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PHASE III Final Report

Advanced Supersonic Propulsion Study

Commercial Products Division
Pratt & Whitney Aircraft Group
United Technologies Corporation

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16. Abstract

The continuation of the NASA/P&WA study to evaluate various propulsion system concepts for advanced supersonic cruise aircraft has resulted in the identification of the Variable Stream Control Engine as the most promising concept. This concept employs variable geometry components and a unique throttle schedule for independent control of two flow streams to provide low jet-noise at take-off and high performance at both subsonic and supersonic cruise. The advanced technology Variable Stream Control Engine offers both a 25 percent improvement in airplane range, and an 8 dB reduction in take-off noise, relative to 1st generation supersonic turbojet engines. Extensive research and technology programs are required in the critical areas unique to this engine to realize its potential benefits. This report summarizes the work conducted under Phase III of the Advanced Supersonic Propulsion Study including refined parametric analysis of selected Variable Cycle Engines, screening of additional unconventional concepts, and preliminary design studies. Additionally, the critical technology areas are described and required programs are summarized.

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FOREWORD

This report summarizes a contracted study of advanced supersonic propulsion systems conducted for NASA by Pratt and Whitney Aircraft. This study, referred to as Phase III, was conducted during the period July 1975 to June 1976. It was a continuation of Phase I, reported in NASA CR-134633, and Phase II, reported in NASA CR-134904.

The NASA project manager for this study contract was Dr. Edward A. Willis, Flight Performance Section, Lewis Research Center, Cleveland, Ohio. Key P&WA personnel were Robert A. Howlett, Study Program Manager, Jack W. Johnson, Joseph Sabatella and Thomas R. Sewall.

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SUMMARY

The National Aeronautics and Space Administration (NASA) is engaged in a study of the application of advanced technology to long-range, supersonic, commercial transport aircraft under the Supersonic Cruise Airplane Research (SCAR) program. As part of this program, P&WA has been conducting advanced supersonic propulsion studies with the overall objective of identifying the most promising advanced engine concepts and related technology programs necessary to provide a sound basis for design and possible future development of an advanced supersonic propulsion system. Phases I and II of this effort were conducted under NAS3-16948 and were reported in NASA CR-134633 and NASA CR-134904, respectively. Phase III, conducted under NAS3-19540, is the subject of this report. The P&WA study effort is continuing in the on-going Phase IV engine, nacelle, airframe integration studies.

In the Phase I studies, a broad spectrum of conventional and unconventional propulsion systems were studied parametrically over a wide range of cycle variables. An advanced turbofan and a series/parallel Variable Cycle Engine (VCE) concept were identified as the most promising engines studied during Phase I. Phase II was a more concentrated parametric study including refined cycle studies, airplane integration studies conducted jointly by P&WA and Boeing, and initiation of preliminary design studies. The two most promising engine concepts that evolved in the Phase II refinement of the Phase I concepts were the Variable Stream Control Engine (VSCE) and a single rear-valve VCE concept. Both of these VCE concepts feature independent temperature and velocity control for two coannular nozzle exhaust streams which, in combination with variable geometry components, provide excellent flow matching over the entire flight spectrum, as well as reduction in jet noise. The resulting improvements in installed performance and lower noise levels provide significant benefits to the supersonic transport relative to current technology designs.

The approach taken in the Phase III studies was to continue parametric refinement and preliminary design studies of the most promising engine concepts, evaluate potential benefits of additional unconventional concepts, and identify critical technology requirements for these concepts.

Based on the results of intensive refinement studies of the rear-valve Variable Cycle Engine (VCE) concept and the Variable Stream Control Engine (VSCE) concept during Phase III, P&WA system study results indicate that the VSCE is the most promising engine for advanced commercial supersonic aircraft. One of the key factors contributing to the overall advantage for the VSCE is its flexibility to vary exhaust conditions from its two-stream coannular nozzle. This capability provides the inverse velocity profile (bypass stream velocity greater than the primary stream velocity) needed to take advantage of the coannular nozzle noise benefit during take-off. Experimental data from a separate NASA/P&WA program indicates the inherent jet noise benefit of the coannular nozzle, with VSCE exhaust conditions, to be approximately - 8 dB relative to a single stream nozzle having the same specific thrust. At subsonic and supersonic conditions, the exhaust can be controlled to provide flat velocity profiles for high propulsive efficiency. Although the rear-valve VCE can approach the inverted velocity profile of the VSCE, it cannot be matched to duplicate either the velocity profile or the required area ratio without significant system penalties.

Relative to first generation supersonic transport (SST) engines, the advanced technology VSCE has the potential for an 8 dB reduction in sideline jet noise and a 25% improvement in range.

A conventional non-augmented Low Bypass Engine (LBE) with a mixed-flow single-stream nozzle was included in the Phase III studies and incorporated the same level of technology as the refined VCE concepts. The LBE has competitive supersonic cruise performance. However, since the coannular noise benefit is not applicable to the single-stream nozzle, the LBE must be oversized to meet FAR Part 36 noise levels and therefore incurs severe system penalties. If a mechanical jet noise suppressor is applied to this engine, the weight, performance, cost and other factors associated with the suppressor result in significant penalties, and the unsuppressed VSCE has greater potential than the suppressed LBE.

The results of preliminary design studies of 6 coannular nozzle concepts indicate that the baseline configuration, which has multi-hinge actuated panels for ejector and reverser flow openings, is an attractive design. Preliminary design of advanced accessories indicate that an increase in nacelle diameter by as much as 5% may be required if the accessories are located within the nacelle. Conceptual cross-sections of the VSCE, rear-valve VCE and the LBE show that each engine is feasible regarding location and arrangement of major engine components.

Critical technology requirements for the VSCE concept are: low noise, high performance coannular nozzle; low emissions, high performance duct-burner; variable geometry components, including the inlet, fan, compressor and nozzle; low emissions, high temperature primary burner; hot section materials and cooling technology; full-authority, electronic control system; and engine/integration features. Programs are recommended to meet these requirements.

1.0 CONCLUSIONS & RECOMMENDATIONS

1.1 REFINED ENGINE STUDIES

Based on the results of an intensive refinement study of the rear-valve VCE concept and on parallel refinement studies of the VSCE concept, P&WA system study results indicate that the Variable Stream Control Engine (VSCE) is the most promising engine for advanced commercial supersonic aircraft. Figure 1-1 shows the range capability versus noise characteristics of these two refined engines. Table 1-I and Figures 1-2, -3, -4 and -5 show the cycle, performance, dimension and weight characteristics of these two engines that contribute to the system characteristics and differences shown in Figure 1-1. A description of both engine concepts is presented in Sections 3.1.1.1 and 3.1.1.2. Detailed definition of both of these refined engine concepts has been released to the NASA/SCAR aircraft contractors for evaluation in their advanced supersonic aircraft designs.

TABLE 1-I

REFINED VCE CYCLE CHARACTERISTICS

	Variable Stream Control Engine (VSCE-502B)	Rear Valve Variable Cycle Engine (VCE-112C)
FPR	3.3	5.8
BPR	1.3	2.5
OPR	20.0	25.0
CET ~ °C (°F)		
Max	1538 (2800)	1538 (2800)
Takeoff	1204 (2200)	1538 (2800)
Augmenter	Duct-burner	Duct-burner
Number of stages	12	17
(Fan–Compressor/HPT-LPT)	(3-6/1-2)	(6-5/1-4-1)
Jet noise control	Coannular benefit	Coannular benefit

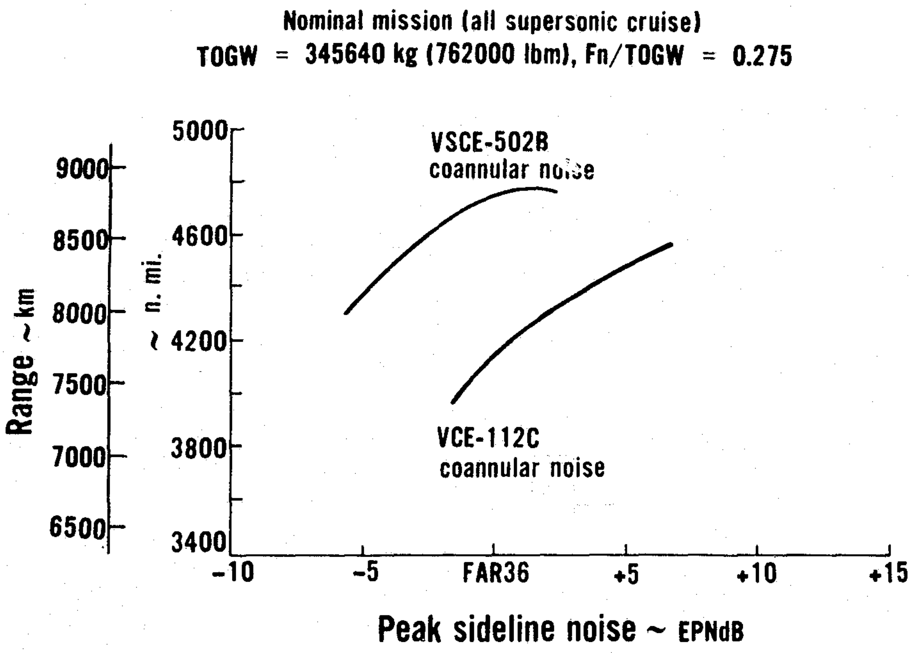


Figure 1-1 Range Comparison of Refined Variable Cycle Engines

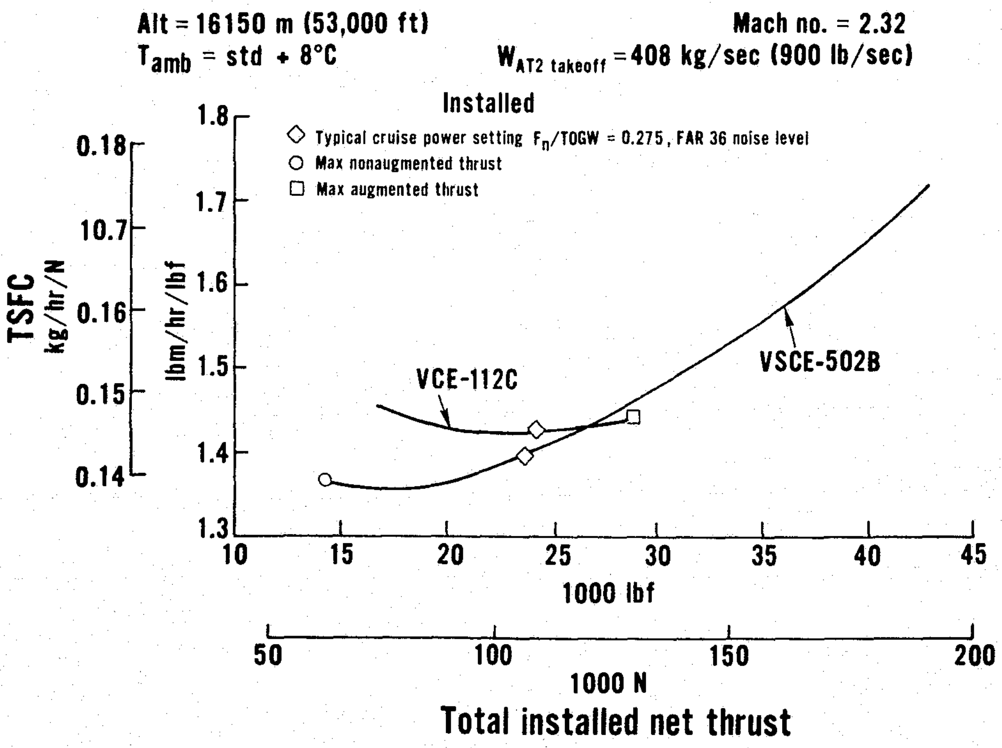


Figure 1-2 Supersonic Cruise Performance Comparison of Refined Variable Cycle Engines

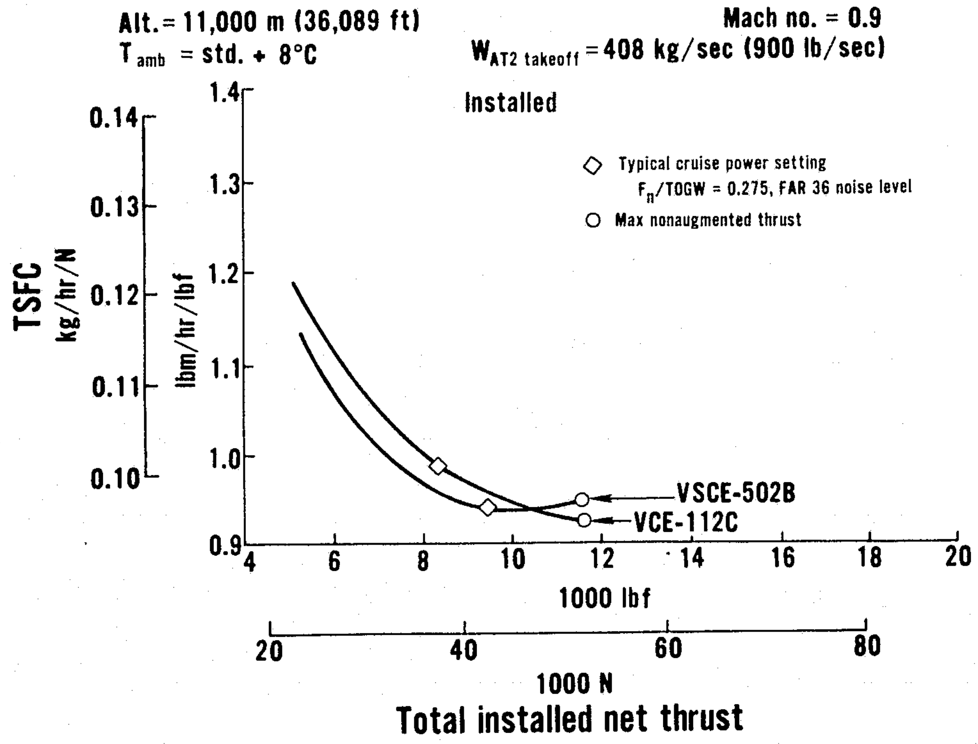


Figure 1-3 *Subsonic Cruise Performance Comparison of Refine Variable Cycle Engines*

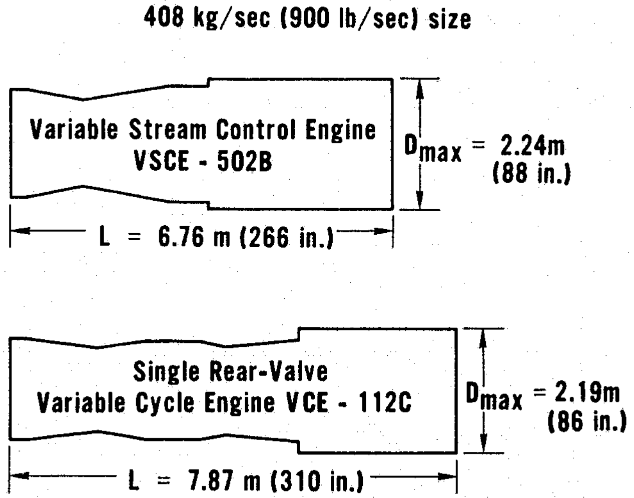


Figure 1-4 *Overall Dimension Comparison of Refined Variable Cycle Engines*

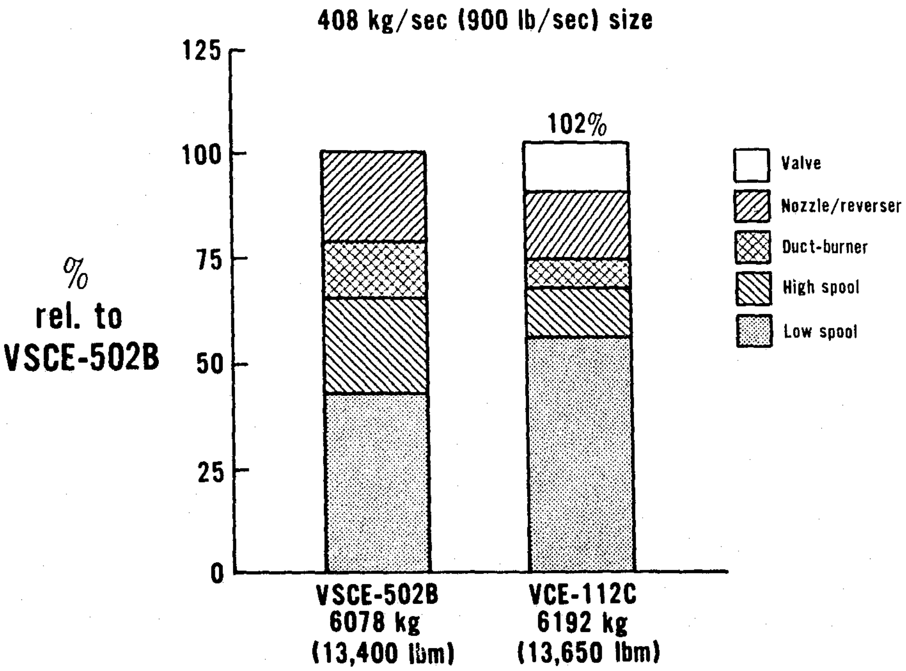


Figure 1-5 *Engine Weight Breakdown for Refined Variable Cycle Engines*

One of the key factors contributing to the overall VSCE advantage is its unique flexibility to vary the exhaust conditions from its two-stream, coannular nozzle. This flexibility is illustrated in Figure 1-6 which shows variations in the coannular nozzle velocity profiles at critical operating points. Of special importance is the inverse velocity profile for reducing jet noise during take-off. In a separate NASA/P&WA program, static and wind-tunnel experimental data indicate that this inverted velocity profile provides an inherent jet noise benefit of approximately -8 dB relative to a single stream nozzle having the same thrust per airflow. In addition to the two inverted velocity profiles corresponding to FAR Part 36 at take-off power settings and at cut-back power for fly-out over the community, Figure 1-6 shows the flat velocity profiles that provide high propulsive efficiency at subsonic and supersonic cruise operation.

Although the rear-valve VCE concept can approach the inverted velocity profile for reduced jet noise during take-off, this engine concept cannot be matched to duplicate either the velocity profile, or the required area ratio, without significant weight and performance penalties. Figure 1-7 illustrates the differences in the nozzle exhaust profiles at take-off operation between these engines. The coannular noise benefit for the rear-valve VCE is -3 to -5 dB, relative to -8 dB for the VSCE. This -3 to -5 dB range is due to uncertainty associated with extrapolating experimental noise data to these exhaust conditions. As a result of these different levels of coannular noise benefit, the rear-valve VCE must be oversized to meet FAR Part 36 noise levels. The total airflow size of the rear-valve VCE is 448 kg/sec (987 lbm/sec) whereas the VSCE size is 354 kg/sec (781 lbm/sec). This size difference is the most significant factor contributing to the range capability of these two engines shown in Figure 1-1.

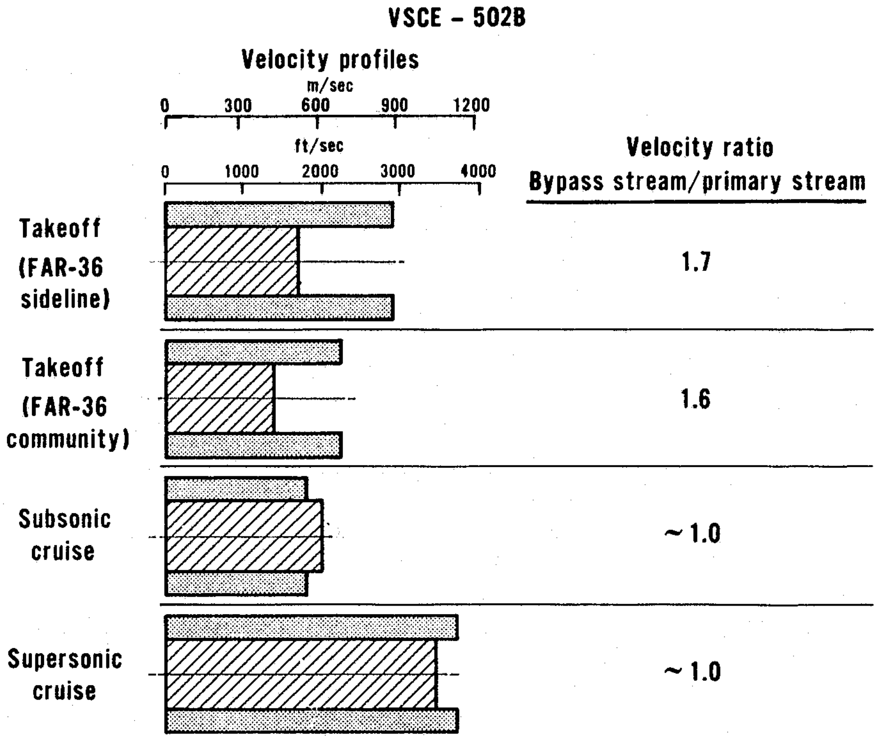


Figure 1-6 Variability of Exhaust Conditions for the VSCE-502B

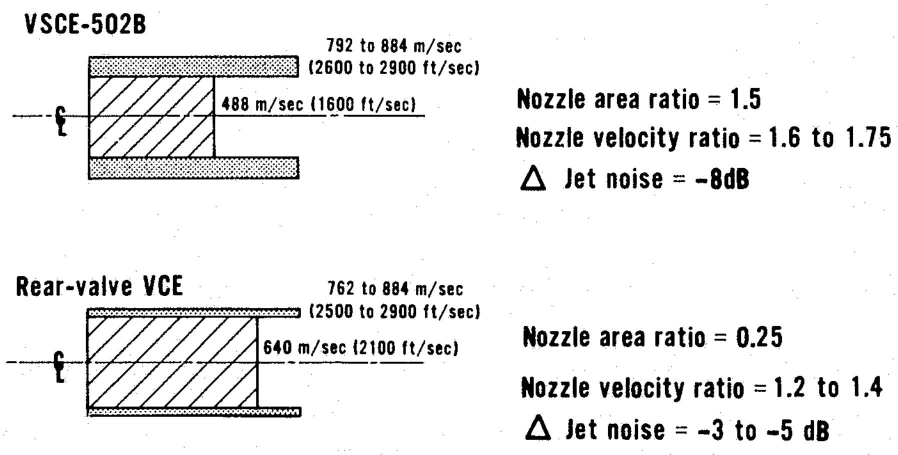


Figure 1-7 Take-off Exhaust Velocity Profile Comparison for Refined Variable Cycle Engines

Studies to determine the sensitivity of these VCE concepts to different airplane characteristics indicate the VSCE has the best overall performance in terms of range, DOC and ROI (all for a fixed TOGW and payload) over the following ranges:

- Fn/TOGW levels ranging from 0.275 to 0.32,
- Engine sizes from 308 kg/sec (680 lb/sec) to 454 kg/sec (1,000 lb/sec),
- Both the all supersonic mission profile and the mixed mission profile with a 1111 km (600 n. mi.) subsonic leg,
- Noise levels from FAR Part 36 down to -5dB.

These P&WA system study results are summarized in Section 3.1.7.

The following areas were included in the rear-valve VCE refinement studies: variation of cycle parameters – bypass ratio, fan pressure ratio, work-split between the two low pressure turbine assemblies, and combustor exit temperature from the duct-burner. Also, cycle variations were evaluated that would involve the coannular noise benefit by optimizing the exhaust stream conditions. A three-stream version of this rear-valve VCE concept was also evaluated. The conclusion that the VSCE is the most promising engine is based on the results from all of these rear-valve VCE refinement studies.

Selection of the VSCE as the most promising VCE concept is further substantiated by the fact that it is a less complex engine than the rear-valve VCE concept.

As an indication of the overall potential improvement of the advanced VSCE concept relative to first generation SST engines, Figure 1-8 shows range capability versus sideline jet noise for both engines. The curves show noise levels corresponding to different engine sizes and throttle settings. The data in this curve is based on a fixed level of airplane technology and shows the impact when going from current technology, unsuppressed turbojet engines, to the advanced technology VSCE concept with the coannular noise benefit. The nominal benefit is expressed in Figure 1-8 as an 8dB reduction in sideline jet noise and a 25% improvement in range capability. The upper curve of the VSCE band represents the additional benefit associated with programmed throttle scheduling. This has the potential to exploit low altitude shielding of engine noise by the airplane configuration, and extra ground attenuation, both for sideline jet noise abatement. This programmed throttle schedule is described in Section 3.1.5.4.

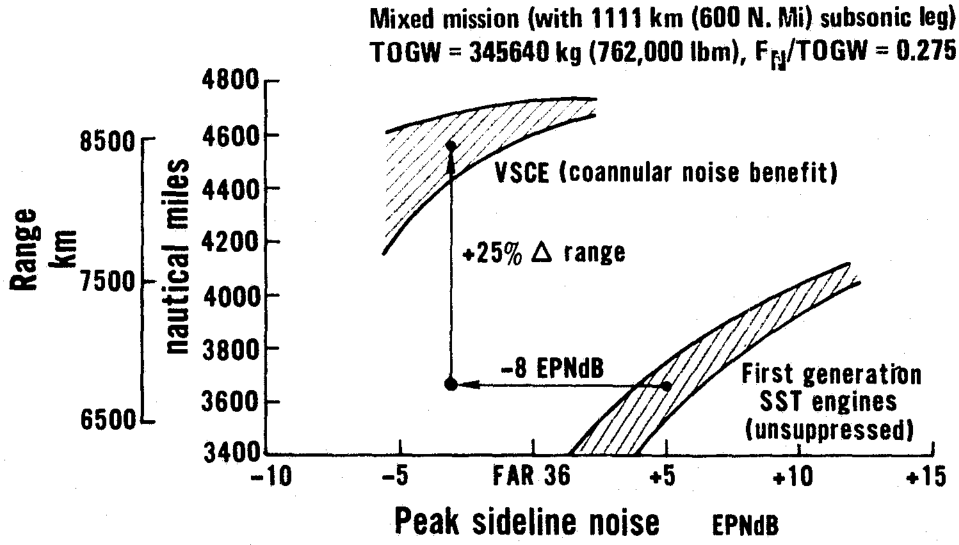


Figure 1-8 *Potential Improvements of Advanced Variable Cycle Engines Over First-Generation SST Engines*

The evaluation of programmed throttle scheduling for further noise reduction of the VSCE shows sufficient potential to warrant further study. This would involve a more detailed evaluation of shielding characteristics and extra ground attenuation effects by the SCAR airplane contractors, as well as a quantitative assessment of the higher duct-burner temperatures that are required to achieve the higher specific thrust levels associated with programmed throttle scheduling.

A conventional, non-augmented, Low Bypass Engine (LBE) with a mixed-flow,single-stream nozzle was included in these Phase III refinement studies. The same levels of advanced technology materials and engine components were incorporated in this LBE design that are in the refined VCE concepts. Also, some of the VCE matching features were included in this refined LBE such as the inverse throttle schedule technique to improve off-design performance, and high-flowing the engine to match the inlet airflow at part-power operation.

Furthermore, some features that are unique to the LBE were also included in this refined engine, such as fan pressure ratio warpage, and Mach number control of the bypass stream, both incorporated to constrain the bypass ratio shift at supersonic cruise operation. These features are described in Section 3.1.4.4.

Because of the single-stream nozzle, the coannular noise benefit is not applicable to this LBE. Therefore, although this engine has competitive supersonic cruise performance, its jet noise characteristics make it necessary to oversize this engine to reach FAR Part 36 noise levels. This oversizing imposes severe system penalties, as shown in Figure 1-9. By applying a mechanical suppressor to the full exhaust area of this engine, jet noise could be reduced, but at the expense of weight, performance, cost and complexity to the overall LBE system. Extensive research and evaluation of jet noise suppressors for single stream nozzles has been conducted as carry-over from the original US SST program. Yet none has been demonstrated in flight to be as effective as static tests would indicate. Because of uncertain in-flight characteristics, a suppressed LBE configuration is not included in this report. Because the coannular noise benefit has greater potential when combined with the VSCE concept than a suppressed LBE, it is recommended that the coannular noise benefit be fully evaluated before experimental work on jet noise suppressors is continued. Further study of the LBE design may lead to concepts that incorporate a coannular nozzle with the inverted velocity profile.

Variable turbine geometry was evaluated for the LBE and was determined to provide no benefit for this engine, primarily because it is a twin-spool design and has a variable area exhaust nozzle. The variable nozzle provides good inlet/engine flow matching characteristics at part power operation, without the complications and penalties associated with variable turbine geometry.

Emission characteristics of the VSCE and the rear-valve VCE at various operating points are not significantly different. Based on the emissions estimates reviewed in Section 3.1.6, neither engine has an advantage. Experimental evaluation of advanced duct-burner concepts is required to substantiate the emissions levels summarized in Section 3.1.6 of this report.

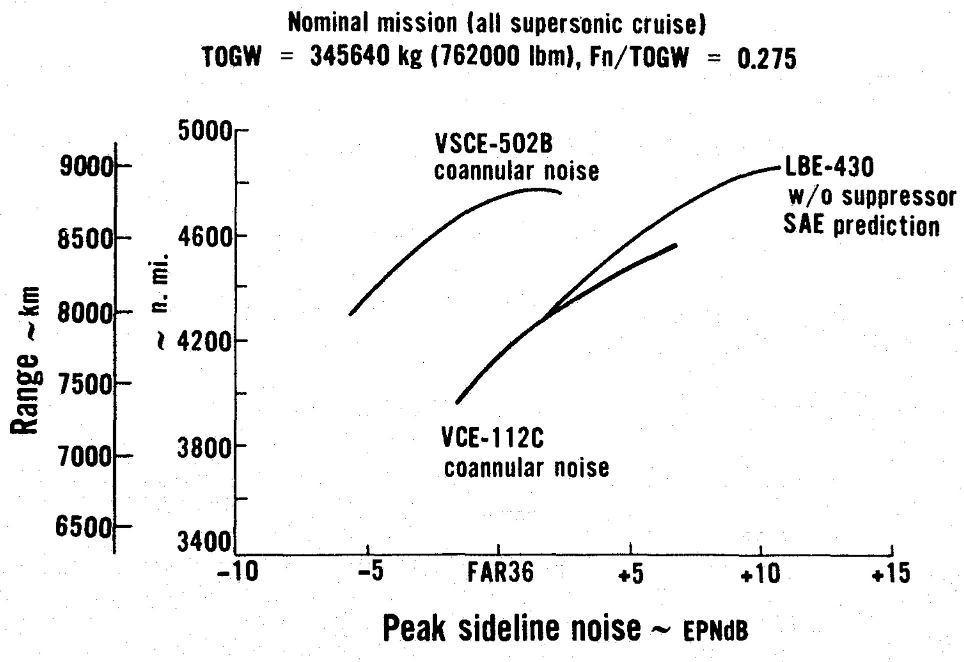


Figure 1-9 Range Comparison of Refined Phase III Engines

1.2 SCREENING STUDIES OF ADDITIONAL UNCONVENTIONAL ENGINE CONCEPTS

An advanced engine with a supersonic fan was defined and compared to the VSCE. It was determined that this concept may have some installation advantages, such as a shorter and lighter nacelle. A preliminary assessment of this supersonic fan engine indicated it has approximately the same supersonic performance characteristics as the VSCE. Because of numerous potential problems and unknowns with the supersonic fan itself, such as shock noise, starting, stability, off-design efficiency and thrust reversing, it was concluded that the supersonic fan may be beyond the time period and level of technology projected for AST engines. The screening study of this supersonic fan engine is summarized in Section 3.3.1.

A boundary layer control concept that has the potential to improve lift and drag performance of the supersonic airplane during take-off and landing was investigated. By bleeding approximately 35% of the bypass stream from the VSCE, and ducting this air to slot nozzles along the hingeline of the wing flap, the lift characteristics of the wing are improved. Evaluation of this concept for reducing noise during take-off, indicates it has no potential benefit. Further evaluation - - using boundary layer control to maintain approach airspeed while reducing wing size (increasing wing loading) shows the potential for a 222 km (120 n.mi.) range improvement. These screening studies are summarized in Section 3.3.2. Further airplane/engine design studies are required to qualify the results of this screening study.

Studies of engine intercooling to increase cycle pressure ratios (Section 3.3.3) and a three-stream reheat cycle (Section 3.3.4) to improve fuel consumption, show there is no overall benefit to either concept relative to less complex engine cycles. No further evaluation of either area is recommended.

The screening study of a three-stream version of the rear-valve VCE showed this concept had more potential than the four preceding unconventional concepts. It was therefore selected for further refinement studies. Refinement of this concept revealed it had approximately the same overall performance as the two-stream rear-valve VCE-112C concept, but had some basic cycle matching problems during off-design operation. Therefore no further evaluation of this concept is recommended.

1.3 PRELIMINARY DESIGN STUDIES

Preliminary design studies and system evaluation of six coannular nozzle concepts indicate the baseline nozzle configuration is the most attractive design. This baseline configuration has multi-hinge, actuated panels for the ejector and reverser openings. These openings are supplemented with short-stroke translating panels that provide additional ejector opening for low speed operation. Reversing is accomplished with internal buckets that block the flow from both engine streams and forces it out through the same openings used for ejector flow. The nozzle concepts that use long-stroke, translating cowls for the ejector openings do not provide any significant advantage over the baseline configuration and translation would require extra landing gear length to provide ground-clearance at airplane rotation during take-off. The coannular plug nozzle design has questionable performance, it is a very complex mechanism, and the applicability of the coannular noise benefit is uncertain. An advanced, balanced-beam nozzle configuration has a significant weight penalty relative to the baseline nozzle. If cascades are required for thrust reversing effectiveness or for targeting the reverse flow, a 5% increase in maximum nozzle diameter is imposed, along with significant weight and complexity problems. Further work is required to determine the need for cascades. These nozzle studies are summarized in Section 3.4.1.

Advanced engine and airframe accessories, if located within the VSCE nacelle, will increase the maximum diameter of the nacelle by as much as 5% relative to that set by the nozzle requirements. Integration studies are required to evaluate remote accessories and gear-drive systems to investigate ways to alleviate this potential installation penalty. Advanced accessories are defined in Section 3.4.2.

Conceptual cross-sections of each refined engine - - the VSCE, the rear-valve VCE, and the conventional LBE - - show that each engine is feasible regarding arrangement of major components, secondary flow systems, location of rotor-support bearings and seals, and structural design of the engine including the engine/airframe mount systems. These cross-sections are shown in Figures 3.4.3-2, -3, and -4.

1.4 CRITICAL TECHNOLOGY REQUIREMENTS AND PROGRAM RECOMMENDATIONS

Critical technology requirements for the VSCE concept are as follows:

*Low noise, high performance coannular nozzle
*Low emissions, high performance duct-burner
Variable geometry components
Low emissions, high temperature primary burner
Hot section materials and cooling technology
Full-authority, electronic control system
Engine/airframe integration features

*Technology programs have been started in these areas.

Program recommendations related with these critical technology requirements are described in Section 3.5. These recommendations include individual component programs, a VCE test bed program to evaluate coannular nozzles and duct-burners in a large-scale engine environment, and follow-on VCE experimental programs.

2.0 INTRODUCTION

As part of the NASA Supersonic Cruise Airplane Research (SCAR) program, P&WA has been conducting advanced supersonic propulsion studies under NAS3-16948 (Phases I and II) and NAS3-19540 (Phase III). The overall objective of this study program is to identify technology programs necessary to provide the basis for design and possible future development of an advanced supersonic propulsion system.

2.1 BACKGROUND

The tasks constituting Phase III of P&WA's advanced supersonic propulsion studies have evolved from broad parametric studies of a large number of engine concepts and from preliminary design studies of the most promising concepts. Phase I consisted of broad parametric studies to evaluate conventional and unconventional engine concepts, assessment of a H_2-fueled supersonic transport and an evaluation of the impact of advanced engine technology versus current technology. The Phase I study showed that noise constraints have a major impact on selection of engine types and cycle parameters. It was also shown that an advanced supersonic commercial transport would benefit appreciably from the application of advanced engine technology in terms of improved system economics and lower noise levels.

As the study progressed into Phase II, refined parametric studies concentrated on the most promising concepts from Phase I: The Variable Stream Control Engine (VSCE) concept, an advanced derivative of a duct-burning turbofan, and other Variable Cycle Engine (VCE) concepts that use valves to vary the cycle. Phase II included a parametric integration study to determine the overall performance and envrionmental engine/airplane characteristics of these concepts, and initiation of preliminary studies. The VSCE and a single rear-valve VCE concept emerged as the most promising engines from Phase II. One of the most promising improvements for these concepts is the potential noise benefit associated with two-stream coannular nozzles. Depending on the flexibility of each VCE concept, this noise benefit can be optimized by independently controlling the temperature and velocity conditions of these coannular flow streams. The trend to more concentrated effort on a few selected engines that was established in Phases I and II was continued into Phase III.

2.2 DESCRIPTION OF PHASE III STUDY TASKS

The overall objective of Phase III was to continue parametric refinement and preliminary design studies of the most promising engine concepts, and to identify critical technology requirements for these engines. Specifically, these concepts were evaluated on an overall basis by P&WA in terms of system parameters (Range, DOC and ROI) and environmental characteristics (noise and emissions). In addition, definition of the most promising engines were provided to NASA SCAR airframe contractors in the form of data-packs for their airplane system assessments.

The following tasks were conducted to meet these program objectives:

Task A – General System Studies

This task continued the parametric evaluation of the rear-valve VCE concepts including adaptability to the coannular nozzle noise benefit, a higher duct-burner temperature and bypass ratio variations. A parametric evaluation of the best engine concept from the Task C Unconventional Engine Studies was also conducted. In addition, the VSCE and a low bypass mixed-flow engine from Phase II were updated and refined to be consistent with the rear-valve VCE concepts.

Task B – Airframe Related Studies

Support to the NASA-Langley SCAR Project Office and their airframe contractors was continued under this task. Data-packs were provided for selected engines and consisted of engine definition in terms of performance, noise and installation characteristics.

Task C – Unconventional Engine Studies

Screening studies of five additional unconventional engine concepts were conducted. The concepts studied were a modified version of the VSCE-502B for a blown-wing airplane, a three-stream rear-valve VCE, a supersonic fan engine, a high pressure ratio engine with intercooling, and a three-stream cycle with reheat. Parametric refinement of the most promising of these unconventional concepts, the three-stream rear-valve VCE, was conducted under Task A.

Task D – Preliminary Design

The preliminary design studies initiated in Phase II were continued under this task. Emphasis was placed on unique engine components, such as the nozzle/reverser system, advanced accessory sizing and location, and design cross-sections of the rear-valve VCE, an updated VSCE, and a low bypass engine with a mixed-flow nozzle.

Task E – Military Applications

Data-packs of militarized versions of selected engines were prepared and provided to NASA-Lewis for overall mission studies.

Task F – Technology Recommendations

Based on the results of the Phase III studies, the critical technology requirements and program recommendations from Phases I and II were reviewed, updated and expanded.

3.0 RESULTS AND DISCUSSION

3.1 PARAMETRIC REFINEMENT STUDIES

3.1.1 Description of Study Engines

Four engine types were selected for refinement studies, three from the Phase II studies and one of the unconventional engine concepts screened during Phase III. The Phase II engines selected were a variable stream control engine, a single rear-valve variable cycle engine, and a low bypass engine. The unconventional concept is a three stream, rear-valve variable cycle engine.

The variable stream control engine (VSCE-502B) was selected for refinement because it was the most promising engine identified in Phase II. The single rear-valve variable cycle engine (VCE-112) was selected because its performance and weight characteristics made it competitive with the VSCE-502B. Also it was the most promising valved VCE identified in Phase II. The unknown element for the VCE-112 concept which required refinement was the applicability of the coannular noise benefit. The Phase I and II studies showed that a low bypass engine configuration with a mixed-flow nozzle has attractive performance characteristics when jet noise levels are ignored. However, it requires a highly effective jet noise suppressor which compromises the potential of this engine configuration. Nevertheless, the low bypass engine (LBE) was selected for refinement in Phase III primarily because it represents a conventional engine for comparison with the VCE concepts. The fourth type of engine, the three-stream, rear-valve VCE concept, was selected because it showed the greatest potential of the additional unconventional engine concepts that were screened under Task C in Phase III. The following sections contain brief descriptions of these four study engines.

3.1.1.1 Variable Stream Control Engine (VSCE)

The Variable Stream Control Engine (VSCE-502B) uses variable geometry components and a unique throttle schedule for independent control of the two flow streams to provide low jet-noise at take-off and high performance at both subsonic and supersonic cruise. Figure 3.1.1-1 shows the basic arrangement of the major engine components. It has a twin spool configuration similar to a conventional turbofan engine. The low spool consists of an advanced technology, multi-stage, variable geometry fan and a low pressure turbine. The high spool consists of a variable geometry compressor driven by an advanced single-stage high temperature turbine. The primary burner is a low-emissions, high efficiency combustor concept such as the Vorbix (vortex burning and mixing) design being evaluated in the NASA/P&WA Experimental Clean Combustor Program. The duct-burner definition will be derived from a NASA/P&WA low emissions duct-burner program currently in progress. The nozzle is a two stream concentric,annular (coannular) design with variable throat areas in both streams and an ejector/reverser exhaust system.

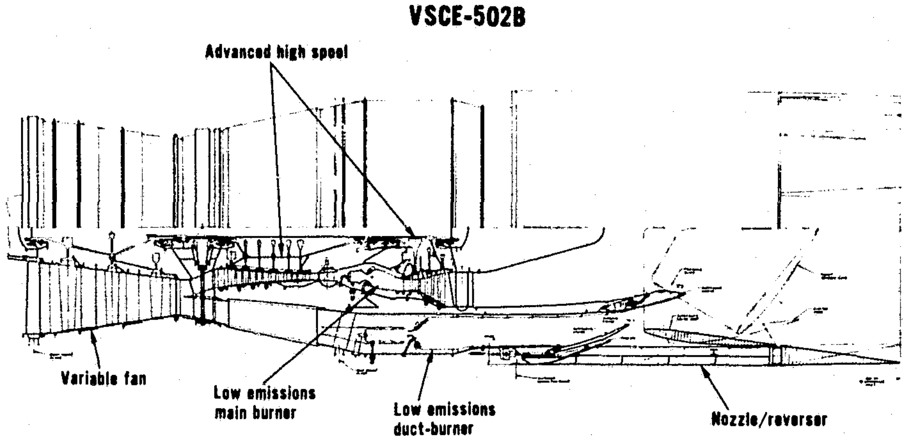


Figure 3.1.1-1 Variable Stream Control Engine (VSCE-502B)

The independent temperature and velocity control for both primary and bypass streams provides an inherent reduction in jet noise. This noise reduction characteristic is based on an inverted velocity profile, where the bypass stream jet velocity is 60 to 70 percent higher than the primary stream velocity during take-off. Model tests conducted both statically and in a wind tunnel simulating take-off flight conditions, resulted in measured noise levels that are approximately 8 EPNdB lower than a single-stream engine operating at the same airflow and thrust level. This coannular noise benefit is being evaluated in a separate NASA-sponsored experimental program conducted by P&WA, and has the potential of being a breakthrough in jet noise control.

Critical Operating Conditions for the VSCE-502B

Take-off – Figures 3.1.1-2a and b depicts the unique inverted velocity profile for take-off operation and also shows related temperature levels in both exhaust streams. As indicated, the primary stream is throttled to an intermediate power setting so that the jet noise associated with the primary stream is low. To provide both the required take-off thrust, and the inverted velocity profile, the duct-burner is operated at its maximum design temperature (1432°C (2610°F)) as shown in Figure 3.1.1-2a. For climb out over the community, both streams are throttled back, and the inverted velocity profile is retained, as shown in Figure 3.1.1-2b. These take-off conditions set the cooling requirements for the duct-burner and nozzle system. Relative to military augmentor systems, which approach stoichiometric combustion (> 2200°C (> 4000°F)), the peak duct-burner temperatures for the VSCE are relatively low, and will not compromise the life capability of this commercial engine.

At the take-off power settings that correspond to FAR Part 36 sideline and community noise levels, the VSCE variable components and throttle settings are matched to "high-flow" the engine. High-flowing is the capability to maintain the maximum design flow of the engine during part-power operation, as required for low noise. This capability compliments the coannular noise benefit to enhance the overall noise characteristics of the VSCE.

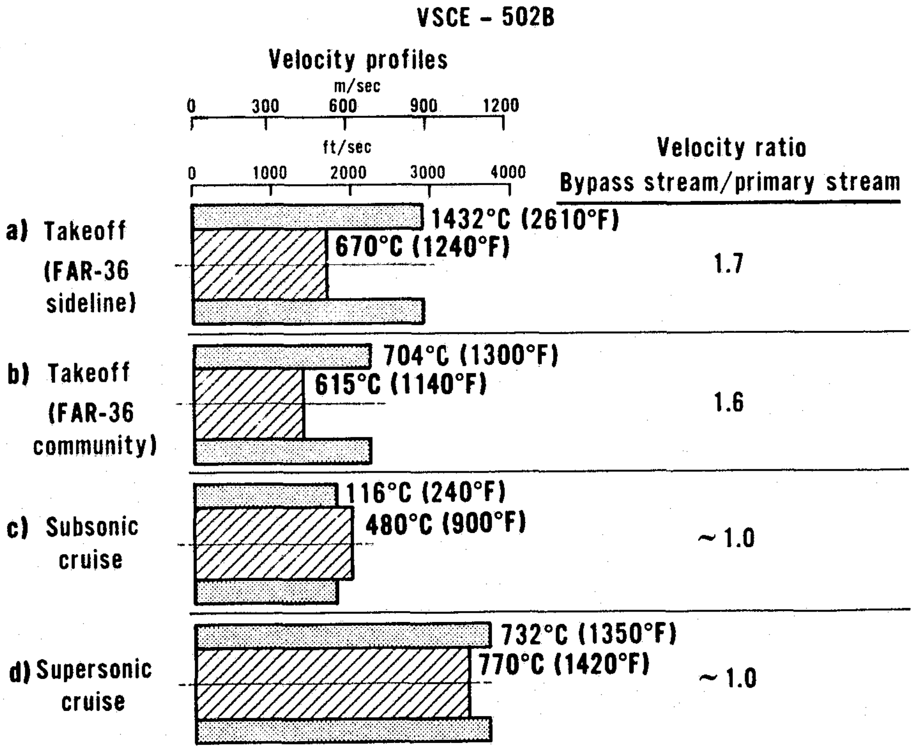


Figure 3.1.1-2 Variability of Exhaust Conditions for the VSCE-502B

Subsonic Cruise – For subsonic cruise operation, the primary burner is throttled to a very low temperature (< 1150°C (< 2100°F)), and the VSCE operates like a moderate bypass ratio turbofan cycle. Exhaust conditions for this third critical operating point are shown in Figure 3.1.1-2c. Again, the variable geometry components are matched to high-flow the engine, so that the engine airflow can be matched almost exactly with the inlet airflow. This greatly reduces inlet spillage and bypass losses, and also improves nozzle performance by working with the ejector to fill the nozzle exhaust area at this part-power condition. This reduces installation losses including boat-tail drag. In this subsonic mode of operation, the VSCE has low fuel consumption that approaches performance levels of current turbofan engines design strictly for subsonic operation.

Supersonic Cruise – For supersonic operation, the VSCE primary burner temperature is increased (relative to take-off), and the high spool speed is also increased. This is accomplished by matching the variable engine components to the higher primary burner temperature. This unique matching technique is referred to as the inverse throttle schedule (ITS) – inverse relative to conventional subsonic engines which cruise at much lower temperatures and spool speeds than occur at take-off conditions. This ITS feature enables matching the high spool to a higher flow rate at supersonic conditions relative to a conventional turbofan. In effect, this high-flow condition reduces the cycle bypass ratio. The level of duct-burner thrust augmentation required during supersonic operation can therefore be reduced. As shown in Figure 3.1.1-2d, the exhaust temperatures from both coannular streams are almost equal, and the variable nozzle areas are set for a flat velocity profile to reach peak propulsive efficiency in both streams. The resulting VSCE fuel consumption characteristics approach those of a turbojet cycle designed exclusively for supersonic operation. The ITS feature enables sizing the VSCE propulsion system for optimum supersonic cruise performance, while also meeting FAR Part 36 noise levels at the other end of the operating spectrum, by means of the coannular noise benefit.

3.1.1.2 Rear-Valve Variable Cycle Engine

The single rear-valve VCE concept incorporates a flow inverting valve which provides the capability for this engine to operate in a turbofan mode for low and intermediate power or in a twin turbojet mode for maximum power. This engine, shown schematically in Figure 3.1.1-3 and in more detail in the cross-section of Figure 3.1.1-4, has a twin spool arrangement. The low spool consists of a multi-stage variable geometry fan driven by two low pressure turbines separated by a flow inverting/mixing valve. The high spool components and burner systems are similar to those of the VSCE. The baseline exhaust system for this engine is similar to that of the VSCE except it has a fixed primary nozzle area.

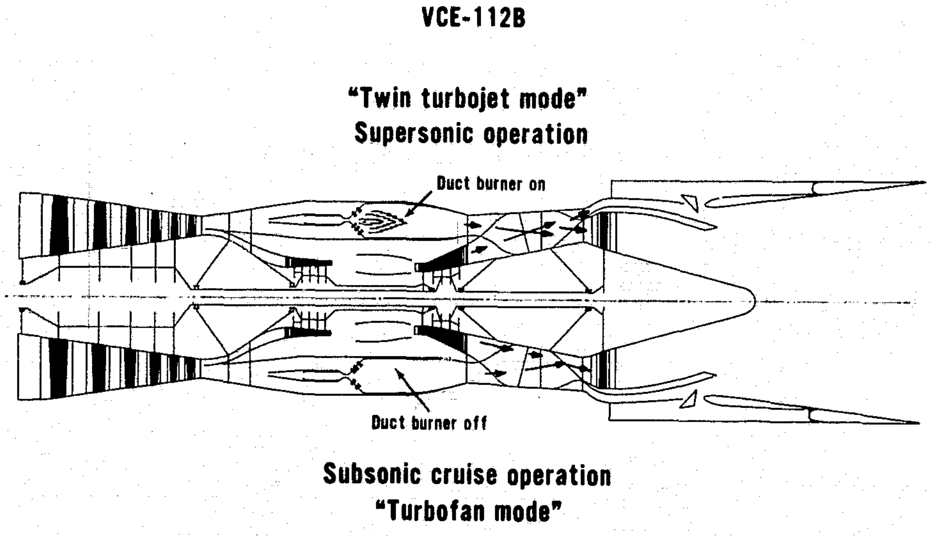


Figure 3.1.1-3 Schematic of the Single Rear-Valve Variable Cycle Engine

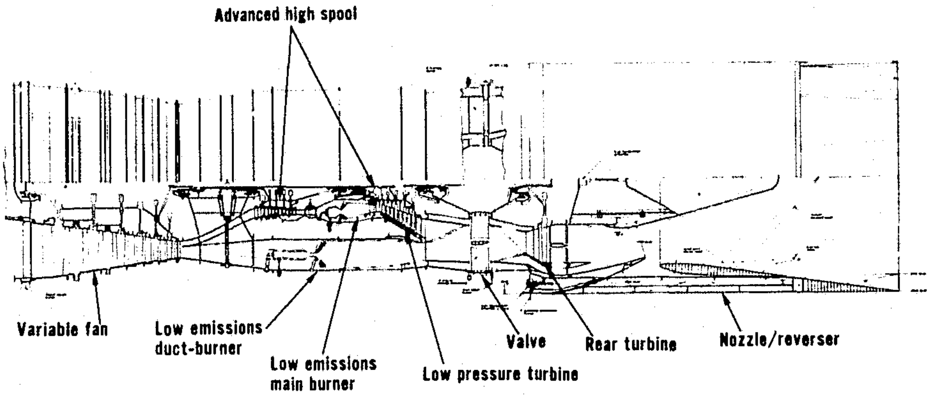


Figure 3.1.1-4 Single Rear-Valve Variable Cycle Engine

This single rear-valve VCE concept has the following features:

- It operates in the twin turbojet mode for high power conditions. This mode (shown in the top half of Figure 3.1.1.3) is especially suitable for supersonic cruise. In this mode, specific fuel consumption is almost constant over the entire thrust range because the duct-burner is upstream of the rear turbine. This flat performance characteristic provides freedom to size the engine for other considerations, including jet noise.

- For take-off, the engine can also be operated in the twin turbojet mode, and the exhaust conditions of both coannular streams can be controlled to approach the inverse velocity profile associated with the coannular noise benefit. The inner exhaust stream can be throttled for intermediate jet velocities by operating the duct-burner at an intermediate temperature. The outer stream velocity can be increased to a maximum level corresponding to the temperature limit of the main burner [1540°C (2800°)].

- At subsonic conditions, in the turbofan mode shown in the bottom half of Figure 3.1.1-3, the high fan pressure ratio is effectively reduced by expansion through the rear turbine. This mode produces a higher bypass ratio and a lower fan pressure ratio cycle similar to the VSCE-502B which is close to optimum for subsonic cruise operation.

- Locating the duct-burner ahead of the valve decreases engine length and improves the flow profile into the duct-burner. This location does, however, require additional bleed air from the fan to cool the valve surfaces.

- The high BPR reduces the gas generator weight and helps to off-set the weight of the valve and additional turbine. This results in a total engine weight comparable to the VSCE concept.

- The parabolic profile from the duct-burner is somewhat attenuated by the rear turbine. This improves the thrust effective efficiency from the duct-burner.

The rear-valve VCE individual stream exhaust conditions are restrained compared to the VSCE, primarily because of the temperature limits of the valve and rear turbine. Therefore, after extensive parametric study in Phase III, it was concluded that the noise reduction benefit of the coannular nozzle does not apply to the rear-valve VCE to the same extent as it does to the VSCE. Consequently, a mixed flow single stream nozzle version of this engine was evaluated in Phase III to determine the potential benefits of an alternate exhaust system.

3.1.1.3 Low Bypass Engine

The low bypass engine (LBE) studied in Phase III is a non-augmented twin spool turbofan configuration with a variable throat area ejector nozzle. Figure 3.1.1-5 is a cross-section of the low bypass engine. This phase III LBE has a higher bypass ratio and increased temperature and cycle pressure ratios relative to the Phase I and II parametric low bypass engines. The details of the cycle differences between the Phase III LBE-430 and the Phase II LBE-405 are described in Section 3.1.4.4.

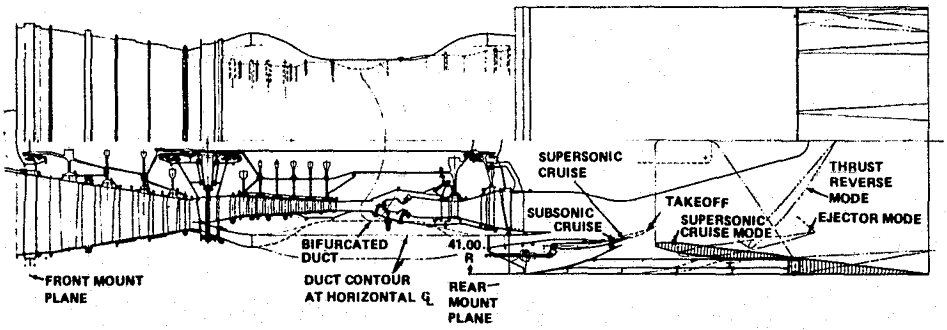


Figure 3.1.1-5 Low Bypass Engine

3.1.1.4 Three Stream Rear-Valve VCE

The three stream rear-valve VCE is a derivative of the two-stream rear-valve VCE described in Section 3.1.1.2. This is a twin spool engine with a portion of the fan flow bypassed around the duct burner and rear turbine. The third stream reduces the flow through the primary and augmented duct streams which in turn reduces the size and weight of the components affected by these streams. The third stream also serves to increase the cruise bypass ratio and improve fuel consumption characteristics but at the expense of specific thrust. A flow-path of the three stream engine is shown in Figure 3.1.1-6.

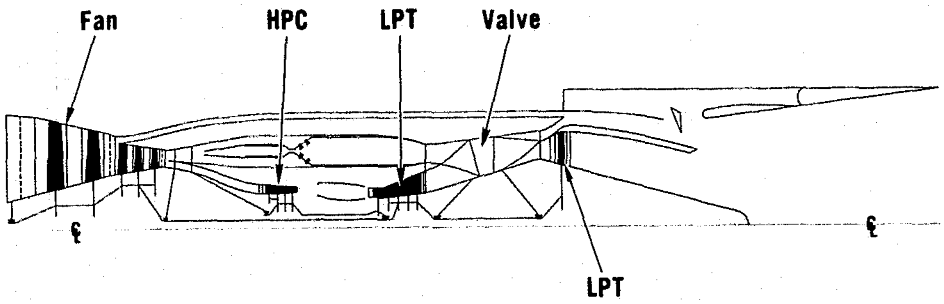


Figure 3.1.1-6 Three Stream Rear-Valve Variable Cycle Engine

3.1.1.5 Other Engines

Other engines that have been studied in Phases I and II, but not selected for Phase III refinement are front and dual-valve VCE's, and afterburning turbofans and turbojet engines. The front and dual-valve VCE, and the afterburning turbofans and turbojets all have weight and/or TSFC penalties that make them non competitive with the engines selected for refinement in Phase III.

3.1.2 General Description of Component Technology

The level of engine component and material technology applied to all the engine concepts that were refined in Phase III is based on advanced technology projected for engine certification in the early 1990's. This allows several years for research and evaluation of the critical technology requirements followed by several years for the engine development program. This section contains a brief description and update of the advanced technology projections that were presented in the Phase II Final Report (Ref. 1).

3.1.2.1 Material Technology

Materials were defined for each engine component with consideration for a proper balance between engine price, weight and design life. An advanced, high-temperature composite material, boron fibers in an aluminum matrix, was selected for fan blades where temperature conditions permitted its use. All other sections of the fan and intermediate case use advanced titanium alloys. In the compressor section, advanced high-temperature titanium alloys were selected for the drum-rotor, hubs, cases and blades for the front stages. For fire safety reasons, steel vanes were used with the titanium blades. Nickel alloys replace the titanium and steel for the hotter rear stages.

The 1538°C (2800°F) CET and 704°C (1300°F) maximum cooling air temperature for the Phase III study engines require high-temperature materials for the engine hot sections. Advanced material projections include high temperature burner liner material (such as an advanced Oxide Dispersion Strengthened material), advanced directionally solidified airfoil materials with internal and external coatings, ceramic endwalls and abradable tip seals, and a high creep-strength disk material. For the rear-valve VCE's, an advanced high-strength nickel sheet alloy was projected for the rear-valve.

3.1.2.2 Component Technology

Advanced technology incorporated in the major components of the Phase III engines are described in the following sections. The component definitions, based on the advanced technology, were used for estimating engine performance, weights and dimensions.

Fan

Variable geometry (variable camber inlet and exit guide vanes and, in some cases, variable pitch stators) is incorporated in the multi-stage fans to provide good subsonic and supersonic cruise efficiency as well as the required stability characteristics. For noise considerations, fan corrected tip speeds were limited to approximately 490 m/sec (1600 ft/sec) and axial spacing between rows of airfoils was set to allow the wakes from upstream airfoils to attenuate before striking the next row of airfoils. The fans are constant mean diameter configurations to obtain high pressure-ratio per stage with minimum cost, weight, and installation dimension penalties.

Compressor

Variable geometry stators are used to obtain good subsonic and supersonic cruise efficiency and stability characteristics. Compressor corrected tip speeds of approximately 400 m/sec (1300 ft/sec), were defined to provide high efficiency while also achieving acceptable pressure ratios per stage. These compressors have a constant mean diameter configuration to provide an optimum combination of aerodynamic loading, weight, cost and diameter match with the fan and primary burner.

Primary Burner

The primary burner is an advanced configuration such as the Vorbix (Vortex burning and mixing) design that minimizes emissions while providing high efficiency and stability. The primary burner depicted in the engine cross-sections contained in this report is based on the NASA/P&WA Experimental Clean Combustor Program (ECCP). Final burner selection will depend on complete results from the ECCP and related main burner emissions programs.

Turbine

All of the Phase III AST engine concepts use a single-stage high-pressure turbine with a multi-stage low-pressure turbine and, for the rear-valve VCE, a second single-stage low-pressure turbine. Variable geometry is not required for the turbine section. Turbine cooling air requirements are set by maximum combustor exit temperature and maximum cooling air (compressor exit) temperatures. Fan exit airflow is used to cool the second low-pressure turbine in the rear-valve VCE. The high-pressure turbine inlet-guide-vanes and first-stage blades employ an advanced multi-hole film cooling technique. The remaining turbine stages are either uncooled or employ convection cooling depending on local gas temperature.

Duct Burners

The duct burner selected for the VCE engines is a low emissions two-stage concept. Final selection of a duct burner concept will be based on complete results of the NASA/P&WA duct burner program (NAS3-19781) and from other advanced combustor programs.

Nozzle/Reverser

A two-stream coannular exhaust nozzle was defined for the VSCE and VCE engines. Because of the coannular nozzle jet noise benefit, these nozzles do not require mechanical suppressors. Variable throat areas and variable exit areas are incorporated for airflow scheduling and matching capability, and good performance. Specifics of the nozzle/reverser are discussed in Section 3.4.1.

Flow-Diverter Valve

The flow-diverter valve is located between the two low-pressure turbine assemblies of the rear-valve VCE's. The valve ducts are sized for a maximum Mach number of 0.5 and a 2% total pressure loss. The valve length is based on duct length-to-height ratio of 4.5. The valve construction was defined as a sheet metal monocoque structure with an internal cooling system for both the stationary and movable surfaces. The level of cooling air was determined as a function of the temperature levels in both engine streams that pass through the valve. The source of cooling air for the valve is the fan stream.

3.1.3 Airplane Study Procedure

The Phase III airplane system studies were basically a continuation of the Phase II evaluation and concentrated on refinement of selected engine concepts. The airplane system study methods and groundrules for Phase III are similar to those used in Phase II. This section briefly reviews the study procedures. A more detailed description is contained in the Phase II Final Report (Ref. 1).

3.1.3.1 Airplane Groundrules

The airplane-related groundrules for Phase III are listed in Table 3.1.3-I. These groundrules were defined at the outset of Phase II by NASA-Lewis after discussions with NASA-Langley and the SCAR airplane and engine contractors. As shown in Table 3.3.3-I, the evaluation of the AST engines has been conducted for a range of airplane system parameters to evaluate sensitivity of unique performance, noise and installation characteristics. As described in Section 3.1.2, all engine definitions in Phase III are based on advanced technology projected for engine certification in the early 1990's.

TABLE 3.1.3-I

AST STUDY GROUND RULES

Airplane Design	Modified Arrow Wing (Langley Reference Airplane)
Flight Mach No.	2.2, 2.4, 2.7
Takeoff Field Length	3200 m (10,500 ft)
Noise Level	FAR Part 36 to -5 EPNdB
Thrust Loading	0.275 and 0.32
Fuel Reserves	Lockheed Report LR 26133
Payload	292 Passengers/27680 kg (61,030 lbm)
Inlet Configuration	Axisymmetric
TOGW	Variable for 7410 km (4000 N. Mi.) Design Range
Range	Variable for TOGW = 345640 kg (762,000 lbm)
Design Mission Profiles	Nominal – All Supersonic Alternate – Mixed with 1110 km (600 N. Mi.) Subsonic Cruise
Economic Evaluation	Based on 4630 km (2500 N. Mi.) Avg. Mission Including 740 km (400 N. Mi.) Subsonic Cruise Leg. Economic model based on NASA CR-134645 (1974 ATA formula)
Engine Technology	For Certification in the Early 1990's

3.1.3.2 Aircraft Characteristics

The baseline aircraft used in the P&WA engine evaluation is the NASA Langley reference aircraft, as described in NASA CR-132374 (Ref. 2). This is basically a modified arrow wing aircraft carrying 292 passengers. The NASA reference aircraft has a TOGW of 345640 kg (762000 lbm) which was held constant while range was determined as propulsion system characteristics changed. For the most promising propulsion systems, the TOGW was scaled to maintain constant design range of 7410 km (4000 n.mi.). An equation defining airframe weight (OEW-pod weight) as a function of TOGW and wing loading was defined by NASA Lewis for refined engine evaluation.

Aerodynamic polars described in NASA CR-132374 were modified for variations in pod drag for each engine, and Reynolds Number changes with flight condition and airplane size. Inlet losses (spillage and/or bypass drag, pressure losses, and boundary layer bleed), engine power extraction, nozzle internal performance, and nozzle boattail drag were evaluated as thrust losses and charged to engine performance. Nacelle external wave and friction drag were book-kept as airplane drag and charged to airplane performance. The nacelle drag was calculated on the basis of an isolated POD with no interference effects.

3.1.3.3 Integration Procedure

The procedures for propulsion system evaluation are identical to those used in Phase II. Climb power setting optimization procedures have been expanded to include the capability to select the optimum climb mode for unique variable cycle engines (VCE).

3.1.3.4 Engine Sizing Procedure

Engine size, as used in the report, refers to the total corrected airflow for each engine. Corrected airflow divided by aircraft take-off gross weight ($WAT_2/TOGW$) is used as the engine size parameter. The range capability of the aircraft is essentially a unique function of $WAT_2/TOGW$ parameter for a given engine type. The take-off field length capability is related to the aircraft thrust loading, i.e., take-off thrust/TOGW. The higher the thrust loading, the shorter the take-off field length capability. Fn/TOGW and $WAT_2/TOGW$ are both defined at 370 km/hr (200 kts) at sea level on a standard +10°C day. Theoretical jet noise of an engine is directly related to its specific thrust (thrust/airflow), which can be calculated from the equation:

$$Fn/WAT_2 = \frac{Fn/TOGW}{4\ (WAT_2/TOGW)}, \text{ for a 4 engine airplane.}$$

Using this equation, theoretical noise can be determined using the particular engine's characteristic noise versus specific thrust relationship. Adjustments are then made for the coannular noise benefit, if applicable to the engine concept being evaluated.

3.1.4 Results of Parametric Refinement Studies

3.1.4.1 Variable Stream Control Engine

Because the Phase II study included extensive refinement of the Variable Stream Control Engine, the Phase III refinement of this concept was relatively narrow in scope and the engine concept was not changed significantly in Phase III. Consequently this engine is still identified as VSCE-502B. A review of the component and installation assumptions for the VSCE-502B identified the following as areas for Phase III refinement and study: 1) nozzle performance, 2) fixed vs. variable primary nozzle and 3) additional schemes for reducing take-off noise.

Nozzle Performance

The refined subsonic cruise ejector nozzle performance trend as a function of power setting for the VSCE-502B is shown in Figure 3.1.4-1. Indicated on this figure is the Phase II performance estimate which was set at CF = 0.93 for all power settings at this subsonic flight condition.* The Phase III refined estimates shown in Figure 3.1.4-1 provide a more precise definition of both internal and overall nozzle performance as a function of flight condition

*At other flight conditions, other representative levels of C_F were applied.

and power setting. This refined nozzle performance estimate results in slightly improved cruise performance, as shown in Figures 3.1.4-2 and 3.1.4-3; and slightly better transonic and subsonic climb TSFC, all of which account for the small range increase shown in Figure 3.1.4-4 for the Phase III VSCE-502B.

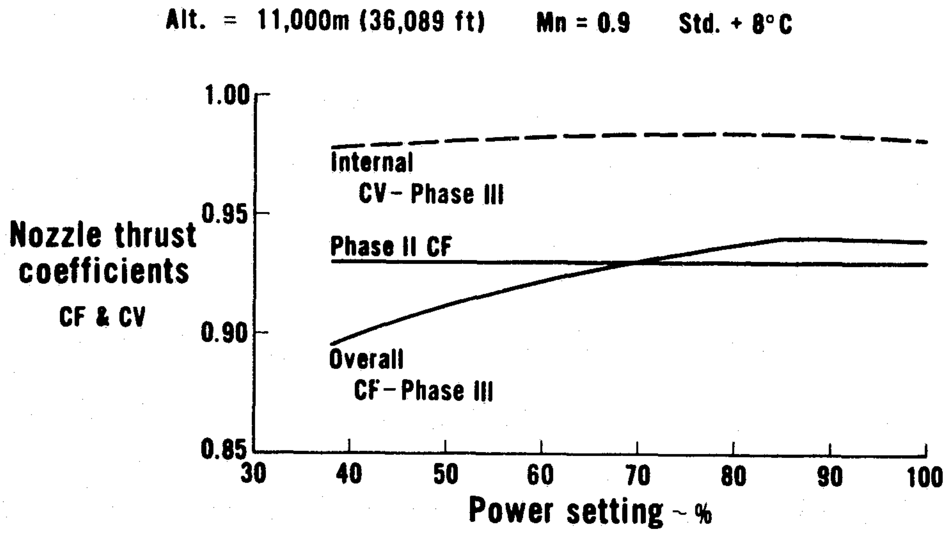


Figure 3.1.4-1 VSCE-502B Nozzle Performance Estimate for Subsonic Cruise

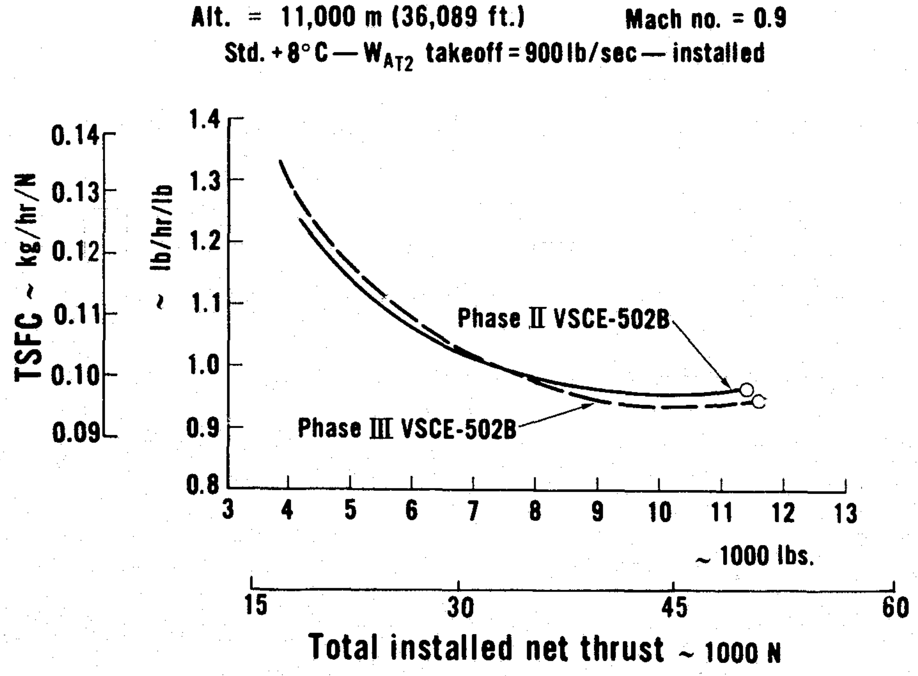


Figure 3.1.4-2 VSCE-502B Subsonic Cruise Performance

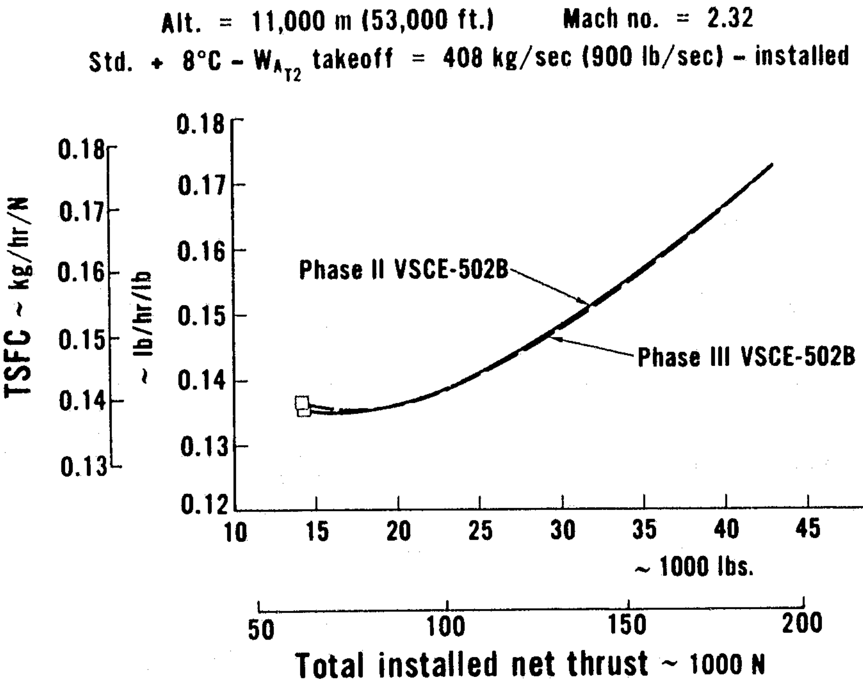


Figure 3.1.4-3 VSCE-502B Supersonic Cruise Performance

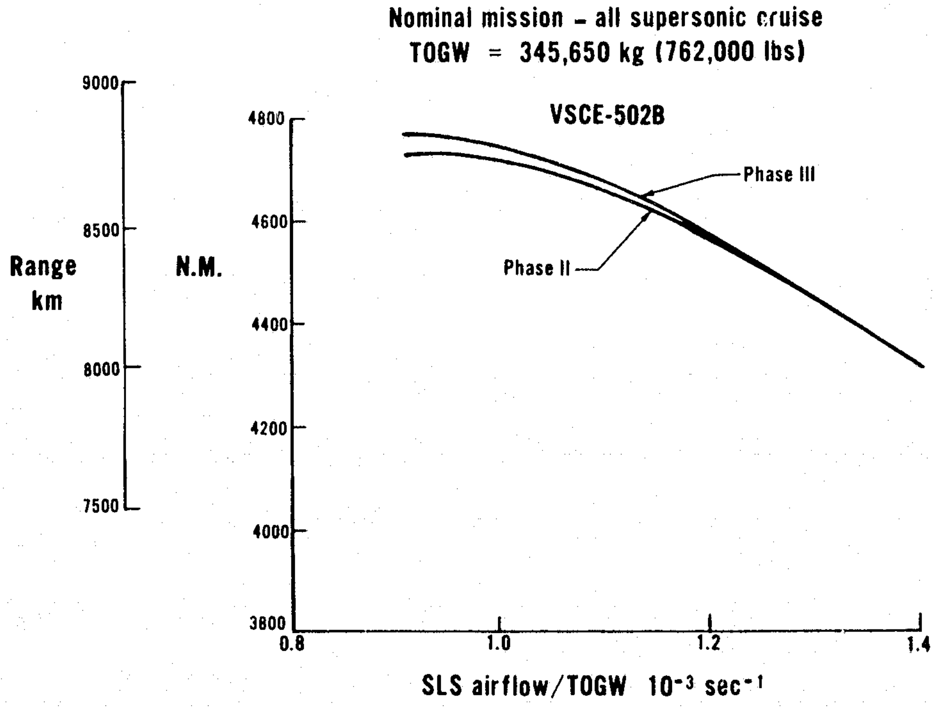


Figure 3.1.4-4 Phase II and Phase III VSCE-502B Range Comparison

Fixed vs. Variable Primary Nozzle

Because the VSCE-502B primary exhaust nozzle variation is small (20% from maximum to minimum), a fixed primary nozzle was evaluated to assess its impact on engine and system performance. The incentive was to simplify the nozzle design. The effect of the fixed nozzle was small except during transonic climb, where the TSFC penalty was significant. At a typical low supersonic climb Mach number (1.3), the TSFC penalty is about 5%. This penalty diminishes with increasing Mn and disappears at about Mn 2.3. The effect of this reduced climb performance in a fixed gross weight aircraft is a 139 km (75 nm) range penalty due to higher fuel consumption during supersonic climb, plus a 55 km (30 nm) range penalty associated with the lower dry thrust available for the cruise to alternate airport fuel allowance. The total range penalty for the fixed primary nozzle is shown in Figure 3.1.4-5 for the nominal and mixed missions.

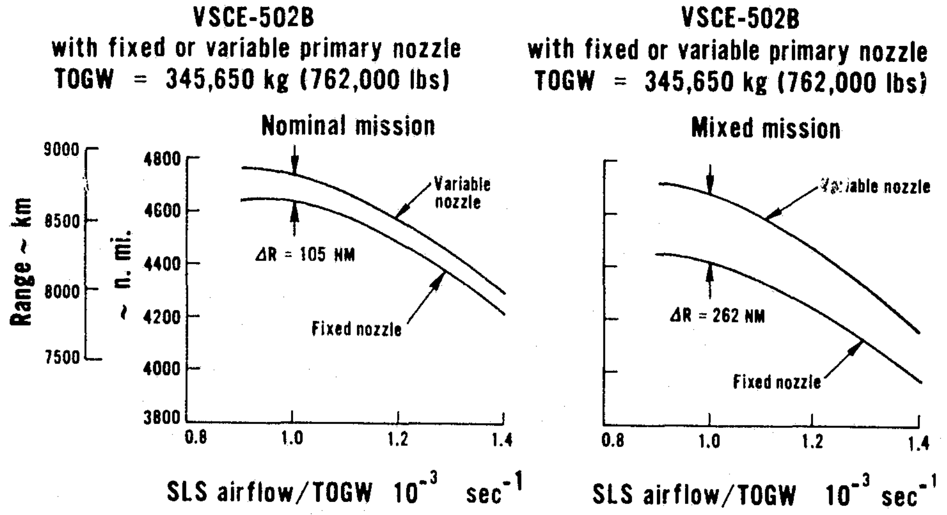


Figure 3.1.4-5 VSCE-502B Range Comparison With Fixed and Variable Primary Exhaust Nozzle

A fixed primary nozzle would result in a lighter engine; however, to offset the 195 km (105 nm) range penalty, weight savings of over 544 kg (1200 lbs) per engine would be required. Weight savings of this magnitude are not possible by going from a variable to a fixed primary nozzle.

The variable primary nozzle also allows better inlet/engine matching, better engine performance over a wide range of power settings and flight conditions, and allows control of exhaust conditions for maximum benefit from the coannular noise reduction effect (reviewed in Section 3.1.5). Therefore, until more detailed trades between performance and life cycle cost improvements with a fixed primary nozzle can be made, the advantages of the variable primary nozzle appear to outweigh the potential weight and complexity benefits of the fixed primary nozzle. The variable primary nozzle is therefore retained in the VSCE-502B definition.

Other Refinements

Two schemes were evaluated as possible means of reducing noise at take-off: duct water injection and fan overflow. This preliminary study indicated that, at constant thrust, 1 to 4 dB reduction in sideline noise is possible for each scheme. Figure 3.1.4-6 shows that depending on the amount of fan overflow at take-off, up to 4 dB reduction in jet noise could be achieved. However, this overflow capability requires oversizing the inlet and fan, with attending installed performance and weight penalties. Similar results could be achieved with water injection into the bypass stream in the region of the duct-burner. This is accomplished at the expense of added system weight and complexity (tankage, plumbing, controls and support equipment).

Further study of these concepts is required to fully assess their potential. These methods for reducing take-off noise should be considered as alternatives to simply oversizing the entire engine for additional noise reduction.

$W_{AT2\ takeoff}$ = 354 kg/sec (780 lbm/sec)
Fn = 2.33 × 10^5 N (52,400 lbs) (const.)
Fn/TOGW = 0.275

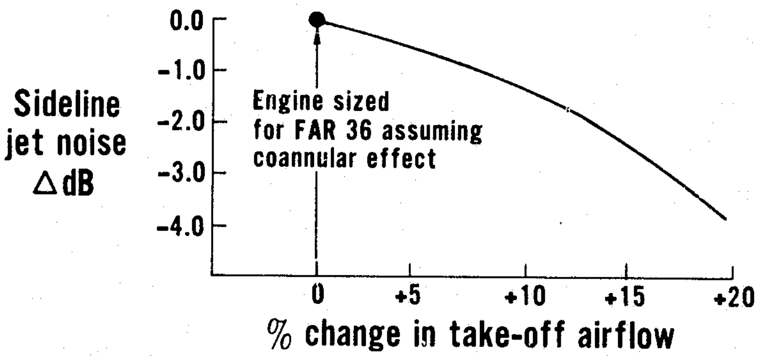


Figure 3.1.4-6 Sideline Jet Noise Reduction With Fan Overflow

Overall Results

Figures 3.1.4-2, 3.1.4-3 and 3.1.4-4 show that the Phase III VSCE-502B is slightly better than the Phase II version. The improvement is primarily the result of the refined definition of the ejector nozzle performance. The variable primary nozzle was retained as a feature of the variable stream control engine concept because of the flexibility it provides and the overall performance advantage. While the preliminary evaluation of fan overflow and duct water injection show potential as possible methods to reduce take-off noise, they are not incorporated in the VSCE-502B because of the related penalties and complexities associated with each.

3.1.4.2 Single Rear-Valve VCE

The single rear-valve VCE-112B was defined late in the Phase II studies and therefore was not refined in Phase II to the same level as the VSCE-502B. The Phase III studies refined the VCE-112B to a level consistent with the VSCE-502B. These studies included refinement of duct-burner efficiency and nozzle performance, and assessment of cycle parameter variation (bypass ratio and primary burner exit temperature) on engine performance, noise and weight. The ability of the rear-valve VCE concept to benefit from the coannular noise effect was also studied. The Phase III refined rear-valve VCE is designated the VCE-112C.

Refinement Studies

For the parametric definition of the VCE-112B, the thrust effective efficiency of the duct burner was set at the same level as the chemical efficiency, i.e., 99.5%. The Phase III VCE-112C duct burner definition includes a temperature profile effect for the air leaving the burner. This profile reduces the thrust effective efficiency to 97.5%. This 2% reduction compares to a 5% reduction for the VSCE-502B which has no turbine stage behind the duct burner to reduce the temperature profile effect. The refined nozzle performance for the VCE-112C is similar to that discussed for the VSCE-502B in section 3.1.4.1.

Performance Comparison

Figures 3.1.4-7 and 3.1.4-8 show the installed performance for Phase II VCE-112B and Phase III VCE-112C at both supersonic and subsonic cruise conditions. The 1.5% increase in supersonic cruise TSFC for the VCE-112C is almost entirely due to the 2% decrease in duct-burner efficiency since at supersonic cruise the refined nozzle performance was unchanged compared to the Phase II values. The slightly higher subsonic cruise TSFC for the VCE-112C is the result of the refined nozzle performance. A range comparison of the Phase II and Phase III engines (Figure 3.1.4-9) shows a range deficit of approximately 222 km (120 n. mi.) for the Phase III VCE-112C. This range deficit is mainly the result of lower duct-burner efficiency (1.5% higher supersonic cruise and climb TSFC) and a small weight increase due to an increase in nozzle diameter.

Expanded Parametric Studies

The ranges of cycle parameters studied during Phase II were expanded in the Phase III rear-valve VCE studies, as shown in Table 3.1.4-I. The overall pressure ratio was held at 25:1 for Phase III as limited by the nominal cruise Mach number of 2.4 and maximum allowable compressor exit temperature of 1300°F.

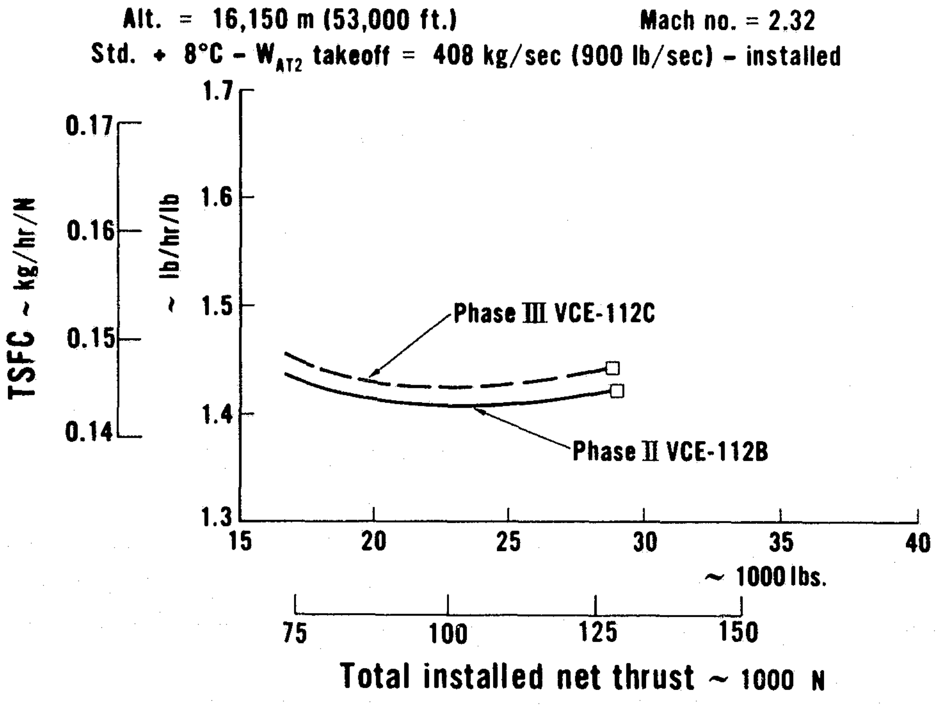


Figure 3.1.4-7 VCE Supersonic Cruise Performance

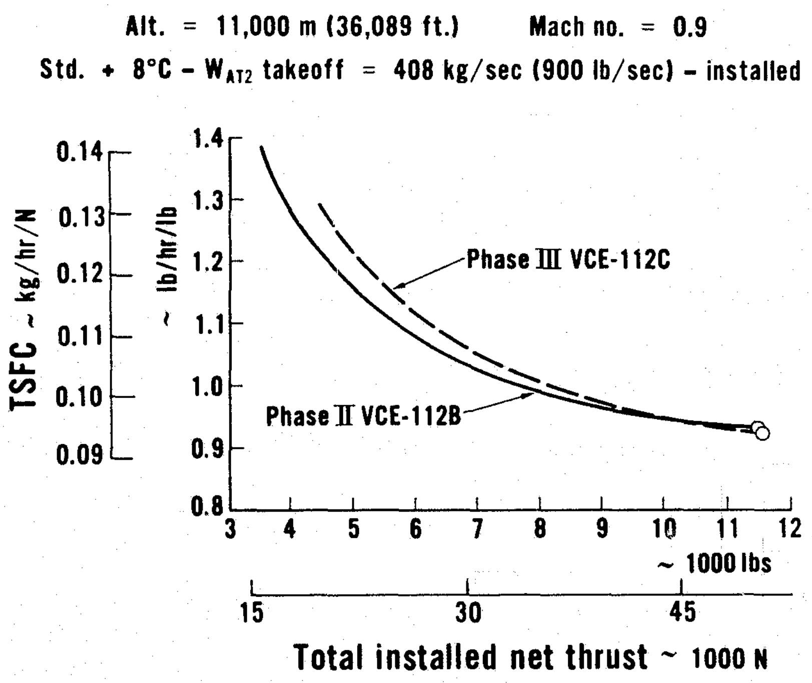


Figure 3.1.4-8 VCE Subsonic Cruise Performance

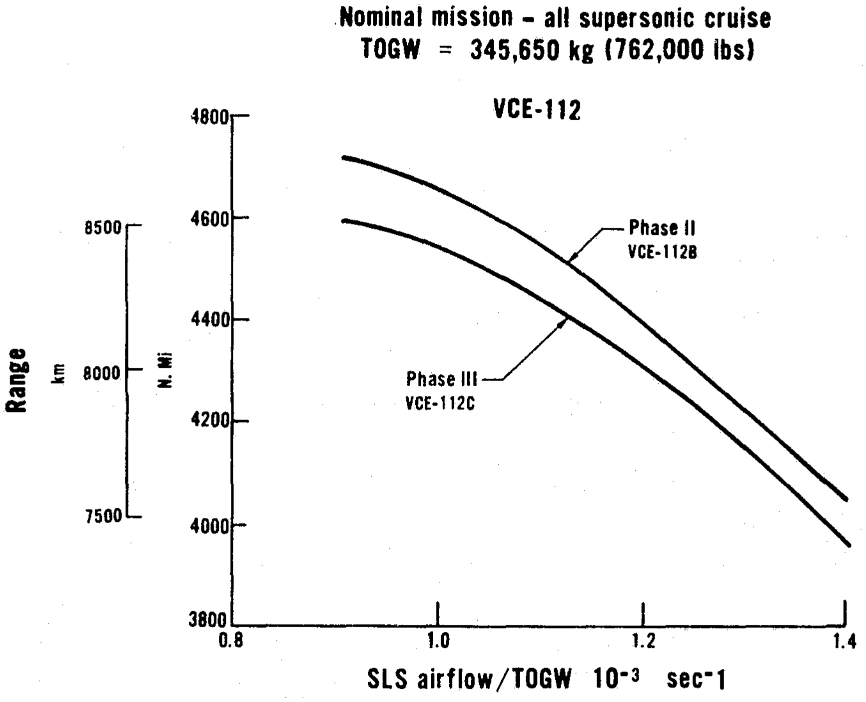


Figure 3.1.4-9 Phase II and Phase III VCE Range Comparison

TABLE 3.1.4-I

RANGE OF VCE CYCLE PARAMETERS STUDIED – Phase III vs. Phase II

Sea Level Static

Parameter	Phase II VCE-112B	Phase III VCE
Fan pressure ratio	4.8 - 5.8	4.8 - 5.8
Bypass Ratio	2.5	1.5 - 3.5
Overall pressure ratio	25:1	25:1
Combustor exit temp., °C (°F)		
Primary burner	1538 (2800)	1538 (2800)
Duct burner	1038 (1900)	1038-1316 (1900-2400)
Turbine work split	Optimized	Optimized

Figure 3.1.4-10 shows the effect of varying BPR and FPR on TSFC and net thrust. As shown, increasing FPR results in improved TSFC but decreased net thrust at supersonic cruise; and increasing BPR results in penalties to both TSFC and net thrust. Decreasing BPR below 2.5 results in insufficient fan surge margin (cross-hatched area on the curve) in the subsonic cruise turbofan mode. Bleeding air from the bypass stream, to increase surge margin, would result in significant penalties to specific thrust. There would also be engine weight penalties associated with the larger high spool required for the lower BPR. Higher BPR, 3.0 and above, would increase the rear-turbine annulus area, requiring a reduced design speed for the low spool and resulting in overall engine weight penalties at these higher bypass ratios. The results of this parametric study indicate that the 2.5 BPR selected in the Phase II studies is about optimum for the rear-valve VCE, based on both performance and weight considerations.

The effect of varying cycle parameters on the coannular noise benefit was also evaluated. For each case evaluated, it was apparent that the valved engine cycle was not as easily adapted to the coannular noise benefit as the VSCE. This is discussed further in Section 3.1.5.2.

Increased Duct-Burner Temperature

A higher duct-burner temperature, 1316°C (2400°F) maximum, was evaluated as a means to offset reduced specific thrust of the higher FPR cycles. The 2.5 BPR, 5.8 FPR VCE-112C with a duct-burner temperature at 1038°C (1900°F) was the base cycle used for this evaluation. The higher duct-burner temperature cycle, designated the VCE-122, and the VCE-112C are compared in Table 3.1.4-II. Higher duct-burner temperature requires an increased level of cooling air flow for the valve and rear turbine which results in reduced rear turbine efficiency.

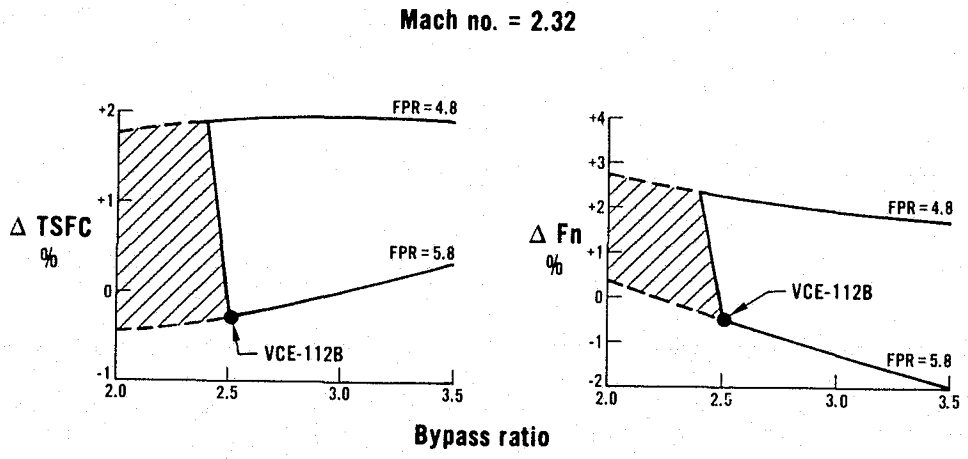


Figure 3.1.4-10 Effect of Varying BPR and FPR On VCE Fuel Consumption and Net Thrust

TABLE 3.1.4-II

SINGLE REAR-VALVE VCE CYCLE COMPARISON
Sea Level Static

	Baseline Separate Stream VCE-112C	Hotter Separate Stream VCE-122
Cycle characteristics		
Corrected airflow, kg/sec (lb/sec)	408 (900)	→
Fan pressure ratio	5.8	→
Bypass ratio	2.5	→
Overall pressure ratio	25:1	→
Combustor exit temp., °C (°F)		
Primary burner	1538 (2800)	→
Duct-burner	1038 (1900)	1316 (2400)
Turbine work split $\sim \frac{\Delta H_{LPT\,1}}{\Delta H_{LPT\,Total}}$	0.40	0.30
Engine weights and dimensions		
Bare engine, kg (lbs)	5194 (11,450)	5216 (11,500)
Engine + nozzle/reverser, kg (lbs)	6192 (13,650)	6214 (13,700) (+0.4%)
Max. diameter, m (in.)	2.18 (86.0)	2.18 (86.0)
Engine + nozzle/reverser length, m (in.)	7.87 (310)	7.82 (308)

Figure 3.1.4-11 compares the supersonic performance of the VCE-112C and VCE-122. The higher TSFC for the VCE-122 is, for the most part, a direct result of the increased cooling air requirement. The increase in maximum thrust for the VCE-122 at subsonic cruise (turbofan mode), shown in Figure 3.1.4-12, is the result of the VCE-122's lower cycle bypass ratio match at this flight condition. The increase in TSFC at subsonic cruise for the VCE-122 is a result of the increased cooling air requirements. For reference, the VSCE-502B is shown in Figures 3.1.4-11 and -12. Based on these and other performance factors, a system evaluation of the VCE-122 was conducted. In the fixed TOGW reference aircraft, the VCE-122 is compared to the baseline VCE-112C in Figure 3.1.4-13. This figure shows aircraft range as a function of the engine size parameter (SLS airflow/TOGW). This figure shows that in either the nominal (all supersonic) or mixed missions (111 km (600 nm) subsonic leg included) the baseline engine is somewhat better than the VCE-122 engine in all engine sizes. However, the greater thrust capability of the VCE-122 in the turbofan mode allows this engine to be sized somewhat smaller than the VCE-112C and still cruise subsonically in the turbofan mode. This point is illustrated by the cross hatched fence shown on the mixed mission system plot. Below these sizes the engine would have to cruise subsonically in the turbojet mode and would thus incur a significant fuel consumption penalty.

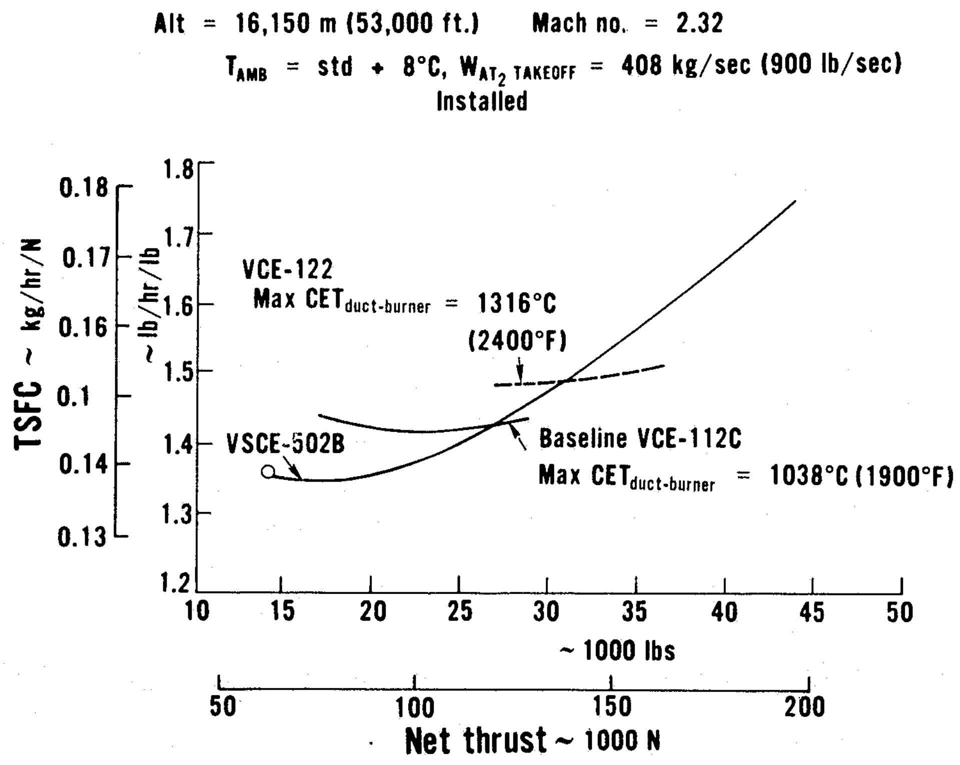


Figure 3.1.4-11 Effect of Increased Duct-Burner Temperature On VCE Supersonic Cruise Performance

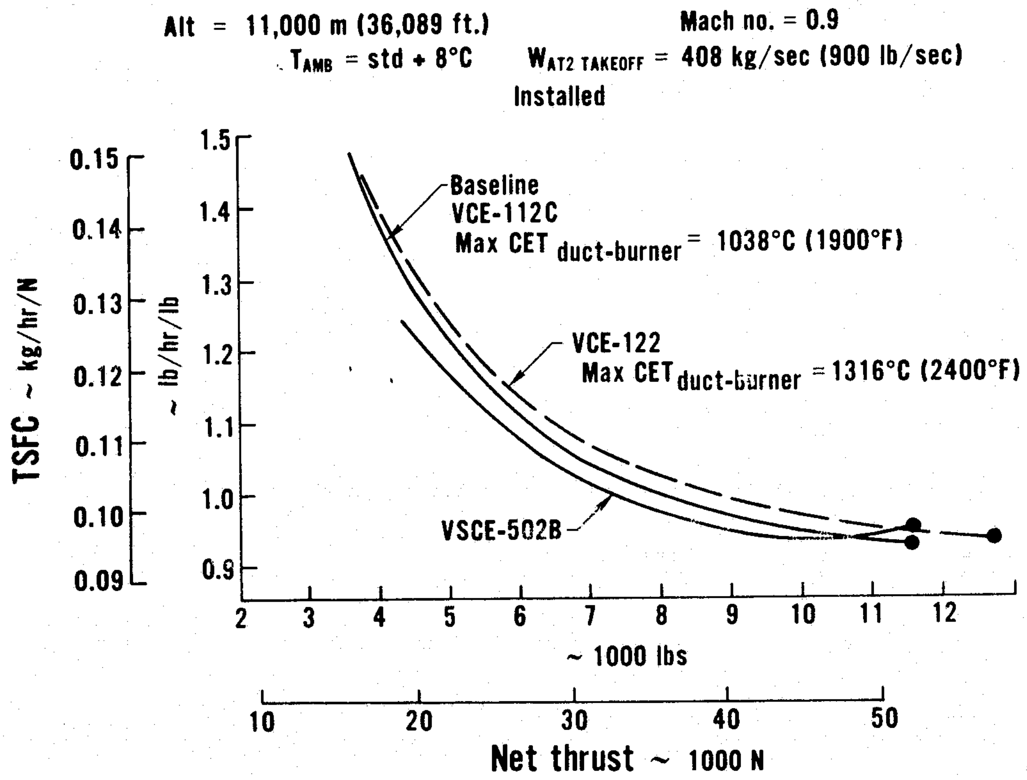


Figure 3.1.4-12 Effect of Increased Duct-Burner Temperature On VCE Subsonic Cruise Performance

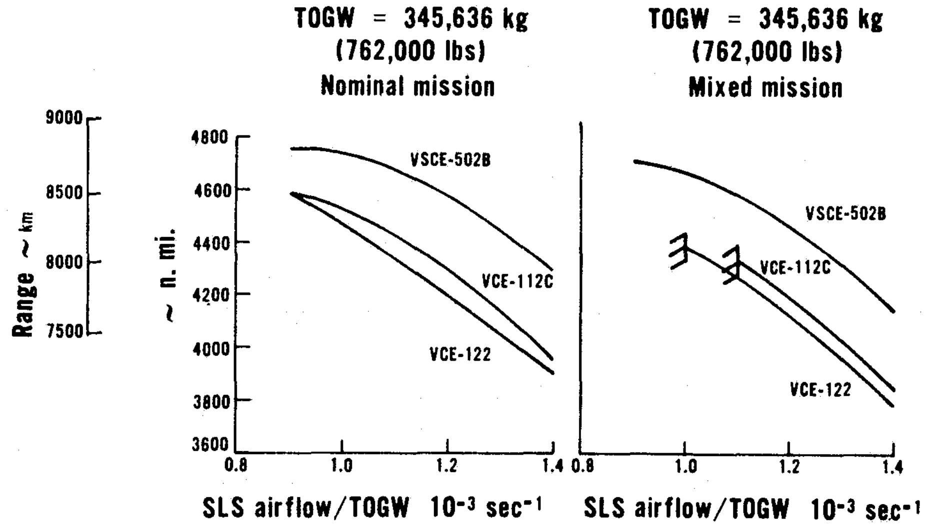


Figure 3.1.4-13 Effect of Increased Duct-Burner Temperature On VCE Range

Because of the higher supersonic cruise TSFC for the VCE-122 and its heavier weight (due to the effect of the hotter duct burner on rear turbine size), no further evaluation of this engine was conducted. Therefore, the 2.5 BPR VCE-112C was retained as the baseline single rear-valve variable cycle engine. As shown in Figure 3.1.4-13, the VSCE-502B has better range capability for all engine sizes.

Single Stream Nozzle Rear-Valve VCE-112M

Since the coannular noise benefit for the rear-valve VCE was determined to be small compared to the VSCE (Section 3.1.5.2), the potential system benefits of a less complex single-stream nozzle was evaluated for the VCE-112. A single-stream nozzle was selected and the mixed flow version of the VCE-112 was designated the VCE-112M. A cross-section of the VCE-112M is shown in Figure 3.1.4-14. The two flow streams are mixed just aft of the rear turbine in the twin-turbojet mode,and, as in the VCE-112C, in the valve in the turbofan mode.

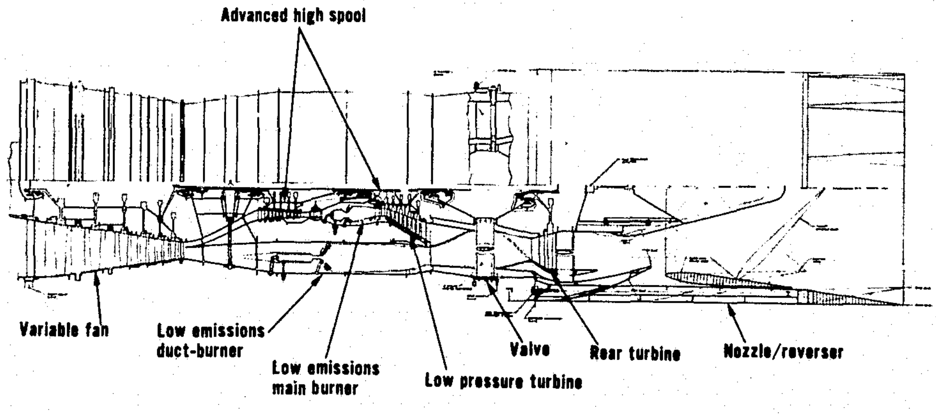


Figure 3.1.4-14 Mixed Flow Variable Cycle Engine (VCE-112M)

The cycle characteristics of the VCE-112M are essentially the same as the VCE-112C (Table 3.1.4-II). Only slight adjustments to the turbine work split between the two low pressure turbine assemblies were required to provide efficient mixing of the outer and inner streams. Figure 3.1.4-15 shows the supersonic cruise performance for the VCE-112M relative to the VCE-112C and the VSCE-502B. As shown, performance at this operating condition is basically unchanged from the separate-stream VCE-112C. This similarity is due to two factors: the cycle changes required to obtain efficient mixing are not significant enough to affect supersonic operation; and the cycle is insensitive to the level of mixing (45% was estimated) because the conditions of the two streams being mixed (temperatures and pressures) are very close. This second factor precludes the need for a mechanical mixer and eliminates associated weight and pressure loss effects. Figure 3.1.4-16 shows subsonic performance characteristics. The maximum dry thrust is lower than the two reference engines because the mixed-flow VCE-112M matches subsonically at a slightly higher bypass ratio.

Figure 3.1.4-17 shows a system comparison of the mixed-flow rear-valve VCE-112M and the VCE-112C and VSCE-502B engines. As shown in the previous figures, differences in engine performance are not significant factors in this comparison; however, there is 5.5% engine weight difference shown in Table 3.1.4-III that accounts for much of the difference in range. This weight increase for the mixed engine is caused by the effects of the rematched cycle, causing a reduction in design speed of the low spool. As was the case with the increased temperature VCE-122, the difference in turbofan mode maximum climb and cruise thrust capability has an effect on the mixed mission minimum engine size. An overall airplane system comparison between the rear valve VCE-112C and the VSCE-502B is presented in Section 3.1.7.

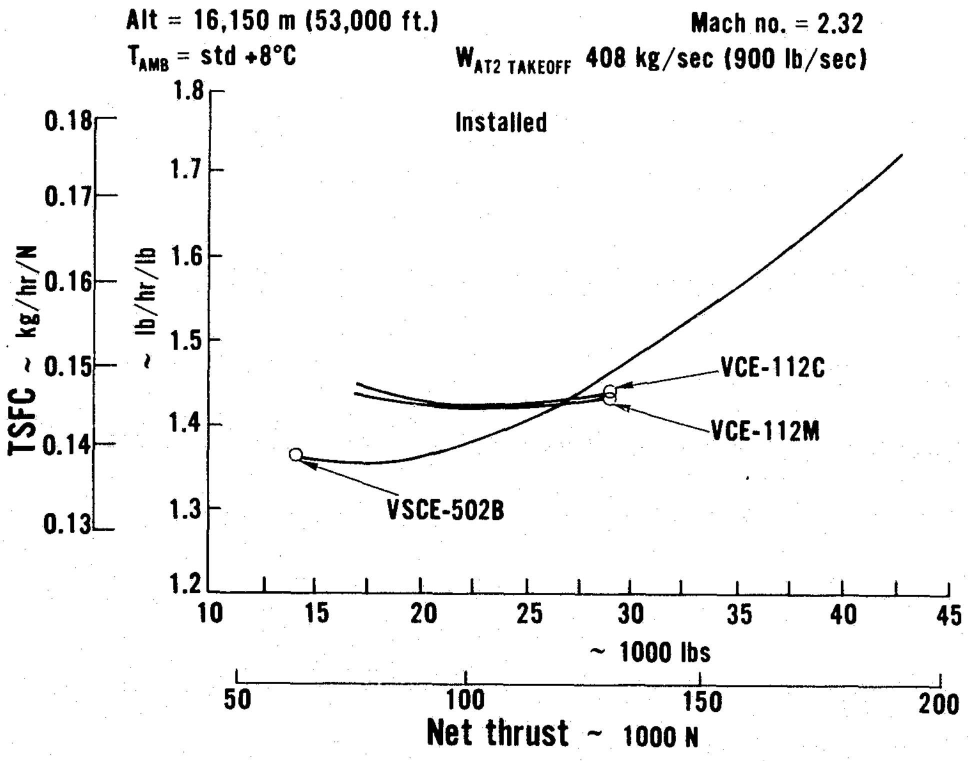


Figure 3.1.4-15 VCE-112M Versus VCE-112C Supersonic Cruise Performance Comparison

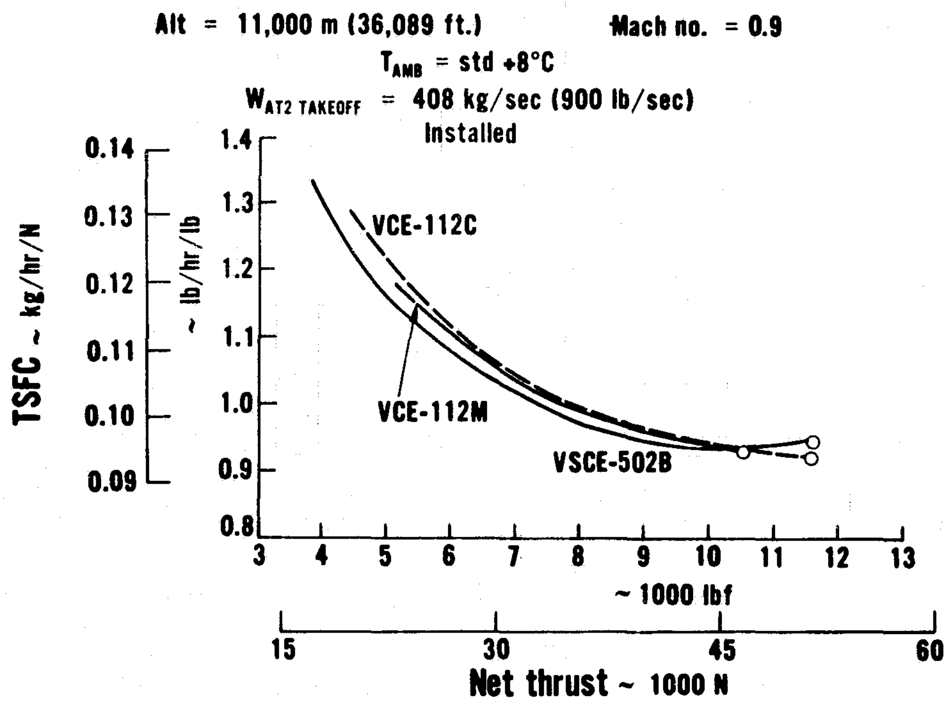


Figure 3.1.4-16 VCE-112M Versus VCE-112C Subsonic Cruise Performance Comparison

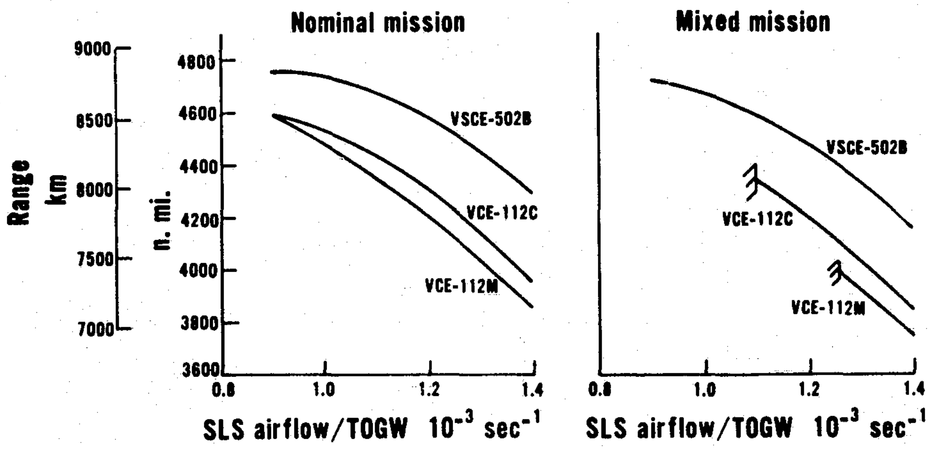


Figure 3.1.4-17 VCE-112M Versus VCE-112C Range Comparison

TABLE 3.1.4-III

SINGLE REAR-VALVE VCE CYCLE COMPARISON
Sea Level Static

	Baseline Separate Stream VCE-112C	Mixed Flow VCE-112M
Cycle characteristics		
Corrected airflow, kg/sec (lb/sec)	408 (900)	→
Fan pressure ratio	5.8	→
Bypass ratio	2.5	→
Overall pressure ratio	25:1	→
Combustion exit temp., °C (°F)		
Primary burner	1538 (2800)	→
Duct-burner	1038 (1900)	→
Turbine work split ~ $\frac{\Delta H_{LPT1}}{\Delta H_{LPT\ Total}}$	0.40	0.47
Engine weights and dimensions		
Engine + nozzle/reverser, kg (lbs)	6192 (13,650)	6532 (14,400) (+5.5%)
Max. diameter, m (in.)	2.18 (86.0)	2.18 (86.0)
Engine + nozzle/reverser length, m (in)	7.87 (310)	8.38 (330)

3.1.4.3 Three Stream Single Rear-Valve VCE

One of the additional unconventional concepts screened under Task C was the three stream rear-valve engine. This concept was selected for refined parametric evaluation because of its potential TSFC improvements relative to the VCE-112C. Table 3.1.4-IV presents the cycle and installation characteristics of the three-stream, rear-valve VCE (designated VCE-130) and, for comparison, those of the two-stream rear valve VCE-112C. For the same airflow size, the three-stream engine is lighter and has a smaller diameter than the VCE-112C.

TABLE 3.1.4-IV

PHASE III REAR-VALVE VCE COMPARISON
Sea level static

	Baseline VCE-112C	Three-Stream Rear-Valve VCE-130	Hotter Duct-Burner Three-Stream Rear-Valve VCE-131
Cycle characteristics			
Corrected airflow ~ kg/sec (lbm/sec)	408 (900) →	→	→
Fan pressure ratio	5.8	6.1 →	→
Bypass ratio	2.5	2.9 →	→
Overall pressure ratio	25:1	22.6:1 →	→
Combustor exit temp ~ °C (°F)			
Primary burner	1538 (2800) →	→	→
Duct-burner	1038 (1900) →	→	1316 (2400)
Engine Weights and Dimensions			
Bare engine ~ kg (lbm)	5195 (11,450)	4650 (10,250)	4680 (10,320)
Engine + nozzle/reverser kg (lbm)	6190 (13,650)	5630 (12,410)	5660 (12,480)
Max diameter ~ m (in)	2.18 (86.0)	2.11 (83.0)	2.11 (83.0)
Engine + nozzle/reverser length ~ m (in)	7.87 (310)	7.26 (286)	7.26 (286)

The higher bypass ratio of the VCE-130 results in smaller core and duct-burner sizes and, therefore, lower specific thrust at climb and cruise. Off setting this reduced thrust, in addition to the lower weight and smaller size, is an improved supersonic cruise TSFC (~2%) for the VCE-130 relative to the VCE-112C. The supersonic performance characteristics of both engines are compared in Figure 3.1.4-18. To provide the required thrust, without changing cycle characteristics, the VCE-130 has to be scaled up 25% in flow size to provide sufficient climb thrust. The scaled VCE-130 is 17% heavier than the VCE-112C. The weight penalty of the scaled VCE-130 causes a 333 km (180 n mi.) range penalty which more than offsets its TSFC advantage (167 km (90 n. mi.) range increase) and results in a lower range capability relative to the VCE-112C. The only significant benefit of the VCE-130 relative to the VCE-112C is, when both engines are scaled to large sizes in order to reduce jet noise, the VCE-130 imposes less penalty to the overall system.

In an attempt to increase the climb and cruise thrust of the VCE-130, and thereby avoiding the significant weight and size penalties associated with the scaled-up engine, a higher duct-burner temperature version was evaluated. This engine is identified as the three stream rear-valve VCE-131 and its cycle and weight characteristics are summarized in Table 3.1.4-IV. As shown in Figure 3.1.4-18, thrust was increased significantly when increasing the duct-burner temperature from 1038°C (1900°F) to 1316°C (2400°F). However, the higher temperature VCE-131 also has a small (1%) increase in supersonic cruise TSFC relative to the VCE-112C. It has an engine weight decrease of approximately 9% relative to the VCE-112C, both sized to the same airflow. The increased rear turbine annulus area and reduced low-spool speed associated with the higher duct-burner temperature increase the weight of the VCE-131 relative to the VCE-130 (both engines in the same flow size).

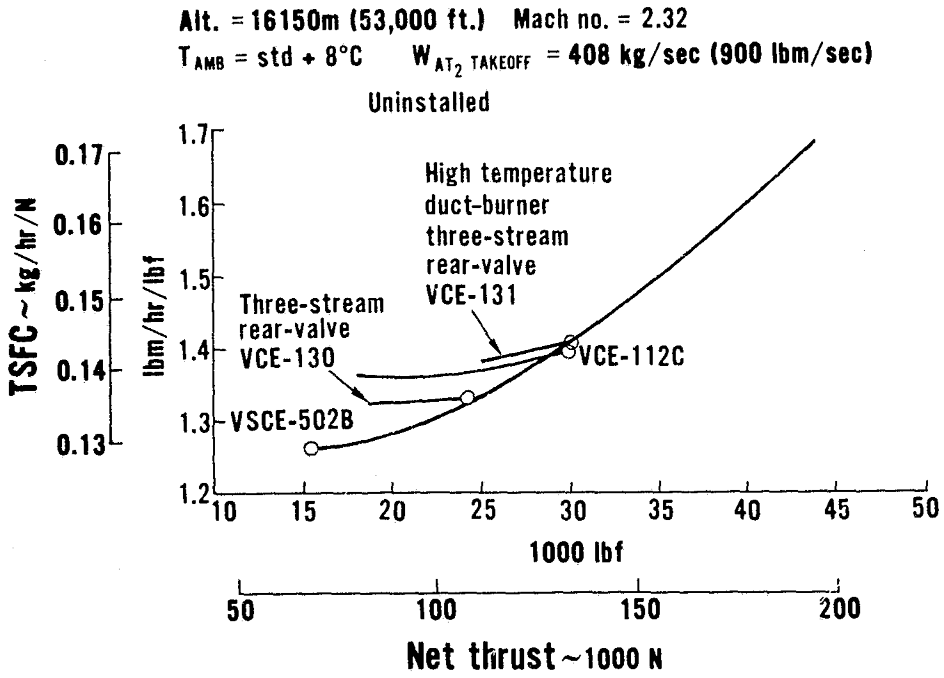


Figure 3.1.4-18 Impact of Increased Duct-Burner Temperature On VCE-131 Supersonic Cruise Performance

A range evaluation indicates the VCE-131 to have an advantage of approximately 90 km (50 n. mi.) over the VCE-112C. This is the net effect of the 1% increase in TSFC (-90 km (-50 n. mi.)) and the 9% reduction in weight (+180 km (+100 n. mi.)). While this hotter duct burner version of the three stream engine appears to be slightly better than the two stream VCE-112C when both are sized for the same flow size, there are several factors that, if evaluated in detail, would tend to offset this advantage. These factors include the relative optimism of the three stream performance estimates (100% mixing efficiency with no additional pressure losses, etc.) and the probability that a variable rear turbine would be required to match the cycle in the turbofan mode of operation (adding weight, increasing the complexity and adversely affecting the performance because of increased turbine cooling requirements). Because of these uncertainties, the small range advantage of the three stream concept was not considered sufficient to justify further study and the two-stream VCE-112C was retained as the baseline rear-valve engine.

3.1.4.4 Low Bypass Engine

A conventional Low Bypass Engine (LBE) selected from Phase II was updated and refined for consistency with cycle assumptions and advanced technology levels that were projected for the refined VCE concepts described in the preceeding sections. These LBE refinement studies included:

- LBE cycle and component studies(cycle and component refinements, fan pressure ratio warpage studies, and flow control of the bypass stream),
- variable nozzle studies,
- variable turbine geometry studies.

LBE Cycle and Component Refinement Studies

The Phase III refined LBE incorporates several features that provide significant improvements relative to the Phase II parametric evaluation of low bypass engines. Some of the features that resulted in improvements in variable cycle engine performance, such as inverse throttle schedule, resulted in improved LBE performance as well. In addition, two new features that are unique in their effect on the mixed-flow LBE performance have been included in this refined engine definition. These improvements include:

- Refined ejector nozzle performance,
- High cycle pressure ratio provided by a twin-spool design,
- Higher combustor exit temperature, 1538°C (2800°F) maximum with the inverse throttle ratio (ITS) feature,
- Variable nozzle throat area for improved performance and engine/inlet matching,
- Beneficial effect of off-design fan pressure warpage (unique benefit to LBE),
- Aerodynamic flow control of the bypass stream at supersonic cruise (unique benefit to LBE).

Cycle Refinements – Table 3.1.4-V summarizes the parametric LBE-405 and VSCE-502 engines at their sea level static aero design points. Also included in this table are the refined Phase III engine cycles (VSCE-502B, VCE-112C and LBE-430). As shown, the parametric engines and the Phase III engines were defined with different cruise Mach number capabilities, 2.7 and 2.4 respectively. The reduction in cruise Mach number from the parametric study level of 2.7 to 2.4 for the refined engines allows an increase in engine cycle pressure while observing the maximum compressor discharge temperature of 704°C (1300°F). To achieve the higher cycle pressure ratio with minimum compressor stages, a twin-spool design was selected for all of these refined engines.

Each of the Phase III refined engines uses a maximum combustor exit temperature of 1538°C (2800°F). For both the LBE and VSCE engines, this represents an increase of 111°C (200°F) from the parametric study level. The supersonic cruise airflow level of the refined engines was increased over the parametric airflow schedule. This resulted in a significant increase in nonaugmented thrust at supersonic cruise. As a result of this cruise thrust increase, the bypass ratio of the refined LBE was increased to 0.4. The 0.4 BPR was chosen to match the 2.4 Mn climb and cruise thrust requirements without an augmentor. As a result of the BPR increase, improvements in subsonic cruise fuel consumption and engine weight were realized, relative to the parametric LBE-405.

Fan Pressure Ratio Warpage Studies – The fan pressure warpage levels used for the refined LBE studies represent the warpage characteristics of advanced, multi-stage fan designs. At the fan aero design point there is no fan pressure warpage. This study showed that relative to a flat fan pressure ratio profile, moderate amounts of fan warpage for off-design operation could result in reductions in cycle BPR at certain critical flight conditions. For this case, warpage is defined as a greater reduction in fan pressure ratio in the bypass stream than in the engine stream, when the engine lapses from subsonic to supersonic operating conditions. By matching the refined engine with this off-design fan warpage characteristic, a 2 percent increase in supersonic cruise thrust and a 0.5 percent reduction in TSFC was obtained relative to the same cycle with unwarped fan characteristics.

TABLE 3.1.4-V

ENGINE CYCLE AND INSTALLATION SUMMARY

	Parametric Engines		Phase III Refined Engines		
Engine Identification	LBE-405	VSCE-502	LBE-430	VSCE-502B	VCE-112C
Mission Mn, Max.	2.7	2.7	2.4	2.4	2.4
Cycle Characteristics (S.L.S. Take-off)					
Fan Pressure Ratio	4.1	3.3	4.0	3.3	5.8
Bypass Ratio	0.1	1.3	0.4	1.3	2.5
Cycle Pressure Ratio	17:1	15:1	21.5:1	20:1	25:1
Max. Combustor Temp. ~ °C (°F)					
Primary Burner	1427 (2600)	1427 (2600)	1538 (2800)	1538 (2800)	1538 (2800)
Duct Burner	–	–	–	–	1900
Total Correction Airflow ~ kg/sec (lbm/sec)	408 (900)	408 (900)	408 (900)	408 (900)	408 (900)
Engine Weights and Dimensions					
Bare Engine Weight ~ kg (lbm)	5985 (13000)	4515 (9950)	5270 (11620)	4760 (10500)	5195 (11450)
Engine + N/R ~ kg (lbm)	7075 (15600)	5785 (12750)	6530 (14400)	6080 (13400)	6190 (13650)
Max. Dia. ~ m (in.)	2.16 (85)	2.24 (88)	2.08 (82)	2.24 (88)	2.19 (86.3)
Engine + N/R length ~ m (in)	7.65 (301)	6.43 (253)	7.06 (278)	6.76 (266)	7.87 (310)

Flow Control of the Bypass Stream – Refinement studies conducted around the LBE – 430 engine showed a significant cruise performance sensitivity to mixing plane conditions. One of the sensitive parameters is the Mach number of the bypass stream. The bypass stream Mach number at the plane where the bypass stream is mixed with the engine stream is affected by either the engine cycle parameters, such as BPR or FPR, or the primary stream mixing plane Mach number. Selection of cycle parameters that result in relatively high bypass stream Mach numbers effectively place a control on the cycle lapse characteristics between design and off-design flight conditions, especially supersonic cruise. As a result of this Mach number control, improvements in engine performance may be achieved at two important flight conditions: supersonic cruise and part-power subsonic cruise. At supersonic cruise, the reduction in the bypass ratio lapse between the sea level static aero design point and cruise condition increases non augmented cruise thrust by 4 percent and improves TSFC by 1 percent relative to an LBE with a lower mixing plane Mach number. At a typical low power setting, corresponding to subsonic cruise, TSFC is reduced by nearly 2 percent.

Impact of Variable Nozzle Throat Area on Engine Performance

For the LBE, a variable nozzle throat area has the capability to:

- Improve engine climb and cruise thrust capability and fuel consumption,
- Offer greater flexibility in matching various inlet airflow schedules, and
- Improve engine installed part power fuel consumption.

Figures 3.1.4-19 and 20 compare the estimated subsonic and supersonic cruise performance characteristics of the Phase III LBE 430 engine matched with both a fixed throat area and a variable nozzle throat area. At supersonic cruise the variable nozzle throat area is used both to achieve a higher inlet corrected airflow and to maintain it during part throttle operation. By increasing cruise airflow, supersonic cruise thrust is increased by 10 percent and TSFC is improved by 1.5 percent (Figure 3.1.4-20). At a typical low power subsonic cruise power setting, the variable nozzle feature of the LBE 430 improves engine fuel consumption (due primarily to improved engine/inlet matching) by 8 percent (Figure 3.1.4-19).

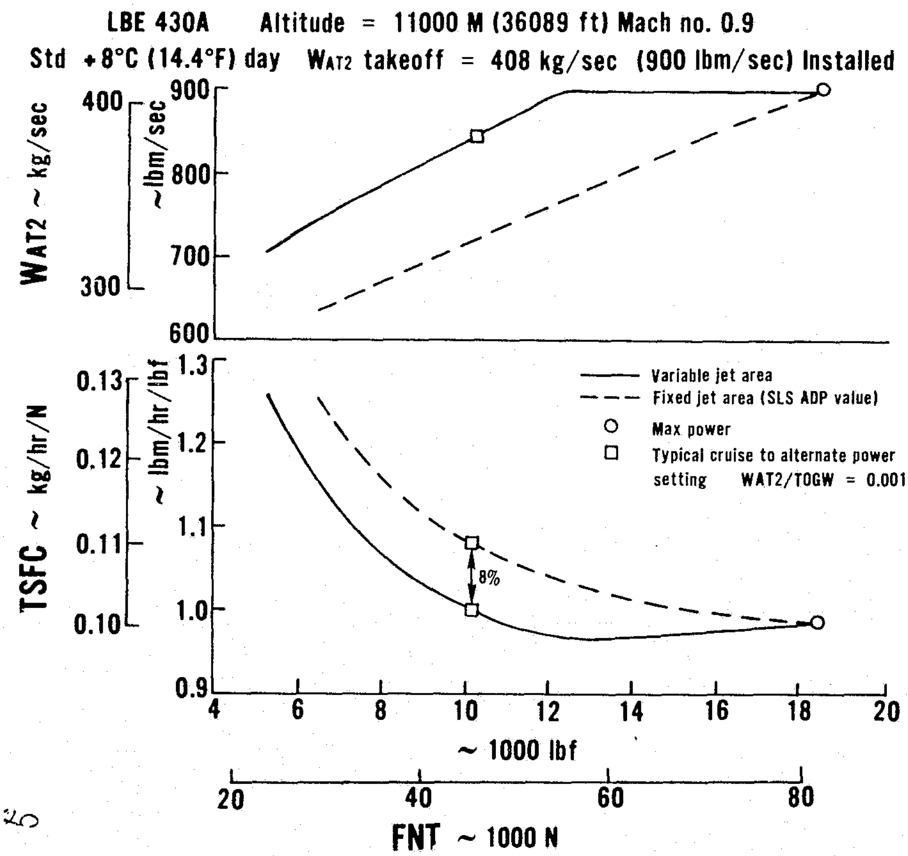


Figure 3.1.4-19 LBE-430A Subsonic Cruise Performance

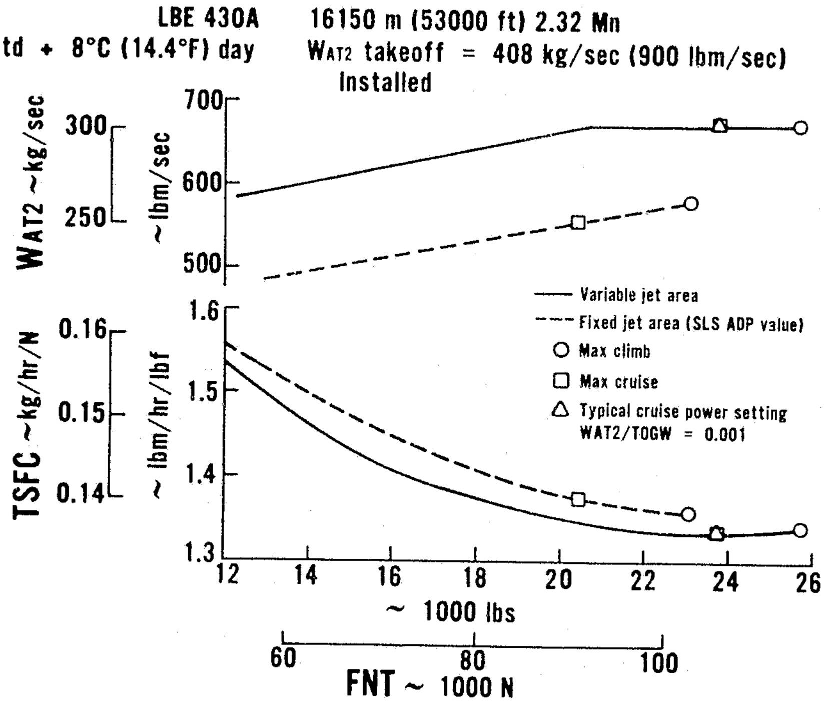


Figure 3.1.4-20 LBE-430A Supersonic Cruise Performance

Variable Turbine Geometry

In this study the combined effects of variable nozzle geometry and a variable area low turbine were assessed in terms of their overall effect on subsonic cruise fuel consumption of the LBE cycle. Only variable turbine geometry in the low pressure turbine was evaluated as previous studies had shown little benefit for variable high pressure turbines in these twin-spool engines.

For single-spool, non-mixed-flow turbojets, variable turbine geometry combined with a variable nozzle throat area provides some part throttle performance benefit. For single spool jets, variable turbine geometry allows the engine to maintain compressor match (holding up cycle pressure ratio) while the variable nozzle feature permits the engine to more closely match supersonic inlet airflow schedules, thus minimizing inlet associated drags at off-design operation, especially subsonic cruise.

However, for the twin-spool design, the mixed-flow LBE does not benefit from variable turbine geometry because of the overriding effect of the mixing plane static pressure balance requirement that limits the cycle flexibility that would otherwise be provided by variable turbine geometry. Although there are some changes in cycle parameters when the low pressure turbine area is varied, there is no performance benefit beyond that achieved with a variable nozzle alone.

System Comparison of Phase II and III LBE'S

The refined Phase III Low Bypass, mixed-flow, non augmented engine (LBE-430), offers significant performance imporvements relative to the parametric Phase II LBE-405 engine. These potential improvements are summarized in Table 3.1.4-VI.

Figures 3.1.4-21 and -22 show the unsuppressed part throttle supersonic and subsonic cruise performance of the Phase II LBE-405 and Phase III LBE-430 engines. Figure 3.1.4-23 shows that, for the nominal mission, nearly a 10 percent improvement in aircraft range can be achieved with the LBE-430 engine relative to the Phase II LBE-405, due to improved performance and installation characteristics (weight and dimensions). Slightly greater improvements would be possible in the mixed mission due primarily to the relatively large improvement in subsonic cruise fuel consumption.

An overall airplane system comparison of the LBE-430 with the variable cycle engines described in the preceeding sections is presented in section 3.1.7.

TABLE 3.1.4-VI

LBE-430 PERFORMANCE IMPROVEMENT RELATIVE TO THE PHASE II PARAMETRIC LBE-405 ENGINE

	Low Power (55%) Subsonic Cruise Δ TSFC ~ %	Supersonic Cruise Δ TSFC ~ %
Cycle and Component Refinements	−12.1	−0.1
Fan Warpage Effect	0.0	−0.5
Bypass Flow Choking Effect	−1.7	−1.1
Variable Turbine Geometry	0.0	0.0
Total	−13.8	−1.7

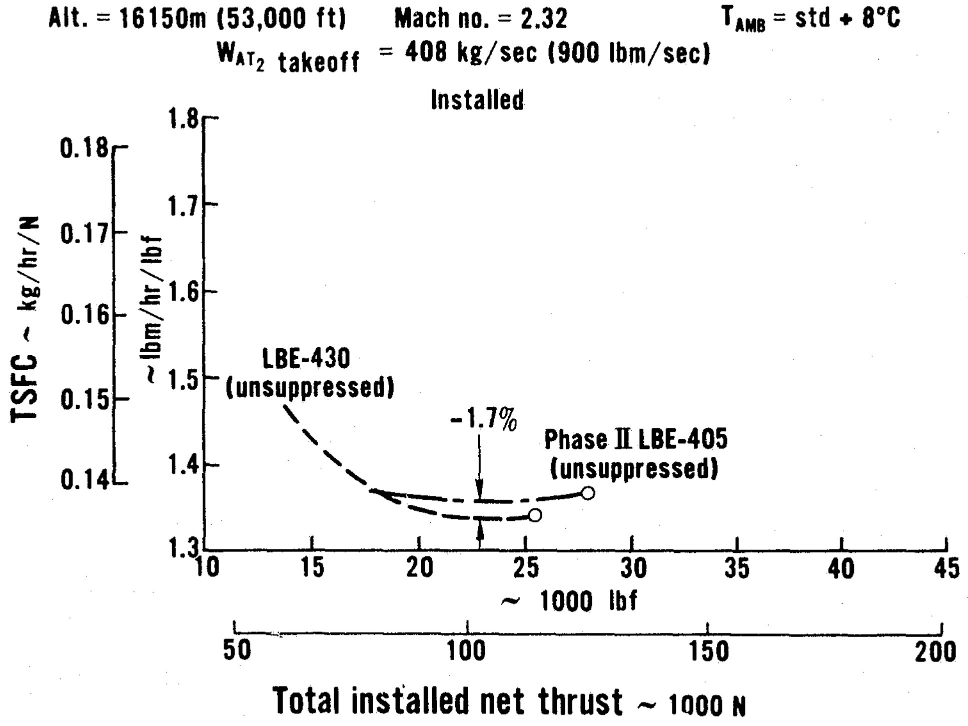


Figure 3.1.4-21 Supersonic Cruise Performance Comparison for Phase II and Phase III LBE's

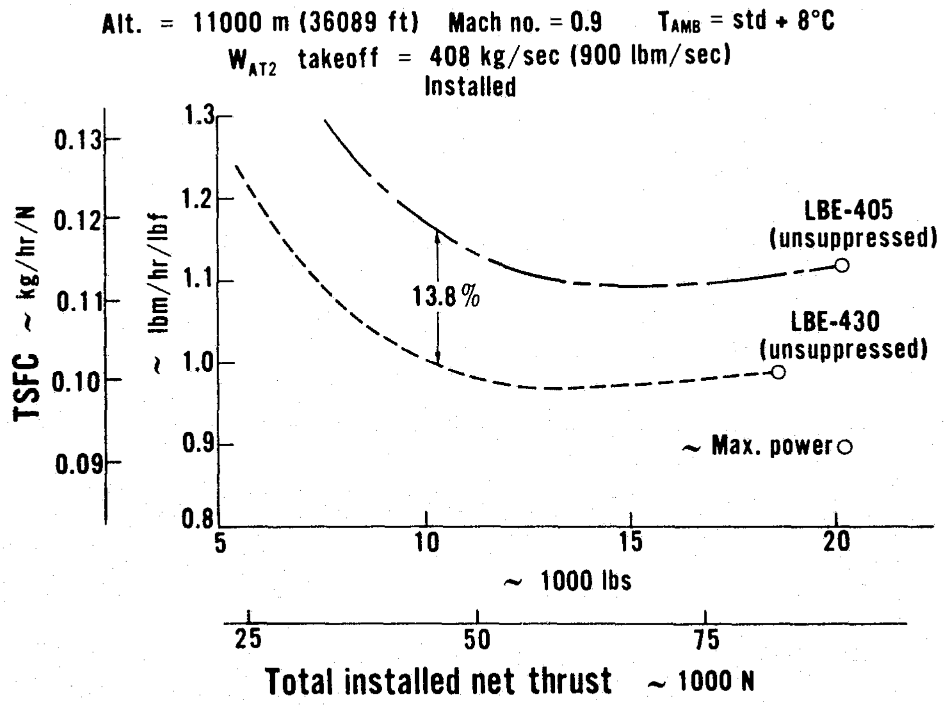


Figure 3.1.4-22 Subsonic Cruise Performance Comparison for Phase II and Phase III LBE's

TOGW = 345640 kg (762000 lbm)

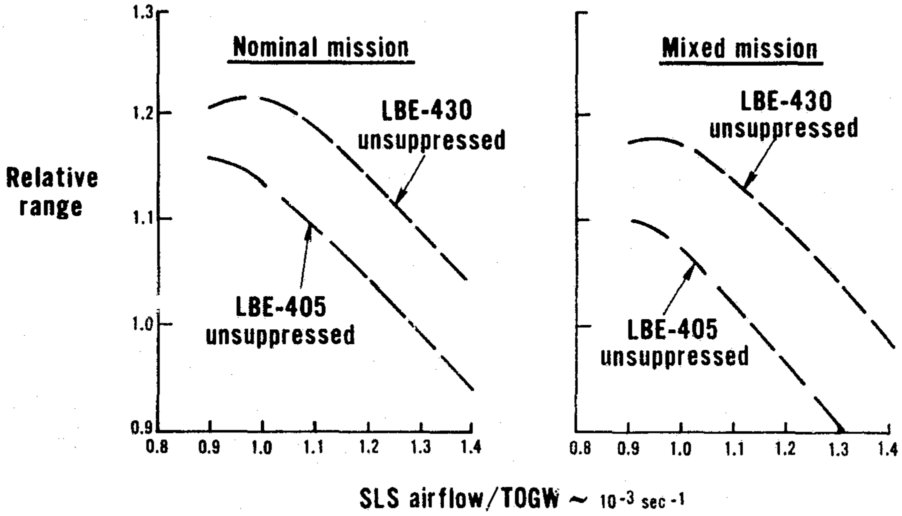


Figure 3.1.4-23 Range Comparison for Phase II and Phase III LBE's

3.1.5 NOISE PREDICTIONS

During Phase III, noise estimates were made for the VCE-112C and the VSCE-502B. The new element in these calculations is the coannular noise benefit based on static test results from another P&WA/NASA program (NAS3-17866). An empirical noise model was developed from this test program and applied to these Variable Cycle Engines with coannular nozzles. Estimates of effective perceived noise, EPNL, for these engines are summarized in Figure 3.1.5-1. For reference, noise for a conventional engine with a single-stream exhaust nozzle (LBE-430) is also plotted in this figure. As shown, the variable cycle engines with coannular nozzles having inverted velocity profiles are inherently quieter than the conventional engine over the entire range of specific thrust. A flow chart of the P&WA computer program used to obtain these noise estimates is shown in Figure 3.1.5-2. This computer program utilizes standardized published noise prediction procedures where possible and specialized modules if published data is not available.

In addition to the basic noise estimates for the two variable cycle engines, a unique programmed throttle schedule procedure was evaluated for the VSCE-502B. This procedure exploits the beneficial low altitude effects of ground attenuation and shielding to reduce takeoff noise levels. This programmed throttle schedule technique and its potential benefits are described in section 3.1.5.4.

3.1.5.1 Noise Prediction Procedure

Jet noise was predicted in accordance with the proposed SAE ARP 876 (Ref. 3). The inverted velocity profile coannular noise prediction system is based on the work done by P&WA under the NASA sponsored Coannular Nozzle/Experimental Program, Contract NAS3-17866.

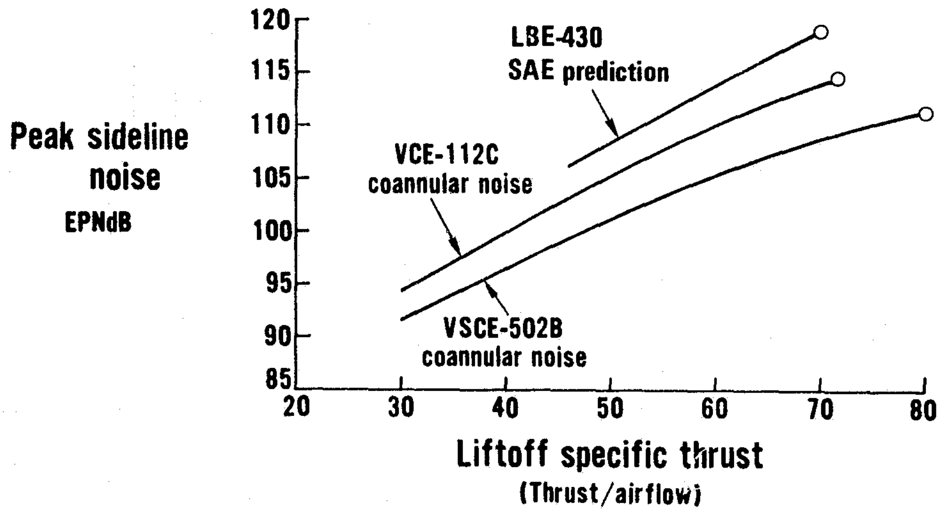


Figure 3.1.5-1 Effective Perceived Noise Levels for Phase III Refined Engines

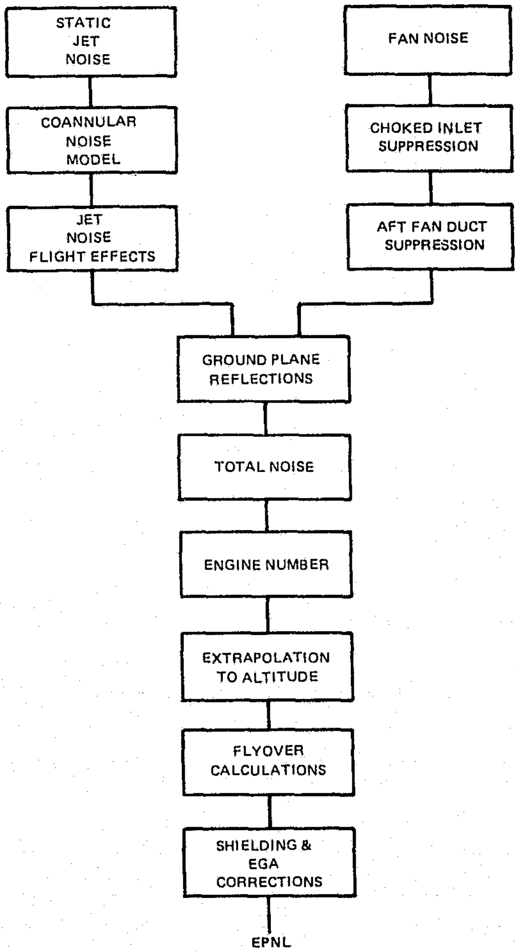


Figure 3.1.5-2 Flow Chart of Noise Estimating Procedure

Based on experimental data from this program, an empirical prediction method was developed and computerized in order to predict jet noise spectra for coannular nozzle configurations having inverted velocity profiles. With the outer bypass stream at high velocities relative to the inner primary stream, the noise measurements for coannular nozzles are significantly lower than single stream convergent nozzles having the same level of specific thrust. In addition to the temperatures and velocity effects in both streams, this prediction method accounts for the effects of fan-to-primary jet area ratio, and for an acoustically treated ejector. The model is based on spectral superposition of low frequency jet noise which is generated by the downstream merged jet, and a high frequency component which represents the jet noise produced close to the nozzle by the high velocity outer stream. Figure 3.1.5-3 is a schematic correlating these two characteristic noise sources with a representative spectral curve. The low frequency noise predictions are based on downstream merged jet properties. The high frequency noise is based on experimental data generated by the high velocity stream in the region close to the nozzle before mixing occurs. The total noise prediction for the coannular nozzle is obtained for each type of variable cycle engine and for each power setting by logarithmically adding the low and high frequency noise components.

The jet noise flight effects module used for these noise calculations (the effect of relative velocity on jet noise) was obtained from Reference 4. This paper proposes a reduction of jet noise at angles greater than 90° from the engine inlet and a slight increase in jet mixing noise at forward angles.

Fan noise prediction draws from P&WA experimental data from both engines and fan rigs. A data base was chosen which represents the tip speed, stage number and blade design of the fans for these variable cycle engines. Blade passing frequency noise and harmonics as well as multiple pure tone noise levels were determined and placed in the proper portion of the noise spectrum. Level corrections based on size, pressure ratio and spacing were made to complete the fan noise estimate.

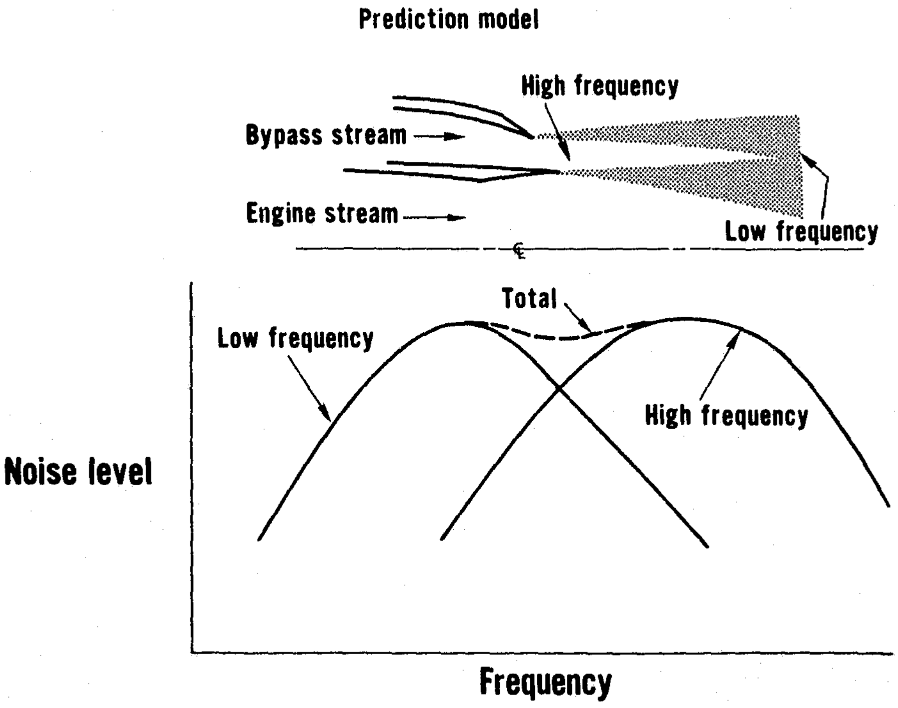


Figure 3.1.5-3 Coannular Nozzle Jet Noise Prediction Model

Based on experimental data from another NASA-sponsored P&WA noise program (NAS3-16311) that include testing a sonic inlet, a 20 dB reduction in engine noise emanating from the inlet was assumed for all frequencies.

In addition to acoustic treatment in the region of the nozzle ejector, fan duct treatment was allowed for in each engine to provide aft fan noise attenuation.

The influence on noise due to ground plane reflections was developed at P&WA and is very similar to the SAE procedure of Reference 5. Extrapolation of noise which accounts for atmospheric absorption was obtained from Reference 6.

Calculation of effective perceived noise was obtained from Reference 7. Because of the relatively high altitude corresponding to the peak sideline noise point, > 245 m (> 800 ft), extra ground attenuation was not used for the basic noise estimates. A 3dB reduction was allowed at 365 m (1200 ft) for sideline shielding.

3.1.5.2 Noise Estimates

For the two variable cycle engines (the VSCE-502B and VCE-112C) with coannular nozzles, Figure 3.1.5-1 shows peak sideline noise, 365 m (1200 ft. altitude), for four engines. These noise levels correspond to engines sized for 340 kg/sec (750 lb./sec) total airflow, and cover a range of specific thrust levels from high to intermediate power levels that represent a range of power settings from peak take-off power to cut-back operation over the community. This curve allows for a 3dB shielding reduction at 365 m (1200 ft) altitude, and the measuring station is at the sideline distance of 650 m (2140 ft). For the VSCE-502B curve, the high levels of specific thrust correspond to high fuel/air ratios in the duct-burner and intermediate temperatures in the main burner. The throttle schedule for both the main burner and duct-burner are controlled to optimize the coannular noise benefit over the entire range of specific thrust shown in Figure 3.1.5-1. The VSCE-502B curve corresponds to the 2.8 FPR take-off mode because it is 1 to 2 dB quieter than the 3.3 design FPR for the same specific thrust. The same noise calculation procedure was followed for the VCE-112C for a range of duct-burner temperatures and for two levels of main-burner exit temperatures, 1340°C (2440°F) and 1540°C (2800°F) which is the maximum design temperature. The VCE-112C noise curve in Figure 3.1.5-1 reflects the maximum possible coannular noise benefits for this rear-valve engine concept that can be achieved without compromising engine performance or weight. For comparison, Figure 3.1.5-1, also shows the noise versus specific thrust curve for the conventional engine configuration (LBE-430), without a mechanical suppressor.

Tables 3.1.5-I and -II summarize the sideline and community noise estimates for the two variable cycle engines. Included in these tables are some of the pertinent engine characteristics corresponding to these noise estimates.

3.1.5.3 Noise Sensitivity Studies

Several factors were evaluated to determine their effect on noise characteristics of the VSCE-502B concept. Included were a fixed primary nozzle (in contrast to the variable primary nozzle in the VSCE-502B baseline engine definition), noise estimates without the coannular noise benefit, a different throttle schedule technique which does not optimize the coannular nozzle exhaust conditions for the maximum noise benefit, the effect of fan pressure ratio, and the effect of acoustic treatment in the region of the nozzle/ejector. Figure 3.1.5-4 summarizes the results of these sensitivity studies. The curve in Figure 3.1.5 – 4A labeled "no coannular benefit" is based on the standard SAE jet noise calculation procedure without allowing for the experimental coannular noise benefit. It indicates a 7 to 8 dB increase in community noise when eliminating the coannular benefit.

The experimentally determined effect of acoustic treatment in the region of the ejector is less than 1 dB. Further experimental evaluation is required to qualify this small benefit from acoustic treatment. Figure 3.1.5-4A also shows a 1 to 1.5 dB reduction when operating the VSCE-502B at a reduced fan pressure ratio (2.8) relative to the design level of 3.3. This flexibility in reducing the fan pressure ratio can be accomplished with no change to the engine design by opening up the bypass stream nozzle. Airflow is held constant and thrust is maintained by increasing the level of augmentation in the duct-burner. Primary nozzle area is not affected by this lower fan pressure ratio. Further evaluation of this small reduction in noise due to a lower fan pressure ratio is required in a large scale test.

TABLE 3.1.5-I

VSCE-502 B Take-off Noise Estimates and Corresponding Engine Conditions — 340 kg/sec (750 lb/sec) engine airflow size

Take-off Noise Estimates for Four Engine Airplane — EPNL						Engine Conditions								
Sideline[1]			Community[2]			Fan Pressure Ratio	Net Thrust		Velocity Ratio[3]	Duct Burner Combustor Exit Temperature		Main Burner Combustor Exit Temperature		
Fan	Jet	Total	Fan	Jet	Total		N	(lbf)		°C	(°F)	°C	(°F)
84.9	90.3	92.3	94.3	97.2	99.4	2.8	97910	22011	1.6	165	330	1220	2230
	95.4	96.3		102.2	103.1		124690	28032		360	675	1240	2260
	101.7	102.0		108.4	108.8		164760	37039		705	1300	1270	2320
	107.1	107.2		113.8	113.9		207935	46746		1160	2125	1320	2410
	109.3	109.4		116.0	116.1		230450	51808		1430	2610	1350	2470
86.2	93.6	95.0	95.7	100.5	101.9	3.3	109060	24517		165	350	1165	2125
	98.8	99.3		105.6	106.3		137580	30930		370	695	1180	2160
	105.4	104.9		112.2	112.4		180700	40623		715	1320	1230	2240
	110.7	110.8		117.4	117.5		228150	51291		1170	2140	1290	2355
	112.9	112.9		119.6	119.6		252980	56872		1440	26225	1330	2425

1) Altitude = 365m (1200 ft)

Sideline Estimates include — 3dB for shielding

2) Altitude = 420m (1370 ft)

3) Velocity Ratio = Absolute Velocity of Outer Exhaust Stream/Absolute Velocity of Inner Stream without mixing effects

TABLE 3.1.5-II

VCE-112C Take-off Noise Estimates and Corresponding Engine Conditions – 340 kg/sec (750 lb/sec) engine airflow size

Take-off Noise Estimates for Four Engine Airplane – EPNL						Engine Conditions								
Sideline[1]			Community[2]								Duct Burner Combustor Exit Temperature		Main Burner Combustor Exit Temperature	
Fan	Jet	Total	Fan	Jet	Total	Fan Pressure Ratio	Net Thrust		Velocity Ratio[3]					
							N	(lbf)			°C	(°F)	°C	(°F)
94.8	112.2	112.4	83.5	105.4	105.5	5.28	161720	36356	1.15		705	1300	1340	2440
95.0	114.0	114.1	83.8	107.3	107.3	5.41	174240	39171	1.2		760	1400		
95.3	116.0	116.1	84.0	109.3	109.3	5.54	185570	41718	1.22		815	1500		
95.5	117.5	117.6	84.2	110.7	110.8	5.67	196090	44082	1.22		870	1600		
95.7	118.8	118.9	84.4	112.1	112.1	5.80	205990	46309	1.21		925	1700		

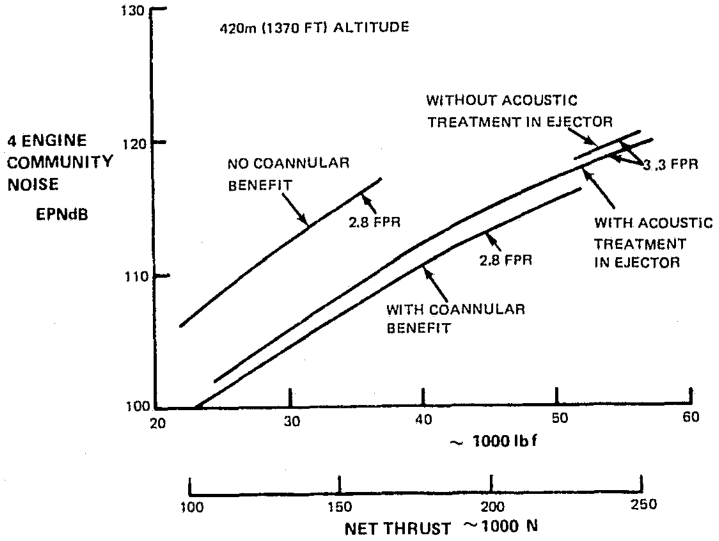
1) Altitude = 365m (1200 ft)

Sideline Estimates include -3dB for shielding

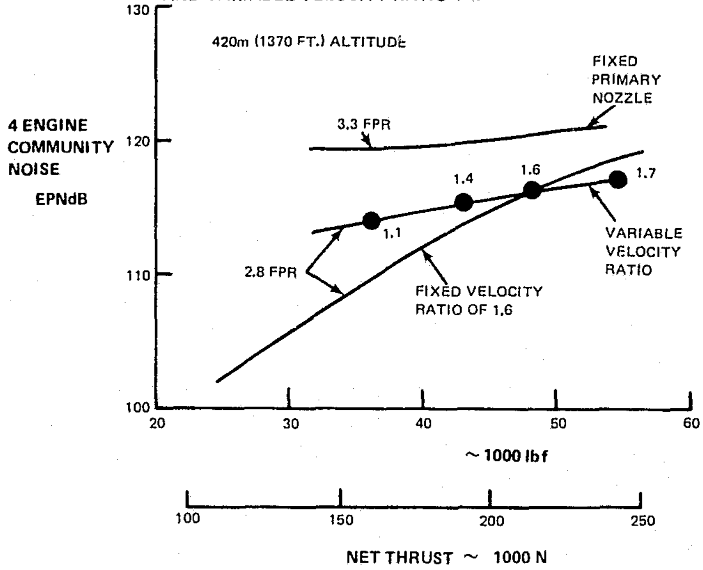
2) Altitude = 420m (1370 ft)

3) Velocity Ratio = Absolute Velocity of Outer Exhaust Stream/Absolute Velocity of Inner Stream without mixing effects

A. CURVES SHOWING LARGE BENEFIT FROM COANNULAR NOZZLE WITH INVERTED VELOCITY PROFILE AND SMALL BENEFIT FROM ACOUTIC TREATMENT IN EJECTOR REGION AND FROM LOWER FAN PRESSURE RATIO



B. CURVES SHOWING LARGE NOISE INFLUENCE OF FIXED PRIMARY NOZZLE AND VARIABLE VELOCITY RATIO (1).



(1) VELOCITY PROFILE = ABSOLUTE VELOCITY OF OUTER EXHAUST STREAM/ABSOLUTE VELOCITY OF INNER STREAM WITHOUT MIXING EFFECTS

Figure 3.1.5-4 Noise Sensitivity Study Results for the VSCE-502B

Figure 3.1.5-4B shows the noise penalty associated with a fixed primary nozzle. As described in section 3.1.4.1, this was investigated as a possible approach to simplify the coannular nozzle design. The primary nozzle was fixed at a throat area 15% smaller than the take-off area setting for the variable nozzle. This 15% reduction minimizes the performance penalty associated with a fixed primary nozzle. It results in a significant increase in primary stream exhaust velocity and a corresponding increase in the engine noise. Based on this noise penalty, as well as the poorer performance associated with a fixed primary nozzle, it is concluded that the variable primary nozzle is desirable for the VSCE-502B concept.

In contrast with the coannular noise benefit associated with a fixed velocity ratio of 1.6 (absolute velocity of outer exhaust stream/absolute velocity of inner exhaust stream without adjustments for mixing effects), Figure 3.1.5-4B shows a noise curve for a variable velocity ratio. This variable ratio is obtained by holding the engine conditions constant (main burner exit temperature held at a fixed level) and varying the thrust by changing the level of augmentation in the duct-burner. At the high levels of thrust, the velocity ratio is 1.7 and the noise level is below the noise curve corresponding to the fixed 1.6 ratio. This indicates the coannular noise benefit can be optimized at high thrust levels by increasing the velocity ratio,

As the duct-burner is throttled back, the velocity ratio diminishes, and the coannular benefit decreases. The locus defined by these curves indicates that below a thrust level of 213515N (48,000 lbf) for the 340 kg/sec (750 lbm/sec) engine airflow size, the velocity ratio should be 1.6. Above this thrust level, the velocity ratio should be increased to obtain the maximum noise benefit from coannular exhaust streams.

3.1.5.4 Programmed Throttle Schedule

The concept of a program throttle schedule is to make use of extra ground attenuation (EGA) and engine shielding to permit higher thrust during take-off and for the initial climb-out to the take-off noise measuring station. The object is to achieve a higher cut-back altitude for reduced community noise or, for a given noise level, to reduce the engine size and achieve greater airplane range. The basic requirement to accomplish this programmed throttle noise benefit is that the engine must have the capability for high specific thrusts. Of the three types of engines that were refined in Phase III, only the Variable Stream Control Engine (VSCE-502B) has this capability for high specific thrust. The following discussion therefore applies only to the VSCE-502B concept.

Typically, for a conventional constant power setting during take-off, the sideline noise peaks at an altitude between 245 m (800 ft) and 365 m (1200 ft). At lower altitudes, EGA and shielding tend to reduce the sideline noise, while at higher altitudes, increased slant distance also tends to reduce sideline noise. Higher power settings can be used at altitudes below that at which peak sideline noise occurs without exceeding the maximum sideline noise level. In principle, the power setting schedule can be tailored to maintain a constant sideline noise during the climb.

Figure 3.1.5-5 illustrates the elements considered in the synthesis of the sideline noise estimate. Single engine noise levels were calculated using the empirical coannular prediction model, including flight effects. The four engine increment for zero shielding was then added as shown. This four engine noise level was considered as the reference value. From this reference value was subtracted (1) an increment for increased distance as the airplane gains altitude, (2) an increment for EGA, and (3) an increment for engine shielding. The remainder, then, is the sideline noise. Each of these three factors is a function of altitude (f (h)) as explained in the next paragraph.

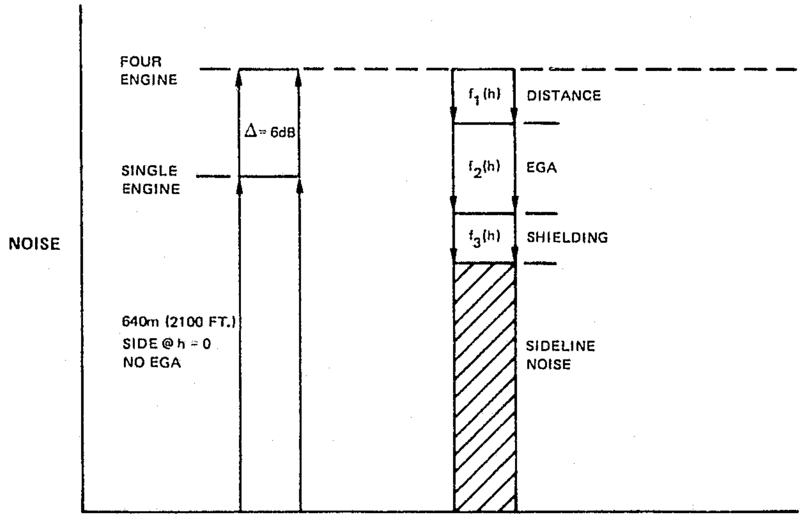


Figure 3.1.5-5 Elements Considered In Programmed Throttle Noise Synthesis

Although the existence of EGA and shielding is well accepted, their magnitude is not well validated. The increments assumed for this study are shown in Figure 3.1.5-6. The magnitudes are representative, and serve to illustrate the technique of programmed throttles and provide an indication of the potential benefit. The EGA is maximum when the aircraft is near the ground, and decreases to zero when the aircraft reaches 180 m (600 ft) altitude. The shielding increment is also maximum when the aircraft is near the ground, and reduces as the aircraft gains altitude . At 365 m (1200 ft) where sideline noise level peaks out, the shielding increment is approximately 3 dB.

Applying the noise increments of Figure 3.1.5-6, the engine power setting that will maintain a constant sideline noise level as the airplane climbs can be determined. Figure 3.1.5-7 shows three typical power setting schedules for a given engine size; the 0.00102 sec^{-1} value of the engine size parameter corresponds to a 354 kg/sec (780 lb/sec) airflow for a 345636 kg (762,000 lb) airplane. The thrust loading parameter on the ordinate scale is really an indicator of power setting variation with altitude, and corresponds to the thrust loading that would be obtained if the engine were operating at the same power setting at 370 km/hr (200 kts) at sea level. Throttle schedule A is the conventional constant power setting baseline schedule. A thrust loading of 0.275 is about the minimum value that satisfies the 3200 m (10,500 ft) field length. The engine size was selected such that the sideline noise would be 108 EPNdB with an engine power setting corresponding to the 0.275 thrust loading. At 365m (1200 ft) altitude, schedule B also has a 0.275 thrust loading, so its sideline noise is also 108 EPNdB at that point. At lower altitudes, the schedule B power setting is increased to maintain a constant 108 EPNdB sideline noise (taking advantage of EGA and shielding). The thrust loading limit of 0.328 corresponds to the maximum thrust available from the VSCE 502B, with its duct-burner operating at a fuel/air ratio of 0.06. This limit is indicated by the cross-hatched barrier in Figure 3.1.5-7. At the altitudes where the engine is operating at its thrust limit, EGA and shielding reduce the sideline noise level below the peak value. Schedule C has a lower thrust loading at 365m (1200 ft) than schedule A or B. This results in a sideline noise level of 104.5 EPNdB instead of 108 EPNdB. Below 365m (1200 ft) the schedule C power setting increases to maintain a constant 104.5 EPNdB sideline noise level, until the thrust limit is reached.

The increased take-off thrust loading of schedules B and C can be used either to shorten the field length or to increase the aircraft climb speed. Preliminary calculations indicate that both approaches result in about the same cut-back altitude, but the higher climb speed of the second approach results in a better aircraft lift drag at cut-back. This permits a lower cut-back power setting and hence, a lower community noise level. For this reason, the climb paths used in this study are based on a constant field length and increased climb speed.

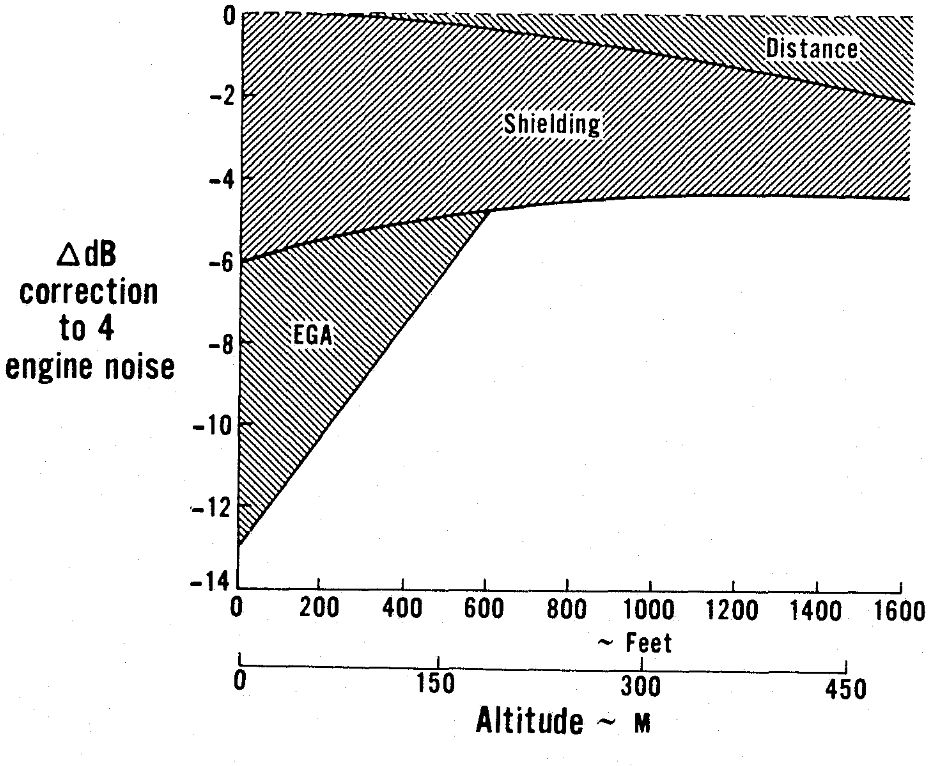


Figure 3.1.5-6 Effect of Altitude On Sideline Noise

3200 M (10,500 ft) field length W_{AT_2}/TOGW = 0.00102 sec^{-1}

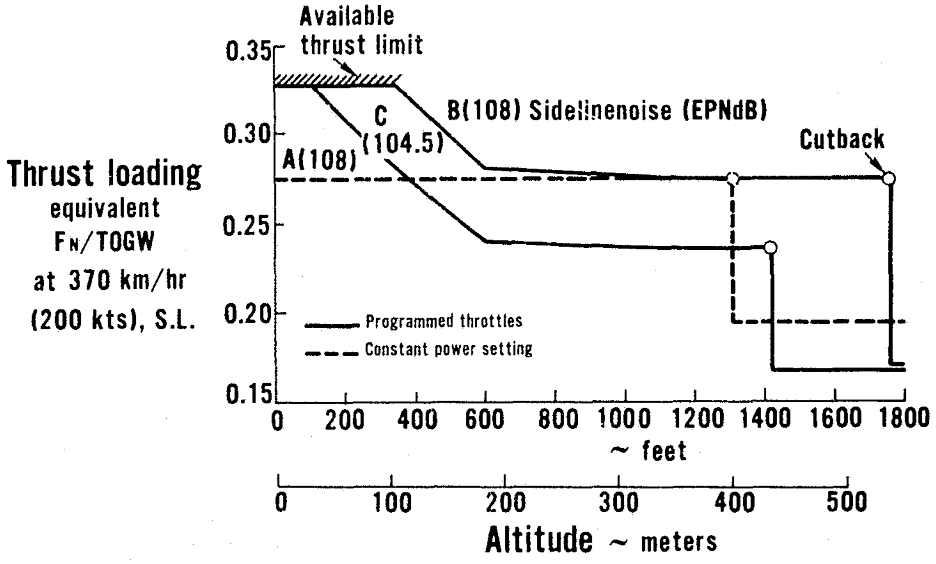


Figure 3.1.5-7 Typical Throttle Schedules for the VSCE-502B for Constant Sideline Noise

The climb paths corresponding to the previously described throttle schedules are shown in Figure 3.1.5-8. The conventional constant power climb schedule A achieves about 400 m (1310 ft) altitude at cut-back and has a corresponding community noise level of 108 EPNdB. Schedule B, which has the same sideline noise level as schedule A, attains an altitude of 535m (1760 ft) at cutback. This high cut-back altitude and the low cut-back power setting result in a 5 EPNdB reduction in community noise relative to schedule A. Throttle schedule C achieves a cut-back altitude of 435m (1420 ft) and a balanced community and sideline noise level of 104.5 EPNdB.

Trades between sideline noise and community noise can be made by selection of the throttle schedule. For example, schedule C achieves a balanced sideline noise and community noise, whereas schedule B achieves a reduction in community noise while meeting 108 EPNdB sideline noise. Other trades are illustrated in Figure 3.1.5-9. Point A represents the sideline and community noise levels achieved with the conventional constant power schedule A. As the take-off power setting is increased to obtain higher thrust loadings, the sideline noise level increases, but the airplane climbs to higher altitude and the community noise decreases. The noise levels achieved with programmed throttle schedules B and C are indicated by points B and C, respectively. This figure was constructed for a fixed engine airflow size. Lower noise levels can be achieved with larger engine sizes, while higher noise levels will result with smaller engine sizes. The grid in Figure 3.1.5-9 corresponds to the 2dB limit when trading noise between the sideline and community stations.

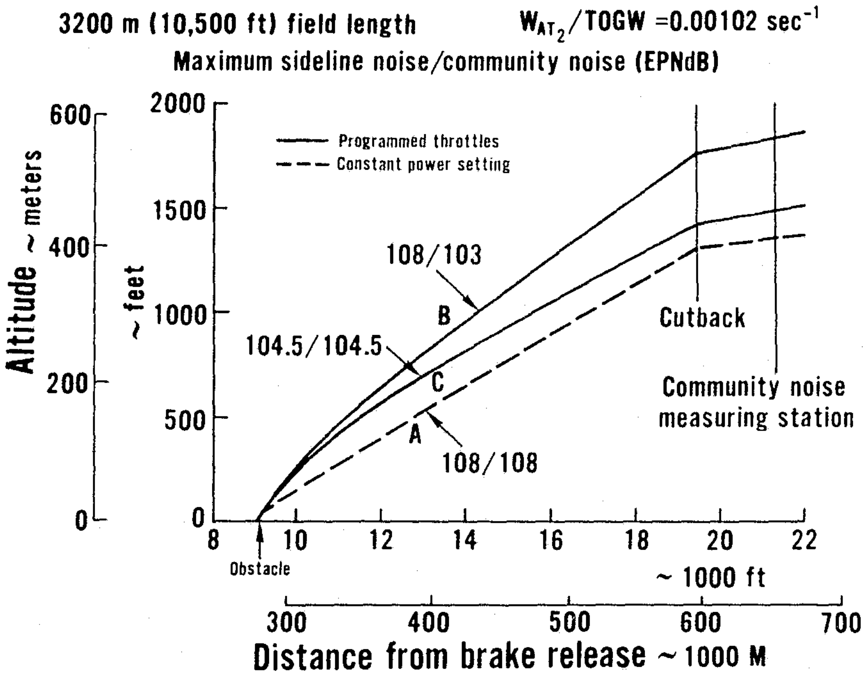


Figure 3.1.5-8 Climb Paths With Typical Programmed Throttle Schedules

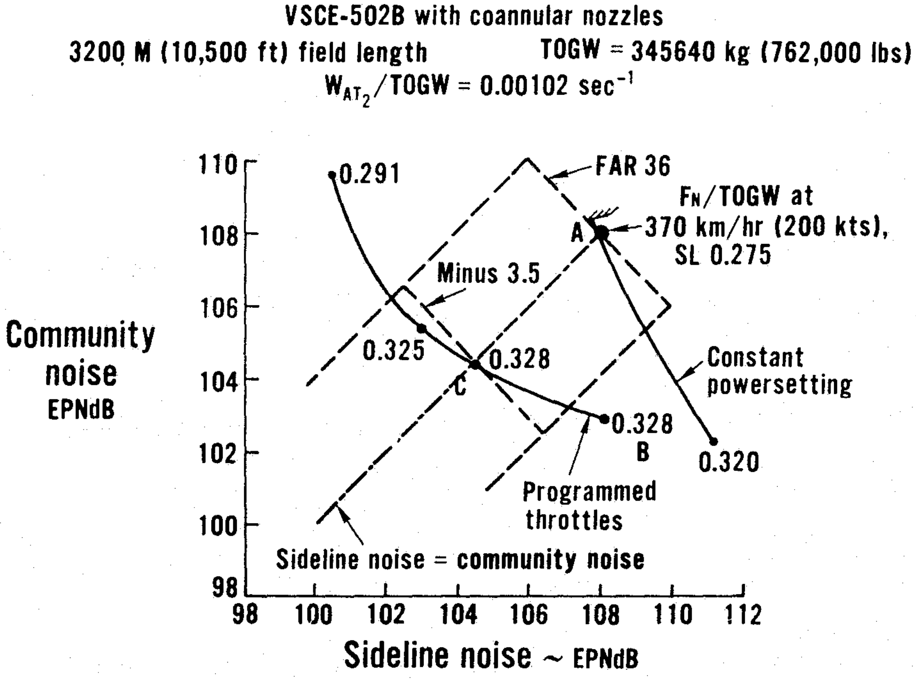


Figure 3.1.5-9 Community/Sideline Noise Trades

Trades between noise level and range (due to engine size) are shown in Figure 3.1.5-10 for the VSCE-502B. These results include only throttle schedules which produce balanced sideline and community noise. Throttle schedules A and C are indicated by points A and C respectively, and show the 3.5 EPNdB reduction that programmed throttles can provide at the same engine size (and range) as the baseline case. Conventional throttle schedule A results in a 70km (38 n.mi.) range penalty to meet FAR 36. This same noise level could be achieved with only a 7.4km (4 n. mi.) range penalty if programmed throttles were used to reduce engine size (point D). Programmed throttles can be used to achieve FAR 36 minus 5 noise levels with only an 157km (85 n.mi.) range penalty, whereas a much larger range penalty would result if constant power throttles are used.

An example of the footprint size reduction that can be achieved with programmed throttles is illustrated in Figure 3.1.5-11, where the 90 EPNdB contours obtained with conventional throttle schedule A and programmed throttle schedules B are shown. Throttle schedule B results in a footprint area reduction of over 50% compared to the conventional constant throttle schedule A.

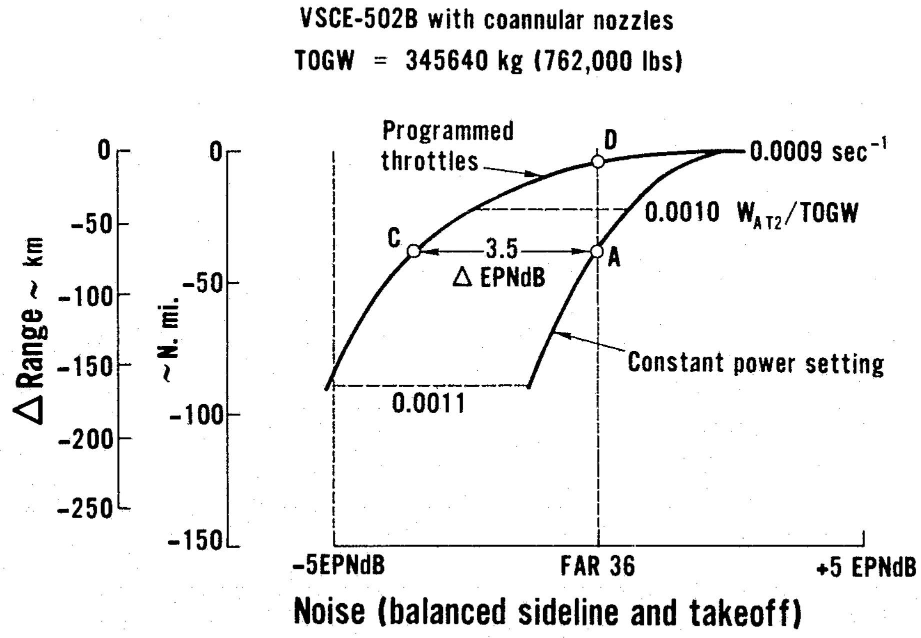


Figure 3.1.5-10 Effect of Programmed Throttle Schedule On Range/Noise Level Trades

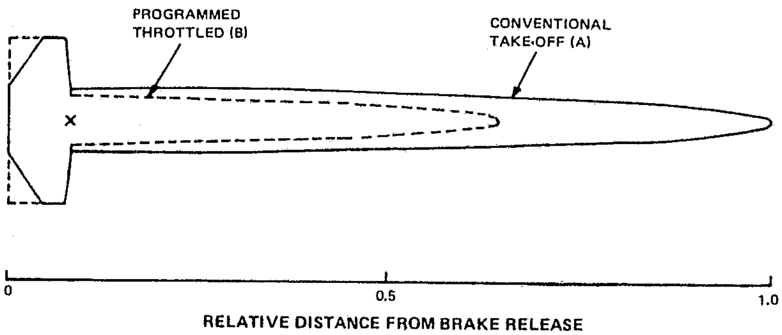


Figure 3.1.5-11 Programmed Throttles Provide Over 50% Reduction In Noise Footprint

3.1.6 Emissions Estimates

The objectives of the emissions portion of the Phase III studies were to: 1) develop an improved procedure for correlating results from various burner programs into emission indices (EI) for AST burners; 2) estimate emission levels for the refined AST engines using the improved correlation procedure; and 3) examine the sensitivity of the emission levels of the refined engines to changes in cycle parameters. The following sections discuss these three areas.

3.1.6.1 Correlation Procedure

The specific emissions considered were oxides of nitrogen (NO_X), carbon monoxide (CO), and unburned hydrocarbons (THC). Production of CO and THC is related to incomplete combustion of hydrocarbon fuel in gas turbine engines, while NO_X production is a product of local temperatures and residence time.

The basis for predicting AST main burner and duct-burner emissions of NO_X, CO, and THC is a correlation of data from the NASA/P&WA Experimental Clean Combustor Program (ECCP), NASA swirl-can combustor results, and P&WA advanced burner testing. A good prediction of emission levels for the main burner can be obtained by extrapolation of the burner rig data to AST cycle operating conditions. However, this main burner data base cannot be applied directly to duct burners because of differences in operating conditions and design characteristics between the duct burners and main burners. Figure 3.1.6-1 shows the differences in burner inlet operating conditions for the Phase III VSCE-502B and VCE-112C engines. This figure illustrates the similarity in main burner inlet operating conditions for these two engines, as well as the difference between main burner and duct burner conditions.

These different inlet conditions require different design considerations for duct burners relative to main burners, i.e., lower inlet pressures and temperatures for duct-burners make them more susceptible to blowout and relight problems than main burners. This must be considered in the basic duct-burner design. Because of these different requirements, a correlation to estimate duct-burner emissions based on ECCP and other data had to be developed.

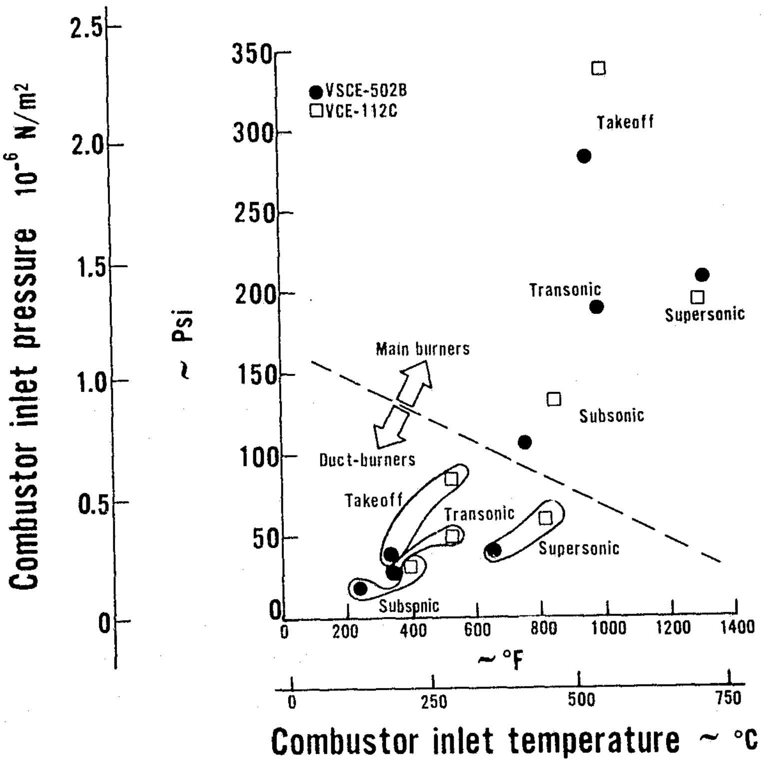


Figure 3.1.6-1 Comparison of VSCE-502B and VCE-112C Burner Inlet Conditions

NO_x Correlation

Figure 3.1.6-2 shows the new correlation that was developed for NO_x emissions. Previous correlations ignored the effects of fuel-air ratio, this new correlation specifically directs itself to fuel-air ratio effects. The correlating parameter is plotted on the ordinate of Figure 3.1.6-2 where P is the combustor inlet pressure, T is the combustor inlet temperature and .0025 is an empirical temperature constant. The pilot-main fuel flow split lines are drawn for the correlation based on ECCP and advanced burner data. The data correlates well at low and moderate fuel-air ratios. A design line for main burners is shown on Figure 3.1.6-2, assuming a 20% fuel flow split. A duct-burner design line is also shown assuming a flow split greater than 20% to compensate for the duct burner's lower combustor inlet pressure and temperature noted on Figure 3.1.6-1. This richer pilot is one way to improve stability. As indicated, NO_x peaks around a fuel-air ratio of 0.01. At a fuel-air ratio of 0.02, the burner secondary stage has just started flowing fuel, and is not at optimum operation. As a result, the peak flame temperatures that cause NO_x are suppressed.

As fuel-air ratio increases, burner efficiency is improved and the production of NO_x increases again. Above stoichiometric, the maximum local temperature peaks and then falls off, resulting in a reduction of NO_x at very high fuel-air ratios.

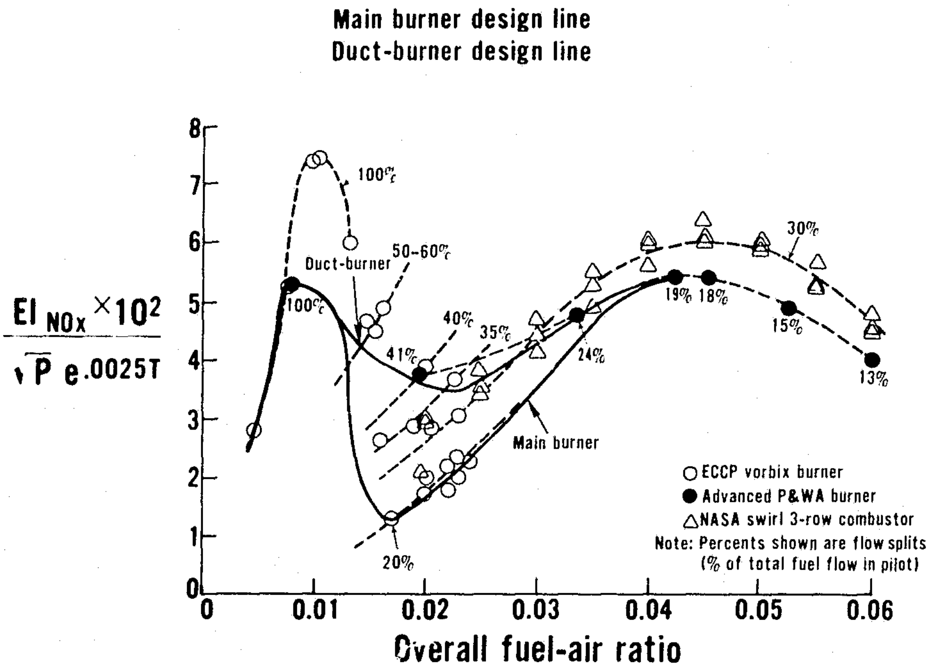


Figure 3.1.6-2 Oxides of Nitrogen Emission Correlation

CO Correlation

A similar analytical correlation was developed for carbon monoxide and is shown in Figure 3.1.6-3. CO is a more difficult parameter to correlate than NO. An attempt to establish the influence of temperature on CO was unsuccessful. Conventional temperature correlation factors for CO produce a trend that is the opposite of data at high fuel-air ratios. As a result, the CO emission correlation plotted as the ordinate in this figure does not include a temperature effect. At low pilot fuel-air ratios, the advanced burner point has a significantly lower CO level than the ECCP data because it is more efficient at low fuel/air ratios. At moderate fuel-air ratios, there is reasonable agreement for the correlation between the ECCP and the advanced burner data. Design curves for the main and duct burners are shown on Figure 3.1.6-3. Again, the higher fuel flow split for the duct burner is used to provide the required stability characteristics. The design lines pass through the advanced burner's pilot point because it is more efficient than the design tested in the ECCP.

CO increases between a fuel-air ratio from 0.01 to 0.02 because the main stage is operating at low efficiencies – well below its optimum fuel-air ratio. As fuel-air increases, burner efficiency improves resulting in reduced CO levels. The Swirl-can data shows CO increasing rapidly at moderate fuel-air ratios of 0.03 - 0.04, while the advanced staged burner shows no change in CO in this range. This is because the staged burner can maintain a higher efficiency level at these higher fuel-air ratios than an unstaged burner. The design lines follow the staged burner data. CO increases above stoichiometric fuel-air ratios since the reaction converting CO to CO_2 is retarded.

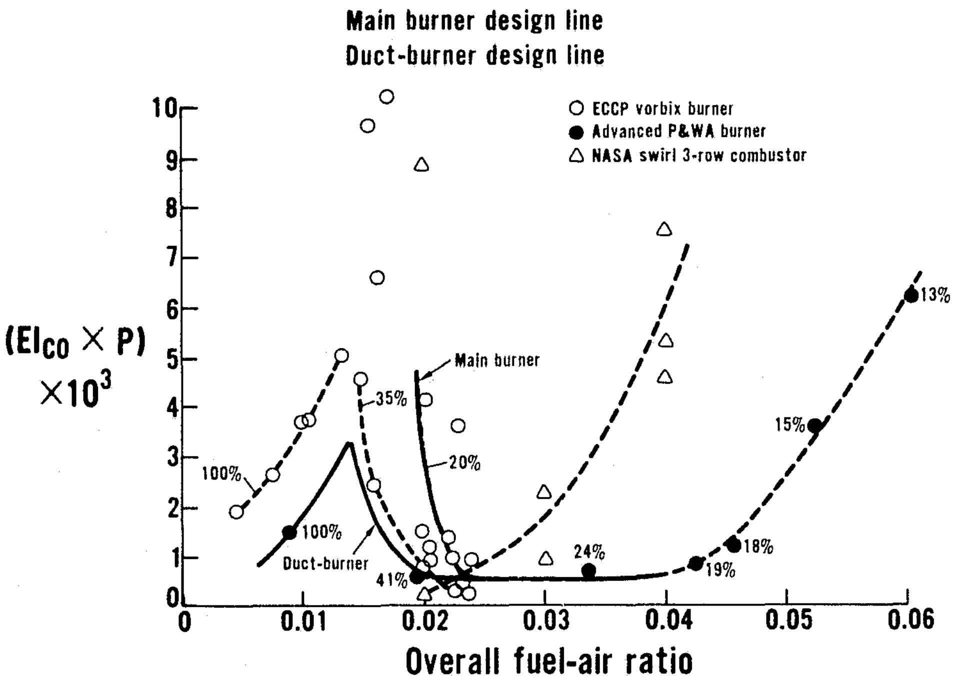


Figure 3.1.6-3 Carbon Monoxide Emission Correlation

THC Correlation

An analytical correlation of THC levels has been established and is shown in Figure 3.1.6-4. This curve indicates that emission indices of THC are significantly lower than those of carbon monoxide.

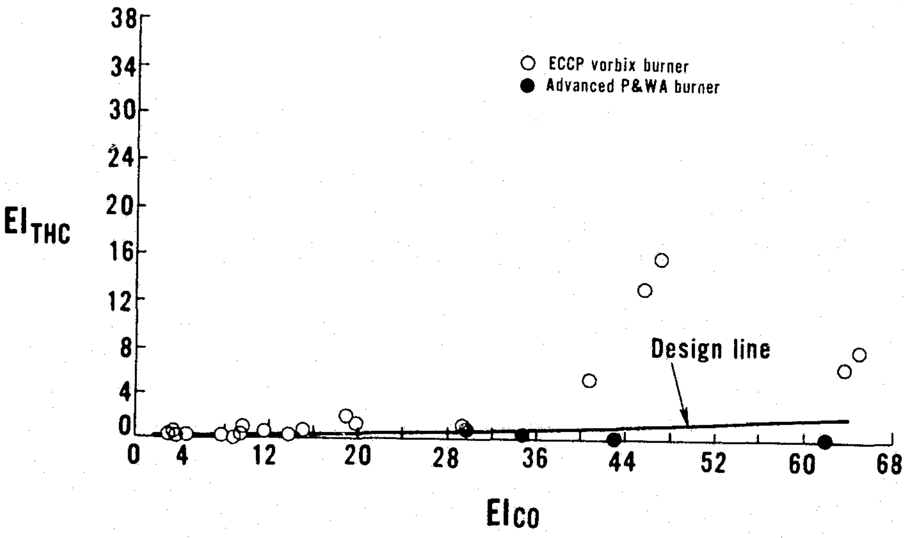


Figure 3.1.6-4 Unburned Hydrocarbon Emission Correlation

3.1.6-2 Emission Estimates

Using these new correlations, emission indices (EI) were estimated for the VSCE-502B and VCE-112C Phase III refined engines at several representative flight conditions. Figure 3.1.6-5 shows the contributions from the main burner and duct burner for CO and NO_x. This figure shows that the main burner produces low CO levels and high NO levels. The duct burner has low NO_x levels but high CO EI's relative to the main burner. The main burner and duct burner fuel flow splits have been optimized for minimum total engine emissions level.

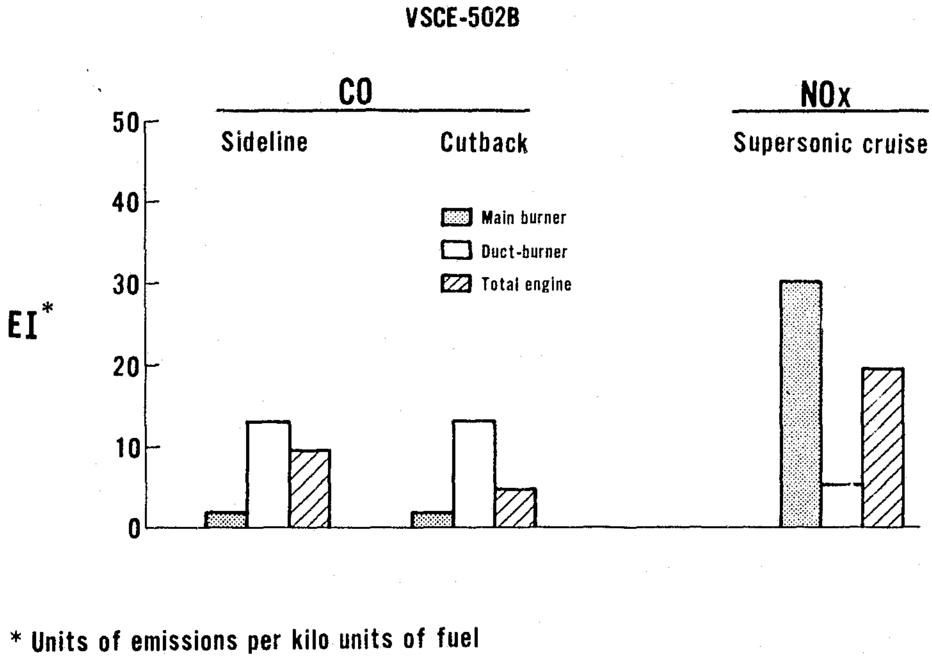


Figure 3.1.6-5 Contribution of the Main Burner and Duct-Burner to CO and NO_x Emissions for VSCE-502B

Figure 3.1.6-6 summarizes all of the emission levels estimated for the Phase III refined engines at representative sideline, cutback, transonic climb, and supersonic cruise flight conditions. The CO levels at cutback and supersonic cruise have been adjusted down, relative to the predicted levels obtained from the previous figures. This was done to allow for the fact that, once specific fuel/air requirements are defined, the duct-burner design can be refined by modifying airflow splits to provide low emission characteristics. Considering the VSCE-502B results, going from sideline to cutback, the influence of the duct burner is reduced by throttling it to a lower power setting, thereby increasing the influence of the main burner. This increases total engine NO_x levels and reduces engine CO levels. NO_x emissions are higher at supersonic cruise relative to take-off conditions because of increased temperature of air entering the main burner. The VCE-112C EI trends shown in Figure 3.1.6-6 are similar to those for the VSCE-502B. The major contributor to the engine's NO_x at all flight conditions is the main burner, while the duct burner is the major contributor to the engine's CO levels. Comparing these VCE-112C and VSCE-502B results, neither engine has a significant advantage over all flight conditions.

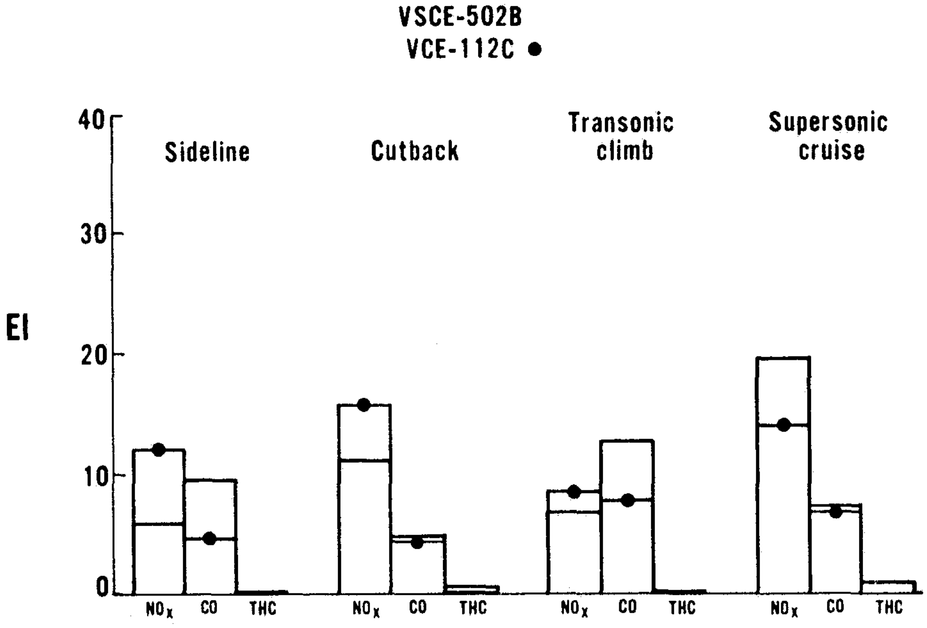


Figure 3.1.6-6 Emission Index Summary for Phase III Refined Engines (VSCE-502B and VCE-112C)

A crossplot of the data used to generate the VSCE-502B emission indices in Figures 3.1.6-5 and -6 results in the NO_X and CO emission index versus duct-burner fuel-air ratio curves shown in Figure 3.1.6-7. Noted on this figure are the approximate fuel-air ratios required for FAR 36 and FAR 36 minus 5 EPNdB jet noise levels. From this comparison, there is no significant change in emission characteristics for the noise range being evaluated for the VSCE-502B. The CO adjustment noted in the previous paragraph was also applied to generate the CO trend curve in Figure 3.1.6-7.

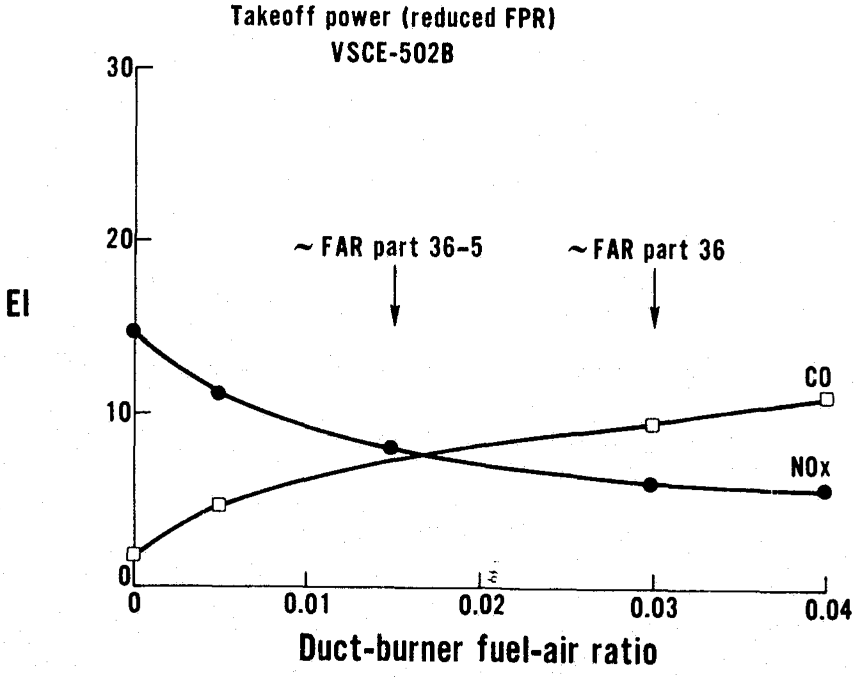


Figure 3.1.6-7 Emission Index Variation Is Small for Range of Noise Levels Evaluated

3.1.6.3 Sensitivity of EI Estimates to Cycle Parameters

This section describes the results of the study to determine the sensitivity of estimated EI levels to changes in engine cycle parameters. Figure 3.1.6-8 compares the Phase II VSCE-502 and Phase III VSCE-502B main burner inlet pressure and temperature at Mn 2.4 supersonic cruise conditions. This figure indicates that the refined VSCE-502B has significantly higher combustor inlet pressure and temperature levels than the Phase II parametric VSCE-502 engine, resulting in a significant increase in NO_X emission estimates for the VSCE-502B. The other symbols in this figure represent other parametric engines that were similarly refined. Figure 3.1.6-9 illustrates this increase, showing the VSCE-502B main burner NO_X emission index at about 30 for supersonic cruise, which is approximately twice the level estimated for the VSCE-502.

Although higher NO_X levels are projected for the refined cycles than for the Phase II parametric cycles, these emission levels are still lower than those obtained with first generation SST engine technology. Applying first generation technology to a main burner operating at the conditions for the VSCE-502B indicates that the EI levels of NO_X at supersonic cruise would be approximately 45, as shown in Figure 3.1.6-10. Based on ECCP and other advanced burner results, the main burner NO_X emission index level is reduced from 45 to approximately 30, also shown in Figure 3.1.6-10. Combining the main burner and duct burner NO_X levels, the total engine emission level for the VSCE-502B drops to approximately 20.

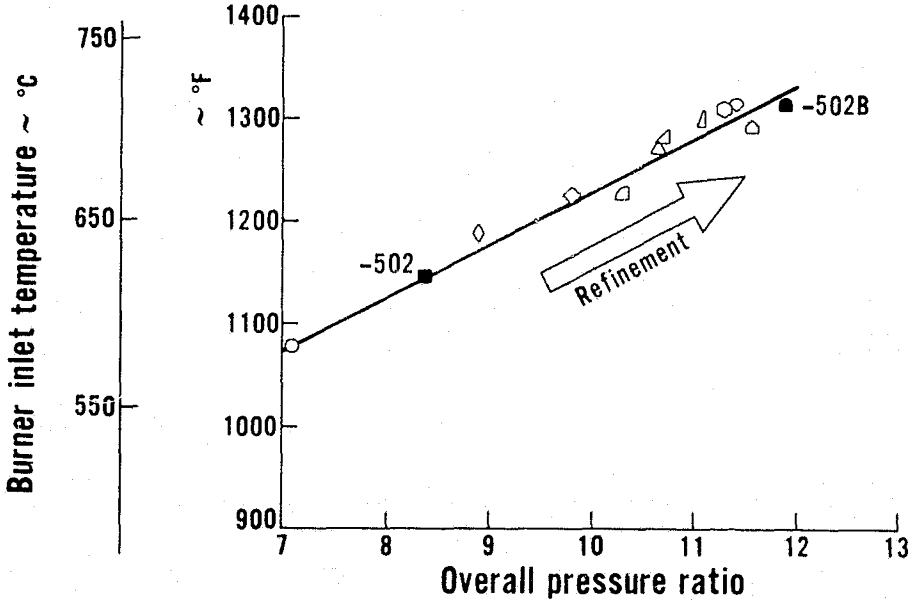


Figure 3.1.6-8 Main Burner Inlet Pressure and Temperature Have Increased Through Refinement of the VSCE

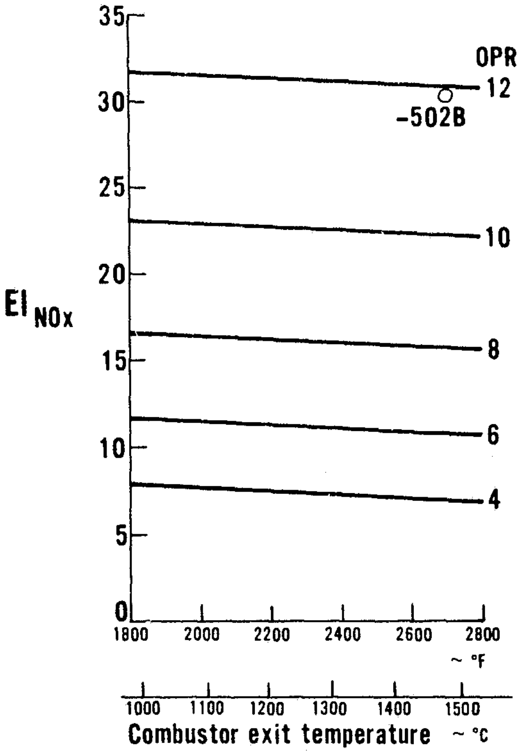


Figure 3.1.6-9 Main Burner NO_x Emission Sensitivity to Variation In CET and OPR

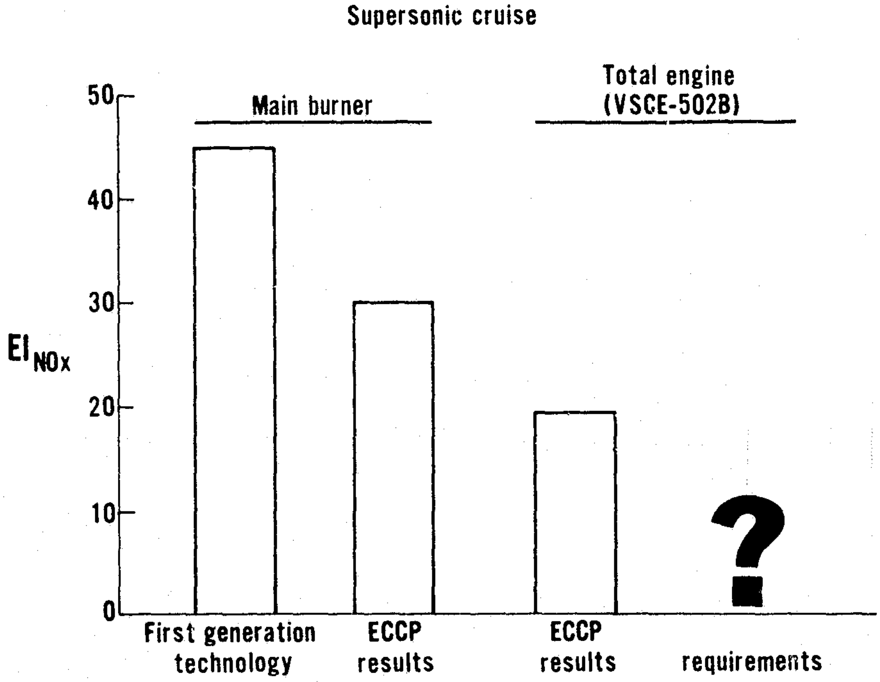


Figure 3.1.6-10 Advanced Technology Reduces NO_x Levels At Supersonic Cruise

Although goals have not been established for these advanced engines, stratospheric chemistry measurement programs that are currently in progress may eventually establish a requirement for EI levels of NO_x below 20. An advanced technology main burner program to further reduce emissions is described in Section 3.6.

3.1.7 Airplane System Comparison of Refined Engines

Refined versions of the most promising engines identified during the Phase III parametric studies were selected for airplane system study and comparison. The engines are the VSCE-502B and the single rear-valve VCE-112C. The coannular noise benefit described in Section 3.1.5 was applied to both engines in determining the installed performance. As explained in Section 3.1.5, the total coannular noise reduction was greater for the VSCE-502B than the VCE-112C. The groundrules, airplane characteristics and study procedures used in the systems studies are described in section 3.1.3.

To illustrate the cycle characteristics of these two engines over the complete flight spectrum, Figures 3.1.7-1 and 3.1.7-2 list the basic engine cycle parameters at several nominal operating points. As indicated, both engines are sized for FAR Part 36 noise levels.

A comparison of the range capability for these engines for a fixed TOGW of 345,640 kg (762,000 lbm) is presented in Figure 3.1.7-3. As shown, the VSCE-502B provides significantly greater range for either the nominal or mixed mission and for all of the engine sizes considered. For the mixed mission, small engine sizes for the VCE-112C provide insufficient thrust when the engine operates in the turbofan mode for subsonic cruise above 8380m (27,500 ft) altitude and when the subsonic leg is at the beginning of the mission (higher aircraft weight). This limitation is indicated by the barrier in Figure 3.1.7-3. The VCE-112C could produce the required thrust in the smaller engine sizes if operated in the twin-turbojet mode but at considerable penalty to total range because of the increase in TSFC. The range curve for this case is not shown in Figure 3.1.7-3. The VSCE-502B can meet FAR 36 noise levels with a much smaller engine size than the VCE-112C. This is because of the greater coannular noise reduction benefit for the VSCE-502B. The engine sizes required to meet FAR 36 are shown by circular symbols in Figure 3.1.7-3.

The VSCE-502B and VCE-112C are compared on a propulsion-system-plus-fuel-weight basis in Figure 3.1.7-4 for a fixed TOGW. As shown in this figure, the propulsion system weight for the VCE-112C is significantly higher than that for the VSCE-502B primarily because of the relatively large engine size for the VCE-112C to meet FAR 36 noise requirements. The VCE-112C also consumes more fuel during the subsonic cruise-to-alternate and loiter legs and thus has a higher reserve fuel requirement. Since the climb fuel (fuel consumed to 1300 km (700 n. mi.) from the airport is nearly the same for both engines, the VSCE-502B has significantly more fuel available for supersonic cruise, approximately 12,700 kg (28,000 lbm).

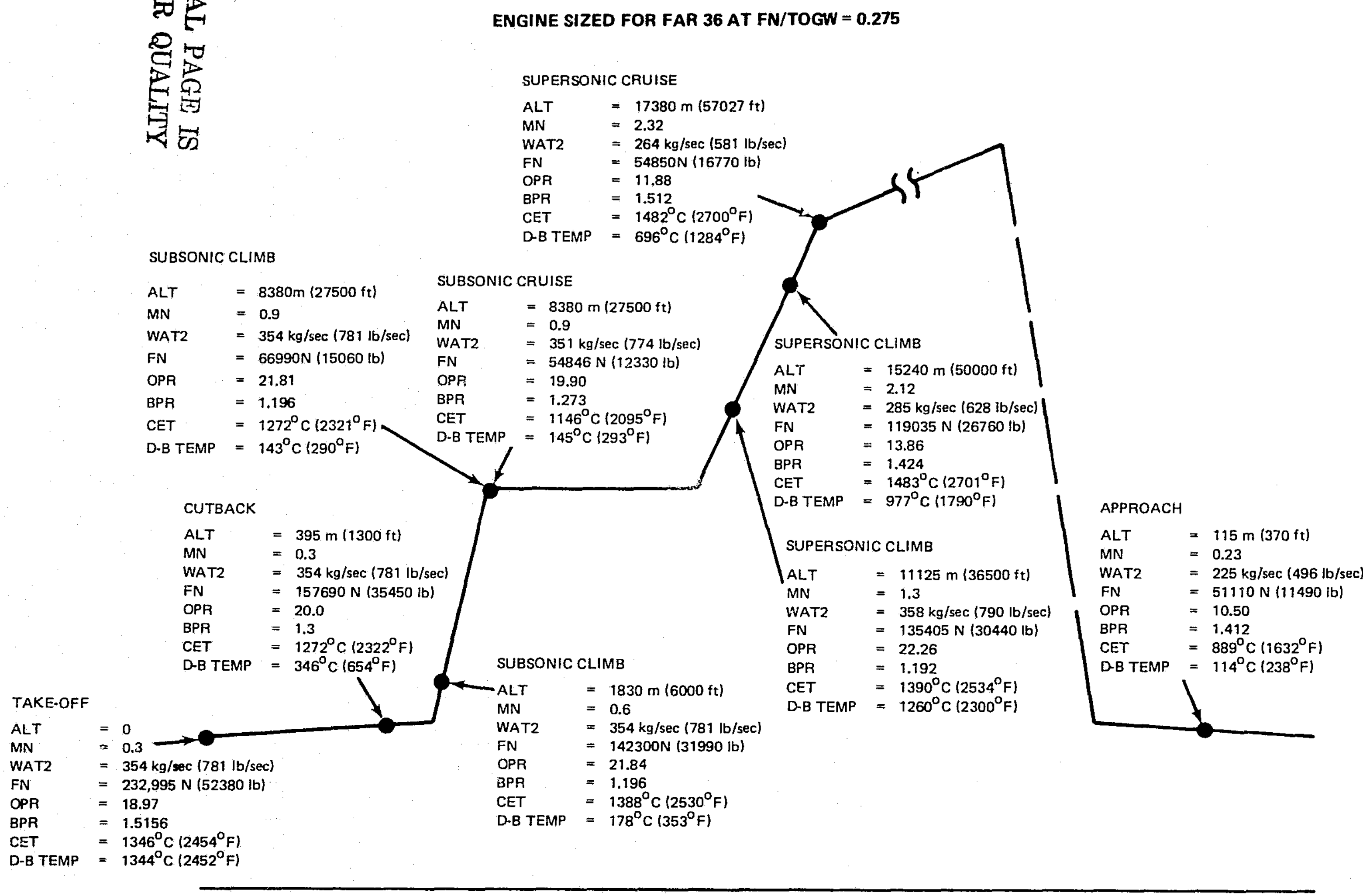


Figure 3.1.7-1 VSCE-502B Engine Conditions At Various Flight Conditions

ENGINE SIZED FOR FAR 36 AT FN/TOGW = 0.275

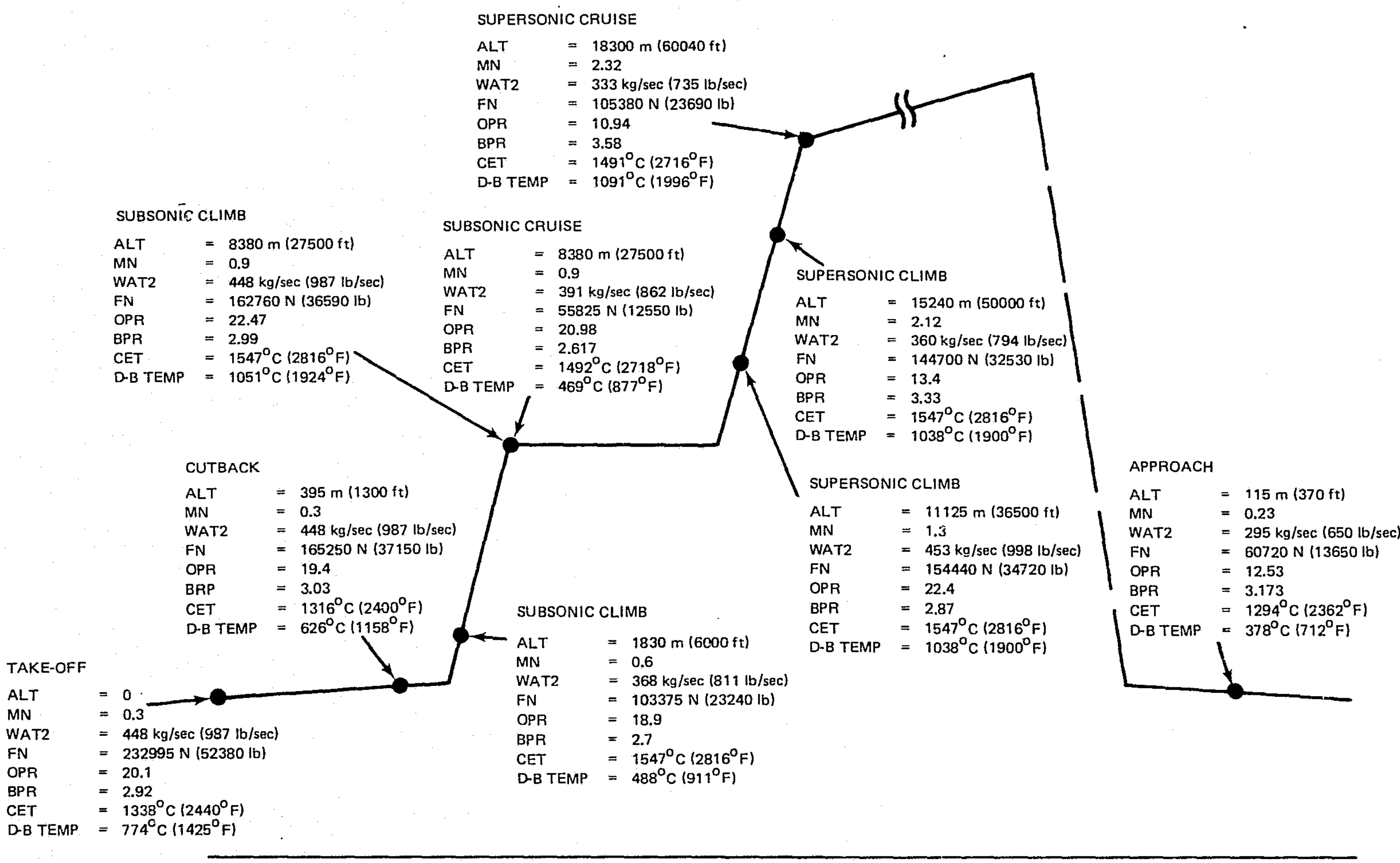


Figure 3.1.7-2 VCE-112C Engine Conditions At Various Flight Conditions

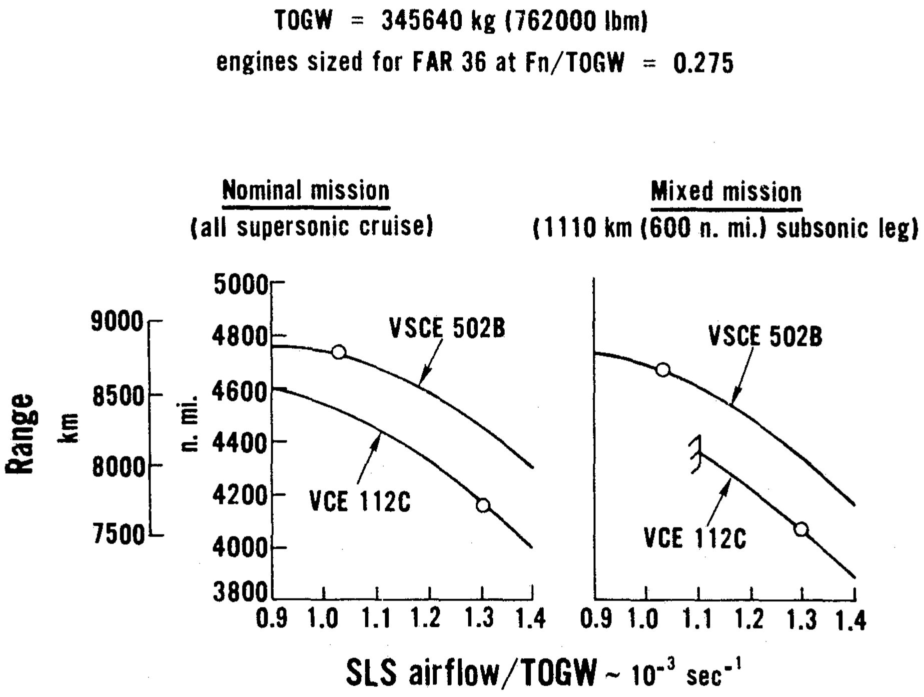


Figure 3.1.7-3 Range Comparison for Phase III Refined Engines (VSCE-502B and VCE-112C)

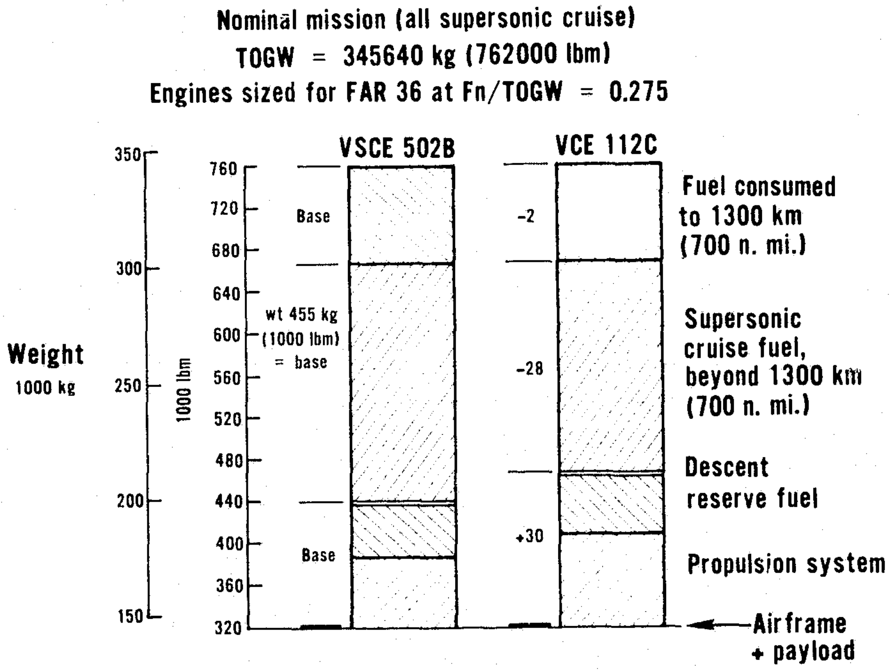


Figure 3.1.7-4 Propulsion-System-Plus-Fuel-Weight Comparison of the VSCE-502B and VCE-112C

A summary of the airplane system parameters for both engines is presented in Table 3.1.7-I. These parameters are based on a nominal mission, TOGW of 345,640 kg (762,000 lbm) with both engines sized for FAR 36 sideline noise. Although the supersonic cruise TSFC and L/D for the VCE-112C would indicate only a 2% poorer Brequet cruise parameter, the average ratio of range per unit of fuel consumed is 6% lower than the VSCE-502B. This is because of the higher end-cruise weight of the VCE-112C which is due to its higher propulsion system and reserve fuel weights. The VSCE-502B also has a significantly higher ratio of range per unit of fuel consumed during the subsonic cruise-to-alternate leg.

TABLE 3.1.7-I

SUMMARY OF KEY AIRPLANE/ENGINE SYSTEM PARAMETERS

All Supersonic Mission, FAR 36 Sideline Noise
TOGW = 345636 kg (762000 lbm)

	VSCE-502B	VCE-112C
Range ~ km (n.mi.)	8758 (4729)	7695 (4155)
WAT_2/TOGW ~ sec^{-1}	0.00102	0.00130
Supersonic Cruise		
TSFC ~ kg/hr/N (lbm/hr/lbf)	0.143 (1.40)	0.149 (1.43)
L/D	9.61	9.58
km/kg fuel (n.mi./lbm fuel)	0.0686 (0.0168)	0.0645 (0.0158)
Subsonic Cruise (CTA*)		
TSFC ~ kg/hr/N (lbm/hr/lbf)	0.096 (0.94)	0.010 (0.98)
L/D	14.3	13.8
km/kg fuel (n.mi./lbm fuel)	0.0813 (0.0199)	0.0710 (0.0174)
Fuel Weight ~ kg (lbm)	170340 (375540)	160530 (353910)
Mission	148120 (326540)	136630 (301210)
Reserve	22230 (49000)	23910 (52700)
Pod Weight ~ kg (lbm)	29720 (65510)	39530 (87150)

*CTA = Cruise to alternate

Figures 3.1.7-5, -6, -7, and -8 summarize the system performance results for the refined engines in terms of range for engines sized for various levels of peak sideline noise. Both nominal and mixed mission results are shown for thrust loadings of 0.275 and 0.32. The unsuppressed LBE-430 is also shown to provide a comparison with a refined conventional engine.

In all cases shown, the VSCE-502B has a significant range advantage over the VCE-112C as well as the conventional LBE-430.

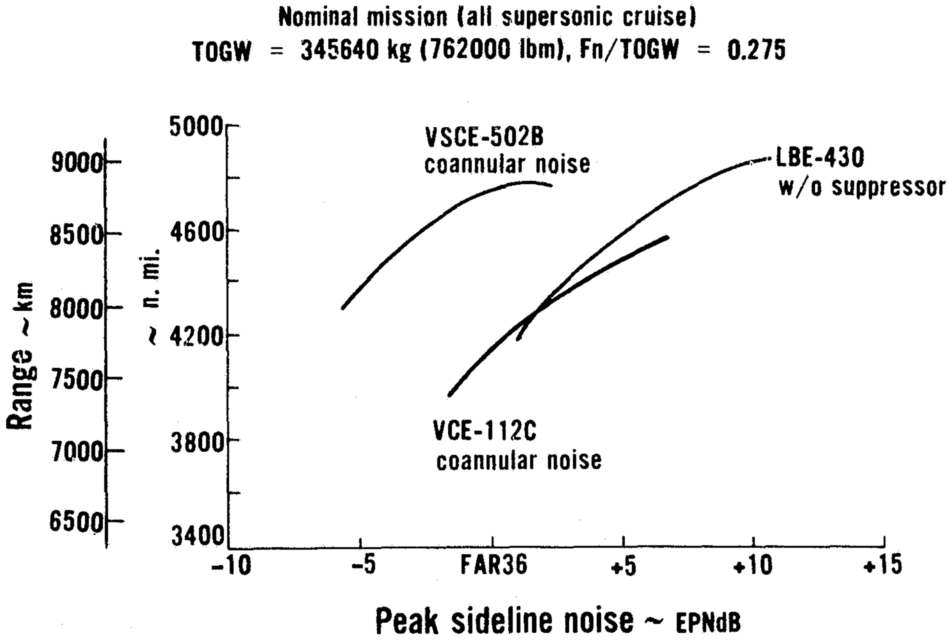


Figure 3.1.7-5 Nominal Mission Range Comparison for Phase III Refined Engines

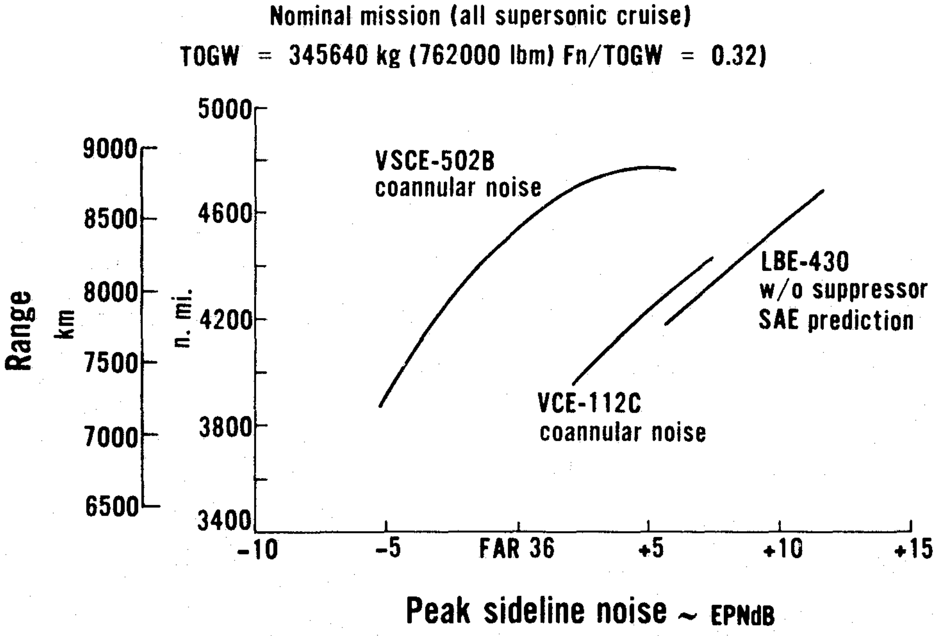


Figure 3.1.7-6 Nominal Mission Range Comparison for Phase III Refined Engines

The TOGW, direct operating cost (DOC) and return-on-investment (ROI) results are shown in Figures 3.1.7-9, and -10 and -11, respectively, for a fixed range of 7410 km (4000 n. mi.). For all three parameters, the VSCE-502B is significantly better than the VCE-112C. It should be noted that VSCE-502B engine size required to meet FAR 36 noise levels (Figure 3.1.7-3) is close to the size for minimum TOGW but somewhat larger than the size for best economics (DOC and ROI).

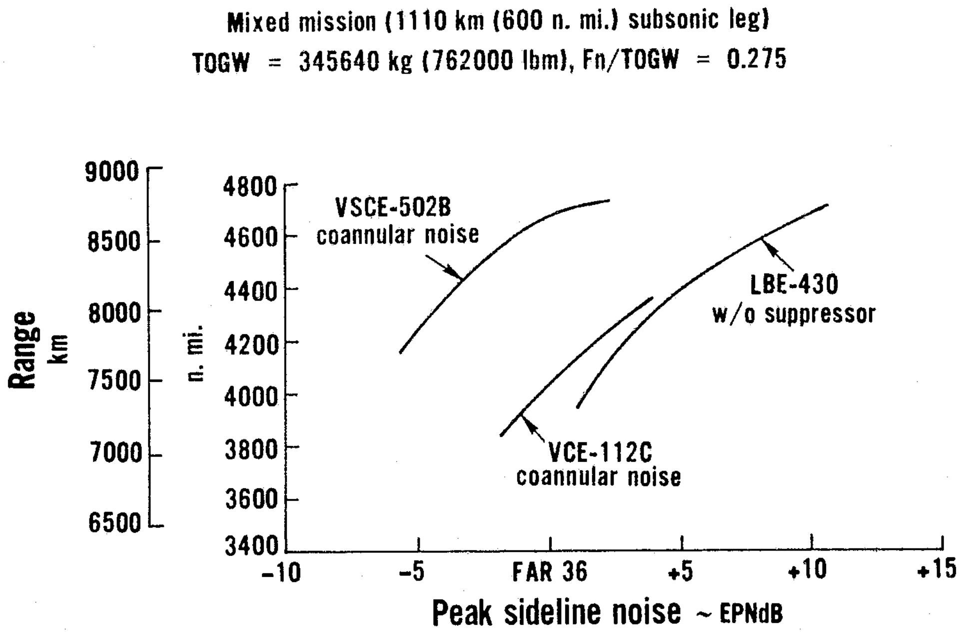


Figure 3.1.7-7 Mixed Mission Range Comparison for Phase III Refined Engines

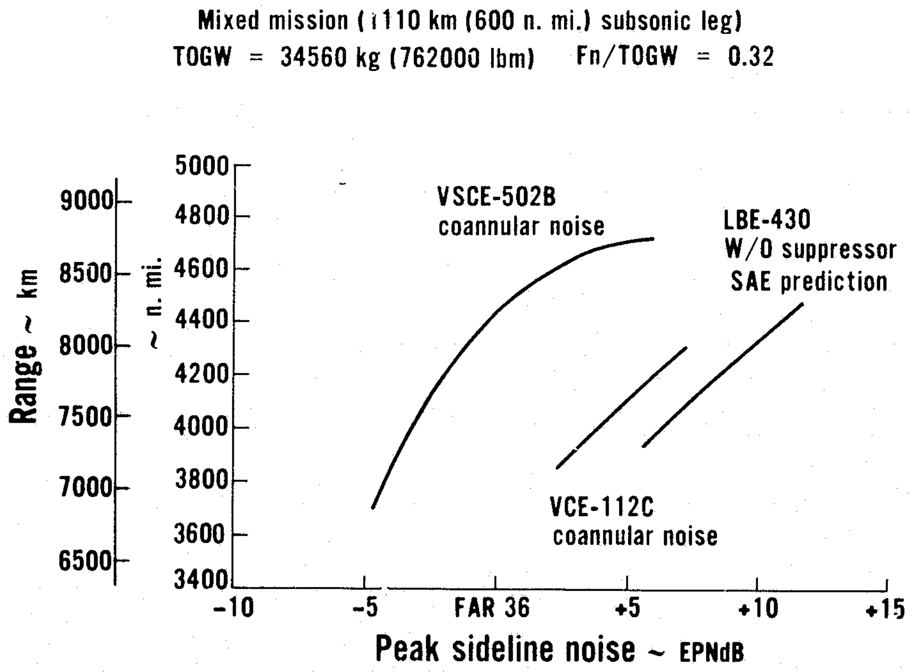


Figure 3.1.7-8 Mixed Mission Range Comparison for Phase III Refined Engines

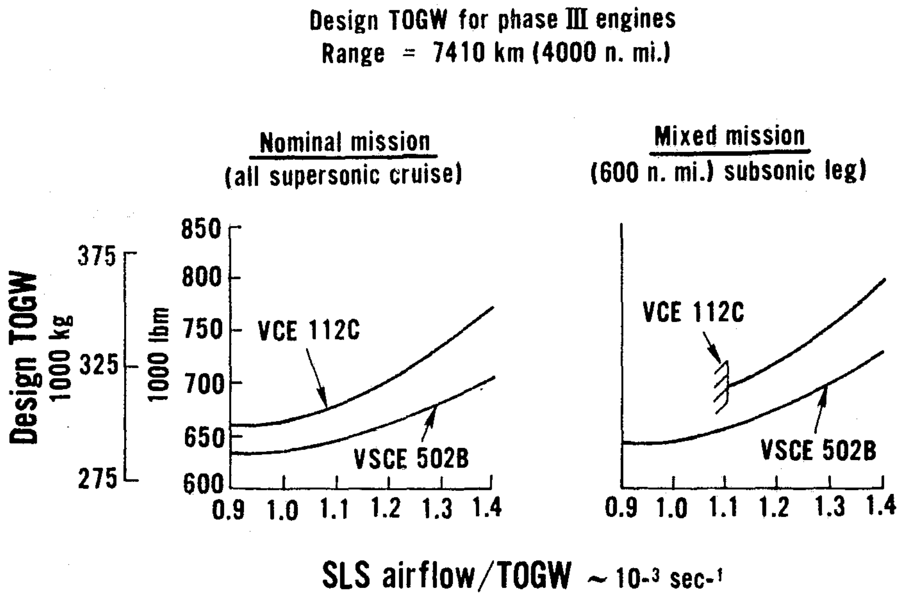


Figure 3.1.7-9 Design TOGW Comparison for Phase III VSCE-502B and VCE-112C

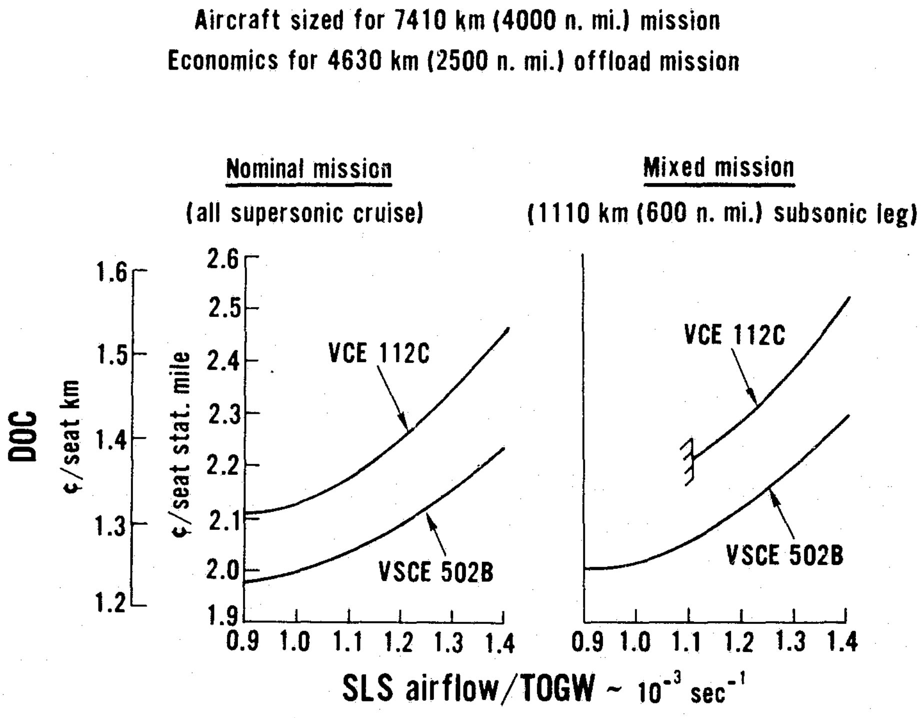


Figure 3.1.7-10 Direct Operating Cost Comparison for Phase III VSCE-502B and VCE-112C

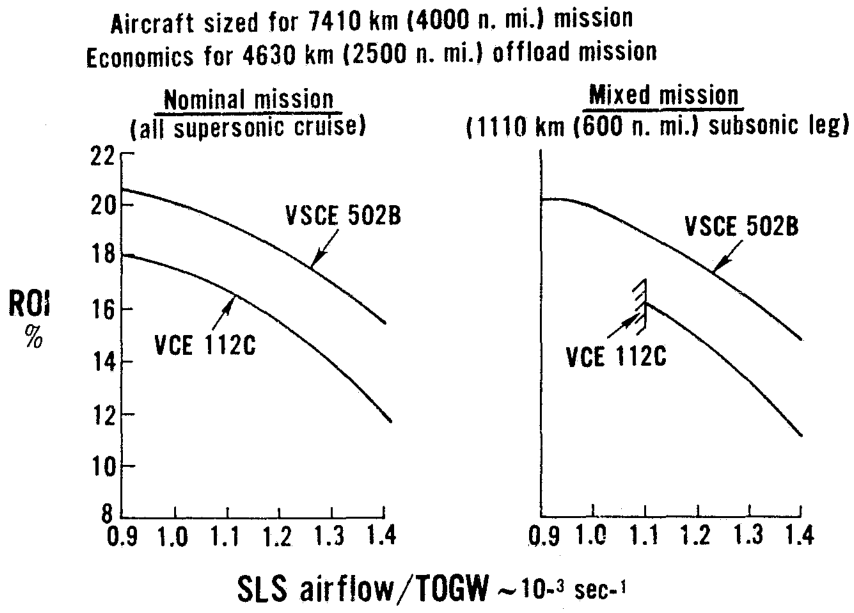


Figure 3.1.7-11 Return on Investment Comparison for Phase III VSCE-502B and VCE-112C

3.2 ENGINE DEFINITIONS PROVIDED TO NASA AND AIRPLANE COMPANIES

Four engines were selected for issue in data-pack form to NASA and associated SCAR airplane contractors for system evaluation. These engines were the Mn 2.4 VSCE-502B and VCE-112C, and the Mn 2.7 VSCE-516 and VCE-121. The information provided in the data-packs is presented in summary tables and figures and briefly described in this section.

3.2.1 Data-Pack Description

The data-packs issued by P&WA were in the form of magnetic computer tapes and punched cards which contained engine performance over the entire flight spectrum. Also included were installation drawings, engine weights and envelope dimensions, scaling data and inlet characteristics and airflow schedules. General engine descriptions completed the data-pack information.

3.2.2 Summary of Data-Pack Information

Table 3.2.2-I presents a summary of the cycle and installation characteristics for the four data-pack engines. Also included in the table are the date of issue and inlet configuration for each engine. The VSCE-502B and VCE-112C were described in detail in Section 3.1.4. The primary difference in the cycle characteristic between the Mn 2.4 and Mn 2.7 engines is a lower OPR for the higher Mach number engines. The OPR's were reduced to meet the higher Mach number capability without requiring further extensions in technology levels. Specifically, the maximum allowable compressor exit temperature is limited to 700°C (1300°F) at supersonic cruise because of material constraints. Figure 3.2.2-1 is an overall size and weight comparison of the VSCE-502B and VCE-112C engines. The dimensions of

the higher Mach number VSCE-516 and VCE-121 vary only slightly from the engines shown in this figure; the maximum diameters are the same, and lengths are 0.13 M (5 in) and 0.10 M (4 in) less, respectively.

TABLE 3.2.2-I

PHASE III DATA PACK ENGINE CYCLE AND INSTALLATION SUMMARY
Sea level static

	Nominal mission Mach No.			
	2.4		2.7	
	VSCE-502B	VCE-112C	VSCE-516	VCE-121
Issue Month Year	Oct '75	Oct '75	Dec '75	Jan '76
Airflow Schedule	Representative Mach 2.4 Inlet		NASA-AMES "P" Inlet	
Cycle characteristics				
Corrected airflow ~ kg/sec (lb/sec)	408 (900)	408 (900)	408 (900)	408 (900)
Fan pressure ratio	3.3	5.8	3.3	5.8
Bypass ratio	1.3	2.5	1.3	2.5
Overall pressure ratio	20:1	25:1	16:1	21:1
Combustor exit temp. ~ °C (°F)				
Primary burner	1540 (2800)	1540 (2800)	1540 (2800)	1540 (2800)
Duct burner	1370 (2500)	1040 (1900)	1370 (2500)	1040 (1900)
Engine weights and dimensions				
Bare engine ~ kg (lb)	4760 (10,500)	5190 (11,450)	4850 (10,700)	5290 (11,660)
Engine + nozzle/reverser ~ kg (lb)	6080 (13,400)	6190 (13,650)	6170 (13,600)	6290 (13,870)
Max. diameter ~ m (in)	2.24 (88)	2.19 (86.3)	2.24 (88)	2.19 (86.3)
Engine + nozzle/reverser length ~ m (in)	6.76 (266)	7.87 (310)	6.63 (261)	7.77 (306)

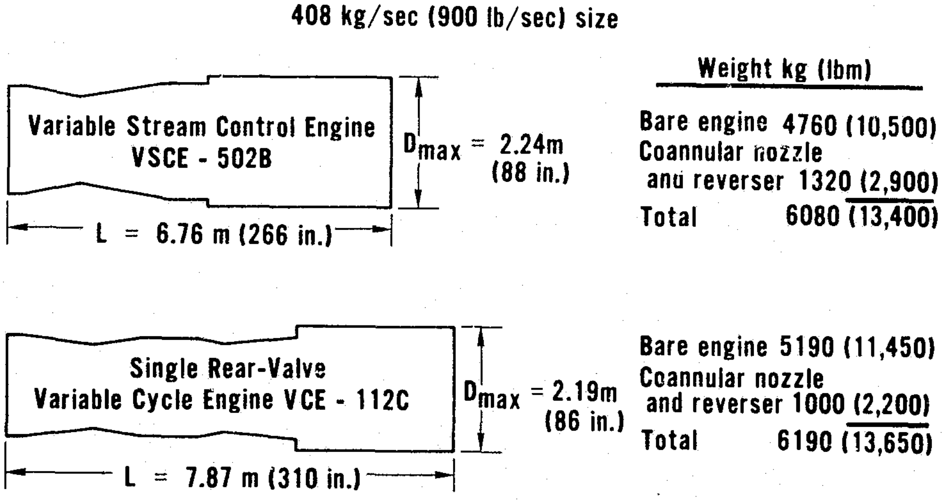


Figure 3.2.2-1 Overall Site and Weight Comparison of VSCE-502B and VCE-112C

Installed cruise performance for the four engines is summarized in Figures 3.2.2-2, -3 and -4. These performance curves include the effects of both internal nozzle performance and external nozzle drag, as well as the effects of inlet pressure recovery and drag (spillage and bleed). These curves show that the VSCE concepts have better performance (lower TSFC) than the rear-valve VCE engines.

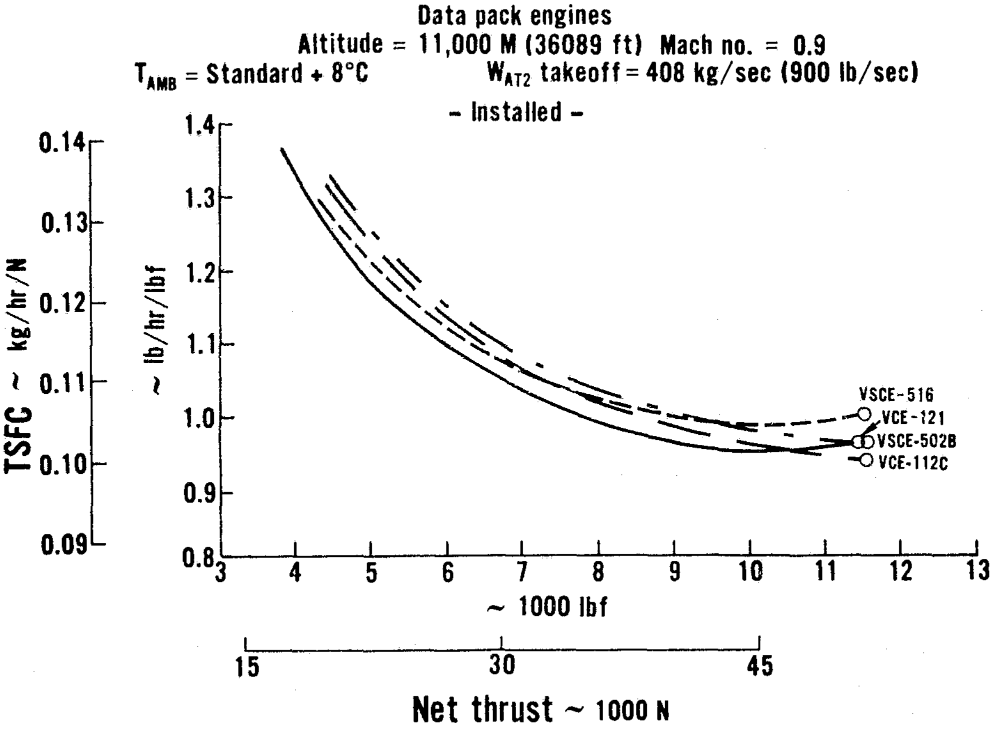


Figure 3.2.2-2 Installed Subsonic Cruise Performance for Data-Pack Engines

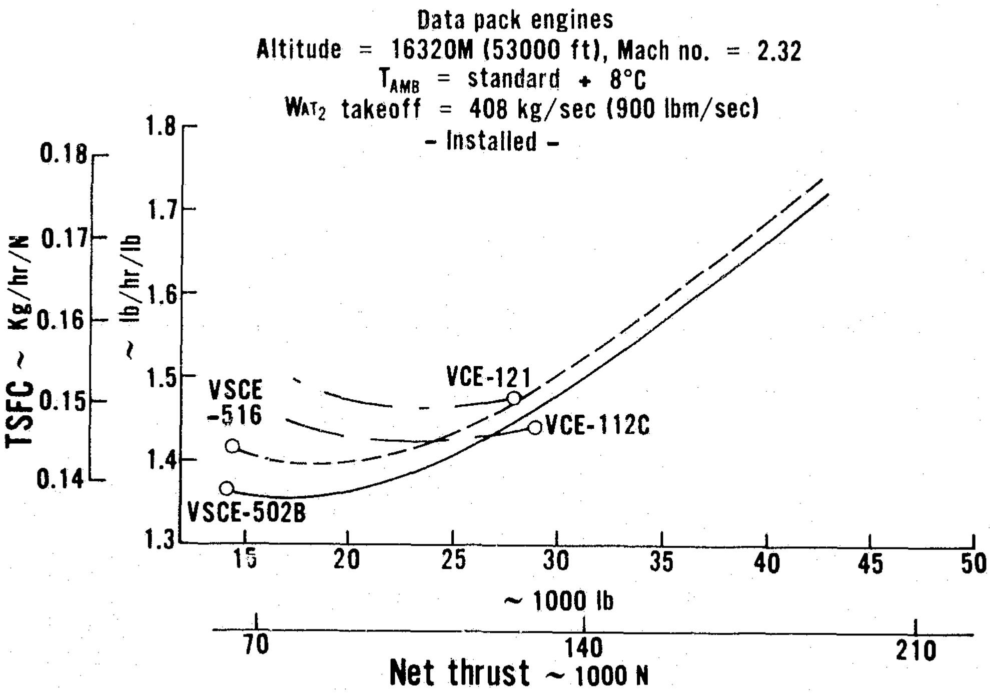


Figure 3.2.2-3 Installed Supersonic Cruise Performance for Data-Pack Engines

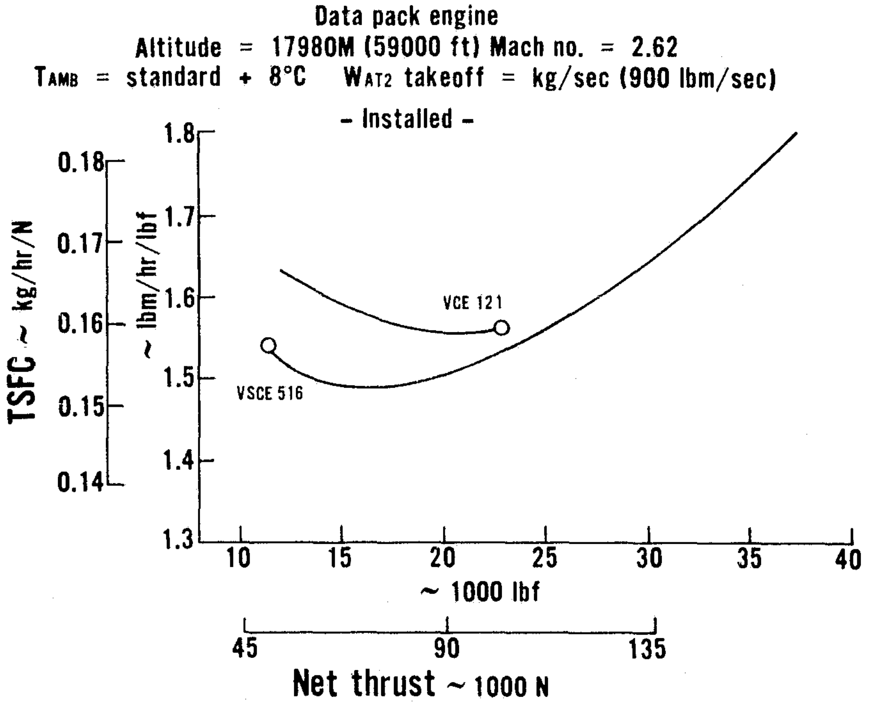


Figure 3.2.2-4 Installed Mn 2.7 Cruise Performance for Data-Pack VSCE-516 and VCE-121

3.2.3 Range Comparison

A comparison of the range achievable for the data-pack engines is presented in Figure 3.2.3-1 for a fixed TOGW and various engine sizes (SLS Airflow/TOGW). System performance for the VSCE-502B and VCE-112C was discussed and compared in Section 3.1.7. That comparison showed the VSCE-502B to have approximately 370 km (200 n.mi.) better range than the VCE-112C for a given engine size. As shown in Figure 3.2.3-1, both of the Mn 2.7 data-pack engines have reduced range; however,cruise Mach number does not change the relative comparison between the VSCE and the rear-valve VCE engines.

3.2.4 Militarized Engines

Militarized versions of two AST engines were provided to NASA-Lewis in data-packs similar to those issued for the commercial engines. The two engines were designated the STF-483, a derivative of the VSCE-502B, and the STJ-484, a derivative of the LBE. Table 3.2.4-I presents a summary of the cycle characteristics and basic installation parameters of these militarized engines.

The STF-483 is a military version of the VSCE twin-spool engine. It was matched for constant inlet corrected airflow at flight Mach numbers below 1.6 and altitude above 6100 m (20,000 ft). The STJ-484 is a single-spool mixed flow afterburning version of the LBE. This engine provides constant inlet corrected airflow from maximum to intermediate power at flight Mach numbers below 2.0 and altitudes between 9140 M and 19810 M (30000 ft and 65000 ft).

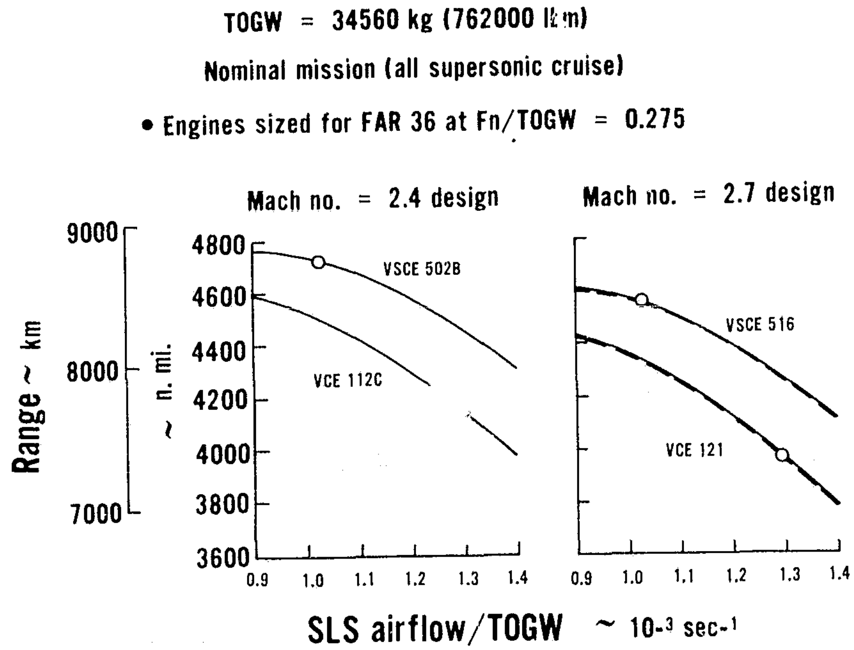


Figure 3.2.3-1 Range Comparison for Data-Pack Engines

TABLE 3.2.4-I

PHASE III MILITARIZED ENGINE CYCLE AND INSTALLATION SUMMARY
SEA LEVEL STATIC

Cycle Characteristics	Militarized VSCE STF-483	Militarized LBE STJ484
Corrected Airflow ~ kg/sec (lbm/sec)	110 (250)	110 (250)
Fan pressure ratio	3.3	2.78
Bypass ratio	1.30	0.20
Overall pressure ratio	20	15
Combustor exit temperature ~ °C (°F)	1198 (2190)	1109 (2029)
Maximum augmented thrust ~ N (lbs)	95640 (21500)	114760 (25800)
Intermediate Thrust ~ N (lbs)	58270 (13100)	72950 (16400)
Engine Weights and Dimensions		
Bare Engine ~ kg (lbm)	1030 (2260)	1340 (2955)
Engine + nozzle ~ kg (lbm)	1270 (2800)	1610 (3550)
Max. Diameter ~ m (in)	1.24 (48.8)	1.18 (46.6)
Engine + nozzle length ~ m (in)	3.37 (132.6)	4.46 (175.7)

3.3 UNCONVENTIONAL ENGINE CONCEPTS

Various unconventional engine concepts were screened in Phases I and II of the AST studies. Two of these concepts, the variable stream control engine (VSCE) and single rear-valve variable cycle engine (VCE), were identified as the most promising AST engines at the end of the Phase II studies. During Phase III, five additional unconventional concepts were screened. Table 3.3-I lists these concepts along with potential benefits and problems associated with each concept. The results of the Phase III unconventional concept screening studies are discussed in the following sections.

TABLE 3.3-I

PHASE III
UNCONVENTIONAL ENGINE CONCEPTS

Concept	Potential Advantages	Potential Problems
Boundary layer control	• Reduced wing size • Reduced jet noise • Improved airplane performance	• Complication to wing design • Complexity
Three-stream rear-valved VCE	• Lighter • Improved fuel consumption	• Complexity
Supersonic fan engine	• Engine and nacelle weight reductions • Improved installation dimensions	• Shock interaction effects • Noise • Starting • Stability • Thrust reversal • Installation
High pressure ratio engine with intercooling	• Improved subsonic cruise fuel consumption	• Weight • Complexity
Three-stream cycle with reheat	• Improved supersonic cruise fuel consumption	• Weight • Reduced specific thrust • Complexity

3.3.1 Supersonic Fan Engine

The supersonic fan engine is a non-augmented, turbofan engine which incorporates a unique component, a supersonic through-flow fan. The supersonic fan engine has the potential for simplifying the inlet and nozzle design of the bypass stream and reducing total installed weight.

To explain the supersonic fan (SSF) concept and point out the differences between this and VSCE-502B cycle, Figure 3.3.1-1 shows the two flowpaths on a common centerline. The freestream flow approaching the inlet of both engines, at supersonic cruise, is at a supersonic Mach number equal to the aircraft flight Mach number. As the flow passes through the mixed compression inlet of the VSCE-502B, it is diffused down to a subsonic Mach number approaching the fan face and exits the fan at a subsonic Mach number. There is a rapid rise in static pressure as the flow is decelerated through the inlet and fan. An augmentor (duct burner) and nozzle system then accelerate the bypass flow to a supersonic Mach number.

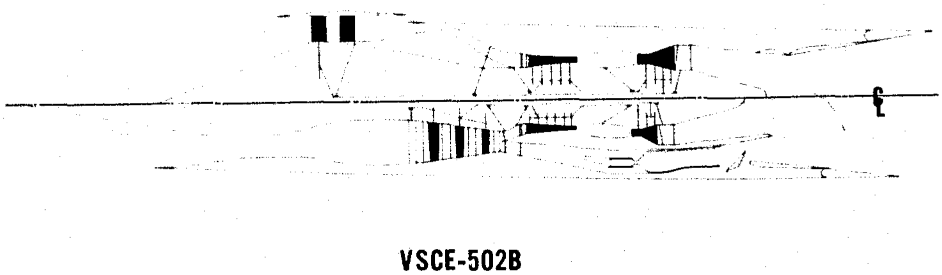
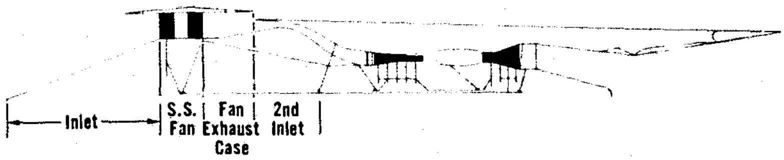


Figure 3.3.1-1 Supersonic Fan Engine/VSCE-502B Flowpath Comaprison

The SSF engine inlet slows the flow to a lower but still supersonic axial Mach number into the fan and the flow exiting the fan is still supersonic. Because of the aero-thermal problems associated with operating a burner in a supersonic stream, a duct burner was not included in this engine. The supersonic fan is essentially a constant static pressure fan since there is no significant static pressure rise across the fan. This concept requires a "second inlet" to decelerate the air entering the high-pressure compressor from the supersonic fan exit flow to a subsonic Mach number. The other engine components that make up the SSF engine are similar to those in the VSCE, and incorporate the same levels of advanced technology.

Figure 3.3.1-2 identifies the components unique to the supersonic fan engine and shows the parametric values defined for cycle studies. Inlet ram recovery is based on a cone semivertex angle of 21.5° and its associated shock loss, and an assumed skin friction loss. The 4% boundary bleed is considered representative of well-designed external compression inlets; this bleed would be ducted overboard to provide thrust and, as such, would not be a total loss to the system. The fan efficiency of 83% was based on the assumption that the supersonic fan would be no more efficient than more conventional advanced technology high pressure-ratio fans. The 5% boundary layer bleed was assumed for the fan to control boundary layer build-up within the fan itself. Because the static pressure of this fan bleed is low, the thrust recovery is small. Nevertheless, the cycle performance evaluation allowed for the small thrust potential of this bleed air. The fan exhaust case pressure loss of 2.5% is considered representative of a well designed, clean wall exhaust case. This pressure loss was not included in the assumed fan efficiency. The pressure loss and boundary layer bleed assumed for the "second inlet" are considered typical of a well designed inlet with uniform flow. While it is realized that this inlet will not see a uniform flow, data to adjust these bleed levels for distortion effects are not available and therefore the levels indicated in Figure 3.3.1-2 used for this study may be optimistic.



Component	Parameter	Value (%)
Inlet	• Ram recovery	96.5
	• % boundary layer bleed	4.0
Supersonic fan	• Stage efficiency	83
	• % boundary layer bleed	5
Fan exhaust case	• Pressure loss	2.5
2nd inlet	• Pressure loss	10
	• % boundary layer bleed	10
Augmenter	None	—

• Remainder of engine defind consistently with VSCE-502B

Figure 3.3.1-2 Supersonic Fan Engine Unique Components

Using these component definitions, cycle studies were conducted for a range of BPR from 0.5 to 2.0, and FPR from 2.2 to 3.4. Overall pressure ratio, airflow size and combustor exit temperature were held constant. The results of these studies are plotted on the supersonic cruise performance curve in Figure 3.3.1-3, along with the VSCE-502B partial augmentation performance curve for comparison. A typical cruise power setting is shown on the curve. Two supersonic fan cycles were selected for screening studies; one offering the lowest supersonic cruise TSFC (0.5 BPR, 3.4 FPR) and one similar to the VSCE-502B cycle (1.5 BPR, 2.2 FPR).

The results of the screening study are shown in Table 3.3.1-I. The 0.5 BPR engine provides slightly better TSFC and significantly lower bare engine weight than the 1.5 BPR engine when both are sized to the same supersonic cruise thrust. The lower bare engine weight for the 0.5 BPR engine is a result of its higher specific thrust. Based on the TSFC and engine weight considerations, the 0.5 BPR engine was selected for flowpath definition and comparison with the VSCE-502B.

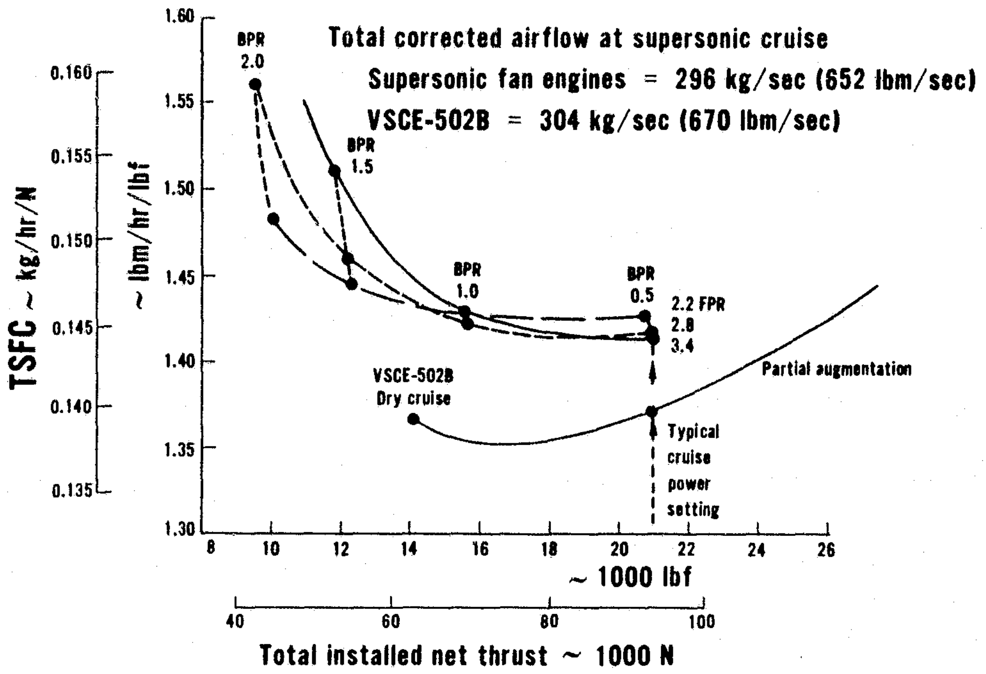


Figure 3.3.1-3 Supersonic Fan Engine Supersonic Cruise Performance

TABLE 3.3.1-I

SUPERSONIC FAN ENGINE SCREENING STUDY RESULTS
Supersonic cruise conditions

Bypass ratio	0.5		1.5	
Fan pressure ratio	3.4		2.2	
Total net thrust ~ N (lbf)	93,860	(21,100)	93,860	(21,100)
TSFC ~ kg/hr/N (lbm/hr/lbf)	0.144	(1.41)	0.147	(1.44)
Corrected airflow ~ kg/sec (lbm/sec)	297	(655)	513	(1130)
Bare engine weight ~ kg (lbm)	5443	(12,000)	8936	(19,700)

Table 3.3.1-II compares the cycle, performance and weight characteristics of the VSCE-502B and SSF engine. The lower SSF overall pressure ratio is required to maintain the compressor exit temperature at 704°C (1300°F) which is dictated by materials limitations. The SSF engine has a 3% higher TSFC than VSCE-502B and a 13% heavier bare engine weight. However, since the nacelle for the SSF engine is significantly lighter, its total pod (engine + nacelle) weight is 17% lighter. These TSFC and weight differences tend to cancel each other and result in no apparent system advantage for the SSF engine over the VSCE-502B. It should be noted that if the 5% boundary layer bleed air assumed for the fan can be reduced, the TSFC for the SSF engine would approach that of the VSCE-502B.

TABLE 3.3.1-II

COMPARISON OF SSF ENGINE WITH VSCE

Cycle at Supersonic Cruise	VSCE-502B	Supersonic Fan Engine
Bypass ratio	1.5	0.5
Fan pressure ratio	2.4	3.4
Overall pressure ratio	11.9	10.2
Combustor exit temp. ~ °C (°F)	1,482 (2700)	1,482 (2700)
Augmenter	Duct-heater on	None
Performance at Supersonic Cruise		
Thrust ~ N (lbf)	93,860 (21,100)	93,860 (21,100)
TSFC ~ kg/hr/N (lbm/hr/lbf)	0.140 (1.37)	0.144 (1.41) (+3%)
Corrected airflow ~ kg/sec (lbm/sec)	304 (670)	297 (655)
Weight kg (lbm)		
Bare engine	4,731 (10,430)	5,352 (11,800) (+13%)
Total pod	8,709 (19,200)	7,257 (16,000) (−17%)

Since this study was conducted for the supersonic cruise condition only, there are many unanswered questions concerning the impact of the supersonic fan on other operating modes. There are also many unknowns concerning such characteristics as noise, off-design efficiency, effect on low rotor critical speed and stability. The effects of structural elements and a towershaft across the supersonic bypass flow on performance are also unknown. Table 3.3.1-III presents a summary of the uncertainties and potential problems associated with the supersonic fan engine concept. The SSF technology is not consistent with the engine time frame being considered in these AST studies. Because of these problems, in addition to the results of this screening study that indicate the SSF engine (based on an optimistic cycle difinition) offers no overall advantage over the VSCE-502B, no further evaluation of the supersonic fan engine is recommended.

TABLE 3.3.1-III

UNIQUE UNCERTAINTIES AND POTENTIAL PROBLEMS
OF THE SUPERSONIC FAN

- Off-design variations in supersonic fan blade incidence and effect on overall cycle performance
- Fan noise during takeoff and approach
- Sensitivity of high hub/tip fan rotor assembly to tip clearance
- Foreign object damage to supersonic fan blades due to very sharp and thin leading edges may affect fan efficiency. However, the low aspect ratio blades may improve overall structural resistance to foreign object damage.
- Critical speed problems with overhung support arrangement of supersonic fan and spike assembly
- Starting and stability problems with supersonic fan and related variable geometry control requirements
- Thrust margin characteristics of nonaugmented engine for transonic and supersonic climb
- Fan distortion effects on supersonic diffuser bleed requirements and pressure loss characteristics
- Thrust reversing for supersonic stream
- Installation performance characteristics of engine, especially effect of support structure across supersonic stream
- Location of engine/airframe accessories and high spool towershaft which crosses supersonic stream
- Effects of rotating spike on inlet boundary layer control and bleed requirements. (In order to avoid having static structure upstream from the fan, a rotating spike was assumed for this evaluation).

3.3.2 Boundary Layer Control Concept

The NASA SCAR program has included wind-tunnel tests of an airplane model with several forms of flap blowing. In the boundary layer control (BLC) concept, air is bled from the propulsion system and ducted to a slot nozzle along the flap hingeline. The lift and drag benefits can potentially be used to improve the take-off and/or landing performance, which in turn could be used to reduce noise or airplane cost.

The 34560 kg (762,000 lbm) NASA-Langley Reference Aircraft Configuration was retained as the base aircraft. The definition of the 408 kg/sec (900 lbm/sec) VSCE-502B was modified to include a collecting scroll, two valves and a valve control to provide 64 kg/sec (142 lbm/sec) bleed from the duct stream. This amount of bleed corresponds approximately to a flap blowing coefficient, $c_{\mu} = 0.02$. A 91 kg (200 lbm) weight increase per engine was included to allow for engine related BLC hardware. A schematic of the modified VSCE-502B is shown in Figure 3.3.2-1. In addition, a weight increment of 14.9 kg per meter (10 lbm per foot) of wing span was added to allow for wing ducts and associated hardware.

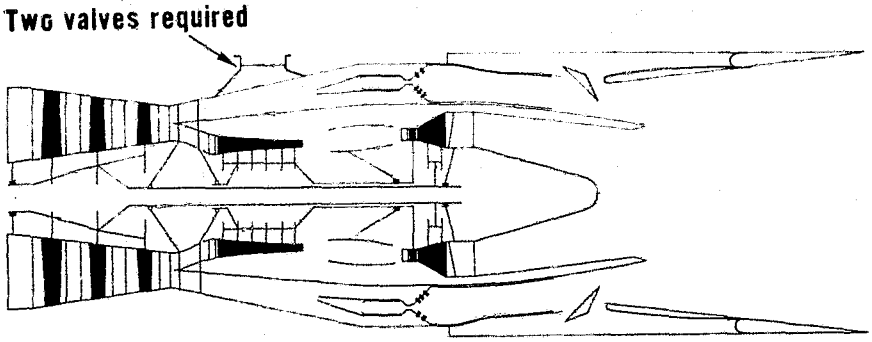


Figure 3.3.2-1 Boundary Layer Control Version of VSCE-502B

The effects of BLC on aerodynamics was obtained by applying BLC lift and drag coefficient increments, as determined by NASA-Langley wind tunnel test data, to the aerodynamics of the Reference Configuration as defined in Reference 2.

For a given engine airflow size and equal sideline noise, the BLC version of the engine has a 19% thrust loss because of the bleed air extraction. Figure 3.3.2-2 shows that with this thrust loss, as indicated by the operating points on the curve, the airplane with flap BLC cannot climb as high as the conventional airplane without flap BLC. This means that the conventional airplane will make less noise over the community than the airplane with flap BLC. Several flap angles were investigated and it was found that a 5° flap angle provided the highest cut-back altitude in all cases. It was therefore concluded that BLC would not benefit take-off operation including noise characteristics of the overall airplane.

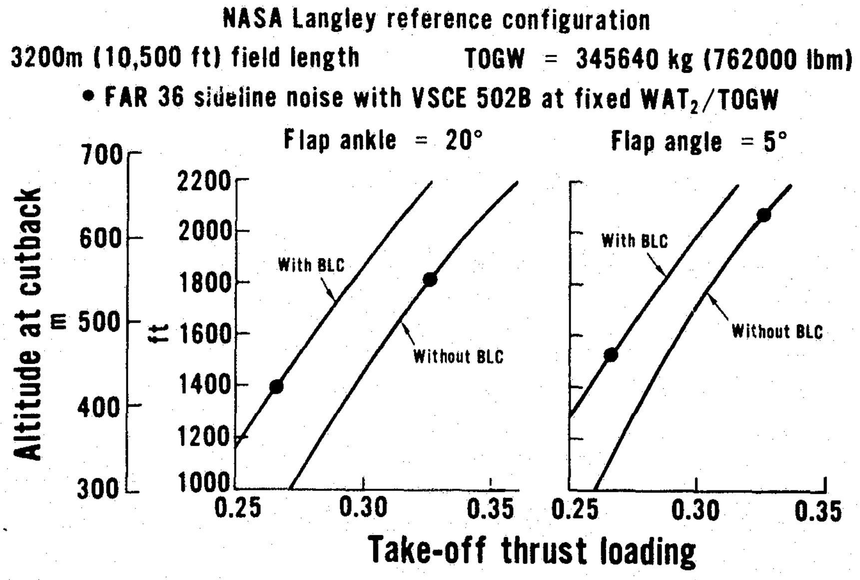


Figure 3.3.2-2 Effect of Flap BLC on Cutback Altitude

The potential benefit during approach was evaluated next. Figure 3.3.2-3 shows that approach speed can be reduced slightly with flap BLC and still permit a reduction in wing area. As shown, the approach speed for a wing loading of 4070 N/m^2 (85 lbf/ft^2) is 276 km/hr (149 knots) with flap BLC, compared to 282 km/hr (152 knots) for the baseline airplane with a wing loading of 3660 N/m^2 (76.4 lbf/ft^2).

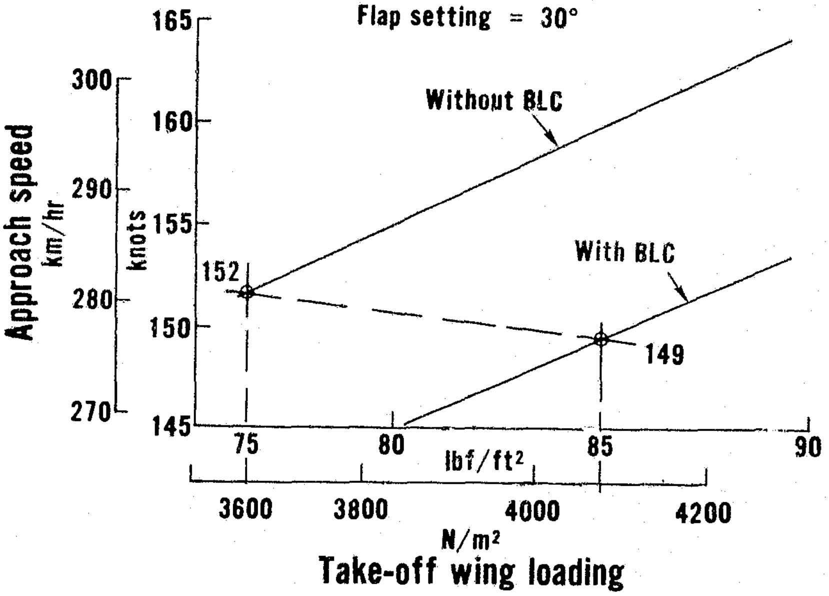


Figure 3.3.2-3 Effect of Flap BLC on Approach Speed

The potential range benefit that can be achieved by use of flap BLC on landing is shown in Figure 3.3.2-4. The base airplane without flap BLC has an engine sized to meet 108 EPNdB at both sideline and cut-back. If the BLC weight penalty is applied to the airplane without any adjustments in engine or wing size, a 93 km (50 n. mi.) range penalty would result. But if the wing size is reduced to provide 4070 N/m^2 (85 lbf/ft^2) wing loading, and the engine size is slightly increased to provide the same noise level, then a 222 km (120 n. mi) range improvement can be achieved relative to the conventional case.

In summary then, flap BLC appears to offer no advantage for take-off, but improvements in landing performance can be utilized to provide a 222 km (120 n. mi.) range improvement. Further airplane/engine design studies are required to substantiate the results of this BLC screening study.

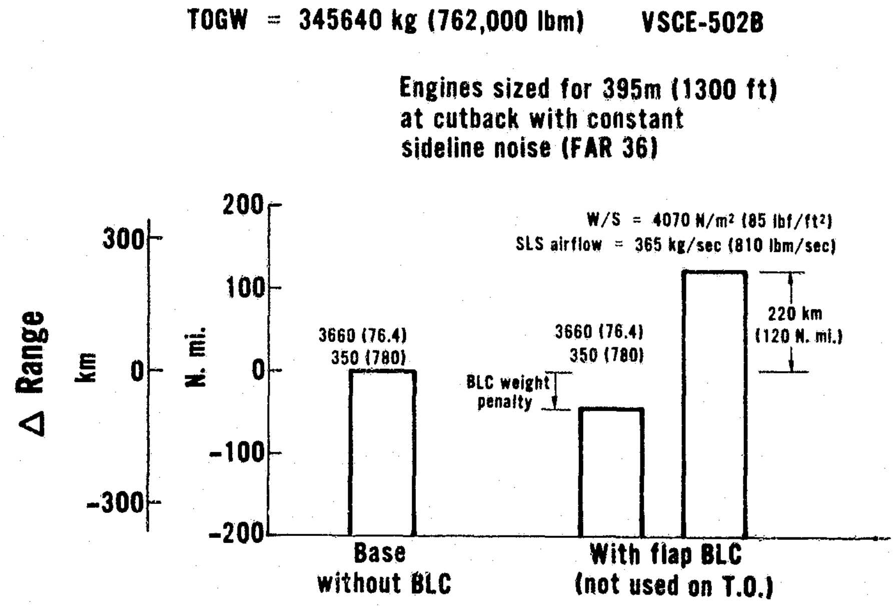


Figure 3.3.2-4 Potential Range Benefit with Flap BLC

3.3.3 High Pressure Ratio Engine With Intercooling

Higher pressure ratio versions of the VSCE-502B engine with intercooling were evaluated to determine their potential for improved engine performance. AST cycle pressure ratio have been limited by a maximum compressor discharge temperature of 704°C (1300°F). Intercooling offered a means of reducing this temperature while at the same time, the transfer of heat to the duct stream would potentially reduce the duct augmentation required during climb and cruise.

Figure 3.3.3-1 is a flowpath of the intercooled variable stream control engine concept. The intercooling system consist of two heat exchangers, one located in the primary stream between compressor assemblies and the other located in the bypass stream diffuser between the fan and duct-burner. Heat is extracted from the primary stream and released to the bypass stream.

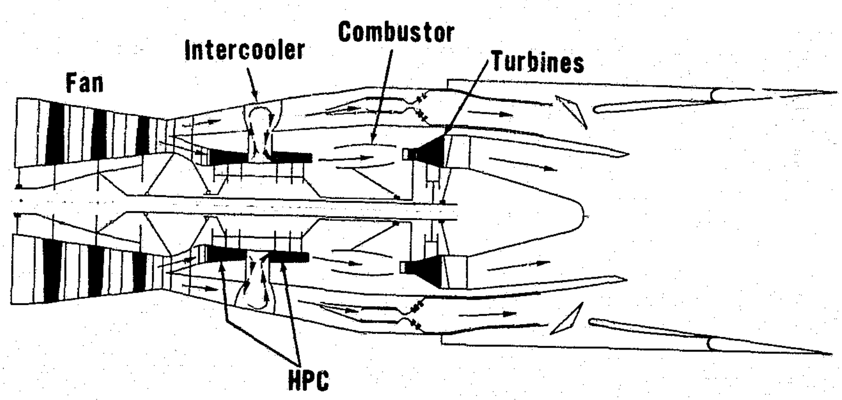


Figure 3.3.3-1 Schematic of Intercooled VSCE Concept

Figure 3.3.3-2 shows the potential improvement in subsonic cruise TSFC when the cycle pressure ratio is increased to 30:1. However, the figure also shows that when intercooler pressure losses and effectiveness are considered,there is a significant TSFC penalty. Although not shown on the figure, with the intercooler shut off during the subsonic portion of the mission, all of the potential for improved fuel consumption with increased cycle pressure ratio is offset by the addition of intercooler pressure losses in both the primary and bypass streams. These losses are severe enough that both subsonic and supersonic fuel consumption are worse than the baseline VSCE-502B even when relatively high heat exchanger effectiveness levels are assumed (See Figure 3.3.3-3). Although the level of augmentation required for cruise and climb is reduced, TSFC levels are higher at both critical operating points. In addition, engine weight is greatly increased because of the bulky heat exchangers. Based on these results, no further study of this concept is recommended.

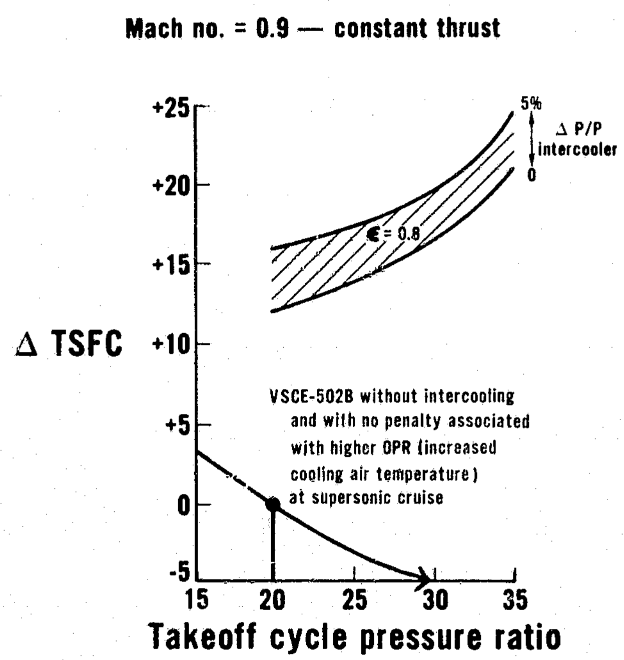


Figure 3.3.3-2 Potential for Improved Subsonic Cruise TSFC with Increased Cycle Pressure Ratio

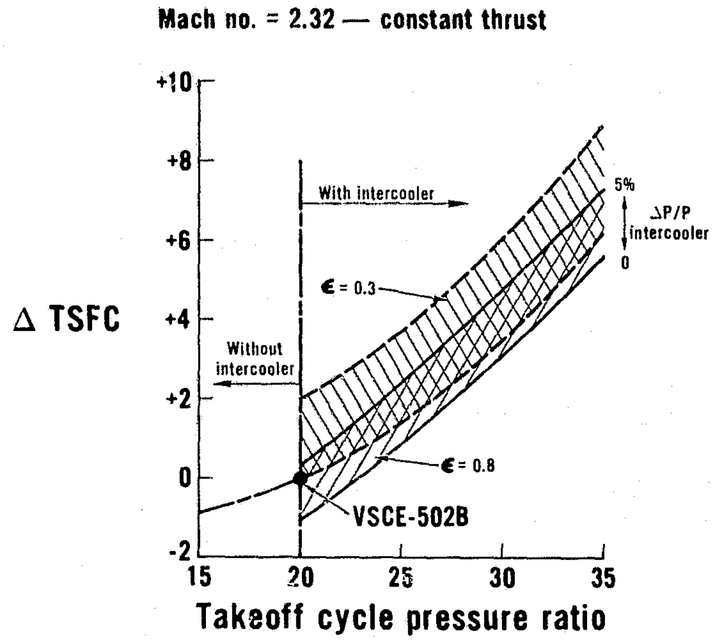


Figure 3.3.3-3 Supersonic Cruise TSFC Penalties Associated with Intercooler

3.3.4 Three Stream Cycle With Reheat

The Three Stream Reheat Cycle, shown in Figure 3.3.4-1, is essentially a low bypass ratio, mixed flow turbofan with a reheat burner that in part provides the energy to drive a moderate pressure ratio fan. The fan both supercharges the core and increases the engine bypass ratio by creating a separate (third) stream. This concept could potentially improve augmented fuel consumption at relatively high supersonic cruise specific thrust levels.

In studying this concept, the effects of reheat burner temperature and bypass flow ratio were evaluated separately for their effects on TSFC and specific thrust (FN/WA). First, the mixed flow turbofan plus reheat portion of the cycle was evaluated to determine the effect of reheat-burner temperature on supersonic cruise TSFC and specific thrust. The change in TSFC and FN/WA with increased BPR was assessed separately by adding a larger fan and rear turbine to one of the reheat cycles.

As shown by Figure 3.3.4-2, increasing reheat burner temperature increases the specific thrust of the core engine but at the expense of TSFC. The effect of adding the third stream (BPR = 0.5) is to improve TSFC but to decrease specific thrust. The potential advantages of the three stream reheat cycle are further degraded when the added weight and complexity of the system are considered. In addition, there are potentially serious off-design matching problems that are created when the reheat burner is at low power or off. A variable area rear turbine could minimize this problem but would add even more weight and complexity to the system.

Overall, this concept appears to be, at best, only competitive with a conventional, low bypass ratio mixed flow turbofan which has been evaluated and eliminated in the early Phase I study. This reheat cycle is therefore not considered to be suitable for advanced supersonic engines and no further evaluation is recommended.

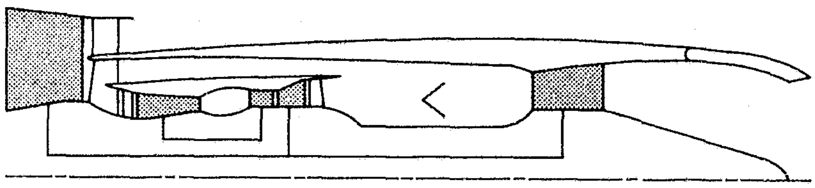


Figure 3.3.4-1 Three Stream Reheat Cycle Schematic

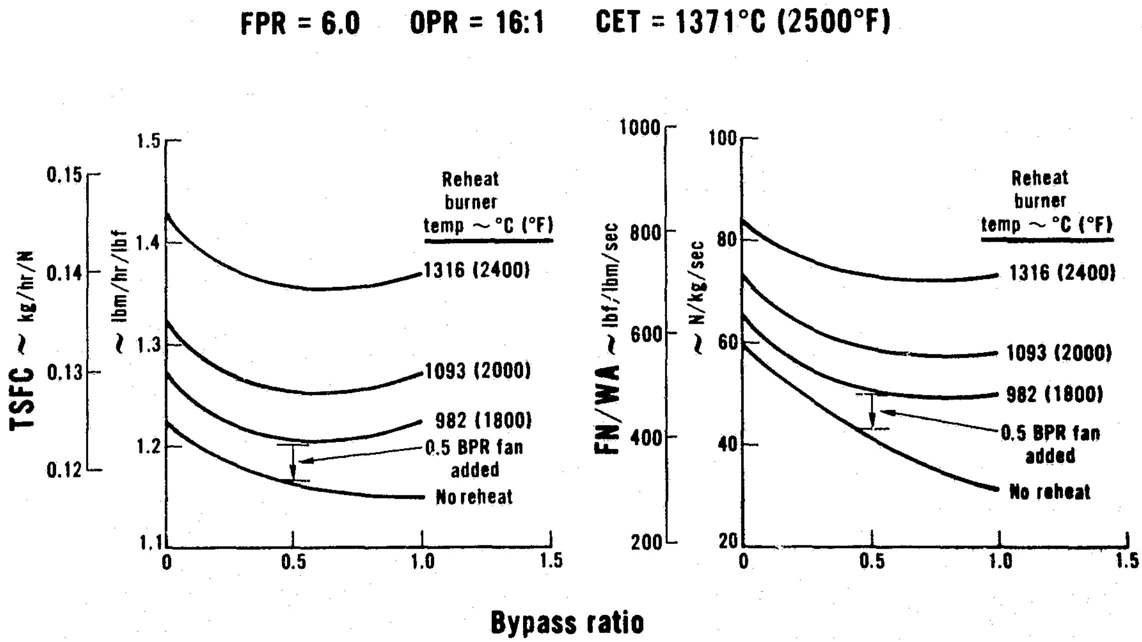


Figure 3.3.4-2 Three Stream Reheat Cycle Supersonic Cruise Performance

3.3.5 Three Stream Rear-Valve VCE

The last unconventional engine concept studied in Phase III was the three stream rear-valve variable cycle engine. The three stream rear-valve VCE is a derivative of the two stream rear-valve VCE and offered the potential for both reduced engine weight and improved engine performance.

Figure 3.3.5-1 shows a flowpath of this engine concept. The distinguishing feature of this engine compared to the two stream rear-valve VCE is the third or bypass stream around the duct-burner and rear turbine. Otherwise, the engine concept is very similar to the single rear-valve VCE-112C concept.

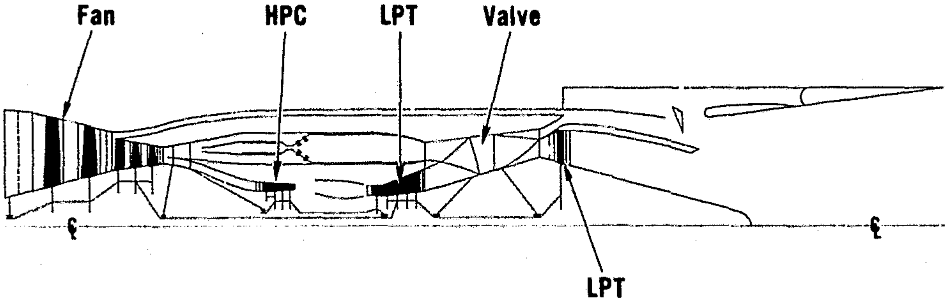


Figure 3.3.5-1 Three Stream Rear-Valve VCE Flowpath

One of the advantages of bypassing a portion of the fan airflow is that component sizes affected by either the primary or augmented duct stream flows can be reduced in size, thereby reducing the weight of the engine. The screening studies indicated that this concept had sufficient potential to warrant more detailed parametric evaluation. This concept was therefore selected for more detailed study. The results of the refined parametric evaluation are discussed in Section 3.1.4.3.

3.4 PRELIMINARY DESIGN

The areas included in the Phase III preliminary design studies are the nozzle/reverser system, advanced accessories, and refined cross-section definition of selected engines. The nozzle/reverser system received the most attention because it represents a large part (almost 25%) of the total bare-engine-plus-nozzle/reverser weight (on the order of 1360 kg (3000 lbm) out of more than 5900 kg (13,000 lbm) for the VSCE-502B). Furthermore, the nozzle/reverser design has a significant impact on the overall engine performance. Definition of advanced accessories including a sizing study was part of the preliminary design effort because the Phase II integration studies indicated that accessory sizes may and probably will affect nacelle diameters. Three engine cross-sections were generated to determine the compatibility of major engine components. These were the VSCE-502B, the rear-valve VCE-112M (mixed flow nozzle) and, for comparison, the conventional LBE-430. This section discusses these three areas.

3.4.1 Nozzle/Reverser

The procedure followed in the preliminary design studies of several coannular nozzle/reverser systems was as follows. First, several nozzle/reverser (N/R) systems for the VSCE-502B were defined and layouts or preliminary design drawings were generated. These layouts were then used to prepare weight and performance data which were used to establish the range differences between the various concepts. Finally, the weight, performance and range parameters, along with an estimate of relative complexity for each concept, were evaluated to select the most promising N/R system.

Prior to starting the N/R preliminary design study, the effect of a fixed versus variable primary nozzle on engine performance was evaluated. Since the primary nozzle area variation required for the VSCE-502B is relatively small (20%), the possible benefits of a less complex fixed primary nozzle were investigated. A systems study was conducted and based on the results of this study (discussed in Section 3.1.4.1), the variable primary nozzle was retained in the nozzle/reverser system definitions.

3.4.1.1 Nozzle/Reverser Concepts

Each of the coannular nozzle concepts evaluated in Phase III is described in this section.

Ejector with Actuated Panels — Baseline Configuration

The baseline configuration used in this study is the same used for the data pack definition, an ejector nozzle with actuated panels. A schematic of this concept is shown in Figure 3.4.1-1 for both the supersonic cruise and take-off positions. For the take-off mode, relative to the supersonic cruise configuration, the primary nozzle is partially closed, the duct nozzle is opened, and double-hinged actuated panels are opened to allow in-flow of ejector air (indicated by the arrow on Figure 3.4.1-1). Panels located immediately downstream of the double-hinged panels are translated aft to provide additional area for the ejector flow, the reverser buckets are lined up with the ejector airflow, and the nozzle exit area is closed down. The translating panels are required in addition to the double-hinged actuated panels to provide adequate ejector flow area; actuated panels alone, sized to provide the total ejector flow area, would be too long, causing problems with the mechanical design of this ejector system. A schematic of this concept in the reverse configuration is also shown in Figure 3.4.1-1. In this mode, the buckets are rotated aft to direct the flow of both streams out through the ejector flow area. The translating panels are again moved fully aft to provide adequate area for the reverse flow.

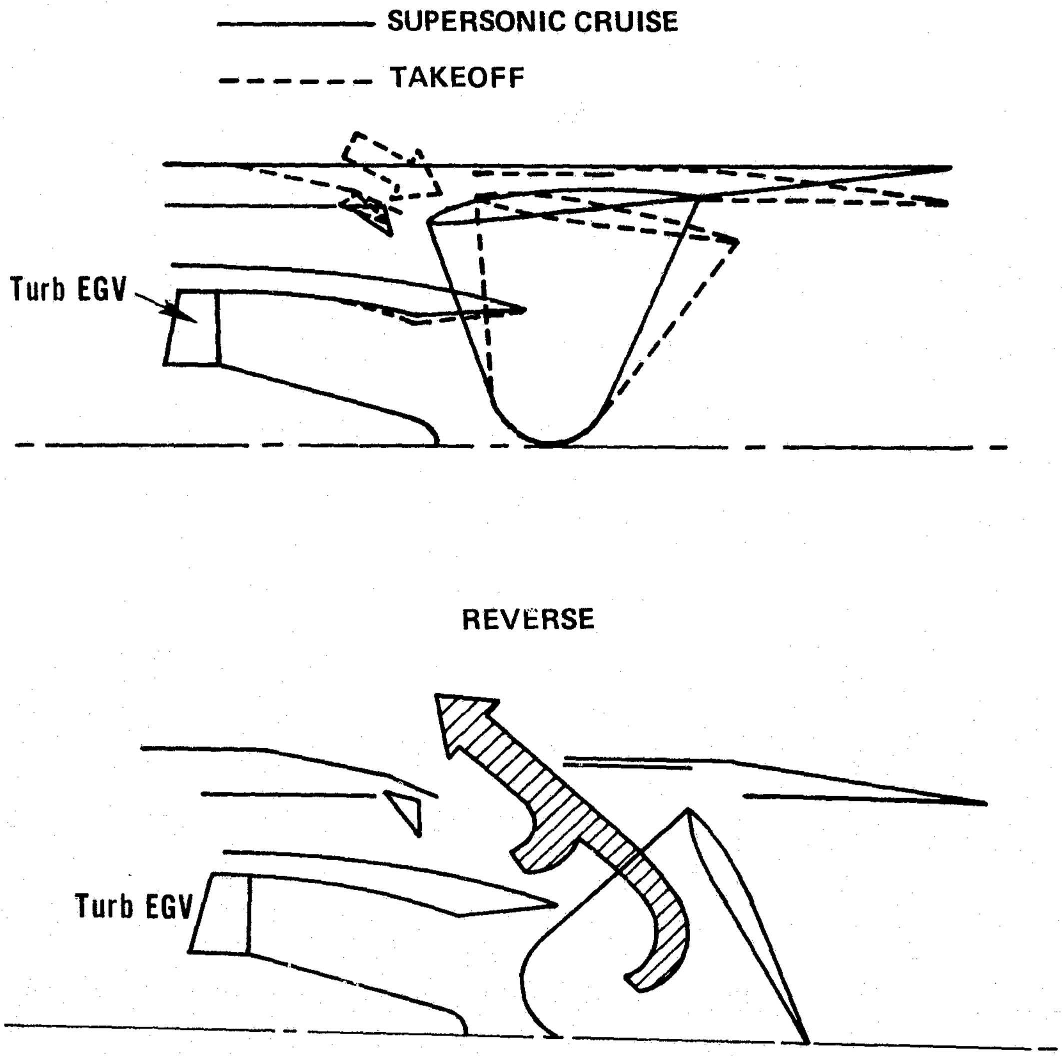


Figure 3.4.1-1 Schematic of the Ejector Nozzle with Actuated Panels – Baseline Configuration

The preliminary design layout for this concept is shown in Figure 3.4.1-2 in the take-off mode. Noted on this figure are the variable components of this N/R system. Four separate systems are required for N/R control; one each for primary and duct jet area control, one for the actuated panels, and the fourth to control both the buckets and translating panels. As currently conceived, these actuation systems would be ball screws driven by an air turbine motor which is driven by engine bleed air. The local environment would probably be too hot for hydraulic actuators, while pneumatic actuators would probably not provide a long enough stroke to be effective. The honeycomb shown on the buckets and tailfeathers would be applicable to all concepts, although it is not shown on all the layouts. The maximum diameter for this N/R system is 2.24m (88 in) when mated to a 408 kg/sec. (900 lbm/sec) airflow size VSCE-502B.

Figure 3.4.1-3 shows the baseline configuration in the subsonic and supersonic cruise modes of operation. Subsonic cruise configuration is similar to take-off; the ejector is flowing in both cases. For supersonic conditions, the double-hinged actuated panels are closed, the translating panels are full forward and the buckets form the initial divergent portion of the nozzle for the duct stream. Figure 3.4.1-4 is a layout of the baseline configuration in the reverse mode.

Ejector with actuated panels
Takeoff

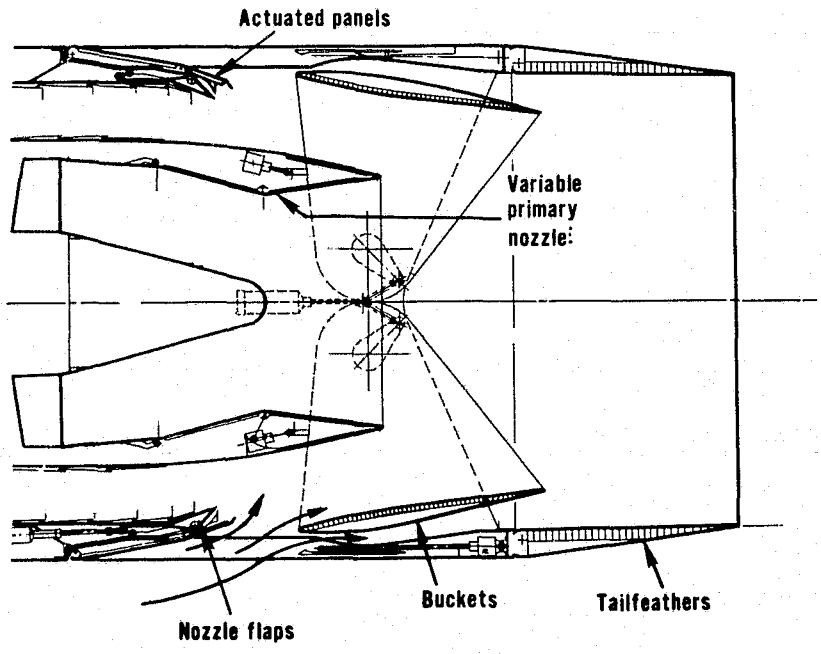
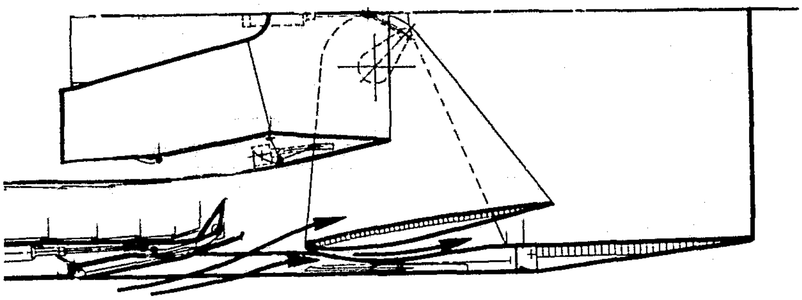
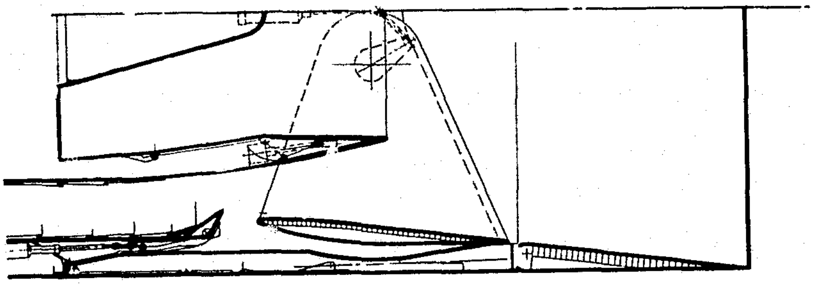


Figure 3.4.1-2 Preliminary Design Layout for the Baseline Configuration in the Take-off Mode

EJECTOR WITH ACTUATED PANELS



SUBSONIC CRUISE



SUPERSONIC

Figure 3.4.1-3 Preliminary Design Layout for the Baseline Configuration in the Cruise Modes

Ejector with actuated panels
Reverse

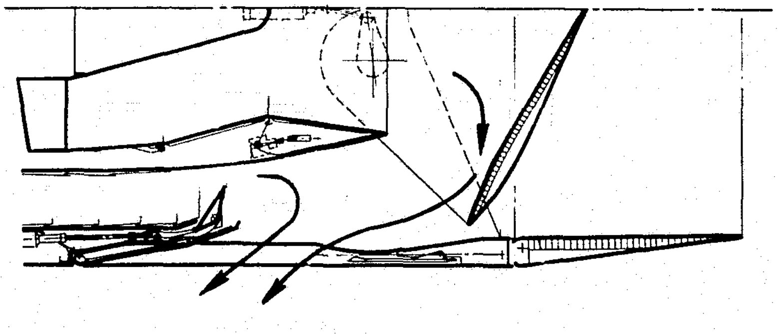


Figure 3.4.1-4 Preliminary Design Layout for the Baseline Configuration in the Reverse Mode

Ejector With Translating Cowl

Another method for providing openings for ejector and reverse flows, other than the actuated panels used in the baseline system, is to translate the entire nozzle cowl aft to provide the required openings. Four configurations using this method were evaluated. The schematics in Figure 3.4.1-5 illustrate the translating cowl concept and represent Configuration 1 of the translating cowl concepts. The supersonic cruise (solid lines) and take-off (dashed lines) modes are shown in the top part of the figure and the reverse mode in the bottom half. In the supersonic cruise mode, the cowl is forward and the ejector opening is closed. Configured for take-off or reverse, the cowl is translated aft to provide the required opening for the ejector or reverse flows (shown by arrows in the figure). Neither the baseline or Configuration 1 have cascades for targeting (or directing) reverse flow. Only the reverse flow openings provide targeting. This is less effective than using cascades and further study may prove cascades are required.

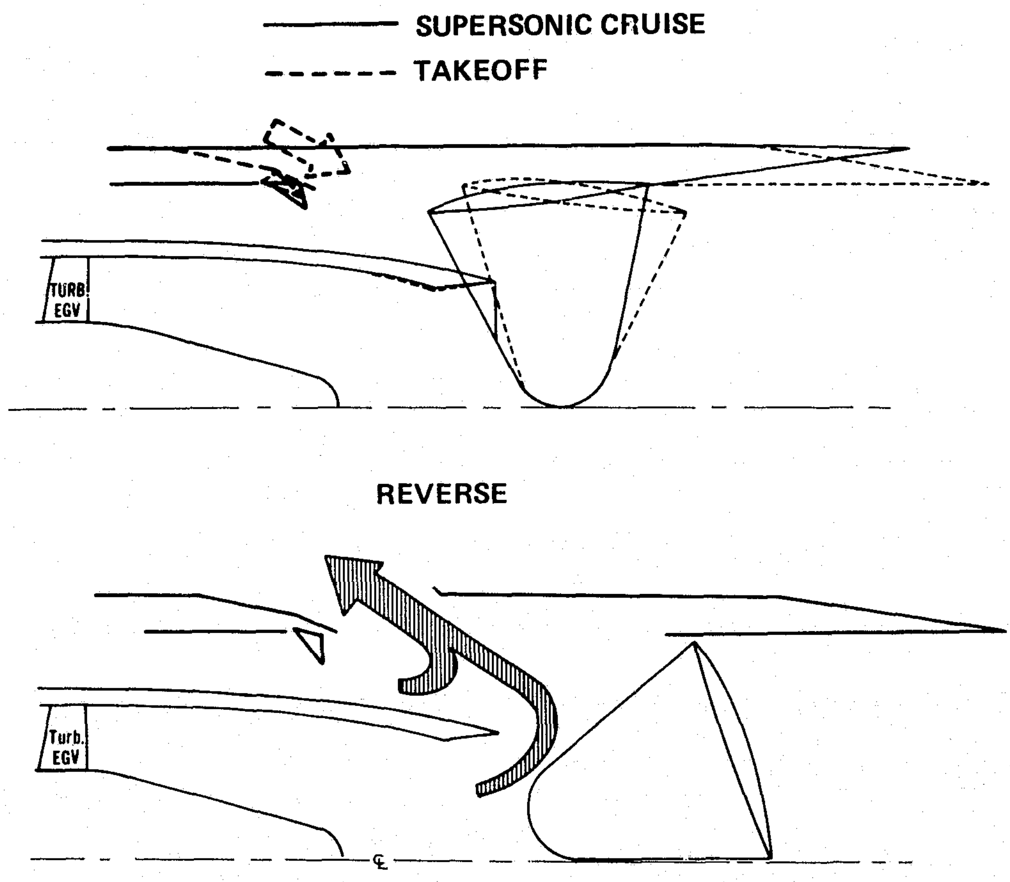


Figure 3.4.1-5 Schematic of the Ejector Nozzle with Translation Cowl Concept

Configuration 2, shown in Figure 3.4.1-6, differs from the baseline in that it incorporates cascades for targeting the reverser flow. Another difference between Configuration 2 and the baseline is the method for varying the duct stream nozzle area. A modified iris nozzle is shown in Figure 3.1.4-6 whereas the baseline uses a flap nozzle. The iris provides slightly better internal performance, but at the expense of a small length increase. For all modes other than reverse, the cascades are stowed around the duct burner, as shown in the bottom of Figure 3.4.1-7. This arrangement imposes a penalty to the system by increasing the maximum diameter from 2.24m (88 in) to 2.33m (91.6 in). This N/R system uses three systems to control the variable components: one each for the primary and duct stream exit area controls, and one for cowl translation and reverser bucket actuation. The cowl and buckets use the same control system since they are actuated at the same time and with a fixed relative schedule.

Figure 3.4.1-6 shows Configuration 2 in the supersonic cruise mode with the cowl and bucket in the ejector (subsonic or take-off) mode shown in phantom in bottom part of the drawing, and the reverse mode in the top part of the drawing, also in phantom. Note that the translating cowl is farther aft in the reverse mode than in the ejector mode to provide the larger opening required. The actuation sequence for the reverse mode is as follows: the cowl is translated fully forward and a lock pin is engaged to lock the cascades to the cowl; the cowl is then translated aft to open the reverser flow area and position the cascades (shown in phantom in the bottom of Figure 3.4.1-6); at the same time, the buckets are rotated to direct the flow of both streams into the cascades.

Ejector with translating cowl

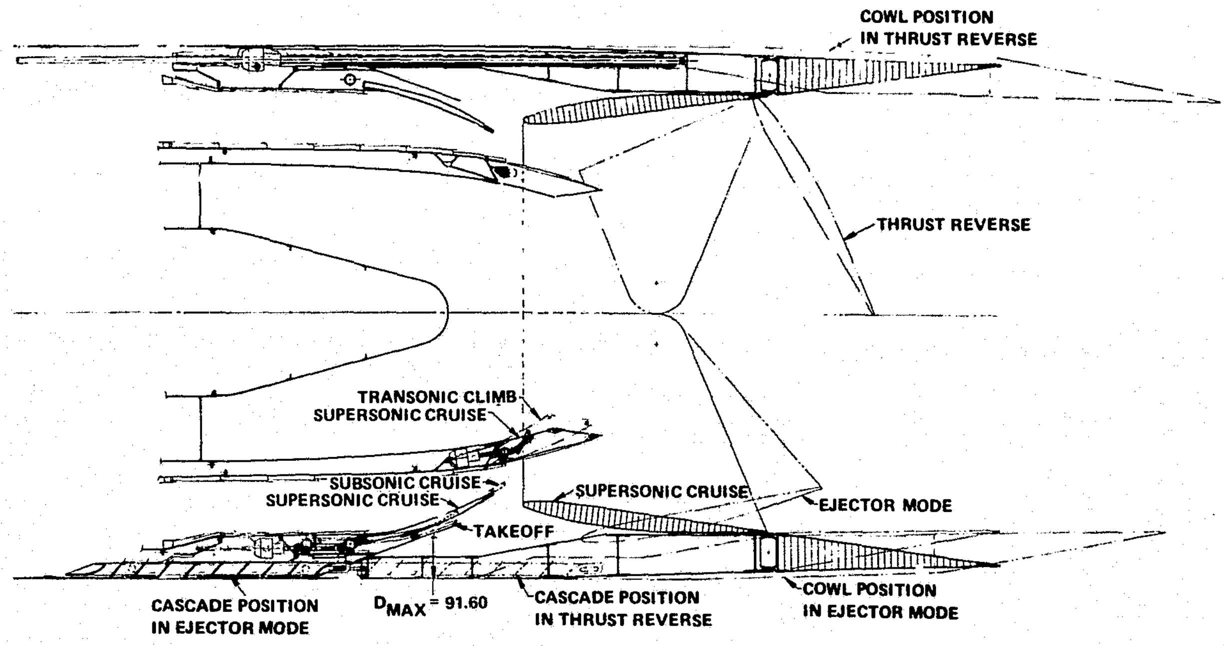


Figure 3.4.1-6 Nozzle/Reverser Configuration 2 Preliminary Design Layout

Ejector with translating cowl

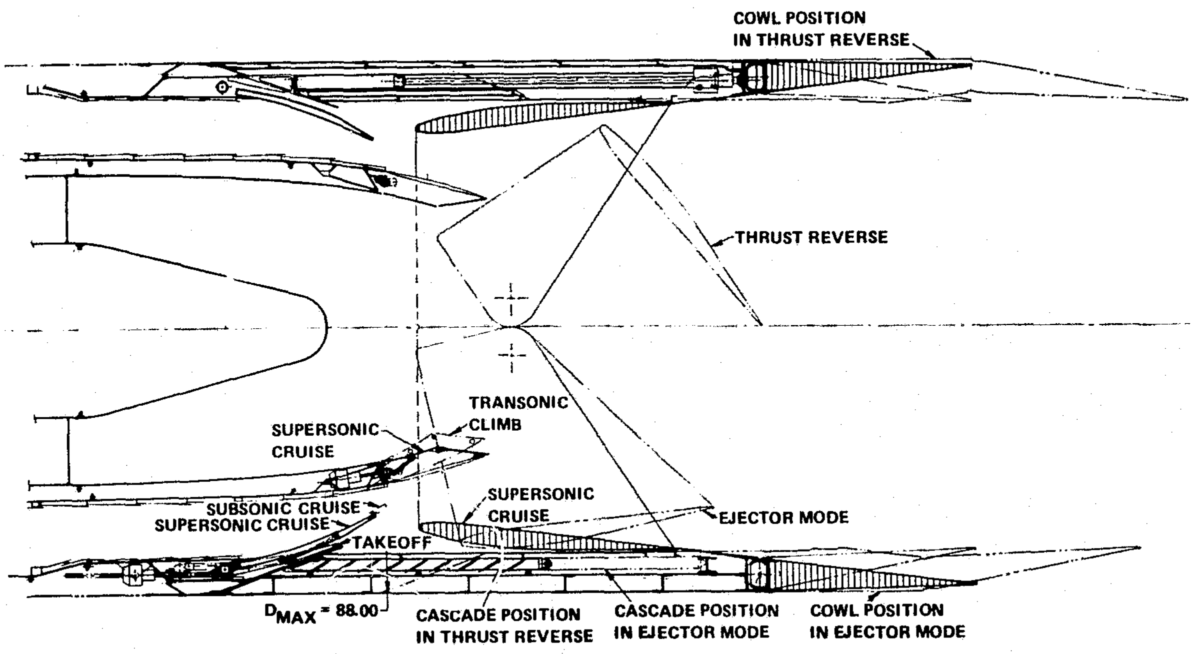


Figure 3.4.1-7 Nozzle/Reverser Configuration 3 Preliminary Design Layout

The maximum diameter penalty imposed by the cascade arrangement for Configuration 2 can be improved by storing the cascades in the translating coal. This scheme is incorporated in Configuration 3, shown in Figure 3.4.1-7. This arrangement maintains the baseline maximum diameter, 2.24m (88 in), but results in an increase in overall length of 0.30m (12 in) relative to Configuration 2. This length penalty is necessary to fit the cascades into the cowl and still provide the required ejector and reverser flow area. The same actuation systems and variable components used with Configuration 2 are used with Configuration 3. The cascades, stowed in the cowl, move within the cowl as it is translated aft for ejector operation. The reverse operation is similar to that for Configuration 2 except that the cascades are locked to the static structure and held in the reverser flow area when the cowl is translated aft.

If it is determined through detailed integration studies that cascades are not required for reverser flow targeting, the cascades could be deleted from Configuration 3. This would shorten the N/R system as shown in Figure 3.4.1-8. This actuation system and variable components would be the same as Configuration 3.

Configurations 2, 3 and 4 use a modified iris nozzle for controlling the duct stream throat area. If the baseline flap nozzle were used in place of the modified iris, a small weight and length savings may be realized but with some penalty to subsonic performance.

Ejector with translating cowl

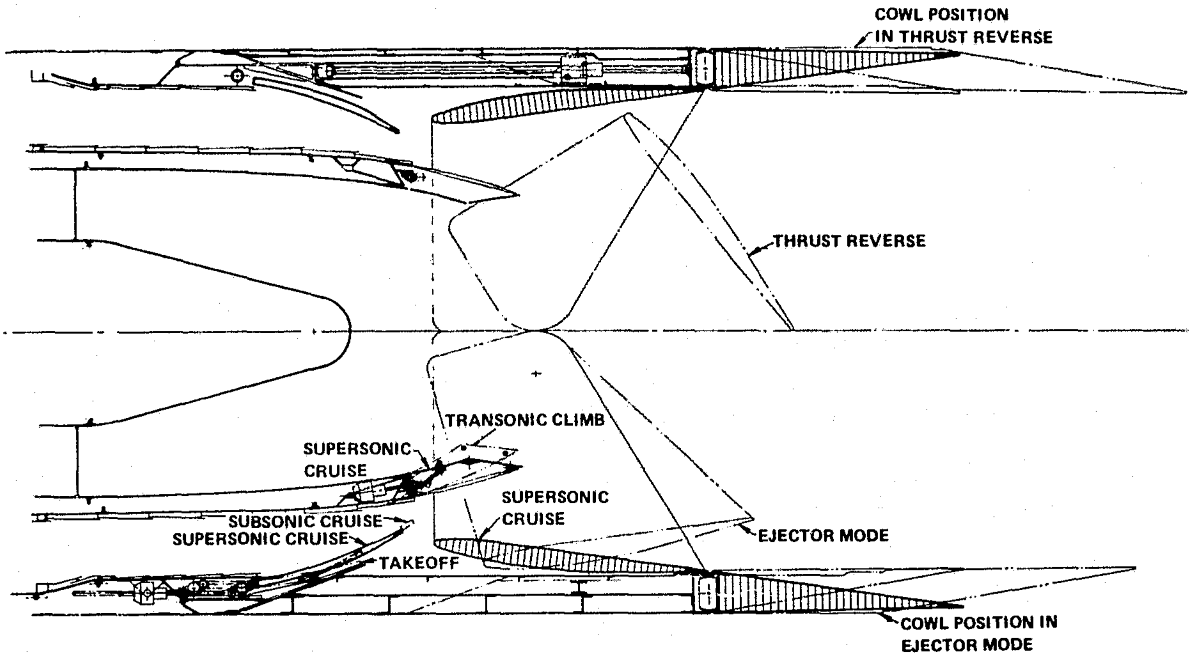


Figure 3.4.1-8 Nozzle/Reverser Configuration 4 Preliminary Design Layout

Collapsing Plug Configuration

The third type of N/R system studied under the preliminary design task was the collapsing plug concept. This concept, designated Configuration 5, is shown schematically in Figure 3.4.1-9. The collapsing plug nozzle configured for supersonic cruise is shown as solid lines in the top figure. In the take-off mode (dotted lines), the primary nozzle area is reduced slightly by expanding the primary plug and the nozzle is changed from a convergent-divergent to a convergent configuration by translating the plug aft. The bypass stream nozzle is opened up by collapsing the duct stream plug and is changed from a convergent-divergent to a convergent arrangement by translating a portion of the outer cowl forward. To obtain reverse thrust, a portion of the outer cowl is translated aft and down, and a portion of the primary plug aft surface is translated forward and up, as shown in the bottom figure. Limited targeting of the reverse thrust can be achieved by proper positioning of selected panels.

Figure 3.4.1-10 is a preliminary design layout of Configuration 5. This concept requires six systems to control the variable components: one each for varying primary and duct nozzle areas by means of collapsing plugs; one for the primary nozzle configuration changes (i.e., from C-D to convergent) by translating the primary plug; one for the bypass stream nozzle configuration changes by translating a portion of the outer cowl; and one each to control the primary and bypass stream reverser panels. The positions of the variable components for take-off, subsonic, transonic, supersonic and reverse modes of operation are shown in Figure 3.4.1-10. Also shown, are the actuators for the variable components. This figure illustrates the complexity of this concept and potential sealing problems for both the reverser panels and collapsing plugs.

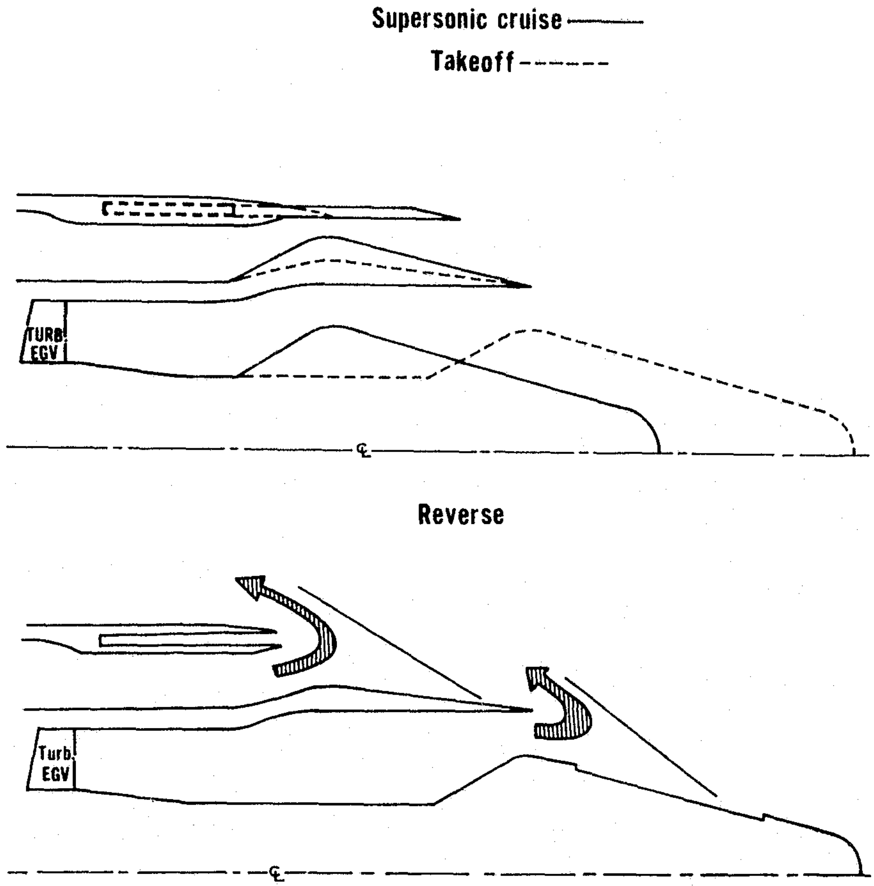


Figure 3.4.1-9 Schematic of the Collapsing Plug Nozzle Concept (Configuration 5)

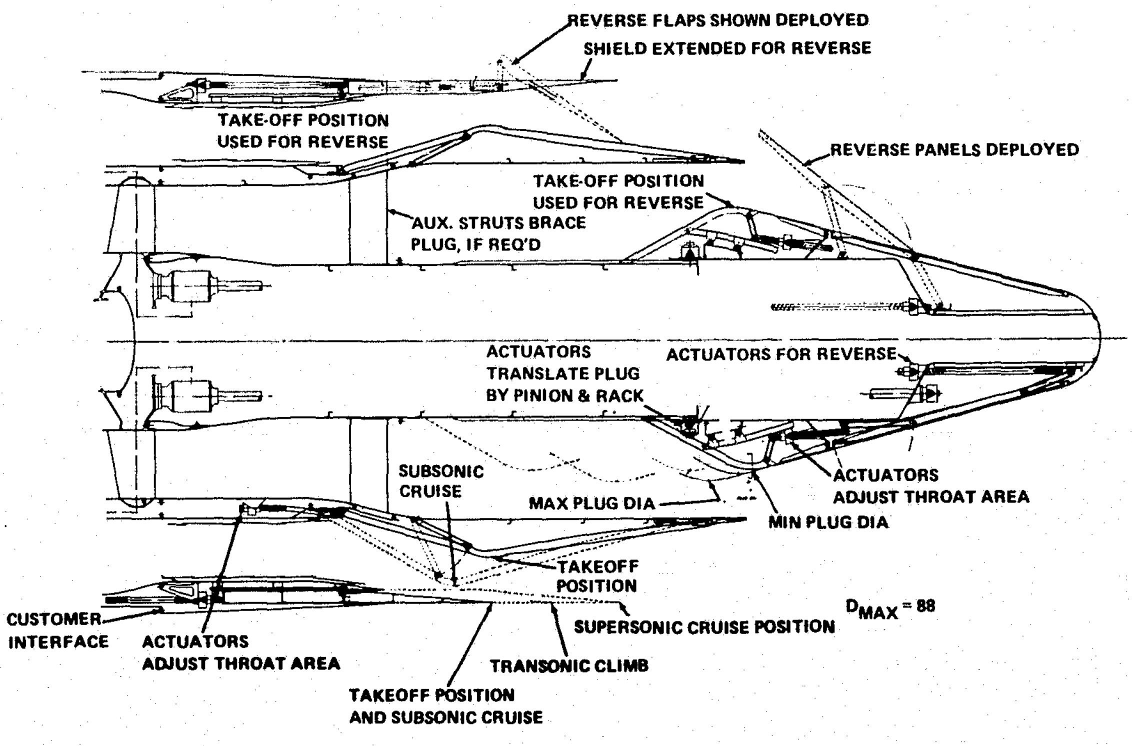


Figure 3.4.1-10 Nozzle/Reverser Configuration 5 Preliminary Design Layout

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Advanced C-D Nozzle

The last nozzle/reverser configuration considered was an advanced convergent/divergent (C-D) nozzle concept based on the balanced beam nozzle used with the P&WA F100 engine. This concept is shown schematically in Figure 3.4.1-11. In this concept, aerodynamic forces acting on the nozzle walls upstream of the duct throat tend to partially offset aerodynamic forces acting on the nozzle walls in the duct throat area and on the divergent portion of the duct nozzle, thereby reducing the actuation force required to effect nozzle configuration variations. The advanced C-D nozzle concept is shown in the supersonic cruise configuration as solid lines in the top of Figure 3.4.1-11. In the take-off mode, the primary nozzle area is reduced by translating the primary plug aft, and the duct nozzle area is opened up and the nozzle OD boattail angle is set for best performance by positioning the divergent flap. For the reverse mode, shown in the lower half of Figure 3.4.1-11, doors are actuated to block the flow of both streams and direct this flow through fixed cascades that are exposed by translating the cowl aft.

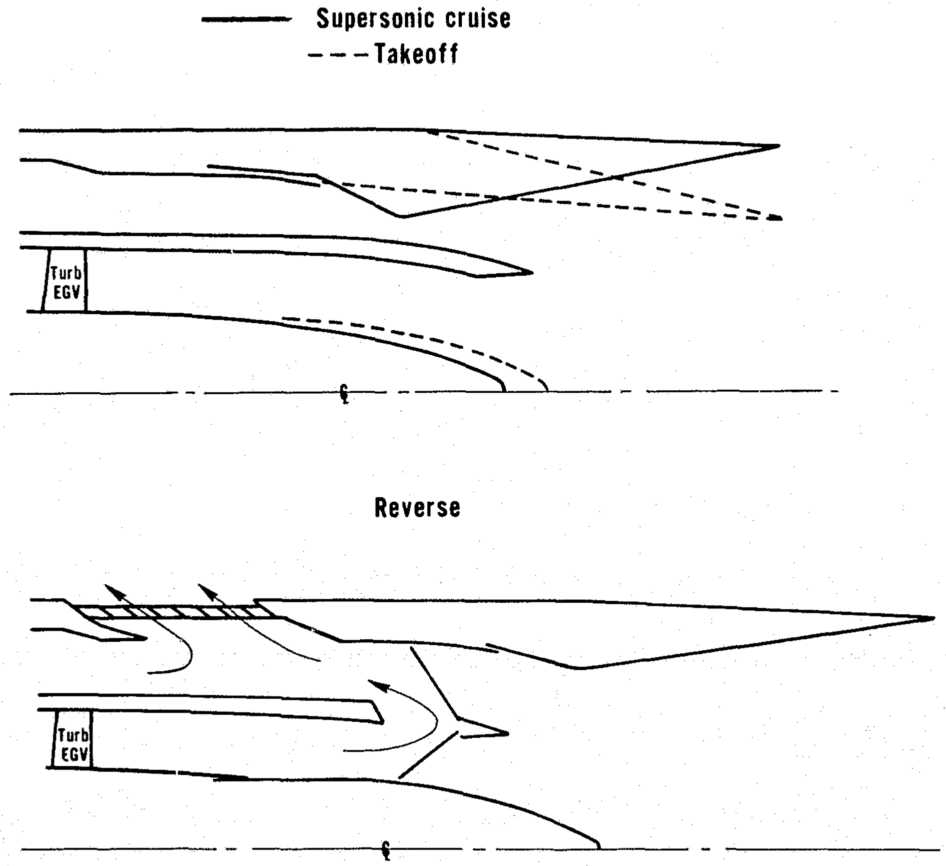

Figure 3.4.1-11 Schematic of the Advanced C-D Nozzle Concept (Configuration 6)

The layout for this concept, designated Configuration 6, is shown in Figure 3.4.1-12. The cascades for the N/R system are located around the duct burner and results in a larger maximum diameter of 2.34m (92.2 in). Five actuation systems are required for N/R control: one for primary nozzle area variation by means of a translating plug; one to position the main flap to vary duct nozzle area; one for positioning the divergent flap; and one each for actuation of the reverser blocker doors and cowl translation for reverse thrust. The variable components and actuation systems for this configuration are identified in Figure 3.4.1-12. Also shown are the positions of the nozzle component for various operational modes. The bottom part of the figure shows the N/R system configured for reverse thrust. As shown, the duct-burner liner is split circumferentially when the cowl is translated aft to expose the fixed cascades and provide an opening for reverse thrust flow. The duct burner is off during this mode of operation. There are two potential problem areas with this concept. One concerns the split burner liner and liner cooling requirements. The junction may require extra cooling to minimize liner durability problems. The other potential problem area is sealing requirements at the point where the translating cowl mates with the fixed nacelle at the front end of the cascades. Leakage in this area could result in performance penalties or durability problems for the duct burner. The solution to these problems would require detailed design studies if this concept shows sufficient promise.

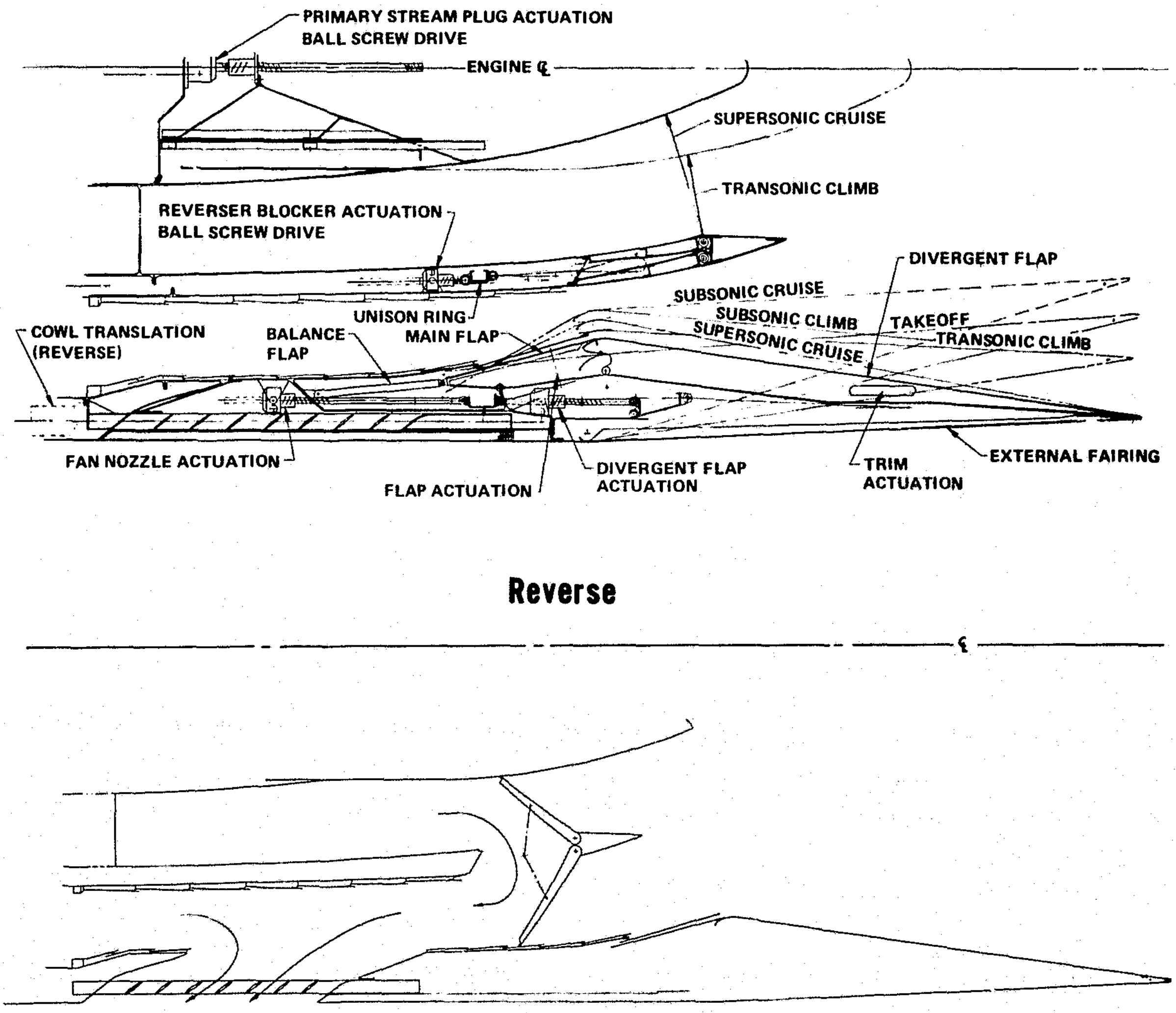

Figure 3.4.1-12 Nozzle/Reverser Configuration 6 Preliminary Design Layout

3.4.1.2 N/R Systems Comparison

A comparison of the N/R systems discussed in the previous section is presented in Table 3.4.1-I. The type of nozzle/reverser system is listed under each configuration identification followed by the dimensional, weight and performance differences, and estimates of reverser effectiveness and relative system complexity.

The length changes listed in Table 3.4.1-I are based on the length from the fan face to the primary nozzle exit plane (length to A_{je}) and fan face to N/R trailing edge in the supersonic cruise position (length overall). The maximum diameter dimension is the largest diameter for the engine-plus-nozzle/reverser. As indicated in the table, the N/R systems with the modified iris duct-nozzle (Configurations 2, 3 and 4) result in the longer overall length and Configuration 3 is the longest because of the cascade being stowed in the translating cowl. Configurations 2 and 6 have the reverser cascades stowed around the duct burner which results in the largest maximum diameters. Since the base engine weight is not affected by changes in the N/R configuration, the weight changes listed are N/R weight changes only. Configuration 1 is heavier than the baseline because of the weight added to the N/R structure to support the translating cowl assembly. Configuration 4 is heavier than 1 because the modified iris duct-nozzle configuration is heavier and also results in a length increase. Configurations 2 and 3 are versions of 4 that have cascades added, significantly increasing their system weight. Similarly, Configuration 6 has cascades that cause its weight to be much higher than the baseline configruation. Performance differences are quoted as changes in nozzle gross thrust parameter (ΔCf) including the effect of boattail drag changes. The baseline and Configuration 1 have a subsonic performance penalty compared to Configurations 2, 3 and 4 because of the flap type of duct-nozzles. Configuration 2 suffers a slight supersonic performance penalty because of its diameter increase. Ranges of performance are shown for the plug nozzle due to limited test data available. Configuration 6, the balanced beam nozzle, has subsonic and supersonic performance penalties because the N/R length is shorter than optimum.

TABLE 3.4.1-I

NOZZLE/REVERSER SUMMARY
408 kg/sec (900 lbm/sec) size

	Configuration						
	Data pack	1	2	3	4	5	6
Concept	Ejector with actuated panels	Ejector with translating cowl →				Collapsing plug	Adv. C-D concept
Duct nozzle type	Flap →		Modified iris →			—	—
Reverser type	Buckets →		Buckets and cascades →		Buckets	Umbrellas	Blocker doors and cascades
Dimensions ~ m (in.)							
Δ length to Aje	0	+0.13 (+5)	+0.38 (+15)	+0.38 (+15)	+ 0.38 (+15)	—	—
Δ length overall	0	0	+0.36 (+14)	+0.66 (+26)	+0.38 (+15)	–0.19 (–5)	0
Max diameter	2.24 (88)	2.24 (88)	2.33 (91.6)	2.24 (88)	2.24 (88)	2.24 (88)	2.34 (92.2)
Δ weight ~ kg (lbm)	0	+145 (+320)	+787 (+1735)	+728 (+1605)	+352 (+775)	+202 (+445)	+540 (+1190)
Δ performance							
Δ Cf subsonic	–0.015	–0.015	0	0	0	0 to +0.02	–0.015
Δ Cf supersonic	0	0	–0.001	0	0	0 to –0.02	–0.006
Δ range km (n. mi.)	0	–46 (–25)	–222 (–120)	–167 (–90)	–46 (–25)	+111 to –556 (+60 to –300)	–352 (–190)
Noise characteristics	Coannular benefit →					?	?
Reverser effectiveness and targetability	Fair	Fair	Good	Good	Fair	Fair	Good
Relative complexity	Average →					Very	More

The range differences shown in Table3.4.1-I are the result of the weight and performance differences. Configuration 1 suffers a 25 nautical mile range penalty relative to the baseline definition because it is over 300 pounds heavier with no change in performance. The better subsonic performance of Configuration 4, relative to Configuration 1, is offset by its heavier weight and results in the same range capability.

The much heavier weights for Configurations 2 and 3, relative to the baseline configuration, more than offsets their performance advantage and results in large range deficits. The variation in range for Configuration 5 is determined by the optimism for the performance characteristics. The large range penalty for Configuration 6 is the result of its weight and supersonic performance penalties relative to the baseline configuration.

The coannular noise benefit is applicable to the baseline and Configurations 1 through 4. The noise characteristics of the collapsing plug and advanced C-D concepts are unknown, as indicated in Table 3.4.1-I. The N/R systems with cascades (Configurations 2, 3 and 6) are estimated to have good reverser effectiveness and targetability while the ejector configurations without cascades are listed as fair. The collapsing plug concept is also given a fair rating; however, this would have to be verified by experimental tests.

Relative complexity ratings have been assigned based on the number of actuation systems required for nozzle/reverser control. Nozzles with three or four systems are rated average (baseline and Configurations 1 through 4). Five actuation systems earn Configuration 6 a more complex rating, while Configuration 5 with six systems is considered very complex.

3.4.1.3 Conclusions

Based on the results of the N/R system preliminary design studies reviewed in the previous sections, no further work on Configurations 2, 3, 5 or 6 is recommended. The most promising concept has been identified as the ejector N/R system, with actuated panels or translating cowl and without cascades. Because the translating cowls may result in a secondary penalty associated with ground clearance requirements of the aircraft, the actuated panel system (the baseline) is considered to be the best N/R system.

While the VSCE-502B was used as the base engine for these N/R studies, the results are also applicable to, and the conclusions would be valid for, the VCE-112C with coannular flow streams.

3.4.2 Advanced Accessories

The preliminary design studies of accessories were conducted in two phases. First, advanced accessories projected for the 1990's were defined and sized. Next, the impact that these projected sizes would have on a representative installation was examined. The engine used for these studies was the 408 kg/sec (900 lbm/sec) size VSCE-502B.

The accessories listed in Table 3.4.2-I are those that may be mounted on the engine. Where possible, these have been sized to VSCE-502B requirements, such as the main fuel pump and duct-burner fuel pump. Sizes for an environmental control system compressor plus heat exchanger and hydraulic pumps came directly from the Phase II integration studies, while the generator is sized for 60 kva and is an integrated drive generator (IDG) unit. For the other accessories, no size projections were available so JT9D sizes were used as representative for the VSCE-502B (TOGW and engine sizes are similar). In accomplishing this accessory study, it was difficult to obtain advanced, 1990 accessory definition because accessory manufacturers have not projected that far into the future. For this reason, the advanced accessory definitions are relatively conservative, and not much different from current technology accessories.

The results of the accessory studies are shown in Figure 3.4.2-1. This drawing is based on the most severe case regarding the installation arrangement, i.e., all accessories listed in Table 3.4.2-I are mounted on the engine. Using the sizes listed in the table and assuming a large diameter N/R system, such as Configuration 2 described in the preceeding section, the maximum nacelle diameter would be set by the N/R system; however, nacelle thickness would be minimal. For a smaller diameter N/R system (such as Configuration 1 or 4), the accessories would set the maximum nacelle diameter. Furthermore, the maximum diameter would be shifted forward, thereby compounding the installation penalty associated with locating accessories within the engine nacelle. It should be noted that scaling the engine to a smaller size will further complicate the installation because accessories do not scale in proportion to engine size. The accessories studies emphasize the need to consider in more detail, advanced accessory sizes and locations in preparing engine installation drawings and conducting integration studies.

TABLE 3.4.2-I

ADVANCED ACCESSORY SIZES

Accessory		Meters	Inches
• Electronic fuel control and main burner fuel pump		0.51 X 0.30 X 0.38	20 X 12 X 11
• Duct-burner fuel pump		0.23 X 0.15 dia.	9 X 6 dia.
• Engine oil pump		0.25 X 0.15 dia.	10 X 6 dia.
• Acc'y drive gearboxes	- engine accessories	0.61 X 0.30 X 0.20	24 X 12 X 8
	- airframe accessories	0.64 X 0.30 X 0.15	25 X 12 X 6
• Starter		0.33 X 0.30 X 0.25	13 X 12 X 10
• Generator (IDG)		0.53 X 0.30 dia.	21 X 12 dia.
• Hydraulic pumps		0.33 X 0.23 X 0.23	13 X 9 X 9
• Environmental control system	- compressor	0.53 X 0.38 X 0.38	21 X 15 X 15
	- bleed system	0.10 m dia. piping	4 in. dia. piping
	- heat exchanger	0.79 X 0.33 X 0.25	31 X 13 X 10
• Air turbine motors		0.30 X 0.23 X 0.23	12 X 9 X 9
• Oil tank and filter		(Shown schematically)	
• Fuel-oil heat exchangers		(Shown schematically)	

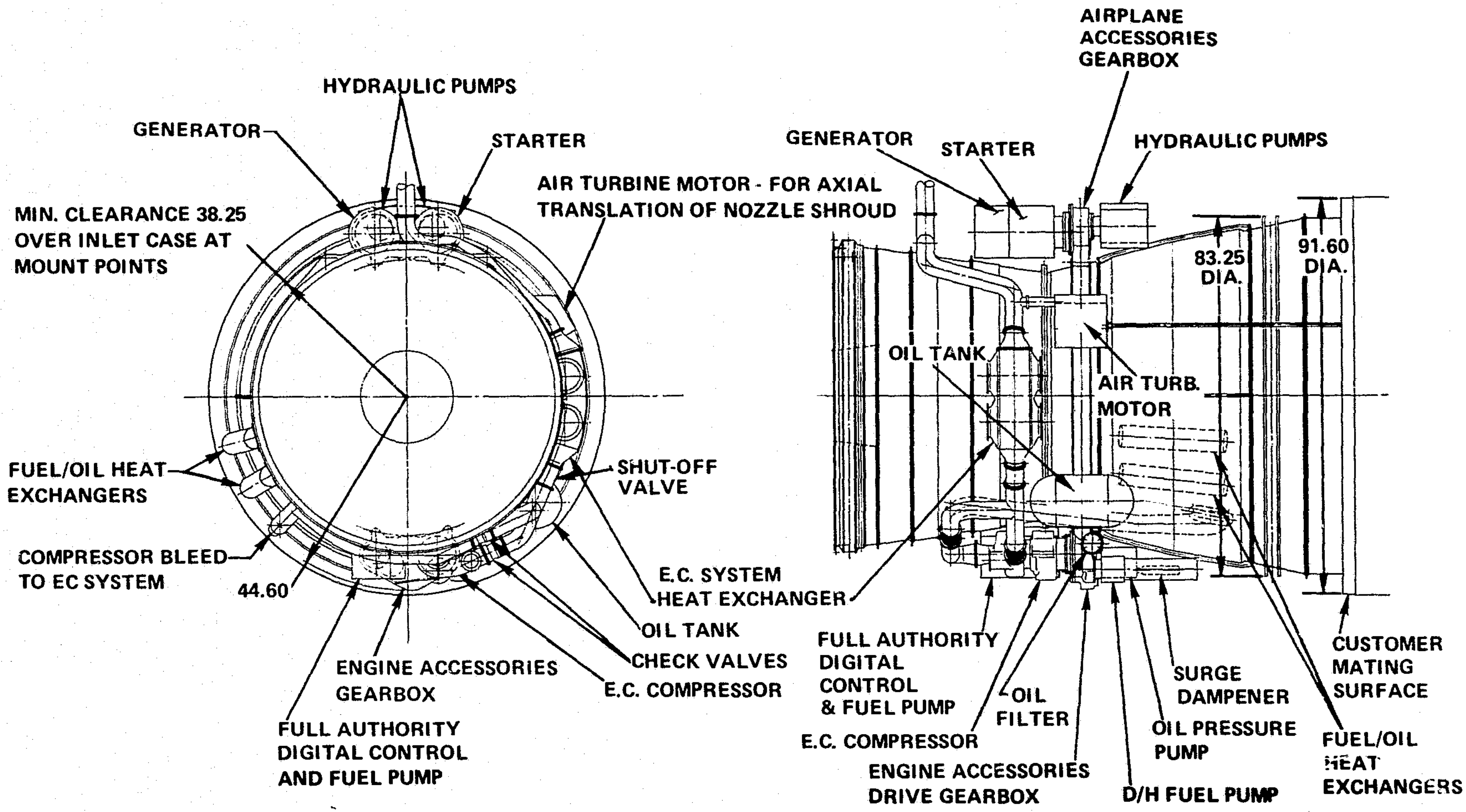

Figure 3.4.2-1 VSCE-502B Accessory Sizing/Location Layout

3.4.3 Engine Cross-Sections

The Phase III preliminary design studies included engine cross-sections for the VSCE-502B, the rear-valve VCE-112M and the LBE-430. These cross-sections are described in the following sections.

3.4.3.1 VSCE-502B

As described in Section 3.1.4.1, the Phase III refined variable stream control engine was not changed significantly from the Phase II refined engine. Therefore, the VSCE-502B designation was retained for the Phase III refined engine and is used to identify the cross-section of the variable stream control engine generated in the Phase III preliminary design studies. For reference, Figure 3.4.3-1 shows the VSCE-502C cross-section which is described in detail in the Phase II Final Report (Ref. 1). The changes made to the VSCE-502C in generating the VSCE-502B cross-section are described in the following paragraphs. These changes are shown in the Phase III cross-section of the VSCE-502B (Figure 3.4.3-2).

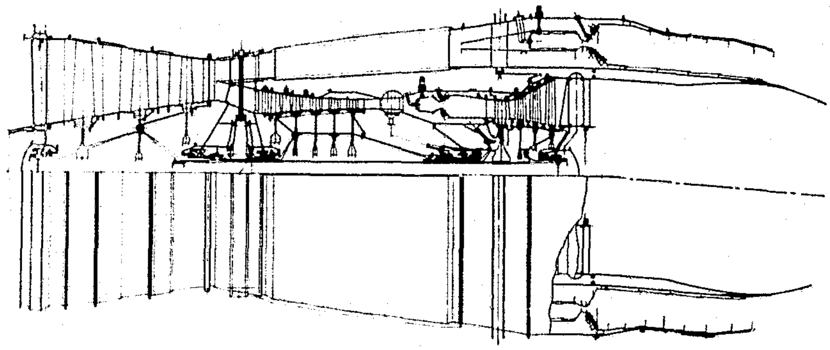

Figure 3.4.3-1 Phase II VSCE-502C Cross-Section

The multi-stage fan is consistent with the VSCE-502C except that the inlet hub/tip ratio was reduced from 0.40 to 0.35 to minimize fan diameter. Sufficient fan rotor speed is available to maintain the 3.3:1 fan pressure ratio without compromising surge margin or without needing a fourth stage. The increased overall pressure ratio (20:1) for the Phase III VSCE-502B over the Phase II VSCE required the number of compressor stages to be increased from 5 to 6. The same level of airfoil loading technology was used in both the VSCE-502C and -502B compressors.

The main burner and duct-burner definitions remain unchanged for the Phase III VSCE except for minor resizing of the bypass ducts due to cycle refinements. The VSCE-502B diffuser, located between the fan and duct-burner, is a more aggressive design than that incorporated in the VSCE-502C.

The increased compressor pressure ratio required a redefinition of the high-pressure turbine; however, it is still a single-stage assembly. Minor adjustments in cycle definition, reviewed in Section 3.1.4.1, together with slightly more aggressive blade loading, allowed a reduction in the number of low pressure turbine stages from 3 to 2.

VSCE-502B

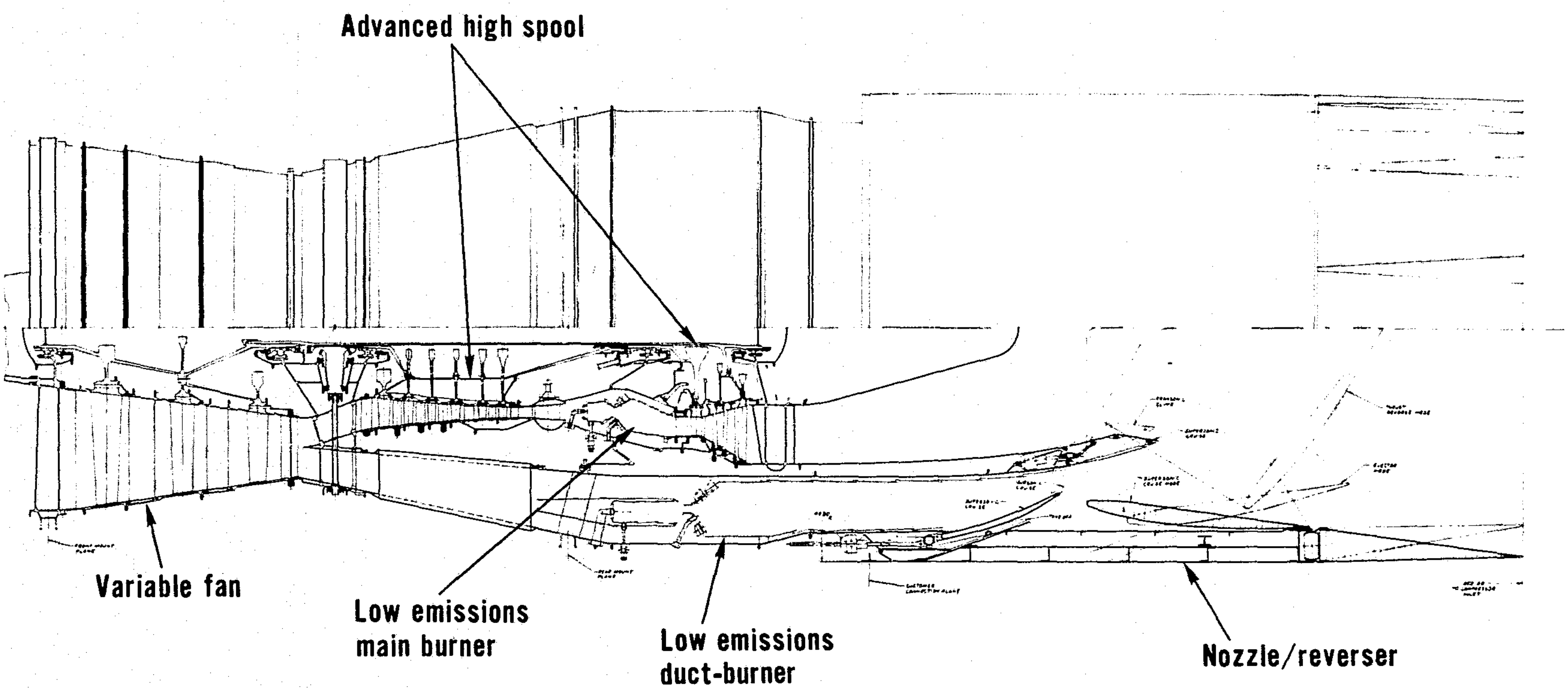

Figure 3.4.3-2 Phase III VSCE-502B Cross-Section

The nozzle/reverser system shown in Figure 3.4.3-2 is Configuration 4 which was described in Section 3.4.1. The engine mount system for the VSCE-502B is similar to the VSCE-502C. The front mounts are the same while the rear mounts differ in the way the aerodynamic struts that cross the bypass duct are attached to the gas generator. In the VSCE-502C definition, these struts were attached at the ID to a thermal spring which was bolted to the turbine case. The thermal spring is attached to the main burner case in the VSCE-502B cross-section.

3.4.3.2 VCE-112M

The VCE-112M is a mixed flow nozzle version of the VCE-112C and is described in Section 3.1.4.2. It was refined during Phase III to a level consistent with the VSCE-502B. Figure 3.4.3-3 is the first cross-section of the single rear-valve VCE concept. The VCE-112M and VCE-112C have essentially identical cross-sections forward of the nozzle/reverser. Because an extensive effort was devoted in Phase III to preliminary design of two stream nozzle/reverser systems, it was decided to include the common flow nozzle/reverser in the rear-valve VCE cross-section, in order to obtain weight and dimensional definition of this mixed-flow nozzle.

The VCE-112M fan is an advanced, six stage assembly designed for a 5.8:1 pressure ratio. It incorporates variable geometry for good efficiency and stability. This variable geometry consists of variable camber inlet- and exit-guide vanes, and two stages of variable stagger stators. The compressor is a five stage 4.3:1 pressure ratio design with variable geometry in the IVG and first two rows of stators. It is designed with the same advanced airfoil loading as in the VSCE-502B compressor.

The primary burner and duct-burner designs are similar to those shown for the VSCE-502B. The fan/duct-burner diffuser is even more agressive (shorter for equivilent level of diffusion) than that required for the VSCE-502B. The diffuser configuration shown in these cross-sections is a branch diffuser consisting of two circumferential vanes upstream of the duct-burner pilot section. These vanes divide the bypass airflow into three streams, thereby reducing the equivalent diffuser conical angle. If the VCE-112M diffuser were designed consistently with the VSCE-502B, it would impose a 0.25 to 0.38 m (10 to 15 in) length penalty on the rear-valve VCE.

The rear-valve VCE has three turbine assemblies. The high-pressure turbine (HPT) is a high speed single stage design incorporating advanced technology materials. The first low-pressure turbine (LPT) assembly, which is close-coupled to the HPT, is a four stage, highly loaded increasing mean diameter design. This assembly is designed for the low rotor speed dictated by the high stress level in the second LPT. Consequently the first LPT has low stress levels. The second LPT, located aft of the flow inverter/mixer valve, is a large, lightly loaded, single stage design which, because of its large annular size, sets the low spool rotor speed. To minimize the speed penalty to other low spool components, this turbine is designed for very high blade stress levels. In addition, this turbine experiences high inlet temperatures because of the duct-burner and, therefore, is comparable to the HPT design in terms of requiring advanced technology materials and cooling systems.

VCE-112M

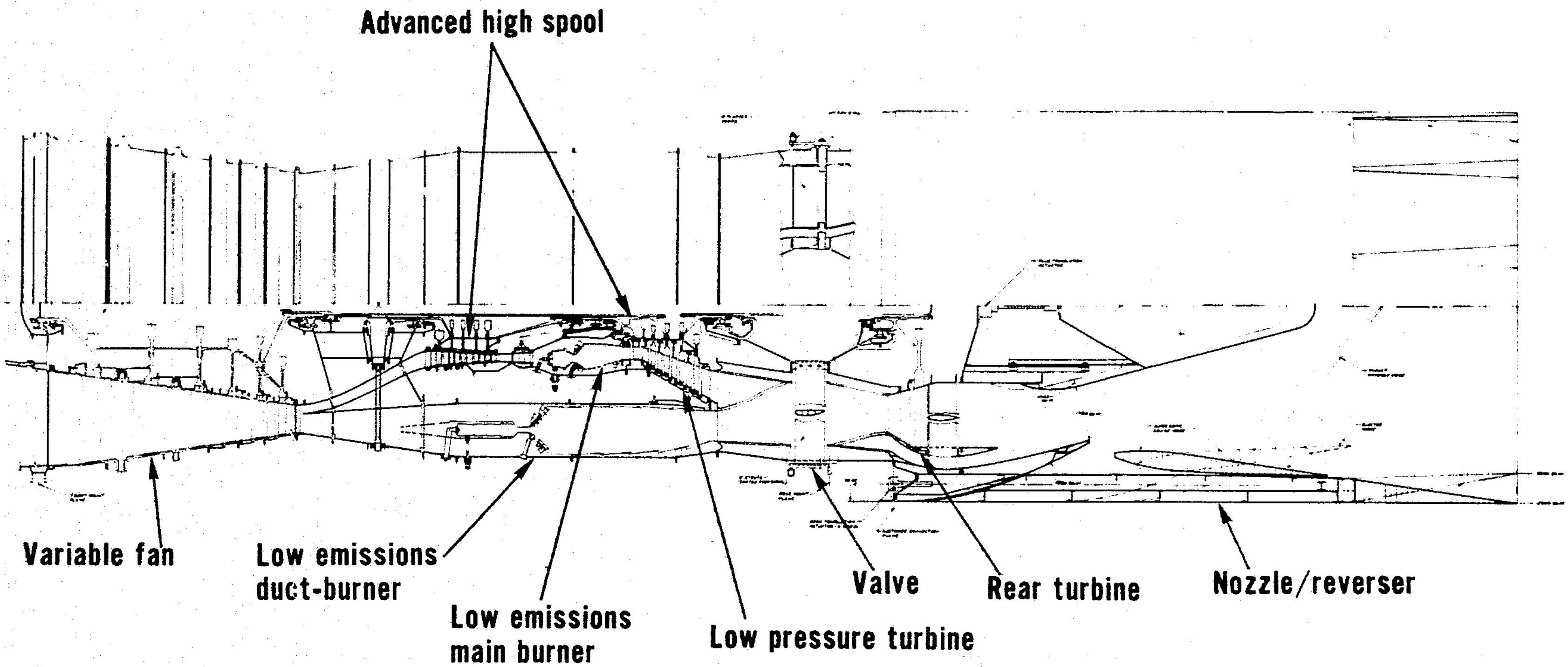

Figure 3.4.3-3 VCE-112M Cross-Section

The flow inverter/mixer valve is the most unique component in this concept and is located between the two LPT assemblies. As shown in Figure 3.4.3-3, the load carrying portion of the cooled valve is separated from the flowpath walls to minimize the effect of thermal expansion on the engine.

The nozzle/reverser for the VCE-112M is a common flow, variable area ejector type system. Since the required area variation is small (~10%), a variable plug system was selected. Although this system is as heavy as the fixed plug/variable iris system, it has the advantage of a less complex actuation system.

The support scheme includes six bearing and eight support struts. The high spool is supported by two bearings and the low spool by four bearings. The alternate (piggyback) bearing arrangement considered for the VSCE in Phase II would not be applicable to the rear-valve VCE because of the large difference between the low and high spool speeds: approximate 10,000 rpm for the VCE-112M versus less than 5,000 rpm for the VSCE-502B. The eight support struts allow the rear mount plane to be located aft of the first LPT (at the mid plane of the inverter/mixer valve). With this arrangement, the axial distance between the front and rear mounts is much longer for the VCE-112M: approximately 4.3 m (170 in) for the VCE-112M versus 2.5 m (100 in) for the VSCE-502B.

It should be emphasized that even though considerable detail is shown in Figure 3.4.3-3, it is still a conceptual design. A more detailed preliminary design would be required to identify and resolve potential problems. Areas of concern include the following:

- The duct-burner diffuser design may be too aggressive. A design that is more consistent with that projected for the VSCE-502B would increase the overall length and weight of the VCE-112M.

- A cooling flow analysis should be conducted for the flow inverter/mixer valve to confirm the values used in estimating the Phase III performance;

- Valve failure modes should be considered if the valved engine continues to be evaluated;

- Techniques to fabricate the large, cooled, blades and vanes required for the second LPT assembly need to be considered.

3.4.3-3 LBE-430

During the Phase II parametric studies, a mixed-flow, nonaugmented, single spool engine with a 0.1 bypass ratio was identified as the best conventional engine. A conceptual drawing of this engine, designated the LBE-405B, is shown in Figure 3.4.3-4. A detailed description of this engine is included in the Phase II final report (Ref. 1).

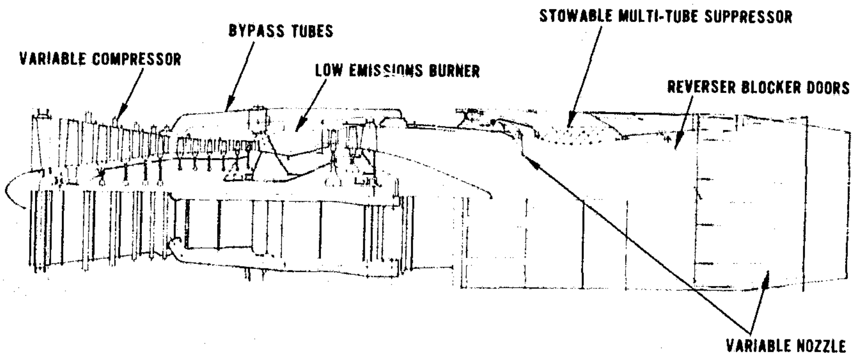

Figure 3.4.3-4 Phase II LBE-405B Conceptual Drawing

As a part of the Phase III studies, a dual-spool, low bypass engine (LBE) was refined to a technology level consistent with the VSCE-502B and VCE-112C. This engine was designated the LBE-430 and is shown in cross-section in Figure 3.4.3-5. Since the LBE-430 has a 0.4 BPR, versus 0.1 BPR for the LBE-405B, a bifurcated duct was defined for the bypass flow rather than the manifold and pipe system that was part of the Phase II LBE-405B. The LBE-430 fan is a four stage design with variable camber for the inlet- and exit-guide vanes. The six stage compressor uses variable geometry stators and reflects advanced airfoil loading. Both the high- and low-pressure turbines are highly stressed single stage assemblies, and the HPT incorporates advanced material technology that is also used for the VSCE-502B and the rear-valve VCE-112C. The high spool is supported by a ball bearing in the front and an inter-shaft "piggyback" roller bearing at the aft location. The low spool is supported by two roller bearings and one ball bearing. The engine mount system is the same for both Phase II and Phase III LBE's.

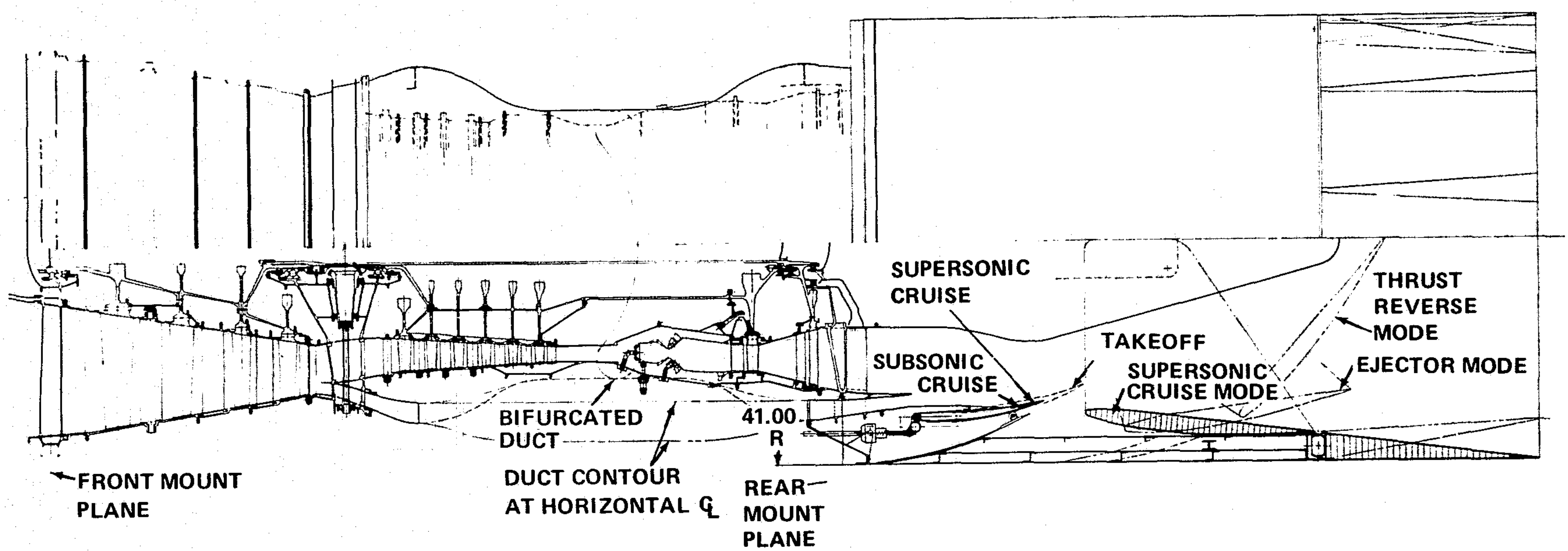

Figure 3.4.3-5 Phase III LBE-430A Cross-Section

3.5 TECHNOLOGY PROGRAMS

One of the primary objectives of the SCAR/AST Propulsion System Studies is to identify the engine-related technologies that offer the greatest potential for improving the environmental and economic characteristics of advanced supersonic commercial transports. The Phase I studies consisted of broad parametric evaluations of a large number of conventional and unconventional engine concepts. These studies showed that advanced propulsion technology has the potential for significant improvements in the environmental and economic areas. Critical technology programs were recommended in the Phase I Final Report (NASA CR-134633, January 1974). The Phase II studies consisted of more concentrated parametric studies including parametric airplane/engine integration evaluations and initiation of preliminary design studies. This phase identified the Variable Stream Control Engine (VSCE) as one of the most promising engines identified in the AST propulsion system studies. A rear-valve Variable Cycle Engine was defined late in the Phase II effort as also being an attractive engine concept. Based on the Phase II study engines, critical technology programs that were recommended in Phase I were updated and expanded to be consistent with the Phase II results. The Phase II technology program recommendations were summarized in the Phase II Final Report (NASA CR-134904, September 1975). As a result of further work accomplished during Phase III, the technology requirements and program recommendation have again been reviewed and updated. This revised information is presented in this section.

The critical technology requirements for the most promising VCE concept, the Variable Stream Control Engine (VSCE) are listed in Table 3.5-I. In general, these same critical areas are also required by the rear-valve VCE concept. This rear-valve engine would also require an advanced technology, high-temperature valve. This requirement has therefore been added to the variable geometry components. The reason for including critical technologies for both VCE concepts, even though the P&WA system studies indicate the VSCE has significantly greater potential, is because the NASA-Langley SCAR studies being conducted by Boeing, Douglas and Lockheed are currently in progress. The results of these studies are required to reach a concensus regarding selection of the most promising VCE concept. The fact that every critical technology requirement in Table 3.5-I (except the valve) applies to both VCE concepts is a strengthening factor in terms of overall applicability of critical technology programs conducted in these areas.

The following sections describe the critical technology requirements and related program recommendations for most of the areas listed in Table 3.5-I.

TABLE 3.5-I

VCE CRITICAL TECHNOLOGY REQUIREMENTS

* Low noise coannular nozzle
* Low emissions duct-burner
- Variable geometry components
  - Fan
  - Compressor
  - Valve
  - Inlet
  - Nozzle
- Low emissions primary burner
- Hot section technology
  - Advanced directionally solidified airfoil materials and coatings
  - Ceramic endwalls and tip seals
  - High creep strength disk material
  - Active tip clearance control system
  - High temperature burner liner material
- Full authority electronic control system
- Propulsion system integration

*Programs are in progress in these areas.

3.5.1 Low Noise Coannular Nozzle

The most promising method for reducing jet noise with minimum penalty to the propulsion system is based on Variable Cycle Engines with coannular nozzles. P&WA is conducting a test program under NASA sponsorship (NAS3-17866) to evaluate this concept and to compare noise characteristics of various suppressor configurations. Based on static test data, unsuppressed coannular nozzles may have the potential for significant reductions in jet noise without the performance penalties and other burdens such as weight, cost and complexity associated with mechanical suppressors. This potential noise reduction is shown in Figure 3.5-1 for various levels of specific thrust. Based on coannular nozzles having unique velocity profiles similar to that shown in Figure 3.5-2, a significant reduction in jet noise has been measured and is shown in Figure 3.5-1 for the two VCE engines relative to SAE predicted noise levels. This profile is obtained through design features of Variable Cycle Engines combined with unique throttle scheduling techniques for the combustors of the engine and bypass flow streams. Figure 3.5-3 illustrates the basic principle that provides this natural suppression for coannular nozzles. The left side of Figure 3.5-3 shows the velocity profile for a single stream nozzle. The right side shows a coannular nozzle. At the Station X downstream from the nozzle exit plane, the profile on the left for the single stream nozzle shows the effect of mixing and momentum exchange with ambient air. The shaded velocity profile indicates the maximum core velocity has not been reduced. For the coannular nozzle, the maximum velocity in the bypass stream is reduced by mixing and momentum exchange with air on both the outer and inner surfaces. The peak velocity has been reduced at the measuring Station X and jet noise is correspondingly lower. The net effect for the coannular nozzle is equivalent to an increase in BPR with a lower jet velocity and reduced noise for the overall engine. The next major step in evaluating the potential benefit of coannular nozzles is to determine the jet noise and performance characteristics at conditions that simulate flight velocities.

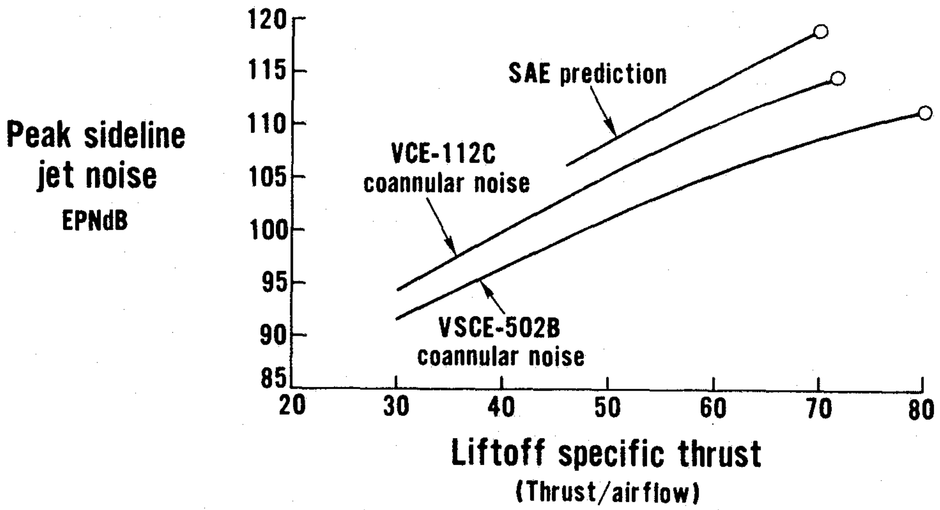

Figure 3.5-1 Potential Reduction in Jet Noise with Coannular Nozzles

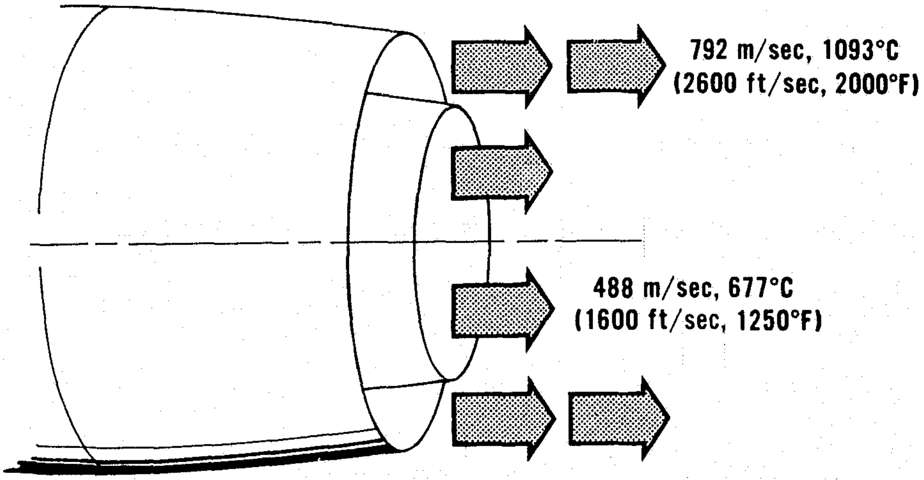

Figure 3.5-2 Coannular Nozzle Velocity Profile Required for Low Noise

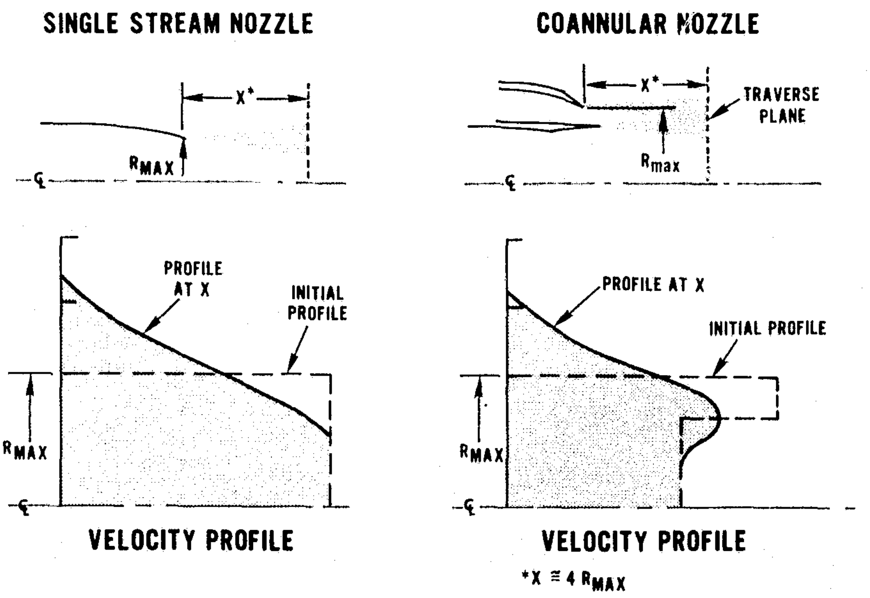

Figure 3.5-3 *Comparison of Single Stream and Coannular Nozzle Velocity Profiles*

Noise and performance testing of axisymmetric coannular nozzles is being conducted at P&WA in the five phases shown in Table 3.5-II. As indicated, the static test program has been completed, the windtunnel test program is presently being conducted, and the other two programs have been recommended and are anticipated.

The static test program established the aero-acoustic characteristics of VCE coannular nozzles over a wide range of exhaust conditions. This program consisted of noise and thrust evaluation of two unsuppressed coannular nozzles and four multielement coannular nozzle/suppressor configurations along with an equivalent convergent nozzle. The results of this program showed significant noise reductions for the coannular configurations relative to the convergent nozzle. Further noise reductions were obtained with the addition of an acoustically treated ejector.

The wind tunnel test program will determine to what extent the noise reduction benefits observed statically can be exploited in flight. Two unsuppressed coannular nozzles (plus one configured with an ejector), and the convergent reference nozzle are being wind tunnel tested over a range of relative velocities simulating takeoff and approach conditions. Basic acoustic and thrust data will be recorded along with aerodynamic properties of the flow at critical locations. Extensive data analysis will establish the relative velocity effects on jet noise characteristics and in particular on the relative levels between the VCE coannular nozzle configurations and the convergent nozzle. The analysis will include the necessary transformations to convert the measured jet noise to that for an aircraft in motion. Nozzle performance in terms of thrust and flow coefficients will be compared over the range of flight speeds to establish the effects of external velocities.

TABLE 3.5-II

COANNULAR NOZZLE NOISE AND PERFORMANCE PROGRAMS

Static Test Program (1974-1975)

- Single-stream convergent nozzle (reference)
- Two-stream, coannular, axisymmetric nozzles
  - Two ratios of throat areas (0.75 and 1.2)
  - Hardwall ejector
  - Acoustically treated ejector
  - Suppressors-bypass stream only
    - Fingers
    - Chutes
    - Tubes

Wind Tunnel Test Program (1975-1976)

- Simulated flight speeds to 137 m/sec (450 fps)
- Nozzle conditions
  - Temperature from 121 to 427°C (250 to 800°F)
  - Pressure ratios from 1.3 to 3.2
- No suppressors

Effect of Nozzle Configurations on Jet Noise and Static Performance (1976-1977)

- Two-stream, coannular nozzles
  - Radial dimensions of outer nozzle annulus
  - Radial dimensions of inner nozzle
  - Axial displacement of throats

Nozzle Performance Tests (1977-1978)

- Simulated flight speeds for selected configuration
  - Subsonic cruise
  - Supersonic cruise

VCE Critical Technology Testbed Program (1978-1980)

The objectives of the two new programs are: (1) to establish an empirical aero/acoustic design system for coannular nozzles and (2) to incorporate the basic aero/acoustic findings into a realistic flight nozzle design and demonstrate nozzle performance at simulated key flight conditions.

To evaluate the effect of coannular nozzle configurations on jet noise and thrust, a series of scale models (approximately 1/12 size) will be tested statically to provide the additional data necessary to formulate a design system reflecting both noise and performance characteristics. Five unsuppressed coannular nozzle configurations will be tested to significantly expand the data base generated during the earlier program. The model test configurations will involve basic coannular nozzle dimensional variations so that the results will allow accurate assessment of the selected parameters, and permit application to the anticipated range of flight type exhaust systems consistent with latest VCE concepts. A brief study will then be conducted, incorporating the above information into a promising nozzle design.

The aero/acoustic design system will be applied to the most promising nozzle concept. Acoustic trades will be integrated along with the requirements for high cruise performance, low weight and simplicity into a preliminary design layout of the exhaust system configuration. A 1/10 scale model of the resultant configuration will be tested at subsonic and supersonic conditions to establish nozzle performance.

Results from these nozzle programs will be used to design the coannular nozzle configuration for the VCE critical technology testbed program which is described in Section 3.6.

3.5.2 Low Emissions Duct-Burner

The duct-burner is a critical technology requirement for the most promising Variable Cycle Engines. Duct-burners are used to augment engine thrust during take-off and climb. For supersonic cruise, these augmentors are throttled back to low fuel/air ratios. Advanced combustion technology is required to provide low emissions and high efficiency without compromising the dimensions, complexity, and operating characteristics (stability, lean blow-out and combustion noise) of these duct-burners. Because of the low noise feature of these engines, the duct-burner operating conditions are much different from conventional after-burners used for military engines. Primary burner concepts and configurations being evaluated in the NASA-sponsored ECCP are not directly applicable to these duct-burners because of the differences in air conditions (pressures, temperatures and flow rates) entering these burners. These differences in operating conditions, combined with the low emissions and noise, and high efficiency requirements, set the scene for applied combustion research for these AST duct-burners. The following three-phase program is recommended.

Phase 1 — Duct-Burner Analytical Screening Program

Pratt & Whitney Aircraft is presently conducting, under NASA Contract NAS3-19781, an eight-month program to investigate low emissions duct-burners. The objective of this study is, through systematic analytical screening, to identify advanced combustor concepts that have the potential for low emissions while meeting the stringent performance requirements and economic considerations dictated by the VCE concepts described in Section 3.1.1. The approach pursued in this study is to define various pilot and secondary stage concepts that range from current state-of-the-art technology to such advanced concepts as prevaporized-premixed systems. These concepts will be screened on the basis of their potential emissions characteristics using, as a reference, data from such programs as: the NASA Experimental Clean Combustor and Can Annular Emissions Reduction Programs, Pratt & Whitney Aircraft's related experience with main burners and augmentors, and the published results of investigations by NASA, other engine manufactures and other research laboratories. Based on the results of this screening, a number of pilot-secondary stage concepts will be combined to synthesize promising duct-burner configurations. Further analysis, involving aerothermal sizing, refined emissions projections, and preliminary design studies, will provide the data necessary to evaluate these concepts against such criteria as: emissions, performance, engine compatability, and engine cost and weight. The study will result in the definition of four concepts that appear, on the basis of these criteria, as most promising for further evaluation.

Since the primary emphasis is on low emissions, the most promising duct burner may be an advanced concept that will have many uncertainties and unknowns in terms of suitability for commercial engine application. The final screening phase will therefore include an assessment of development risks. Two of the selected concepts will require moderate level of advanced technology and will be the candidates recommended for the testbed engine program. The other two will be more advanced, and will require more analysis and basic research before conducting applied studies and rig tests.

Phase 2 – Experimental Evaluation of the Selected Duct-Burner Concept

Following the analytical screening program, a rig test program is recommended. The objective of this effort is to design, optimize and demonstrate the performance and emissions capabilities of one of the concepts identified in the screening study. This program will serve the duel purpose of providing the necessary experimental qualification of the duct-burner for the testbed engine program while also providing experimental substantiation of the emissions and performance predictions made during the screening study.

This experimental rig program will involve designing the duct burner in a size compatible with the bypass stream of the selected VCE concept. A two-dimensional segment rig version of this duct burner will be fabricated with the segment representing approximately a forty-degree sector of the full annular duct burner. The rig will be tested in a facility capable of duplicating the bypass stream pressure, temperature, and corrected flow per unit area of the selected VCE at the simulated takeoff operating point and also at supersonic cruise, and transonic climb conditions. The test will be conducted over this range of conditions and data obtained to define the emissions characteristics as well as such duct-burner performance parameters as cold and hot flow pressure loss, thrust efficiency, stability, lighting characteristics and propersity for acoustic instabilities. This recommended experimental program will result in a well-defined, advanced-technology, low-emissions duct-burner design.

Phase 3 – Engine Demonstration of the Selected Duct-Burner Concept

Phase 3 of the overall duct-burner program would involve experimental evaluation of a large-scale, duct-burner configuration in the VCE critical technology testbed program, described in Section 3.6.

3.5.3 Duct-Burner Noise Program

With the possibility of using coannular nozzles to reduce jet noise, and sonic inlets to reduce fan noise propagating from the inlet, noise that is released from the fan duct and nozzle remains a potentially significant noise source. In particular, the effect of duct-burner combustion on aft noise has not been established. An accurate evaluation of these potential noise sources is not possible at this time as procedures do not exist to predict duct-burner noise or the effect of the duct burner on aft propagating fan noise. The objectives of this recommended program are to develop a prediction procedure for the far field noise produced by a duct burner based on combustion noise prediction models developed by P&WA under an FAA Combustion Noise contract, and then evaluate this procedure in a test of a segment of the duct burner designed for the VCE testbed program (Section 3.5.2 – Phase 2).

As reductions are achieved in other aircraft engine noise sources, combustors have emerged as significant noise sources. The generating mechanisms of combustion noise have been identified and are understood to varying degrees. P&WA currently is developing prediction methods for the combustion noise generated by main burners under contract to the FAA. However, there are no reliable procedures to predict duct-burner combustion noise levels. The direct and indirect combustion noise prediction models developed by P&WA under FAA funding (Contract DOT-FA-75WA-3663) will be extended to AST duct burning configurations to predict combustion noise levels, spectra and directivity patterns.

To determine the validity of this prediction method, noise tests will be conducted on the AST duct burner rig following the performance and emissions test programs described in Section 3.5.2. This rig hardware can be the same duct-burner segment, and the tests would be performed in a P&WA outdoor combustion noise test facility. Far field noise data will be obtained while the rig is operated over a range of burner pressures, temperatures and corrected flow levels, with each of these parameters being varied independently. Internal instrumentation will be installed to obtain dynamic pressure (internal noise) measurements in the burning region and in the duct hardware downstream of the burner.

The prediction procedure will be evaluated by comparing predicted values with data obtained from the duct-burner noise experimental program. These data will be examined to determine the effects of burner inlet temperature, pressure, airflow rate and burner temperature rise on duct-burner noise levels, spectra and directivity. The prediction models will be modified to reflect these results, if such modifications are required. The prediction model will then be used to estimate duct-burner combustion noise for the VSCE concept.

3.5.4 Variable Geometry Multi-Stage Fan

Another critical technology requirement for Variable Cycle Engines is a multi-stage fan with variable geometry. The variable geometry consists of variable stators plus a possible variable geometry splitter behind these fans. This level of variable fan geometry, in conjunction with variable geometry for the supersonic inlets and nozzles, provides the following potential benefits for these Variable Cycle Engines:

- Improved surge margin. This provides the capability for better off-design matching characteristics for these engines during subsonic and supersonic cruise.

- High-flowing the engine at part-power operating conditions. This feature is beneficial for reducing jet noise during take-off (to supplement the coannular noise benefit). It also improves installed performance at subsonic cruise by making the engine swallow the inlet airflow rather than spilling or bypassing it. This capability to high-flow the engine in order to match the inlet airflow schedule further improves installed performance at subsonic cruise by filling the nozzle exit area and reducing the boat-tail drag. Further evaluation of this flow matching capability may substantiate the potential for significant improvements to the supersonic inlet. These improvements would be in terms of a less complex inlet design, brought about by reducing the requirement for bypass doors during subsonic cruise and blow-in doors for maximum power during transonic climb.

- Reduced windmilling drag in the event of an inflight shutdown. This feature has special significance for supersonic transports because of the high drag associated with an inoperative engine at supersonic conditions and the corresponding effect on the airplane design.

In addition to these potential variable geometry benefits, there are several other advanced technology areas and related design features which may be applicable to the multi-stage fans of these Variable Cycle Engines. Some of these are:

- Advanced aerodynamic airfoils such as controlled shock designs which may improve the fan efficiency, especially for the high tip speeds projected for these advanced engines.

- Elimination of part-span shrouds by using low aspect ratio, composite fan blades or by improving the tip seal designs to incorporate the shroud in the end-wall region.

- Reducing the front case diameter of the engine by designing the fan for slightly lower hub/tip ratios. This is an installation improvement for the nacelle design and was identified in the Phase II integration studies.

- Reducing the exit Mach number for the fan in preparation for the duct-burner. This requires more diffusion in the fan and, for a constant surge margin, tends to reduce the allowable pressure ratio per stage.

- Incorporation of low noise features in the fan design such as wide blade-to-stator axial spacing, selective matching of the number of airfoils in adjacent rows, and various combinations of aerodynamic loading and rotational speeds.

- Design for compatibility with a low-noise, sonic inlet which is especially appropriate for these AST engines because of the variable geometry inlet required for supersonic operation. This inlet can accommodate the area change to provide the near-sonic internal condition to prevent engine noise from being released through the inlet. The near-sonic condition can be obtained not only for take-off but also at approach which is more difficult because total engine airflow is reduced.

The summation of these technologies present a series of fan requirements that are unique for AST Variable Cycle Engines. For comparison with a current technology fan, the projected technology goals for AST VCE fans are summarized in Table 3.5-III. The following fan program is recommended to analytically evaluate these features, to incorporate the most promising in a representative fan design, and then demonstrate these features in an experimental program.

TABLE 3.5-III

COMPARISON BETWEEN CURRENT-TECHNOLOGY AND ADVANCED VCE FAN REQUIREMENTS

	Number of Stages	Pressure Ratio	Inlet Hub/Tip Ratio	Full-Span Adiabatic Efficiency	Maximum Corrected Tip Speed
Current-Technology Fan	3	2.8	0.4	83%	448 m/sec (1470 ft/sec)
Advanced-Technology VCE Fan Goals	3	3.3	0.35	85%	~490 m/sec* (1600 ft/sec)

*limited by turbine blade stress levels

Multi-Stage Variable Geometry Fan Program

A two phase program is recommended; a design study and an experimental demonstration.

The first phase consists of aerodynamic and acoustic design studies to evaluate advanced fan technologies for the most promising Variable Cycle Engines. Drawing from the conceptual and preliminary design studies being conducted as part of the SCAR/AST propulsion system studies, a more detailed evaluation of these potential advanced technology features will be conducted. The product of this effort will be a baseline design of a multi-stage, variable geometry fan that reflects the optimum balance between aerodynamic and acoustic features. The objective of this design is to incorporate as many compatible advancements as possible to attain the aerodynamic goals listed in Table 3.5-III. These goals are in addition to the goal of reducing fan noise released from the inlet and nozzle.

The second phase is to utilize some of the hardware from an existing NASA fan rig, add a stage, and use it to demonstrate the basic aerodynamic and acoustic advancements that are selected from the design study and are considered critical for AST engines. This approach of modifying an existing fan rig is recommended to minimize cost of the experimental portion of this program. There are at least three existing experimental fans from other NASA programs that might be considered for this demonstration program.

3.5.5 Low Emissions Primary Burner

The P&WA Experimental Clean Combustor Program (ECCP) sponsored by NASA is concentrating on advanced combustion concepts and designs for primary burners of subsonic engines in order to reduce emissions in both the airport environment and at high altitudes. An AST addendum to this program was conducted to reduce NOx at high altitude supersonic cruise conditions without compromising other burner requirements such as efficiency, stability, weight, cost and emission characteristics at other operating conditions. Application of these results to AST study engines (Section 3.1.6) indicate further improvements are required to reduce emission levels for AST engines. The reason for needing further improvements is due primarily to the differences between AST engine cycles and advanced subsonic engine cycles. For example, the AST engines have lower bypass ratios, lower overall pressure ratios, and employ augmentors. They also experience significantly higher inlet temperatures going into the main burner at supersonic cruise. The sensitivity between the level of NOx that is generated during supersonic cruise in the stratosphere and cycle pressure ratio is shown in Figure 3.1.6-9. This sensitivity, plus the requirements for low emissions in the airport vicinity require advanced combustor technology for VCE primary burners as well as for duct-burners (Section 3.5.2).

To further explore the emission characteristics of advanced burner concepts for AST VCEs, a continuation of the work started during the ECCP AST Addendum is recommended. This would be an analytical and experimental program to control fuel/air mixtures and residence times in the hot combustion zones. Areas to be evaluated include:

- studies of lean combustion – premixed and prevaporized systems
- effect of turbulence on premixed and prevaporized systems
- effect of engine transients (accel/decel) on stability (auto ignition and flash-back) of premixed combustors
- techniques to enhance lean combustion stability such as recirculation of hot gas, heat pipes, chemical techniques, etc.
- concepts to vaporize fuel externally from the main combustor system
- variable geometry concepts for lean combustion control

To reduce the cost of experimental programs in these areas, it may be possible to use existing hardware from the ECCP Phase II program or from other experimental burner programs.

3.5.6 Hot Section Critical Technology Requirements

Several critical technology requirements have been identified for the hot section of these AST engines. They are high temperature turbine airfoil materials (advanced directionally solidified alloys), high temperature end wall materials (ceramics), high creep-strength turbine disk materials, active tip clearance control technology, and high temperature burner liner material. The basic reasons that AST engines are very sensitive to these areas of hot section technology are:

- Projected turbine inlet temperatures are in the 1427°C to 1538°C (2600°F to 2800°F) range. At supersonic cruise, cooling air temperatures are in the 593°C to 704°C (1100°F to 1300°F) 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.

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

- 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. This characteristics, along with the selected turbine blade material, sets the maximum design speed for the high spool which, in turn, dictates the elevation and number of stages in the compressor.

3.5.6.1 High Temperature Turbine Airfoil Materials

Advanced Directionally Solidified (DS) materials (single crystal alloys and eutectic alloys) show promise for high strength, high temperature capability for turbine blades and vanes relative to the best DS superalloys currently available. Figure 3.5-4 shows the potential creep strength improvement for a single crystal alloy relative to a current technology DS alloy. For the stress levels corresponding to turbine vane requirements, a 28°C (50°F) improvement in metal temperature is possible. DS eutectic alloys have the capability for even higher levels of temperature, although they require more extensive research and evaluation than single crystal alloys. Figure 3.5-5 shows the potential stress-rupture benefit from a DS eutectic alloy relative to current DS alloys. As indicated, there is the potential for 55 to 111°C (100 to 200°F) increase in metal temperature or a 40 to 60% increase in creep strength. In addition, hot spot capability can be improved. To complement these advanced materials, high temperature, oxidation-resistant coatings are required for the inner cooling passages and the exterior surfaces of these airfoils.

Numerous research and technology programs are being conducted by P&WA so that these potential improvements can eventually be applied to advanced engines. Some of these programs are summarized in the following section. Included is the program title, the contract number, the time period, the objective, and major accomplishments at the time of this writing.

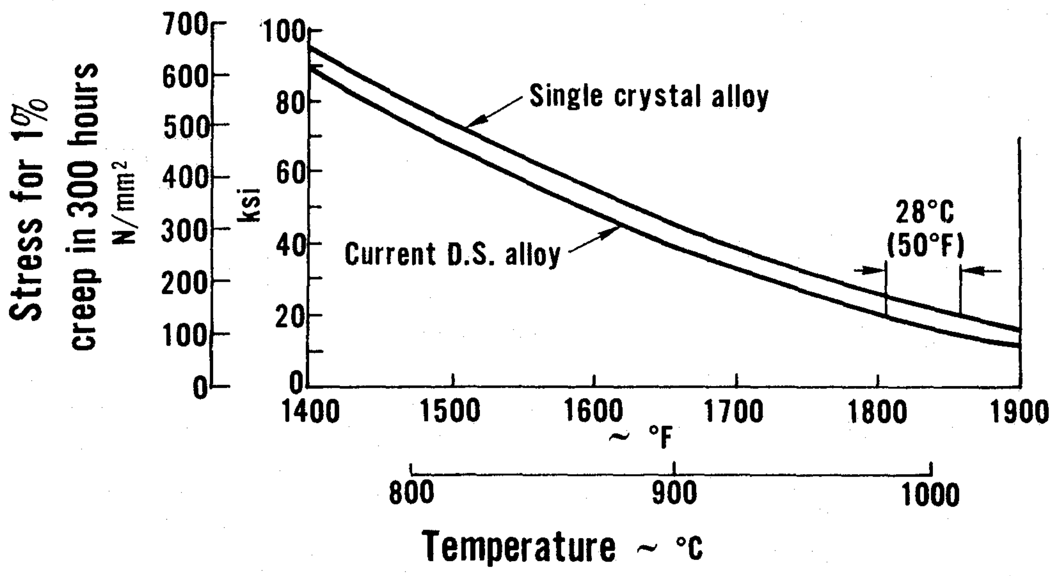

Figure 3.5-4 Potential Creep Strength Improvement for Single Crystal Alloy

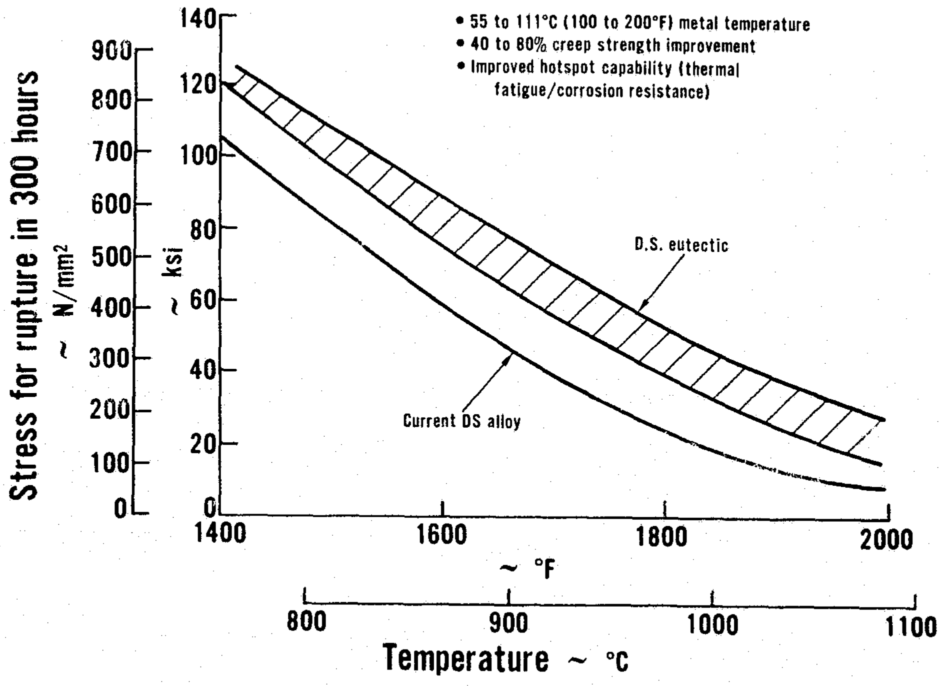

Figure 3.5-5 Potential Stress-Rupture Improvement for DS Eutectic Alloy

- Title: Reduce Cost Processing of D. S. Eutectics
  Contract Number: F33615-74-C-5018
  Time Period: 2/74 - 7/76

  Objective:

  Establish reliable, reproducible, low cost processing techniques for Directionally Solidified Eutectic turbine airfoils.

  Major Accomplishments:

  Both solid and hollow air cooled blade airfoils of various sizes were cast and process variables optimized.

- Title: Alloy and Structural Optimization of Lamellar D.S. Eutectics
  Contract Number: NAS3-17811
  Time Period: 3/74 - 4/76

  Objective:

  Evaluate baseline eutectic alloy and investigate alloy modifications for improvement of off-axis properties.

  Major Accomplishments:

  Optimized alloy shows 39°C (+70°F) advantage in creep-rupture properties over D.S. MAR-M-200 + Hf.

- Title: Refinement of Promising Coatings for D.S. Eutectics
  Contract Number: NAS3-18920
  Time Period: 6/74 - 9/76

  Objective:

  Evaluate modification of oxidation and corrosion resistant coatings for D.S. eutectic alloys.

  Major Accomplishments:

  Selected coating exhibited 1000 hours of protection at 1090°C (2000°F) in laboratory tests. Procedures were developed for coating internal airfoil surfaces.

- Title: Stress Analysis and Thermal Fatigue Evaluation of Hollow Directionally Solidified Eutectic Blades
  Contract Number: NAS3-19714
  Time Period: 6/75 - 12/76

Objective:

Evaluate the capability of D.S. eutectic alloy to sustain the airfoil thermal fatigue loads anticipated in advanced hollow turbine blades.

Major Accomplishments:

Preliminary test results indicate that the smooth section thermal fatigue capability is adequate for advanced hollow turbine blade applications. Influence of leading edge cooling holes on fatigue capability is being studied.

- Title: Effects of Hafnium Segregation on Superalloys
  Contract Number: F33615-75-C-5204
  Time Period: 7/75 - 7/77

Objective:

Evaluate the influence of hafnium on the solidification kinetics of superalloys.

Major Accomplishments:

Improved understanding has been achieved for definition of optimum hafnium concentration in PWA 1422 alloy (MAR-M-200).

- Title: Directional Solidification of Reinforced Eutectic Turbine Blades
  Contract Number: N62269-75-C-0121
  Time Period: 8/75 - 10/76

Objective:

Improve process techniques required for casting turbine blades and optimize the solidification conditions of the liquid metal cooling process.

Major Accomplishments:

Fully lamellar eutectic turbine blades were cast at increased solidification rates.

- Title: Root Evaluation of Eutectic Alloy Hollow Blades
  Contract Number: NAS3-19732
  Time Period: 9/75 - 12/76

Objective:

Evaluate the capability of eutectic alloy to sustain the root attachment thermal fatigue loads anticipated in advanced hollow turbine blades.

Major Accomplishments:

Specimens are being machined for testing; no conclusions as yet.

- Title: Deformation, Fracture of D.S. Eutectics
  Contract Number: F44620-76-C-0028
  Time Period: 10/75 - 11/76

Objective:

Determine longitudinal, off-axis, and compressive yield strength of DS eutectics.

Major Accomplishments:

Determined cause of directionality ductility variation and identified prospects for future alloy development.

To extend and to supplement these programs, a two phase AST program is recommended. The first phase consists of an evaluation of various eutectic alloys that would be suitable for advanced commercial supersonic engines. An intensive study will be made to identify higher melting temperature alloy systems which may form a basis for a new class of eutectic alloys. In particular, chromium base alloys will be given special attention because of their high melting point combined with lower density and good oxidation resistance. The most promising alloy will be evaluated for creep-strength and ductility in the 760 to 980°C (1400 to 1800°F) range. Several solidification rates will be investigated and the best combination of solidification rate and alloy composition will be identified. The second phase will concentrate on coating requirements for the selected eutectic alloy. A series of overlay coating alloys will be evaluated by dynamic oxidation-erosion rig testing and interdiffusion analysis. Coating ductility and fatigue crack initiation and propagation will also be used to screen the candidate coatings. Attention will also be given to providing a root coating compatible with both the mechanical requirements in the attachment region and the substrate material. This second phase would also include an evaluation of internal surface coatings. Outward diffusion aluminide types of coating are preferred to minimize the influence of harmful substrate alloying elements, such as columbium, on coating performance. Conventional pack cementation and advanced vapor deposition techniques will be evaluated. Selection of the prime candidate will be on the basis of oxidation protection, capability of complete coverage of internal cooling passages and film cooling hole surfaces, cost, and ease of processing.

3.5.6.2 High Creep Strength Turbine Disk

Section 3.4.2.2 of the Phase II final Report (Ref. 1) describes the design analysis of the turbine disk and the attending creep strength requirements. A program is recommended to determine the feasibility of various approaches to meet the creep strength requirement for these turbine disks. Some of the approaches to be explored in this high temperature disk program are: new alloys to extend the high temperature creep strength capability beyond some of the research alloys that are currently being evaluated such as NASA IIIB-11; composite disks including fiber-wound, multi-alloy or laminated configuration; and cast disks fabricated by hot isostatic press techniques, possibly improved by thermal-mechanical treatment, such as explosive shocking. The goal for these advanced disk materials is to obtain a 670 N/mm^2 (97 ksi), 680°C (1250°F), 0.2% creep strength in 10,000 hours with no compromise to either low cycle fatigue or oxidation resistance characteristics relative to current disk materials.

3.5.6.3 Active Tip Clearance Control System

Preserving engine component efficiency through the life of AST engines will depend on effective sealing of the airflow throughout the engine flowpath and especially at the blade tips. Rapid engine power transients which result in differential thermal growth between rotor assemblies and cases, engine structural deflections from case temperature gradients, and aircraft flight and ground induced loads all contribute to significant running clearances in these critical seal regions. A program is recommended to conduct exploratory research and analysis of systems to actively modulate turbine and compressor blade tip clearances throughout the flight envelope. Compressor and turbine operational characteristics that affect gas path sealing will be analyzed and various concepts will be studied to compensate for factors which contribute to operating clearance. For example, compressor blade tips may show a steady-state cruise operating clearance of 0.05 mm (20 mils) when designed for minimum clearance at sea level take-off conditions. Mechanical, pneumatic, and thermal schemes for activating tip seal controls, will be appraised with a goal of reducing clearance to near zero at the cruise point. Concepts for reducing the clearances will be evaluated and cost, weight and complexity differences will be considered relative to potential TSFC reductions for the AST engine mission.

3.5.6.4 Oxide Dispersion Strengthened Burner Liner Material

Oxide Dispersion Strengthened (ODS) sheet alloys have the potential to retain high creep strength at elevated metal temperatures relative to the best liner materials currently available for gas turbine burner liners. Although definition of the properties of this ODS material is in the preliminary stages, data are available which allow metal temperature projections to levels which are several hundred degrees higher than present day sheet materials. Figure 3.5-6 shows the potential relative to Hastelloy X which is a current technology liner material. This capability will have special significance when designing the cooling air distribution for advanced, low emission burner systems, including main-burners and thrust augmentors. Furthermore, the need for higher temperature liners for the main burner system is especially critical for AST engines because the compressor exit temperature at supersonic cruise may be as high as 700°C (1300°F). Without high temperature liner materials, performance may be penalized by restrictions on the overall engine pressure ratio at supersonic cruise. This material may also be appliedto the duct-burner design to reduce the liner cooling air requirement and thereby improve the thrust efficiency (thermal profile) in the bypass stream.

A program is recommended to first identify the composition and processing techniques for candidate ODS sheet materials. This initial program would be followed by the evaluation of fabrication techniques and establishing design data leading to the fabrication and testing of experimental burner liner segments. Engine tests of the most promising concepts in high temperature operating environments would verify the applicability of this type of material to the main-burner and duct-burner liners for AST engines.

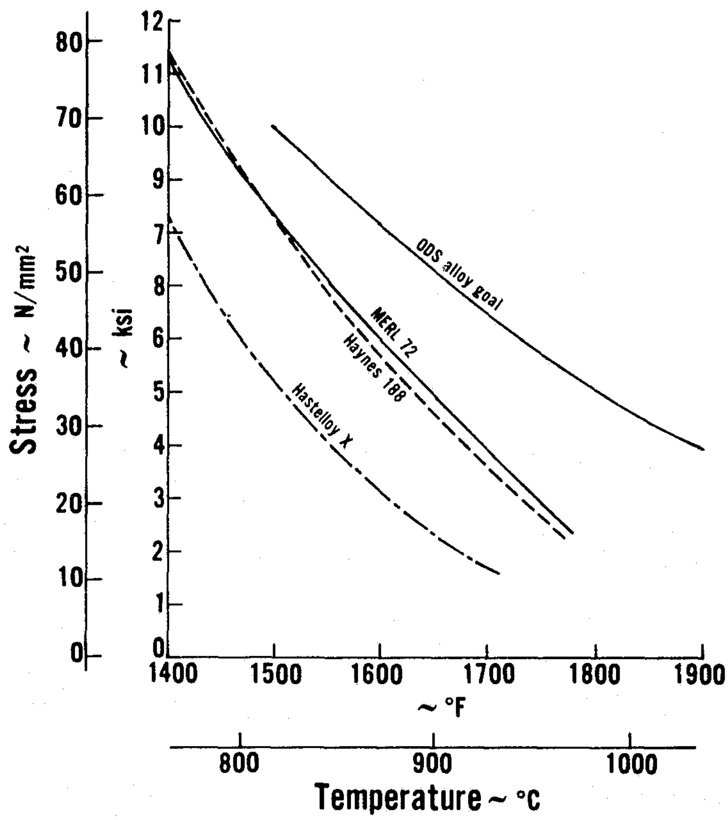

Figure 3.5-6 Potential High Creep Strength/High Metal Temparature Capability of ODS Alloy

3.5.7 Electronic Control System

A full-authority, digital, electronic control system is critical technology for AST propulsion systems. The eight control system variables listed in Table 3-5-IV for a representative Variable Cycle Engine are a convincing indication that hydromechanical controls would result in an expensive and heavy system which cannot properly fulfill the control function. In contrast with these eight variables, current-technology subsonic commercial engines have only three basic control system variables. For the more complex AST engines, a full-authority digital electronic control system has the potential for numerous improvements relative to an equivalent hydromechanical system. These potential benefits are listed in Table 3.5-V.

P&WA is presently conducting extensive research and development activity in the area of electronic controls and it is difficult to isolate a portion of this overall effort that has unique meaning to AST engines. Instead, a study program is recommended. This program is subdivided into four tasks:

- Study of closed loop control of convergent-divergent nozzles for optimum performance

- Definition and evaluation of an integrated airplane/engine control system

- Cost effectiveness studies of an AST engine condition monitoring system
- Study of methods for experimentally determining reliability of the electronic control system

TABLE 3.5-IV

AST PROPULSION SYSTEM CONTROL REQUIREMENTS
FOR A REPRESENTATIVE VARIABLE CYCLE ENGINE

- Variable geometry inlet
- Variable geometry fan
- Variable geometry compressor
- Primary burner fuel flow
- Augmentor fuel flow
- Variable duct nozzle
- Variable engine nozzle
- Reverser/ejector system

TABLE 3.5-V

POTENTIAL BENEFITS FOR AST ENGINE
ELECTRONIC CONTROL SYSTEM

- Better control accuracy – improved performance.
- Reduced cost and weight.
- Automatic rating schedules.
- Improved maintainability from quick mount computer designs and printed circuit modules.
- Flexibility to reprogram during development.
- Digital data links facilitate integration with inlet control, condition monitoring system, and power management system.
- Self testing capability.
- Self trim capability.

3.5.8 Propulsion System Integration

The most promising AST engines identified in these studies will feature most and possibly all of the following unique components.

- Variable geometry supersonic inlets designed for near-sonic internal Mach numbers for noise abatement during take-off and approach
- Low noise coannular nozzles combined with thrust reverser systems
- Programmed throttle scheduling to reduce noise contours during take-off
- Low emissions and low noise thrust augmentors
- Variable geometry components including the inlet, fan, compressor, turbine, nozzles, ejector and thrust reverser
- Structural nacelles for independently supporting the engine, inlet and nozzle/reverser systems
- Advanced airframe and engine accessories
- Acoustic treatment in the exhaust streams
- Digital electronic control and lightweight actuation systems

New design approaches are required to integrate these unique components into an overall propulsion system that provides the reliability, stability, safety and maintenance standards that are critical for the commercial acceptability of an advanced supersonic transport. New concepts for structural support, aerodynamic pod design, thermal management, plus advanced control and actuation systems must be applied to these Variable Cycle Engines. A joint airframe-engine contractor program is recommended to study propulsion system integration. Based on the judgement of both the airframe and engine contractors, a baseline Variable Cycle Engine design will be selected for these integration studies. This integration study will focus on the following areas:

- Overall pod geometry for optimum installed engine performance. Defining the optimum pod dimensions requires intensive trade studies between pod performance and the bare engine performance including weight and cost.
- Inlet characteristics including: inlet/engine structural and aerodynamic interactions; sonic design features for noise abatement; air flow matching characteristics over the entire operating spectrum and corresponding variable geometry requirements for the inlet; and inlet-to-inlet shock interference and unstart interactions.

- Thrust reverser location, targeting and effectiveness requirements and attending effects on the overall pod dimensions.

- Service, inspection and maintenance requirements and nacelle definition that corresponds with these requirements.

- Definition of major engine/airframe interface requirements including engine support locations, thermal management (flow and temperature requirements for the oil and fuel systems), engine airflow bleed requirements, engine power extraction requirements; and airframe accessory definitions.

- Operational procedures for noise abatement and the effect on augmentor and main burner throttling schedules.

- Overall installed engine performance, including nozzle external drag with an ejector, the effects of nacelle secondary cooling requirements, and inlet performance including the effect of boundary layer bleed.

- An integrated airplane/engine electronic control system.

Sensitivity and trade studies conducted throughout this integration study will lead to an optimum pod definition. This integration study will provide the background for preliminary design studies of the overall airplane and propulsion systems.

3.6 APPROACHES FOR VCE EXPERIMENTAL PROGRAMS

In addition to identifying critical technology requirements and recommending related programs, approaches are being formulated for evaluating and demonstrating these technologies in experimental engines. The basic objective is to integrate the critical technologies into a selected engine configuration in order to demonstrate overall benefits, characteristics, and interactions of the selected technologies.

3.6.1 VCE Critical Technology Test-Bed Program

The VCE critical technology test-bed program has been defined for minimum cost and entails demonstrating the critical environmental technologies for the most promising VCE concepts. The objective of this program is to demonstrate, in a large-scale engine environment, the noise and thrust characteristics of a coannular nozzle with an inverted velocity profile, and the emissions, performance and noise characteristics of an advanced duct-burner design. For this approach, experimental configurations of critical components would be applied to an existing engine. Candidate P&WA engines that may be suitable for demonstrating these critical technologies are the F100, the TF30 or the TF33. Each of these turbofan engines can be modified for two separate flow streams, the engine stream and the bypass stream, and can also accommodate an experimental duct-burner and a coannular nozzle system. These modifications can be accomplished without affecting the rotating machinery and support structure of these engines. These AST components would be designed for testing over a range of conditions simulating take-off, supersonic cruise, transonic climb and landing operations. Modifications to the existing engine control systems would be made to provide separate throttle control for the primary burner and the duct-burner. This would allow testing over a broad range of jet exhaust temperatures and velocities to evaluate the coannular noise benefit and corresponding emissions levels. This demonstrator approach could include both static and simulated flight testing as well as simulated subsonic and supersonic cruise testing in an altitude chamber. For minimum cost, the experimental hardware added to these engines would not have to be flight weight in design or construction characteristics.

The basic plan for this test-bed program is to remove the afterburner and nozzle assemblies from an existing engine and replace them with a duct-burner and a coannular nozzle/ejector system. Using an advanced production engine such as the F100 to simulate VCE conditions, large-scale designs of the coannular nozzle and the duct-burner would be designed and fabricated to fit behind the F100. Figure 3.6-1 shows the basic test-bed arrangement. This behand-the-engine arrangement was chosen for cost reasons — — it minimizes the changes to the F100 engine — — and also, by reducing annular radial dimensions, it provides the duct height required to accommodate the advanced (zoned and staged) duct-burner. As indicated in Figure 3.6-1, the TF30 iris nozzle can be used for the variable throat area in the bypass stream. A non-flight weight ejector and coannular nozzle with acoustic treatment completes the nozzle design. This test-bed program will be preceded by separate duct-burner and nozzle analytical and experimental programs described in Sections 3.5.1 and 3.5.2 to provide the baseline designs of these unique components. This test-bed program would be conducted statically in an outside facility that is suitable for measuring noise and emissions over a range of engine and duct-burner power settings. Table 3.6-I lists the specific areas that can be evaluated in this program. After this static test program, the test-bed configuration could be used to evaluate low velocity (< 0.3 Mn) flight effects on coannular nozzle noise characteristics by conducting further testing in a large wind tunnel such as the NASA-Ames 12.2m x 24.4m (40 ft x 80 ft) facility.

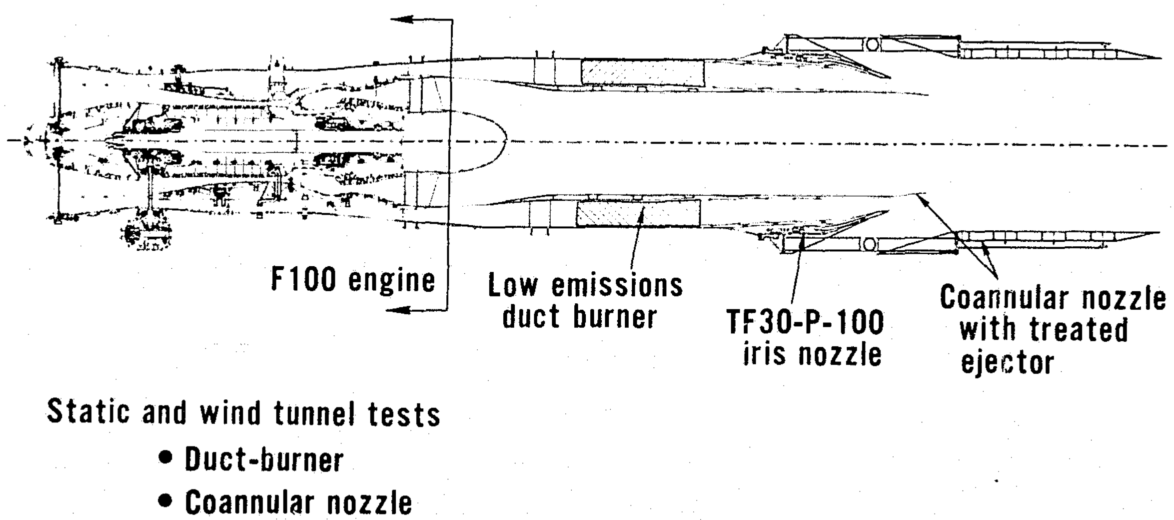

Figure 3.6-1 Basic VCE Test Bed Arrangement

Table 3.6-I

VCE Critical Technology
Test-Bed Program Objectives

- Determine the coannular nozzle noise benefits with large-scale engine over a broad set of operating conditions simulating take-off and landing power settings.
- Evaluate emissions and performance characteristics of a large-scale duct-burner over a wide range of fuel/air ratios and simulated VCE conditions.
- Evaluate the overall compatibility of a multi-stage fan, a low emissions duct-burner and a coannular nozzle and ejector system designed for low jet noise.
- Evaluate the noise characteristics of a duct-burner.
- Evaluate the influence of the duct-burner on aft propagating fan noise.
- Determine the effectiveness of acoustic treatment in the fan duct and along the ejector/nozzle surfaces.
- Evaluate stability characteristics between the engine, the duct-burner, and the variable geometry nozzle.
- Measure the sensitivity of ejector configurations on jet noise and possibly on nozzle performance.
- Determine the level of turbine noise and other core noise sources relative to fan and jet noise levels.
- Demonstrate some of the VCE cycle characteristics such as the inverse throttle schedule and operating the fan at maximum flow but partial pressure ratio for noise reduction.

This test-bed program would be extended further by evaluating the areas listed in Table 3.6-II.

Table 3.6-II

Additional Areas for
Evaluation in Test-Bed Program

- Evaluate emissions and performance characteristics of a refined duct-burner designed to incorporate the results from the initial test-bed program as well as other related experimental work.
- Evaluate a coannular nozzle and ejector system that is optimized for the selected VCE and is a more exact configuration of a flight design than the initial configuration.

Table 3.6-II (Concluded)

- Adapt the nozzle/ejector system to include a thrust reverser for noise, effectiveness and stability testing. This could be done statically and in simulated flight by testing in a large wind-tunnel.
- As back-up to the coannular noise benefit, a mechanical jet noise suppressor could be added to the high velocity bypass stream.
- Evaluate a variable geometry supersonic inlet for noise, stability and transient characteristics.
- Include an integrated electronic control system to evaluate overall transient and stability characteristics.
- Evaluate military technology requirements such as low weight coannular nozzles designed for low infra-red signatures.

Approaches are being evaluated to include other areas of critical technology in an overall VCE Experimental (VCEE) program. These would include:

- Evaluation of the aero/acoustic characteristics of a variable geometry multi-stage fan designed specifically for the requirements of the selected VCE concept.
- Compatibility testing of this multi-stage fan with a supersonic inlet designed for low noise with near-sonic internal Mach numbers during take-off and approach. This would include measuring distortion sensitivity and stability characteristics.
- A low emissions primary burner designed for a high temperature environment.
- A high speed, single-stage, high-pressure turbine.
- Advanced cooling and sealing technology systems for the high pressure turbine.
- High temperature materials associated with the high spool components.
- Advanced rotor support concepts that remove bearing compartments from the hot section of the engines.
- An advanced, high speed, low-pressure turbine.

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LIST OF ABBREVIATIONS

AST	Advanced Supersonic Technology
BPR	bypass ratio
°C	degrees Celsius
CET	combustor exit temperature
Cv	nozzle velocity coefficient
CO	carbon monoxide
DOC	direct operating cost
DOT	Department of Transportation
ECCP	Experimental Clean Combustor Program
EGV	exit guide vane
EI	emissions index
EPNdB	effective perceived noise decibels
°F	degrees Fahrenheit
FAR-36	Federal Aviation Regulation - Part 36
Fn	net thrust
FPR	fan pressure ratio
IGV	inlet guide vane
ft	feet
ITS	Inverse Throttle Schedule
kg	kilograms
km	kilometers
lbf	pounds, force
lbm	pounds, mass
LBE	Low Bypass Engine
L/D	lift/drag ratio
LPT	low-pressure turbine
m	meters
Mn	Mach number
N	Newtons
n. mi.	nautical mile
NO_x	oxides of nitrogen
N/R	nozzle/reverser system
OPR	overall pressure ratio
psi	pounds per square inch
ROI	return on investment
SCAR	Supersonic Cruise Airplane Research
sec	second
SLS	sea level static
THC	total hydrocarbons (unburned hydrocarbons)
TOGW	take-off gross weight
TSFC	thrust specific fuel consumption
VCE	Variable Cycle Engine
VSCE	Variable Stream Control Engine
WAT	total airflow