio duct-heating turbofan to provide low noise for takeoff and approach while providing good performance for subsonic cruise and climb. An integral ramjet provides good supersonic cruise performance with the potential of increasing the cruise speed to Mach 4 to improve aircraft block-time. The turbofan and ramjet utilize a common duct heater type burner to minimize weight, complexity, and dimensions. A schematic of the concept is shown in Figure 45. Changes in operation from turbofan to ramjet are accomplished by activating a set of valves – one valve of the set is used to close off the inlet to the system not being operated and the other valve for isolating the fan during ramjet operation.

For this study a 3.2 bypass-ratio, conventional duct-heating turbofan with a fan pressure ratio of 2.5 was used as an accelerator engine to provide low noise at takeoff and good subsonic performance. The ramjet was used at high ram temperature conditions to provide good high supersonic performance.

The turbofan ramjet concept will require additional technology development in the valve system and the combination ramjet/duct-heater.

PRELIMINARY SYSTEMS ANALYSIS (TASK II)

Series/Parallel Concept Evaluation

In evaluating the various series/parallel type variable cycles, an effort was made to be optimistic in the analysis in order to take full advantage of their potentials. For example, the airplane was not penalized for the very long installed engine pods which might not fit under the wing. For each engine, airflow size was treated as a parameter so that a curve of TOGW versus sideline noise could be obtained, as shown in Figure 46. Low sideline noise levels correspond to large airflow sizes and high engine weights. The results show the VBE 1 type cycles to be the most attractive of all series/parallel types. All of the engines without a splitter suffer from the desupercharging effect which results in high engine weights when sizing to meet thrust requirements. VBE IA appears to provide the lowest TOGW over most of the noise levels of interest. The width of the band represents the TOGW difference between operation in parallel mode for all subsonic conditions and operation in series mode for all subsonic conditions (except takeoff). Although this curve shows noise down to very low levels, the values shown are sideline jet noise only, and it is possible that at low noise levels the main engine core noise or an other noise source may become dominant. Figure 47 presents the corresponding ROI summary of the various series/parallel concept cycles and, as can be seen, shows trends similar to the TOGW results.

Because of the uncertainty in engine weight estimates for the variable engines, engine weight was varied parametrically. The impact of this engine weight variation on TOGW, DOC, and ROI is shown in Figures 48 and 49 for VBE IA; the estimated weight for VBE IA is noted on the curves. Likewise, because of the uncertainty associated with engine price estimates, engine price was varied parametrically. The impact of VBE IA engine price variation on DOC and ROI is shown in Figure 50. It should be noted that even though the weights of the variable cycle engine are greater than for the duct-heating turbofan in the same cruise thrust size, the variable cycle engine achieves lower noise levels.

Augmented Wing Concept Evaluation

In this analysis, the augmented wing-flap system was considered as a remote jet noise suppressor without net performance benefits – aerodynamic benefits were cancelled by pressure losses in the duct system. No additional benefit was taken in takeoff thrust loading reduction as might be possible with some powered lift. A baseline weight penalty of 30 pounds per foot (44.6 kg/m) of wing span was assumed for the wing duct and additional flap weight required by the concept in order to give a preliminary evaluation of the merit of the overall system.

The comparison between 3.3 FPR and 4.8 FPR duct-heating turbofan engines powering an augmented wing airplane is shown in Figure 51. Duct-heating was not used at takeoff for this comparison. The noise scale shows only the primary stream jet noise at the sideline condition. The duct jet noise was assumed to be suppressed to at least the level of the primary stream, adding a maximum of 3 dB to the primary noise level. As the primary jet noise is decreased by throttling, the engine size must be increased to maintain sufficient thrust for takeoff. This results in increased engine weight and, hence, increased TOGW. Heating the duct stream to maintain thrust would minimize the oversizing required at the low noise levels, but it would also complicate the system because of the increased duct temperatures in the wing environment. The 4.8 FPR engine has considerably lower TOGW's for equal levels of primary stream noise, but the amount of suppression required for the fan stream would also be higher. The higher fan pressure ratio engine will require smaller wing ducts because of the lower volumetric flow.

Sideline jet noise at takeoff is only one part of the total noise problem; therefore, estimates were also made for the amount of suppression required during approach operation, as shown in Figure 52. The value of the duct jet noise shown is that which would result if the duct flow had not been diverted to the wing flap/ejector system. The fan aft and fan inlet noises are hardwall source levels. The fan aft noise would have to be attenuated within the wing ducting system, and a sonic inlet would probably be employed to attenuate the fan inlet source noise.

Auxiliary Engine Concept Evaluation

Figure 53 presents TOGW of the auxiliary engine concept parametrically with auxiliary engine installed Fn/Wt. Thrust is measured at the 200 knot (370 km/hr) takeoff speed, and weight includes all installation and mechanisms associated with retracting the auxiliary engines. This concept can be seen to depend on achieving high levels of installed thrust-to-weight for the auxiliary engines. The uninstalled Fn/Wt of the auxiliary turbofans used in this study was estimated to be about 6.3 at 200 knots (370 km/hr). Installation penalties will decrease this considerably. No assessment was made of the practicality of retracting these auxiliary turbofans into the aircraft.

Turbofan-Ramjet Concept Evaluation

The turbofan-ramjet concept used a 2.5 FPR duct-heating turbofan for all flight conditions up to Mach 2.7, at which point the engine translated to the ramjet mode. Mach 3.2 and Mach 4.0 cruise speeds were evaluated at several different ramjet airflow/turbofan airflow ratios. The results shown in Figure 54 indicate that this concept is not very promising in the cruise Mach number regime investigated in this study.

Variable Cycle vs. Conventional Engine Comparison

A TOGW comparison of the VBE I and augmented wing variable cycle engines with conventional duct-heating turbofans is presented in Figure 55. It can be seen that the variable cycle engines are competitive with the conventional engines at noise levels of FAR 36 minus 10 EPNdB and have the potential of reducing the noise level even further. As mentioned previously, the airplane liftoff thrust loading can have a significant effect on the results. The value of 0.245 used in Tasks I and II may be too low for good field length and climbout capability. A higher value of thrust loading will have the effect of steepening the curves so that the penalty associated with low noise levels will be higher. It will also have the effect of penalizing VBE IA less than the conventional engines at FAR 36 minus 10 EPNdB. Refinements included in the Task V analysis make the results presented there a more up-to-date comparison between the conventional and variable cycle engines. But even the Task V evaluation revealed areas of further improvement in the series/parallel variable cycle engines.

EMISSIONS (TASK II)

Basic pollutant levels are shown in Figure 56 as a function of noise level for takeoff operation. As the engine is throttled back to reduce jet noise levels, the maximum local temperature in the primary zone of the burner is reduced and increased quenching reduces temperatures in the dilution zone. The effect of throttling on pollutants is as follows: a reduction in the NO_2 level approaching the AST takeoff goal of 10; an increase in CO by as much as a factor of 2 at the FAR 36 -20 EPNdB noise level; and a slight increase in total-unburned-hydrocarbons (THC), reflecting a decrease in combustion efficiency as the engine is throttled back. Thus, throttling for noise improves NO_2 but compromises CO and THC levels. The net effect on the overall emission problem due to noise throttling must be assessed for each variable cycle before burner design improvements and advanced combustion technology can be applied to obtain the best balance between the emissions (NO_2, CO, and THC) and noise requirements.

All the parametric engines met the smoke goal at sea-level takeoff. This was basically due to the relatively high combustor exit temperatures under consideration in the parametric study. Increased combustor exit temperatures reduced smoke due to the higher peak flame-temperatures which provided increased carbon oxidation. Also, the advanced burner design had a higher density of fuel-injection sites. This provided more uniform fuel-air mixtures so that carbon formation in fuel-rich regions was reduced.

CO and THC emission goals can be met by most engines with the possible exception of those engines sized for very low noise levels. The concept of a staged, premixed burner with the first stage optimized for idle operation, used throughout these studies, provided high burner efficiency at low power. This design concept satisfied most variable cycles sized in the conventional manner at sea-level takeoff. For this operating point, the temperatures and pressures entering the burner were appreciably above ambient conditions. Emissions trends resulting from studies indicate that at decreasing temperatures the CO index increases rapidly in spite of a relatively constant efficiency achieved by the staged burner. This is probably a combined result of lower flame temperatures and more rapid quenching of the CO to CO_2 reaction with cooler air. Oversizing the engines for sea-level takeoff at low sideline noise levels resulted in idle operation at significantly lower inlet temperatures and pressures and lower flame temperatures than cycles sized in the conventional manner. Therefore, in spite of the low power stage being optimized for ground idle operation, the required CO index may be difficult to achieve.

TASK III
ADVANCED TECHNOLOGY BENEFITS FOR CONVENTIONAL AND VARIABLE CYCLES
(1980 Technology)

INTRODUCTION (TASK III)

Economic and environmental improvements over the present generation of supersonic transports will require significant advances in propulsion system design and technology. The intent of the Task III study was to identify and evaluate those areas of advanced technology that indicate the greatest potential benefits to the noise, emission, and economic characteristics of an advanced supersonic transport propulsion system. Based on these evaluations, the critical areas of advanced technology that showed the greatest potential benefits were identified in Task VI, along with the component research and development programs necessary to realize these benefits.

Advanced technologies which appeared to offer a substantial potential benefit were selected for evaluation in the most promising conventional and variable cycle engines from the Task I and II studies. The engine types selected were the non-afterburning turbojet, duct-heating turbofan, and series/parallel variable cycle engines. The impact of the selected advanced technologies (1980) was evaluated relative to the 1975 technology base of Tasks I and II.

SUMMARY (TASK III)

The intent of the Task III study was to evaluate those areas of advanced technology that indicated the greatest potential improvements in the area of economics, range, emission, and noise. Based on these study results, technology programs were formulated in Task VI for those technologies that are considered critical to advanced supersonic propulsion systems.

Table IX shows the areas of advanced technology which indicated a potential benefit and were selected for evaluation. The areas of propulsion advanced technology that were judged critical (most important) to the success of a commercial supersonic transport are identified in the table. The indirect noise benefit refers to the improved system economics at lower engine jet noise levels. There are additional areas of advanced technology that are also critical for an advanced supersonic transport propulsion system which did not lend themselves to quantitative evaluation in Task III. These include the engine control and some of the technologies which improve the engine environmental characteristics. Critical advanced technologies are identified in Task VI along with the required research and development programs.

Numerous other areas of advanced technology may also provide potential benefits for an advanced supersonic transport propulsion system. The intent of Task III was to evaluate those areas that indicate the greatest potential benefits in order to identify the required technology programs in Task VI.

TABLE IX

RESULTS OF ADVANCED TECHNOLOGY EVALUATION
[Potential Benefits]

	Selected Advanced Technology	Environment Noise	Environment Emissions	System Economics	Judged Critical
1.	High Pressure Turbine Materials and Aerodynamics	X		*	*all engines
2.	Compressor/Primary Burner	X	*	*	
3.	Composite Fan/ Compressor	X		*	*for D/H T.F. and VBE
4.	Low Pressure Turbine	X		*	
5.	Augmentor/Nozzle/ Suppressor	*	*	*	*all engines
6.	Flow Diverter Valve	*		*	*for VBE

* indicates a direct potential benefit
X indicates an indirect potential benefit

The major engine benefits realized in the Task III studies were in the areas of engine weight and price, where substantial improvements without loss in performance or emission characteristics were realized using 1980 technology. These benefits were to structural changes, materials advances, higher aerodynamic loadings, and fabrication improvements. The resulting engine weight and price trends for the best 1975 and 1980 technology engines are shown in Figures 57 and 58. The 1980 technology engines include all of the advanced technologies listed in Table IX. The impact of these improvements in engine weight and price plus the improvements in associated performance and dimensions resulted in the the system TOGW and ROI trends shown in Figures 59 and 60 for the non-afterburning turbojet, duct-heating turbofan and variable bypass engines.

ADVANCED TECHNOLOGIES EVALUATION (TASK III)

Definition of 1980 Technology

The 1980 technology is defined as technology that can be available by 1980 for incorporation into an advanced supersonic transport engine development program. This allows a six year period for research and demonstration to qualify and gain confidence in the selected advanced technologies prior to the start of the engine development program. The availability of these advanced technologies by 1980 is contingent on successfully conducting the research and engineering programs outlined in Task VI. Depending on the complexity of the engine cycle selected, a 6 to 8 year engine development program could lead to certification in the late 1980's or 1990, with production beginning around 1990.

Advanced Technology Areas Selected for Evaluation

A survey was conducted of possible advanced technologies that would be appropriate to an advanced supersonic transport propulsion system. The results of this survey are listed in Table X. This list was screened and those technologies with the most potential for improving environment and economics of an advanced supersonic transport propulsion system were selected for evaluation. Table XI shows the selected technology areas that were individually evaluated. Each of the areas is discussed in more detail under "Results of Advanced Technology Evaluation." All of these are included in the 1980 engine definition shown in the systems results in Figures 59 and 60. Additional areas of advanced technology were also evaluated but were not included in the 1980 engine definition because of smaller benefits, questionable availability by 1980, or were improvements to components that were outside of the engine definition (e.g., the inlet).

TABLE X

COMPREHENSIVE LIST OF ADVANCED TECHNOLOGY FOR ADVANCED SUPERSONIC TRANSPORT

COMPONENT	TECHNOLOGY	POTENTIAL IMPROVEMENT
Inlet	Increased Mn	Pressure recovery, length
	Choked	eliminates acoustical treatment
Fan	Composite materials	Weight
	Increased aerodynamic loading	Diameter, weight, cost
	Tip speed, spacing	Fan source noise
	Vane diffuser	Length
	Acoustical treatment	Weight, noise
Compressor	Aerodynamic loading	Weight, cost
	Materials	Weight
Primary	Increased Mn	Length
Burner	Materials	Weight
	Burner Design	Emissions
Turbine	Aerodynamic loading	Weight, cost
	Materials	Cooling air, higher strength
Augmentor	Burner design	Emissions
	Increased Mn	Diameter, length
	Materials	Cooling air
Nozzle/	Advanced design	Weight, cost
Reverser/	Improved aerodynamics	Performance
Suppressor	Improved suppressor	Noise, performance
Controls	Full electronic	Weight, cost

TABLE X (Cont'd)

COMPONENT	TECHNOLOGY	POTENTIAL IMPROVEMENT
Flow Diverter Valve	Advanced design	Weight, cost
Integration	Modular pod design Materials	Weight, maintenance Weight

TABLE XI

SELECTED ADVANCED TECHNOLOGIES
FOR ADVANCED SUPERSONIC TRANSPORT EVALUATION

Component	Selected Advanced Technology	POTENTIAL BENEFITS Environment Noise	Emissions	System Economics
High-Pressure Turbine	Aerodynamic Loading Materials	X		*
Compressor/Primary Burner	Aerodynamic Loading, Materials, Burner Design	X	*	*
Composite Fan/ Compressor	Composite Materials	X		*
Low-Pressure Spool	Aerodynamic Loading Materials	X		*
Augmentor/Nozzle/ Suppressor	Burner Design, Materials, Suppressor Design	*	*	*
Flow Diverter Valve	Valve Design	*		*

* Indicates a direct potential benefit
X Indicates an indirect potential benefit

All selected advanced technologies offer potential system economic improvements which in turn improve the system noise, as shown in Figures 59 and 60. Advanced technology in the propulsion system can be utilized to improve the economics, the jet noise level, or a combination of both. This indirect noise benefit due to the various advanced technologies is indicated in Table XI.

Consistent with what was considered to be attainable by 1980, quantitative projections of each selected advanced technology were made in the fields of materials, aerodynamic parameters, component structural/mechanical design, and fabrication so that the benefits to the propulsion system could be evaluated. The technology projections were based on the current status of related technology and research, development, test, and evaluation programs that could be conducted by 1980 to demonstrate this technology with a reasonable probability of success. Finally, technical experts at Pratt & Whitney Aircraft provided judgements regarding the physical, theoretical, and practical limits of the advanced technologies.

An example of quantitative projection of advanced technology is the projection shown in Figure 61 of the creep strength of a turbine blade material. The figure shows 1980 projected creep strength as a function of metal temperature for a directionally solidified, eutectic turbine-blade-material relative to a current technology material. The evaluation of how to best use the improved properties of this advanced material was to use some of the improvement to increase the blade design stress level and the remainder to increase the design metal temperature. Therefore, a fifty percent increase in design blade stress was selected which allowed the rotor speed to be increased. The remaining improvement permitted a 200°F (93°C) metal temperature increase, thus lowering turbine cooling air requirements and increasing cooled turbine efficiency.

Application of Selected Advanced Technologies

The selected advanced technology benefits were assessed for the most promising conventional and variable cycle engines from the Task I and Task II studies. These engines are the non-afterburning turbojet, the duct-heating turbofan, and the variable bypass engines. Representative cycle parameters for these engines are shown below:

Engine	Non-afterburning Turbojet	Duct Heating Turbofan	Variable Bypass Engine
Combustor Exit Temp. - °F (°C)	2800 (1538)	2800 (1538)	2800 (1538)
Fan Pressure Ratio	-	3.3	4.1*
Overall Pressure Ratio	12	15	15
Bypass Ratio	-	2.1	1.5

*In series mode

The impact of advanced technology (1980) was evaluated for these engines relative to the 1975 technology base used in Tasks I and II. It should be noted that the airframe definition used in the system studies was the same for both technology levels. Consequently, the system benefits shown in Figures 59 and 60 are due solely to propulsion system improvements associated with advanced technology.

The benefits of advanced technology will be reviewed at representative sideline jet noise levels for the above engines with representative jet noise suppressor systems. These typical configurations were used to assess the impact of advanced technology but should not necessarily be viewed as the most optimum engine configurations. The duct-heating turbofan benefits are shown at two sideline jet noise levels to show the system sensitivity to noise.

Improved engine component performance and reduced levels of turbine cooling air necessitated refinements in the cycle parameters shown above. The combustor exit temperature was reduced from 2800°F (1538°C) to 2650°F (1454°C) in order to maintain constant rotor inlet temperature as the turbine inlet guide vane cooling air was reduced and, thus, preserve the selected thermodynamic cycle. For the turbofan engines, a slight increase in bypass ratio at constant fan pressure ratio resulted from maintaining a jet noise balalnce between the primary and fan duct exhausts.

RESULTS OF ADVANCED TECHNOLOGY EVALUATION (TASK III)

High-Pressure Turbine

Advanced, high-pressure turbine technology includes both advanced turbine materials and increased turbine aerodynamic loading. The following table shows the turbine material changes for advanced technology for the selected engines:

Technology	1975	1980
Inlet Guide Vane	ODS Alloy	Ceramic
2nd Vane (If 2 Stages)	DS Ni Alloy	DSE
Blades	DS Ni Alloy	DSE
Disks	IN 100	Advanced Gatorized IN 100
Tip Seals	Abradable Alloy	Ceramic Thermal Response

ODS - Oxide Dispersed Strengthened
DS - Directionally Solidified
DSE - Directionally Solidified Eutectic

These improved turbine materials allowed increases in material temperatures and, therefore, a reduction in turbine cooling air for constant rotor inlet temperature. An efficiency improvement was realized because of reduced cooling air interference with the turbine aerodynamics. As turbine inlet guide vane cooling air is reduced, the combustor exit temperature can be reduced to maintain constant rotor inlet temperature and, thus, preserve the selected thermodynamic cycle.

The higher strength, directionally solidified, eutectic blades permitted an increase in blade stress (approximately 50%) in addition to the metal temperature increase already mentioned. This allowed an increase in rotor speeds which resulted in a decrease in turbine diameter and fewer compressor stages with no change in compressor technology. Two stages were eliminated from the 12-stage turbojet engine compressor and one stage was eliminated from the seven-stage duct-heating turbofan high-pressure compressor.

The improvement in turbine aerodynamic loading permitted lower turbine wheel speed with no loss in efficiency and resulted in reduced turbine diameter. For the turbojet engine, the option of eliminating one of the two turbine stages was examined and rejected in favor of reducing the turbine diameter. A detailed study of one versus two stages is needed before a final decision in this area is made.

The impact of advanced high-pressure turbine technology was very substantial, especially for the turbojet engine, because the turbomachinery of a turbojet engine was a larger portion of the total engine than the gas generator portion of a turbofan engine. The following table shows the impact of advanced high-pressure turbine technology for the non-afterburning turbojet, duct-heating turbofan, and variable bypass engines. The duct-heating turbofan engine is shown at two sideline jet noise levels to show the system sensitivity to noise. The impact of advanced technology improvements was sensitive to the propulsion system size and weight relative to the vehicle TOGW. Consequently, as the engines were throttled to reduce sideline jet noise and increased in size to meet takeoff thrust requirements, advanced technology had a greater system impact.

Engine	Non-afterburning Turbojet	Duct-Heating Turbofan	Duct-Heating Turbofan	Variable Bypass Engine
Sideline Jet Noise	FAR 36	FAR 36	FAR 36-10	FAR 36-10
Suppression Level	high	none	low	none
Advanced Technology Impact				
Δ Performance				
Δ Turbine Efficiency - pts	1.3	1.4	1.4	1.4
Δ Turbine Cooling Air - % Reduction	-50	-50	-50	-50
Δ Engine Weight - %	-15	-4.0	-4.0	-3.5
Δ Engine Price - %	-13	-4.5	-4.5	-3.0
Δ TOGW - %	-11.5	-2.5	-3.0	-3.5
Δ ROI - pts	+4.0	+1.0	+1.0	+1.0

It should be noted that the engine weight and price changes are for constant airflow sized engines while the TOGW and ROI system changes reflect resizing the engine as was necessary after incorporating the performance, weight, and dimensional changes.

Compressor and Primary Burner

Advanced compressor technology includes both improved materials and increased aerodynamic loading. Advanced titanium alloys were used further back into the rear stages of the compressor blades and disks before the increasing temperature required the use of a nickel alloy with its greater weight. A combination of higher axial velocities and increased diffusion factor was incorporated into the compressor design to increase the aerodynamic loading. This resulted in the elimination of two more compressor stages in the non-afterburning turbojet engine. The combined effects of advanced turbine and compressor technology resulted in a reduction in the total number of compressor stages from 12 to 8. In the case of the duct-heating turbofan engine, one additional high-pressure compressor stage was eliminated by advanced compressor technology. The combined effects of advanced turbine and compressor technology reduced the total number of stages from 7 to 5.

The advanced burner can be designed to accept higher Mach number flow from the compressor while maintaining high efficiencies. The in-progress NASA Experimental Clean Combustor Program, NAS3-16829, being conducted by Pratt & Whitney Aircraft will provide the primary burner technology to reduce emissions. Results from this program are not yet available regarding the best burner configuration or the levels of improvements to be expected in emissions for primary burners. The emission requirements at supersonic cruise may require additional design features, and research is now under way as part of the NASA Experimental Clean Combustor Program.

The following table shows the impact of advanced compressor and primary burner technology for the non-afterburning turbojet, duct-heating turbofan and variable bypass engines.

Engine	Non-afterburning Turbojet	Duct-Heating Turbofan	Duct-Heating Turbofan	Variable-Bypass Engine
Sideline Jet Noise	FAR 36	FAR 36	FAR 36-10	FAR 36-10
Suppression Level	high	none	low	none
Advanced Technology Impact				
Δ Performance	none	none	none	none
Δ Engine Weight - %	-7.5	-1.5	-1.5	-1.5
Δ Engine Price - %	-3.5	-1.0	-1.0	-0.5
Δ TOGW - %	-3.0	-0.5	-1.0	-1.0
Δ ROI - pts	+1.0	0.	+0.5	+0.5

The engine and system improvements were less for the turbofan engine because of the smaller gas generator size relative to the turbomachinery size of the turbojet.

Composite Fan/Compressor

Advanced, high temperature, composite materials were applied to turbofan engine fan blades and turbojet engine front compressor blades in place of titanium. The composite materials offered a reduction in engine weight but with a projected price penalty due to more costly fabrication techniques. There was a direct weight savings in the blade itself and an indirect weight savings in the containment, disk, and rotor structure due to the lighter blades. In order to obtain a substantial weight reduction, low density composite was selected. The material evaluated was a boron fiber in a polyimide resin matrix which could be applied either as a solid composite or as the shell material for a spar and shell design. Boron/polyimide has a density 50% lower than titanium and a projected maximum temperature capability of approximately 700°F (370°C); therefore, it can be incorporated in the front three stages of the turbojet compressor blades and turbofan blades.

The use of composite blade materials provided a small efficiency improvement by elimination of the partspan rotor shrouds. The following table shows the impact of advanced composite materials for the non-afterburning turbojet, duct-heating turbofan, and variable bypass engines.

Engine	Non-afterburning Turbojet	Duct-Heating Turbofan	Duct-Heating Turbofan	Variable Bypass Engine
Sideline Jet Noise	FAR 36	FAR 36	FAR 36-10	FAR 36-10
Suppression Level	high	none	low	none
Advance Technology Impact				
Δ Performance				
Δ Fan Efficiency - pts	0.2	0.5	0.5	0.5
Δ Engine Weight - %	-2.0	-4.5	-4.5	-4.0
Δ Engine Price - %	+1.0	+0.5	+0.5	+0.5
Δ TOGW - %	-1.0	-1.5	-2.0	-2.0
Δ ROI - pts	0.	+0.5	+0.5	+0.5

Savings in engine weight were realized in the blades, disks, and containment. There was a larger weight reduction in the turbofan engines because the fan was a larger proportion of the engine weight then the front stages of the turbojet compressor and because of the higher fan tip speed compared to the turbojet compressor tip speed. Disk and containment design was sensitive to tip speed and consequently the weight savings were greater for the higher tip speed turbofans.

In order to realize these results, technology programs will be necessary to develop the composite materials, improve their resistance to foreign object damage, and develop low cost fabrication techniques. Further study is also needed to more accurately determine the specific composite material to be used. This depends on the results of material development programs and further weight/cost trade studies.

Composites were not applied to nonrotating parts, such as cases and stators, where the only benefit would be the direct substitution of the lower density material. This did not indicate as large a benefit as applying composites to rotating parts. However, more study is required in this area to determine potential benefits for composite materials.

Low-Pressure Spool

Advanced technology in the low-pressure spool of the turbofan engines includes increased low-pressure turbine aerodynamic loading, improved fan disk materials, and a shortened fan/high-pressure-compressor transition section.

Increased low-pressure turbine aerodynamic loading permitted lower turbine diameters and hub/tip ratios. This reduction in diameter produced a more compatible configuration between the high-pressure and low-pressure turbines and also reduced the augmentor diameter.

The following table shows the impact of advanced low-pressure spool technology for the duct-heating turbofan and variable bypass engines.

Engine	Duct-Heating Turbofan	Duct-Heating Turbofan	Variable Bypass Engine
Sideline Jet Noise	FAR 36	FAR 36-10	FAR 36-10
Suppression Level	none	low	none
Advanced Technology Impact			
Δ Performance	none	none	none
Δ Engine Weight - %	-1.0	-1.0	-1.0
Δ Engine Price - %	0	0	0
Δ TOGW - %	-1.5	-1.5	-2.0
Δ ROI - pts	+0.5	+0.5	+0.5

Augmentor/Nozzle/Suppressor

Advanced technology for the duct-heating turbofan and variable bypass engine augmentor included an advanced diffuser and burner design and advanced materials. The nozzle/reverser/suppressor systems for all the engine configurations had many diverse requirements and offered potential improvements over their presently conceived designs.

A vane diffuser design reduced the augmentor diffuser length by approximately 50 percent while an advanced burner design capable of accepting a higher inlet Mach number allowed a reduction in the augmentor diameter. Finwall® liners along with an advanced burner design permitted a 50 percent reduction in cooling air which in turn improved the augmentor thrust efficiency by reducing the adverse effects on thrust of the cooling air temperature profile. Turbine servicing problems may be complicated by the augmentor hot-section surrounding the turbine. A further design study is required to establish an acceptable augmentor configuration with regard to this problem.

The augmentor on supersonic transport engines may be used at takeoff as well as supersonic flight conditions. It was estimated that a substantial reduction in emissions relative to today's augmentors will be required. Additional research and development work will be required, in addition to the NASA Experimental Clean Combustor Program, NAS3-16829, to develop low emissions augmentor configurations. A duct heater program is recommended and outlined in Task VI.

A potential for improvement exists in the nozzle/reverser/suppressor designs of supersonic transport engines. These systems must provide:

1) good performance over a wide range of nozzle expansion ratios from takeoff to supersonic cruise,

2) variable throat areas to obtain good inlet airflow matching characteristics,

3) a thrust reversing system, and

4) probably a jet noise suppressor.

Improved integration of these varied requirements will result in a decrease in nozzle diameter required to package these systems. The turbojet engines, with a high suppression level, multi-element suppressor, realized a five percent nozzle diameter improvement while the turbofan engines, assuming a low-level simplified suppressor, did not lend themselves to as much potential integration improvement; only two percent nozzle diameter reduction was realized.

It was assumed that further increases in jet noise suppression relative to today's suppressors can be accomplished through applying the results of research efforts now under way (such as the NASA AST Jet Noise Suppressor Program). Additional research and development programs, as summarized in Task VI, will be required to improve jet noise suppression capability for duct-heating turbofan engines.

The following table shows the impact of advanced augmentor/nozzle/reverser systems for the non-afterburning turbojet, duct-heating turbofan, and variable bypass engines. (Of course, there is no advanced augmentor technology in the non-afterburning turbojet engine.)

Engine	Non-afterburning Turbojet	Duct-Heating Turbofan	Duct-Heating Turbofan	Variable Bypass Engine
Sideline Jet Noise Suppression Level	FAR 36 high	FAR 36 none	FAR 36-10 low	FAR 36-10 none
Advance Technology Impact				
Δ Performance				
Δ Augmentor Efficiency pts	–	4.0	4.0	4.0
Δ Engine Weight - %	-2.0	-1.5	-1.5	-1.5
Δ Engine Price - %	-1.0	-1.5	-1.5	-1.5
Δ TOGW - %	-0.5	-4.0	-4.5	-4.0
Δ ROI - pts	0	+1.0	+1.0	+1.0

Flow Diverter Valve

Because flow diverter valves are still in an early stage of development, there is potential for a more sophisticated flow diverter design which would result in a shorter and lighter flow diverter. These potential improvements were estimated to reduce the flow diverter length and weight by 50 percent but, because of a potential increase in complexity, did not affect engine price.

The following table shows the impact of an improved flow diverter valve design on the variable bypass engine.

VARIABLE BYPASS ENGINE

Sideline Jet Noise Suppression Level	FAR 36-10 EPNdB none

ADVANCED TECHNOLOGY IMPACT ON VARIABLE BYPASS ENGINE

Δ Performance	none
Δ Engine Weight - %	-5.5
Δ Engine Price - %	0
Δ TOGW - %	-3.0
Δ ROI - pts	+0.5

Overall Advanced Technology Impact

The overall improvement in the engine designs for 1980 technology as compared to 1975 technology is shown in Figures 62, 63 and 64 for the non-afterburning turbojet, duct-heating turbofan, and variable bypass engines, respectively. The 1980 technology engines include the six selected areas of advanced technology discussed above (i.e., high-pressure turbine, compressor and primary burner, composite fans/compressors, low-pressure spool, augmentor/nozzle/suppressor, and flow diverter valve). Figures 65 and 66 show a summary of the individual advanced technology impacts on system TOGW and ROI, respectively. TOGW and ROI are shown in Figures 59 and 60 as functions of sideline jet noise for 1975 versus 1980 technology.

It is important to point out that the system benefits due to advanced propulsion technology are very sensitive to the base vehicle system and the mission economic and jet noise models assumed in the study. Variations in aircraft thrust loadings, cruise L/D's, aircraft structure, direct and indirect operating costs, subsonic range, supersonic range, cruise Mach number, number of passengers, airplane pricing, and noise attenuation, for example, are all items that will affect the potential benefit of advanced technology. It should also be recalled that the system results are shown for typical engine configurations in order to assess the impact of advanced technology and do not necessarily represent the most optimum engine configurations.

Substantial potential benefits are shown for high-pressure turbine material and aerodynamic loading technology, composite fan materials for turbofan and variable bypass engines, low-emission augmentors for duct-heating turbofan and variable bypass engines, compressor aerodynamic loading for turbojet engines, and flow diverter valves for variable bypass engines. No improvements in jet noise suppression beyond the optimistic levels assumed in the Task I and II (1975) studies were projected. Consequently, no benefits for an improved suppression capability were shown in the Task III results. Research and development programs will be required, however, to achieve the suppression levels used in the base (1975) suppressor definition.

Other Advanced Technologies Evaluated

The following additional areas of advanced technology were felt to be important but were not included in the above 1980 engine definition because the benefits were hard to quantify or the availability by 1980 was highly questionable.

Controls

A cooled, full-authority, electronic control system is an area of advanced technology very critical to an advanced supersonic transport propulsion system, but difficult to quantify. This control system is needed due to the increase in control complexity required, compared to a subsonic transport. This increased engine control complexity includes increased fan and compressor variable geometry, possible variable turbine geometry, variable geometry nozzle, possible stowable jet noise suppressor, a variable geometry supersonic inlet, an augmentor, and a possible flow diverter valve. A full-authority, electronic control system would reduce the weight and cost penalty that would be associated with a hydromechanical control that employs a supervisory electronic control. In addition, a full-authority, electronic control has the potential to make numerous improvements over conventional control technology. These include improved accuracy resulting in better engine performance, automatic rating schedules, improved engine maintainability, flexibility, self-testing capability, and improved integration with the inlet control, condition monitoring system and power management system.

Ceramic Turbine-Blade

Ceramic blades for high-pressure turbines have a potential for large system improvements but were felt to be beyond the technology that could reasonably be expected to be demonstratable by 1980.

Rear Compressor Stage Composites

Higher temperature composite compressor blades, beyond the first three lower temperature (700°F, 370°C) composite stages previously discussed, were also evaluated. A higher density material, such as borsic^{R}/titanium, is required to operate in this higher temperature environment. The results of the greater density composite indicated a smaller benefit than that shown for the lower density composite incorporated in the front stages. However, additional work is required in this area to determine potential benefits for high temperature composite materials.

Nozzle Performance

A large impact of improved nozzle performance was shown and emphasizes the necessity of achieving an integrated nozzle/suppressor/reverser design without penalizing nozzle performance.

Acoustic Treatment

Up to this point in the Task III study, jet noise has been the only noise considered. During landing approach with the engines throttled to perhaps 30 percent maximum power, turbo-machinery noise is dominant over jet noise. Unless more sophisticated approach techniques are established, such as a two-segment approach, reduction of turbo-machinery noise will be required. Since a choked inlet was assumed, the study addressed itself to the problem of reducing fan exit and turbine exit noise signatures. This requires an increase in fan blade spacing to allow more attenuation of the wake from the upstream airfoil before the air strikes the downstream airfoil and a more effective acoustic wall treatment and acoustically treated splitters in the fan duct.

Figure 67 shows the system penalty associated with reducing approach noise to the sideline jet noise levels for both 1975 and 1980 technology. The solid and dashed lines on the chart show, respectively, the 1975 and 1980 technology TOGW trends as the engine was throttled back and oversized to meet sideline jet noise levels. These curves include sufficient wall treatment in the fan duct to meet FAR 36 at approach. The two shaded bands show the additional penalty associated with the increased fan spacing and additional fan duct acoustic treatment required to make the approach noise match the sideline jet noise level. The weight penalties are shown as a band due to uncertainty as to the actual penalty. With advanced materials and integral engine structure and nacelle construction, reduced acoustic treatment penalties could probably be achieved.

The noise footprint of an advanced supersonic transport shows that the noise problem is primarily in the takeoff lobe (sideline and takeoff). This brings into question the desirability of accepting the penalties associated with reducing the approach noise below FAR 36 levels.

Combustor Exit Temperature Evaluation

An investigation was made to determine whether the optimum combustor exit temperature shifted between 1975 and 1980 technology. In the Task III study, the maximum rotor inlet temperature was held constant at approximately the optimum values selected from Tasks I and II. Since the ceramic inlet-guide-vanes in the advanced technology turbine required less cooling, the combustor exit temperature was about 150°F (83°C) lower in Task III for the same rotor inlet temperature. Figures 68 and 69 show that the effect of combustor exit temperature or TOGW and ROI with 1980 technology is similar to the effect with 1975 technology. It should be noted that the ATA economic model used in the ROI estimates does not account for possible changes in engine maintenance costs with increasing combustor exit temperature. Because of these considerations, the optimum cycle should be selected toward the lower combustor exit temperature.

TASK IV

HYDROGEN-FUELED ENGINES
(1980 Technology)

INTRODUCTION (TASK IV)

In Task IV, the 1980 technology engines from Task III were reexamined to determine how their design would be affected by the use of hydrogen fuel. Estimates of engine weight, size, thrust, TSFC, noise, emissions, and prices were determined for the selected engine cycles based on the use of hydrogen fuel. In addition, any technology problems or differences associated with the use of hydrogen fuel in the engine and the associated fuel system were identified. Preliminary systems studies were also performed to help guide the selection of the engine design parameters and engine cycles. These studies were conducted based on airplane aerodynamics and mission ground rules supplied by NASA.

SUMMARY (TASK IV)

Liquid hydrogen offers many potential advantages as a fuel including higher heating value, greater cooling capacity, improved combustion characteristics, reduced emissions and a potentially vast supply. The use of hydrogen fuel will have an impact on the engine design in several areas such as the fuel and control system, materials selection, cooling schemes, and combustor design.

The Task IV results indicated that there are no technical barriers to the use of hydrogen fuel in an engine as hydrogen produces rapid and clean combustion and can readily be used in gas turbine engines without requiring development of any new technology. However, the price of hydrogen fuel and distribution system relative to JP fuel will have to be reduced significantly from current projections if hydrogen fueled systems are to be economically competitive with JP fueled systems. The results also indicate that hydrogen fueled vehicles tend to be less sensitive to reduced sideline jet noise levels than the hydrocarbon fueled systems because the significantly improved fuel consumption of the hydrogen fueled vehicles makes them less sensitive to changes in engine weight.

POTENTIAL ADVANTAGES OF HYDROGEN FUEL (TASK IV)

Liquid hydrogen offers many potential advantages as a fuel for an advanced supersonic transport engine. These advantages include a higher heating value, greater cooling capacity, improved burner blowout limits, improved thermal stability, reduced emissions, and a potentially vast hydrogen supply.

Specific fuel consumption is reduced by a factor of 2.8 because of the increase in lower heating value per unit of fuel weight. Of course, liquid hydrogen's energy per unit of volume is only 23 percent that of JP fuel due to its low density, which results in increased fuel-storage volume required in the aircraft.

The increased specific heat and thermal stability of hydrogen provide a significant usable heat-sink capacity which could be used for cooling the combustors, turbines, lubrication system, and electronic controls. The corresponding reduction in compressor bleed air needed for cooling purposes results in an engine performance gain. In addition, the specific heat increase provides an increased work capability across the turbine which also results in a performance gain.

Hydrogen fuel, which would be injected into the burner in the vapor phase, has improved reaction rates and mixing characteristics relative to JP fuel. These characteristics produce high heat release rates which result in reduction of the required combustion volume such that combustion lengths can be reduced by 30 percent without compromising efficiency, pressure loss, or temperature pattern leaving the combustor. In addition, improved reaction rates and vapor phase injection require fewer augmentor zones, smaller flameholders, and elimination of premixing.

Hydrogen is the most abundant of all elements in the universe and, thus, offers a potentially vast supply. However, because the processes required to produce usable hydrogen fuel from its naturally occurring states are very costly at present, the viability of hydrogen fuel is dependent on making its price competitive with JP fuel.

Emissions from a hydrogen fueled engine are less than for hydrocarbon fuels because of the elimination of carbon-monoxide, unburned hydrocarbons, and smoke from the products of combustion and by a reduction in NO_2 emissions due to the reduced engine size required.

IMPACT ON ENGINE DESIGN (TASK IV)

Both the advantages and technology concerns associated with hydrogen fuel have an impact on the engine design in several areas, including the fuel and control system, materials selection, cooling schemes, and combustor design. However, no technical barriers are forseen in using hydrogen fuel in gas turbine engines.

Fuel/Control System

There are several areas in the engine control and engine fuel system which are identified as affecting the design of hydrogen fueled engines. Safety limits for hydrogen leakage and ignition must be established to guide the design. The engine fuel system will probably require venting to prevent the collection of hydrogen in the event of a leak. Hydrogen, an extremely light gas, lends itself to a venting system. Seals and fuel shutoff valves will have to be developed that can operate at cryogenic temperatures and meet commercial aircraft life requirements.

Insulation of the fuel system is required to prevent fuel vaporization, to avoid condensation of water on fuel plumbing which leads to icing problems, to avoid formation of liquid air which poses a fire threat with oil around the engine or asphalt runways, and to prevent freezing of the oil in the lubrication system.

Perhaps the major control development consideration is with problems associated with controlling and pumping two-phase flow. Fuel volume/response/stability problems are a threat throughout the fuel handling and control system due to the nonlinearities of compressible flow. This creates fuel metering problems, nonsteady flow rates, and response lags.

Percolation and cavitation present pumping problems, particularly during starting and during varying G loading. Pumps with commercial engine reliability and durability for the supersonic transport range of flight operation will need to be developed.

Purging of the fuel system may be necessary prior to engine start-up to purge contamination and moisture in the fuel system and after engine shut down to purge hydrogen from the fuel system.

Materials Selection

Cryogenic hydrogen presents embrittlement problems which will affect materials selection in the fuel system. Also, because of the lightness of hydrogen, materials which are too porous will have to be avoided in areas such as fuel pump castings. The clean exhaust, due to the absence of hydrocarbons, will permit the use of reflective surfaces to assist in controlling metal temperatures.

Cooling Systems

The heat-sink capacity of hydrogen can be exploited by using hydrogen to cool the turbine, augmentor, electronic controls, and lubrication system as well as vehicle subsystems.

Turbine Cooling Schemes

In the turbine, hydrogen fuel offers cooling possibilities beyond the conventional turbine air cooling scheme. Perhaps the most practical exploitation of hydrogen in this area is through the use of a hydrogen-air heat exchanger to chill compressor bleed air used to cool the turbine. This scheme reduces the amount of turbine cooling air required and, therefore, reduces the performance penalty associated with bleeding this air. This heat exchanger could be placed in the normal turbine cooling air flowpath so as not to require additional plumbing for the cooling air.

A cooling system which eliminates all the cooling air was also studied. To eliminate all the turbine cooling air, except for a small amount needed to pressurize the engine compartments along the turbine flowpath, a closed loop of liquid metal in the airfoils and disks could be used along with a hydrogen/liquid-metal heat exchanger to transfer the heat from the liquid metal to the hydrogen. This system represents the ultimate reduction in compressor bleed air required to cool the turbine and, therefore, the least performance penalty. However, due to the required transfer of either hydrogen or the liquid metal to and from the rotating turbine disk, this scheme may be stretching the 1980 technology base. This cooling system was included in this study to show the end point of the various turbine cooling schemes which progressively reduce the required turbine cooling air.

As turbine cooling air was reduced, the bypass ratio was increased to maintain balanced primary and duct stream jet noise at constant fan pressure ratio and combustor exit temperature. Reducing turbine cooling air also improved the high-pressure turbine cooled efficiency by reducing the aerodynamic interference effect of ejecting the cooling air in the turbine.

The scheme incorporating a hydrogen-air heat exchanger to chill the turbine cooling air was chosen as the base system for comparison of the various liquid hydrogen engines. This scheme showed a 0.5 to 1.5 percent improvement in TOGW over the conventional air cooled turbine, depending on the technology level of turbine materials which affects the amount of cooling air required. The hydrogen/liquid-metal cooling scheme showed a potential for an additional 0.5 percent improvement in TOGW.

Other Engine Cooling Systems

The augmentor may be cooled conventionally with air cooled, high temperature liners, or, to capitalize on the usable heat sink capacity of the hydrogen fuel, the augmentor could be directly cooled by the hydrogen. This could be accomplished by removing the liners and replacing them with tubes running the length of the augmentor with a manifold at each end, similar to the RL10 rocket engine cooling scheme. An auxiliary pump would pump the hydrogen fuel through these tubes and into the augmentor to be burned. Even though all of the air is not required for combustion in a typical AST augmentor and, therefore, would appear to be available for cooling, direct cooling of the augmentor with the hydrogen fuel offers a potential performance improvement. This is due to an improved temperature profile in the engine exhaust and the corresponding thrust penalty caused by the layer of cooling air. The performance improvement, with the engine weight increase, results in a one percent improvement in TOGW. The major disadvantage of directly cooling the augmentor for commercial application is the durability and approximately two percent increase in engine price associated with the cooling tubes, manifolds, and auxiliary pump.

The electronic control and engine lubrication system would be fuel cooled, as would be the case in a JP fueled engine. The advantage of hydrogen is that it can do the cooling job without approaching the thermal stability limits of the fuel as is the case with JP fuel. This is important for the AST where aircraft thermal management is a critical design problem.

Combustor Design

The combustion length of the primary burner and augmentor can be reduced because of hydrogen's improved reaction rates and mixing characteristics. Smaller flameholders, fewer zones, and elimination of premixing are also possible, which could result in a 25 percent reduction in the cold pressure loss of the combustion section. The use of hydrogen fuel eliminates the need for a pilot zone in the primary burner which is required for a JP burner for reduced low power emissions. The impact of hydrogen fuel on emissions is discussed in a latter section

IMPACT ON ENGINE PERFORMANCE (TASK IV)

The difference between the lower heating values of hydrogen and JP fuel accounts for a 63 percent improvement in TSFC at constant combustor exit temperature. Additional effects, including a lower fuel mass flow, difference in gas properties which affects turbine work capability, and the bypass ratio increase required to maintain balanced primary and duct stream jet noise, result in a net additional improvement of about one percent.

The effect of hydrogen fuel on performance, weight and price of 1980 technology engines is shown in Table XII. The base hydrogen fueled engine design incorporates a hydrogen-air heat exchanger to chill the turbine cooling air, as discussed in the previous section, and a conventional air cooled augmentor because of the durability problems and cost associated with direct hydrogen cooling. The changes in engine weight and price reflect the changes in the engine design discussed previously. This includes the bypass ratio increase due to the change in gas properties and reduction in turbine cooling air, the addition of a hydrogen-air heat exchanger, and reduced combustor lengths.

TABLE XII

1980 TECHNOLOGY ENGINE COMPARISON JP VS. H_2

ENGINE	D/H TF	D/H TF	DRY TJ	DRY TJ	VBE 1A	VBE 1A
Fuel	JP	H_2	JP	H_2	JP	H_2
CET, ~°F (°C)	2,650 (1,454)	2,650 (1,454)	2,650 (1,454)	2,650 (1,454)	2,650 (1,454)	2,650 (1,454)
WAT_2 ~lb/sec (kg/sec)	900 (408)	900 (408)	900 (408)	900 (408)	900* (408)	900* (408)
FPR	3.3	3.3	–	–	4.1*	4.1*
OPR	15.0	15.0	12.0	12.0	15.0*	15.0*
BPR	2.2	2.7	–	–	1.5*	1.5*
Suppressor Included	Yes (5dB)	Yes (5dB)	Yes	Yes	No	No
Engine Weight, lb (kg)	10,350 (4,695)	9,950 (4,513)	15,300 (6,940)	15,350 (6,963)	13,250 (6,010)	13,150 (5,965)
ΔEngine Price ~ %	0	-0.2	0	0.6	0	0.4
ΔThrust, SLS (NonAug), %	0	0	0	6	0	8.0*
T/W ~SLS (NonAug)	3.9	4.1	5.5	5.9	3.6*	3.9*
ΔTSFC, Cruise (NonAug), %	0	-64	0	-63	0	-63*

* in series mode

IMPACT ON EMISSIONS (TASK IV)

Burning hydrogen, as compared to JP fuel which is a hydrocarbon, eliminates carbon monoxide, unburned hydrocarbons, and smoke from the engine exhaust and allows burner design efforts to be directed at reducing NO_2 emissions. The pilot zone, which is needed in JP burners to provide good low power efficiency for reduced CO and THC, is not required for a hydrogen burner.

NO_2 production depends on the time spent at peak temperature in the combustion section. Even though hydrogen burns stoichiometrically, approximately 100°F (55°C) higher than JP fuel, the improved reaction rates and mixing characteristics of hydrogen, which reduces residence times, will permit burner designs to be tailored to reducing the time spent at peak temperature. The hydrogen burner will probably be able to produce lower NO_2 emissions than a JP burner in parts per million of engine exhaust.

The vehicle analysis results show that the engine size required is reduced by approximately one-third for a hydrogen fueled aircraft because of the TOGW reduction achieved with the reduced fuel weight. This engine size reduction will further decrease the total NO_2 emissions per flight by approximately one-third.

SYSTEMS ANALYSIS (TASK IV)

Systems studies were performed to help guide the selection of hydrogen fueled engine design parameters and engine cycles. The vehicle ground rules for the previous task were adjusted by NASA-Lewis to reflect the changes in the hydrogen fueled aircraft, including fuel storage in the fuselage instead of the wing, and fuel insulation. Economic analysis procedures specified by NASA-Lewis were also used including a base liquid hydrogen cost of 13 ¢/lb and a JP cost of 1.85¢/lb. However, no adjustments were made to the Indirect-Operating-Costs (IOC) to reflect the ground handling equipment and storage facilities required by cryogenic hydrogen fuel, which was considered beyond the scope of the engine study.

Figures 70, 71, and 72 show TOGW, ROI, and DOC, respectively, for the hydrogen fueled aircraft as a function of sideline jet noise. The figures show the duct-heating turbofan to be the best engine. The supersonic thrust deficiency of the dry turbojet becomes more critical with hydrogen-fueled airplanes because proportionally less fuel is burned off during acceleration, resulting in higher begin-cruise drags relative to JP-fueled airplanes. The figures also show hydrogen fueled aircraft to be less sensitive to reducing sideline jet noise than JP fueled aircraft, making lower sideline jet noise levels appear reasonable. This reduced sensitivity is due to the significantly improved TSFC of the hydrogen engines resulting in much lower sensitivity to engine weight increases associated with decreased jet noise. However, the noise levels shown do not accurately account for engine core noise nor do they include fan/compressor noise which may dominate at the low noise levels. Therefore, the results below FAR 36 minus 10 EPNdB should be viewed with caution. Although the use of hydrogen reduces the TOGW required to accomplish the mission, its relatively higher price produces ROI levels below that of the JP fueled systems.

Figure 73 explores the sensitivity of ROI to fuel cost. The nominal price for JP and hydrogen used in the AST studies is indicated. The lowest future projected price obtained at this time for liquid hydrogen fuel is 17¢/lb based on fuel industry and independent researcher's projections. Figure 73 shows that the price of JP fuel would have to increase to 4.5 to 6¢/lb to yield the same ROI as the base liquid hydrogen price and the lowest projected price, respectively.

The low density and cryogenic storage temperatures and pressures required by the liquid hydrogen tankage system presents increased complexity relative to the JP fueled system. Since the liquid hydrogen tankage weight is not known accurately, the sensitivity of the vehicle system to the tankage and associated weight was investigated. The results indicated a 10 percent change in structure weight results in a 16 percent change in TOGW, ROI, and DOC.

Additional systems studies showed that the effect of combustor exit temperature on TOGW for hydrogen fueled vehicle is similar to that of JP fuel and, based on 1980 technology, there is little or no advantage to increasing the turbine rotor inlet temperature above the 2600° to 2700°F (1330°C to 1380°C) range regardless of the turbine cooling scheme.

TASK V

REFINED CONVENTIONAL AND VARIABLE CYCLE ENGINE STUDY (1975 Technology)

INTRODUCTION (TASK V)

Non-afterburning (dry) turbojets, duct-heating (D/H) turbofans, and series/parallel flow variable-bypass engines (VBE) with rotating 2nd-fan splitters were identified during Tasks I and II as the propulsion systems of greatest interest for an advanced supersonic transport. During Task V, the effects of perturbations in the cycles of these propulsion systems were evaluated and both the engine definition and the systems analysis models were refined. These refinements became practical because of the reduced scope of propulsion variables in Task V relative to Tasks I and II and as a result of the knowledge obtained from all previous tasks. Task V covered the 2.2 Mn and the 2.7 Mn cruise speeds based on the 1975 technology, as defined for Tasks I and II, and included the following:

1. Refined Engine Data Study - Performance of attractive engines derived under Tasks I and II was recomputed to incorporate refinements.

2. Additional Parametric Engine Data Study - Performance was calculated for additional parametric engines thought to be attractive.

3. Sensitivity Studies - System studies were performed to determine how variations in airplane and mission might affect engine cycle selection.

4. Noise Study - Footprint contours were calculated for selected engines and operating conditions.

5. Military Applicability of Variable Bypass Engines - The military applicability of variable cycle concepts derived in Task II was studied for two missions.

The ground rules for the systems and economic analyses for commercial transport application were basically the same as those for Tasks I and II; however, parametric variations of mission parameters were made in some cases to evaluate the impact of these variations on cycle selection.

SUMMARY (TASK V)

The results of the Task V study show that the duct-heating turbofan and some series/parallel variable cycle engines remain competive propulsion systems for advanced supersonic transports. In addition, the results show that the non-afterburning turbojet would be competive around FAR 36 noise levels if a very high level of jet noise suppression can be achieved. The lowest takeoff gross weight (TOGW) systems at noise levels down to FAR 36 minus 5 EPNdB were provided by duct-heating turbofans. The series/parallel variable bypass engines changed their position relative to Task II studies and showed competitive TOGW's from FAR 36 down to FAR 36 minus 10 EPNdB, with a potential for further improvements. The non-afterburning turbojets could approach the low TOGW's of the duct-heating turbofan engines for missions

without a subsonic cruise leg; however, the achievement of FAR 36 noise levels would require a minimum jet noise suppression of from 12 to 15 PNdB with low thrust losses. Certain assumptions in the economic calculations were sometimes found to produce DOC differences between engines of about 5 percent over what could be reasonably justified. For this reason, economic differences of this magnitude should not be considered significant.

The duct-heating turbofans studied in Task V incorporated only duct jet noise suppressors which are considered to be a more practical design than suppressors on both streams or across the total stream. Although duct-heating turbofans would also benefit from a high level of jet noise suppressors such as would be required by the turbojet engines, the duct-heating turbofans can obtain almost as good results at FAR 36 noise levels with a more realistic 5 PNdB suppressor. Until a highly effective jet suppressor can be demonstrated to provide at least 12 to 15 PNdB suppression with low thrust loss for large scale engines at takeoff speed, a supersonic transport propulsion system relying on these suppressors must be considered as a high risk.

The penalty associated with aircraft/propulsion systems designed for sideline noise levels below FAR 36 depends greatly on the thrust loading of the aircraft. The higher the takeoff thrust loading, the higher the TOGW penalty for a given sideline noise level. However, higher thrust loading aircraft climb out faster after takeoff and have smaller noise "footprints". The takeoff lobe of the SST noise contours was significantly larger than the landing lobe; therefore, the most dramatic reduction in footprint size can be achieved by reducing sideline and takeoff noise.

An evaluation of combinations of fan pressure ratios (FPR) and bypass ratio indicated the optimum fan pressure ratio of the duct-heating turbofans to be dependent on the type of suppression assumed and the design noise level. The optimum fan pressure ratio varied from a FPR of 4 with highly effective jet suppression at a FAR 36 noise level down to about 2.5 FPR at FAR 36 minus 5 EPNdB noise level. Variations in bypass ratio did not have a strong effect for any given FPR. The subsonic and supersonic range factors were about equal for the duct-heating turbofans, providing flexibility in mixing subsonic and supersonic legs without range penalty.

Refinements in the turbojet overall pressure ratio and airflow schedules showed the optimum overall pressure ratio of the non-afterburning turbojets to be between 15:1 and 18:1 for both 2.7 Mn and 2.2 Mn cruise speeds when takeoff exit gas temperature limit restrictions were considered for the jet suppressor. High flowing the turbojet engine at supersonic conditions relative to the Task I airflow schedule was found to provide lower cruise TSFC and higher supersonic thrust, resulting in improvements in TOGW as well as better supersonic thrust-to-drag margins. While the duct-heating turbofan and the variable bypass engines were able to achieve lower noise levels by increasing takeoff airflow size, the higher weight of the turbojet engines at equal airflow sizes resulted in a very steep variation of TOGW with noise and made this approach impractical for the turbojet engines. The success of the turbojet engine depends on achieving a high level of jet noise suppression.

The variable cycle engines improved their Task II position relative to engines with other cycles, primarily as a result in refinements in fuel scheduling and pod weight estimates. Further refinements in engine matching and configuration appear possible, which could provide further reduction in TOGW. The military application of the variable bypass engines was evaluated in bomber and fighter-bomber missions. The results indicate that variable bypass engines designed specifically for the military application could show a small improvement relative to a conventional engine on the design missions; however, there could be potentially large improvements on alternate missions.

ENGINE PERFORMANCE (TASK V)

Non-Afterburning Turbojets

The non-afterburning turbojets for which data were sent to the Langley airframe-contractors are listed in Table XIII.

TABLE XIII

NON-AFTERBURNING TURBOJETS

ENGINE IDENTIFICATION	A-A	A-B	A-C	A-D	A-E	A-G	A-I	A-J
Cruise Mach No.	2.7	2.7	2.7	2.7	2.7	2.2	2.2	2.2
Airflow Schedule	low	low	low	low	high	low	low	high
CYCLE CHARACTERISTICS								
Combustor Exit Temp. °F	2800	2800	2800	2800	2800	2800	2800	2800
°C	1538	1538	1538	1538	1538	1538	1538	1538
Cycle Pressure Ratio	9	12	15	18	12	12	18	12

The low airflow schedule is the same as used on all previous tasks. The high airflow schedule was based on the NASA Ames "P" inlet and is shown in Figure 74. The pressure recovery for this inlet is shown in Figure 75. The advantage of this inlet is that it is mechanically relatively simple in that it incorporates a translating spike and does not need the additional complexity of either a collapsing spike or cowl throat doors to achieve a reasonable throat area variation. A supersonic cruise performance comparison between baseline (low) flow and high flow engines is shown in Figure 76. The increased supersonic flow of the high flow engine provided not only increased maximum thrust but better TSFC's at the high power settings where the engine operated at cruise. A comparison of performance at the subsonic cruise condition is shown in Figure 77. The high flow turbojet had a slightly poorer partially installed performance at this condition. Inlet spillage drag also will tend to make the high flow turbojet a little worse when this drag in included in the performance. The key differences between the high and low flow turbojets are summarized below in Table XIV.

TABLE XIV

NON-AFTERBURNING TURBOJET CHARACTERISTICS

TOTAL AIRFLOW = 900 lb/sec   Cruise Nn = 2.7
= 408 kg/sec

	BASE FLOW	HIGH FLOW
CYCLE CHARACTERISTICS AT TAKEOFF		
Combustor Exit Temp., °F	2800	2800
°C	1538	1538
Cycle Pressure Ratio	12	12
RELATIVE ENGINE WEIGHTS		
Bare Engine	Base	1.01
Eng. and Noz./Rev.	Base	1.01
Eng. and Noz./Rev./Supp.	Base	1.01
RELATIVE INLET WEIGHT	Base	1.00
SUPERSONIC CRUISE PERFORMANCE		
Relative Turbine Temp.	Base	1.00
Relative Thrust	Base	1.17
Relative TSFC	Base	0.98

The weight of the high flow turbojet was slightly higher than the low flow turbojet because of the increased rotor speeds at the supersonic condition. The inlet weight for the high and low flow engines was estimated to be approximately equal for a given level of takeoff airflow. The large capture area of the high flow design was offset by its less complex mechanical design. The effects of overall pressure ratio on the non-afterburning turbojets was reevaluated for Task V. The primary difference between this evaluation and the Task I evaluation was in nozzle geometry (and resulting performance) refinements. The differences between the Tasks I and V performance are shown in Figure 78.

Duct-Heating Turbofans

The duct-heating turbofan engines for which data were sent to the Langley airframe-contractors are listed in Table XV below. The list covers bypass ratio variations for two levels of fan pressure ratio: 3.3 FPR and 4.1 FPR. A P&WA internal evaluation of 2.5 FPR engines at three levels of BPR was also made. The high and low airflow schedules are the same as previously discussed for the dry turbojets.

TABLE XV

DUCT-HEATING TURBOFANS

		C-A	C-B	C-C	C-D	C-E	C-F	C-G	G-H
ENGINE IDENTIFICATION									
Cruise Mach No.		2.7	2.7	2.7	2.7	2.2	2.7	2.7	2.7
Airflow Schedule		low	low	low	high	low	low	low	low
CYCLE CHARACTERISTICS									
Fan Pressure Ratio		3.3	3.3	3.3	3.3	3.3	4.1	4.1	4.1
Bypass Ratio		2.1	1.9	2.3	2.1	2.2	1.6	1.3	1.9
Cycle Pressure Ratio		15	15	15	15	15	15	15	15
Combustor Exit Temp.,	°F	2800	2800	2800	2800	2800	2800	2800	2800
	°C	1538	1538	1538	1538	1538	1538	1538	1538

The supersonic and subsonic partpower performance curves are presented in Figures 79 and 80 for the 3.3 FPR and 4.1 FPR engines, respectively. The variation of TSFC with bypass ratio was not large, with the general trend indicating that supersonic TSFC improved somewhat with decreasing bypass ratio. The maximum subsonic climb and cruise thrust also increased with decreasing bypass ratio, which could be important under some engine sizing conditions.

Low Bypass Ratio Turbofans

The potentials of very low bypass ratio turbofans ("leaky" turbojets) were briefly explored. A typical schematic of this type engine is shown in Figure 81. The main advantages of these engines are that they provide a means of cooling the nozzle as well as providing lower weight for a given airflow size (because the gas generator is smaller than that of a turbojet). The big disadvantage of these engines is that they loose a significant amount of supersonic cruise thrust, making this the critical sizing condition. The cycle characteristics of two typical low bypass ratio turbofan engines are compared below (Table XVI) to a conventional non-afterburning turbojet.

TABLE XVI

LOW BYPASS RATIO ENGINE COMPARISON

TOTAL AIRFLOW = 900 lb/sec
= 408 kg/sec

CRUISE Mn = 2.7

ENGINE CONFIGURATION		NON-AFTERBURNING TURBOJET	LOW BPR TURBOFANS	
AIRFLOW SCHEDULE		high	high	high
CYCLE CHARACTERISTICS				
Combustor Exit Temp.,	°F	2800	2800	2800
	°C	1538	1538	1538
Cycle Pressure Ratio		12	12	12
Bypass Ratio		none	0.3	0.66
Fan Pressure Ratio		none	3.8	3.3
RELATIVE WEIGHTS				
Bare Eng.		1.0	0.81	0.68
Eng. and Noz./Rev.		1.0	0.83	0.72
Eng. and Noz./Rev./Supp.		1.0	0.82	0.72

Variable Cycle Engines

Task II study results indicated that VBE IA, a series/parallel variable bypass engine with a rotating splitter, was the most promising of the variable bypass engine concepts. A higher bypass ratio version, VBE IB, was also studied during Task II, but it was not as good as VBE IA except at very low noise levels. A lower bypass ratio version, VBE IC, was evaluated during Task V. A comparison of this engine with other VBE I cycles is shown in Table XVII. The supersonic performance of VBE IC in relation to VBE IA and a non-afterburning turbojet is shown in Figure 82. The high fan pressure ratio of VBE IC resulted in improved supersonic performance relative to VBE IA, but the lower bypass ratio resulted in a higher weight for the same airflow size. The noise characteristics are shown in Figure 83. This figure indicates that at FAR 36 noise levels, VBE IA and IC had about the same thrust, even though VBE IC had less total airflow in the parallel mode. This indicates that the VBE IA cycle could probably have been improved by engine matching. This is also a problem because only one stream was being augmented. More work could be done in this area to improve the cycle for lower noise.

Still another variation of the series/parallel VBE concept is the use of a second valve and a second low-pressure turbine, as shown in Figure 84. In the parallel high bypass mode the configuration was identical to VBE IA, but in the low bypass mode the duct heated duct-flow was diverted through a valve into a second low-pressure turbine which was on the same shaft as the rest of the low-pressure spool. The flow from the first low-pressure turbine was diverted through the same valve and out a separate nozzle. Preliminary calculations indicated that the supersonic performance of this cycle can be made to approach that of a dry turbojet while the subsonic performance should be comparable to a conventional turbofan. This cycle concept is still in the early evaluation stages and further evaluation and refinement are necessary.

TABLE XVII

VBE I CYCLE CHARACTERISTICS
(Sea-Level Static – Standard Day Operation)

CYCLE	VBE IC		VBE IA		VBE IB	
MODE OF OPERATION	SERIES	PARALLEL	SERIES	PARALLEL	SERIES	PARALLEL
Corrected Airflow, lb/sec	900	1235	900	1340	900	1450
(kg/sec)	(408)	(560)	(408)	(608)	(408)	(658)
Bypass Ratio	1.0	1.5	1.5	2.4	2.5	4.1
Fan Pressure Ratio – 1	2.8	3.2	2.2	2.5	1.8	2.0
Fan Pressure Ratio – 2	2.4	3.5	1.9	2.6	1.6	2.1
Fan Pressure Ratio - Overall	6.7	–	4.1	–	2.9	–
Cycle Pressure Ratio	15.0	16.5	15.0	16.5	15.0	16.5
Combustor Exit Temperature °F	2800	2800	2800	2800	2800	2800
°C	(1538)	(1538)	(1538)	(1538)	(1538)	(1538)
Net Thrust, lb	53,300	60,000	46,000	54,000	38,500	47,000
newtons	(236,000)	(266,000)	(204,000)	(240,000)	(171,000)	(208,000)
Relative Stream 1 Area	Base	+13%	Base	+20%	Base	+24%
Jet Velocities, ft/sec						
(m/sec)						
Stream 1	1985	1870	1870	1640	1670	1330
	(605)	(570)	(570)	(500)	(509)	(406)
Stream 2	2100	1600	1710	1310	1395	1080
	(640)	(488)	(521)	(400)	(426)	(330)
Stream 3	–	1530	–	1300	–	1070
		(466)		(396)		(326)

SYSTEMS STUDIES (TASK V)

Propulsion System Comparison

Aircraft thrust loading at liftoff was found to have a dramatic impact on the TOGW required to perform the prescribed mission for a given level of sideline noise. Liftoff thrust loading is an important parameter in the aircraft's takeoff field length capability, a subject of some controversy. For these reasons, liftoff thrust loading was treated as a parameter in the Task V systems studies; two values of thrust loading were used: 0.245 (used in Tasks I through IV) and 0.275 – some results are also shown parametrically for thrust loading values from 0.245 to 0.35.

Since the ability to obtain high levels of jet suppression with low thrust loss has not been demonstrated for practical suppressors under realistic takeoff conditions, two levels of suppressor effectiveness were evaluated. One of the suppressors, shown in Figure 3, was identical to that assumed in all previous tasks. This suppressor was assumed to have a very high amount of suppression (18 PNdB maximum) with a very low thrust loss at high jet velocities. This first suppressor represents an optimistic level of performance. The second suppressor used in the evaluation represents a more realistic level of suppression. This second suppressor, shown in Figure 85, was assumed to have a maximum jet suppression of 10 PNdB at high jet velocities with a one percent gross thrust loss per PNdB of suppression. Because of mechanical considerations, the gasflow through these suppressors would have to be limited to temperatures between 1300°F and 1500°F (705°C – 815°C).

The inclusion of a 600 nautical mile (1,150 m) subsonic cruise leg in the baseline design mission has been the subject of some controversy. In order to permit assessment of the impact of this mission on the cycle selection, the results are presented both with and without the subsonic cruise leg. All missions include FAR 121.648 reserves. Figure 86 shows the engine comparison for 2.7 Mn (2.65 Mn hot day) nominal mission. In all cases, the curve on the left side of the figure is for a thrust loading of 0.245 and the curve on the right for a thrust loading of 0.275. The effect of increasing the thrust loading was to increase the penalty for going to low sideline noise levels. The lowest TOGW systems at noise levels down to FAR 36 minus 5 EPNdB were provided by duct-heating turbofans. The series/parallel variable bypass engines improved their positions relative to Task II studies primarily as a result of refinements in fuel scheduling. Further refinements in engine matching and inlet/nacelle design appear to be possible which could provide further reductions in TOGW.

Both the non-afterburning turbojets and the 4.1 fan pressure ratio (FPR) duct-heating turbofan used the suppressors shown in Figures 3 and 85. The noise level that could be achieved with the systems using these suppressors was highly dependent on the amount of suppression provided by the suppressors. The turbojet, or a very high fan pressure ratio (low BPR) turbofan, could meet FAR 36 noise levels only with the optimistic 18 PNdB max. suppressor; if only 10 PNdB max. can be achieved, the noise level would exceed the FAR 36 level.

For duct-heating turbofans using the 5 PNdB suppressor, the 3.3 FPR provided the lowest TOGW at FAR 36 noise levels. At noise levels of FAR 36 minus 5 EPNdB and lower, the 2.5 FPR duct-heating turbofan provided the lowest TOGW. The lower FPR engine had the advantage of lower jet noise for a given thrust and airflow size because of the reduced density of the low FPR duct stream. However, the nonaugmented subsonic cruise thrust became a limiting sizing condition at small engine airflow sizes which occurred at the higher noise levels. Use of the augmenter at subsonic speed could eliminate this problem.

The results for the 2.7 Mn all supersonic cruise mission is summarized in Figure 87. The conclusions are the same as for the baseline mission although the non-afterburning turbojet improved its position somewhat relative to the other cycles.

The results for the 2.2 Mn baseline and the all supersonic cruise missions are presented in Figures 88 and 89, respectively. At 2.2 Mn the non-afterburning turbojet improved its position to the point where it had a TOGW that was competive with the TOGW of the duct-heating turbofan on the all supersonic cruise mission; however, its noise level was still highly dependent on suppressor characteristics.

An engine comparison summary of the 2.7 Mn TOGW results as a function of the engine size parameter, airflow/TOGW, is shown in Figure 90 for a thrust loading of 0.245 and 2.75. This figure is useful for comparing engine airflow sizes required to achieve a given noise level for each type of powerplant. It should be noted that at an exit gas temperature of 1500°F (815°C) the non-afterburning turbojet and the 4.1 FPR duct-heating turbofan had essentially equal values of airflow/TOGW; in addition, this value could also have been achieved by the variable bypass engines at FAR 36.

Noise Footprint Study

The noise considerations discussed to this point have been mainly with regard to takeoff sideline jet noise. Consideration also had to be given to the takeoff flyover measuring station noise as well as the takeoff footprint area. In addition, consideration had to be given to the noise at the approach measuring station as well as the approach footprint area.

Typical takeoff noise footprints for a non-afterburning turbojet engine are shown in Figure 91. The 90 EPNdB takeoff contour was greatly increased when the turbojet engine was cutback to reduce the noise level at the takeoff flyover noise measuring station. This was due to the reduction in suppression capability of the turbojet jet suppressor that occurred when the engine was cutback in power and the exhaust jet velocity was reduced. The suppressor characteristics assumed for these calculations are the same as those assumed for Task I and are presented in Figure 3.

Based on a liftoff thrust loading of 0.25, the turbojet engine did not meet FAR 36 at the flyover noise measuring station. In order to meet the FAR 36 noise level at the takeoff flyover condition, a higher liftoff thrust loading would have to be utilized which would fly the airplane to a higher altitude over the flyover noise measuring station, as shown in Figure 92. However, to meet sideline noise requirements, the amount of jet suppression would have to be increased beyond that which is already assumed to be highly optimistic, or the turbojet engine would have to be increased in airflow size as the thrust loading is increased with a resulting penalty in range payload.

The duct-heating turbofan did not encounter the large increase in the 90 EPNdB contour area during cutback because it was not dependent on the large amounts of jet suppression required by the turbojet engine. In contrast, at the same liftoff thrust loading (Fn/TOGW = 0.25), the duct-heating turbofan contour area was greatly reduced (Figure 93) while, at the same time, meeting the FAR 36 noise levels at the takeoff flyover noise measuring station. Figure 94 shows the improvement in takeoff footprint areas (90 EPNdB contours) obtained by designing the duct-heating turbofan engine to meet lower sideline noise levels as well as by increasing liftoff thrust loadings.

The approach noise footprint area was very small when compared to the takeoff footprint based on takeoff and approach both meeting FAR 36 at the noise measuring stations. In addition, the footprint area on approach could have been made almost negligible, by comparison, by operating the airplane on a two segment approach, as shown in Figures 95 and 96. If the engines were required to meet levels below FAR 36 at the approach noise measuring station without the use of a two segment approach, additional acoustic treatment would have to have been included with a resulting appreciable performance penalty, as shown in Figure 27, while only negligibly reducing the combined total approach and takeoff footprint area.

When comparing footprint areas, it is very important to understand the ground rules and methods used to estimate the footprint areas. For example, Figure 97 compares the 90 EPNdB footprint areas calculated by two different methods with both methods estimating the same noise level at the 2100 ft (640m) sideline noise measuring station. The differences in the estimating procedures for these two systems might appear to be negligible but resulted in appreciable differences in footprint areas at the 90 EPNdB contour point.

Engine Sensitivity Studies

Non-Afterburning Turbojet OPR Optimization

A carpet plot showing the relationship between TOGW, airflow/TOGW, and overall pressure ratio (OPR) for 2.7 Mn cruise aircraft is presented in Figure 98. Airflow/TOGW is an engine size parameter which is convenient for use in airplane studies where the TOGW is varied to satisfy mission requirements. The parameter can be considered as the airflow size in lb/sec per pound (kg/sec per kilogram) of airplane gross weight. For example, for a 750,000 lb (340,000 kg) airplane, a 0.001 value of airflow/TOGW would correspond to an airflow size of 750 lb/sec (340 kg/sec). Referring to the figure for a given level of OPR, increasing engine size results in increasing TOGW because of the heavier engine. The hatched line represents the engine size required for a thrust/drag margin of 1.2 at the end of the supersonic acceleration. The thrust loading lines (Fn/TOGW) satisfy the conditions for an exit gas temperature limit of 1500°F (815°C) at takeoff. The results indicate that the penalty due to oversizing the engine by throttling for a 1500°F (815°C) temperature limit can be minimized by increasing OPR.

Figure 99 shows the OPR optimization results for a 2.2 Mn cruise aircraft. The optimum OPR for all gas temperature conditions was between 15 and 18.

Non-Afterburning Turbojet Airflow Schedule Comparison

The comparison between the high airflow schedule and baseline airflow schedule turbojets for a 2.7 Mn cruise mission is presented in Figure 100. TOGW is shown plotted vs engine size, and the engine size required to limit the EGT to 1500°F (815°C) is shown for three values of Fn/TOGW. The advantages of the high flow jet are:

1) Lower TOGW for a given engine size parameter because of the lower supersonic cruise TSFC

2) Better supersonic acceleration characteristics because of increased thrust at supersonic speeds.

In addition, the high flow engine may permit use of a mechanically simpler inlet (e.g., NASA Ames "P" inlet).

Fixed Cycle Non-Afterburning Turbojet System Performance

The systems performance capability of the baseline airflow schedule dry turbojet is presented in Figure 101 for a nominal 2.7 Mn cruise mission – nominal mission includes 600 nm (1150m) subsonic cruise leg. Each line of constant thrust loading was constructed by varying the engine size parameter, airflow/TOGW. The power setting required to achieve the thrust loading determined the exit gas temperature, jet velocity, and jet noise. The thrust losses for the Task I tube-type suppressor have been incorporated into the calculations. The jet suppression required can be easily determined by subtracting the desired noise level from the unsuppressed sideline jet noise for a given set of conditions (i.e., thrust loading and engine size or gas temperature). The table in the upper right hand corner gives the relative jet velocity for each gas temperature (power setting). Figure 102 presents the results for all supersonic missions. Figure 103 presents the results for the high airflow schedule turbojet on the nominal mission, and Figure 104 presents the results for a 2.2 Mn cruise mission.

Duct-Heating Turbofan Cycle Optimization

Three levels of bypass ratio were evaluated for each of three levels of FPR. These cycle parameters were evaluated as to their effect on both noise and TOGW. Figure 105 shows the effect of cycle parameters on noise for unsuppressed engines and engines with 5 PNdB duct jet suppressors. Thrust/airflow was used as a figure of merit since it was desirable to maximize this quantity. The results indicate that bypass ratio did not have a strong influence on noise over the range studied. However, this would only have been true if the gas generator power setting and the degree of duct augmentation were properly selected, as was done to obtain the results shown. It should be noted that there was a trend to larger values of Fn/WAT2 as fan pressure ratio decreased (for a given level of noise). This is attributable to the effect of duct stream density which decreased with decreasing FPR.

Figure 106 presents the TOGW as a function of engine size (i.e., WAT2/TOGW), bypass ratio, and fan pressure ratio for three types of jet suppressors. The TOGW decreased somewhat with decreasing FPR for equal values of WAT2/TOGW. This fact, coupled with the noise benefit, would make it desirable to select a low FPR cycle. However, the subsonic nonaugmented thrust requirements limit the minimum engine size for low FPR engines. At noise levels of about FAR 36 minus 5 EPNdB or lower, however, a 2.5 FPR cycle looks best. Use of the augmenter subsonically could extend the application of this engine to higher noise levels.

Duct-Heating Turbofan Airflow Schedule Comparison

A high flow 3.3 FPR duct heating turbofan was compared with the baseline low flow turbofan, and the results are presented in Figure 107. The high and low flow schedule duct-heating turbofans yielded almost identical results. The choice would then be made on the basis of best integration with the inlet and airframe.

Fixed Cycle Duct-Heating Turbofan System Performance

Figure 108 presents the takeoff gross weight results for a 3.3 FPR, duct-heating turbofan with a 5 PNdB suppressor. Duct jet suppressors are considered to be a less difficult design problem than suppressors on both streams or across the total stream as required on a turbojet engine. Also, a suppression level of about 5 PNdB is considered to be realistic for commercial supersonic transport propulsion systems. Results for both the nominal, i.e., including 600 nm (1150 m) subsonic leg, and the all-supersonic mission are shown in the figure. The curves are similar to those provided for the non-afterburning turbojet. The unsuppressed sideline noise is plotted along the abscissa while lines of constant suppressed noise are indicated.

Figure 109 shows the TOGW results for the 3.3 FPR duct-heating turbofan with the Task I tube type suppressor incorporated in the duct stream. The calculations were made with the primary burner partially throttled, so that the primary stream noise did not contribute significantly for any suppressed total jet noise level down to FAR 36 minus 5 EPNdB. The amount of duct jet suppression required, therefore, can be calculated by subtracting the desired noise goal from the unsuppressed noise level plotted along the abscissa. The table in the upper left hand corner lists the duct jet velocity corresponding to each duct exit-gas-temperature line shown on the curve.

Figure 110 presents the TOGW results for the 4.1 FPR duct heater fan with a Task I tube duct jet suppressor for a 2.7 Mn nominal mission. The primary burner was partially throttled to obtain these results, so that the same comments apply as for the previous figure. Figure 111 presents the TOGW results for a 3.3 FPR duct-heating turbofan with a 5 PNdB suppressor for a 2.2 Mn mission, and Figure 112 presents the results for a 3.3 FPR turbofan with a Task I tube duct jet suppressor for a 2.2 Mn nominal mission.

Airplane Sensitivity Studies

Several perturbations were made to airplane related variables to determine their impact on cycle selection. However, as the following curves show, these airplane related variables did not have a strong influence on cycle choice. Figure 113 shows the effect on TOGW of varying the operating-weight-empty (OWE). As can be seen, a 10 percent decrease in OWE can have a dramatic effect on TOGW. Figure 114 shows the effect on TOGW of varying the supersonic cruise L/D of the airplane.

The effects on DOC of changes in economic variables are shown in Figures 115 through 120. Figures 115 through 118 show the effects of fuel cost, airframe price, utilization, and engine price on DOC. Figure 119 shows the effect of ticket yield on ROI.

In some cases the non-afterburning turbojet was better economically than the duct-heating turbofan even though the TOGW and fuel weight of the airplane with the duct-heating turbofan were significantly lower than the airplane with the non-afterburning turbojet engine. An investigation made to clarify this situation identified the following assumptions in the DOC calculations as the key contributing factors:

(1) ATA utilization and subsequent calculations for airplane miles flown

(2) engine price assumptions

(3) engine maintenance costs.

The airplane utilization (number of hours flown per year) was calculated from an ATA curve which provided utilization as a function of block time. The utilization differences for the various engines with the same cruise Mach number were not very significant, but the block time differences were significant in some cases. Therefore, when an almost constant utilization was divided by a varying block time, the number of trips per year varied from engine to engine. Therefore, when DOC is presented ¢/seat st. mile, the airplane with the lowest block-time has an advantage because it flies more miles per year. In reality, the number of miles flown per year should be calculated from detailed route simulations, which is beyond the scope of this study. Block time differences are not significant for this type of airplane unless it allows an extra trip to be made each day, which is unlikely for block time differences of the magnitude encountered between engine cycles. Further, the block time differences may not be real because engine operation was not optimized with minimum block time as a consideration. The duct-heating turbofan lost considerable time relative to the non-afterburning turbojet during subsonic climb from takeoff to Mn = 0.95. If the duct heater was lit during this segment, this time difference could probably have been eliminated or even been reversed in favor of the duct-heating turbofan.

The engine price affects the total investment per aircraft, which is depreciated over 15 years. The original estimated price of the duct-heating turbofan engine was sufficiently higher than the nonaugmented turbojet to offset the lower airframe-price of the airplane with the duct-heating turbofan, resulting in a higher depreciation of flight equipment. Since engine prices were estimated on a very conceptual basis, the price differences between engines cannot be considered to be accurate and, therefore, the differences in DOC due to estimated engine prices cannot be considered real.

The engine maintenance cost is another factor that cannot be estimated accurately. Engine maintenance material is the dominant part of the engine maintenance cost, and this is tied directly to engine price by the ATA formula. Because of the previous discussion on engine price, estimated maintenance cost difference cannot be considered real.

Figure 120 summarizes the results of perturbating the assumption as discussed above. It can be seen that the duct-heating turbofan had a DOC that was 1.5 percent higher than the afterburning turbojet under the ground rules used in the present study; however, the DOC of the duct-heating turbofan can be more than four percent less than the non-afterburning turbojet under the slightly modified calculations. These modified ground rules assumed that both the non-afterburning turbojet and the duct-heating turbofan had equal block times and, therefore, equal productivity.

MILITARY APPLICATIONS (TASK V)

Two military-missions were synthesized for evaluation of variable cycle engines – a bomber mission and a fighter-bomber mission, both of which contained mixed subsonic and supersonic legs in the mission profile. The systems analysis was performed on a propulsion system plus fuel weight basis for fixed gross weight aircraft. For each application, a cycle optimization was performed for both conventional and variable bypass engines. The results of the bomber study are summarized in Table XVIII which shows the fuel and propulsion weight breakdown for the best engines of each type. The AST variable bypass engine 1A is a military version of the commercial variable bypass engine 1A. Compared to the other engines studied, the commercial version of this military engine had a low fuel weight to do the mission, but its engine weight more than offsets this advantage. The military variable bypass engines were designed as military engines from the start and do not have commercial engine life-times or safety features. The results show that VBE 1A has the potential to be slightly better than conventional engines for this mission.

TABLE XVIII
RELATIVE FUEL AND PROPULSION WEIGHT
BOMBERS

(Conventional Vs. Variable Cycle Engines)

	Conventional Turbofans A/B	Conventional Turbofans D/H	AST VBE 1A D/H	Mil. VBE 1A D/H	Mil. VBE 2A D/H
FUEL	0.893	0.873	0.839	0.843	0.861
Climb & Acceleration	0.116	0.110	0.112	0.116	0.116
Supersonic Cruise	0.340	0.326	0.319	0.334	0.334
Subsonic Cruise	0.372	0.372	0.342	0.331	0.348
Reserve–Loiter	0.022	0.023	0.026	0.022	0.022
–5% Fuel	0.043	0.042	0.040	0.040	0.041
PROPULSION	0.107	0.120	0.168–0.179	0.136–0.145	0.143–0.152
Fuel System	0.018	0.017	0.016	0.017	0.017
Bare Engine & Nozzle	0.048	0.056	0.077–0.088	0.064–0.073	0.068–0.077
Installation	0.041	0.047	0.075	0.055	0.058
TOTAL FUEL & PROPULSION	1.000	0.993	1.007–1.018	0.979–0.988	1.004–1.013

The results of the fighter-bomber study are summarized in Table XIX. Afterburner rather than duct heater versions of the engines were best for this application. The military VBE 1A has the potential to equal the conventional engine for this mission.

TABLE XIX
RELATIVE FUEL AND PROPULSION WEIGHT
FIGHTER-BOMBER
(Conventional Vs. Variable Cycle Engines)

AFTERBURNER ENGINES

	Turbofan A/B	Mil. VBE 1 A/B	Mil. VBE 2 A/B
FUEL	0.591	0.566	0.577
Climb & Acceleration	0.210	0.210	0.211
Penetration	0.109	0.109	0.113
Subsonic Cruise	0.104	0.094	0.097
Combat	0.091	0.079	0.081
Reserve – Loiter	0.049	0.047	0.048
–5% Fuel	0.028	0.027	0.027
PROPULSION	0.409	0.434–0.474	0.458–0.498
Fuel System	0.117	0.112	0.114
Bare Engine & Nozzle	0.203	0.224–0.264	0.239–0.279
Installation	0.089	0.098	0.105
TOTAL FUEL & PROPULSION	1.000	1.000–1.040	1.035–1.075

One important point that should be mentioned concerning military applications of variable-bypass engines is the potential flexibility offered for multi-mission applications. For example, if the VBE 1A showed only a small advantage on the mixed subsonic/supersonic mission, it could show a large improvement on an all subsonic alternate missions. Similarly, the VBE 1A might show a significant advantage over the conventional engine on an all subsonic mission for the fighter/bomber.

TASK VI
TECHNOLOGY REQUIREMENTS

INTRODUCTION (TASK VI)

One of the primary objectives of the AST Propulsion System Study was to identify the engine-related technologies which have the greatest potential for improving the environmental and economic characteristics of an advanced supersonic commercial transport. Work done during previous Tasks has shown that advanced propulsion technology has the potential for significant improvements in the environmental and economic areas; however, in order to realize these improvements, component research-and-development programs must be undertaken.

Tasks I, II and V of this study provided the parametric base to determine overall system effectiveness of conventional and variable cycle engines in the environmental and economic areas. These tasks were based on advanced, 1975 technology projections; Task III evaluated the impact of more advanced technologies (1980 projections). Based on these study results, component technology programs were formulated for the technologies that are considered most critical to advanced supersonic propulsion systems.

The following criteria were applied in selecting and recommending specific technologies for these follow-on programs:

1) Unique components were recommended that are essential to meeting improved environmental characteristics that are projected for AST propulsion systems. These include jet noise suppressors, clean augmentor systems and unique requirements of variable cycle engines such as the annular inverter valve.

2) Technology areas that provide significant economic benefit to the overall system are recommended. Examples of critical technology are high temperatures composite materials for fan blades and high-temperature high-strength turbine blade materials such as directionally solidified eutectic alloys.

Programs for the long lead-time advanced components and technology that meet either criterion 1 or 2 are recommended at this time. These are categorized into a group herein identified as the Phase A programs.

Other technology areas, Phase B Programs, have been identified as also being important to advanced supersonic propulsion systems. However, specific programs cannot be recommended for these technologies until one or more of the following requirements or qualifications have been met:

1) General requirements including noise goals, supersonic cruise Mn and the subsonic leg should be established for advanced supersonic transports so that the optimum airframe/inlet/engine configurations can be determined. Selection of the configuration will have the effect of accenting the benefit of some advanced technology components and deemphasizing others.

2) Further study and analytical evaluation of conventional and variable cycles should be conducted to determine specific technology requirements including the best manner of applying the Phase B, advanced technologies to the candidate engine configurations.

3) Related programs currently in progress should be completed prior to starting follow-on work. For example, results from the NASA Experimental Clean Combustor Program for primary burners will provide the foundation for follow-on AST programs.

The projected schedule for development of advanced supersonic technology is shown in Figure 121. This schedule would lead to the capability for a United States entry into the supersonic transport market by the late 1980's or early 1990's.

SUMMARY (TASK VI)

In Task VI, critical technology and unique components were identified that can have a major impact on the AST propulsion systems. Based on results from Tasks I, II, III, and V, seven advanced technologies are recommended for follow-on work. The basis for this recommendation is these technologies have the potential to make significant improvements to the environment and/or economic characteristics of the overall AST engine/airplane system. In order to initiate an orderly development of these technology requirements, the following programs are recommended:

1. Jet Noise Suppressor Integrated With Nozzle/Reverser System for Duct-Heating Turbofan and Variable Cycle Engines

2. A Low Noise, Clean Duct-Heater for Turbofan and Variable Cycle Engines

3. An Annular Inverter Valve (AIV) for Variable Cycle Engines

4. Directionally Solidified Eutectic Material and Coating for Turbine Blades

5. Ceramics for Turbine Vanes

6. High Temperature Composite Fan Blades

7. A Full-Authority Electronic Control System

Additional technology requirements have been identified, but the programs can be deferred until progress has been made in one or more of the following areas: selection of the AST airframe/propulsion system configuration, further studies to determine specific technology requirements, and/or completion of related programs currently in progress. These additional technology requirements are listed later in this report.

This portion of the report presents a summary of the Task VI technology program recommendations. An expanded review of these technology program recommendations was presented in a limited edition report (PWA-4871) to NASA-Lewis.

RECOMMENDED ADVANCED TECHNOLOGY PROGRAMS – PHASE A (TASK VI)

The following Phase A programs have been formulated for seven critical areas of technology. Each can be started immediately. In general, the programs describe the work necessary to establish a technical base that is sufficient to determine technical feasibility and acceptability. Further development is required to determine optimum component performance, integration, durability, and manufacturing factors. Most of these programs cover a two to three year period. Where appropriate, these recommended Phase A programs are related with currently active research programs being conducted by P&WA and NASA or other government agencies to indicate how the recommended AST technology programs will interface with and benefit from these other programs.

Jet Noise Suppressor Integrated With Nozzle/Reverser System for Duct-Heating Turbofan and Variable Cycle Engines

The AST propulsion system study indicates that duct-heating turbofan and variable cycle engines may benefit significantly by applying jet noise suppressors to the fan streams of these engines. For duct-heating turbofans, a 5 to 10 percent reduction in TOGW is possible for noise levels from FAR 36 to FAR 36 minus 10 EPNdB. The engine cycle can be designed so that jet noise from the primary stream does not dominate. By applying a jet noise suppressor to the fan stream, less throttle-reduction would be required to meet a certain noise level. In effect, the fan pressure ratio can be increased at takeoff to provide more thrust per pound of airflow and the engine size (total engine flow) can then be reduced.

As follow-on work to the original SST program, there has been an extensive effort on tube and chute suppressors that apply to turbojets. This work provides basic technology to suppress noise generated in high velocity (high noise) turbojets. The results are not directly applicable to the lower velocities of turbofan and variable cycle engines that have the potential to meet FAR 36 and lower noise levels.

NASA has initiated an exploratory program (NAS3-17866) with P&WA to evaluate two suppressor configurations for turbofan engines: a convoluted type and a multi-tube design. A supplementary program is recommended to continue this evaluation of suppressors for turbofan engines. This program will consist of a design study of integrated suppressor/nozzle/reverser configurations, wind tunnel evaluation of candidate configurations including noise and performance measurements, and design of a flight-type suppressor/nozzle/reverser system for the candidate AST engine configurations.

A Low Noise, Clean Duct-Heater for Turbofan and Variable Cycle Engines

The Tasks I and II study results indicate that the best turbofan and variable cycle engines require thrust augmentation. Furthermore, duct-heating in just the fan stream rather than afterburning in both the engine exhaust and fan streams has been identified as the optimum type of augmentation for these noise-limited engines.

To meet sideline noise restrictions, duct heaters for these AST propulsion systems operate in a completely different regime than military afterburners. At takeoff, the AST studies showed that the duct heater fuel/air ratio was anywhere from 0 (no augmentation) at the very low noise levels to approximately 0.010 at FAR 36. In addition, the engines may be throttled back for low noise and, therefore, must be oversized to provide the required thrust. This oversizing reduces the level of augmentation required for climb and supersonic cruise. Optimum engine performance is obtained with fuel/air ratios in the 0.01 to 0.025 range for supersonic cruise and maximum climb power. The AST duct heaters will operate in completely different power and temperature regimes than military afterburner systems which operate with fuel/air ratios as high as 0.06. Duct heater technology has been developed by P&WA to the point of determining their feasibility in the previous United States SST and B-1 aircraft competitions. This technology has not passed the demonstration stage. This technology status, combined with the low emission requirements for the overall AST propulsion system, dictates the need for an advanced technology, duct-heater program.

The recommended program will establish emission, noise, performance, and stability characteristics of advanced technology, duct-heater systems relative to current technology designs. Basically this program will provide the same type of experimental evaluation of duct-heater technology that the NASA Experimental Clean Combustor Program is providing for primary combustor systems. Advanced techniques that will accelerate the rates of fuel vaporization, distribution, mixing, burning and dilution will be investigated.

Annular Inverter Valve

The annular inverter valve (AIV) is a unique and critical component of the variable cycle engine concept. This valve allows two separate fan assemblies to operate either in parallel for low noise and for good subsonic performance or in series for good supersonic performance. A single AIV located between fan assemblies provides the capability for varying the bypass ratio of a turbofan engine. It can also be applied to two separate turbine assemblies so that, together with the fan AIV, a turbofan cycle can be converted to a turbojet cycle. The potential noise and performance benefits of these variable cycle engines are being evaluated relative to conventional engines in the on-going AST propulsion system studies.

The AIV concept is presently in the early stage of aerodynamic evaluation. P&WA and the Boeing Company are conducting an analytical and experimental program under Air Force sponsorship (F33657-73-C-0619). A JT8D turbofan engine has been modified to accept an AIV between the two fan stages. This program will provide a preliminary evaluation of the basic AIV/variable-cycle engine concept. Although only preliminary test results are available, AIV evaluation to date is encouraging. Because the AIV related technology is in its infancy, an extensive research effort is required to bring this component to a level of understanding that is equivalent to the other AST engine components.

An AIV program is recommended to advance the level of aerodynamic technology that can be applied to the valve design. Optimum AIV configurations will be evaluated analytically and experimentally to determine performance sensitivity to distortion and offdesign operation. Candidate designs will be analytically evaluated on an overall installed engine basis to determine the optimum balance between pressure loss, weight, cost, and installation dimensions of the complete propulsion system.

Advanced Turbine Technology

The Task III evaluation of advanced technology shows that each of the candidate engine configurations is very sensitive to turbine technology. There are three reasons for this:

A. Projected turbine inlet temperatures are in the 2500°F to 2800°F (1371°C to 1538°C) range. At supersonic cruise, cooling air temperatures are in the 1100°F to 1300°F (593°C to 704°C) range. In this hot environment, current technology materials and cooling systems will require large quantities of cooling air, imposing a penalty on the cycle and turbine efficiency.

B. The integrated stress-time-temperature requirements for AST turbines present more severe creep and oxidation conditions than do current technology subsonic engines.

C. Cycle characteristics of the AST engines, namely low pressure ratios of the high spools, in conjunction with unique flow schedule of the engine during supersonic operation, cause high stresses in the turbine blading.

These factors are common to all of the AST engine configurations. Two technologies are recommended on the basis of their potential to provide significant improvements in the turbine area: directionally solidified eutectic material and coating for turbine blades, and ceramic turbine vanes. A supporting reason for selecting these technologies is they both involve longer research and development programs than some of the other advanced turbine technology that will eventually be required for the AST engine.

Directionally Solidified Eutectic Material and Coating for Turbine Blades

Directionally solidified (DS), eutectic alloys show promise for higher strength, higher temperature capability for turbine blades relative to the best DS superalloys currently available. For example, a Ni-23.1 Cb-4.4 Al eutectic alloy combined with a high temperature coating has the potential for a 50 percent increase in blade design stress and a 100°F to 200°F (55°C to 110°C) increase in metal temperature. Applied to high pressure turbine blades, this material system could lead to a 20 percent higher rotational speed, resulting in reduced elevation turbine designs and fewer compressor stages. In addition, turbine cooling requirements can be decreased. The recommended program will determine the feasibility of applying this specific alloy and other eutectic alloy systems to commercial AST engines. Chromium base alloys will receive special attention because of their low density, high melting point and good oxidation resistance. Creep rupture strength and ductility will be determined as a function of solidification rates and alloy composition. Candidate coating materials for the external and internal surfaces will be screened by dynamic oxidation-erosion and ductility rig testing and by inter-diffusion analysis. The most promising eutectic alloy and coating systems will be tested for general compatibility when exposed to AST turbine environment and stress/cycle conditions.

Ceramics for Turbine Vanes

Substantial progress has been made in improving ceramic material capability for gas turbines in the last several years. Thermal shock resistance, high temperature strength, and corrosion resistance appear suitable for applying this material to nonstructural turbine vanes in all of the AST engine configurations. The 500°F (278°C) and higher temperature improvement of ceramics over metal alloy counterparts will reduce the vane cooling requirement and yield an improvement in turbine efficiency. Additional cost and weight benefits would also be obtained. Uncertainty exists in defining and evaluating thermal fatigue and impact capability and also in designing for these brittle materials.

The recommended program is aimed at developing a wide body of ceramics knowledge by a characterization of the properties of hot pressed silicone nitride and silicon carbide. Fabrication processes and the capability of these ceramics to withstand the AST turbine environment will be determined. In addition, basic work on attachment and cushioning schemes necessary for the integration of ceramic vanes into AST engines will be conducted.

High Temperature Composite Fan Blades

A high temperature, low density composite material such as boron fiber in a polyimide resin matrix applied to fan blades in the AST turbofan and variable cycle engines in place of titanium has the potential to reduce engine weight from 2 to 4.5 percent, depending on the engine configuration. These blades are exposed to a thermal environment in the 500°F to 700°F (260°C to 370°C) range – 500°F (260°C) corresponds to the AST engine inlet temperature at 2.7 Mn operation and 700°F (370°C) is the maximum projected temperature for the boron/polyimide material. The two basic development problems associated with composite blades are fabrication cost and resistance to foreign object damage (FOD). A program is recommended that will determine the feasibility of applying this type of composite material to fan and compressor blades for the AST engines. It would lead to a follow-on program that would concentrate on the two basic development problems.

The recommended program consists of two tasks. The first will be a screening of candidate materials for basic structural, physical, and processing properties. Two potential material systems will be selected for more detailed evaluation in the second task. Stability of these selected systems will be determined by exposure at temperatures and pressures characteristic of the AST engines. Stress rupture life, fatigue strength, torsional creep strength, and thermal cycling characteristics will be determined as functions of temperature. At the conclusion of this program, the basic feasibility of this composite material for application to the AST engines will be determined and the decision to continue into the development areas of fabrication cost and FOD resistance can be made.

Electronic Control System

A full authority digital electronic control system is critical technology for the AST propulsion systems. The number of control system variables may range from 7 to 10 compared to 3 for current technology subsonic commercial engines. For these complicated AST propulsion systems, a full authority digital electronic control has the potential to make the following improvements relative to an equivalent hydromechanical system: improved control accuracy, lower weight and cost, improved maintainability, reprogramming flexibility, integration with condition monitoring and power management systems, and self testing and trim capability.

A control system study program consisting of two tasks is recommended. The first involves optimal control analysis techniques for representative AST control systems for each basic engine configuration. The second is a study of closed loop control of supersonic converging-diverging nozzles for optimum performance.

ADDITIONAL TECHNOLOGY REQUIREMENTS – PHASE B (TASK VI)

Additional technology areas have been identified as also being important to the AST propulsion systems but are not recommended for follow-on experimental work at this time. Action in these areas should be deferred until one or more of the following conditions is met: the airframe and engine configurations are chosen and specific technology requirements can be defined; related programs currently in progress can be completed, or further propulsion system studies can be conducted. These additional (Phase B) technology areas are:

1. Critical Technology for Variable Cycle Engines
    - flow inverter (this is a recommended Phase A Program)
    - inlet (separate or integral)
    - nozzle configuration
    - seal system for fan splitter
    - mechanical and structural design
    - propulsion system integration with airframe
    - burner and turbine technology for a two-valve, variable cycle engine
    - augmenter technology
2. Low Emission Primary Burner
3. Multi-Stage Low Noise Fan
4. Advanced Compressor
5. Advanced Low-Pressure Turbine
6. Propulsion System Integration
7. Low Noise Thrust Reverser
8. Low Noise Inlet
9. High Temperature Lubricating Oil
10. Advanced Accessories and Drive Systems
11. Advanced Bearings and Seals
12. Low Cost Fabrication Technology
13. Jet Noise Suppressor for Dry Turbojet Engines
14. Propulsion System Safety
15. Advanced Aerodynamic High Pressure Turbine
16. Ceramic Tip Seal System for Turbine Rotors
17. Turbine Endwall Cooling
18. High Temperature, Lightweight Acoustic Treatment

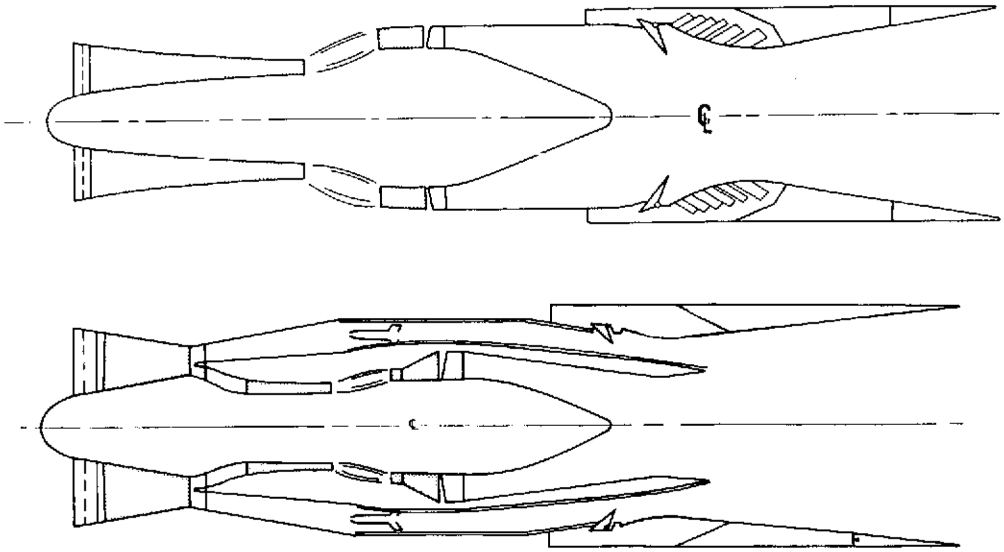


Figure 1 Schematics of Non-Afterburning Turbojet (top) and Duct-Heating Turbofan (bottom) Engines

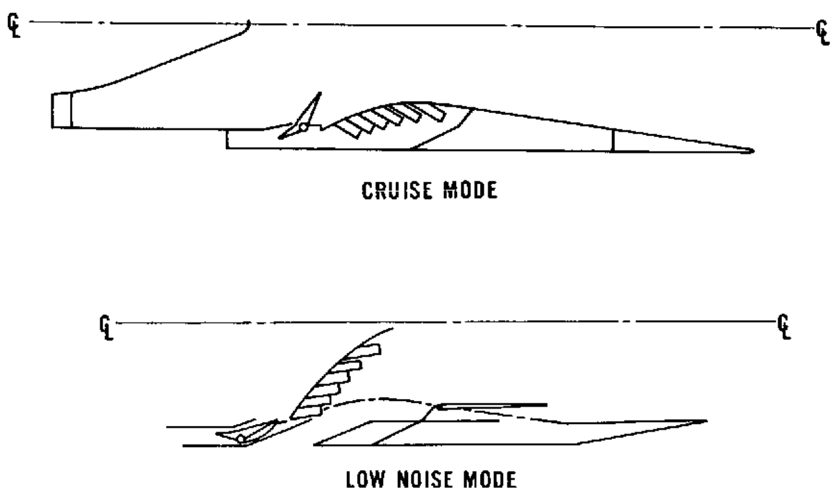


Figure 2 Schematic of Nozzle/Reverser/Suppressor For Turbojet

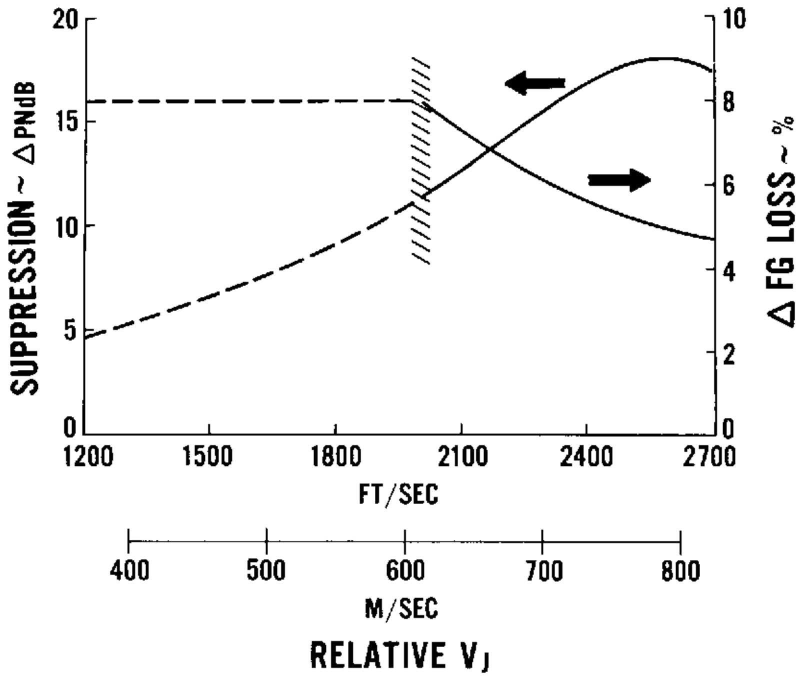


Figure 3 Characteristics of 18 PNdB (max.) Jet Suppressor

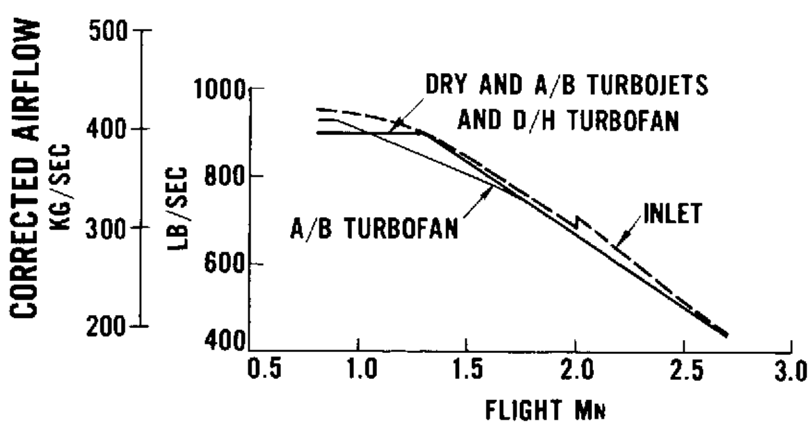


Figure 4 Corrected Airflow Schedule

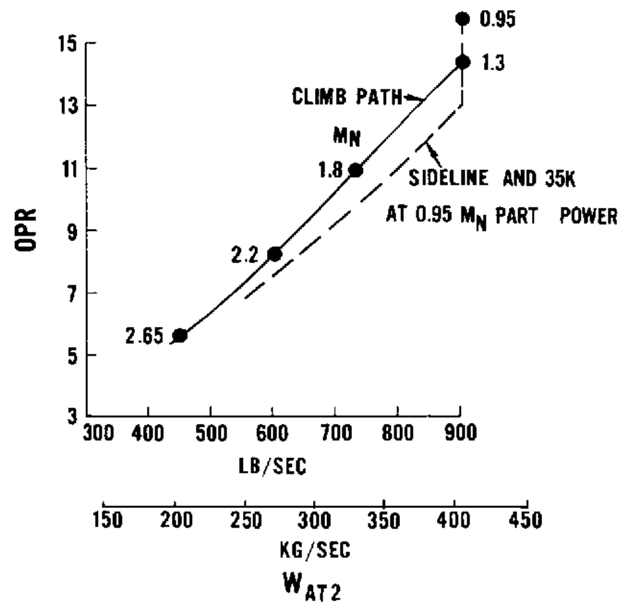


Figure 5 Typical Turbojet Compressor Operating Line

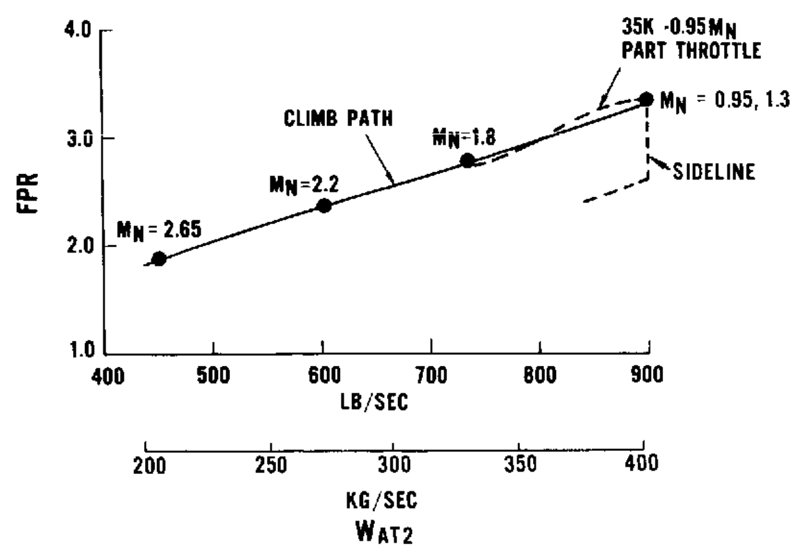


Figure 6 Typical Duct-Heating Turbofan Fan Operating Line

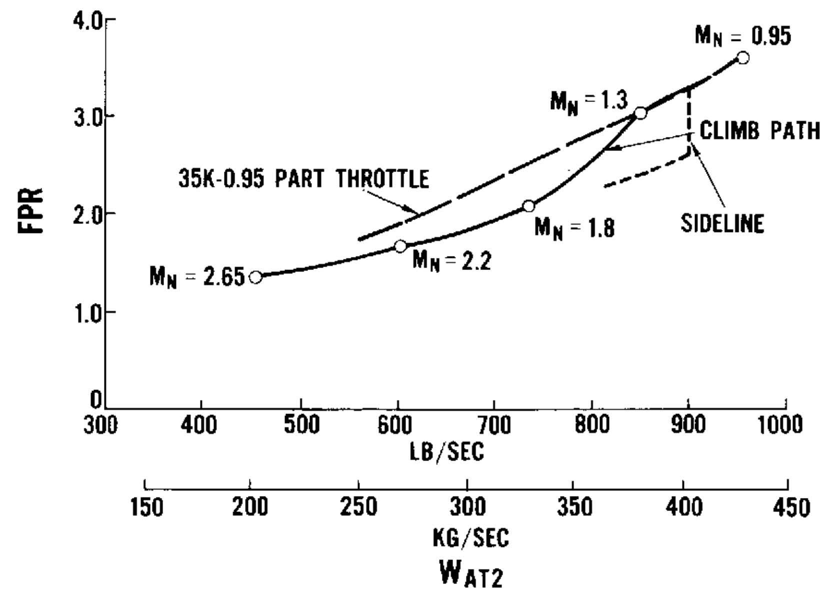


Figure 7 Typical Afterburning Turbofan Fan Operating Line

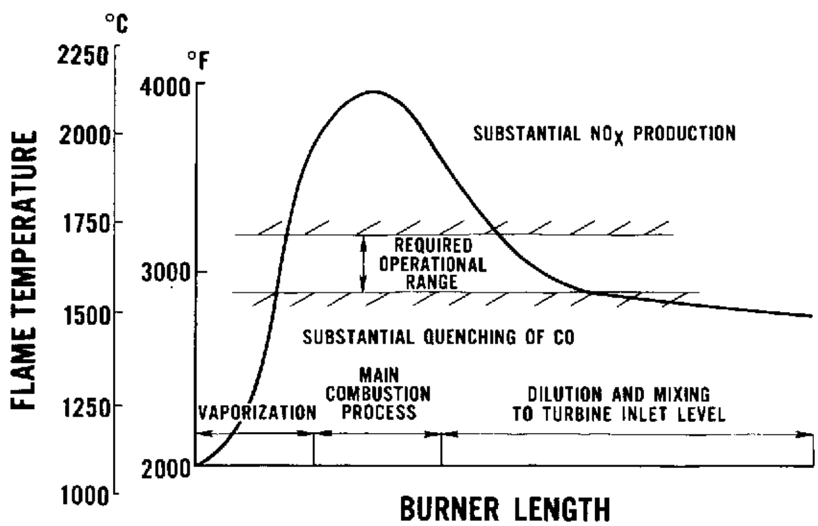


Figure 8 Basic Emission Problem Showing Operational Range Limit Required to Minimize NO_X Production and Substantially Quench CO to CO_2

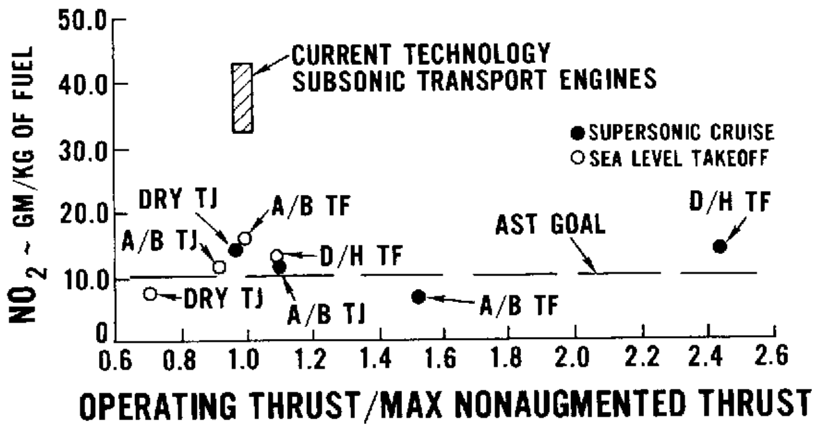


Figure 9 Estimated NO_2 Emission Levels

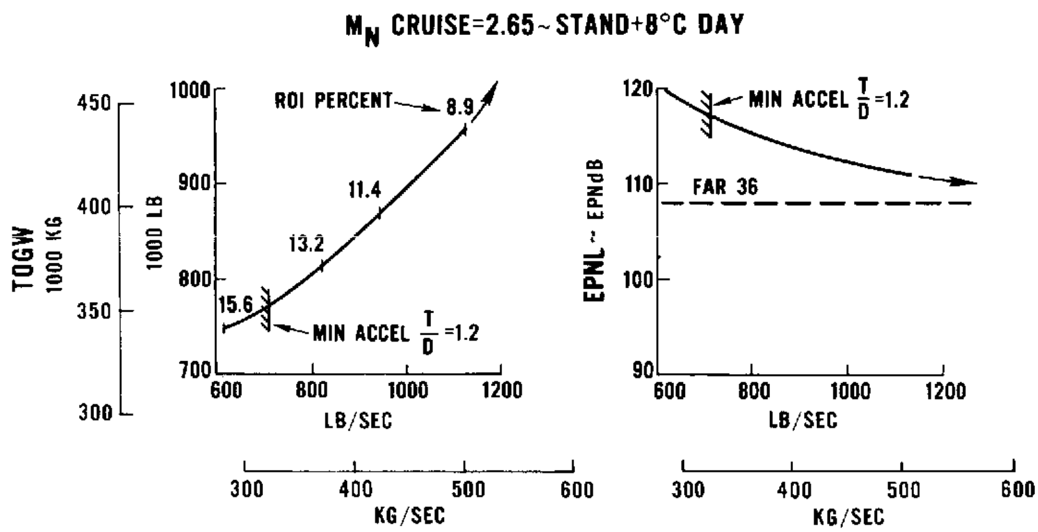


Figure 10 System Performance of Unsuppressed Non-Afterburning Turbojet

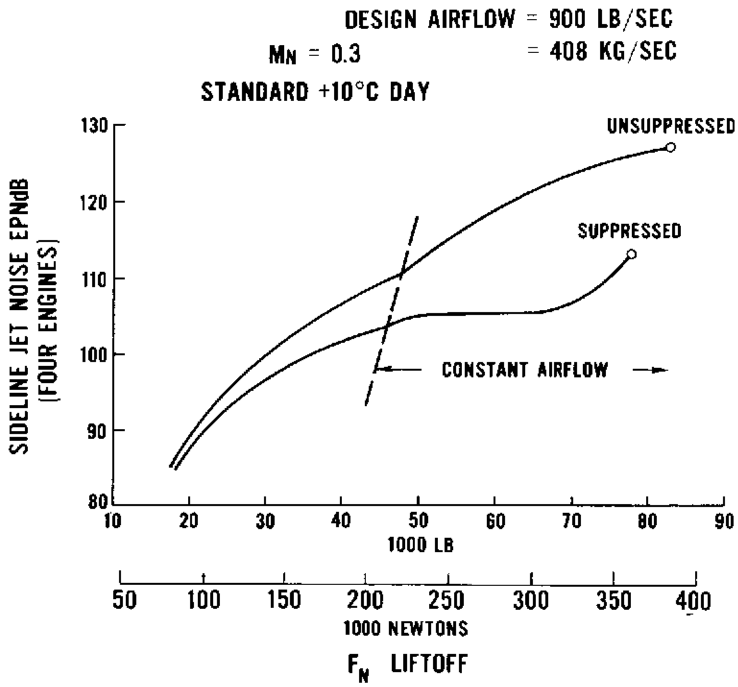


Figure 11 Sideline Noise of Typical Non-Afterburning Turbojet

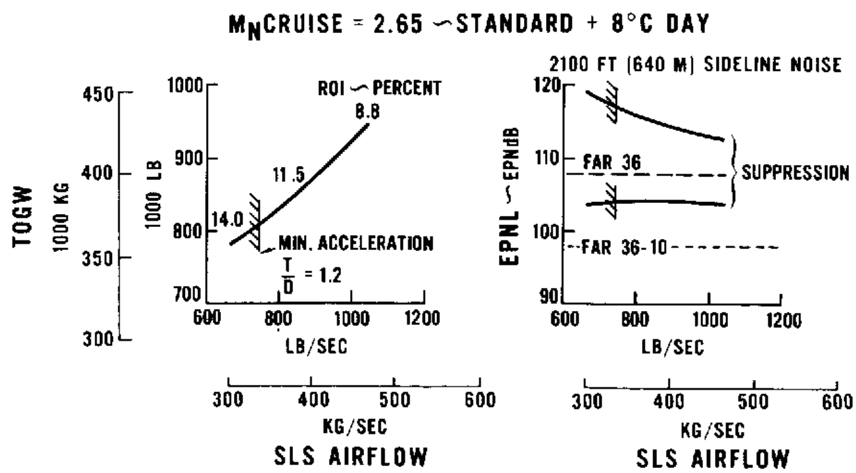


Figure 12 System Performance of Suppressed Non-Afterburning Turbojet

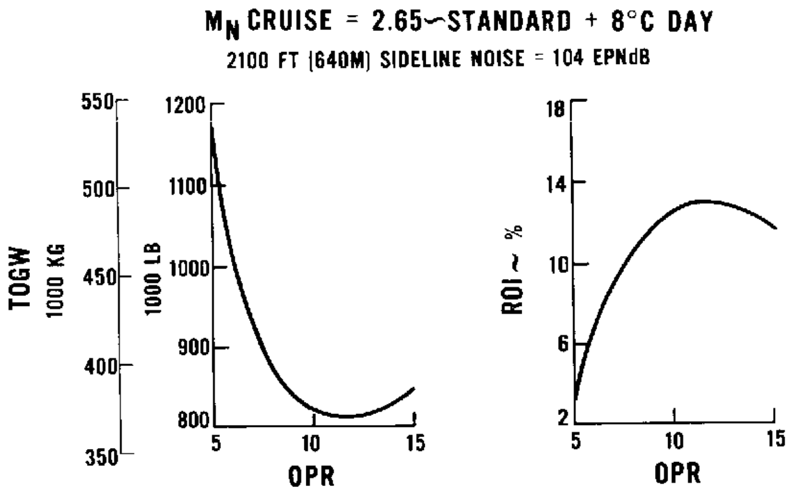


Figure 13 Overall Pressure Ratio Optimization for Non-Afterburning Turbojet – Engines Sized for Acceleration Thrust/Drag = 1.2

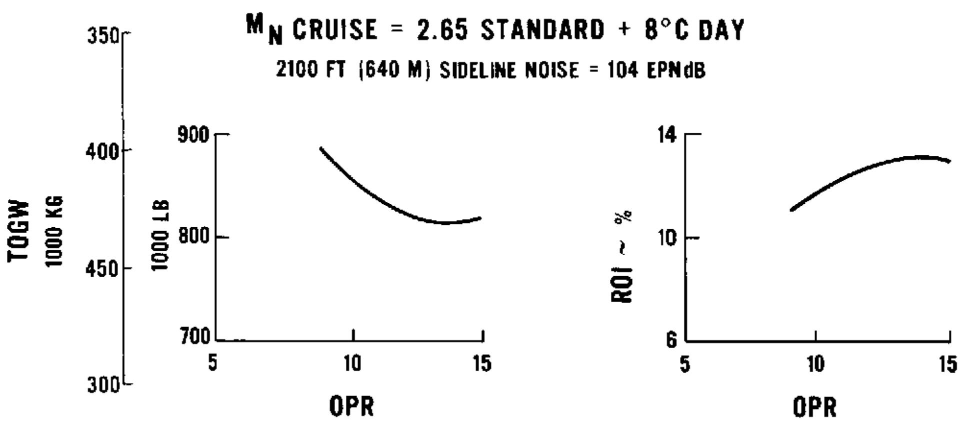


Figure 14 Overall Pressure Ratio Optimization for Afterburning Turbojet

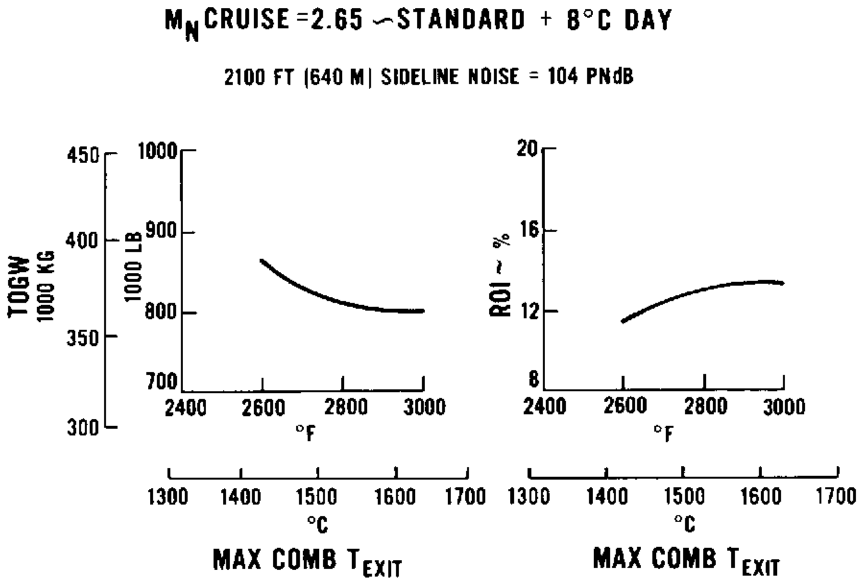


Figure 15 Combustor Exit Temperature Optimization for Non-Afterburning Turbojet – Engines Sized for Acceleration Thrust/Drag = 1.2

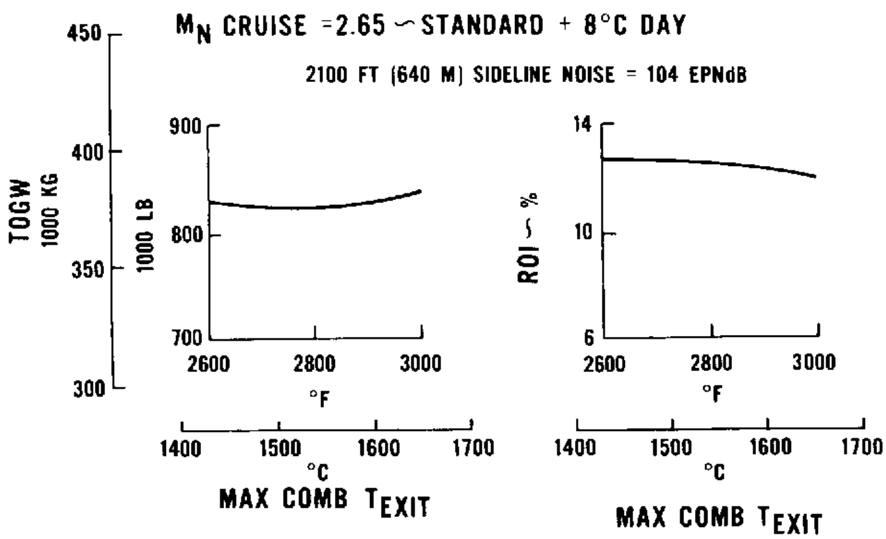


Figure 16 Combustor Exit Temperature Optimization for Afterburning Turbojets

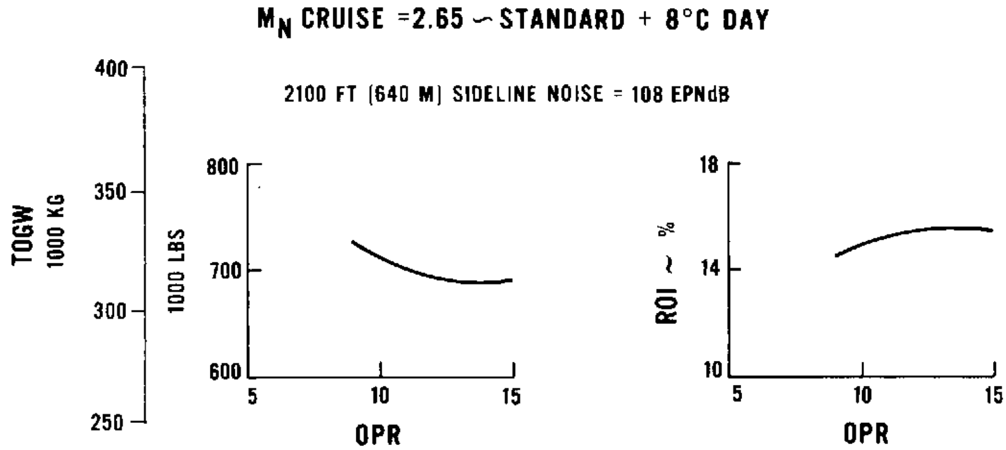


Figure 17 Overall Pressure Ratio Optimization for Duct-Heating Turbofans

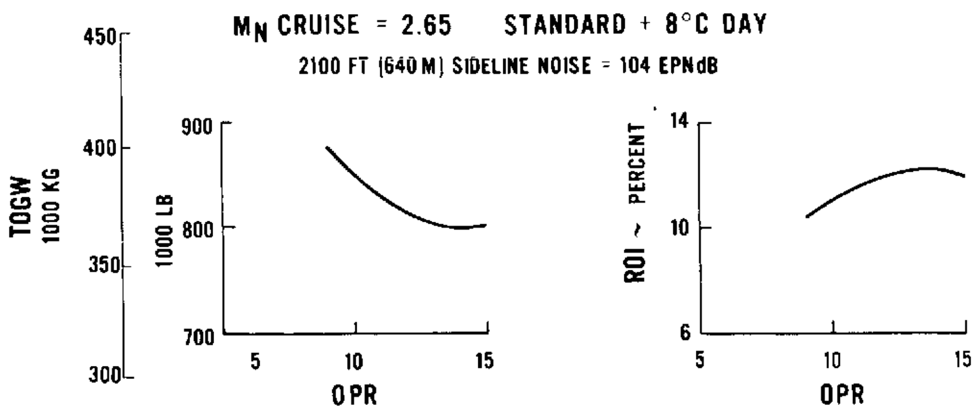


Figure 18 Overall Pressure Ratio Optimization for Afterburning Turbofans

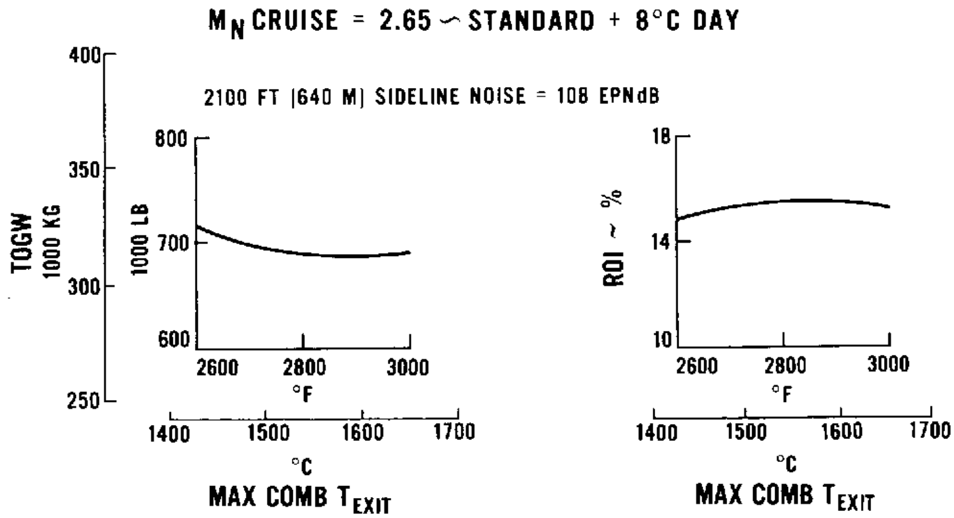


Figure 19 Combustor Exit Optimization for Duct-Heating Turbofans

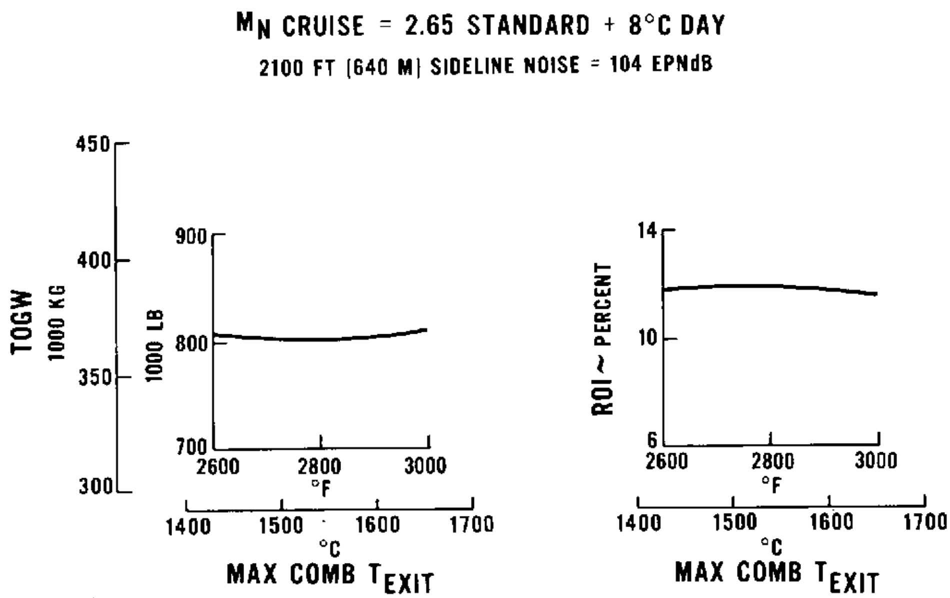


Figure 20 Combustor Exit Optimization for Afterburning Turbofans

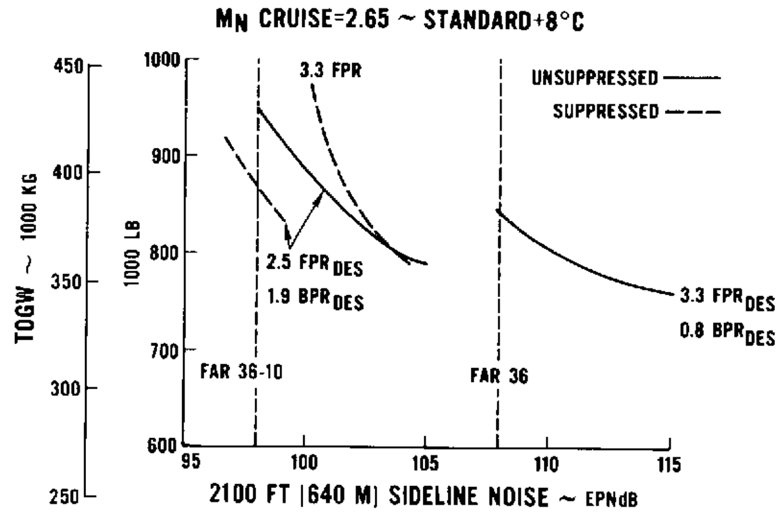


Figure 21 TOGW Sensitivity to FPR/BRP for Afterburning Turbofans

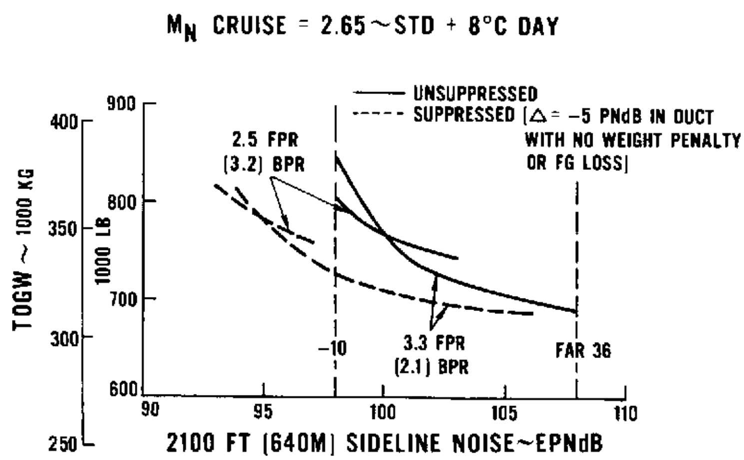


Figure 22 TOGW Sensitivity to FPR for Duct-Heating Turbofans

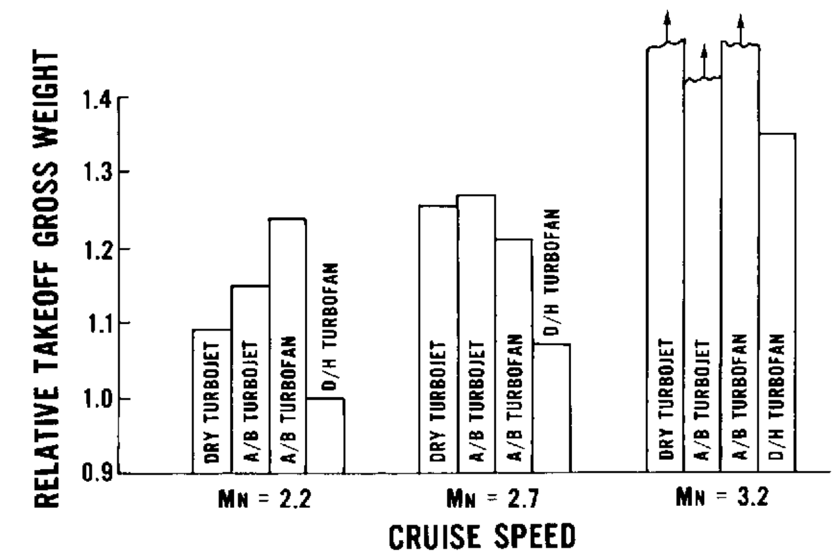


Figure 23 TOGW Comparison of Engine Types at FAR 36 Sideline Noise Limits

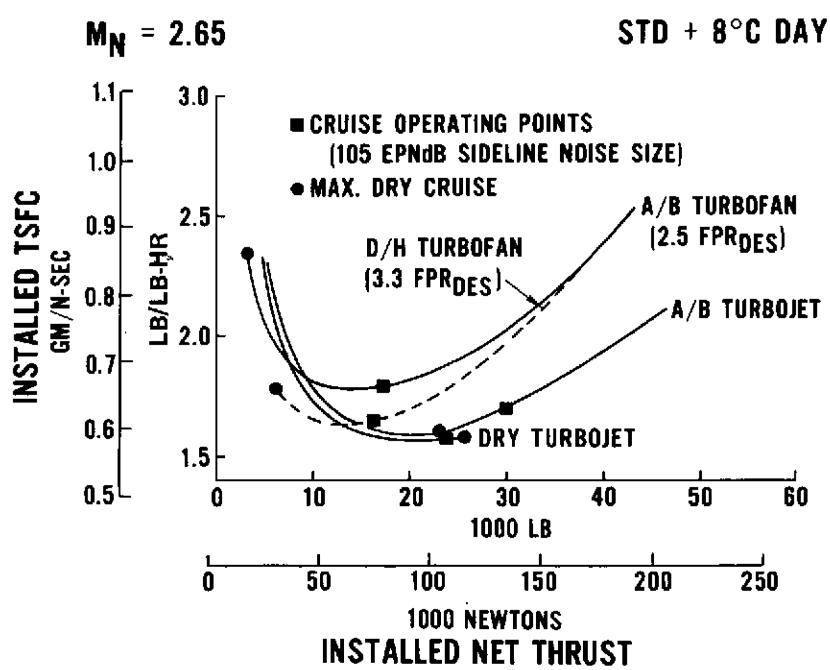


Figure 24 Supersonic Cruise Performance Comparison of Engine Types

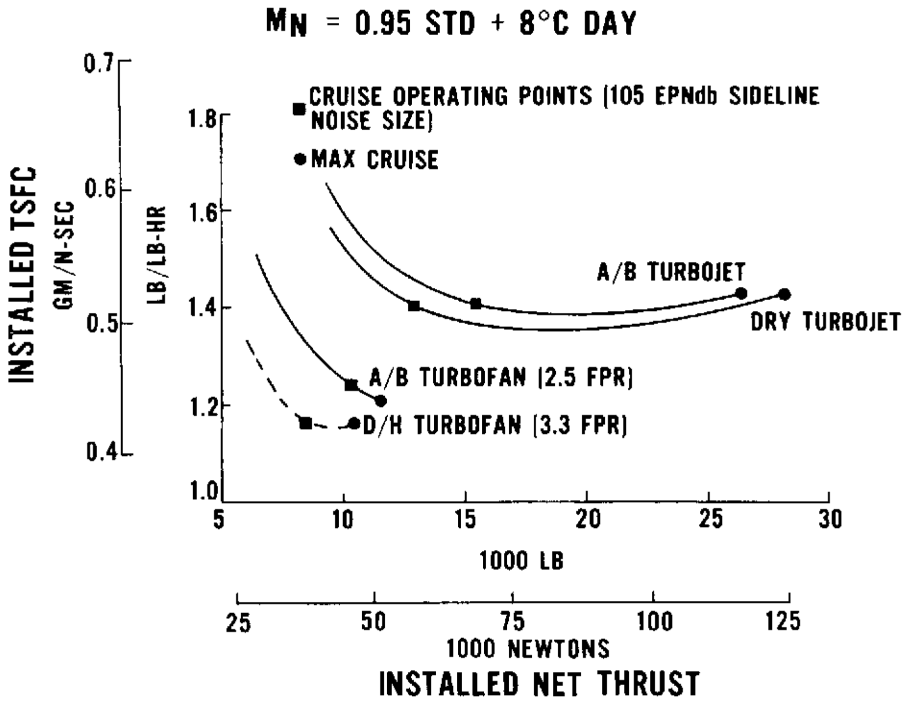


Figure 25 Subsonic Cruise Performance Comparison of Engine Types

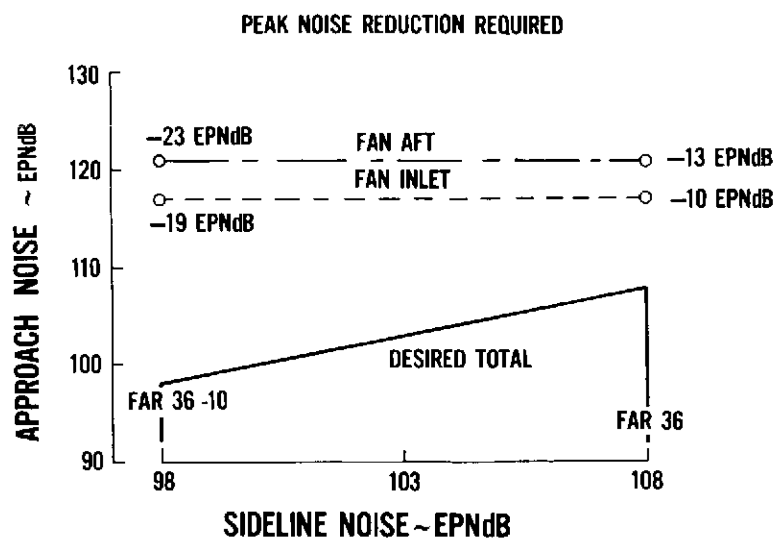


Figure 26 Approach Noise Level of Duct Heating Turbofans

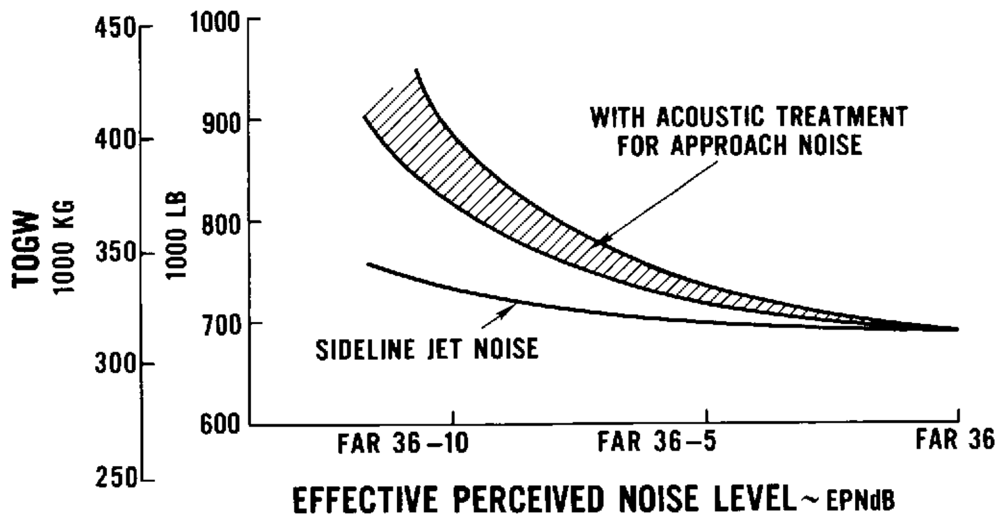


Figure 27 TOGW Penalty for Meeting Low Approach Noise Levels – Duct-Heating Turbofans

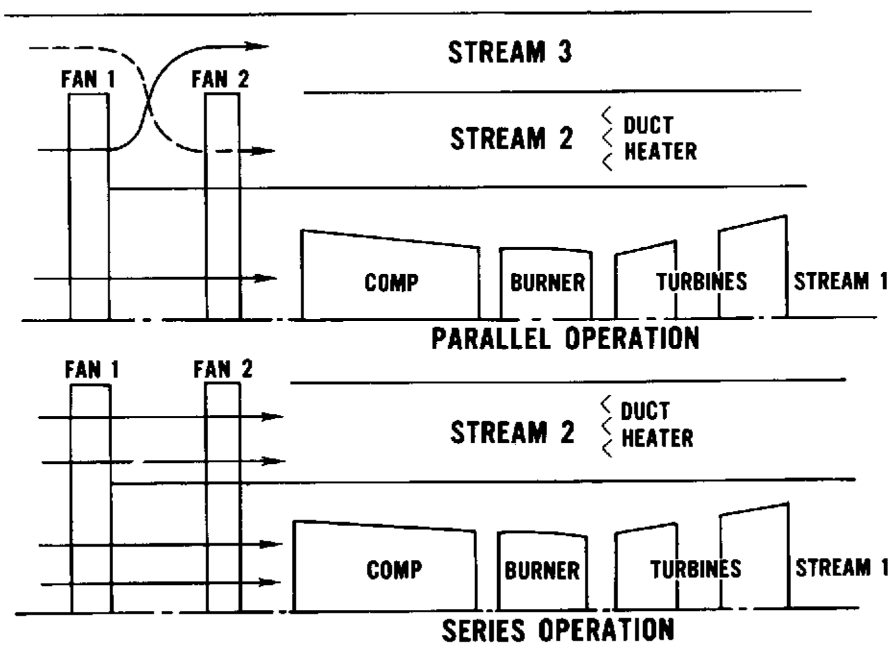


Figure 28 Schematic of Series/Parallel Fan Variable Cycle Engine With Splitter (VBE I)

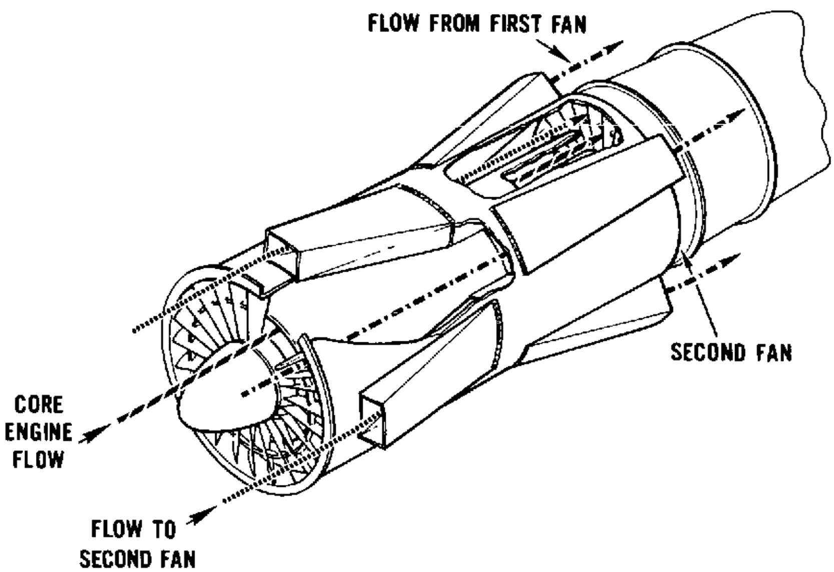


Figure 29 Typical Ducting Arrangement for Series/Parallel Variable Cycle Engine – Ducts Shown in Takeoff Position

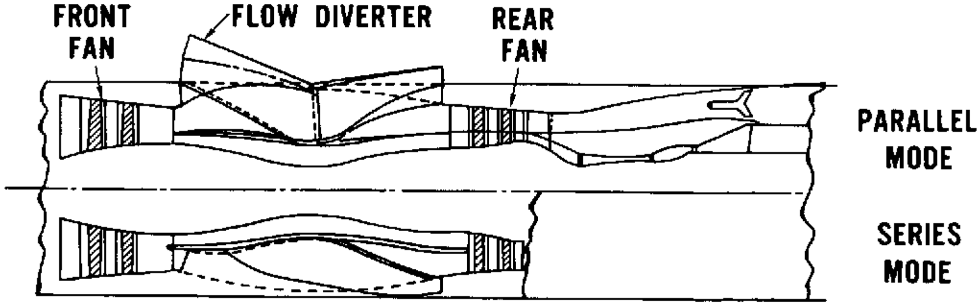


Figure 30 Typical Series/Parallel Engine Flowpath

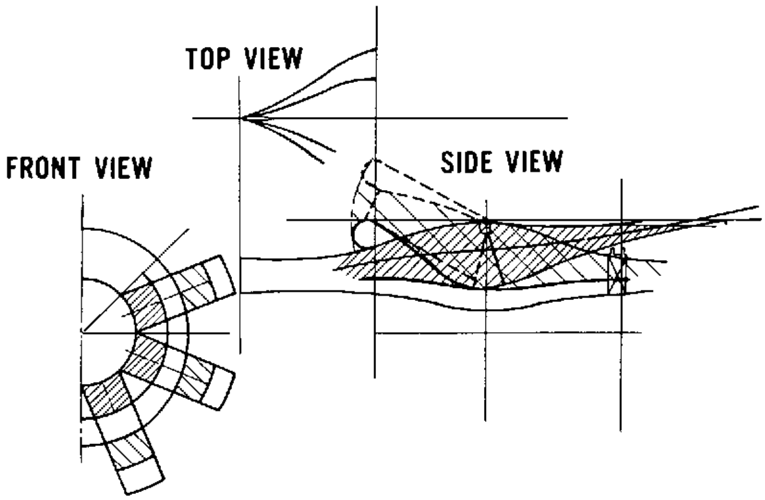


Figure 31 Series/Parallel Concept With 270 Degree Chute Arrangement – Installation Arrangement With Chute Feed (Parallel Mode Shown)

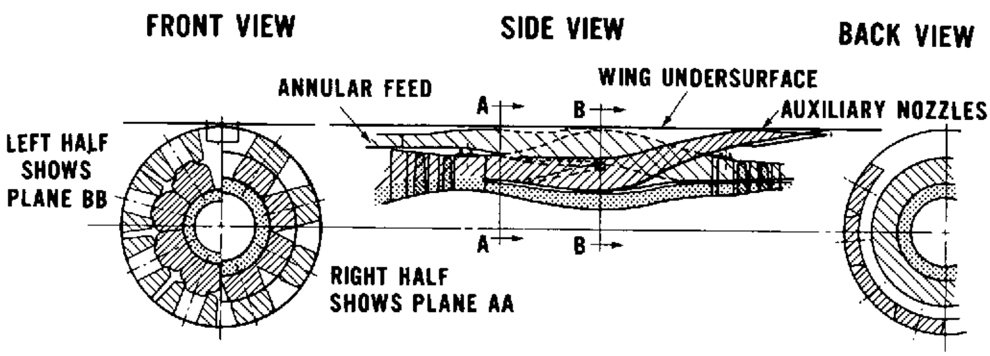


Figure 32 Series/Parallel Concept With 360 Degree Annular Feed – Installation With Internal Annular Feed (Parallel Mode Shown)

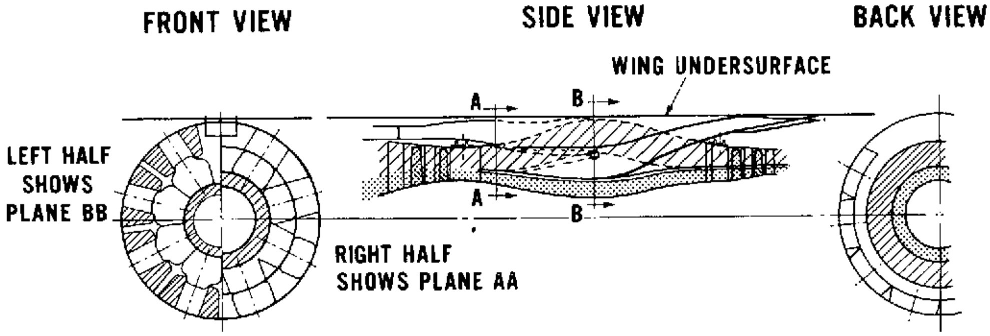


Figure 33 Series/Parallel Concept With 360 Degree Annular Feed – Installation Arrangement With Internal Annular Feed (Series Mode Shown)

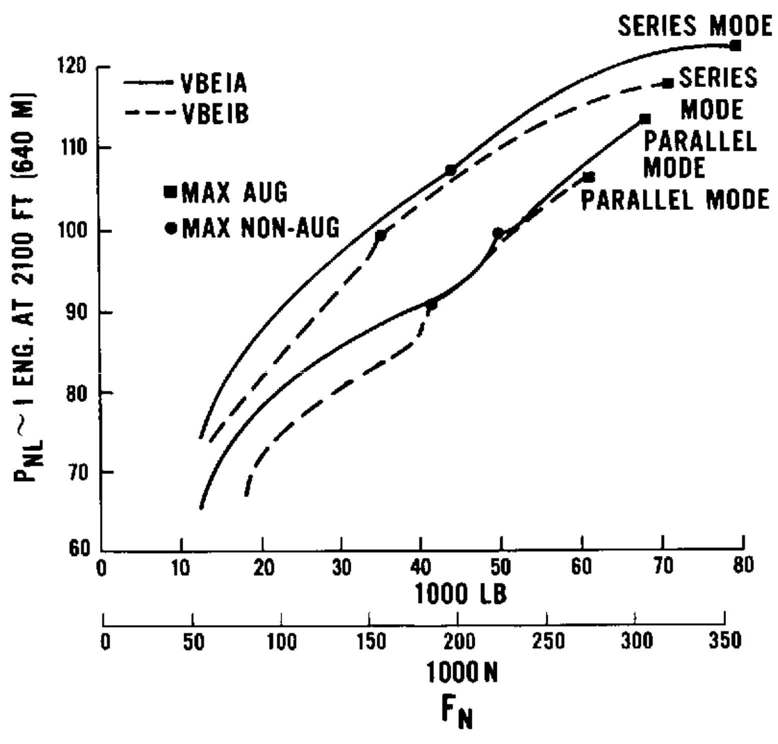


Figure 34 VBE I Sideline Noise Characteristics – Series Mode Airflow Size is 900 lb/sec (408 kg/sec) for Both Engines

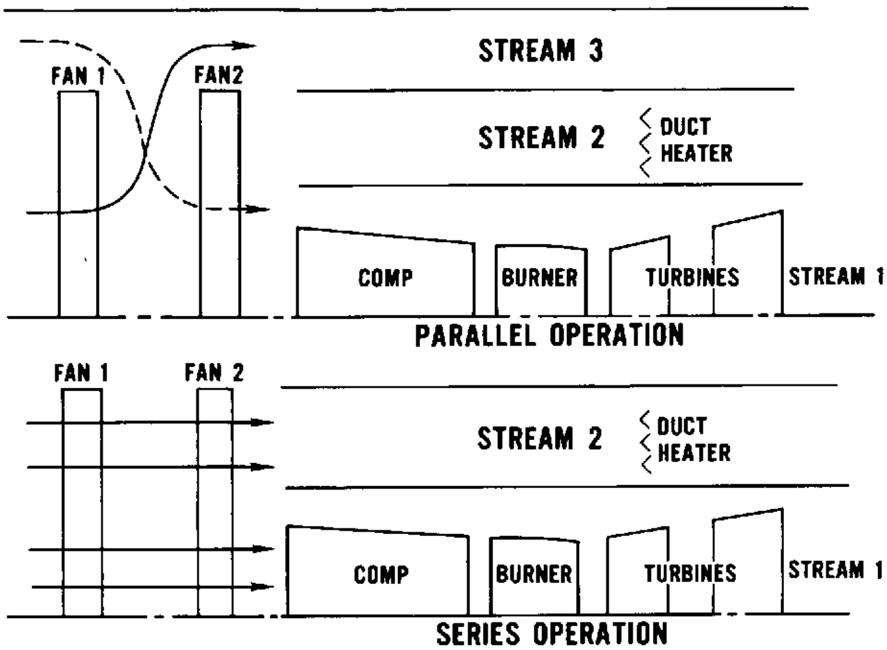


Figure 35 Schematic of Series/Parallel Fan Variable Cycle Engine Without Splitter (VBE II)

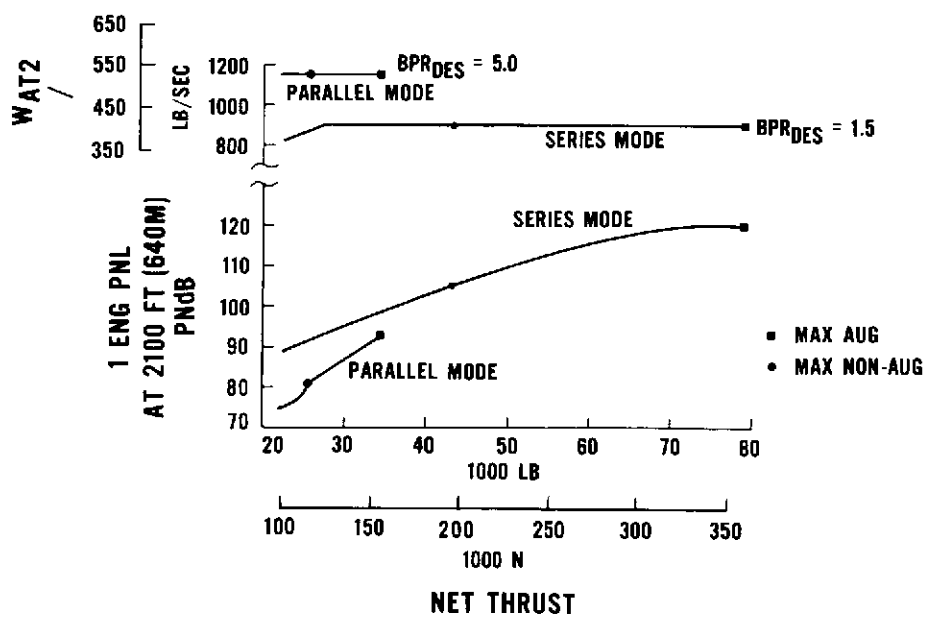


Figure 36 VBE II Sideline Noise Characteristics

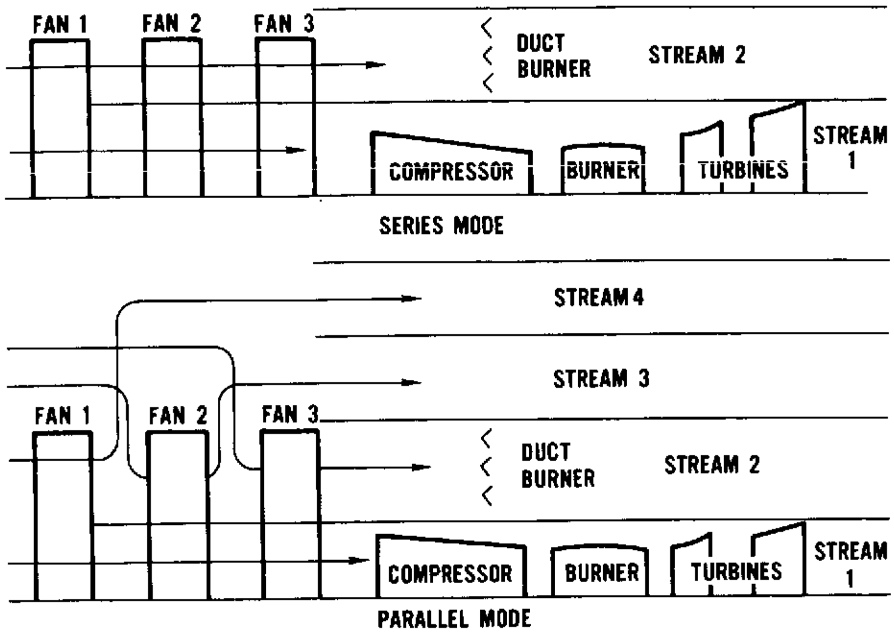


Figure 37 Schematic of Series/Parallel Three-Fan Variable Cycle Engine Concept With Splitter (VBE III)

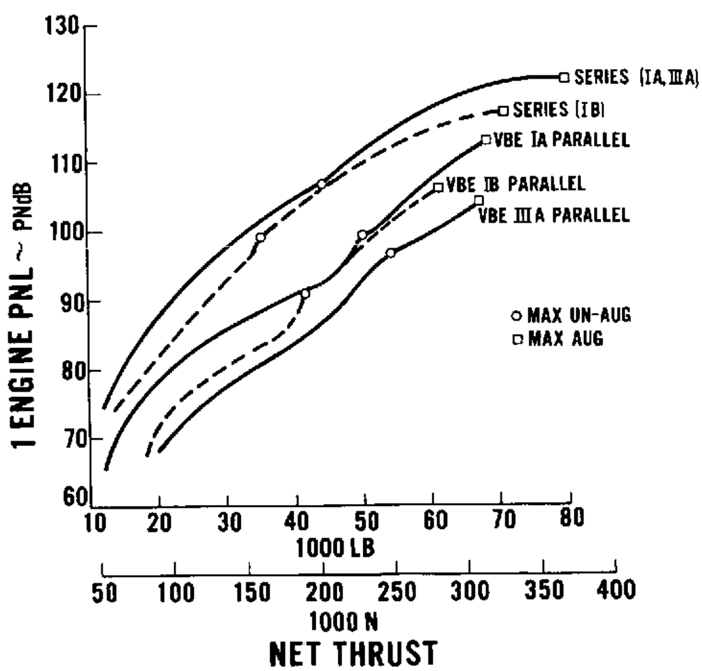


Figure 38 VBE III Sideline Noise Characteristics – Series Mode Airflow Size is 900 lb/sec (408 kg/sec) for Both Engines

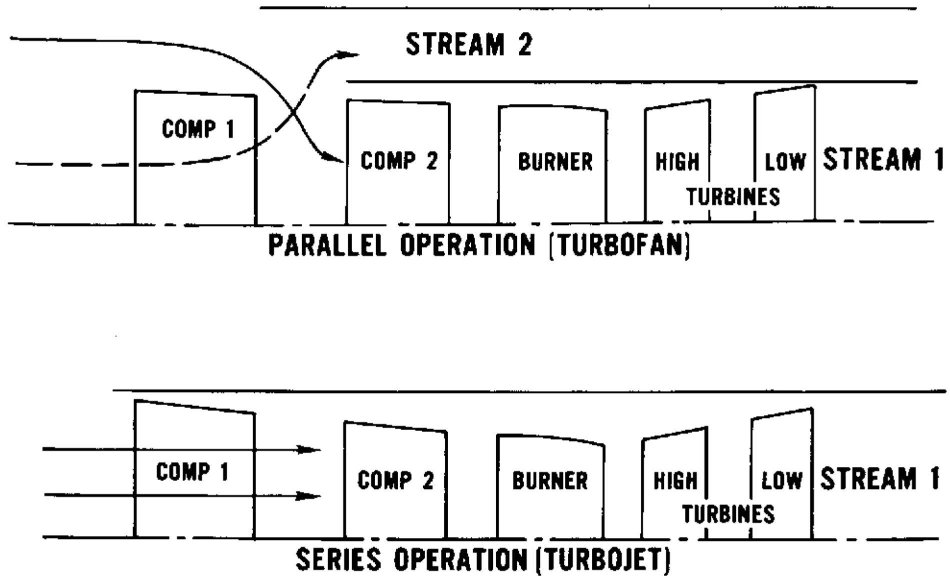


Figure 39 Schematic of Series/Parallel Compressor Variable Cycle Engine (VBE IV)

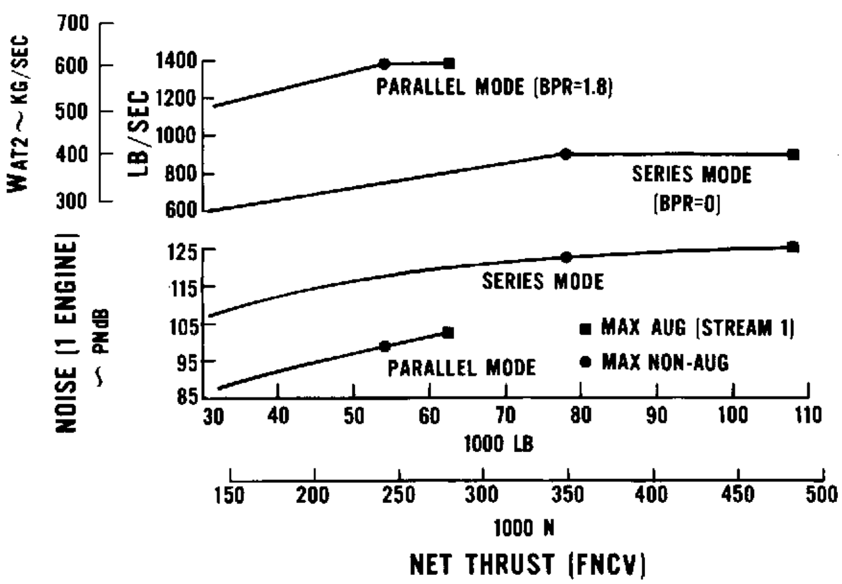


Figure 40 VBE IV Sideline Noise Characteristics

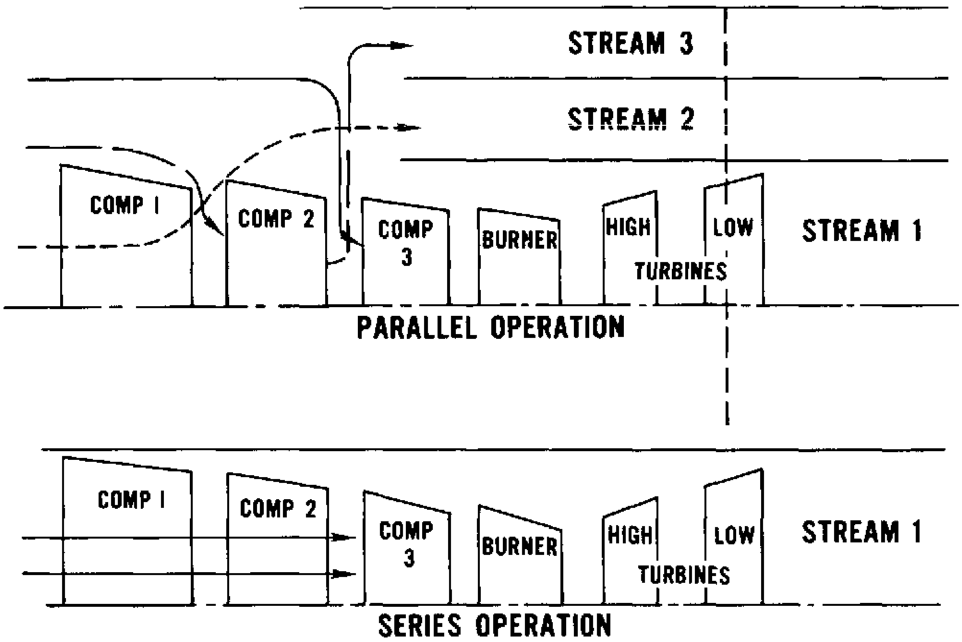


Figure 41 Schematic of Series/Parallel Compressor Variable Cycle Engine (VBE V)

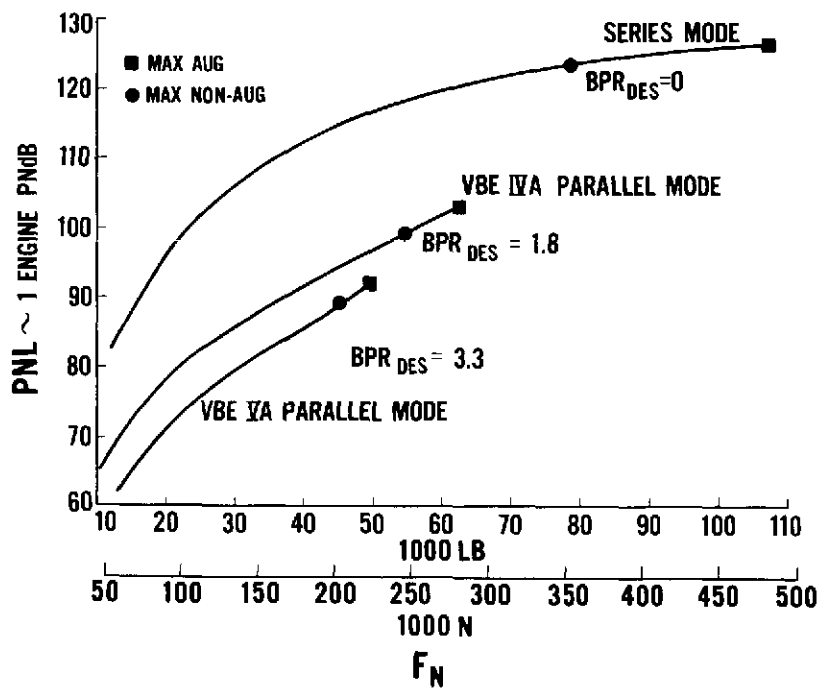


Figure 42 VBE V Sideline Noise Characteristics – Series Mode Airflow Size is 900 lb/sec (408 kg/sec) for Both Engines

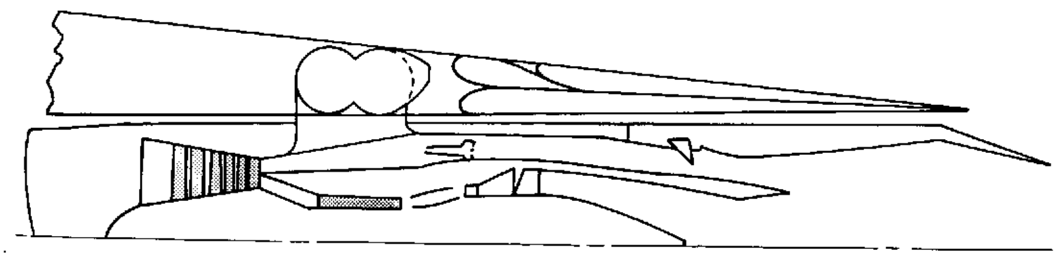


Figure 43 Typical Arrangement of Augmented Wing Concept

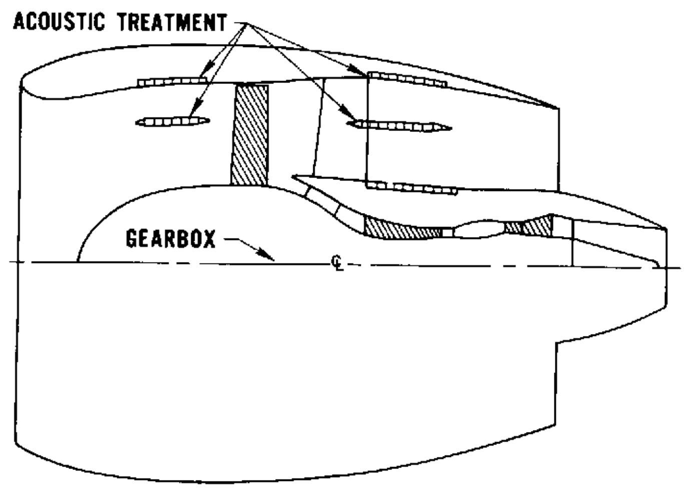


Figure 44 Auxiliary Engine Concept - Remote Turbofan

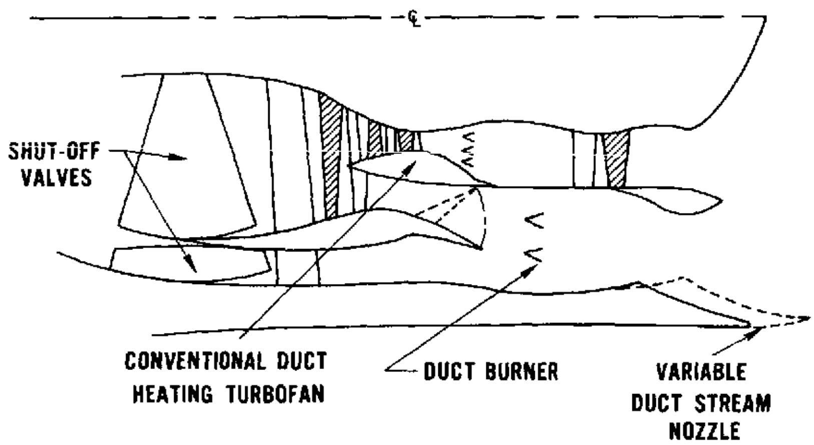


Figure 45 Turbofan-Ramjet Concept

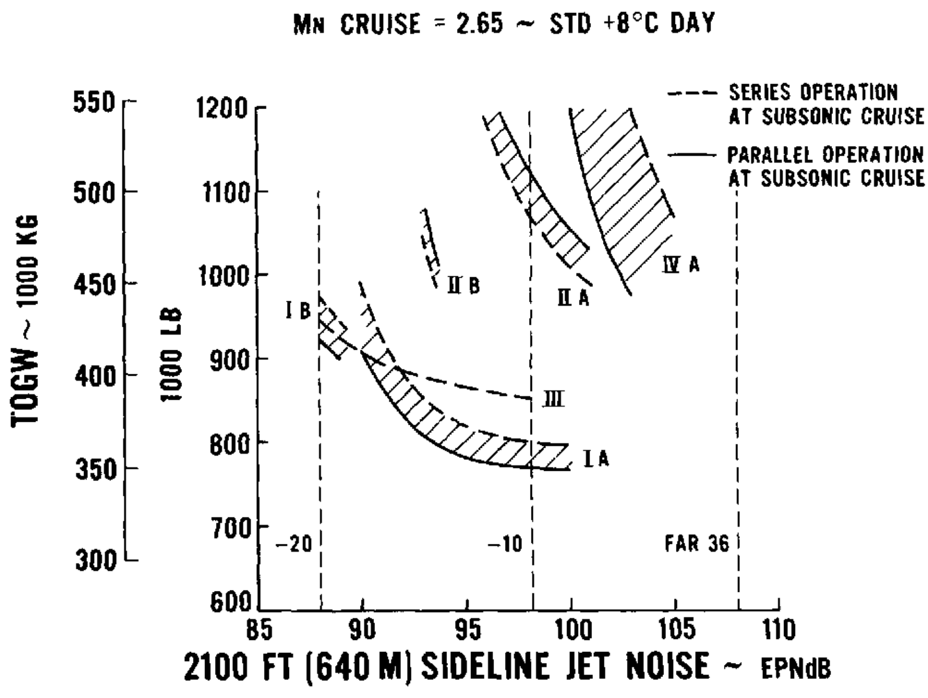


Figure 46 Series/Parallel Variable Cycle Engine TOGW Comparison

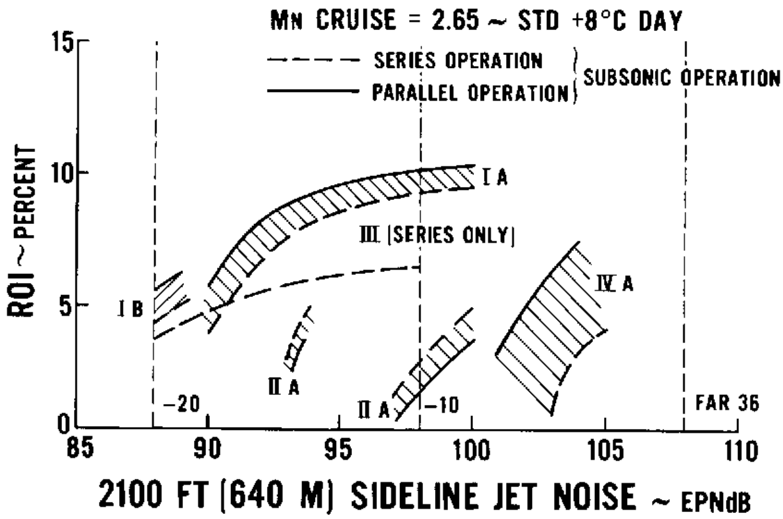


Figure 47 Series/Parallel Variable Cycle ROI Comparison

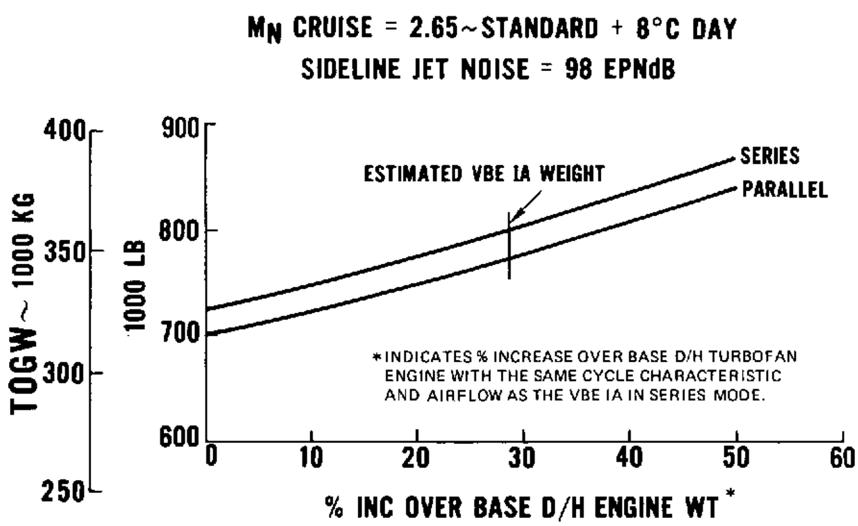


Figure 48 Effect of VBE I Engine Weight on TOGW

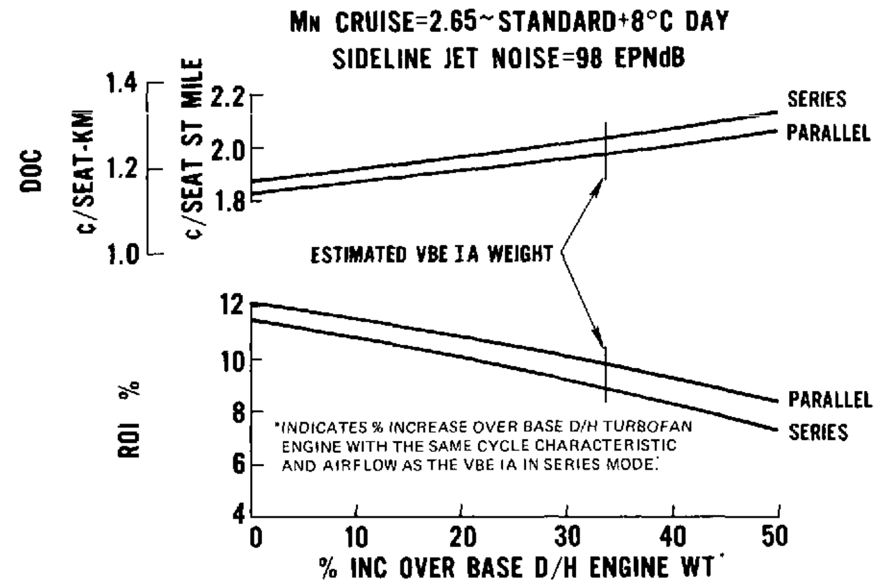


Figure 49 Effect of VBE I Engine Weight on Airplane Economics

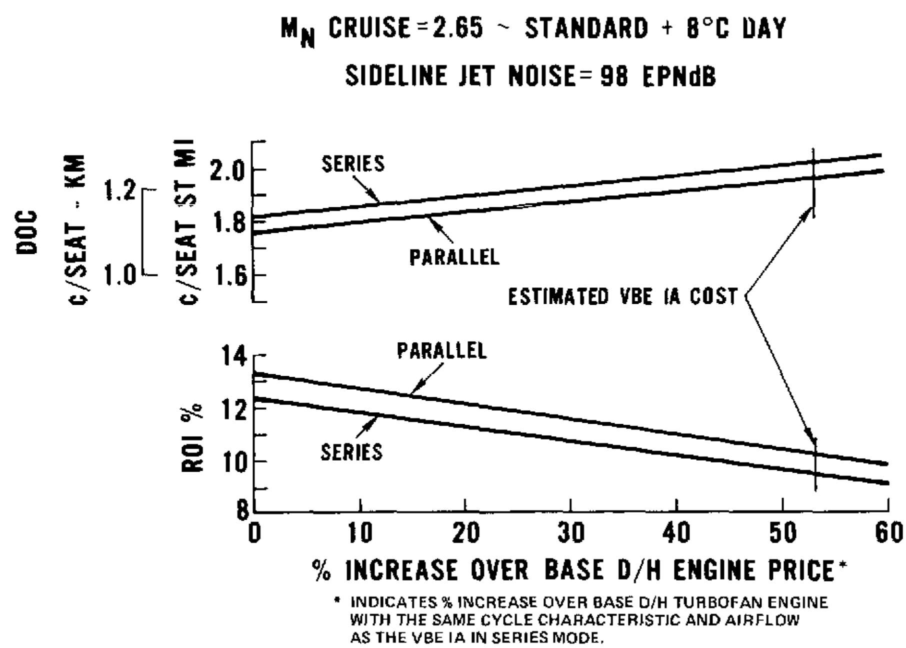


Figure 50 Effect of VBE I Engine Price on Airplane Economics

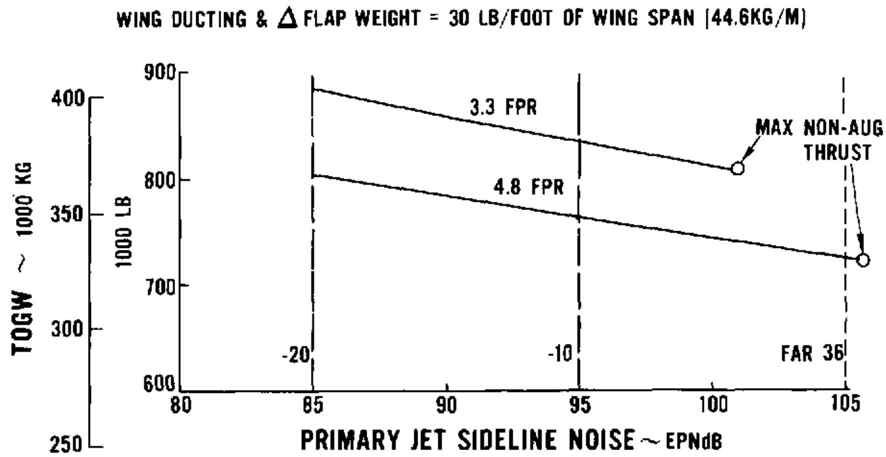


Figure 51 TOGW for Augmented Wing Concept – Duct-Heating Turbofan Engines

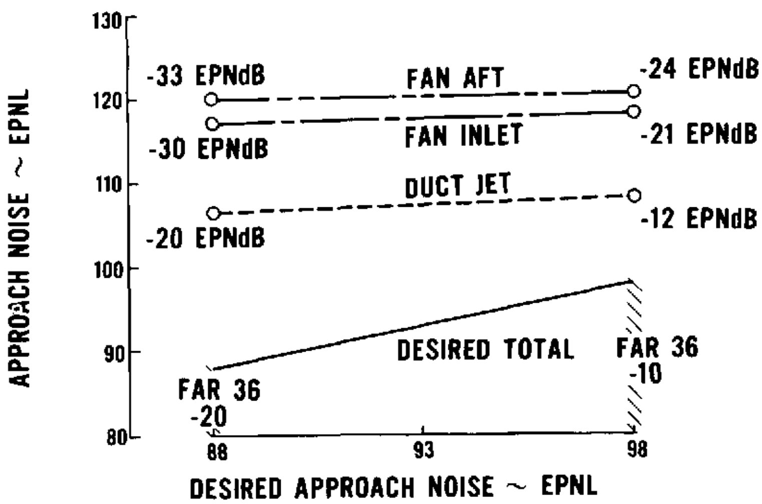


Figure 52 Noise Attenuation Requirement for Augmented Wing Concept – Duct-Heating Turbofan Engine, FPR_{Design} = 4.8

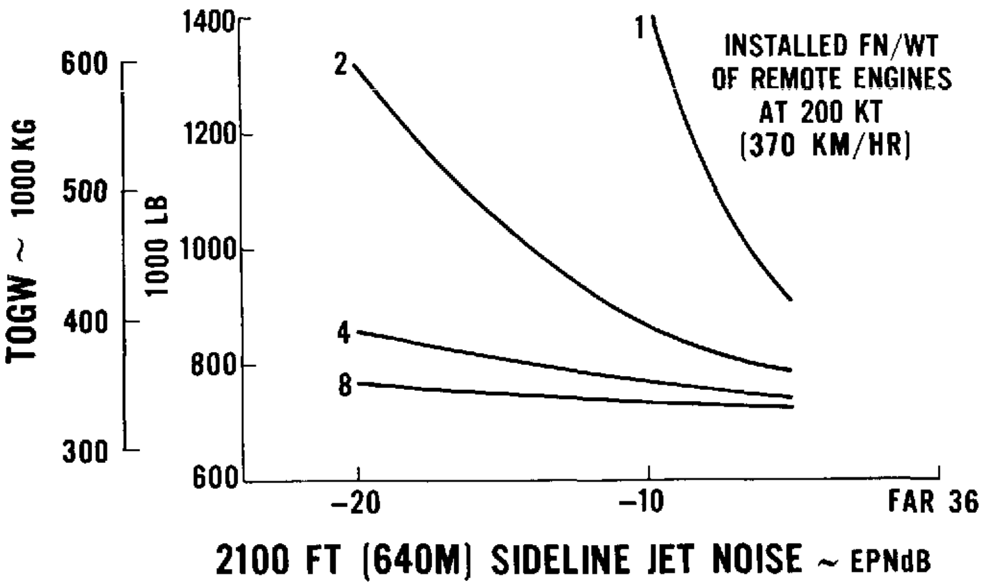


Figure 53 TOGW for Auxiliary Engine Concept

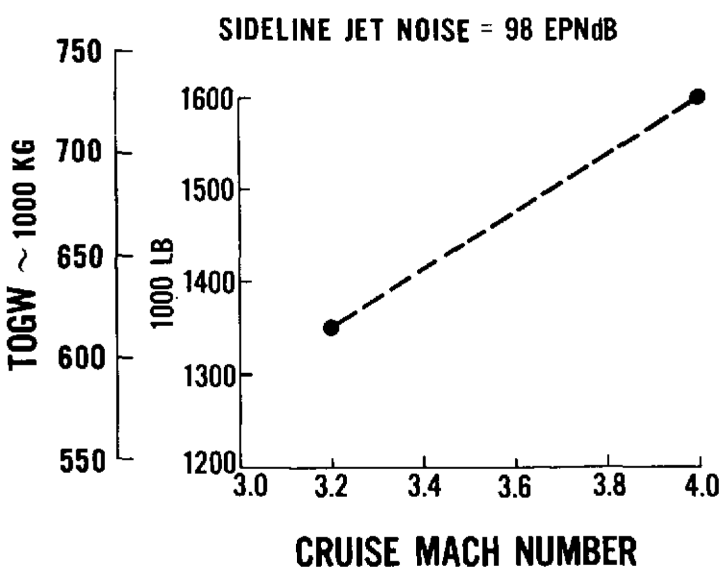


Figure 54 TOGW for Turbofan-Ramjet Concept

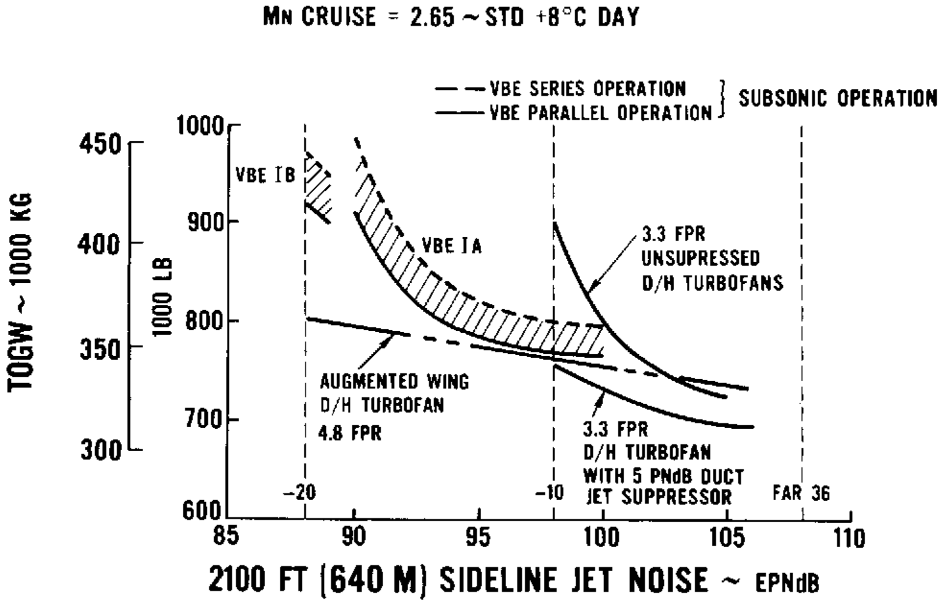


Figure 55 TOGW Comparison of Variable Cycle Engines and Conventional Engines – Task II

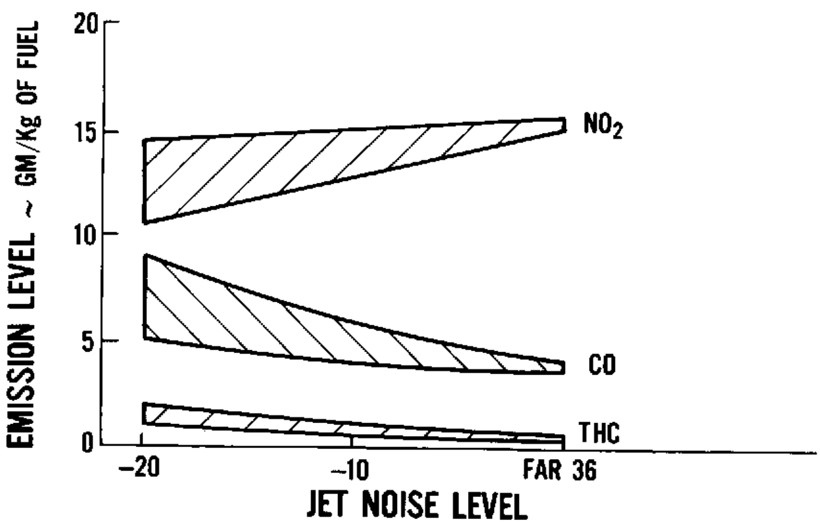


Figure 56 Emission Trends of Variable Cycle Series/Parallel Engines – Takeoff Operation

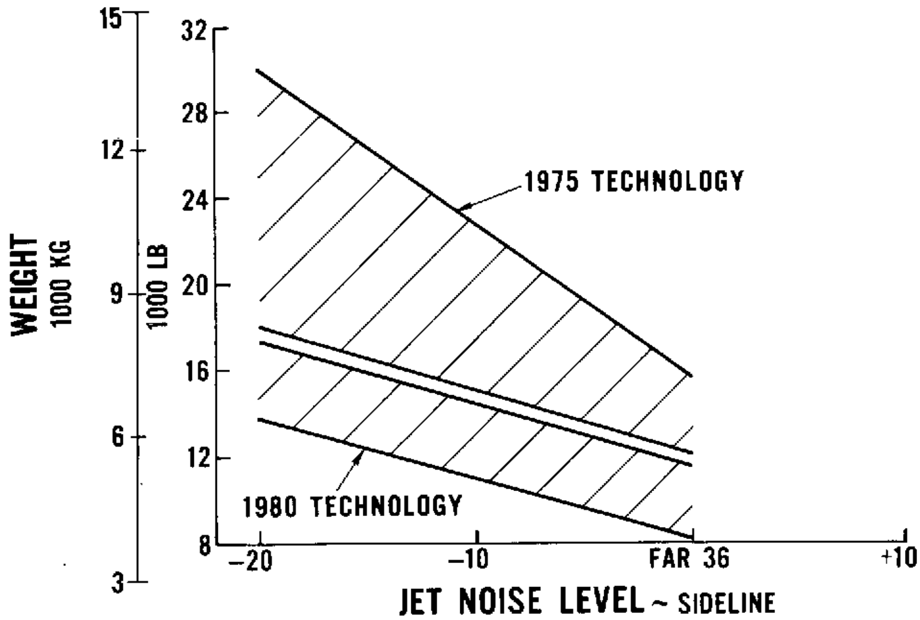


Figure 57 Effect of Advanced Engine Technology on Engine Weight

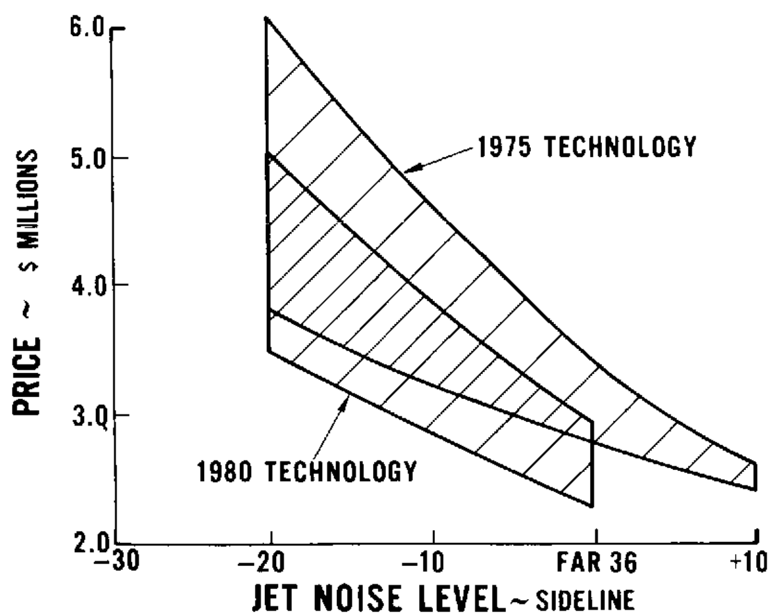


Figure 58 Effect of Advanced Engine Technology on Engine Price – 1972 Dollars

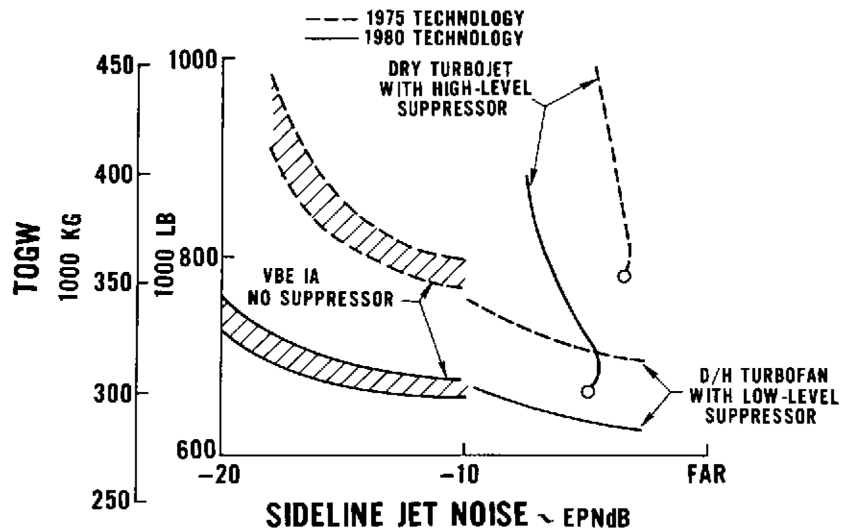


Figure 59 Effect of Advanced Engine Technology on TOGW Comparison of Engines

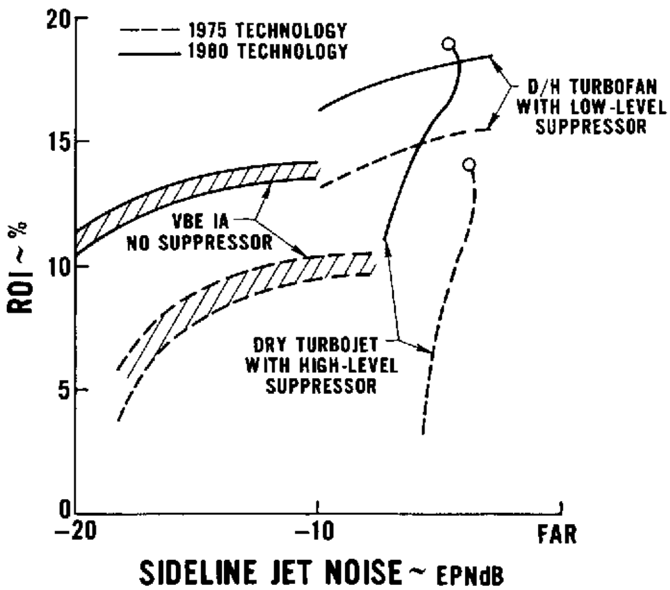


Figure 60 Effect of Advanced Engine Technology on ROI Comparison of Engines

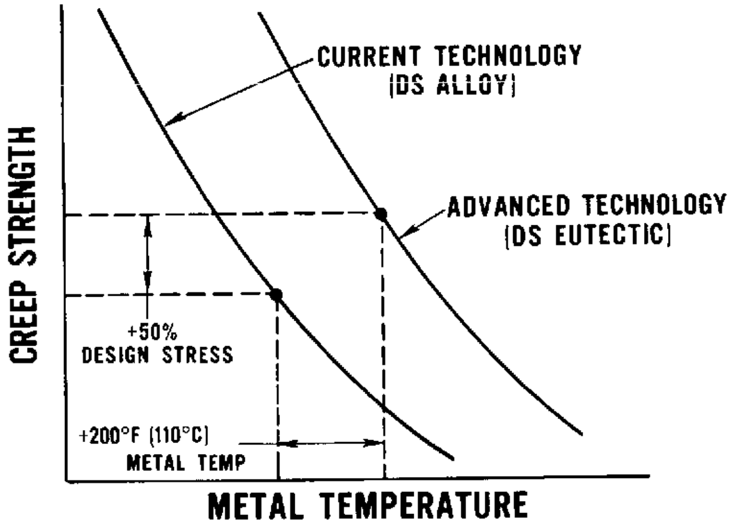


Figure 61 Technology Projection of Turbine Blade Material Creep Strength

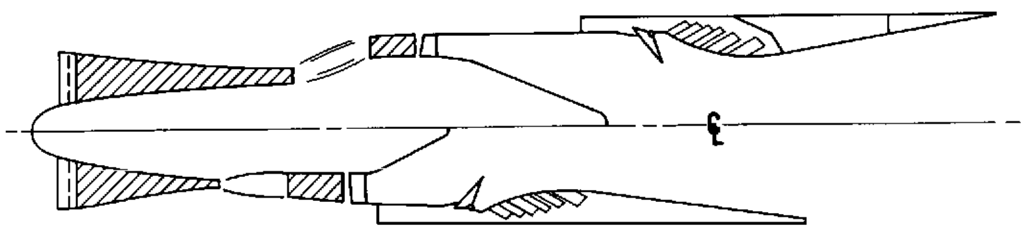


Figure 62 Effect of 1980 Engine Technology on Turbojet Engine Design

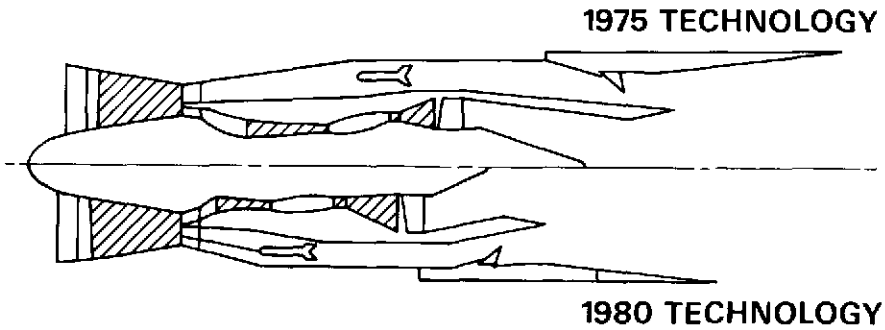


Figure 63 Effect of 1980 Engine Technology on Duct-Heating Turbofan Engine Design

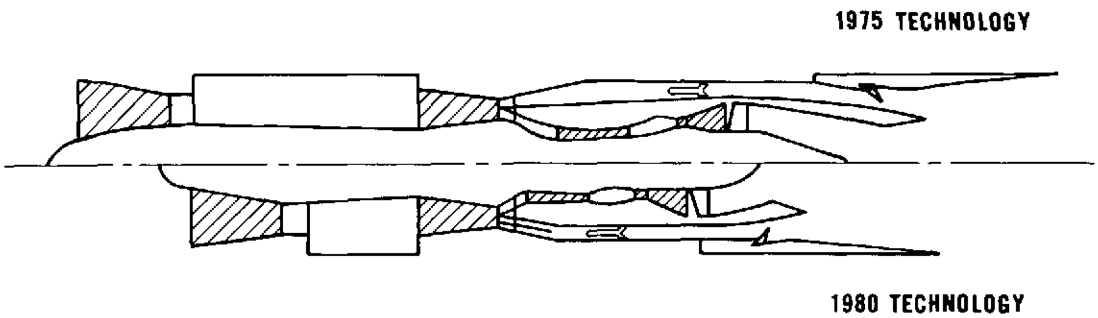


Figure 64 Effect of 1980 Engine Technology on Series/Parallel Variable Bypass Cycle Engine Design

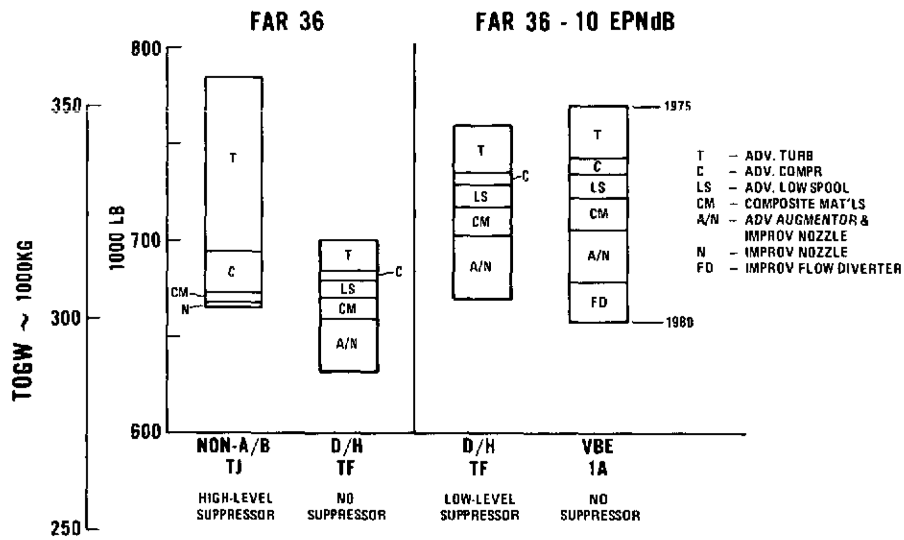


Figure 65 Effect of Engine Component Technology on TOGW

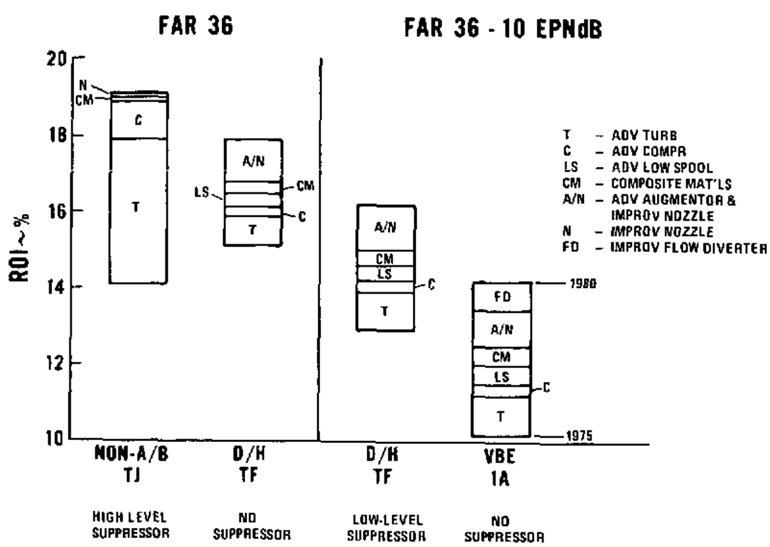


Figure 66 Effect of Engine Component Technology on ROI

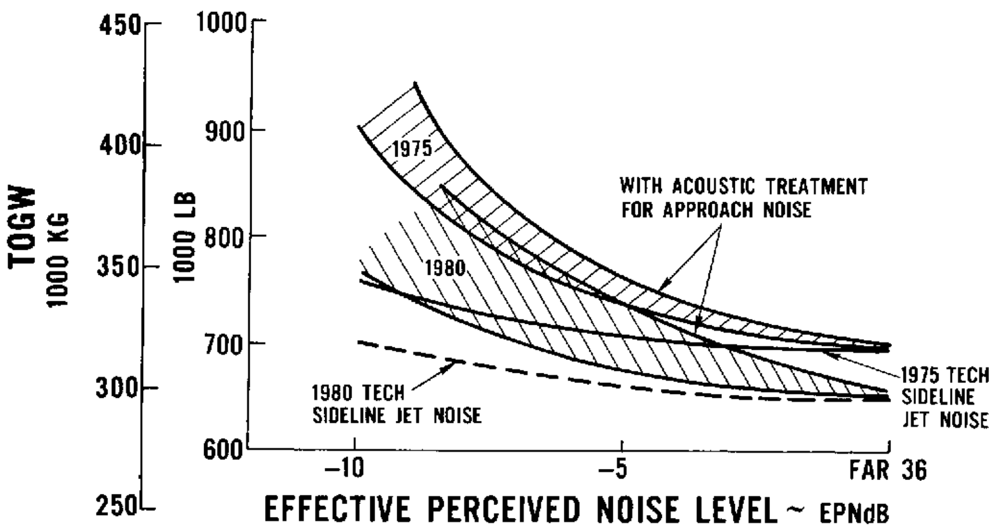


Figure 67 Effect of Advanced Technology on AST Approach Noise Treatment Penalty – Duct-Heating Turbofan Engine

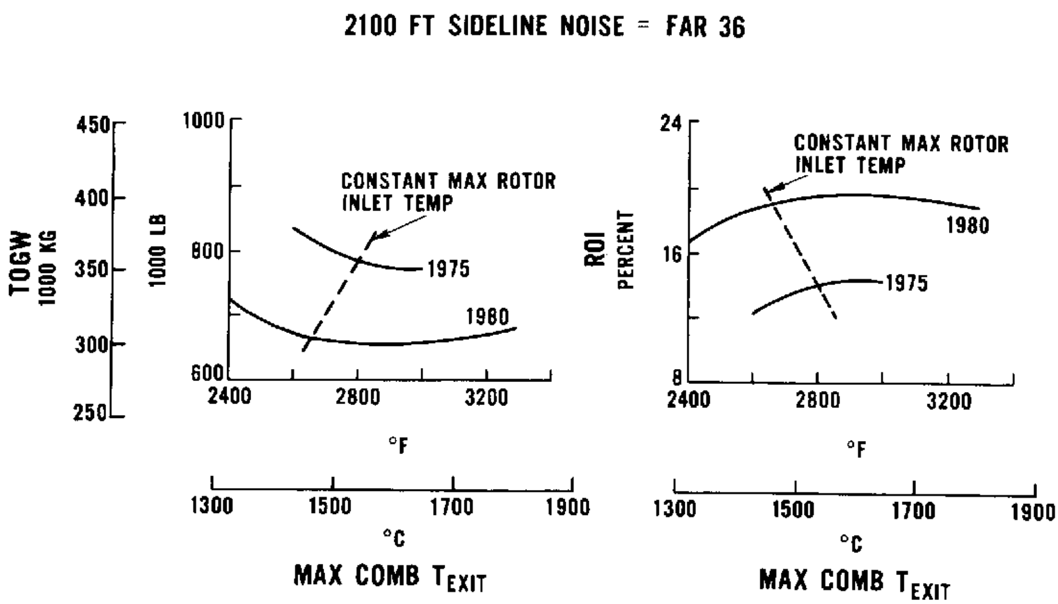


Figure 68 Non-Afterburning Turbojet Combustor Exit Temperature Optimization

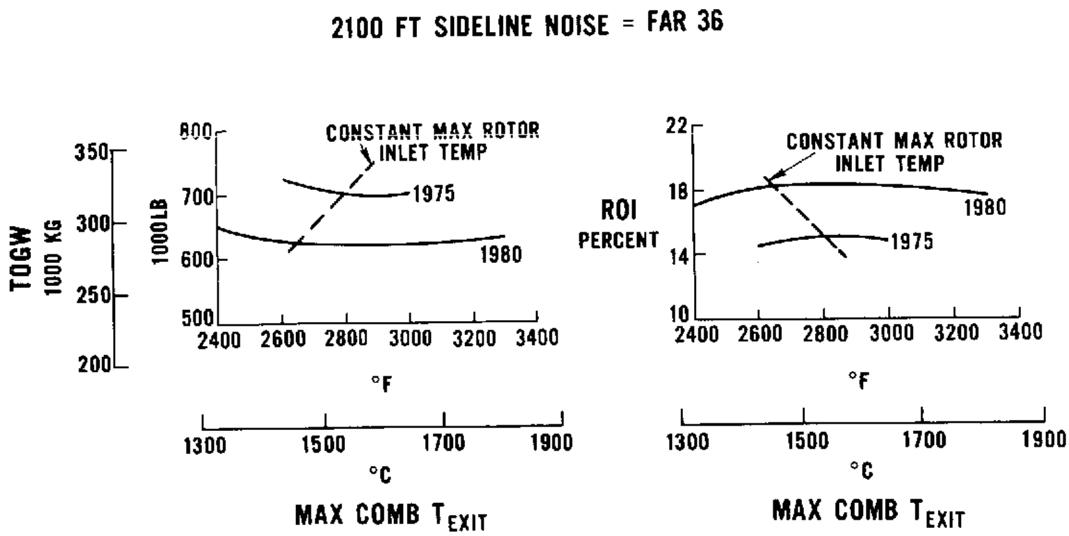


Figure 69 Duct-Heating Turbofan Combustor Exit Temperature Optimization

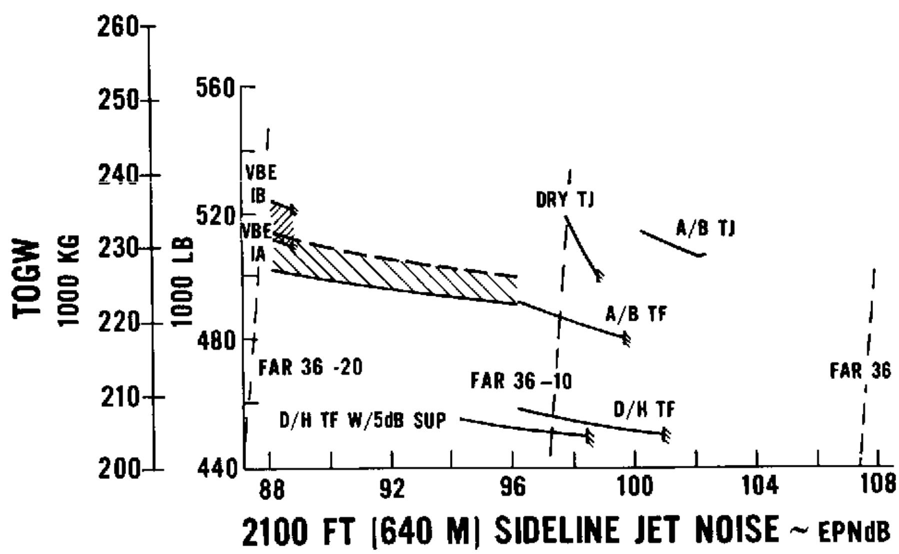


Figure 70 TOGW Comparison of Hydrogen Fueled Engine

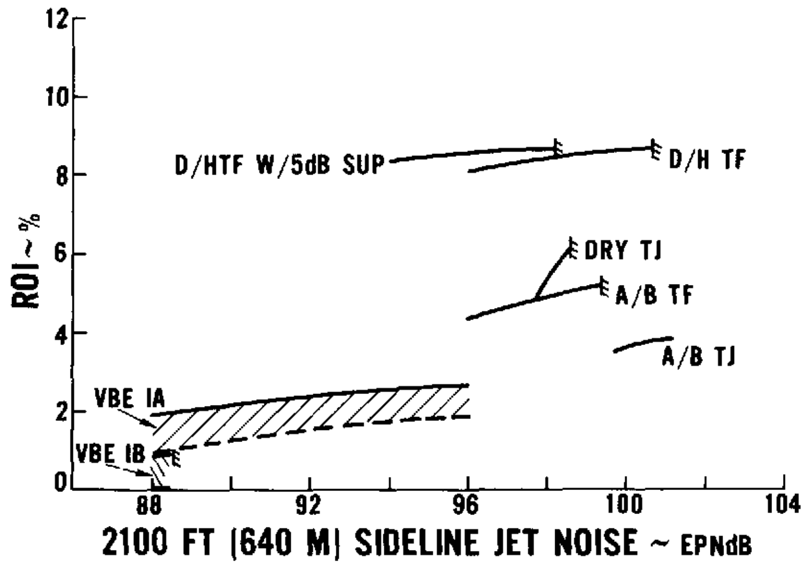


Figure 71 ROI Comparison of Hydrogen Fueled Engine

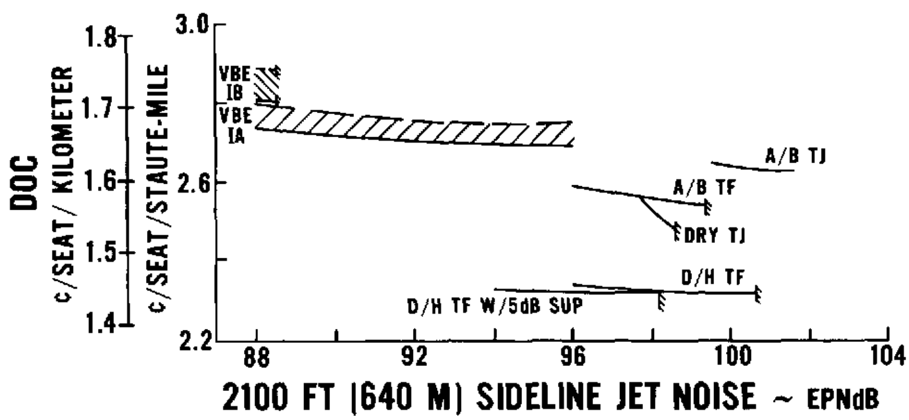


Figure 72 DOC Comparison of Hydrogen Fueled Engine

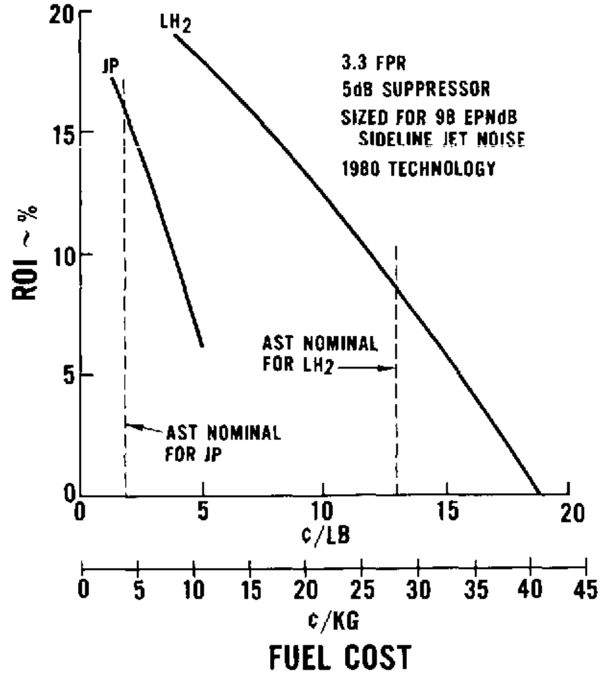


Figure 73 Effect of Fuel Cost on Airline ROI for Hydrogen Fueled Engine

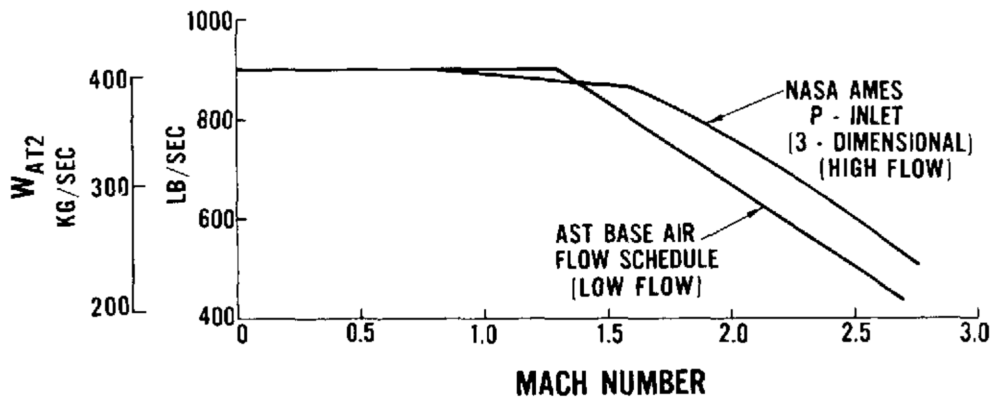


Figure 74 Inlet Airflow Schedule Comparison, Low Flow Vs. High Flow (Design Mach Number 2.7)

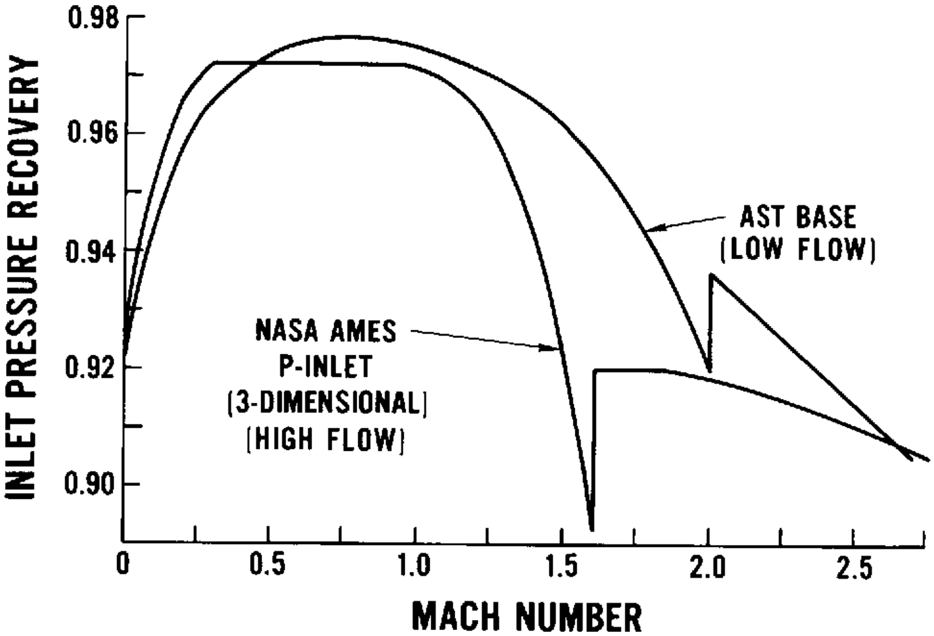


Figure 75 Inlet Pressure Recovery Comparison, Low Flow Vs. High Flow (Design Mach Number 2.7)

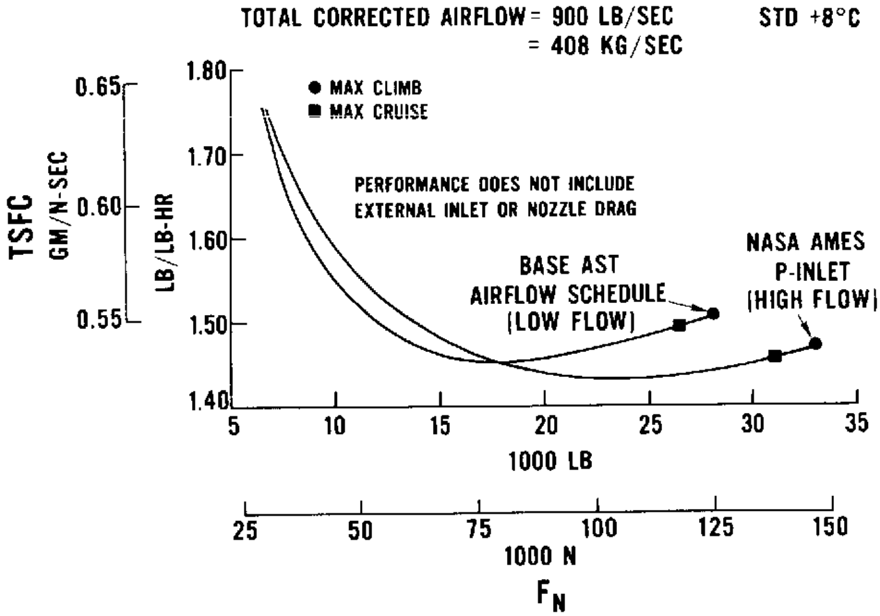


Figure 76 Supersonic Cruise Performance of Dry Turbojet Cycles, Altitude 59,000 ft (18,000 m), Mach Number 2.65

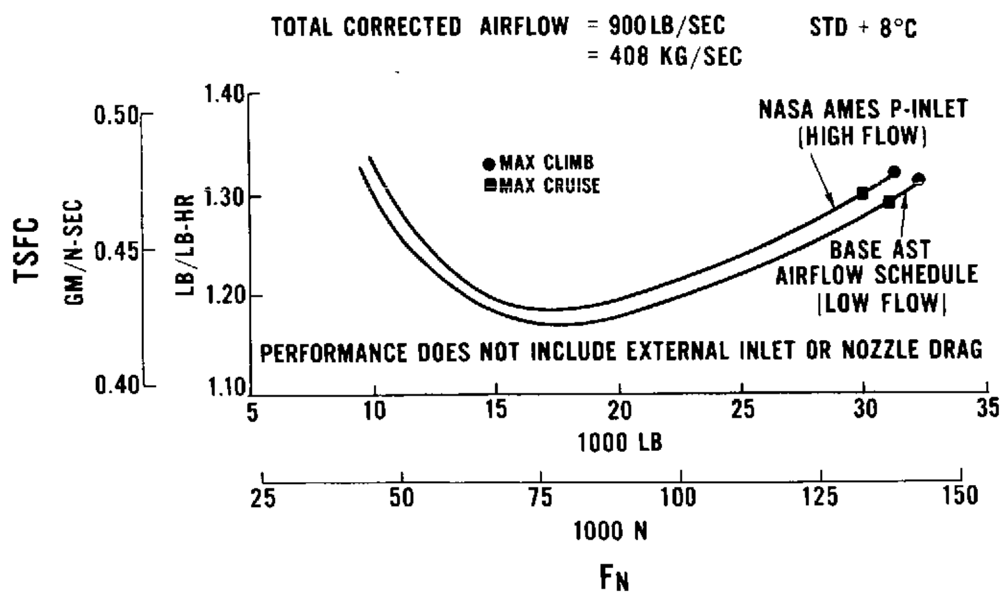
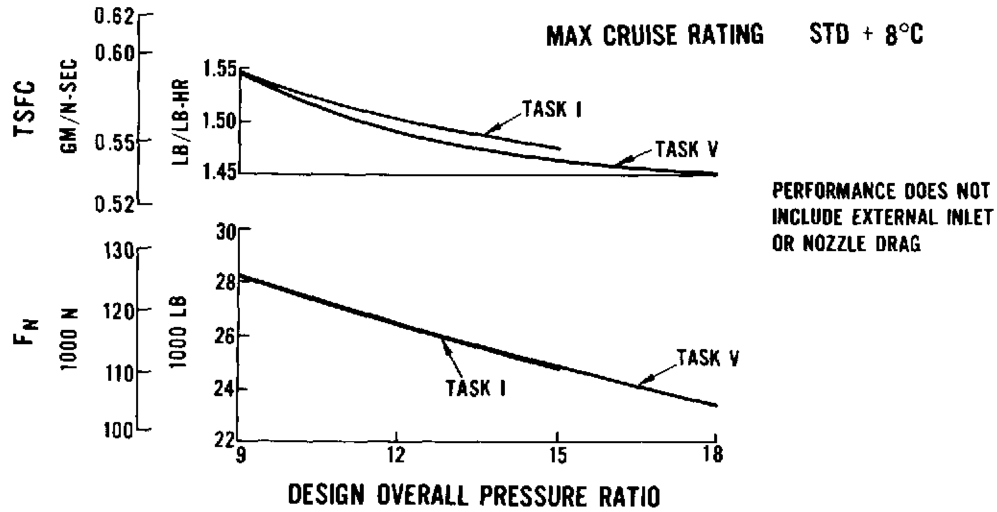
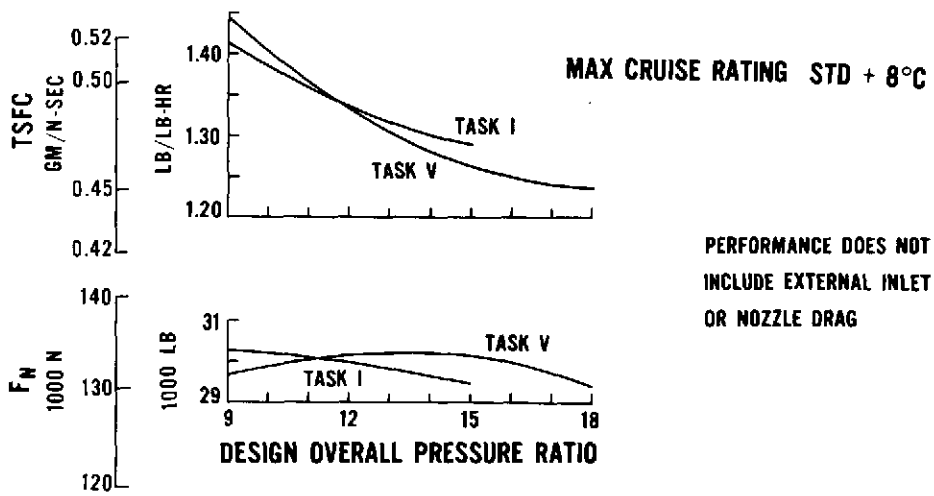


Figure 77 Subsonic Cruise Performance of Dry Turbojet Cycles, Altitude 35,000 ft (10,700 m), Mach Number 0.95

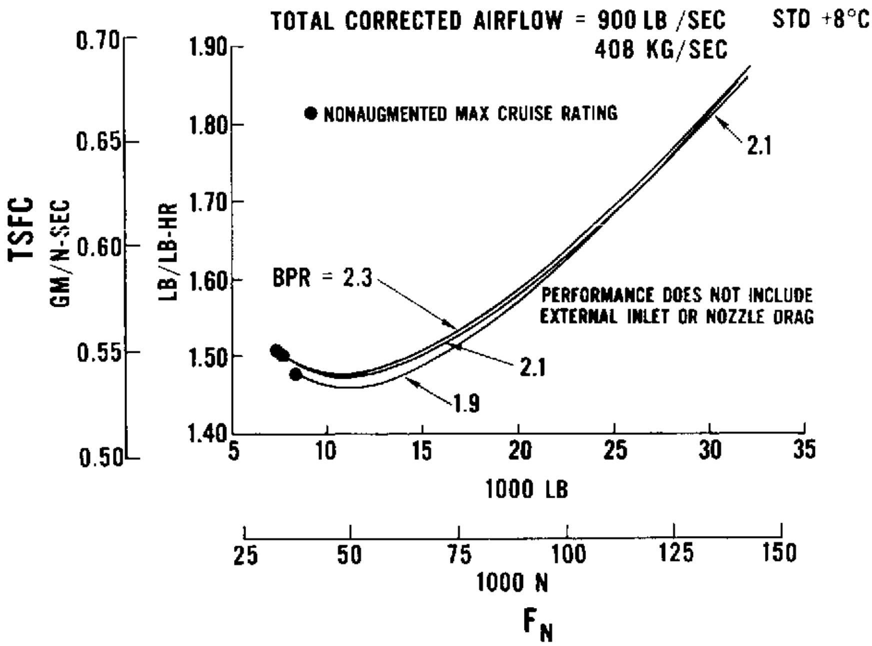


Supersonic Cruise Performance, Mach Number 2.65, Altitude 59,000 ft (18,000 m)

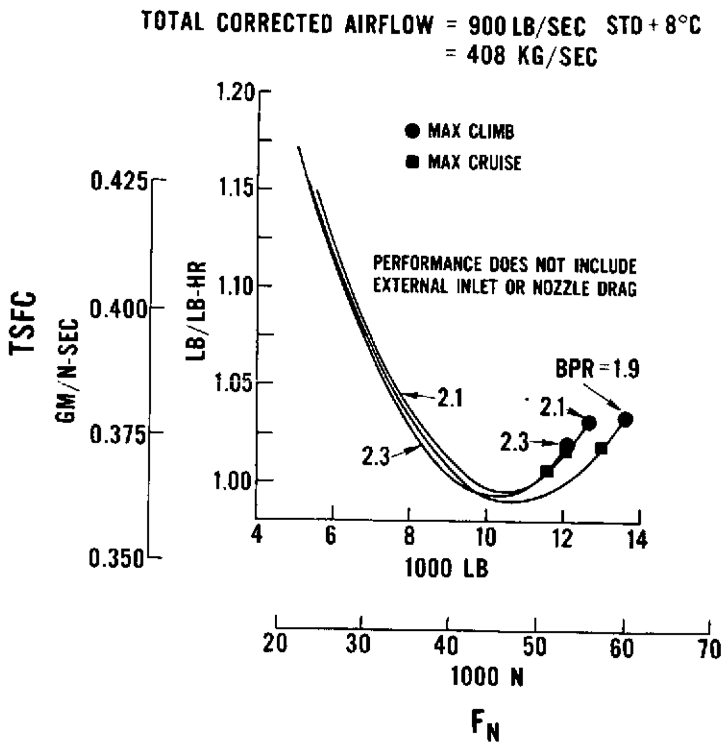


Subsonic Cruise Performance, Mach Number 0.95, Altitude 35,000 ft (10,700 m)

Figure 78 Overall Pressure Ratio Effect on Performance of Dry Turbojet

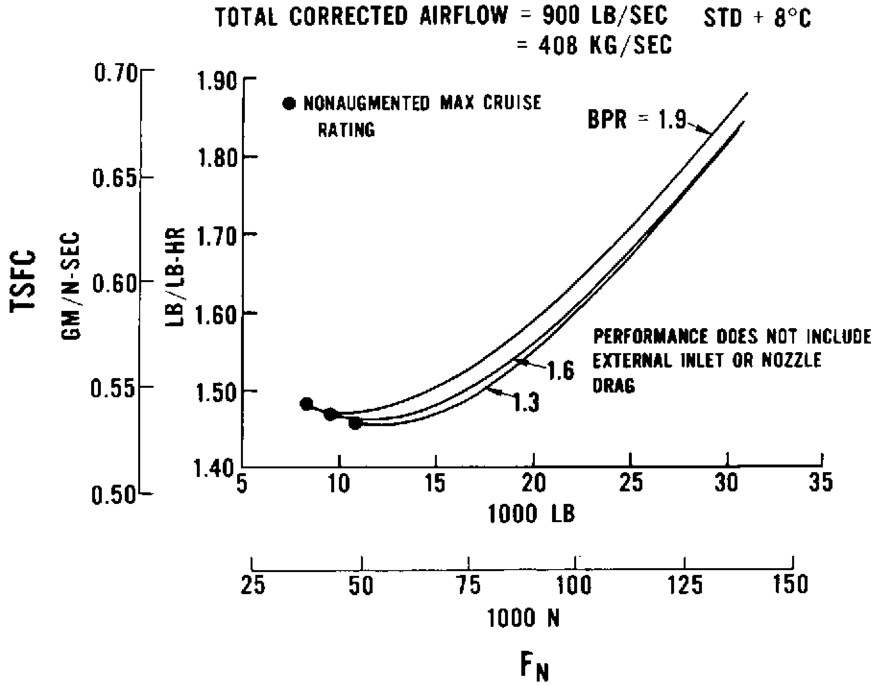


Supersonic Cruise Performance, Mach Number 2.65, Altitude 59,000 ft (18,000 m)

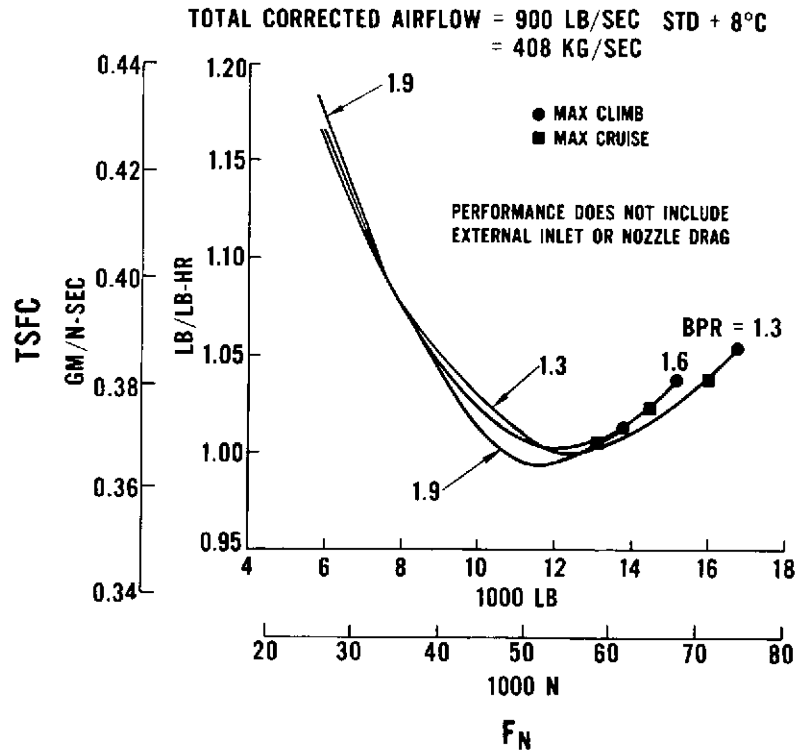


Subsonic Cruise Performance, Mach Number 0.95, Altitude 35,000 ft (10,700 m)

Figure 79 Bypass Ratio Effect on Performance of Duct-Heating Turbofan With a 3.3 FPR

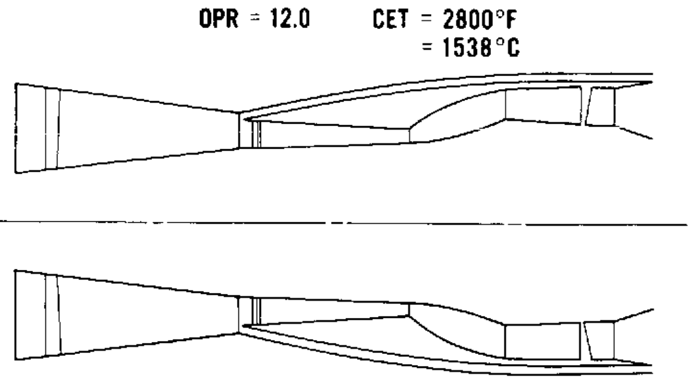


Supersonic Cruise Performance, Mach Number 2.65, Altitude 59,000 ft (18,000 m)



Subsonic Cruise Performance, Mach Number 0.95, Altitude 35,000 ft (10,700 m)

Figure 80 Bypass Ratio Effect on Performance of Duct-Heating Turbofan With a 4.1 FPR



BPR	R_{FAN}	R_{COMP}
0.3	3.8	3.2
0.65	3.3	3.6

Figure 81 Schematic of Low Bypass Ratio Turbofan

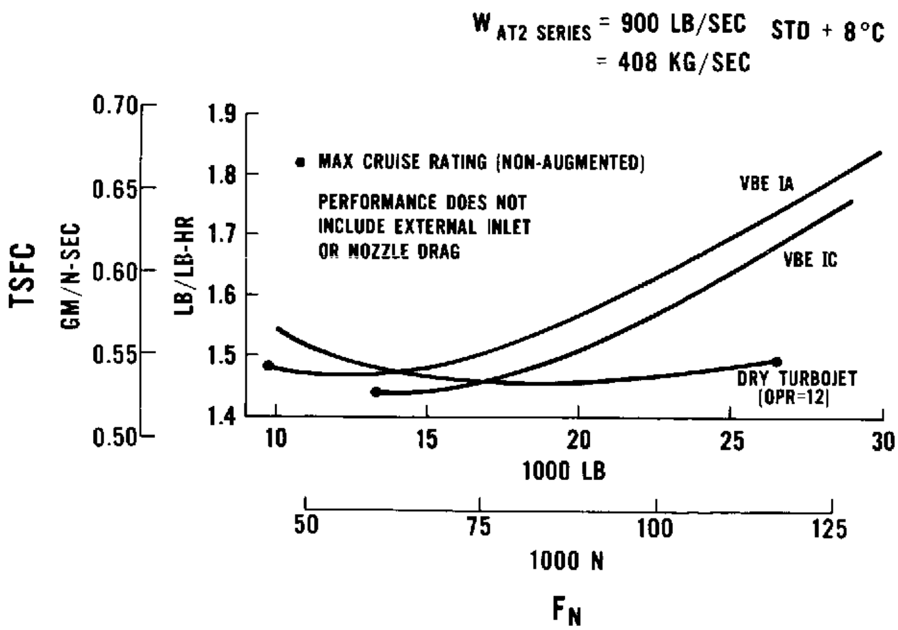


Figure 82 VBE I Supersonic Cruise Performance, Mach Number 2.65, Altitude 59,000 ft (18,000 m)

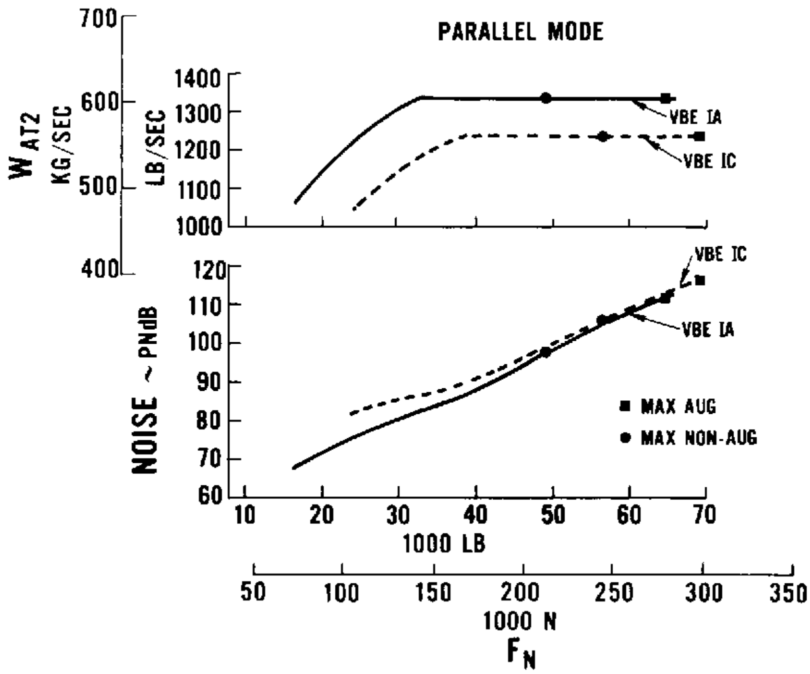


Figure 83 VBE I Sideline Jet Noise Characteristics

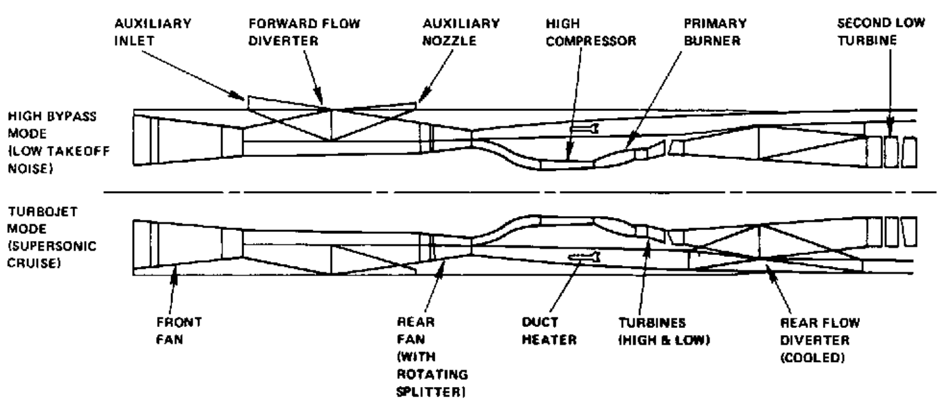


Figure 84 Schematic of Dual Valve Variable Cycle Engine

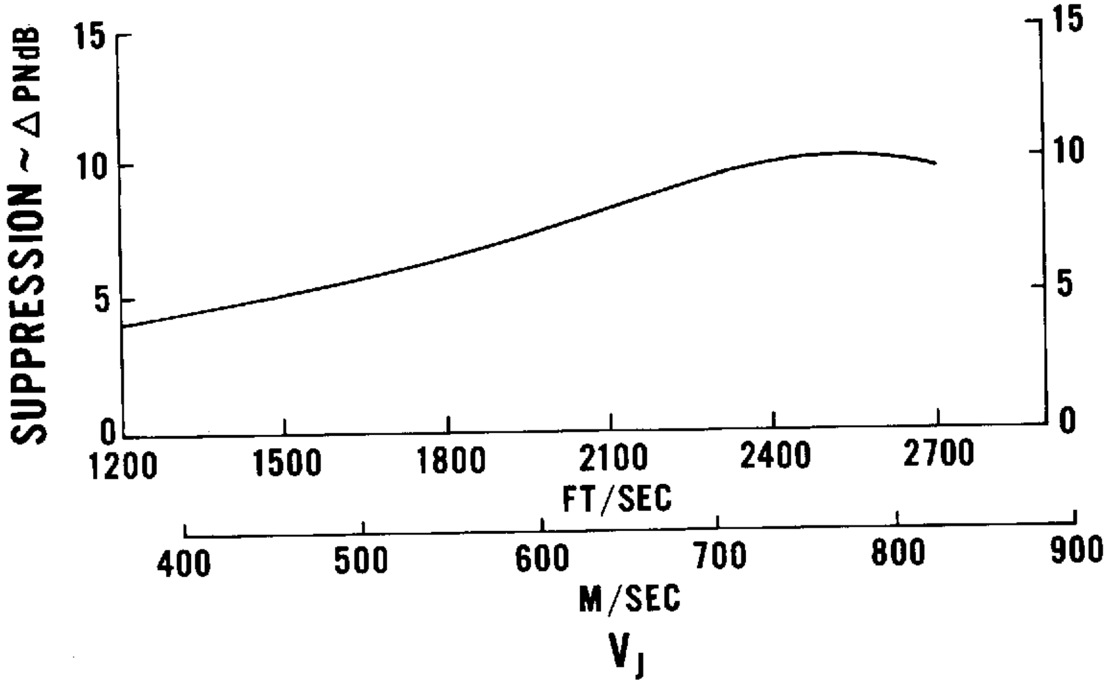


Figure 85 Characteristic of 10 PNdB (Maximum) Suppressor

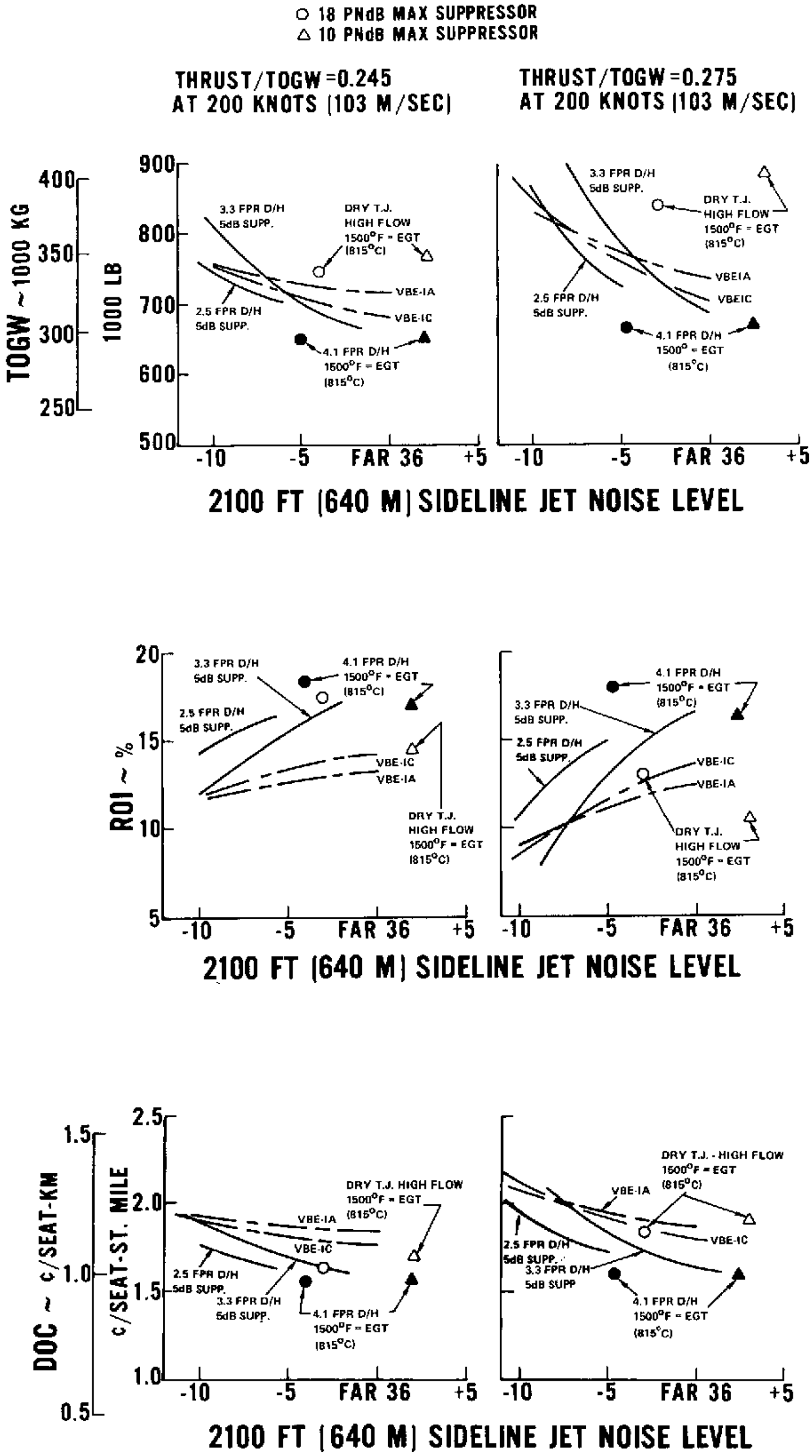


Figure 86 TOGW, ROI, and DOC Comparisons for Mach 2.65 (Hot Day) Nominal Mission

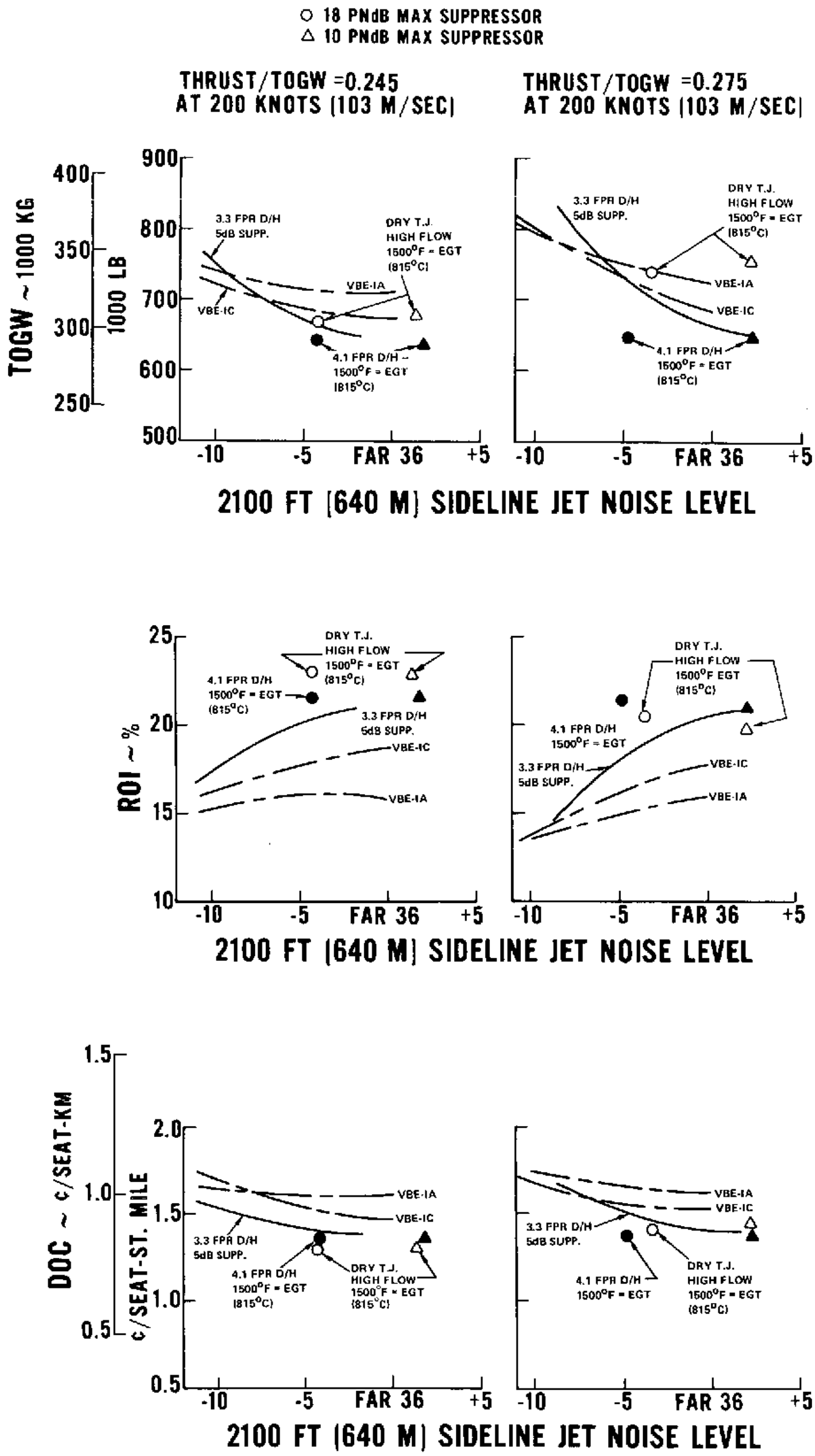


Figure 87 TOGW, ROI, and DOC Comparisons for Mach 2.65 (Hot Day) All Supersonic Mission

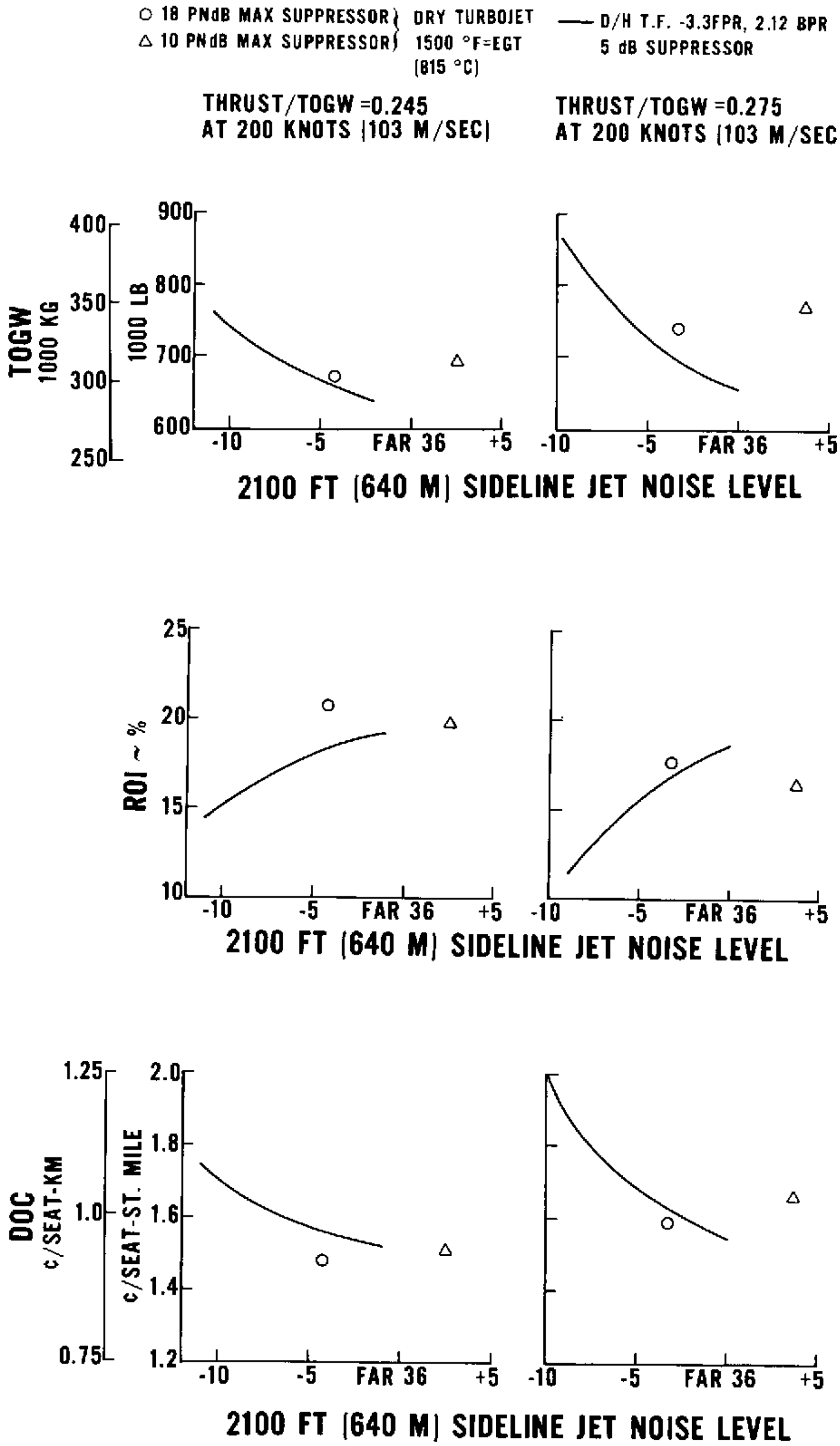


Figure 88   TOGW, ROI, and DOC Comparisons for Mach 2.16 (Hot Day) Nominal Mission

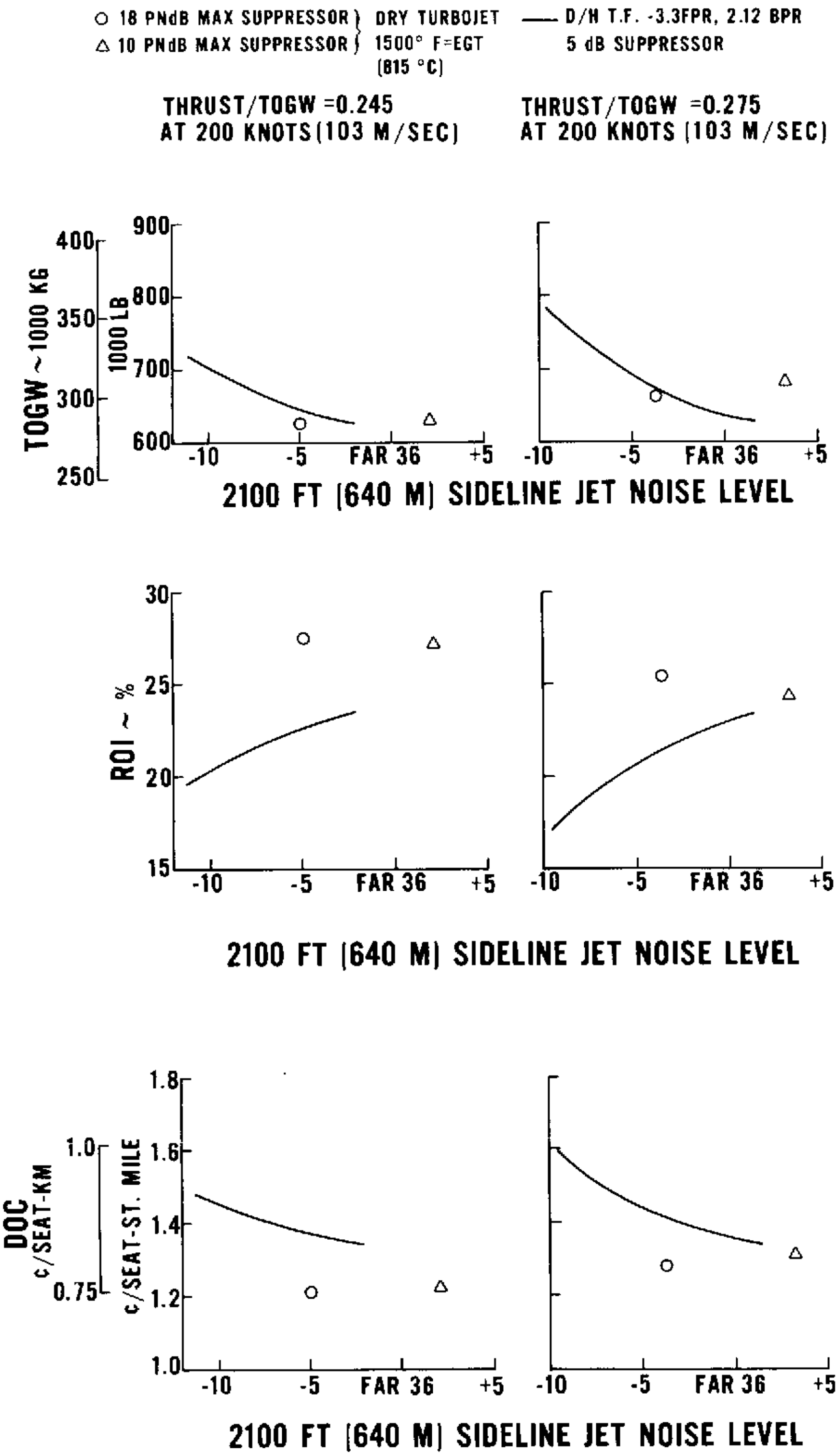


Figure 89 TOGW, ROI, and DOC Comparisons for Mach 2.16 (Hot Day) All Supersonic Mission

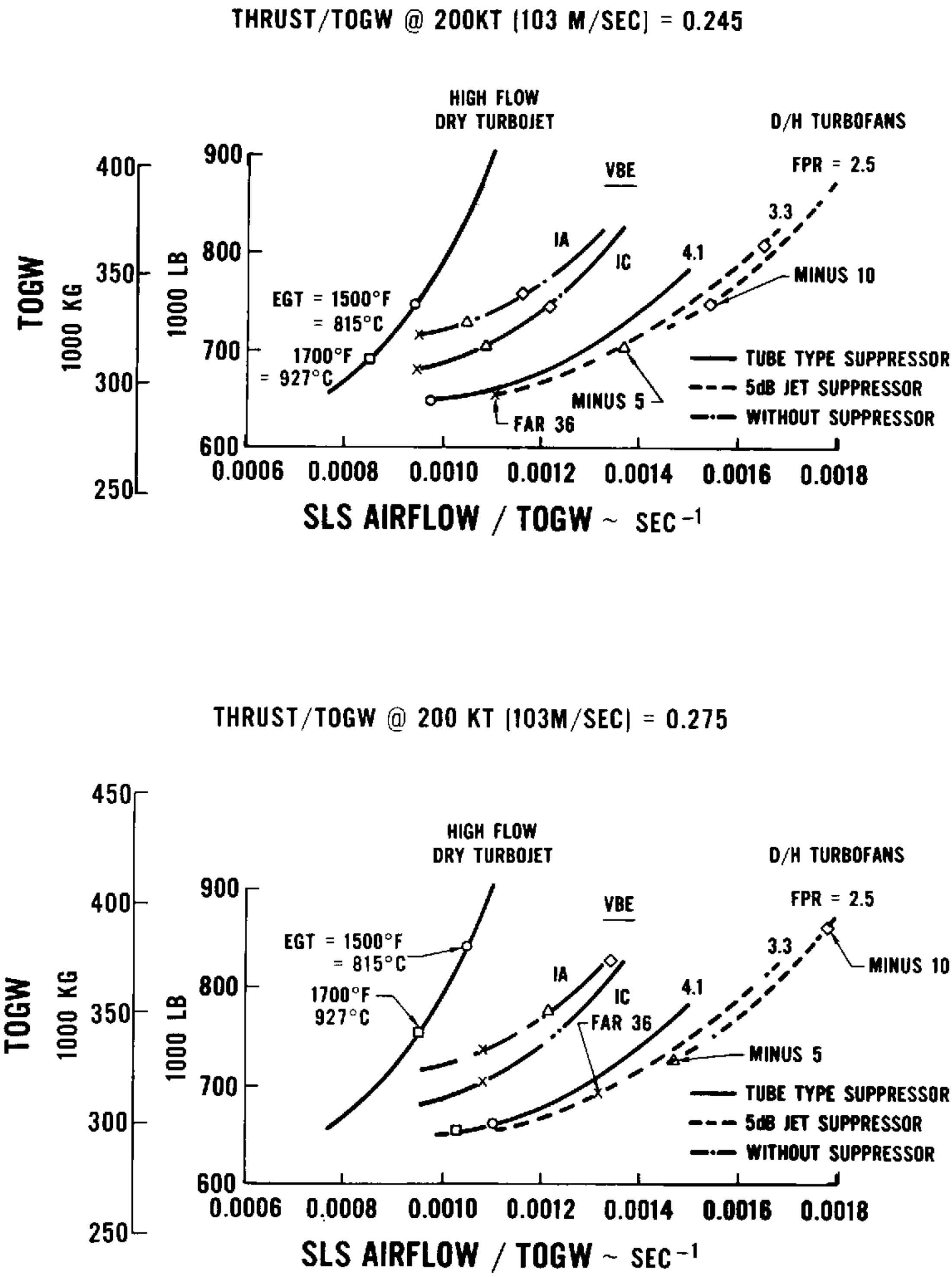


Figure 90 Airflow Size Comparison for Mach 2.65 Nominal Mission

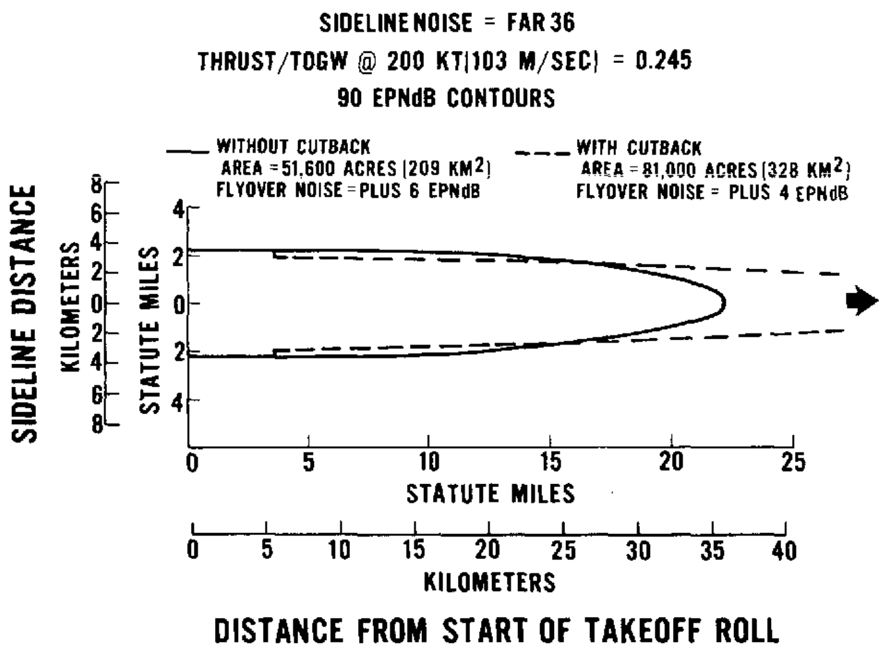


Figure 91 Non-Afterburning Turbojet Takeoff Noise Contour Plot

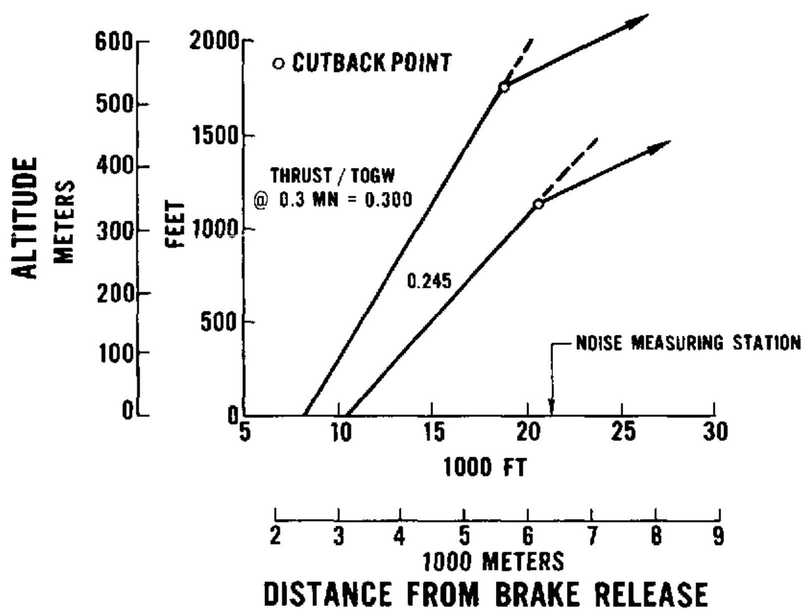


Figure 92 Climb Path Used for Footprint Analysis

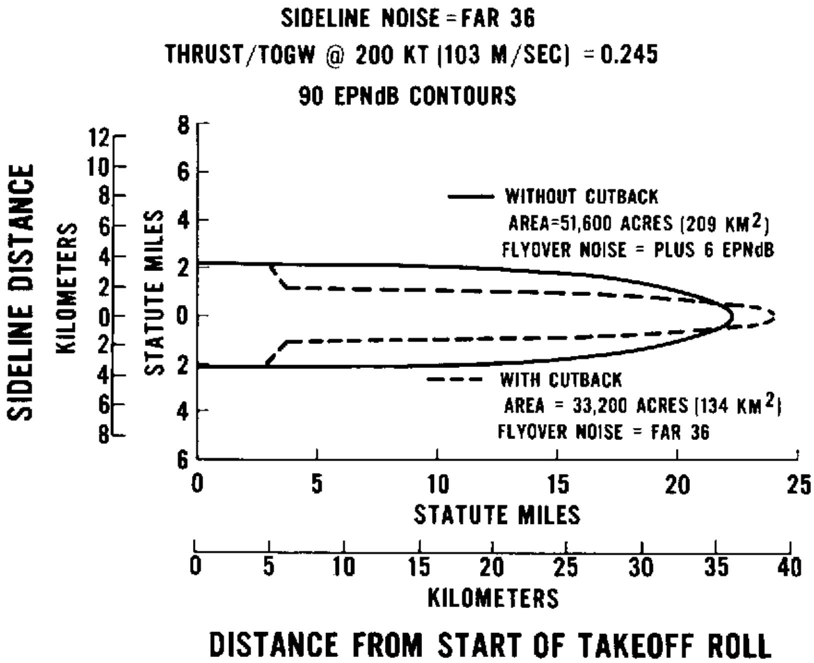


Figure 93 Duct-Heating Turbofan Takeoff Noise Contour Plot

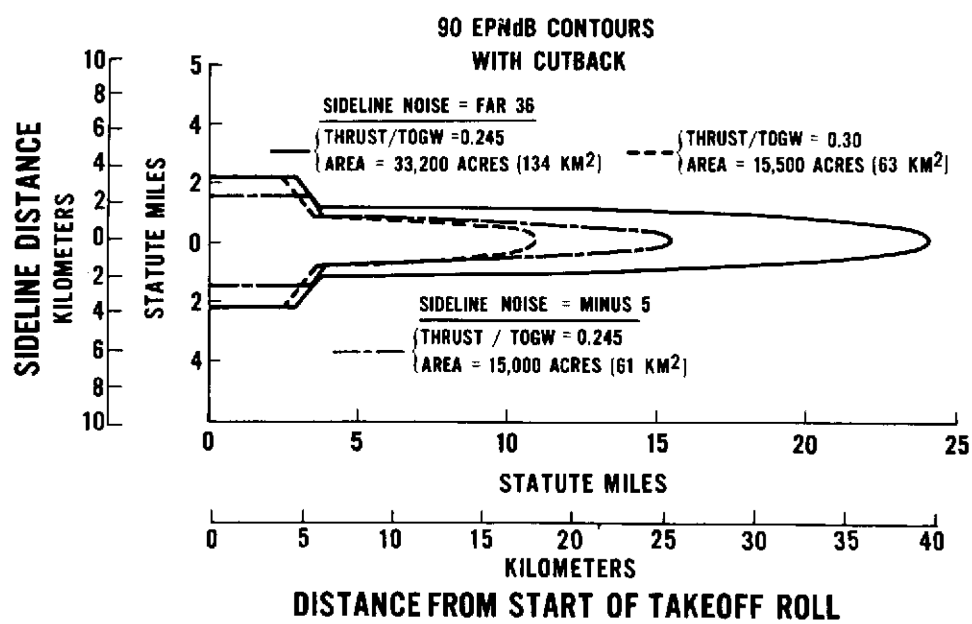


Figure 94 Duct-Heating Turbofan Takeoff Footprint Perturbations

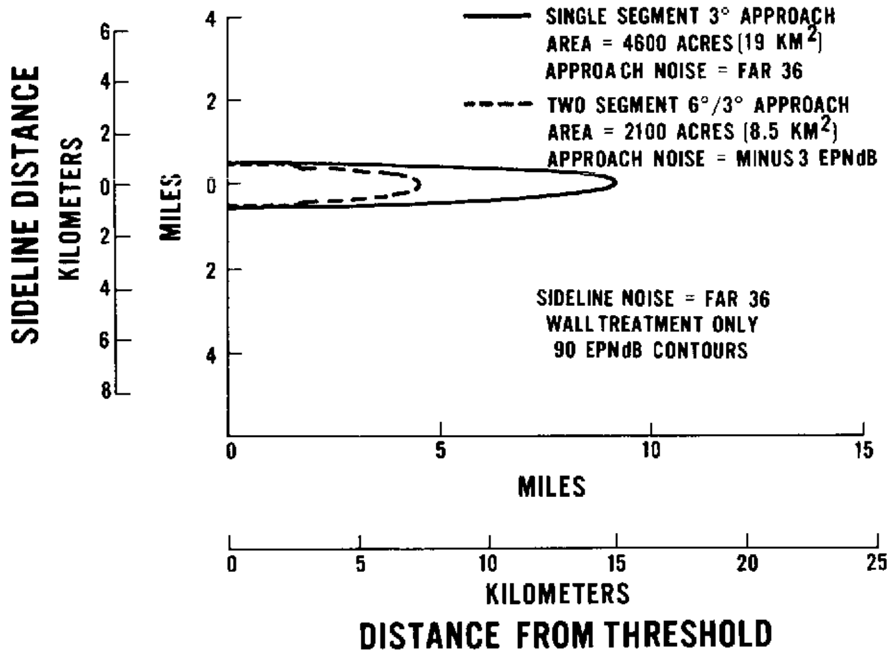


Figure 95 Duct-Heating Turbofan Approach Noise Contour Plots

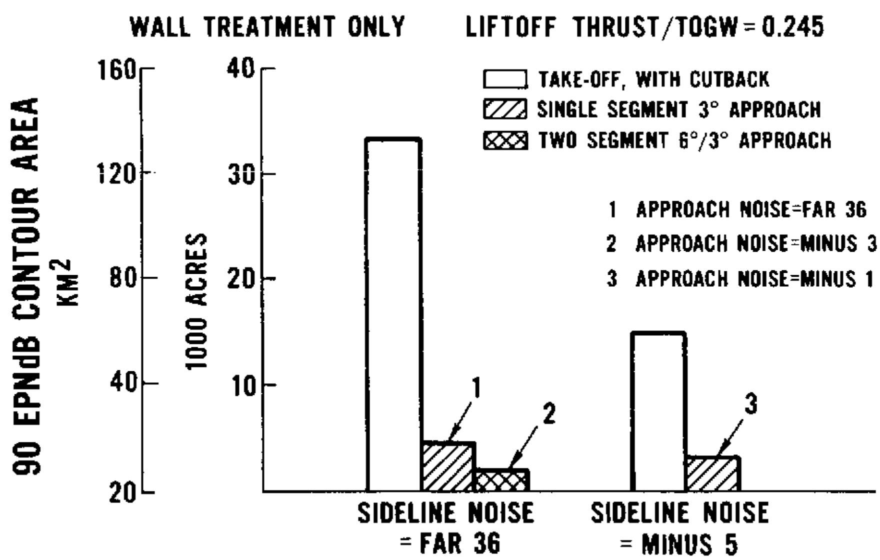


Figure 96 Duct-Heating Turbofan Contour Area Summary

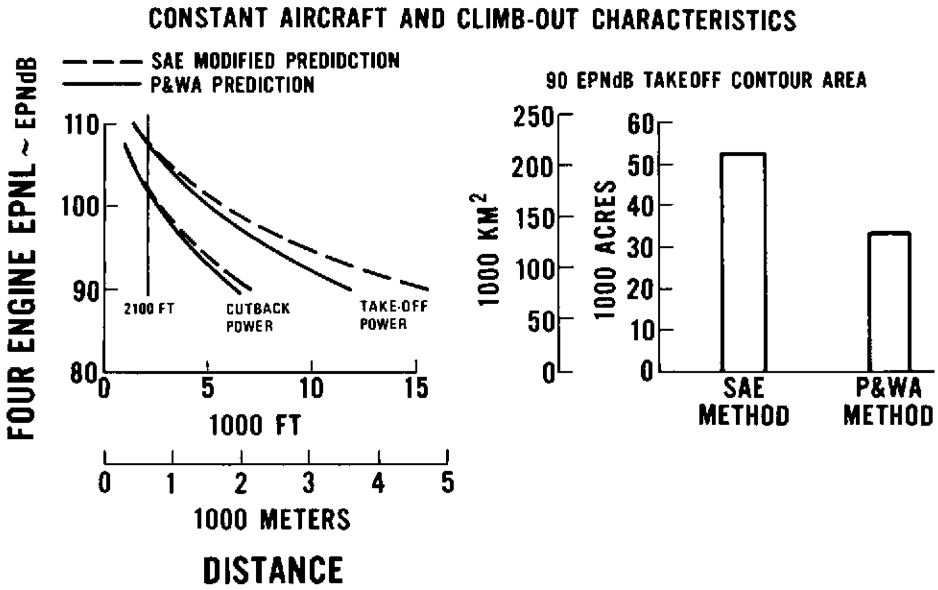


Figure 97 Footprint Area Sensitivity to Noise Prediction Calculation

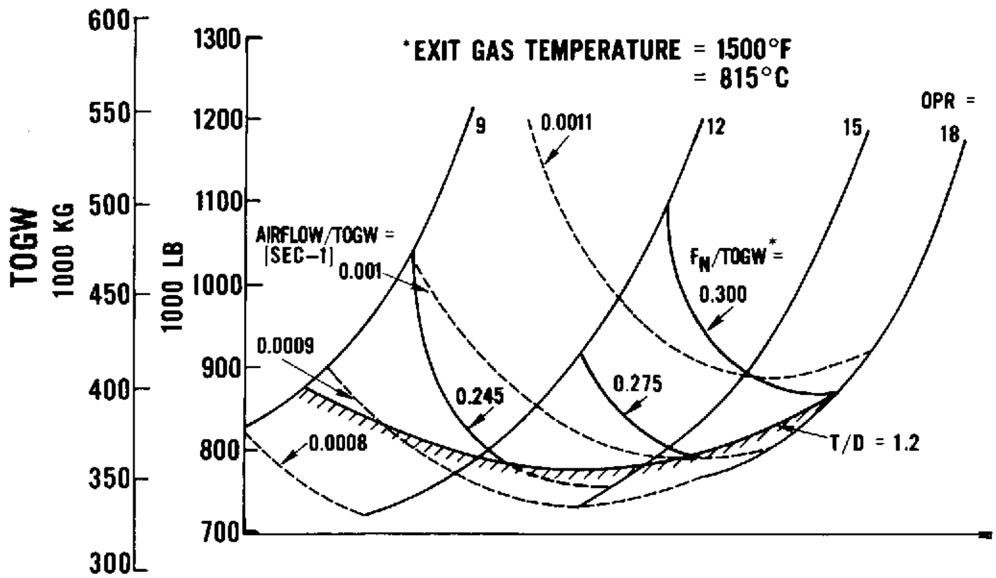


Figure 98 Non-Afterburning Turbojet OPR Optimization for Mach 2.65 Nominal Mission With Jet Noise Suppressor

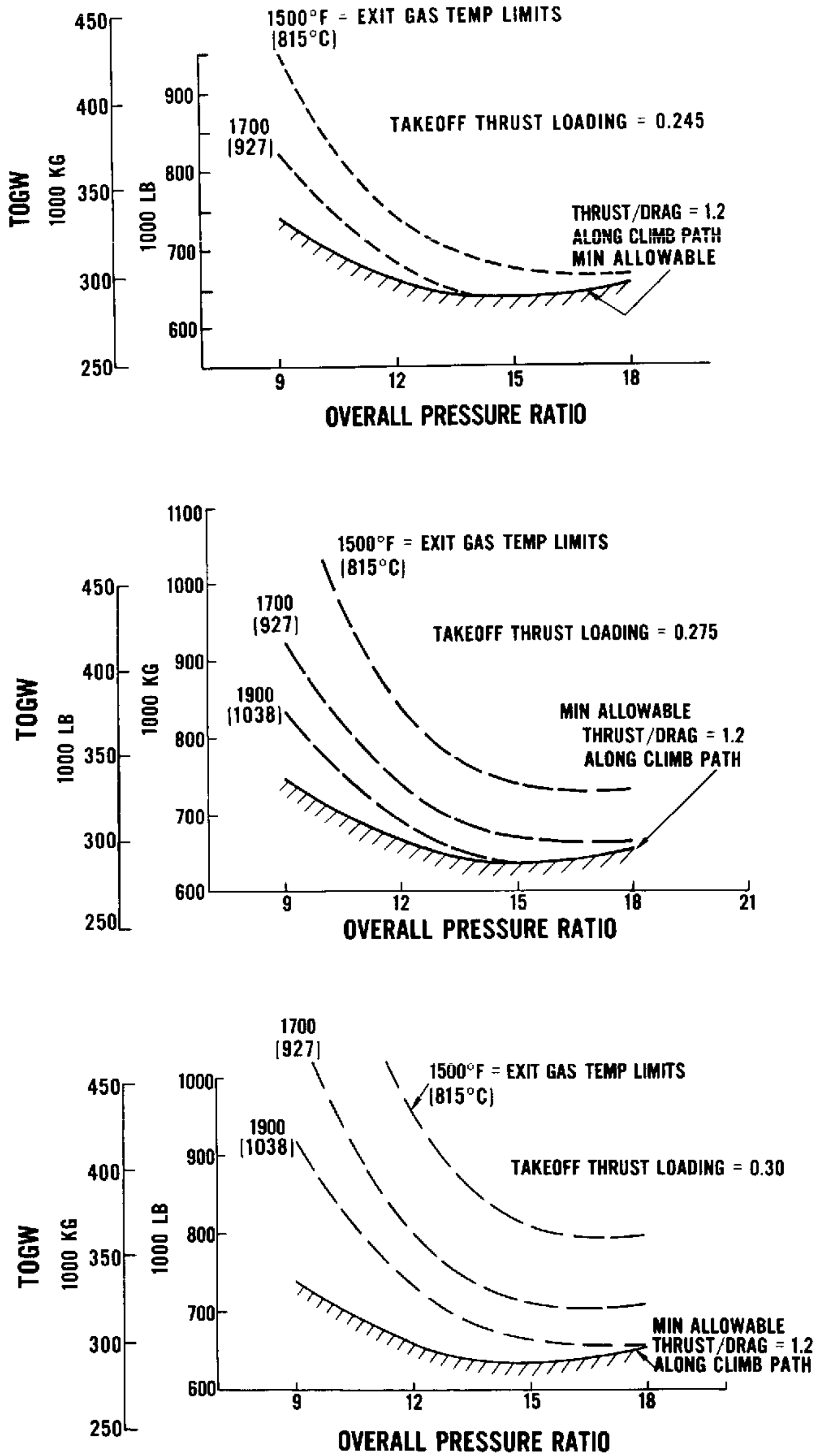


Figure 99 Non-Afterburning Turbojet OPR Optimization for Mach 2.16 Nominal Mission at Three Takeoff Thrust Loadings With Jet Noise Suppressor

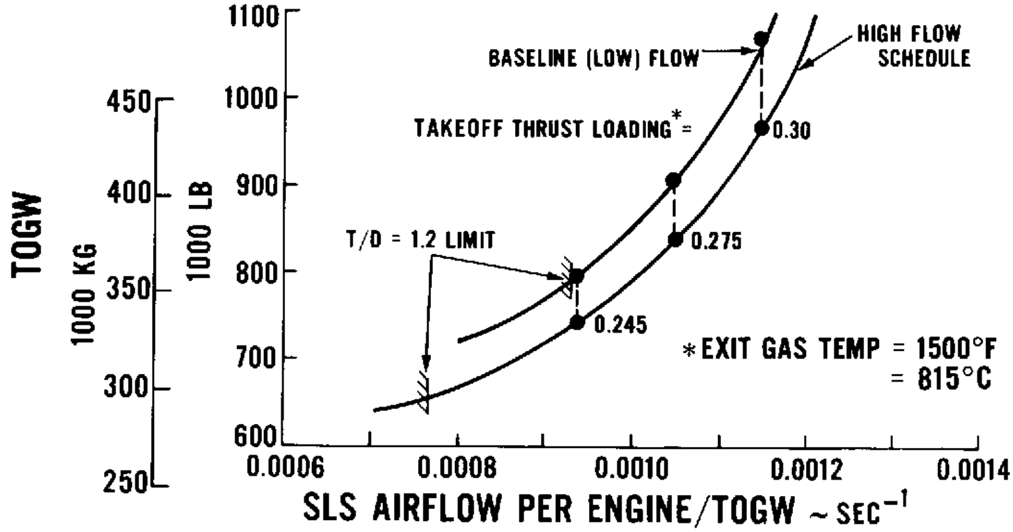


Figure 100 TOGW Comparison of High and Low Flow Non-Afterburning Turbojets for Mach 2.65 Nominal Mission, OPR = 12

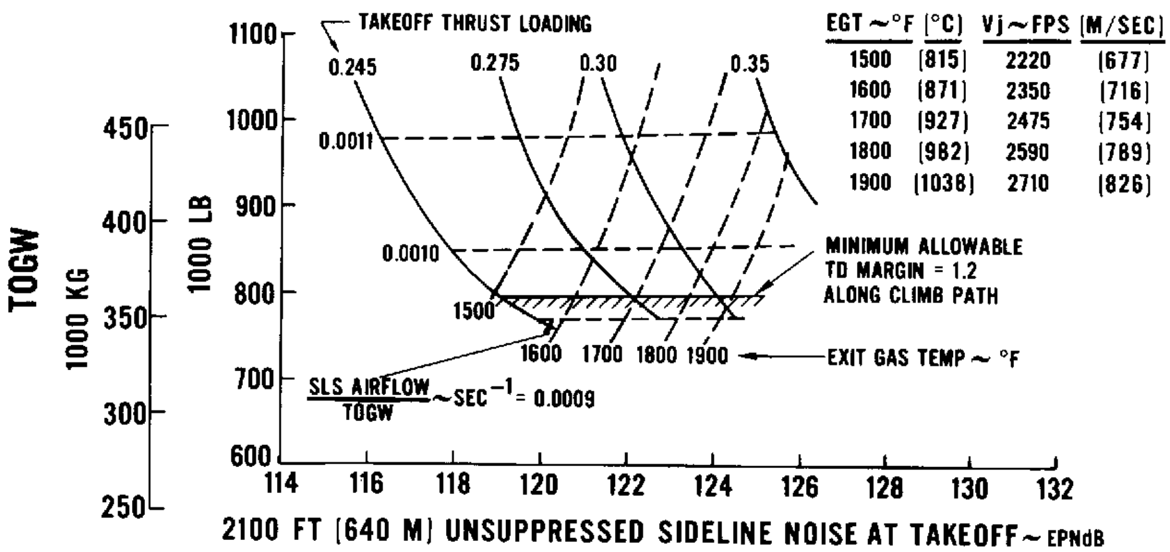


Figure 101 System Performance of Low Flow Non-Afterburning Turbojets for Mach 2.65 Nominal Mission With Tube Suppressor, OPR = 12

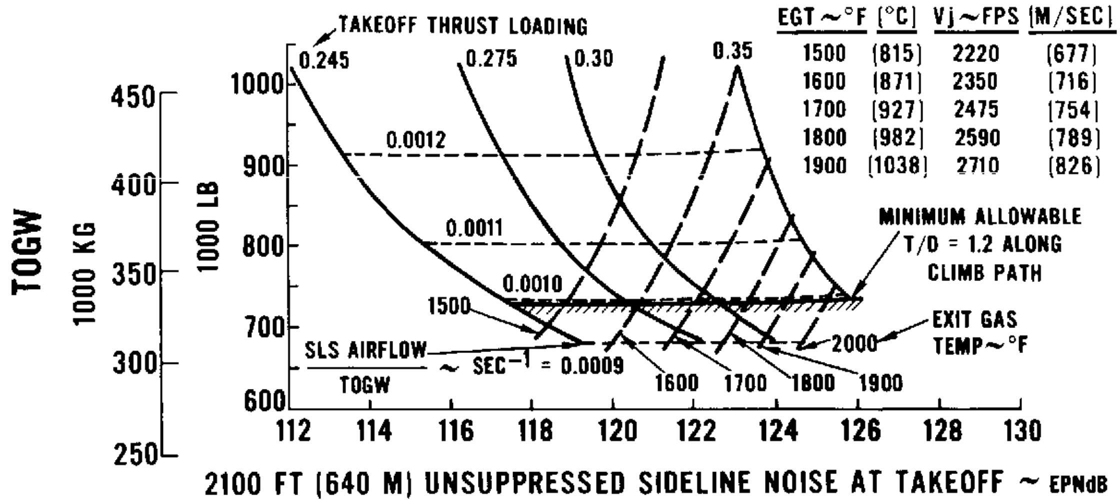


Figure 102 System Performance of Low Flow Non-Afterburning Turbojet for Mach 2.65 All Supersonic Mission With Tube Suppressor, OPR = 12

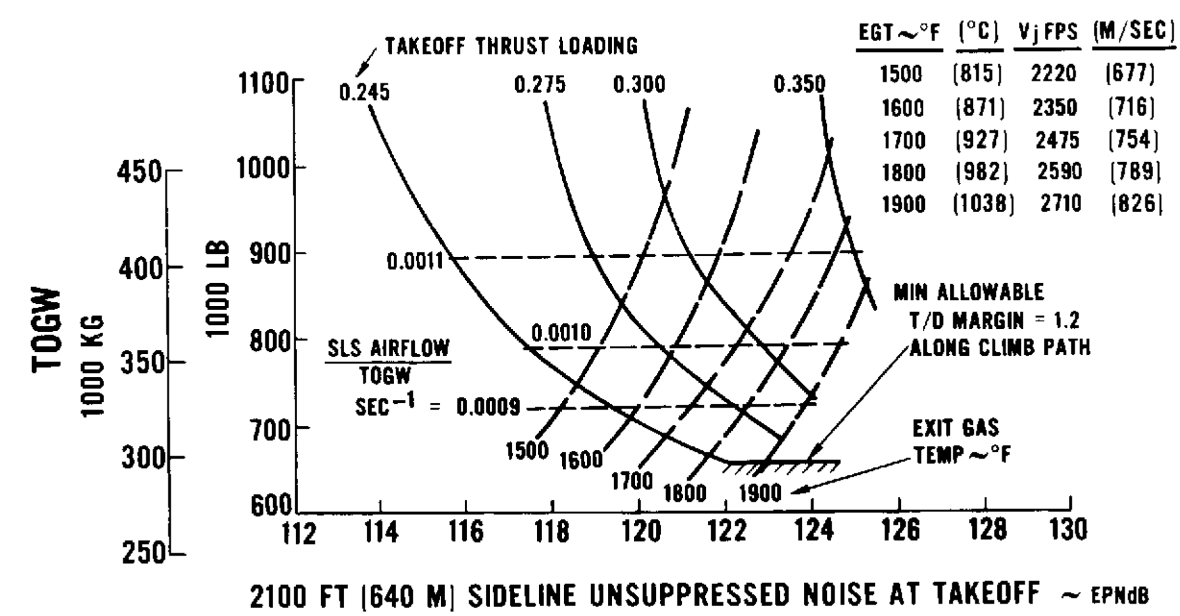


Figure 103 System Performance of High Flow Non-Afterburning Turbojet for Mach 2.65 Nominal Mission With Tube Suppressor, OPR = 12

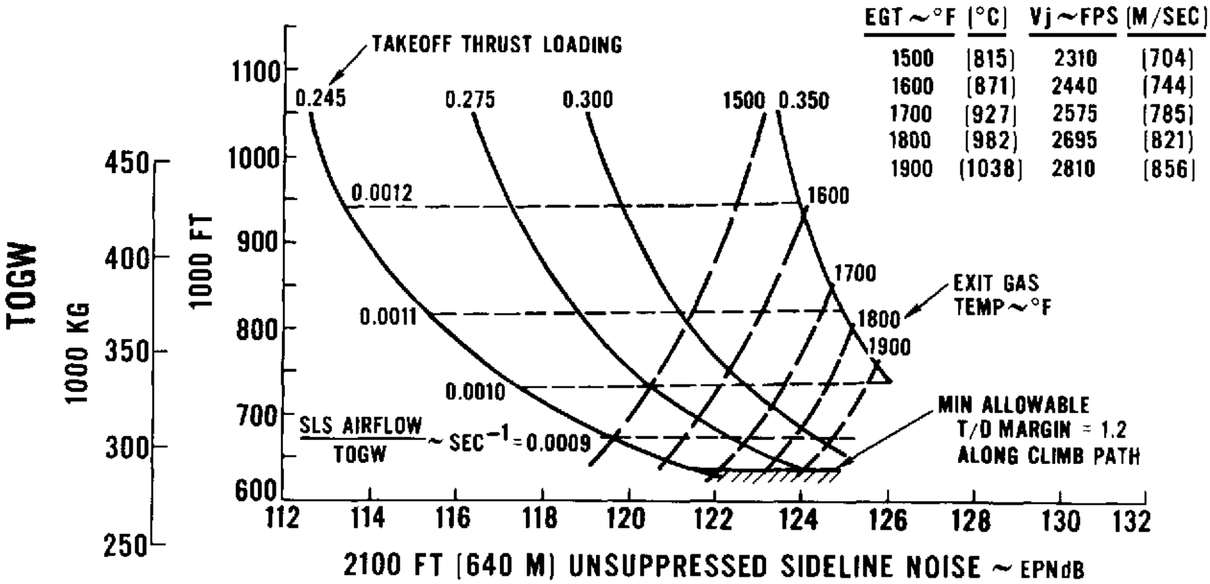
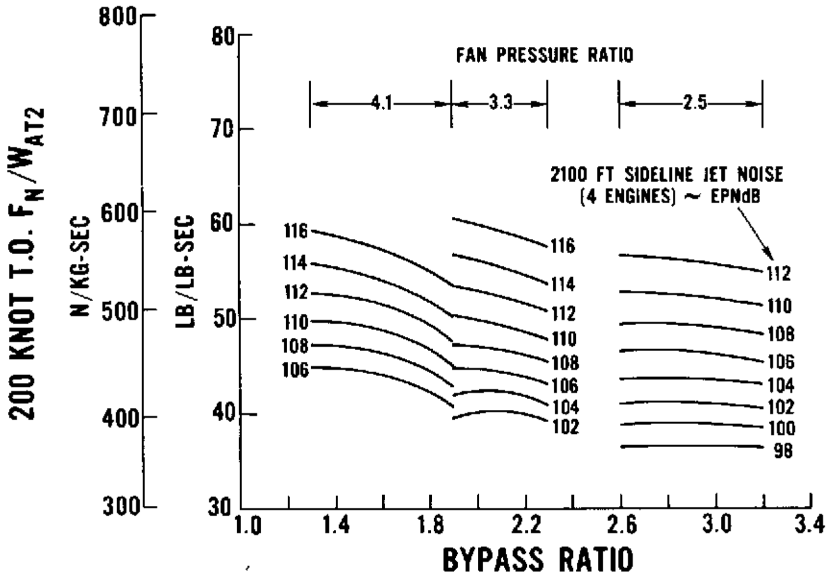
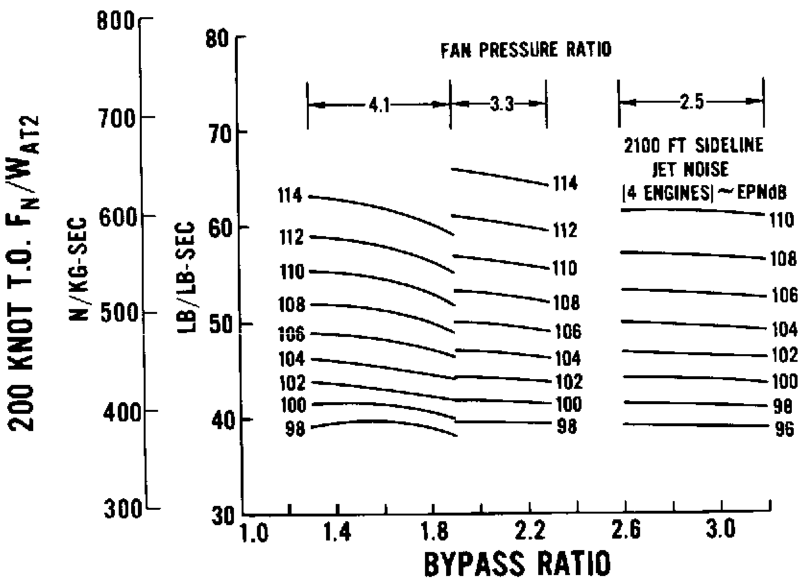


Figure 104 System Performance of Non-Afterburning Turbojet for Mach 2.16 Nominal Mission With Tube Suppressor, OPR = 15



Duct-Heating Turbofan Without Suppressor



Duct-Heating Turbofan With 5PNdB Duct Suppressor

Figure 105 Effect of Cycle Parameters on Jet Noise for Duct-Heating Turbofan Without Suppressor and With a 5 PNdB Duct Suppressor, Airflow Size = 900 lb/sec (408 kg/sec)

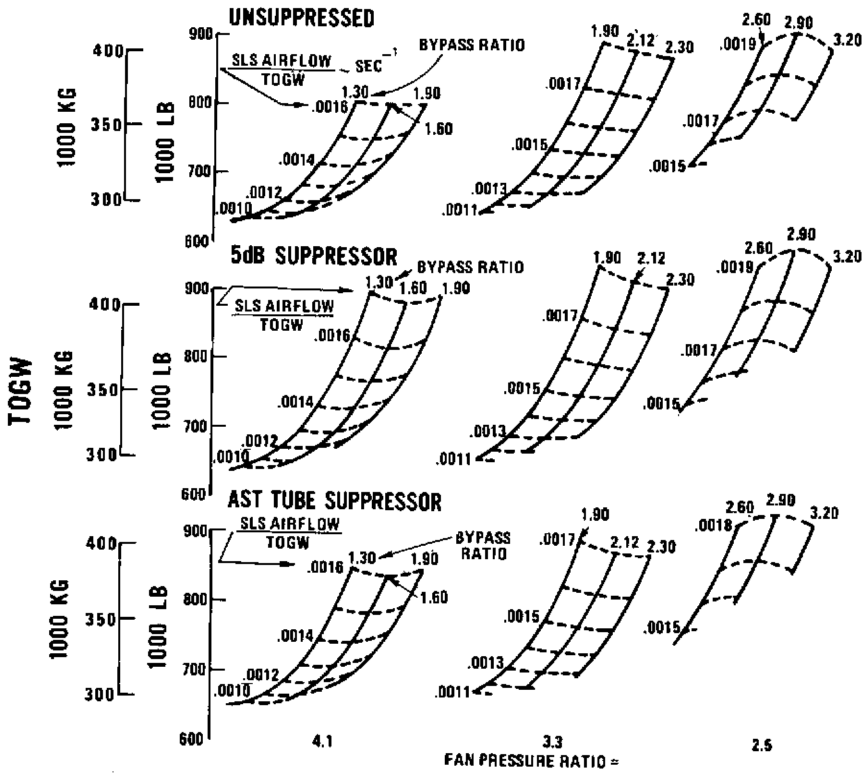


Figure 106 Effect of Duct-Heating Turbofan Cycle Parameters for Mach 2.65 Nominal Mission

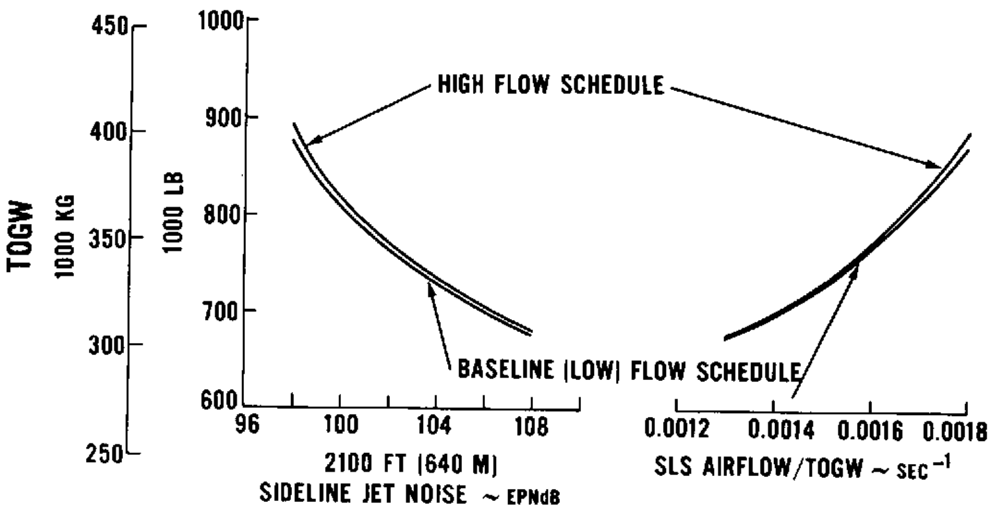


Figure 107 Effect of Duct-Heater Turbofan Flow Schedule on TOGW for Mach 2.65 Nominal Mission, FPR = 3.3 and BPR = 2.1

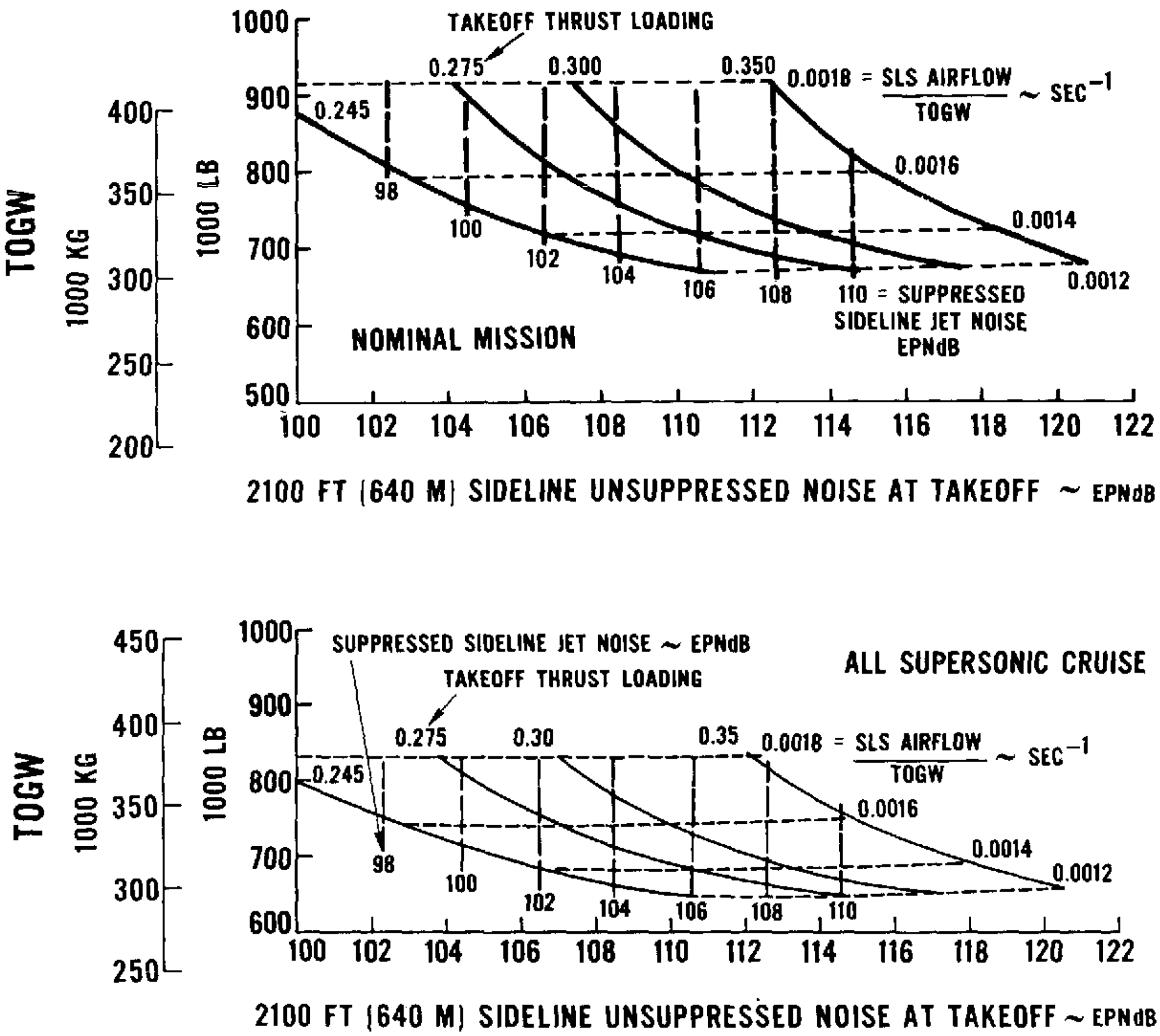
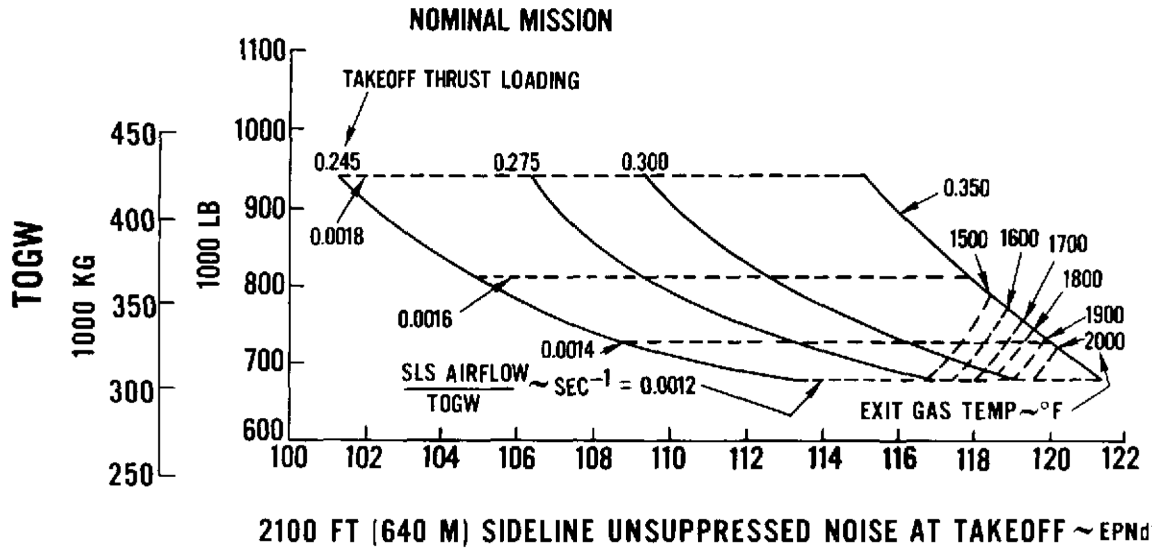


Figure 108 System Performance of 3.3 FPR Duct-Heating Turbofan With 5 PNdB Duct Jet Suppressor for Mach 2.65 Nominal and All Supersonic Missions

EGT ~ °F	(°C)	Vj ~ FPS	(M/SEC)
1500	(815)	2190	(668)
1600	(871)	2250	(686)
1700	(927)	2310	(704)
1800	(982)	2360	(719)
1900	(1038)	2420	(738)
2000	(1093)	2480	(756)



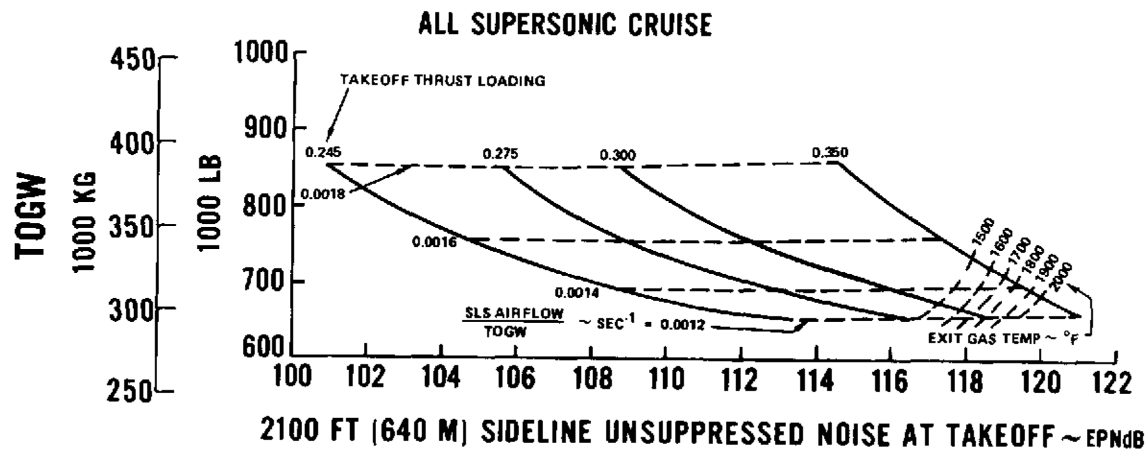


Figure 109 System Performance of 3.3 FPR Duct-Heating Turbofan With Tube Type Duct Suppressor for Mach 2.65 Nominal and All Supersonic Missions

EGT, °F	(°C)	V_j ~ FPS	(M/SEC)
1500	(815)	2400	(731)
1600	(871)	2470	(753)
1700	(927)	2550	(777)
1800	(982)	2620	(798)
1900	(1038)	2690	(820)
2000	(1093)	2750	(838)

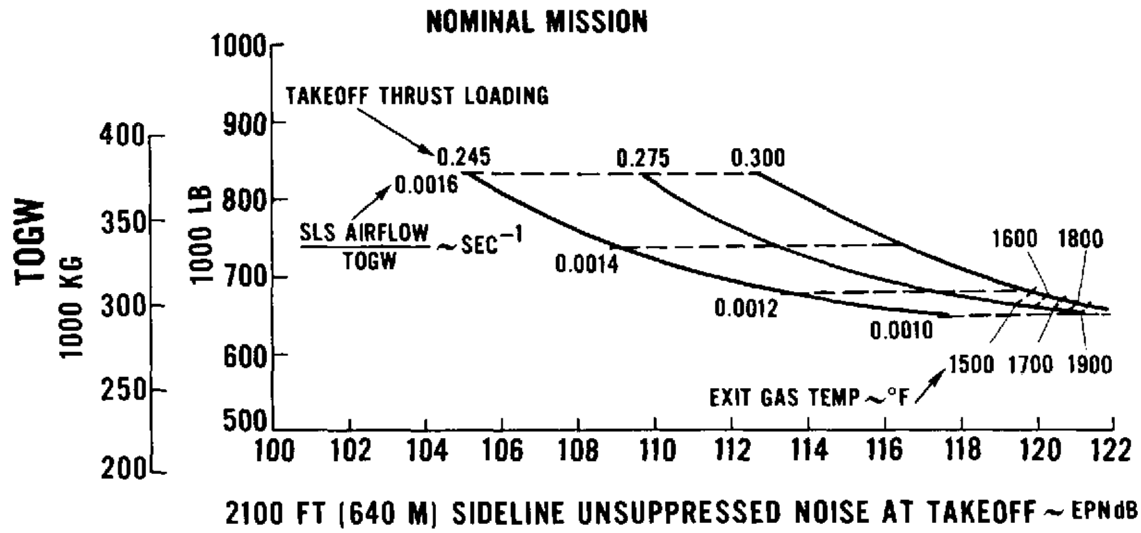
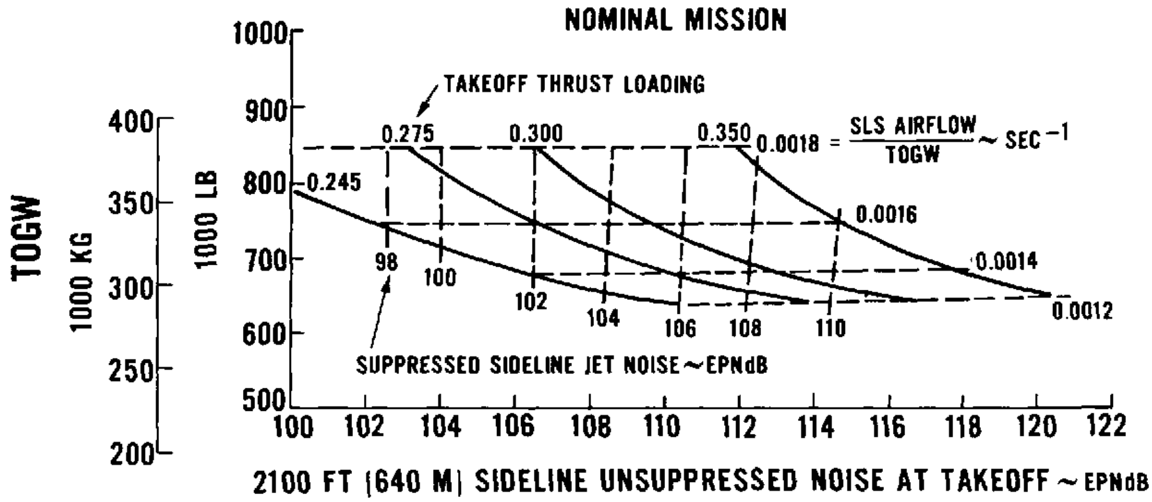


Figure 110 System Performance of 4.1 FPR Duct-Heating Turbofan With Tube Type Duct Suppressor for Mach 2.65 Nominal Mission



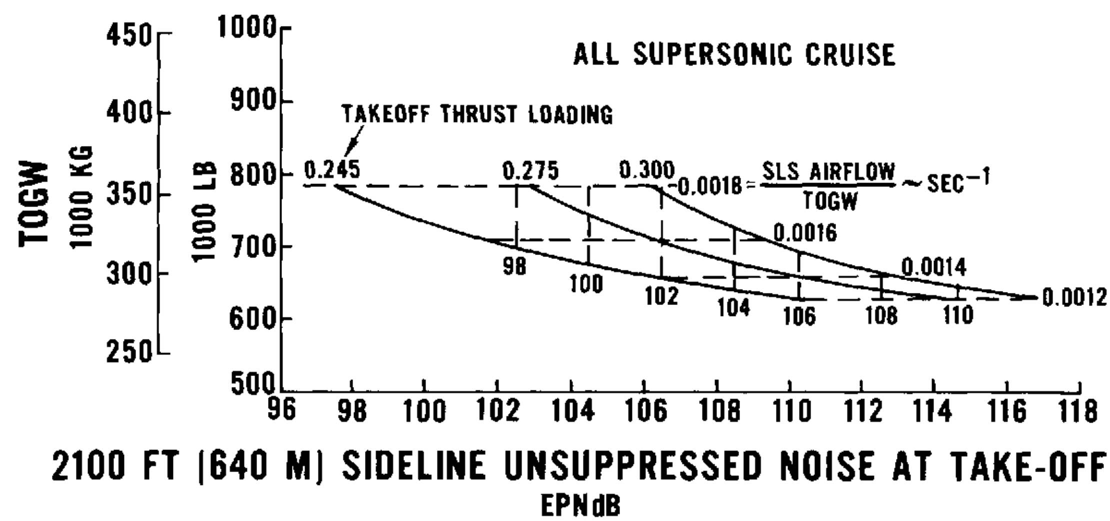


Figure 111 System Performance of 3.3 FPR Duct-Heating Turbofan With 5 PNdB Duct Jet Suppressor for Mach 2.16 Nominal and All Supersonic Missions

EGT~°F	(°C)	Vj~FPS	(M/SEC)
1500	(815)	2130	(668)
1600	(871)	2250	(686)
1700	(927)	2310	(704)
1800	(982)	2360	(719)
1900	(1038)	2420	(738)
2000	(1093)	2480	(756)

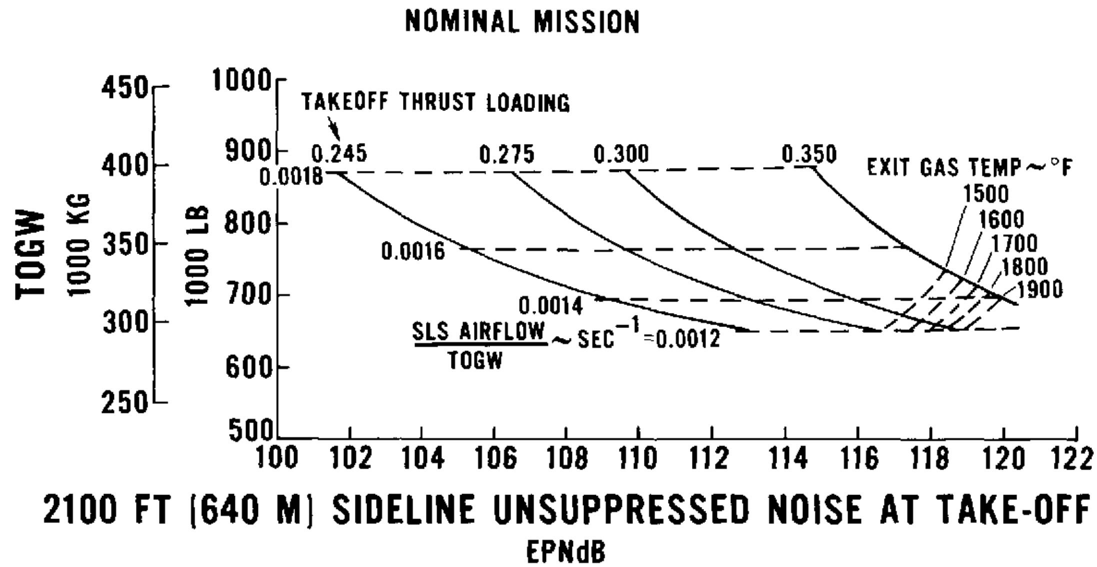
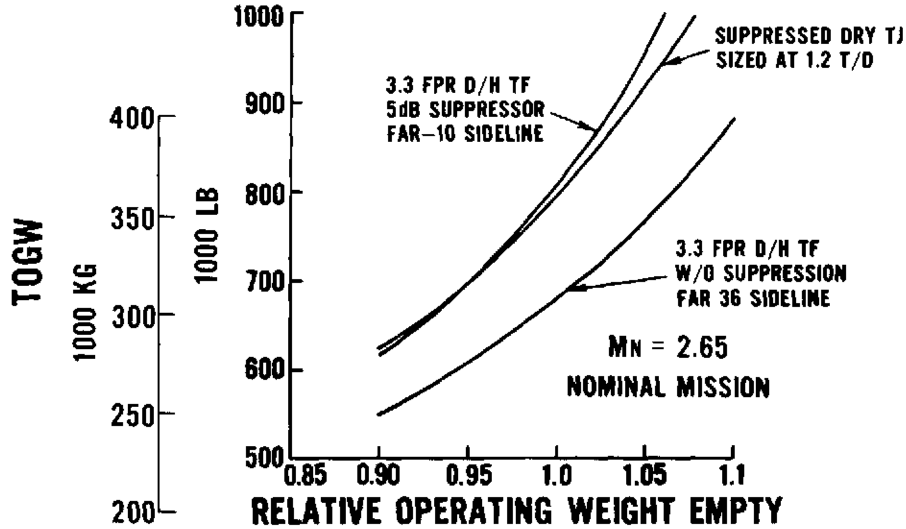


Figure 112 System Performance of a 3.3 FPR Duct-Heating Turbofan With Tube Type Duct Suppressor for Mach 2.16 Nominal Mission



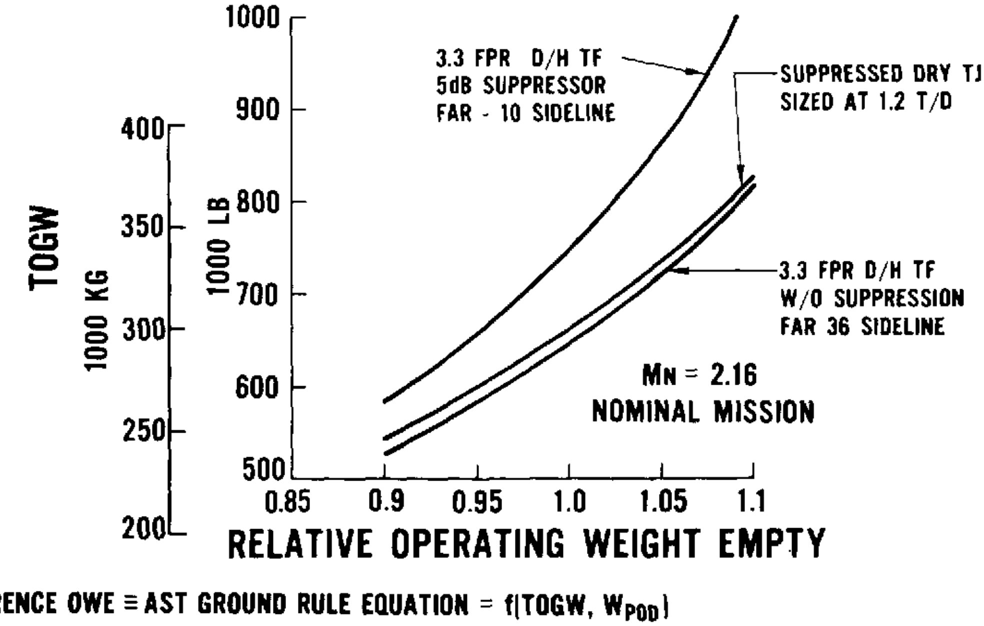


Figure 113 TOGW Sensitivity to OWE for Mach 2.65 and 2.16 Nominal Missions

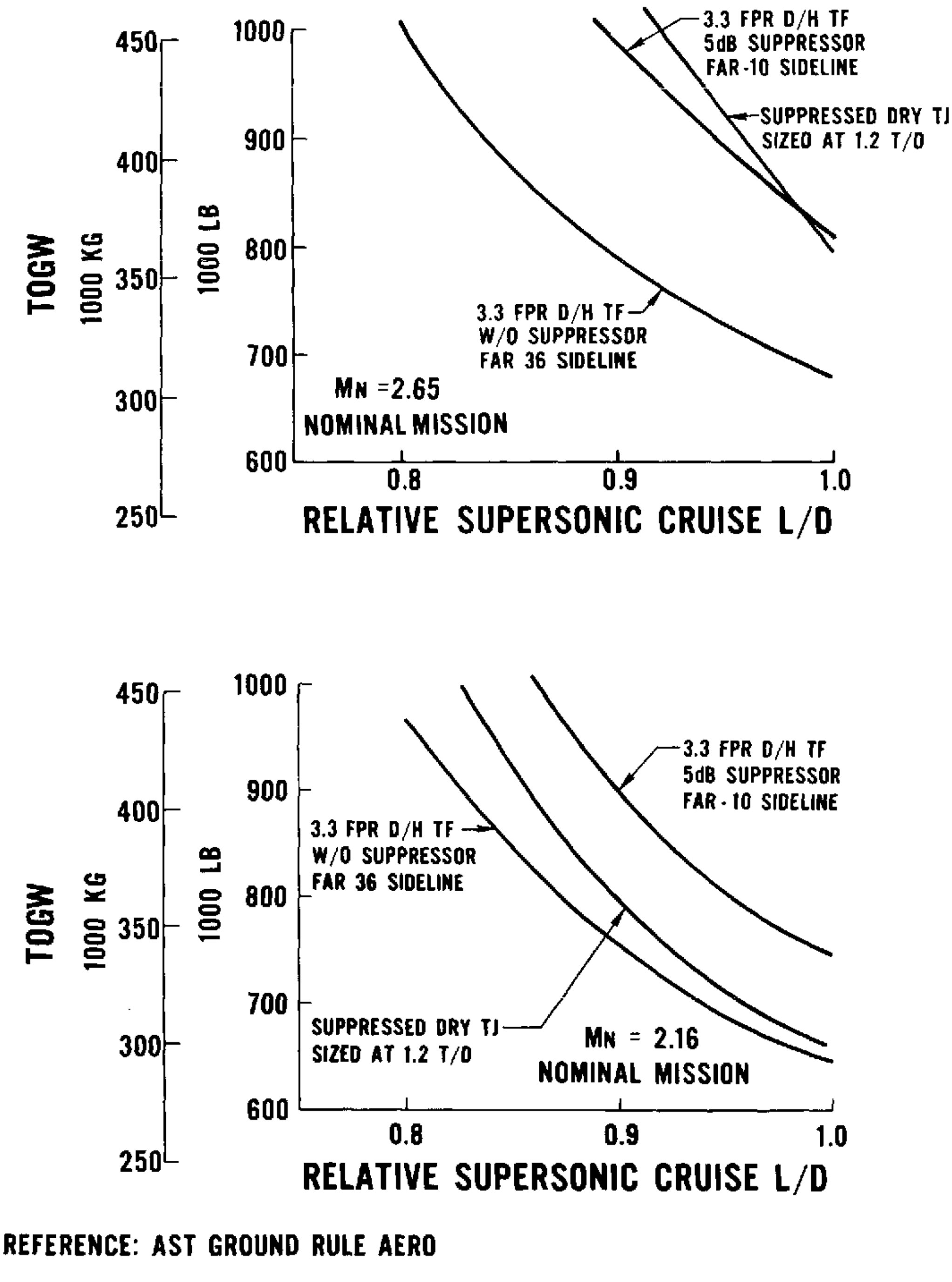
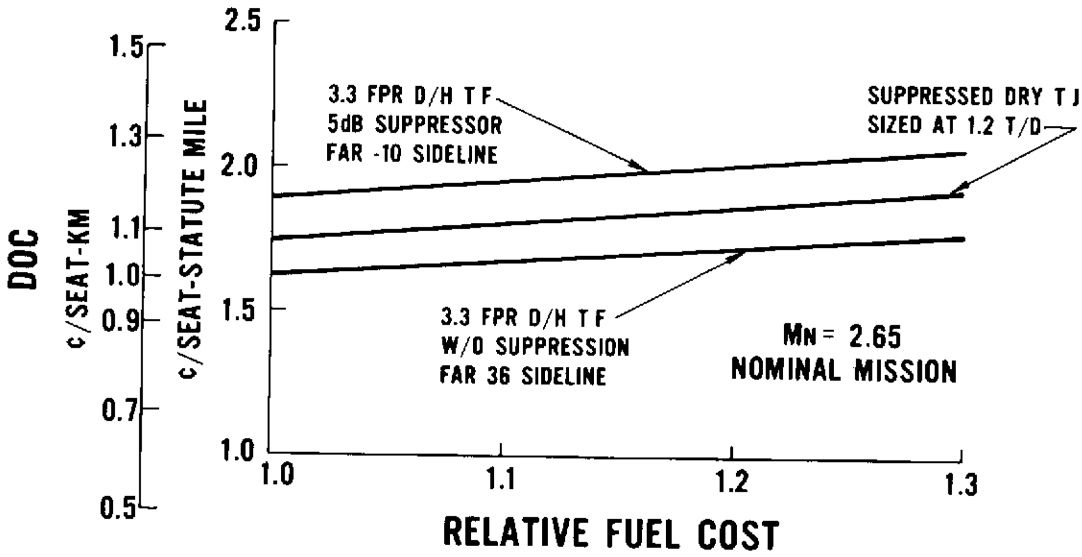
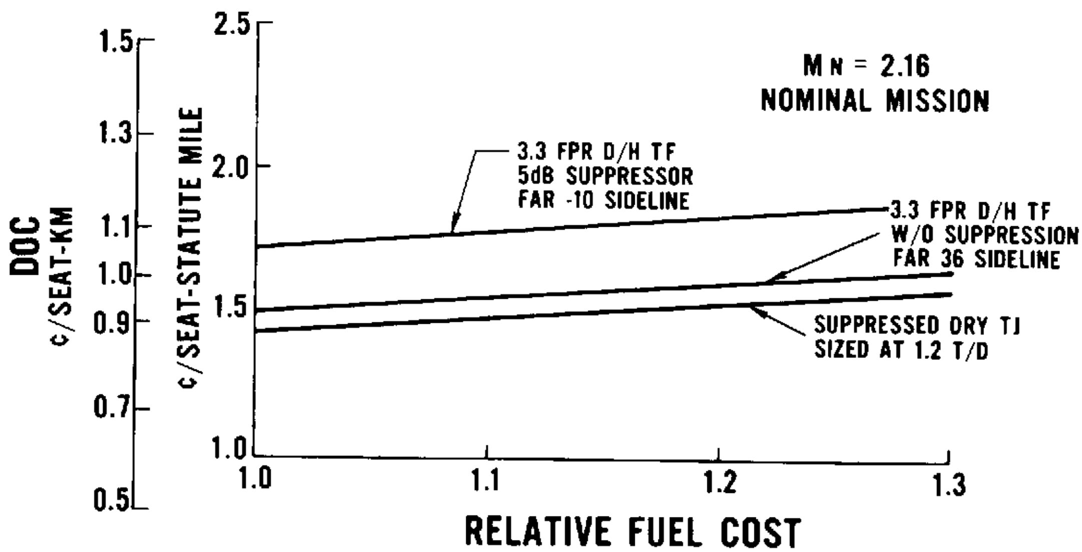


Figure 114 TOGW Sensitivity to Cruise L/D for Mach 2.65 and 2.16 Nominal Missions





REFERENCE FUEL COST = 1.85 ¢/LB

Figure 115 DOC Sensitivity to Fuel Cost for Mach 2.65 and 2.16 Nominal Missions

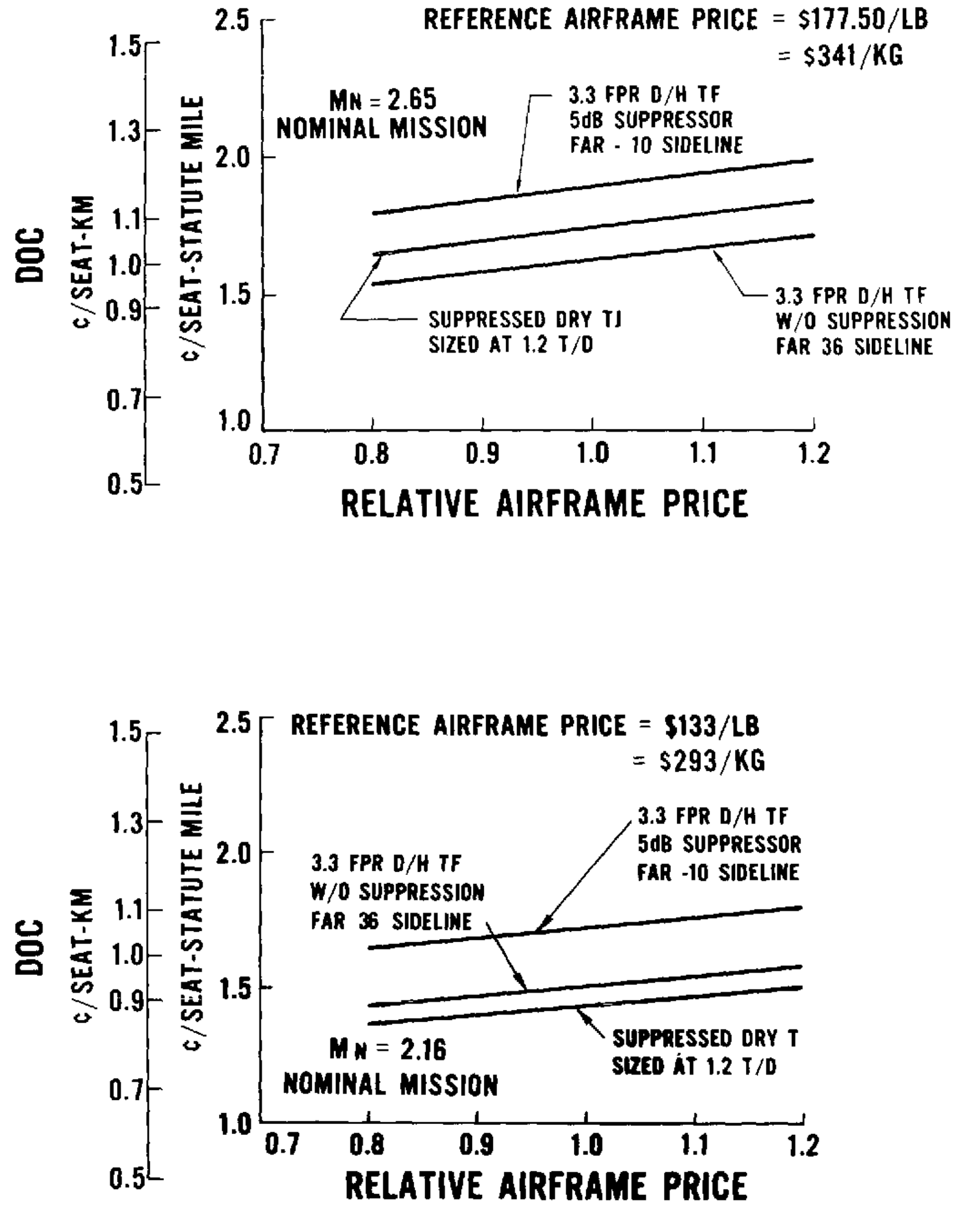
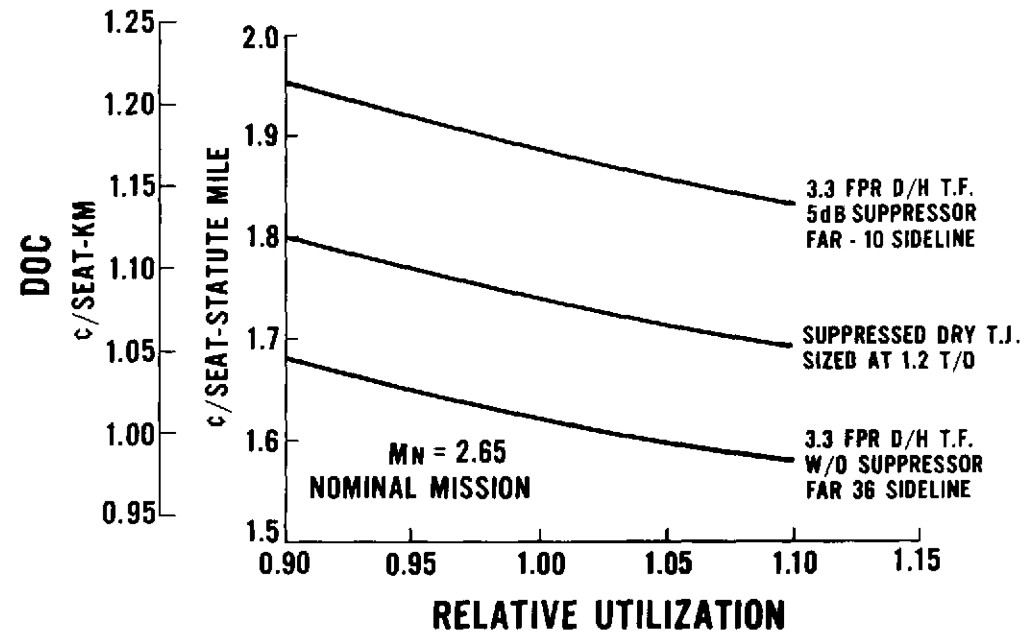


Figure 116 DOC Sensitivity to Airframe Price for Mach 2.65 and 2.16 Nominal Missions

REFERENCE: ATA METHOD BASE UTILIZATION ≅ 4160 HR/YEAR



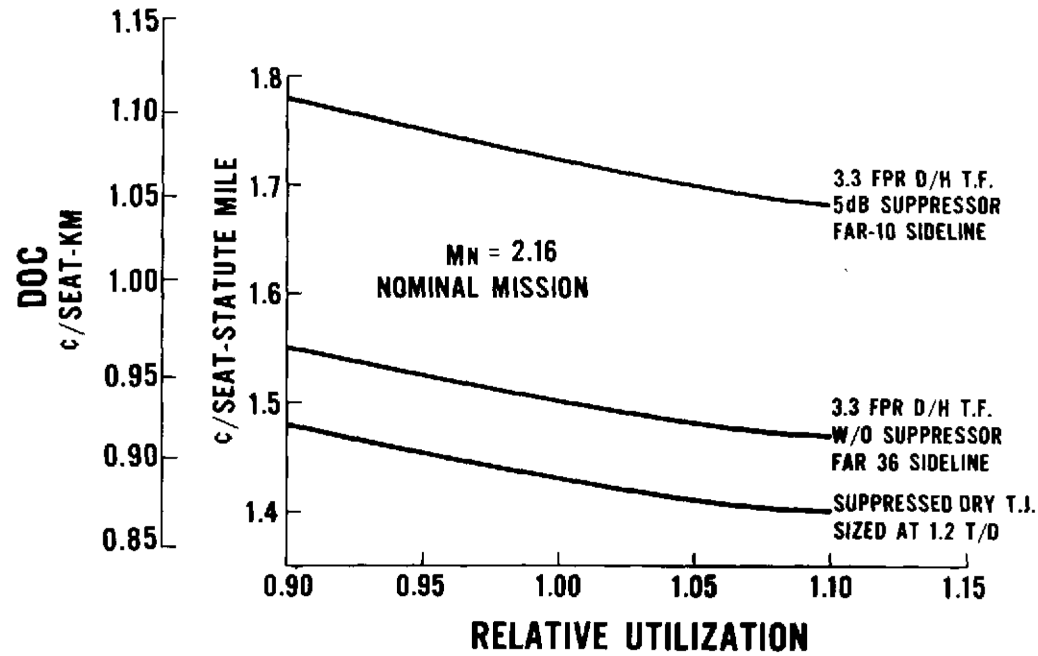


Figure 117 DOC Sensitivity to Utilization for Mach 2.65 and 2.16 Nominal Missions

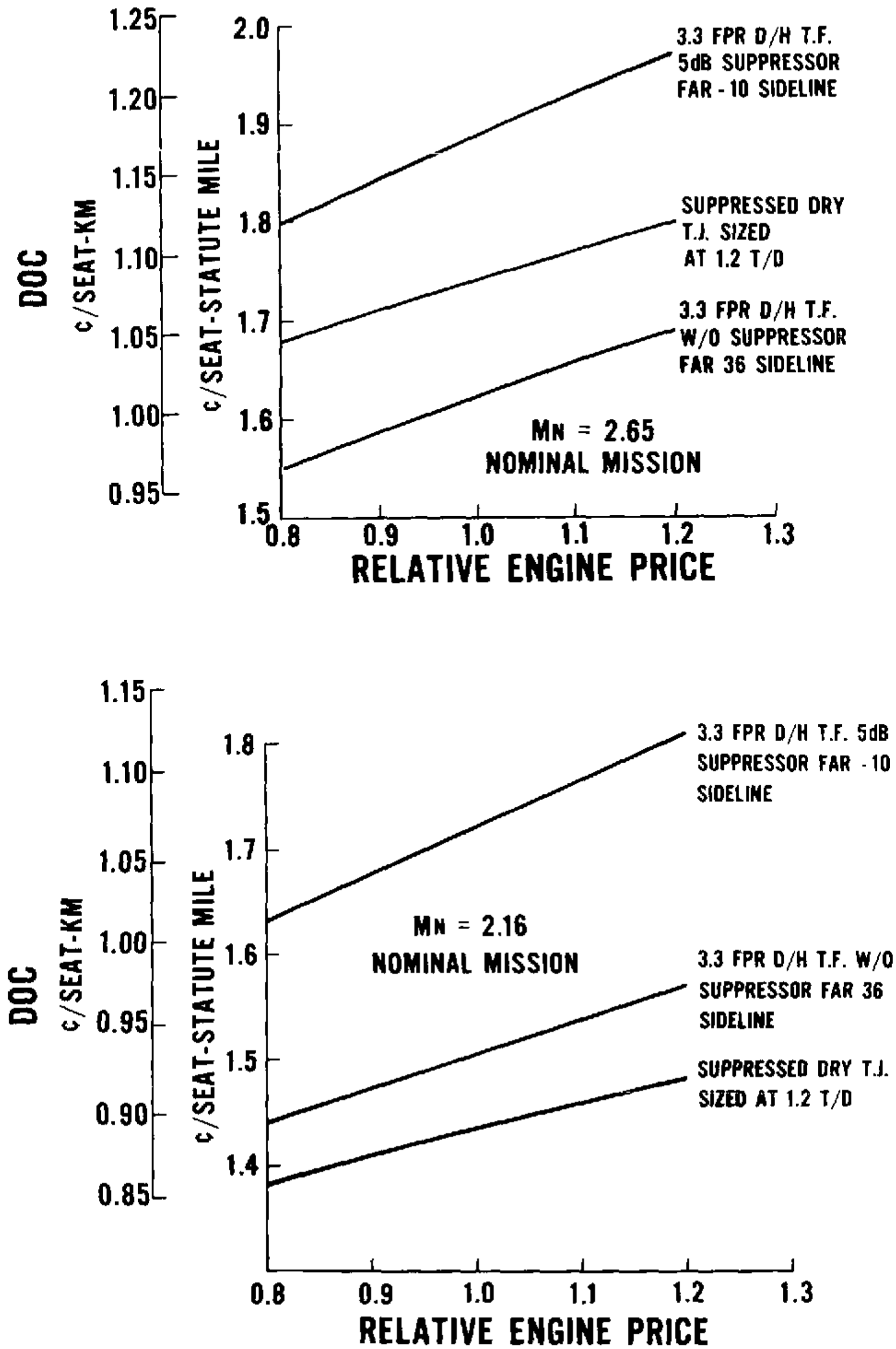


Figure 118 DOC Sensitivity to Engine Price for Mach 2.65 and 2.16 Nominal Missions

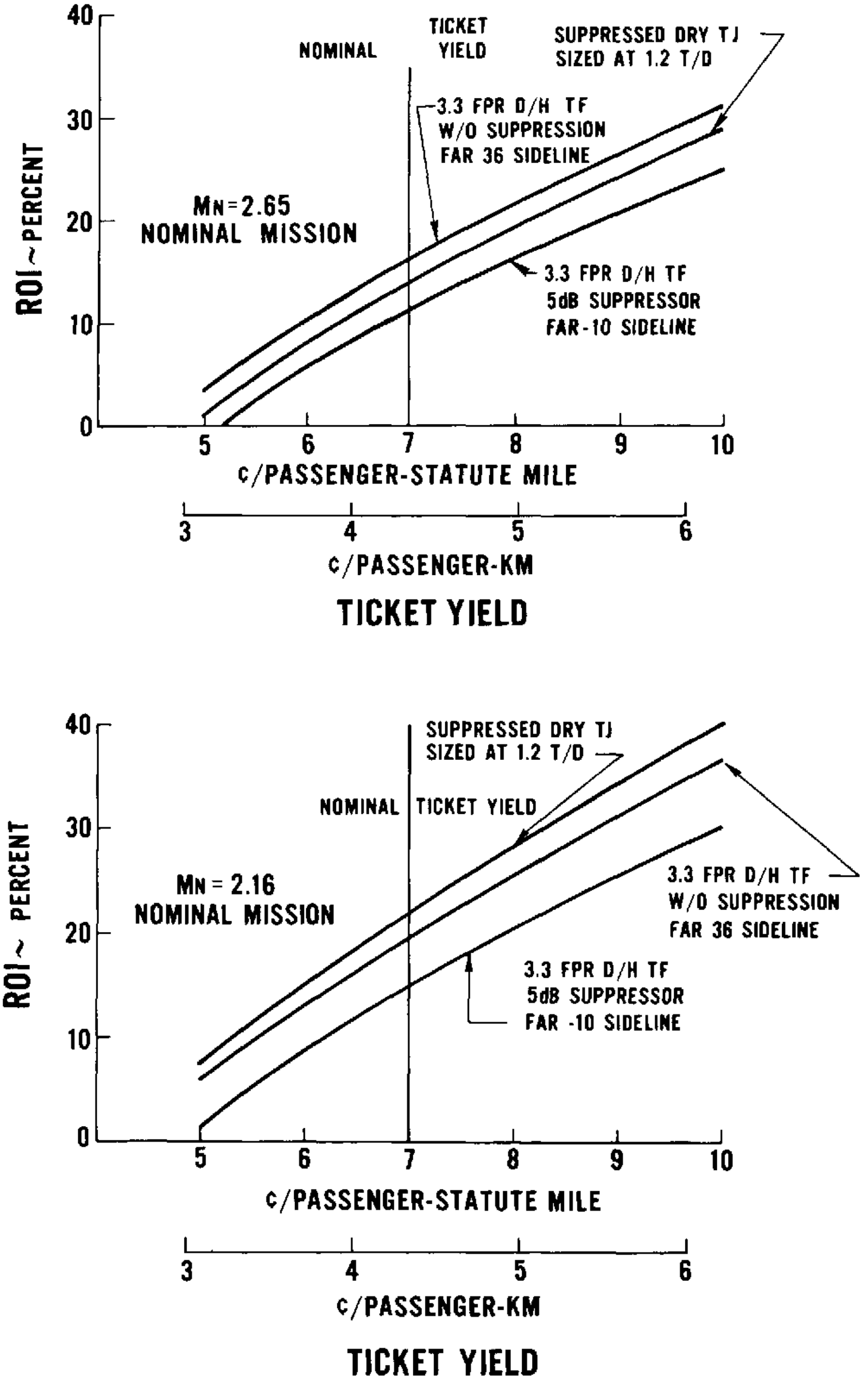


Figure 119 ROI Sensitivity to Ticket Yield for Mach 2.65 and 2.16 Nominal Missions

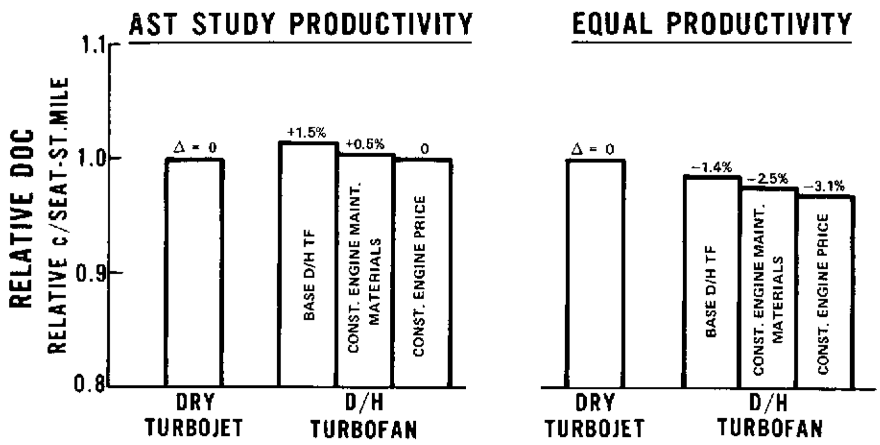


Figure 120 DOC Sensitivity to ATA Method Ground Rules for Mach 2.65 Nominal Mission

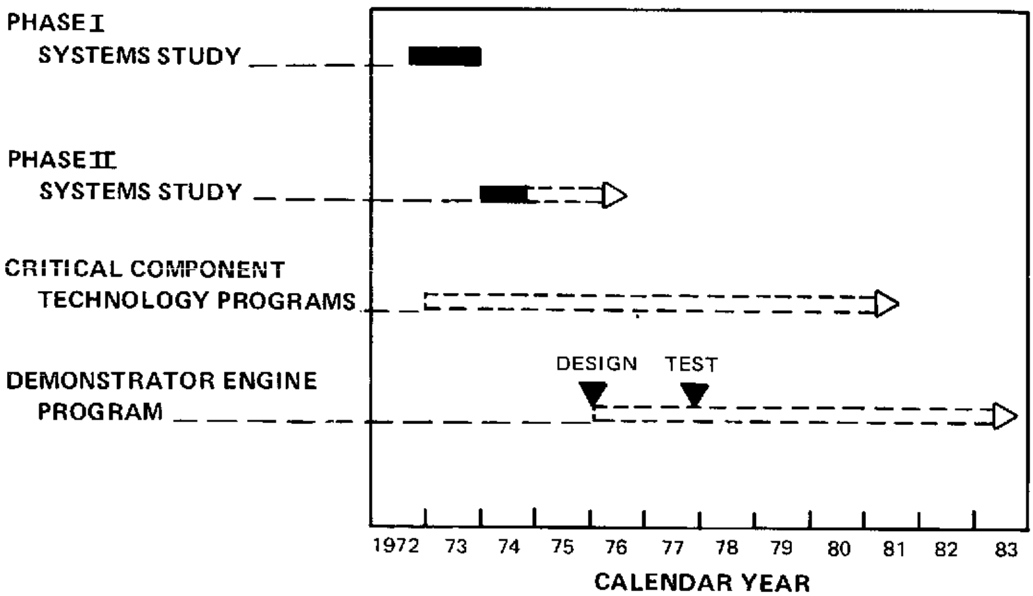


Figure 121 Projected Advanced Supersonic Technology Propulsion Schedule

LIST OF ABBREVIATIONS

A/B	=	afterburning or afterburner
AIV	=	Annular Inverter Valve
AST	=	advanced supersonic technology
AUG	=	augmentor or augmented
BPR	=	bypass ratio
CET	=	combustor exit temperature
D/H	=	duct heating or duct heater
DOC	=	direct operating cost
Dry	=	non-afterburning
EGT	=	exit gas temperature
EPNL	=	effective perceived noise level – decibels
F_G	=	gross thrust
F_N	=	net thrust
FAR 36	=	Federal Aviation Regulations, Part 36 noise limits
FAR 36 minus x PNdB	=	xPNdB below FAR 36 noise limits
FPR	=	fan pressure ratio
L/D	=	lift to drag ratio
OPR	=	overall pressure ratio
OWE	=	operating weight empty
PNL	=	perceived noise level – decibels
PR	=	pressure ratio
ROI	=	return on investment
SLS	=	sea level static
SST	=	supersonic transport
T/D	=	thrust to drag ratio
TF	=	turbofan
THC	=	total unburned hydrocarbons
TJ	=	turbojet
TOGW	=	takeoff gross weight
TSFC	=	thrust specific fuel consumption
Vj	=	jet exhaust velocity relative to free stream
VBE	=	variable bypass engine
WAT2	=	total corrected airflow
TCA	=	turbine cooling air

The provisions of NASA Policy Directive (NPD) 2220.4 dated May 14, 1970, subject: Use of the International System of Units (SI) in NASA Publications, have been waivered under authority of subparagraph 5.5, NPD 2220.4.