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VSCE TECHNOLOGY DEFINITION STUDY
FINAL REPORT

By

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FOREWORD

This report summarizes a contracted study of an advanced supersonic propulsion system conducted for NASA by Pratt & Whitney Aircraft during the period from October 1978 through July 1979.

The NASA project manager for this study was Laurence Fishbach assisted by Leo C. Franciscus, Flight Performance Section, NASA Lewis Research Center, Cleveland, Ohio. Key P&WA personnel were Robert A. Howlett, Study Program Manager, Richard B. Hunt, Assistant Manager, and George Aronstamm, Preliminary Design Coordinator.

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SECTION 1.0

SUMMARY

Refined design definition of the Variable Stream Control Engine (VSCE), an engine concept for advanced supersonic transports, has been accomplished in a NASA-sponsored, P&WA study contract. This design definition complements experimental programs that are being conducted for two of the unique and critical components that make up this engine; a high performance, low emissions duct burner for thrust augmentation, and a high performance, low noise coannular nozzle system. The refined VSCE definition incorporates the latest results from these experimental programs, as well as updated design definition for all of the major engine components, with emphasis on the hot section of the engine core.

Previous studies have indicated that the very severe thermal and stress environment at supersonic cruise, coupled with the fact that at least 50 percent of the engine operating time is spent at these conditions, dictate the need for very advanced materials and cooling systems for the main burner and turbine components. The impact of high temperature technology alone on the overall system is greater than 5% in airplane range. The study results summarized in this report update and expand the critical technology requirements for these hot section components, and provide basic information that can be used for formulating and planning future VSCE critical research and technology programs.

Based on these hot section component requirements, a test program is recommended in which advanced materials and cooling system technologies are combined and applied to high performance aerodynamic designs of the VSCE main burner and single-stage high pressure turbine, and experimentally evaluated in a complete high spool engine. This recommended program would be the initial step in verifying and substantiating the performance and durability characteristics of high temperature technology required for viable advanced supersonic engines. The updated VSCE definition described in this report is based on successfully conducting this recommended advanced high temperature technology program over the next several years.

It is projected that all of the advanced technologies incorporated in this updated VSCE could be ready for commercial service by the early to mid 1990's time period. The resulting VSCE design has 3.0% better specific fuel consumption at supersonic cruise relative to the preceeding parametric version of this engine.

SECTION 2.0

CONCLUSIONS AND RECOMMENDATIONS

2.1 Conclusions

- The updated and refined VSCE-515 resulting from this technology definition study has the following characteristics relative to the preceeding VSCE-502B parametric engine definition:

  - A 3% improvement in fuel consumption at supersonic cruise resulting from increased component efficiencies, improved cycle matching (higher core flow at supersonic cruise) and from a reduction in overall pressure ratio (from 20:1 to 15:1) due to temperature constraints affecting hot section (burner and turbine) design life requirements. This performance gain includes the effect of improvements in duct burner efficiencies based on results from the on-going VCE technology programs (99.5% chemical efficiency and 96% thrust efficiency at supersonic cruise).

  - A 0.9% increase in subsonic cruise fuel consumption due to the reduction in overall pressure ratio.

  - A 3% increase in engine weight.

  - When the effects of these performance and weight changes are combined and evaluated in terms of changes to airplane range:

    the all supersonic mission range is increased by 2.2% and,

    the mixed mission range (includes a 600 N.Mi subsonic leg) is increased by 1.7%

- Critical Technology Requirements for the VSCE-515 are:

  - Low Noise, High Performance Coannular Nozzle*

  - Low Emissions, High Performance Duct Burner*

  - High Temperature, High Performance, Long Life Turbines

  - High Temperature, Long Life, Low Emissions Main Burner

  - Variable Geometry Components

    Inlet

Fan

Compressor

Nozzle/Ejector/Reverser System

- Integrated Electronic Control System

*Programs are in progress on these components

o Of all the advanced technologies that are required to meet these projected performance levels, the hot section of the engine core is one of the most critical areas. A burner/turbine VCE-High Temperature Validation (VCE-HTV) program is recommended as the next major VCE Technology Program. It will combine critical elements of advanced materials and cooling technology with high performance designs of a main burner and a new single-stage high pressure turbine. The selected hot section technologies will first be substantiated individually and then collectively in component rig tests. They will then be evaluated and substantiated in a complete high spool engine. Results from this program will be applicable to all candidate AST engines, including VSCE's, Low Bypass Engines, and Inverted Flow Engines. It will also benefit advanced military engines. This recommended program is summarized in Section 4.3.

o The refined VSCE-515 retains all of the unique operational and cycle matching features of the VSCE-502B that are essential for AST economic and environmental requirements, including:

- Inverted Velocity Profile (IVP) for providing the coannular nozzle noise benefit.

- Inverse Throttle Schedule (ITS) for the main burner for providing the coannular noise benefit and for low fuel consumption at subsonic and supersonic cruise. This includes the capability to high flow the engine core at supersonic cruise in order to control the lapse in cycle bypass ratio for low fuel consumption.

- A staged duct burner to cover a wide range of critical operating points over the entire flight regime, including low noise and low emissions for takeoff, high thrust for transonic/supersonic climb, and low fuel consumption for supersonic cruise.

- Flexibility to tailor the exhaust conditions for optimizing nozzle performance as well as the coannular noise benefit. At any one power setting, different throttle schedules for the duct burner, in addition to unique fan and nozzle matching, can vary the coannular nozzle velocity ratio, temperature ratio, and pressure ratio to minimize the takeoff noise. These variables affect the following aft noise sources: jet, shock, combustion and turbine.

- In conjunction with several of these features, the VSCE-515 retains the capability of providing the IVP coannular noise benefit over a wide range of power settings. This programmed throttle schedule is a critical feature for noise abatement through operational procedures being evaluated by the Supersonic Cruise Research (SCR) airplane contractors under NASA-Langley Research Center contracts.

- Compatibility with a choked inlet to suppress forward noise.

o For the 340 kg/sec (750 lb/sec) size, the total VSCE-515 weight, including the nozzle/reverser system and engine accessories, is 5,216 kg (11,500 lbs). This is 3% heavier than the VSCE-502B when both are scaled to the same airflow size. Section 4.2.2 summarizes the VSCE-515 weight estimate.

o For the 340 kg/sec (750 lb/sec) size, the VSCE-515 length from the fan front flange to the nozzle trailing edge is 625 cm (246 inches). The D max over the duct burner/coannular nozzle interface is 203.7 cm (80.2 inches). These are identical to the VSCE-502B dimensions.

o Updated noise estimates, using a refined prediction procedure, indicate that operational procedures will be required, and possibly some degree of oversizing and throttling will be necessary to meet FAR Part 36 Stage 2 (1969) noise levels, with a corresponding economic penalty. If FAR Part 36 Stage 3 (1978) rules are imposed on advanced supersonic aircraft, significant changes to the VSCE will be required, such as adding a stowable suppressor to the outer, high velocity stream, and/or modifying the cycle, resulting in even greater economic penalties. Section 4.2.3 summarizes the VSCE-515 noise update.

o EPA parameter (EPAP) estimates for the VSCE-515 in the airport vicinity, based on application of VCE duct burner experimental results, show significant reductions in the CO EPAP resulting from refinements made to the duct burner during the test program. However the EPA rule that has been set for advanced supersonic engines (Class T5 engines) requires even lower CO levels. Also, a very advanced and complex main burner is only marginal in meeting the NO_x EPA rule. Because the EPA rule was largely derived from goals for advanced subsonic engines, and because of the distinct differences between advanced supersonic and subsonic transports and engines in terms of total projected numbers, takeoff and landing procedures, and the airports they will operate from, it is concluded that the EPA rule for Class T5 engines requires a complete review. Special consideration should be given to the uniqueness in design and operating characteristics of advanced supersonic transports.

Section 4.2.4 summarizes the emissions update.

2.2 Recommendations

VCE Technology Programs

- Initiate the VCE-High Temperature Validation (VCE-HTV) program described in section 4.3. Based on the results of this VSCE Technology Definition Study, this VCE-HTV program has been formulated and is recommended as the next major VCE critical technology program. The approach is to select critical elements of advanced hot section technology, and experimentally evaluate and substantiate them in an advanced main burner and a new single-stage high pressure turbine design. Sufficient experimental component and rig testing will be required to qualify the selected technologies first individually and then collectively. They would then be substantiated in a hot diagnostic test using either a complete high spool system for the testbed, or a high temperature burner-turbine rig facility. This diagnostic test will be instrumented to correlate measured temperatures and stress levels with life characteristics of the hot section components and materials. This program concentrates on two critical VCE technology areas: high temperature materials combined with advanced cooling systems. Advanced aerodynamic design features will be included so that a high level of turbine efficiency can also be demonstrated. In addition to being applicable to the VSCE hot section main burner and high pressure turbine, this program would also provide a technology base for other AST engine concepts such as the Low Bypass Engine (LBE) and the Inverted Flow Engine (IFE). In general, this program would benefit most advanced commercial and military engines, including conventional designs as well as unique concepts such as VCE's.

- Complete the VCE Testbed Program, especially the large scale acoustic test, in order to gain confidence in the coannular noise benefit for the full size VSCE. This program will also indicate the significance of various noise sources, especially jet, shock, duct burner combustion and fan exhaust noise. The effectiveness of an acoustically treated ejector will also be determined.

- Continue refinement of the staged duct burner through further rig and testbed testing in support of the VSCE concept. Future work should concentrate on simplification of the duct burner for application to commercial engines.

- Continue the coannular nozzle program by designing and testing coannular nozzle models that have high subsonic performance, while retaining high performance in the supersonic mode, and design features that provide the coannular noise benefit. Once these features are established, evaluate the installed characteristics of representative coannular nozzles in AST airplane model designs.

- Evaluate a stowable jet noise suppressor which could be integrated into the outer, high velocity stream of the VSCE coannular nozzle models designs. Conduct acoustic and thrust loss tests in simulated flight on suppressed nozzle model configurations that include tuned acoustically treated ejectors.

AST-VCE Studies

- Develop updated and refined design definition of alternate AST engine concepts; viz. the Low Bypass Engine (LBE) and the Inverted Flow Engine (IFE) in order to bring these engines up to the same level of design definition as the VSCE-515 which is summarized in this report. Apply stowable suppressor designs to all three engines and conduct comprehensive noise versus system economic studies. These study results will help direct future VCE programs.

- Continue the joint propulsion integration studies.
  - Generate custom-tailored engine definitions of the VSCE-515 for the NASA-Langley SCR airplane contractors.
  - Continue programmed throttle schedule studies for noise abatement through operational procedures
  - Define and evaluate the overall impact of concepts that have the potential for meeting FAR Part 36 Stage 3 noise levels, including new VCE concepts, thermal acoustic shields that reflect and refract exhaust noise, stowable jet noise suppressors, and choked inlets.

SECTION 3.0

INTRODUCTION

3.1 AST-VCE Program Overview

For the past several years, P&WA has been conducting NASA-sponsored analytical and experimental programs for Advanced Supersonic Technology (AST) engine concepts. Parametric studies of many types of conventional and unconventional engine concepts (1, 2, 3), including Variable Cycle Engines (VCE's) and propulsion integration studies jointly conducted between Pratt & Whitney Aircraft and the Supersonic Cruise Research (SCR) contractors (4,) have identified the Variable Stream Control Engine (VSCE) as having the greatest potential for meeting both the economic and environmental requirements of future supersonic transports. The overall feasibility of the VSCE concept is based on two unique components, a duct burner for thrust augmentation and a low noise coannular nozzle. Progress is being made in experimentally evaluating and verifying the critical features of these two unique components, including performance and environmental characteristics (5, 6).

To provide engine information for planning and formulating follow-on VCE critical technology programs, a technology definition study was conducted for the VSCE, concentrating on the hot section components, the main burner and the turbine designs. The reason for concentrating on the hot section can be illustrated best by reviewing the results of a technology sensitivity study, which was conducted as part of the 1977 propulsion integration studies (4). Two levels of technology were evaluated for the VSCE, an advanced and an intermediate level. Areas of technology were isolated, and the impact of each area on engine performance was evaluated. Figures 3.1-1 and 3.1-2 show the results of these technology sensitivity studies. The intermediate level of main burner and turbine technology increases supersonic thrust specific fuel consumption approximately 2 percent and subsonic fuel consumption approximately 5 percent relative to advanced technology levels. In addition, the total engine weight increases approximately 15 percent, primarily due to a reduction in bypass ratio. Combining these effects, the high temperature technology impacts the VSCE performance by 463.3 Km (250 N.Mi) for the all supersonic mission, which is approximately 5 percent of the design range. It is apparent from Figures 3.1-1 and 3.1-2 that the impact of high temperature technology is dominant relative to the other technology areas. Studies conducted on alternative types of engines show similar sensitivities. Based on these results a high temperatures technology program has been identified as a critical element for future VCE work. In preparation for formulating and planning this recommended program, the parametric definition of the VSCE was updated and refined in this technology definition study. This report summarizes the results of this VSCE technology definition study.

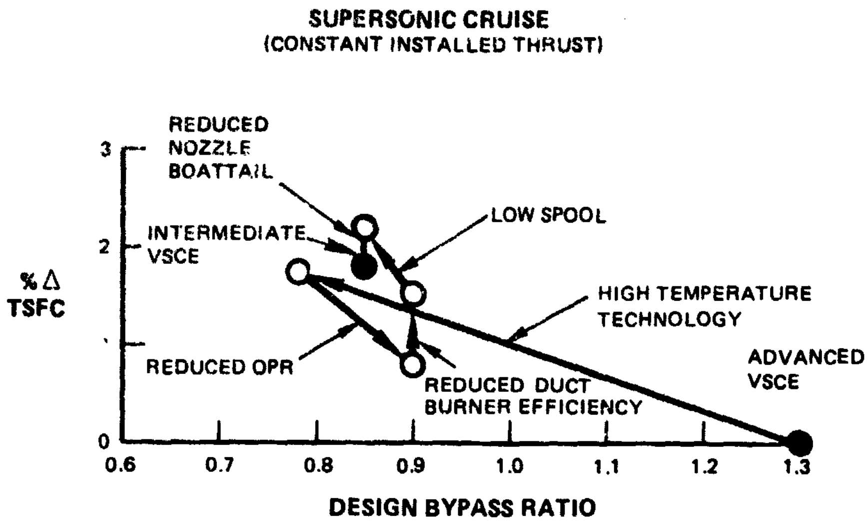


Figure 3.1-1 Effect of Technology on VSCE Supersonic TSFC

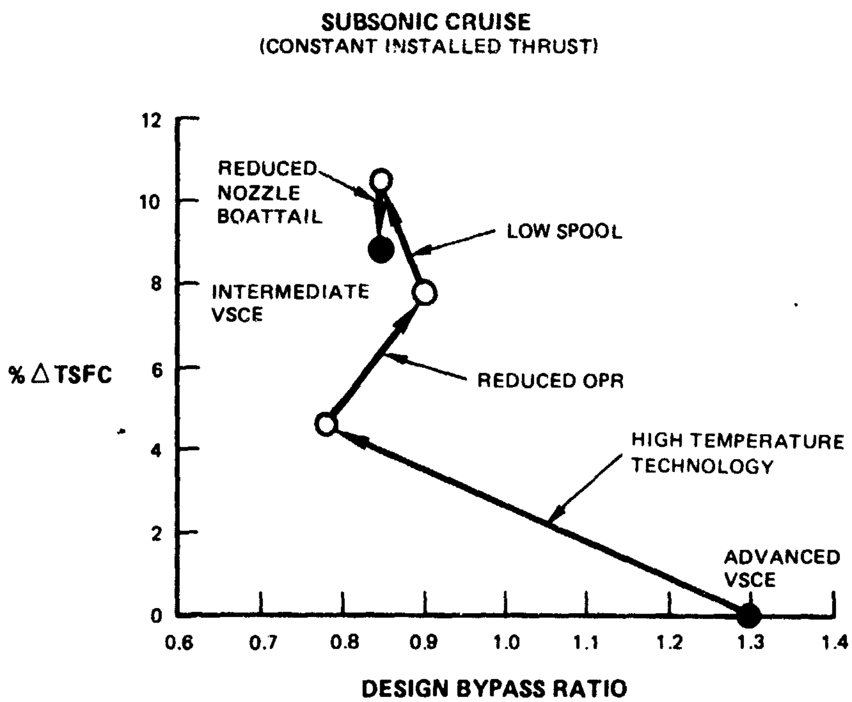


Figure 3.1-2 Effect of Technology on VSCE Subsonic TSFC

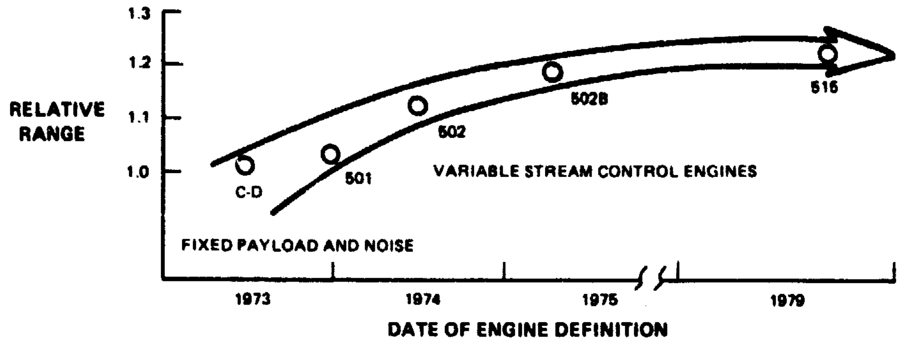
3.2 VSCE Background

As the VSCE concept has evolved through NASA-funded Pratt & Whitney Aircraft programs, significant progress has been made in refining and improving this engine. Figure 3.1-3 charts this progress from the early parametric definitions (1973 and 1974) through the VSCE technology definition study being reported on (1979). The most recent version is identified as the VSCE-515 and reflects results from the on-going VCE duct burner and coannular nozzle programs. It is also based on updated advanced technology projections that extend the high performance components of the NASA/Pratt & Whitney Aircraft Energy Efficient Engine (E^3) Program approximately 5 years further out in time. The VSCE-515 is therefore consistent with technology that could be ready for application to an engine development program by the late 1980's. The corresponding timing for certification would be the early to mid 1990's. As Figure 3.1-3 illustrates, the VSCE-515 has 25 percent better range capability relative to the early C-D definition, and is approximately 2 percent better relative to the VSCE-502B. As indicated by this evolution chart, refinement of the VSCE concept has resulted in significant improvements over the several year period. Further changes or improvements to the overall engine can only be obtained by verifying and refining the elements of technology that constitute each major component. Future VSCE work should concentrate on verifying new areas of critical technology, in addition to the duct burner and coannular nozzle, to eventually realize the full potential of this engine concept. Also, concepts that compliment the coannular noise benefit in reducing total engine noise even further should be explored, including stowable jet noise suppressors and thermal acoustic shields that reflect and refract exhaust noise. The technology definition study summarized in this report provides design information for starting additional VCE critical technology programs.

3.3 VSCE Technology Definition Study

This report summarizes the results of a VSCE technology definition study sponsored by NASA and conducted by P&WA in the time period from late 1978 through mid 1979. This study takes the critical technology requirements identified in previous NASA-sponsored Advanced Supersonic Technology (AST) Propulsion Studies that have been conducted by Pratt & Whitney Aircraft, makes quantitative technology projections to meet these requirements, and incorporates these projections in a refined engine design definition. The advanced technology projections are applied to the major engine component designs and performance levels. The resulting advanced components are integrated into a refined VSCE design definition. Results from the on-going VCE technology programs, including the Duct Burner Rig Program (5), and the VCE Testbed Program (7) are reflected in this refined engine definition.

The purpose of this VSCE study is to provide engine design definition and quantitative description of critical technology requirements, especially for the hot section of the engine, that will be used in structuring future VCE research and technology programs.



VSCE NUMBER	TYPE	REFERENCE
C-D	DUCT-HEATING TURBOFAN	BEST ENGINE FROM PHASE I PARAMETRIC STUDIES
501	PRELIMINARY VSCE CONCEPT	FIRST DERIVATIVE OF C-D ENGINE
502	IMPROVED VSCE CONCEPT WITH INVERSE THROTTLE SCHEDULE	PARAMETRIC ENGINE
502B	VSCE WITH HIGHER FLOW SCHEDULE AND IMPROVED DUCT-BURNER	REFINED PARAMETRIC ENGINE
515	UPDATED AND REFINED VSCE FROM TECHNOLOGY DEFINITION STUDY	PRELIMINARY DESIGN ENGINE

Figure 3.1-3 VSCE Evolution Code for Variable Stream Control Engines

The results of this study are an updated definition of the VSCE concept, identified as the VSCE-515, consisting of:

- Engine component design definition including critical technology requirements for the hot section of the engine core. Section 5.3.1.

- Cross-section drawings of the complete engine showing the major components, and the important structural and mechanical details such as the rotor support arrangement, the cooling and secondary system airflow and leakage characteristics. Section 4.1.2.2.

- Refined engine performance, weight, and environmental estimates. Section 4.2.

- Recommendations for the next VCE critical technology program are to conduct a VCE High Temperature Validation (VCE-HTV) Program. Section 4.3.

SECTION 4.0

PROGRAM RESULTS - VSCE-515 DESIGN FEATURES, ADVANCED TECHNOLOGY REQUIREMENTS AND PROGRAM RECOMMENDATIONS

4.1 Overall Description of VSCE

4.1.1 Operating Features of the VSCE Concept

Inverted Velocity Profile (IVP)

A fundamental requirement for obtaining the coannular noise benefit is to provide a significantly higher velocity in the outer exhaust stream relative to the inner stream. For the VSCE-515 at a representative sideline takeoff power setting, the relative velocity of the outer bypass stream is approximately 792.4 M/sec (2600 ft/sec.), and that of the inner engine stream is 426.7 M/sec (1400 ft/sec). These levels correspond to an outer/inner absolute velocity ratio of 1.7. To obtain this unique Inverted Velocity Profile (IVP), the main burner exit temperature is at an intermediate level (1177-1260°C (2150 to 2300°F) - depending on the noise level) and the duct burner is operating at its maximum design temperature (in the range from 1094-1427°C (2000 to 2600°F) - again depending on the noise level). For flyout over the community, the coannular benefit is preserved at cutback power settings by throttling the burners in both streams and rematching the engine and nozzle. Figure 4.1-1 illustrates representative VSCE-515 exhaust conditions corresponding to sideline and community operation.

Inverse Throttle Schedule (ITS)

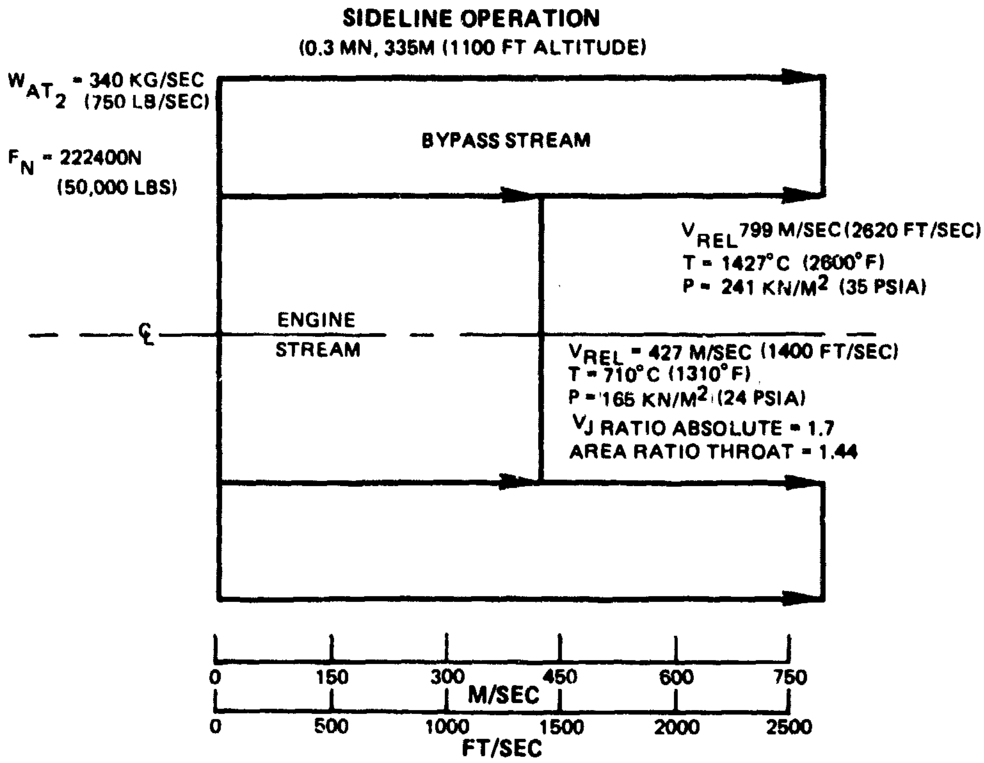
Current commercial engines for subsonic transports take off at maximum burner exit temperatures and then throttle back to lower temperatures for cruise. Representative levels are 1316-1371°C (2400 to 2500°F) for takeoff and 1204-1260°C (2200 to 2300°F) for cruise. For three major reasons, exactly the opposite schedule, referred to as the Inverse Throttle Schedule (ITS), is employed to provide significant VSCE matching features:

(1) To meet the unique thrust schedule of advanced supersonic transport aircraft over the entire flight spectrum,

(2) To provide one of the basic prerequisites for the coannular noise benefit - a low inner stream exhaust velocity, and

(3) To minimize fuel consumption at supersonic cruise by high flowing the core engine to control the cycle bypass ratio.

As described in the preceeding IVP section, the VSCE main burner exit temperature at take off is at an intermediate setting -- in the 1177-1260°C (2150 to 2300°F) range. At supersonic cruise, it is 1482°C (2700°F,) the maximum level.



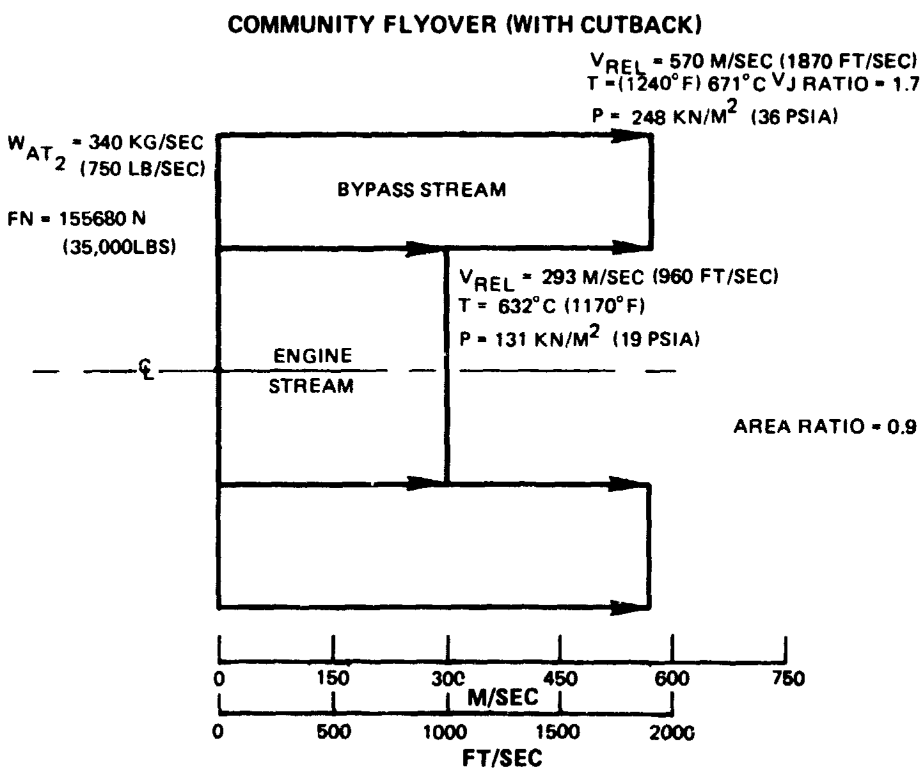


Figure 4.1-1 VSCE-515 Coannular Nozzle Exhaust Conditions During Takeoff

This ITS feature enables matching the high spool to a higher flow rate for supersonic operation than would be possible at lower temperatures. High flowing reduces the cycle bypass ratio, increasing core engine thrust. The level of duct-burner thrust augmentation can be optimized and supersonic TSFC is improved. It should be noted that ITS combines the most severe thermal conditions (highest cooling air temperature and burner exit temperature in the engine stream) together with maximum rotational speed of the high spool. Because at least 50 percent of the VSCE operating time is spent at supersonic cruise, high temperature materials and advanced cooling systems are critical technology requirements that result from this ITS feature. Figures 4.1-2 through 4.1-5 graphically show the differences between more conventional subsonic engines and the VSCE in terms of temperature, stress, cooling level and time.

Programmed Throttle Scheduling

Use of an integrated electronic control system can minimize total noise contours or footprints by varying engine power settings from start of roll, through lift-off and along the climb-out trajectory. This technique takes advantage of the effects of engine shielding and Extra Ground Attenuation (EGA), both of which decrease as the aircraft gains altitude. At low altitude where shielding and EGA are effective, the engine power setting can be increased in one or both exhaust streams, and then progressively decreased as the aircraft gains altitude. The throttle schedule can be programmed to hold sideline noise constant, and the increased thrust provides a higher altitude and/or airplane velocity for community fly-over, thus reducing community noise. This VSCE feature is illustrated in Figure 4.1-6. For the 60 percent to 100 percent thrust levels, the optimum value of IVP can be obtained. At low altitudes, the beneficial effects of shielding and EGA allow the use of higher power settings in the airport vicinity and a "bent throttle" schedule can be applied to the main burner, increasing thrust by as much as 25 percent. This causes an increase in inner stream velocity, and the IVP ratio decreases, as shown in Figure 4.1-6. Although this compromises the coannular noise benefit in the airport vicinity, it has the potential to reduce the overall takeoff noise contours. Included in this capability is the tailoring of exhaust conditions (temperatures, pressures and velocities) in both streams to optimize the coannular benefit as a function of power setting. The SCR airplane contractors are presently evaluating various definitions of programmed throttle scheduling, and the VCE Testbed Program acoustics test will provide information regarding the sensitivity of the coannular noise characteristics to the IVP ratio. Programmed throttle schedules are of special interest because, in contrast with most approaches for reducing noise, the benefits of this technique can be obtained with no performance penalty to the overall system.

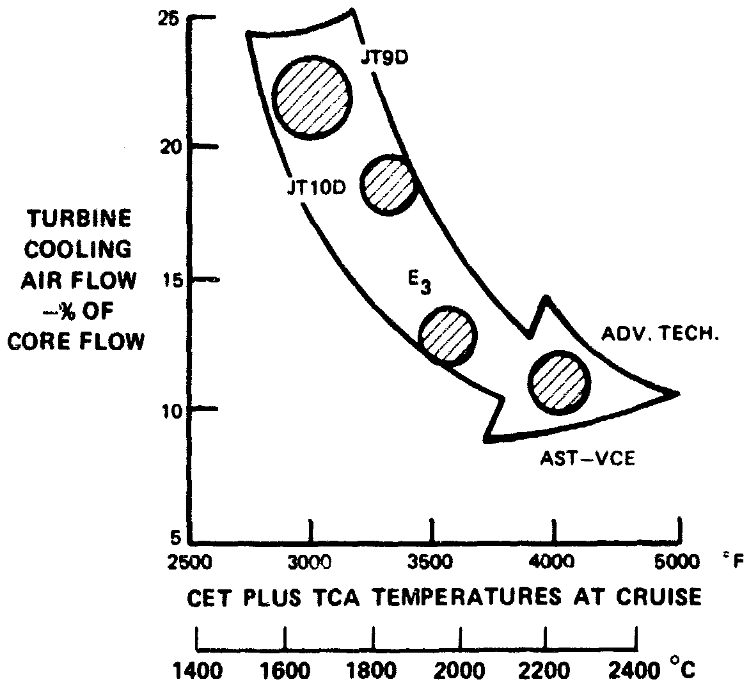


Figure 4.1-2 The VSCE Requires Very Advanced Technology to Reduce Cooling Flow in the High Temperature Environment at Cruise.

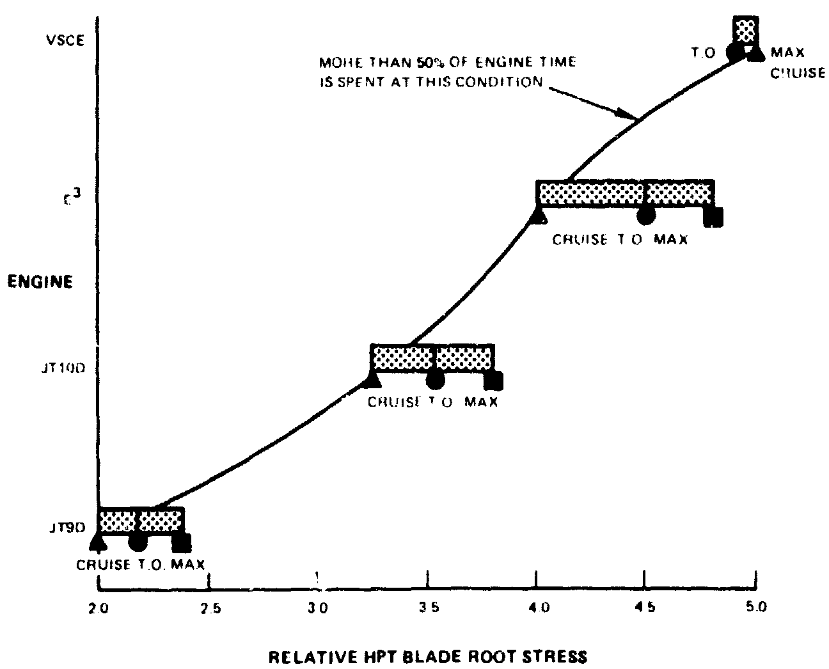


Figure 4.1-3 For Minimum Fuel Consumption, the VSCE core is High-Flowed at Supersonic Cruise. This Results in Maximum Rotor Speeds (Maximum High Pressure Turbine Blade Stress) at High Temperature Cruise Condition

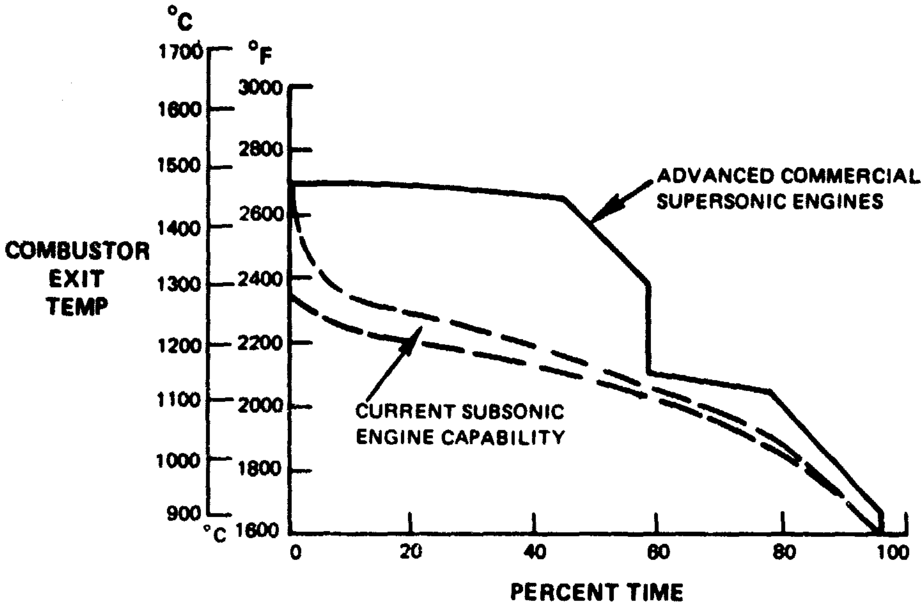


Figure 4.1-4 The VSCE Spends 50% of Its Operating Life at Maximum Temperatures and Stress Levels.

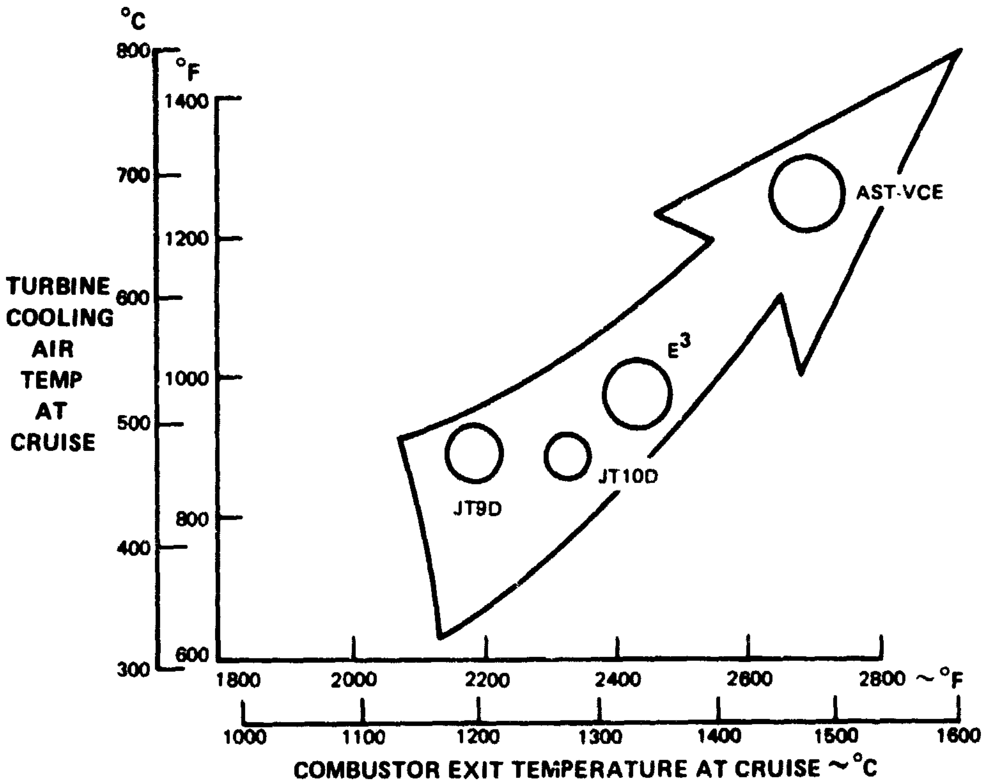


Figure 4.1-5 The VSCE Main Burner and Turbine are Exposed to Very High Hot Section Temperatures at Cruise.

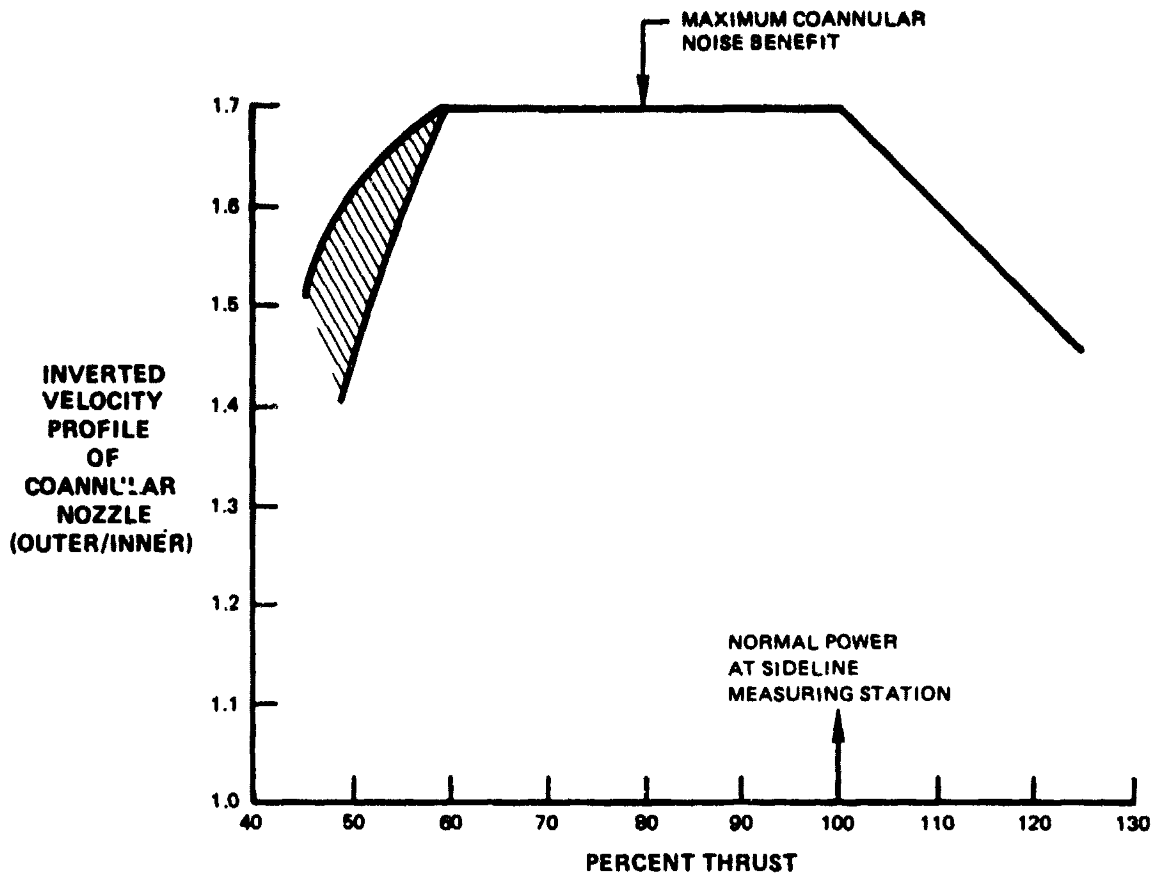


Figure 4.1-6 Takeoff Thrust Available for Programmed Throttle Scheduling.

Compatibility with a Choked, Low Noise Inlet

Inlet studies being conducted by the SCR airplane contractors indicate at least 6 EPNdB reduction in total engine noise at approach if the inlet can be choked. At the low power settings corresponding to approach conditions, total airflow of a conventional engine is low, making it difficult to design the inlet for choked conditions. With the flexibility of the VSCE-515, especially flow scheduling provided by the variable nozzle system, the engine can be high-flowed at low power settings to minimize the complications of choking the inlet. Further integration studies are required to optimize this feature of the VSCE concept.

As the VSCE-515 is tailored to each of the advanced supersonic airplane designs being evaluated by the SCR contractors, all of these features will be refined and optimized.

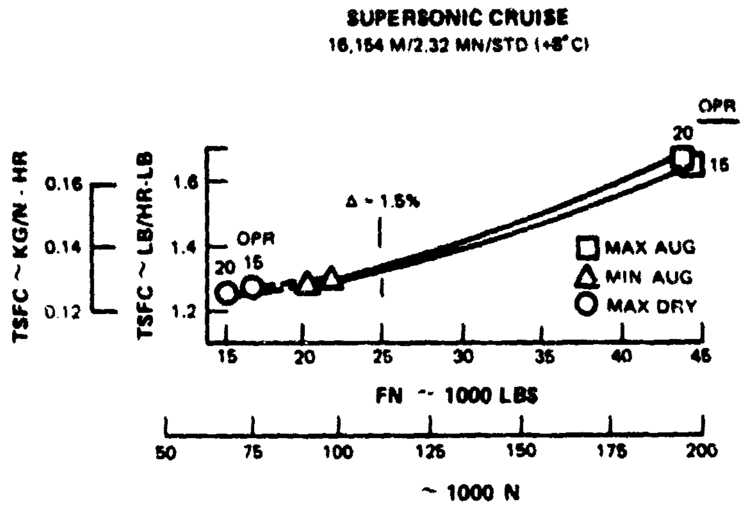
4.1.2 VSCE-515 Description

4.1.2.1 VSCE-515 Cycle

The VSCE-515 cycle is similar to the parametric VSCE-502B cycle except for the overall pressure ratio (OPR). A reduction in OPR from 20:1 to 15:1 resulted from the updated technology projections for the engine hot section. At supersonic cruise, the compressor exit temperatures corresponding to the 20:1 and 15:1 OPR's are 704°C (1300°F) and 649°C (1200°F). If the 704°C supersonic cruise compressor exit temperature of the VSCE-502B had been retained, the hot section design, based on the updated and refined technology projections, would have become too complex, and the advanced burner/turbine materials and cooling systems would have been beyond the projected time period. By reducing the compressor exit temperature to 649°C (1200°F), it was possible to design the hot section components on a basis that is more realistic for advanced commercial engines for the projected time frame. It should be noted that 649°C (1200°F) is 55°C (100°F) higher than the maximum compressor exit temperature for the Pratt & Whitney Aircraft Energy Efficient Engine (E^3) cycle. The engine size was reduced from 408 kg/sec (900 lb/sec total) corrected airflow to 340 kg/sec. (750 lb/sec). This brings the VSCE-515 size closer to the range being evaluated by the SCR airplane contractors.

By isolating the effect of the lower OPR on the VSCE-502B (no component efficiency or turbine cooling air changes), the impact on supersonic and subsonic performance was assessed. Figure 4.1-7 shows plots of TSFC versus thrust for supersonic and subsonic cruise. As indicated for supersonic operation, the reduced OPR increases the dry (non-augmented) thrust of the cycle. This shifts the TSFC curve of the 15 OPR cycle to the right, resulting in a 1.5 percent improvement in augmented TSFC at a representative power setting. For subsonic cruise, the reduced OPR cycle causes a 4.1 percent increase in TSFC. When combined, these performance changes represent a 0.4 percent increase in range for the all supersonic mission, and a 0.25 percent decrease for the mixed mission with a 1,112 Km (600 N.Mi.), subsonic leg. Based on this relatively insensitive effect, the reduction in OPR was considered to be a small concession to gain realism in the updated VSCE definition, and the change was therefore incorporated into the VSCE-515.

Table 4.1-I summarizes the cycle parameters for the VSCE-502B and VSCE-515, reflecting the reduced OPR along with improvements in component efficiencies which are summarized in the next section. The reduced take-off CET for the VSCE-515 main burner is made possible by these improvements in component efficiencies. This results in more Inverse Throttle Schedule (ITS) capability, and a corresponding increase in the level of core engine high-flowing for supersonic operation, leading to a lower Bypass Ratio (BPR) for the VSCE-515 at supersonic operation, and improved fuel consumption, as reviewed in Section 4.2.



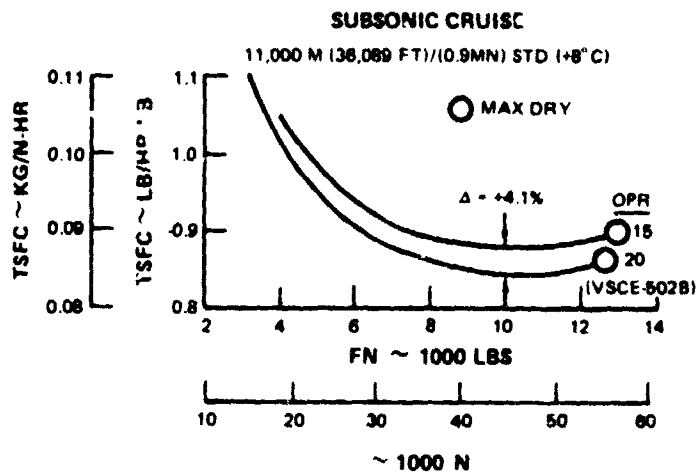


Figure 4.1-7 Performance Effects of Cycle Overall Pressure Ratio (OPR) on VSCE.

TABLE 4.1-I

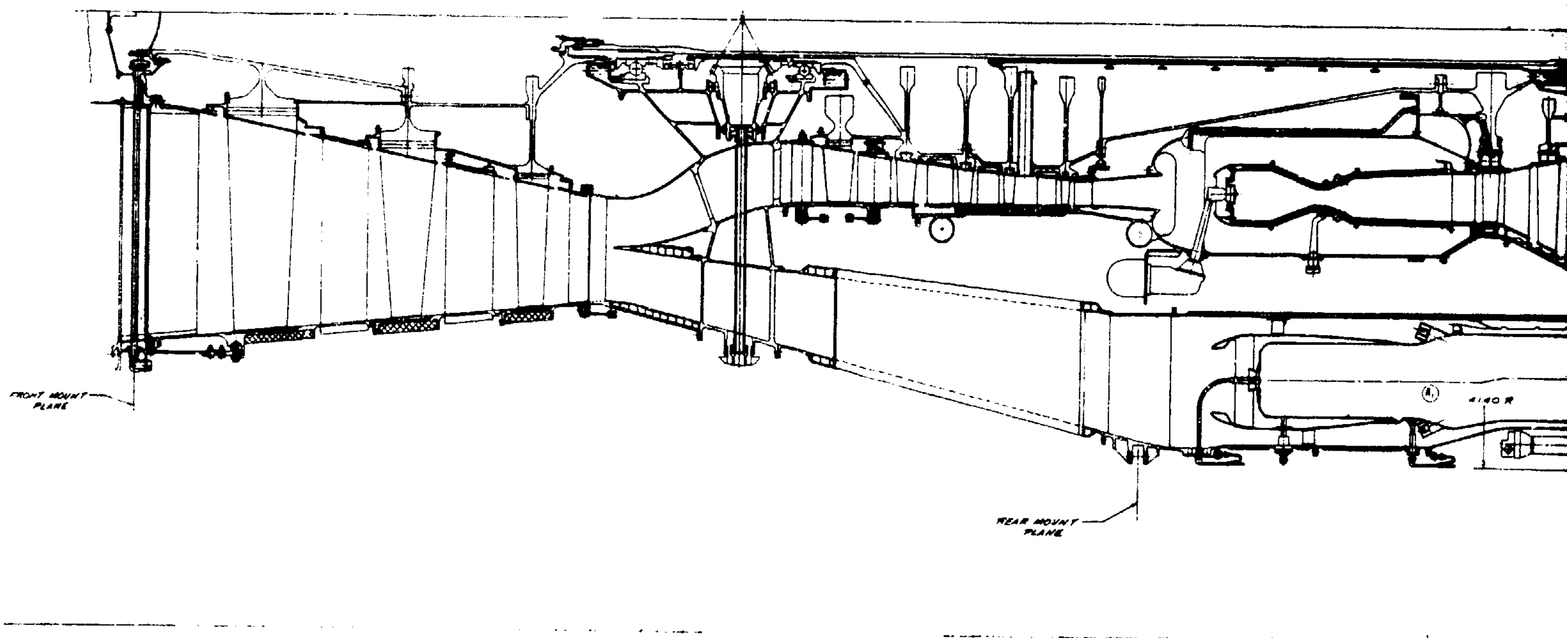
VSCE CYCLE COMPARISON OF THE UPDATED VSCE-515 (15 OPR) RELATIVE TO THE PARAMETRIC VSCE-502B (20 OPR)

	SLTO		Subsonic Cruise		Supersonic Cruise	
	0 Ft	0 Mn	11,000 m(36,089 Ft)	0.9 Mn	16,154 m(53,000 Ft)	2.32 Mn
Engine	-502B	-515	-502B	-515	-502B	-515
OPR	20	15	22	14.5	11.9	9.4
W_{AT2} kg/sec(lb/sec)	408(900)	340(750)	408(900)	340(750)	304(670)	254(558)
FPR	3.3	3.3	3.3	3.3	2.45	2.45
BPR	1.3	1.3	1.2	1.3	1.5	1.4
CET °C(°F)	1199(2190)	1116(2040)	1177(2150)	1007(1840)	1482(2700)	1482(2700)

4.1.2.2 VSCE-515 Cross-Section

Figure 4.1-8 shows a complete cross-section of the VSCE-515 design. It has a two rotor configuration with a staged duct burner located around the main burner and turbine assemblies. The coannular nozzle/ejector/reverser system is close-coupled to and supported from the outer engine case structure. The low pressure rotor consists of a three-stage fan driven by a two-stage low pressure turbine. Making up the high pressure rotor is a five-stage compressor driven by a single-stage turbine. The close-coupled arrangement of these components provides an optimum flow-path by avoiding awkward transition ducts in either the engine stream or the bypass stream. The variable geometry components are the fan, the compressor, and the nozzle system. The structural interface with the airframe is located at two planes, one in the region of the fan inlet guide vanes, and the other just upstream of the duct burner. The low pressure rotor is supported by three main bearings, and the high rotor by two. The fan is straddle mounted and the low pressure turbine is supported by radial rods contained in the exhaust case. Axial and radial support for the low rotor is provided by a thrust (ball) bearing located behind the fan and supported through static structure making up the intermediate case. Radial and axial support for the high spool is provided by a ball bearing also located in the intermediate case. This arrangement allows the two thrust bearings to be contained in one compartment. Rear support for the high rotor is through a low-to-high rotor intershaft bearing. This design eliminates the need for either a hot strut between turbine assemblies or for a separate (fourth) bearing compartment located in the hot region under the main burner. This five bearing arrangement with only three bearing compartments provides the best tip clearance control to maintain high performance, and minimizes the cooling requirements associated with hot structure. The clearance for the high components is further improved by the large diameter hub connecting the compressor and the turbine. The two rotors are designed for co-rotational operation. The supersonic inlet can either be supported directly from the inlet case of the engine with only a small increase in engine weight, or it can be hung independently off the nacelle structure.

Figures 4.1-9 and 4.1-10 show cross sections for the VSCE-515A and VSCE-515B respectively. The VSCE-515A incorporates an alternate high compressor-diffuser design and the VSCE-515B a main burner based on a conventional single-stage configuration with aerating nozzles rather than the two stage vorbix design incorporated in the VSCE-515 and 515A. These variations to the VSCE-515 design are discussed in the following sections of this report.



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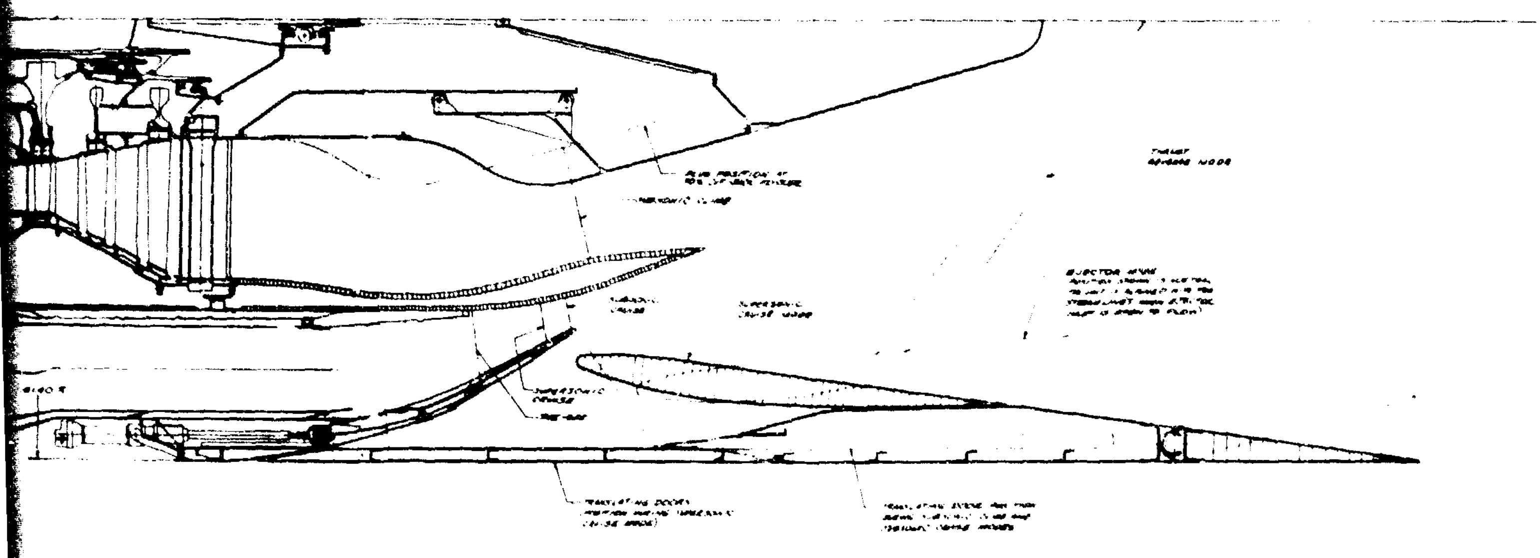
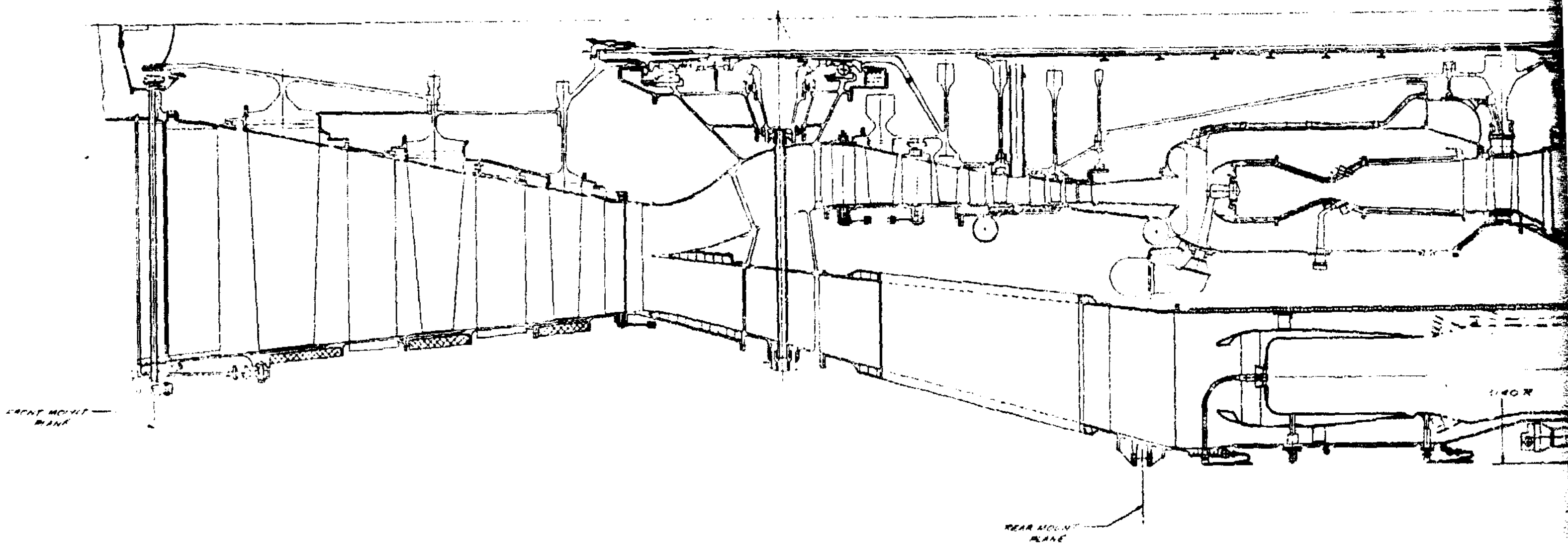


Figure 4.1-8 Cross-Section of the VSCE-515


FRONT MOUNT PLANE
REAR MOUNT PLANE

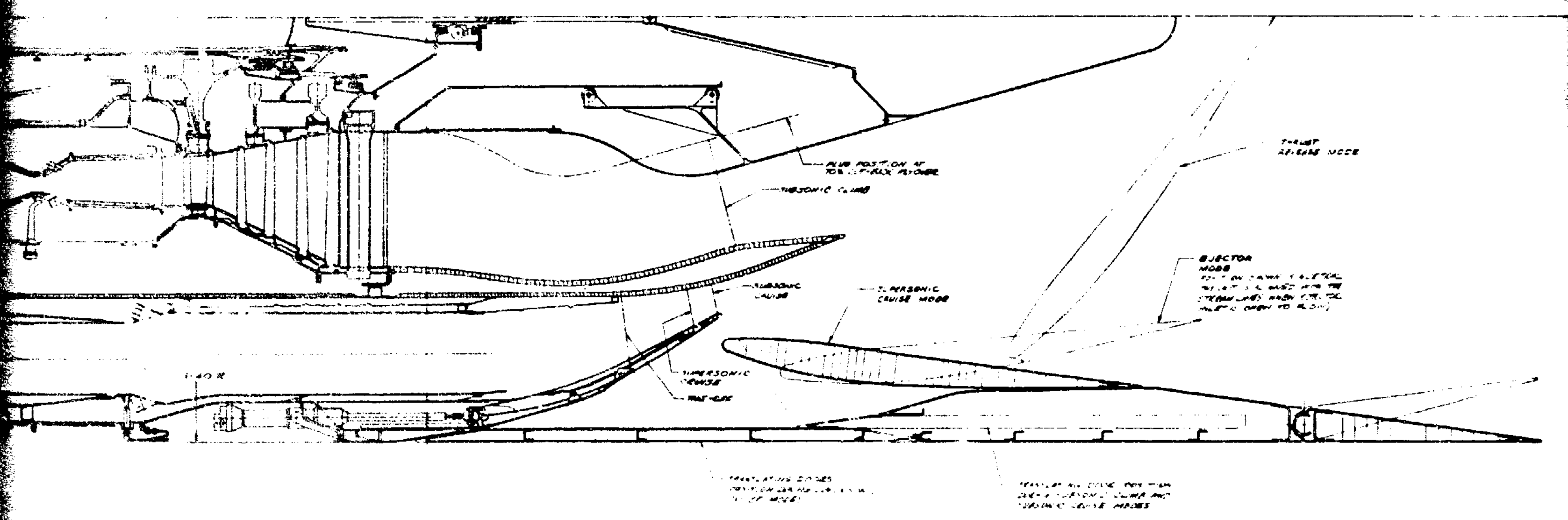
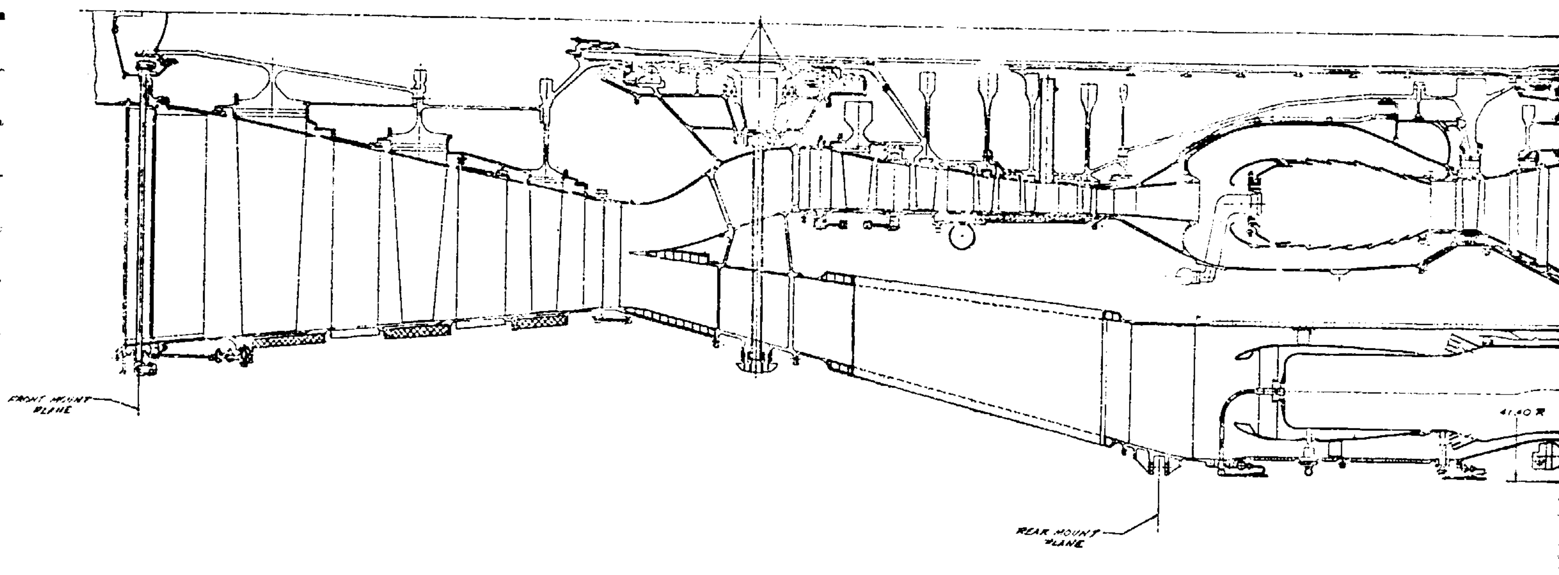


Figure 4.1.9 Cross-Section of the VSCE-515A



FOLDOUT FRAME 1

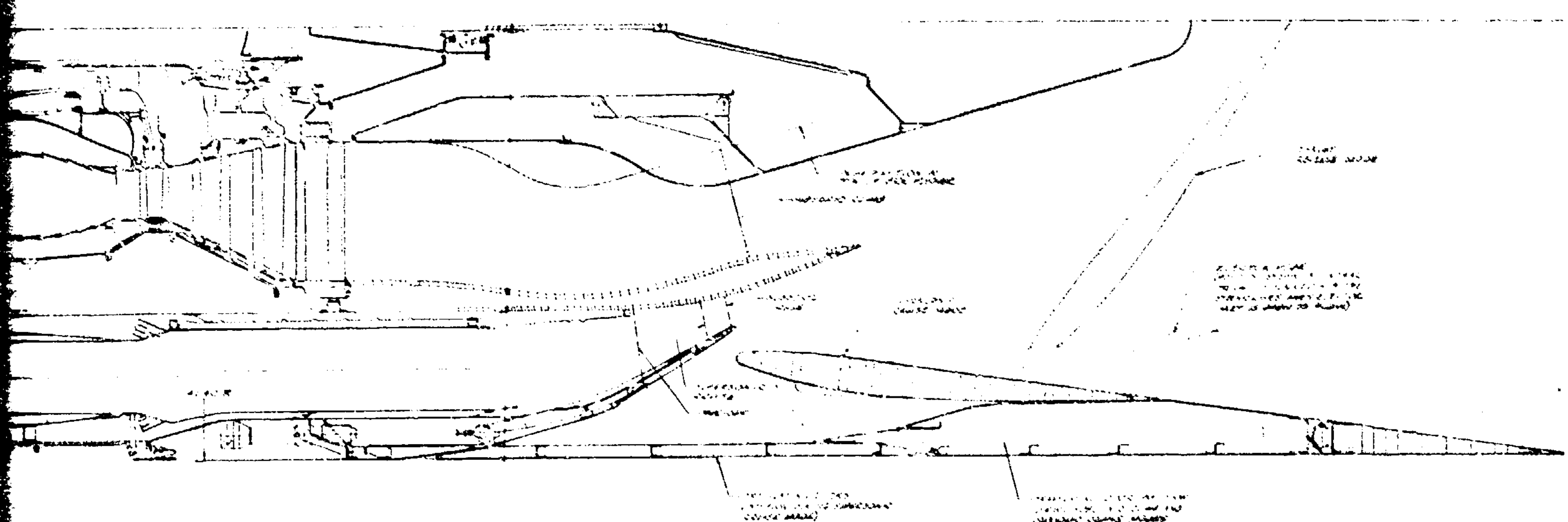


Figure 4.1.10 Cross-Section of the VSCE-515B

4.1.2.3 Engine Components

The most significant changes made in updating the VSCE components are the improvements in efficiencies. Some of these improvements are from the on-going VCE duct burner rig tests and Testbed Programs. Other efficiencies are based on extensions of the technology base being developed by the NASA/Pratt & Whitney Aircraft E^3 program. All of the component efficiencies as projected and applied to the VSCE-515 are listed in Table 4.1-II. For reference, the equivalent VSCE-502B efficiencies are listed. Table 4.1-III summarizes the design features and characteristics of the VSCE-515 major components. Also listed is a breakdown of the hot section cooling system. Table 4.1-IV lists the advanced technology projections that were incorporated into the major components of the VSCE-515.

TABLE 4.1-II

COMPONENT EFFICIENCIES FOR THE UPDATED VSCE-515 RELATIVE TO THE PARAMETRIC VSCE-502B

	Design Point	Design Efficiency	
Engine		-502B	-515
Fan	Sea Level Static Operation	83.9%	85.7%
Compressor	Sea Level Static Operation	87.2%	88.9%
Main Burner	Sea Level Static Operation	100.0%	100.0%
High Pressure Turbine	Supersonic Cruise	89.3%	92.0%
Low Pressure Turbine	Supersonic Cruise	91.4%	92.0%
Duct Burner	Supersonic Cruise	94.5%	96.0%*

*Thrust efficiency

Fan

The advanced, three-stage fan design emphasizes high efficiency at supersonic cruise, compatibility with supersonic inlets (especially stability, flow matching and choking for noise reduction), and compatibility with the duct burner. This duct burner compatibility requires high diffusion in the basic fan design. Also, for reduced aft noise, the fan has graduated spacing between the blades and vanes of three stages. The first stage has 50 percent spacing, the second has 75 percent and the third has 100 percent, all expressed as the axial gap at the outer diameter relative to the axial chord of the upstream airfoil.

TABLE 4.1-III

DESIGN FEATURES OF VSCE-515 MAJOR COMPONENTS
(Engine Size = 340 kg/sec (750 lb/sec) Total Airflow)

FAN

(Fan Aero Design Point = Sea Level Static Operation)

Design Pressure Ratio	3.3:1
Number of Stages	3
Design Corrected Airflow Size	340 kg/sec (750 lb/sec)
Design Corrected Specific Airflow	210 kg/sec/m^2 (43.0 lb/sec-ft^2)*
Design Corrected Rotational Speed (rpm)	6107
Design Corrected Tip Speed	488 m/sec (1600 ft/sec)*
Exit Axial Mach No.	0.40
Inlet Hub/Tip Ratio	0.33*
Exit Hub/Tip Ratio	0.64
Adiabatic Efficiency (%)	85.7
Surge Margin (%)	> 20
Structural Definition	Unshrouded Blades

*At leading edge of first blade.

Fan Airfoil Definition

Stage No.	-	1	1	2	2	3	3
Airfoil	IGV	R_1	S_1	R_2	S_2	R_3	S_3
Number of Airfoils	18	24	40	34	42	50	65
Root Aspect Ratio	3.0	2.8	3.8	2.8	[illegible].8	3.0	3.0
Root Gap/Chord	0.44	0.40	0.42	0.44	0.44	0.50	0.49
Root Chord cm	18.3	17.5	11.4	14	12.2	9.9	8.4
(inches)	(7.2)	(6.9)	(4.5)	(5.5)	(4.8)	(3.9)	(3.3)
Taper Ratio (Tip/Root Chord)	1.0	1.38	1.0	1.20	1.0	1.10	1.0
Variable Camber	X	-	-	-	-	-	X

COMPRESSOR

(Compressor Aero Design Point = Sea Level Static Operation)

Configuration	Constant Outer Diameter
Design Corrected Airflow Size (lb/sec)	55.3 kg/sec (122 lb/sec)
Pressure Ratio	4.6:1
Number of Stages	5
Corrected Tip Speed (ft/sec)	363 m/sec (1190 ft/sec)
Hub/Tip Ratio	
Inlet	0.70
Exit	0.87
Average Aspect Ratio	1.3
Adiabatic Efficiency, (%)	88.9
Surge Margin, (%)	> 20
Number of Blades and Vanes	453

MAIN BURNER

(Main Burner Design Point = Sea Level Static Operation)

Temperature	683°K (1230°R)
Fuel/Air Ratio	0.0224
Heat Release Rate (Btu/hr-atm-ft^3)	6.0 x 10^6
Residence Time (sec)	0.008
Burner Length*	54.1 cm (21.3 in)
Burner and Diffuser Length*	88.9 cm (35.0 in)
Chemical Efficiency, (%)	100.0
Pressure Loss (%)	5.2

*Vorbix Configuration

TABLE 4.1-III (Cont'd)

HIGH PRESSURE TURBINE

(HPT Aero, Cooling and Structural Design Point = Supersonic Cruise Operation)

Expansion Ratio	2.3:1
RPM	11,286
AN^2	3.7×10^7 m^2/min^2 (5.8×10^{10} in^2/min^2)
Blade Root Stress (ksi)	413.640 k n/m^2 (60 ksi)
Mean Velocity Ratio $\frac{U\ mean}{\sqrt{2gJ\,\Delta h}}$	0.58
Axial Velocity/Wheel Speed	0.60
Rim Speed	404 m/sec (1325 ft/sec)
Cooling and Leakage Flow (% core flow)	6.2
Cooled Efficiency (%)	92.0
Average Blade Turning (°)	91.0

LOW PRESSURE TURBINE

(LPT Aero/Cooling and Structural Design Point = Supersonic Cruise)

Expansion Ratio	3.1:1
Number of Stages	2
RPM	6616
AN^2	3.87 m^2/min^2 (6×10^{10}) in^2/min^2
Second Blade Root Stress	413,640 kn/m^2 (60 ksi)
Mean Velocity Ratio ($U_m/\sqrt{2gJ\Delta h}$)	0.49
Axial Velocity/Wheel Speed	1.04
Rim Speed	221 m/sec (724 ft/sec)
Cooled Efficiency (%)	92.0
Cooling and Leakage Flow (% Core Flow)	3.97
Average Blade Turning (°)	87.0

SUMMARY OF TURBINE COOLING AND LEAKAGE AIRFLOW

High Pressure Turbine	Flow (% Core Flow)
1st Vane	1.9
1st Blade	2.5
Disk and Case Cooling and Seal Leakage	1.8
	6.2 Subtotal
Low Pressure Turbine	
1st Vane	0.7
1st Blade	1.4
2nd Blade	1.1
Disk, Case and Tailcone Cooling and Leakage	0.8
	4.0 Subtotal
	10.2 TOTAL

DUCT BURNER

Design features to be obtained from on-going VCE Technology Programs

COANNULAR NOZZLE/REVERSER SYSTEM

Design features to be obtained from on-going VCE Technology Programs

TABLE 4.1-IV

ADVANCED TECHNOLOGY PROJECTIONS INCORPORATED
IN VSCE-515 MAJOR COMPONENTS

FAN

- o Shroudless Boron/Aluminum blades for first two stages
- o Low-loss, variable-camber inlet and exit guide vanes
- o Advanced aerodynamic airfoil contours, including controlled diffusion airfoils
- o Abradable trench tip rubstrips
- o Low noise features, including compatibility with a choked inlet and axial spacing

COMPRESSOR

- o Controlled endwall losses
  - Abradable trench tip rubstrips
  - Low-volume inner seal cavity design
- o Multiple circular arc controlled diffusion airfoils
- o Airfoil coatings to preserve surface finish
- o High-temperature, dual property disks (649°C (1200°F) rim capability)
- o High temperature case and diffuser material (677°C (1250°F) capability)

MAIN BURNER

- o Oxide dispersion strengthened (ODS) liner material with a thermal barrier coating
- o Advanced cooling system for liner (impingement - transpiration cooling)
- o High temperature case material
- o Low emissions configuration (either from NASA/P&WA Experimental Clean Combustor Program (ECCP) or derived from more conventional burner designs)

HIGH PRESSURE TURBINE

- o Advanced materials
  - Airfoils made from single crystal alloy or Rapid Solidification Rate (RSR) powder metallurgy techniques
  - Thermal barrier coating and substrate oxidation coating for airfoils, endwalls and platforms
  - Dual property disks (649°C (1200°F) rim capability)
  - High temperature case material
  - Abradable ceramic seal

TABLE 4.1-IV (Cont'd)

- o Advanced cooling system
  - High effectiveness convection cooling for airfoils, using wavy walls or trip strips
  - Film cooling using low angle holes for releasing coolant
  - Improved design of airfoil trailing edges such as elliptical pedestals
  - Improved feed of disk/blade cooling air with advanced tangential onboard injection and multi-source (mid-compressor) bleed
  - Air/air heat exchanger to cool the turbine cooling air, using fan air as the cooling medium

- o Advanced aerodynamic technology
  - Low Mach number (high annulus area), high rotational speed design
  - Low loss vane endwalls
  - High airfoil loading levels designed for mid transonic operation
  - Radial load coefficient varied with blade taper to minimize blade pull stress

<u>LOW PRESSURE TURBINE</u>

- o Advanced two-stage design
  - High included wall angle
  - Supercritical exit guide vanes
- o High strength blade material (single crystal or RSR) with tapered contours and mini-shrouds
- o High temperature case material

<u>DUCT BURNER</u>

- o Simplified two-stage design that retains high efficiency, low emissions and good operational characteristics demonstrated in VCE technology Programs
- o High cooling effectiveness, oxide dispersion strengthened liner with thermal barrier coating
- o Low pressure loss diffuser

<u>COANNULAR NOZZLE</u>

- o Light weight configurations/mechanisms for variable area control for low noise and high performance requirements
  - Approximately 40% area change for primary stream
  - Approximately 200% area change for duct stream
  - Ejector opening controlled as function of Mach number
    Self-positioning tail feathers
  - Targetable reverser
- o Inverted velocity profile optimized for low jet and shock noise
- o Lightweight acoustic treatment integral with ejector/reverser components

To meet nacelle envelope dimensions established by the SCR airplane contractors for good installed performance, as well as to provide space for packaging accessories around the fan case, the fan is designed to have a low elevation (low hub/tip ratios). Due to stress limitations in the low pressure turbine blades, and also because of the emphasis on high efficiency and low noise, the design tip speed of the fan is optimum at approximately 487.7 M/sec (1600 ft/sec). To provide high efficiency at subsonic cruise in addition to supersonic cruise, variable camber inlet and exit guide vanes are required to accommodate the swing in air velocities entering and leaving the first and last stages. Low aspect ratio, unshrouded composite Boron/Aluminum material was assumed for the blades of the first two stages. The higher temperatures of the third stage require titanium blades.

Compressor

The five-stage compressor is designed for maximum efficiency at supersonic cruise. The high operating temperature — air exits at 649°C (1200°F) at supersonic cruise — and the fact that it has a relatively low number of stages because of its low pressure ratio of 4.6:1 and high rotational speed, make the VSCE-515 compressor design unique relative to other advanced commercial engines.

Main Burner

There are two special operating requirements that affect the design of the main burner; long design life (durability) in the severe thermal environment at supersonic cruise, and low emissions in the airport vicinity. The durability requirement dictates the need for an advanced burner liner configuration that has high cooling effectiveness, combined with high temperature materials. The emissions goals — EPA Rules and Regulations, Title 40, Chapter 1, established for advanced supersonic engines - Class T5 - were set in August, 1976 at:

Pollutant	EPAP
THC	1.0
CO	7.8
NO_x	5.0

These goals are extremely agressive and will require a very advanced main burner configuration to compliment the advanced technology duct burner being evaluated in the VCE Technology Program.

Three main burner configurations were defined for the VSCE-515, two were a two-stage VORBIX design derived from the NASA/Pratt & Whitney Aircraft Experimental Clean Combustor Program, and the third was an advanced single stage configuration which is an extension of conventional annular main burner designs with aerating nozzles. The VORBIX types have the potential for lower emissions, but present significant compromises in terms of weight and complexity. A concentrated research and technology program will eventually be required to define the most suitable burner concept for advanced supersonic commercial engines. Durability of the burner liner and case is a common requirement regardless of the burner configuration, and therefore is one of the critical technology elements included in the VCE-HTV program recommended in Section 4.3.

High Pressure Turbine

The most unique and critical advanced technology features of this single-stage turbine design are those associated with long design life (durability) and high efficiency at the high temperature - high stress conditions at supersonic cruise. These features include high temperature materials for the blades and vanes, thermal barrier coatings applied to the outer surfaces of these airfoils, high efficiency airfoil designs contoured to reduce the pull stress at maximum rotational speeds, and an advanced cooling system, consisting of a lightweight, compact heat exchanger to cool the turbine cooling air, a tangential on-board injector for efficient transfer of blade cooling air from the static to rotating reference, and high heat transfer effectiveness of the internal cooling passages of the vanes and blades. Collectively, these advanced technologies have the greatest overall impact on the VSCE-515 performance and life. Furthermore these same requirements are just as critical in affecting the performance of all other candidate AST engines, including alternative VCE concepts as well as conventional engines. The VCE-HTV program recommended in Section 4.3 concentrates on these requirements.

Low Pressure Turbine

The low pressure turbine is designed for high efficiency and for high rotational speed. The high speed allows the turbine to be a two stage configuration and provides a low elevation flowpath for the three-stage fan. The turbine flowpath also has a low profile to minimize the duct burner diameter. This is a critical design consideration in that the low pressure turbine and duct burner together set the maximum diameter of the nozzle. These performance and dimension requirements result in the low pressure turbine design having airfoils with subsonic exit conditions. This yields a relatively large exit annulus which, when combined with the high rotational speed (high AN^2) requires the same high strength blade material as is applied to the high pressure turbine blade. To compliment this high efficiency design, the turbine exit guide vanes which house the radial supports for both rotors is a supercritical airfoil design. To provide high efficiency for off-design operation (subsonic cruise) and to avoid the complication of having variable geometry in this hot region of the engine, elliptical leading edges are included in these vane designs for reducing sensitivity to air angle mismatches.

The recommended VCE-HTV program in Section 4.3 applies not only to the high pressure turbine, but also to the most critical requirement for this low pressure turbine -- the high strength material and thermal barrier coating for the airfoils of both stages, especially the second blade.

Duct Burner

The VSCE-515 duct burner is a simplified, two-stage version of the three-stage configurations being evaluated in the on-going VCE Technology Programs. The two-stage design retains the operating flexibility that provides essentially two design points: one is a low fuel/air condition for supersonic cruise where duct burner performance (thrust efficiency*) is a critical parameter; and the other for maximum power operation which occurs at takeoff and during supersonic climb. At takeoff, EPAP emissions rules constitute another basic design consideration. Because the VCE duct burner research programs are continuing, the design definition incorporated in the VSCE-515 is preliminary and, unlike the other major components that make up this engine, it does not reflect the ultimate configuration or all of the advanced technology features that are anticipated for this unique component for the projected late 1980's time frame.

Coannular Nozzle/Ejector/Reverser System

The preceding comments on the duct burner apply also to the coannular nozzle design incorporated in the VSCE-515. The on-going VCE nozzle programs are emphasizing higher levels of subsonic performance while retaining the coannular noise benefit and high supersonic performance. Progress anticipated from the present analytical design effort, and from follow-on model tests are expected to revise and improve the present definition of the coannular nozzle design, especially the aerodynamic contour of the ejector, and the thrust reverser concept.

4.2 VSCE-515 Performance

4.2.1 Thrust Specific Fuel Consumption

The updated and refined VSCE-515 cycle offers a 3% TSFC improvement at supersonic cruise and a 0.9% TSFC penalty at subsonic cruise relative to the VSCE-502B. Figure 4.2-1 shows TSFC versus thrust characteristics for both engines over a range of power settings at these two operating points. The higher efficiency components, based on results from the VCE programs and by extending E^3 technology out another five years, were the most significant contributions in improving supersonic fuel consumption. The reduction in cycle overall pressure ratio (OPR) would have caused a large increase in subsonic fuel consumption, but the higher efficiency components largely offset this penalty.

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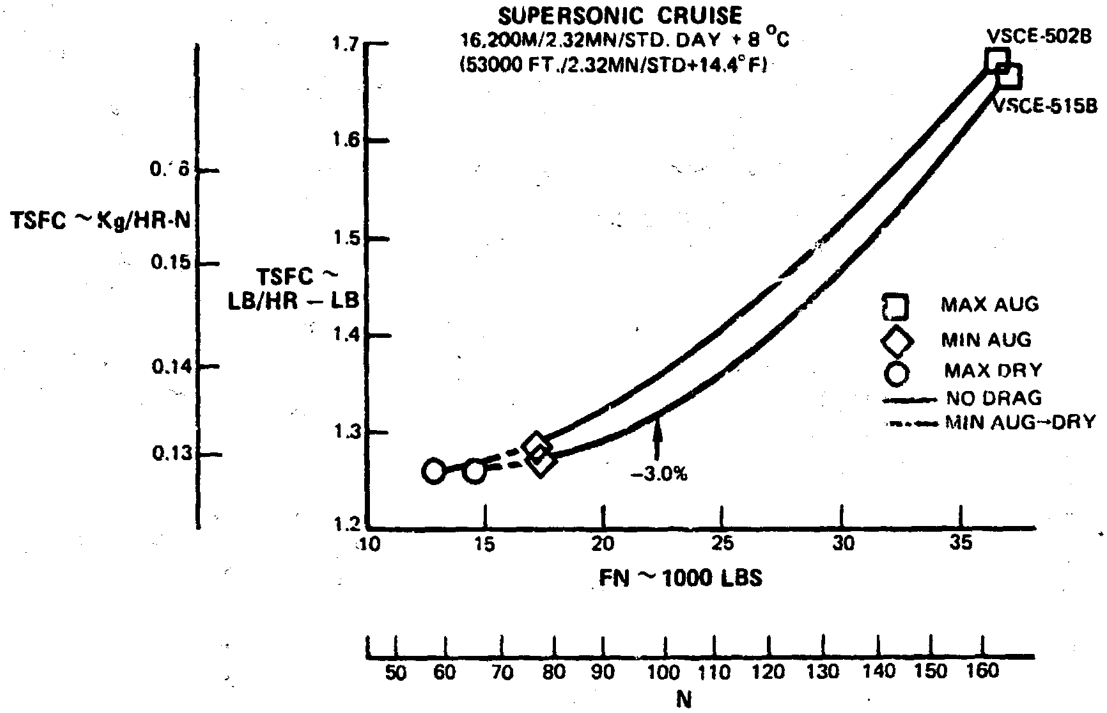
*Thrust efficiency combines the effects of nonuniform temperatures and pressures in the duct burner exhaust with depressed temperatures resulting from chemical inefficiency and dissociation in the combustion process. The method for calculating this efficiency involves integrating the momentum flow radially and circumferentially across the duct burner exhaust and comparing this integrated thrust with the ideal thrust that would be obtained with 100% chemical efficiency, no dissociation, and no thermal or pressure gradients in the exhaust stream.



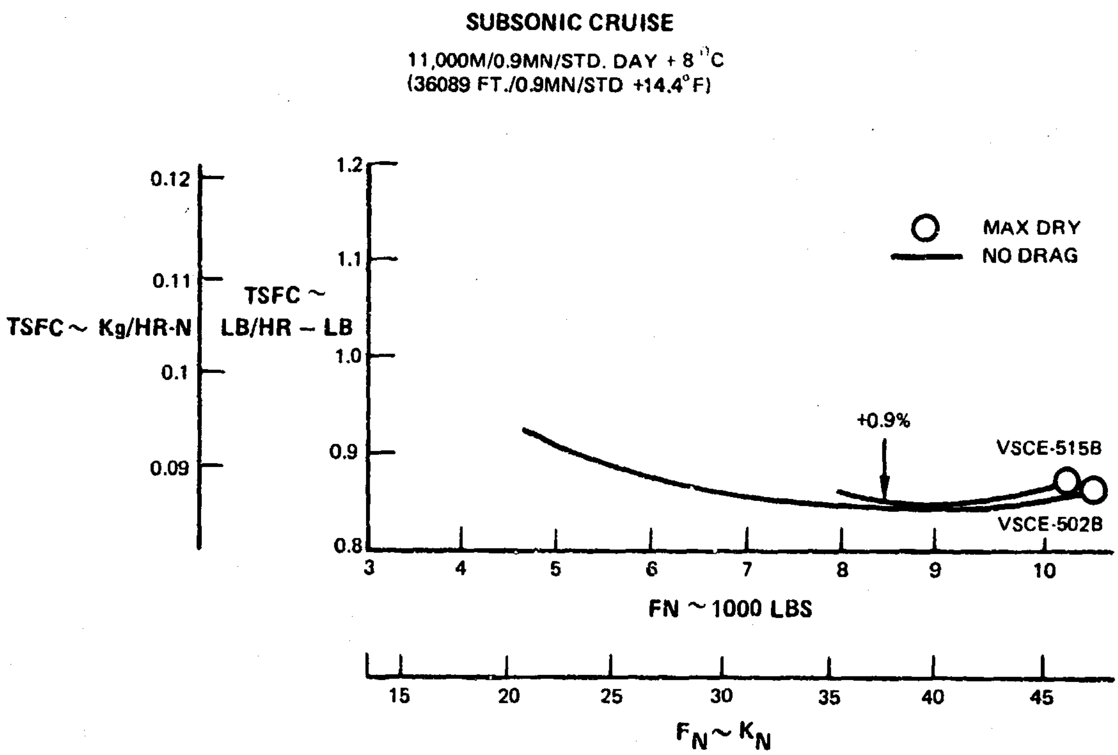


Figure 4.2-1 TSFC Versus Thrust Characteristics for Refined VSCE-515 Relative to Parametric VSCE-502B
Engine size = 340 kg/sec (750 lb/sec)

Table 4.2-1 provides visibility in the transformation from the VSCE-502B to the VSCE-515 by isolating some of the major factors affecting TSFC at supersonic and subsonic cruise. The high efficiency components are summarized in section 4.1.2.3.

TABLE 4.2-1

MAJOR FACTORS THAT AFFECT VSCE TSFC UPDATE

	SUPERSONIC CRUISE 16,154M (53,000 FT) ALT. 2.32 Mn Standard Day +8°C (+14.4°F)	SUBSONIC CRUISE 11,000M (36,089FT) ALT. 0.9 Mn Standard Day +8°C (+14.4°F)
VSCE-502B	% Δ TSFC Base	% Δ TSFC Base
Reduced OPR (from 20 to 15)	-1.0	+4.2
Revised TCA Distribution	+0.2	-0.6
Constant FPR at Part Power Operation	0.0	+0.8
High Efficiency Components	-1.8	-3.6
1st Vane Heat Exchanger	-0.4	+0.1
VSCE-515	-3.0	+0.9

4.2.2 Weight

The bar chart of Figure 4.2-2 summarizes weight estimates for the VSCE major components. The left side of the bar represents the parametric definition of the VSCE-502B scaled to 340 kg/sec (750 lb/sec) total airflow. The right side is consistent with the VSCE-515 engine definition shown in the cross-section of Figure 4.1-9. Based on the present status of the VCE Critical Technology Programs, weight estimates for the duct burner and coannular nozzle are 3.4% and 4.8% higher than for the VSCE-502B components. However, because these components are still in the basic research stage, their designs do not reflect the full potential associated with the projected late 1980's technology readiness time period. Furthermore, these components are affected by environmental constraints in addition to other commercial engine design considerations, and more design work, plus experimental evaluation is required before their final configurations and weights can be determined with confidence. Therefore, at this time, the weight increase for these components is not being incorporated in the updated VSCE-515 study engine definition.

The official weight for the advanced VSCE based on the late 1980's technology projections is 5216 kg (11,500 lbs).

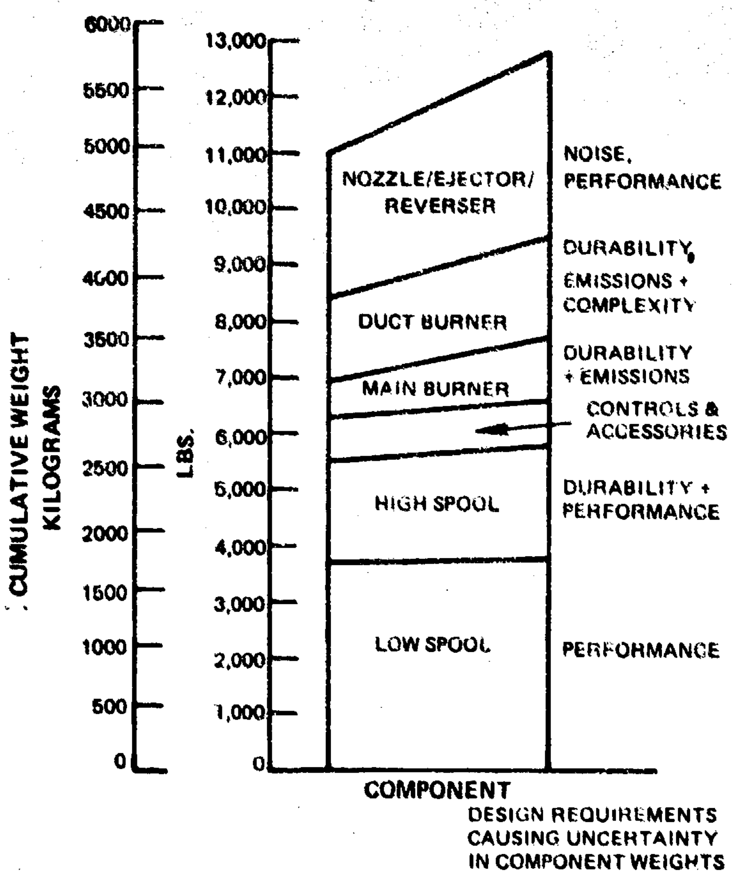


Figure 4.2-2 VSCE Weight Summary
Engine Size = 340 kg/sec (750 lb/sec) Total Airflow

4.2.3 Noise

Figures 4.2-3, 4.2-4 and 4.2-5 summarize the updated VSCE-515 noise estimates. Relative to previous prediction procedures. an improved technique has been used. Specific areas that have been updated are:

- A more accurate procedure for estimating jet and shock noise levels for coannular nozzles with inverted velocity profiles. For the first time, this includes the effect of nozzle geometry (radius ratio) in Pratt & Whitney Aircraft VSCE noise estimates. This improved procedure was developed from nozzle model test data obtained under NASA/Pratt & Whitney Aircraft contract NAS3-20061 and described in reference 6.

- A revised procedure for flight effects, described in the same final report.

- Correction to some of the previous sideline and flyover noise estimates in allowing for the proper number of engines.

- Allowance for a more realistic ground plane reflection effect.

Table 4.2-II summarizes the bases for these updated prediction procedures.

Figure 4.2-3 for sideline noise indicates that a specific thrust level of about 62 corresponds to FAR Part 36 (1969), when the effects of shielding and extra ground attenuation (EGA) are included. Figure 4.2-4 for community flyover indicates a specific thrust of about 42 meets the rule. A 32 percent reduction in power setting is required for community flyover to meet the rule at both measuring stations. These results also show that the maximum power setting (70 specific thrust) exceeds the sideline rule by approximately 3dB. Therefore programmed throttle scheduling combined with other operational procedures is required if the penalties associated with oversizing and throttling back the engine are to be avoided.

Figure 4.2-5 shows a breakdown of the engine noise sources at the sideline condition. The total noise (top) curve is the same as Figure 4.2-3. Jet and shock are the major noise sources, and although the procedure for estimating duct burner combustion noise is not considered to be very accurate, it may add approximately 1 to 2 dB to the total noise, as illustrated in Figure 4.2.5. With the choked inlet and the level of acoustic treatment assumed for the duct and nozzle systems, fan and low pressure turbine (LPT) noise and other core sources are insignificant.

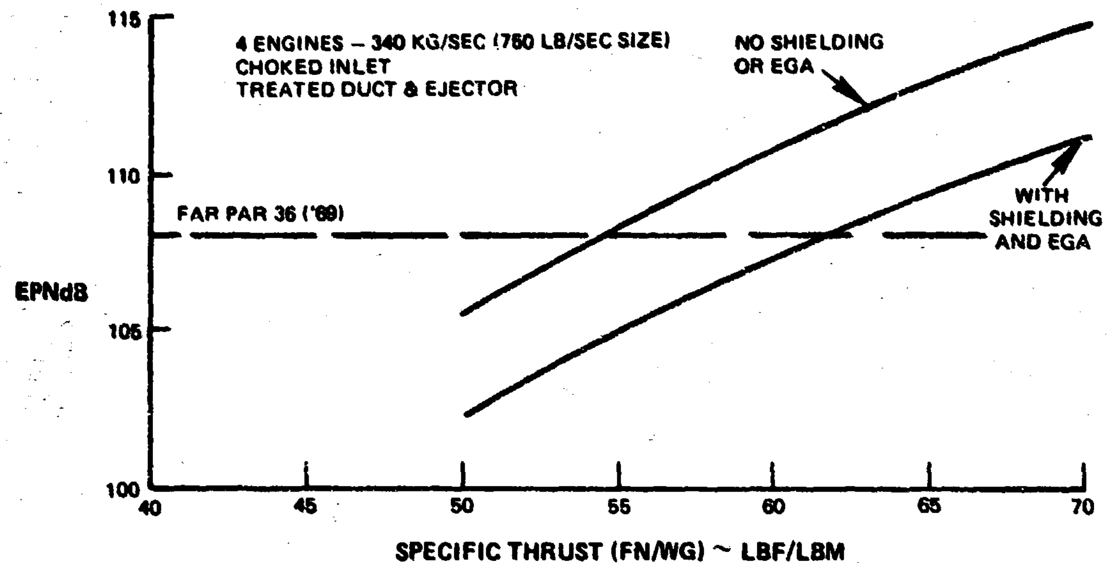


Figure 4.2-3 VSCE-515 Noise Estimates - 0.35 N.M. Sideline 335m (1100 ft.) ALT, 0.3 MN

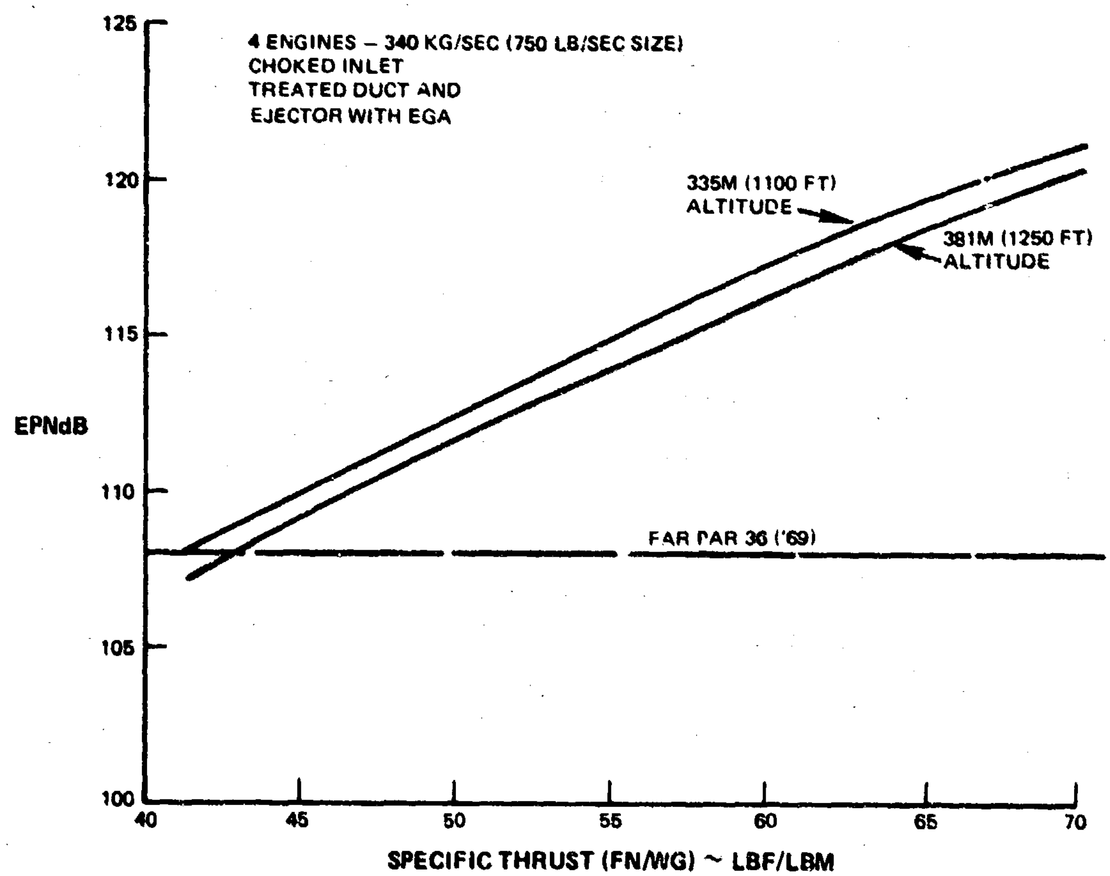


Figure 4.2-4 VSCE-515 Noise Estimate - Community Flyover 0.3 MN

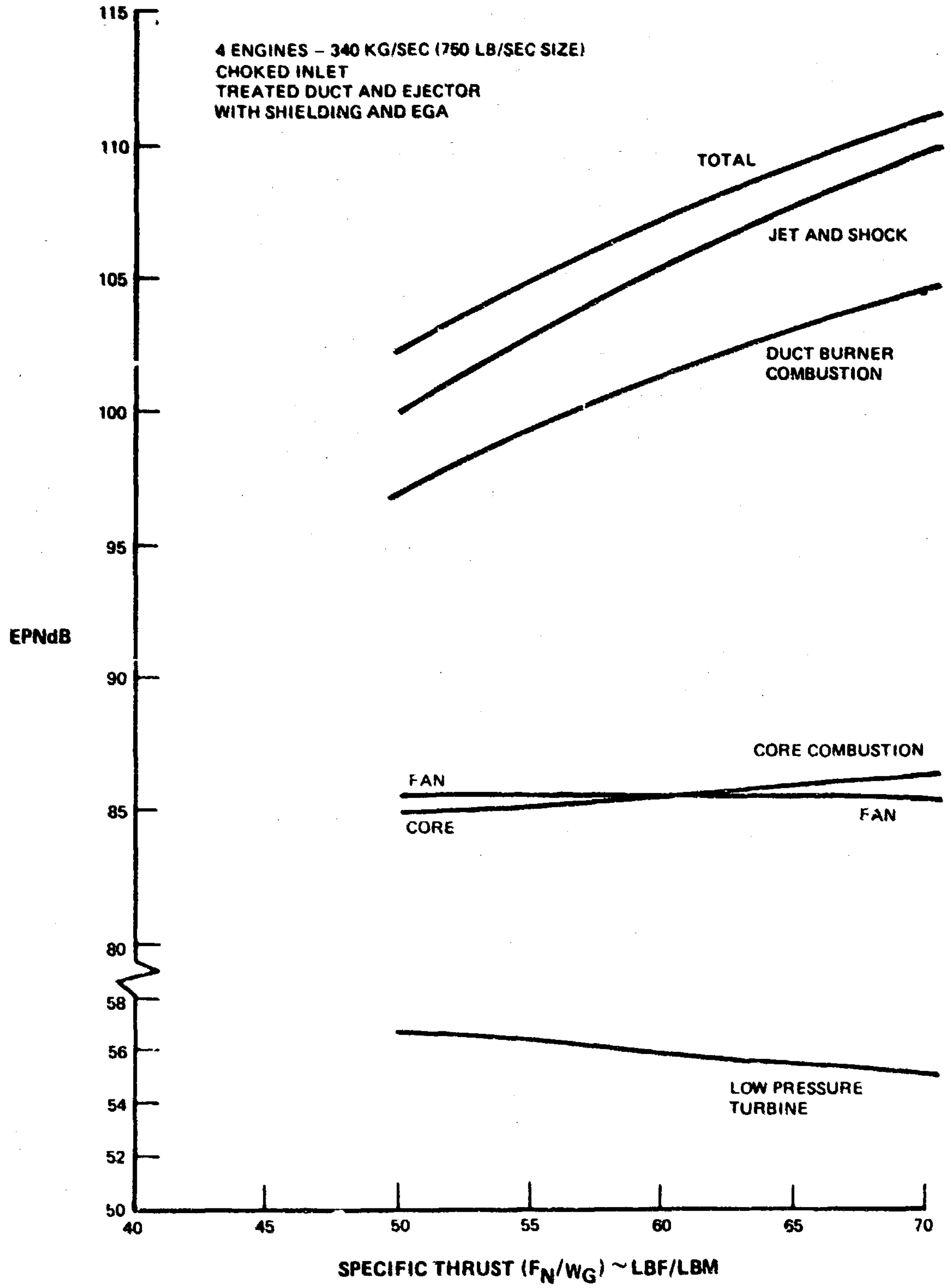


Figure 4.2-5 VSCE-515 Noise Estimate - Sideline Source Analysis 335m (1100 ft.) ALT, 0.3 MN

TABLE 4.2-II

BASIS FOR VSCE-515 NOISE ESTIMATE

Basis for Estimating Noise Sources:

- Jet and shock: based on model data for coannular IVP nozzles and developed under contract NAS3-20061 (accounts for nozzle geometry as well as exhaust flow conditions) (reference 6)

- Fan: based on engine/rig data as a function of:
  - o tip speed
  - o stages and blade number
  - o spacing
  - o size

- Turbine: empirically derived as a function of:
  - o work
  - o speed
  - o stage and airfoil number
  - o size
  - o shielding by fan stream

- Main and Duct Burner: empirically derived from main burner data and scaled as a function of:
  - o size
  - o local Mach number
  - o geometry
  - o fuel/air ratio
  - o attenuation through turbomachinery

Fan Spectral Attenuation:

- Forward Quadrant: Near sonic "choked" inlet yields a 20 dB reduction in fan noise

- Rear Quadrant: Duct attenuation equivalent to acoustic treatment having an L/H = 16

Corrections for Flight System:

- Fan and turbine noise corrected from test stand conditions to free field
- Jet and burners at free field
- Jet noise adjusted for flight effects
- Sources adjusted for doppler shift and convective amplification
- Data extrapolated to aircraft distances and ground reflections applied representative of aircraft flight data
- Extra ground attenuation applied to all sources
- Shielding applied for sideline conditions

From these estimates, it can be concluded that a significant reduction in jet and shock noise will be required to meet the more stringent Stage 3 FAR Part 36 1978 Noise Rule, if it is imposed on advanced supersonic engines. Figure 4.2-6 compares the two FAR Part 36 Rules, showing that an 8 dB reduction at sideline, and a 1 dB reduction at the community point are required to meet the newer rule. As noted, the sideline measuring station for the 1978 rule has been moved in from 650 meters (0.35 N.Mi.) to 450 meters (0.25 N. Mi.). The sideline noise level shown in Figure 4.2-6 includes the effect of this closer distance.

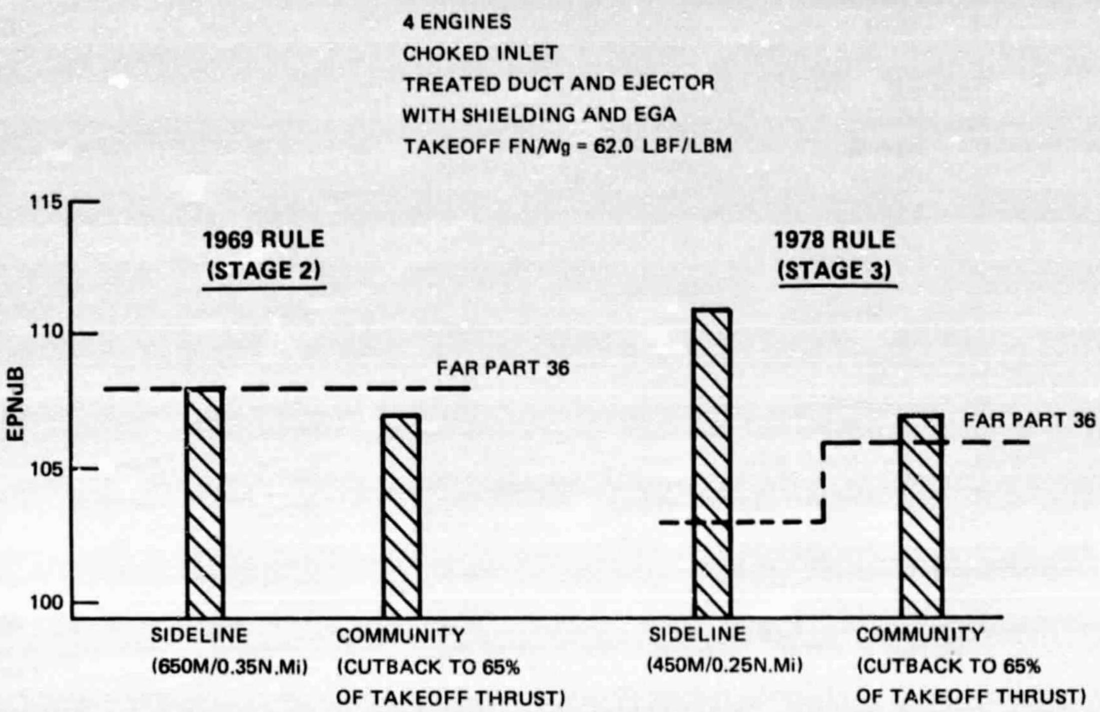


Figure 4.2-6 VSCE-515 Noise Estimates Relative to FAR Part 36 Noise Rules

At the approach measuring station, either a choked inlet, or one with highly effective acoustic treatment will be required. Figure 4.2-7 is a summary of the VSCE noise sources at the approach condition relative to the two rules. The reduction in total noise provided by the choked inlet gets to within 2 EPNdB of the 1978 rule.

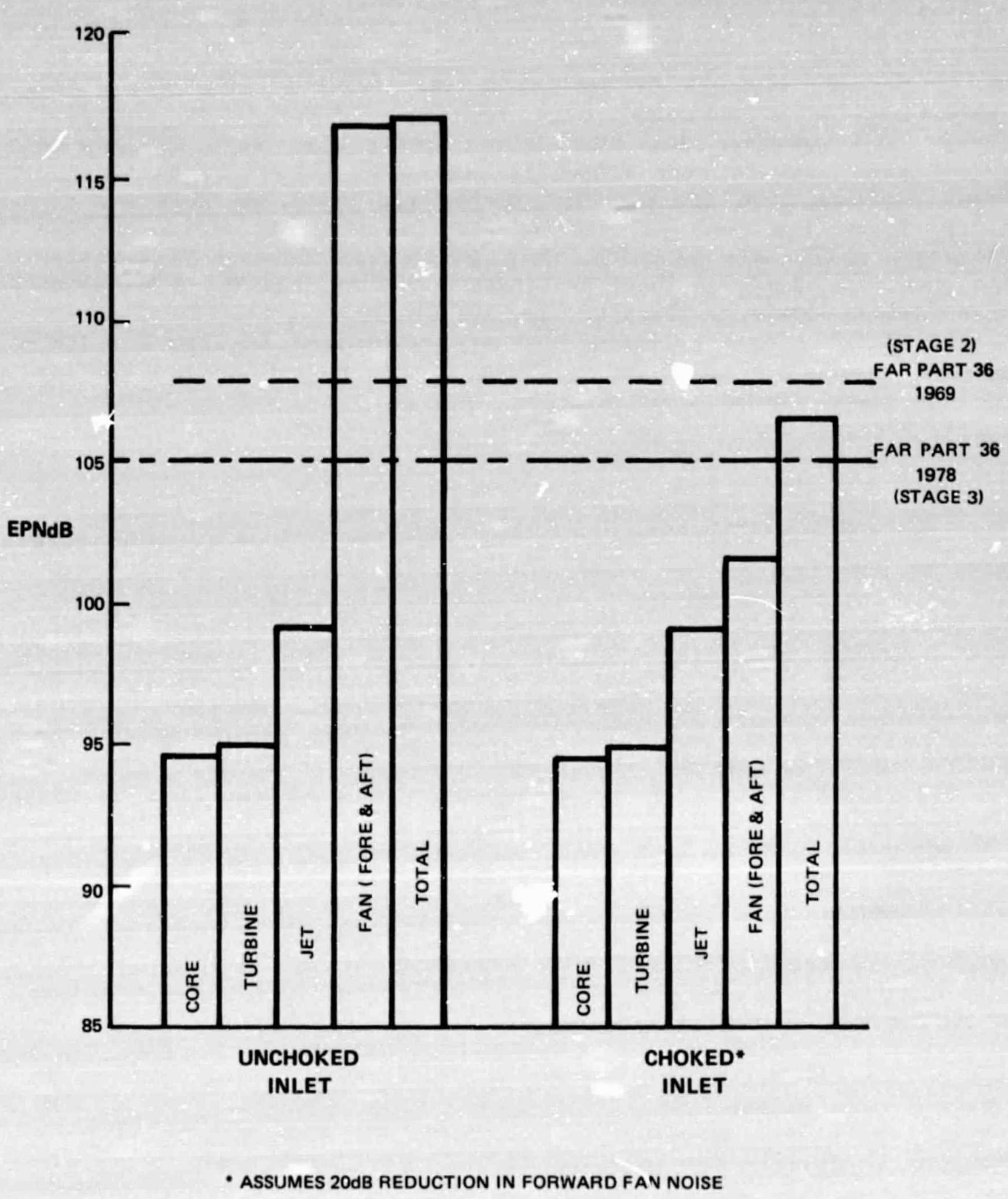


Figure 4.2-7 VSCE-515 Noise Estimates at Approach Measuring Station

4.2.4 Emissions

One of the new elements in estimating the VSCE-515 emissions is the availability of experimental data from the on-going VCE programs. Figure 4.2-8 compares the duct burner goals that were established several years ago for the VSCE-502B (shown by the white bars), and those resulting from the VCE duct burner rig tests and from the VCE Testbed Tests (the black bar labeled test results). As shown, the two efficiency goals were exceeded. Only the pressure losses were higher than predicted. Applying these performance results, and the corresponding emissions levels to the VSCE-515, the EPA Parameters (EPAPs) in the airport vicinity were estimated and are summarized in Figure 4.2-9. These estimates are based on an advanced main burner concept such as the two-stage VORBIX configuration derived from the NASA/Pratt & Whitney Aircraft Experimental Clean Combustor Program.

As shown in Figure 4.2-9, the NO_x EPAP is 3.5. When the effects that are associated with production engines are allowed for, as indicated by the cross-hatched areas, the VSCE-515 just meets the NO_x EPAP goal which is indicated by the broken line. For CO, the level is 11.1, and with production allowances, is slightly over 15, or approximately twice the goal. Most of the CO contribution is from the duct burner. Therefore, although considerable progress has been made in the VCE duct burner program to date, further chemical efficiency gains would be required to meet the CO EPAP goals. The required improvement in CO would render the THC level to below the rule. The appropriateness of the EPA rule for advanced supersonic transport and engines (class T5 engines) should be reviewed, as recommended in Section 2.2.

4.3 VCE Critical Technology Requirements and Program Recommendations

4.3.1 Summary

Based on the results of this VSCE Technology Definition Study, a VCE-High Temperature Validation (VCE-HTV) Program has been formulated and is recommended as the next major VCE critical technology program. The approach is to select critical elements of advanced high temperature technology, and experimentally evaluate and substantiate them in an advanced main burner and a new single-stage high pressure turbine design. Sufficient experimental component and rig testing will be required to qualify the selected technologies first individually and then collectively. They would then be substantiated in a high temperature diagnostic test using either a complete high spool system for the testbed, or a high temperature burner-turbine rig facility. This diagnostic test will be instrumented to correlate measured temperatures and stress levels with life characteristics of the hot section components and materials. This program concentrates on two critical VCE technology areas: high temperature materials combined with advanced cooling systems. Advanced aerodynamic design features will be included so that a high level of turbine efficiency can also be demonstrated. The elements

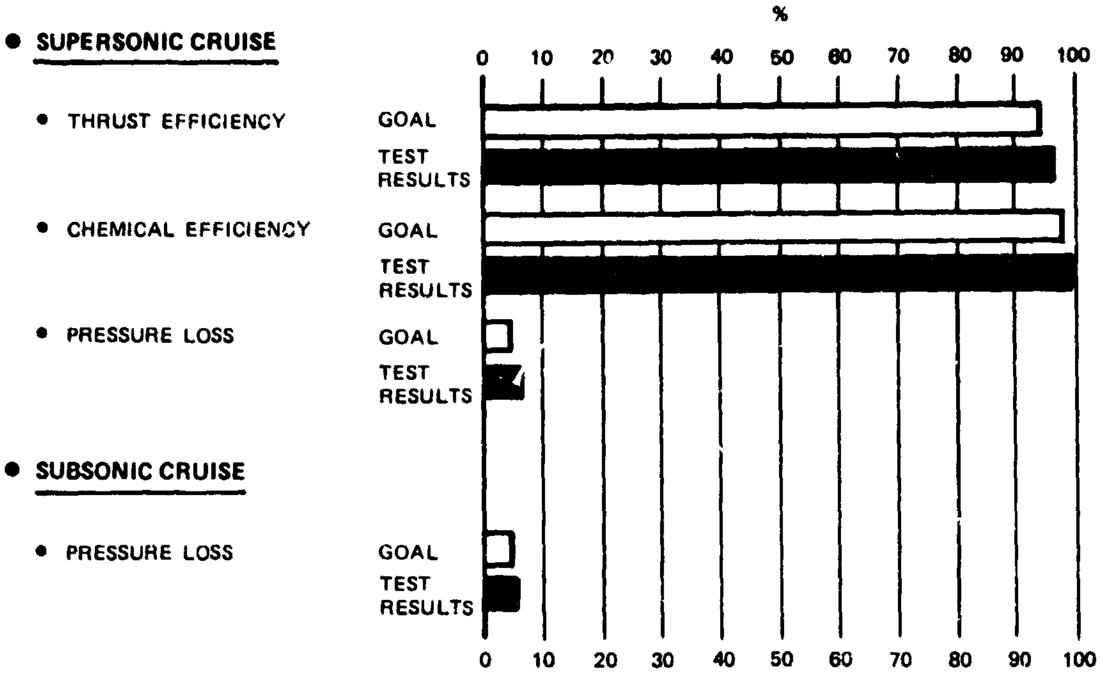


Figure 4.2-8 VSCE-515 Duct Burner Performance Update (Based on Rig & Testbed Data)

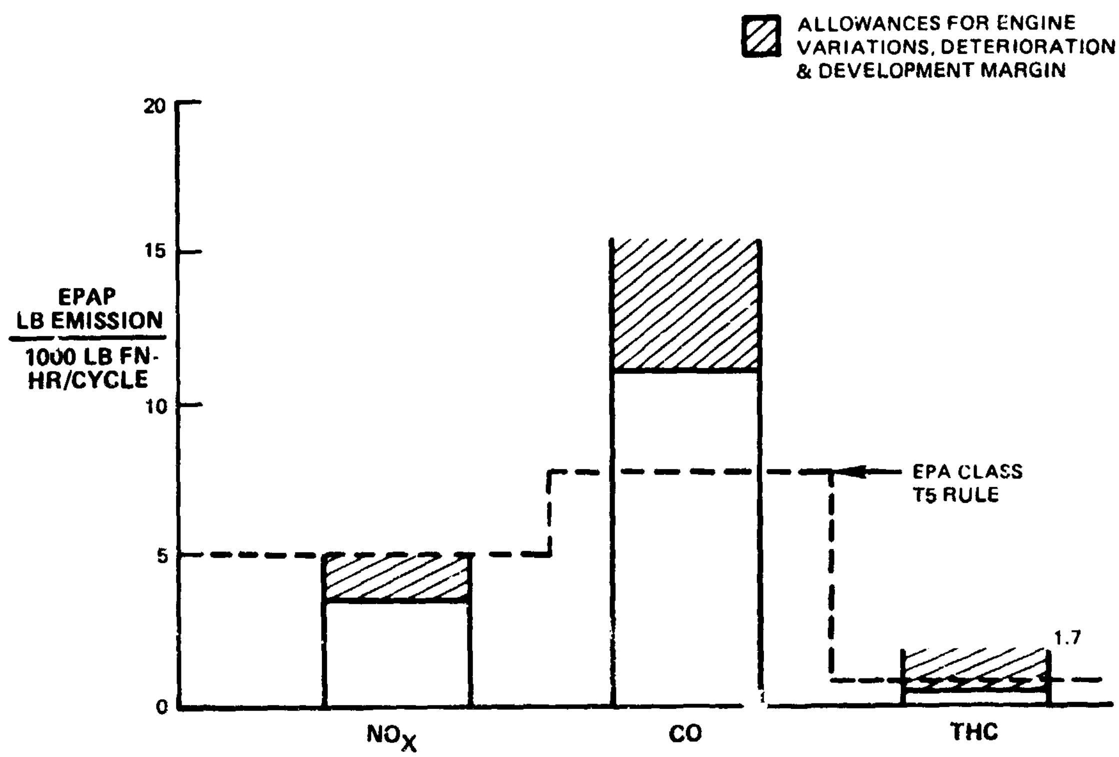


Figure 4.2-9 VSCE-515 Duct Burner Emissions Update (Based on VCE Rig & Testbed Data)

that make up this VCE hot section program are shown in Figure 4.3-1. In addition to being applicable to the VSCE hot section main burner and high pressure turbine, this program would also provide a technology base for other AST engine concepts such as the Low Bypass Engine (LBE) and the Inverted Flow Engine (IFE). In general, this program would benefit most advanced commercial and military engines, including conventional designs as well as unique concepts such as VCE's.

4.3.2 Program Objectives

The objectives of this VCE-HTV Program are to evaluate and substantiate high temperature material capability, advanced cooling effectiveness, and high efficiency for an advanced main burner and a single-stage high pressure turbine (HPT) design for VCE's, using a high spool engine as the experimental testbed. The technical goals for the commercial AST engines that would use these hot section technologies are:

- o Burner Exit Temperature$_{max}$ = 1482 to 1538°C (2700 to 2800°F)
- o Compressor Discharge Temperature$_{max}$ = 649 to 704°C (1200 to 1300°F)
- o HPT cooled efficiency $\geq$ 90 percent
- o HPT cooling and leakage airflow < 8 percent W_{ae}
- o HPT design life = 10,000 hours/5000 cycles (of the 10,000 hours, 5000 hours are at maximum rotational speed, maximum CET and maximum CDT).

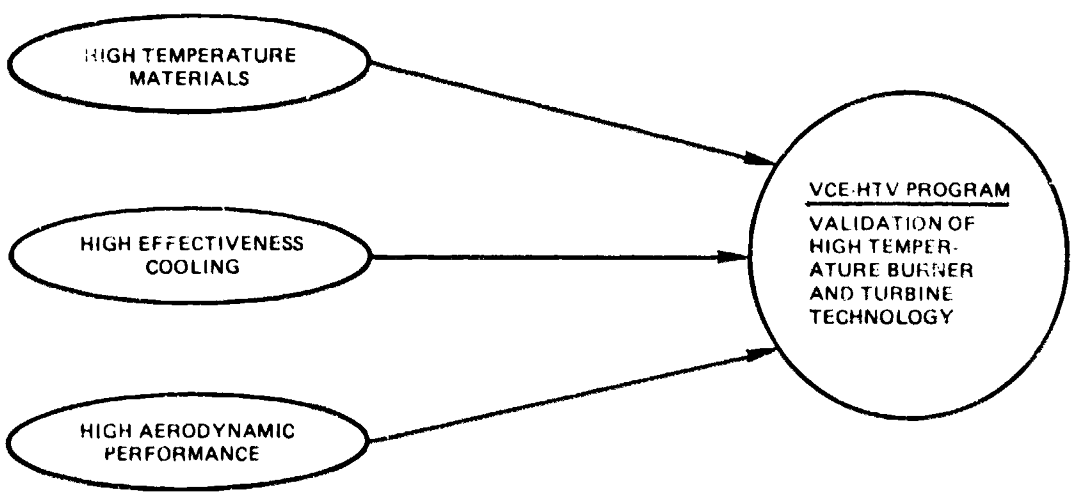


Figure 4.3-1 VCE-HTV is a Technology Applications Program

4.3.3 Program Elements

This VCE-HTV Program consists of four major elements:

1. Screen, evaluate and apply advanced materials and cooling concepts to an advanced main burner and to a single-stage HPT design.

2. Through individual component and rig tests, qualify the selected technologies with respect to the design and operational requirements of these two components.

3. Conduct cascade tests, uncooled (cold) rotating rig tests, and cooled (warm) rotating rig tests to refine the HPT design in order to incorporate the advanced materials and cooling systems.

4. Experimentally evaluate the advanced main burner and HPT using either a complete high spool assembly or a high temperature burner-turbine rig facility. Diagnostic techniques using high temperature instrumentation will be used to measure cooling effectiveness, thermal gradients, metal temperatures, stress levels, pressure losses and efficiency. Detailed post-test inspection of airfoils, seals, disks, and other critical components will be required to determine the existence and extent of creep levels, bowing, cracking, flaking, etc. that may occur during the high temperature, high speed, steady state and cyclic operation.

4.3.4 Description of VCE-HTV

4.3.4.1 Selection of Critical Technology

Figure 4.3-2 lists the candidate technologies for this VCE-HTV program. Additional technologies that will also be considered are listed in Figure 4.3-3. High strength turbine blade and disk alloys are required to accommodate the high turbine temperatures and stress levels. Single crystal alloys and Rapid Solidification Rate Directionally Recyrstallized (RSRDR) alloys offer the best potential for high strength blades and vanes. Since the VSCE turbine is operating at high speeds as well as at high temperatures at supersonic cruise, a high strength, high temperature capability for the rim of the disk is required. Thermal barrier coatings and substrate metallic coatings will be applied to the airfoil surfaces. These coatings must be compatible with both the substrate alloys and with the high effectiveness cooling system incorporated in the airfoil designs.

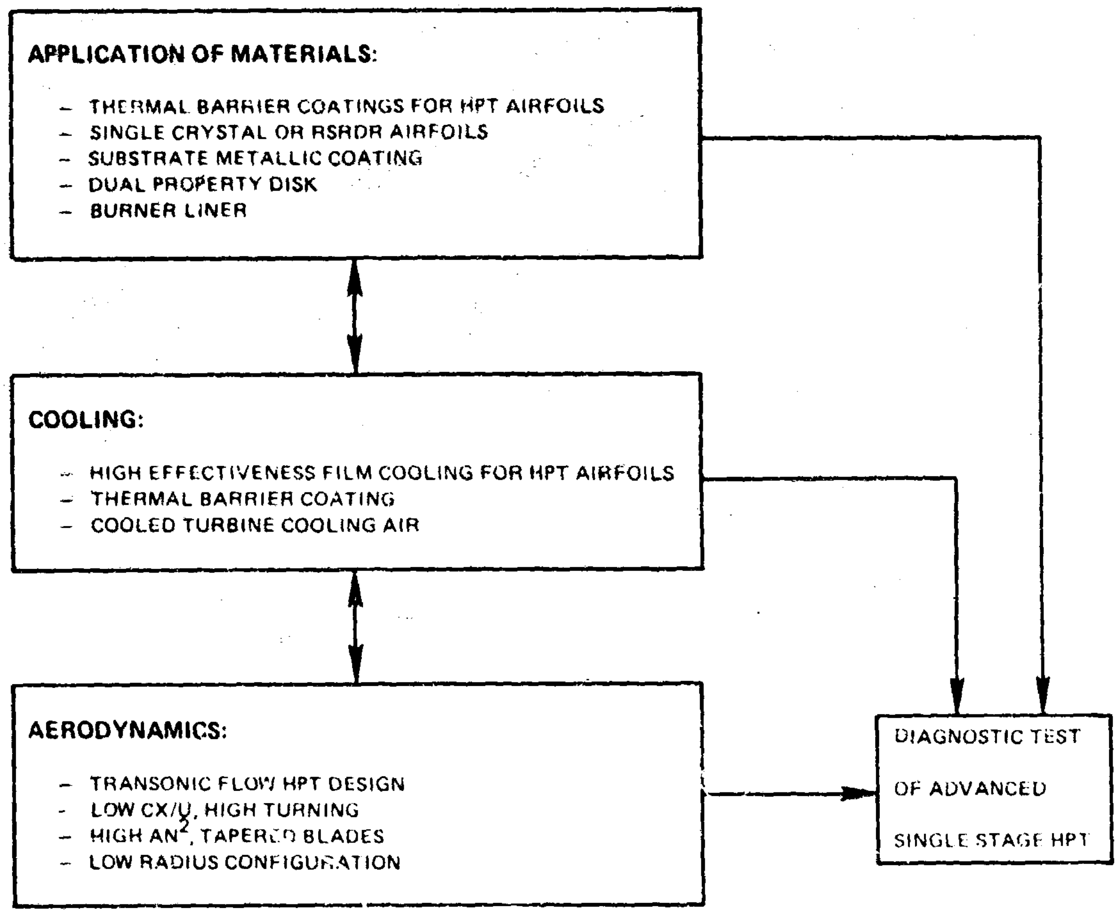


Figure 4.3-2 Candidate VCE-HTV Technologies

MAIN BURNER:

- LONG LIFE LINER MATERIAL (ODS OR CERAMIC)
- ADVANCED LINER COOLING SYSTEM
- LOW EMISSIONS

HPT

- ACTIVE CLEARANCE CONTROL
- ABRADABLE TIP SEALS
- LOW WINDAGE DISK
- IMPROVED SEAL SYSTEMS (REDUCED LEAKAGE)

Figure 4.3-3 Additional High Temperature Technology Considerations for AST-VCE Program

4.3.4.2 Technology Evaluation and Substantiation

The advanced technologies selected for this VCE-HTV Program will be combined and tested for overall compatibility and suitability for the engine or hot rig test. Material tests will be conducted first, including thermal cycling, creep, oxidation resistance, and compatibility testing. Fabrication procedures, especially for applying the thermal barrier coatings to the airfoils with advanced cooling systems, will be evaluated. Figures 4.3-4 through 4.3-7 list some of the candidate hot section materials and qualification testing required for this program.

The heat transfer technologies and aerodynamic design features of the turbine will initially be worked separately and later integrated through more detailed design and testing to evaluate and substantiate the cooled turbine performance. Figures 4.3-8 and 4.3-9 list the program elements for each of these areas. Airfoil cascade tests will be conducted to evaluate the aerodynamic characteristics of the transonic single-stage turbine, first separately and then together with the advanced cooling system. Aerodynamically, the objective is to design highly loaded airfoils with high turning but with low aerodynamic losses. To accomplish this, trade-offs between endwall contours, airfoil contours, solidity, reaction, airfoil taper and turbine flowpath will be made. The heat transfer technology will address the cooling of high velocity regions (transonic flow regions) such as the airfoil suction side walls, while minimizing injection losses. The technology required for precooling the turbine cooling air will also be considered and could be included in this program. Once the basic materials, aerodynamic and cooling technology are confirmed by cascade testing, further testing and design substantiation will be accomplished in an uncooled (cold) rotating turbine rig. Several design refinements of the single stage HPT will be evaluated under highly instrumented testing to meet the high level of performance. The next step is to combine all of the advanced cooling and aerodynamic design features for testing the HPT in a cooled (warm) rotating rig. Cooled performance will be substantiated in this test sequence.

BENEFIT:*

- INCREASE BLADE TEMP. BY 83°C (150°F)
- INCREASE VANE TEMP. BY 98°C TO 111°C (175°F TO 200°F)

RECOMMENDED PROGRAM:

- ALLOY COMPOSITION EVALUATION FOR AST REQUIREMENTS
- MATERIAL VERIFICATION TESTS
- DESIGN VERIFICATION ENGINE TESTS

* RELATIVE TO CURRENT TECHNOLOGY

Figure 4.3-4 Single Crystal or RSRDR Blades & Vanes

BENEFITS:

- EFFECTIVE REDUCTION IN BLADE & VANE TEMP. UP TO 167°C (300°F)

  YIELDS REDUCED TCA, INCREASED η

RECOMMENDED PROGRAM:

- LAB. TESTS – CONDUCTIVITY/THERMAL EXPANSION/DENSITY/ THERMAL SHOCK/SPALLING/ CORROSION RESISTANCE

- RIG TESTS OF SELECTED COATINGS (TOGETHER WITH SINGLE CRYSTAL OR RSRDR ALLOYS, ADV. COOLING SYST. ETC.)

- TEMPERATURE/CYCLIC/LIFE ENGINE TESTS

Figure 4.3-5 Thermal Barrier Coating

BENEFITS:

- REQUIRED TO REALIZE BENEFITS OF SINGLE CRYSTAL OR RSRDR ALLOYS WITH THERMAL BARRIER COATINGS

RECOMMENDED PROGRAM:

- LABORATORY & RIG TESTS TO EVALUATE OXIDATION RESISTANCE, COMPATIBILITY BETWEEN SUBSTRATE AND OVERLAY COATING, ADHERING CHARACTERISTICS, ETC.

- TEMPERATURE/CYCLIC/LIFE ENGINE TESTS

Figure 4.3-6 Metallic Substrate Coating (Under Thermal Barrier Coating Over Single Crystal or RSRDR Alloys)

BENEFITS:

- INCREASE RIM TEMP. BY 28°C (50°F) OVER ASTROLOY
- MAINTAIN TENSILE/LCF LIFE OF IN 100

RECOMMENDED PROGRAM:

- REVIEW/SCREEN ALLOY AND PROCESSING COMBINATIONS FOR TEMP./STRENGTH/ LCF REQUIREMENTS
- EVALUATE ALLOYS AND FABRICATION PROCEDURES FOR MATERIAL TRANSITION (BIMETALLIC JOINT)
- TEST STRENGTH PROPERTIES
- FABRICATE AND TEST DISK
  - SPIN/BURST/LCF RIG TESTS
  - ENGINE TESTS

Figure 4.3-7 Dual Property Disks

ELEMENTS FOR SINGLE STAGE HPT FEATURING:

- TRANSONIC DESIGN
- LOW SOLIDITY
- HIGH TURNING
- LOW CX/U
- HIGH AN^2
- HIGH AIRFOIL TAPER
- CONTOURED ENDWALLS
- LOW RADIUS CONFIGURATION

BENEFITS:

- HIGH SPEED, HIGH EFFICIENCY DESIGN

RECOMMENDED PROGRAMS:

- DESIGN STUDIES
- CASCADE TESTS
- ROTATING WARM FLOW RIG TESTS
- HOT ENGINE TESTS – PERFORMANCE, COOLING, DURABILITY

Figure 4.3-8 High Pressure Turbine Aerodynamic Technology

ELEMENTS:

- HIGH EFFECTIVENESS FILM COOLING
- COMPATIBILITY WITH:
  - ADVANCED AIRFOIL MATERIALS
  - TRANSONIC DESIGN (SUCTION SIDE)
- COOLED COOLING AIR (HEAT EXCHANGER)

BENEFITS:

- MINIMUM TCA
- HIGH EFFICIENCY

RECOMMENDED PROGRAM:

- DESIGN STUDIES
- CASCADE TESTS
- ROTATING WARM FLOW RIG TESTS
- HOT ENGINE TESTS – PERFORMANCE, COOLING, DURABILITY

Figure 4.3-9 High Pressure Turbine Cooling Technology

4.3.4.3 Hot Validation Test

All of the advanced materials and cooling system design features will be applied to the high performance HPT design for diagnostic testing in a hot rotating environment that simulates all critical operating conditions of the VSCE, especially supersonic operation. An altitude chamber may be required for this phase of the program. To obtain these rigorous conditions, a complete high spool is considered most suitable. Hot turbine rigs could also be used, and are considered to be options for this phase of the program. A completely new, advanced technology single-stage HPT will be designed and fabricated, incorporating as much of the advanced technology described in the preceding sections as is feasible. This test will include extensive turbine instrumentation to verify component metal temperatures, cooling effectiveness, and stress levels while the engine is operating at elevated temperatures. Instrumentation will be included to measure and substantiate turbine performance. Post-test burner and turbine measurements will indicate the overall suitability of these technology elements in meeting the durability and performance requirements in the thermal and stress environment of an AST engine. If damage occurs during hot testing, the extent of creep, bow, oxidation, diffusion, cracking, corrosion, erosion, fretting or other distress will indicate what weaknesses exist that will need further evaluation before the overall capability of these component designs can be validated.

4.3.4.4 VCE-HTV Schedule

Figure 4.3-10 shows a nominal 5 year schedule for this VCE-HTV Program.

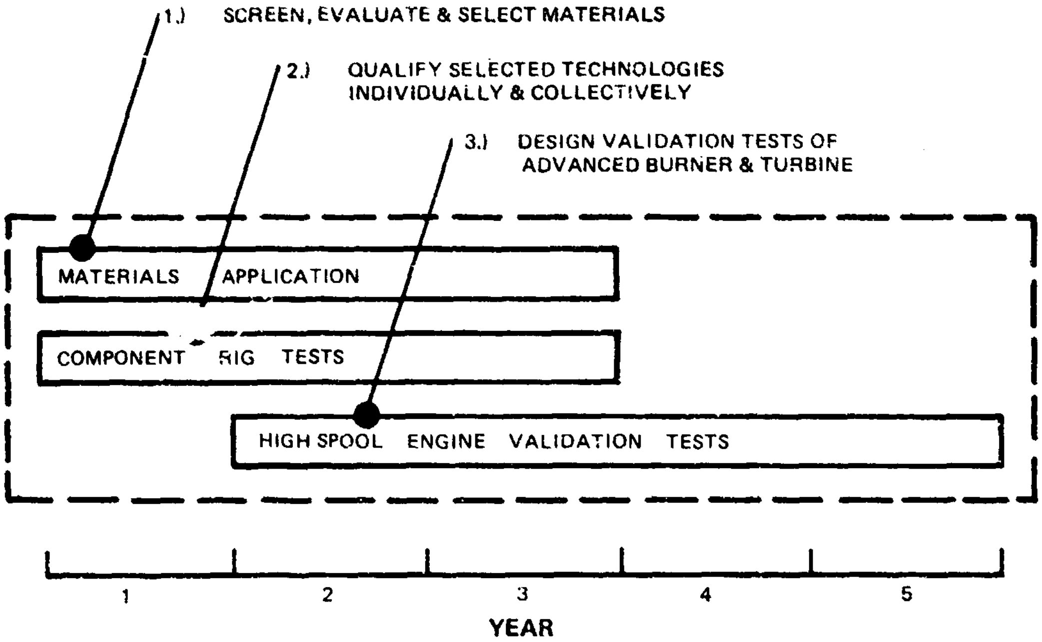


Figure 4.3-10 VCE-HTV Program Schedule

SECTION 5.0

PRELIMINARY ENGINE DESIGN

5.1 Design Considerations

5.1.1 Major Elements

Figure 5.1-1 shows the major elements of the preliminary design process used in this VSCE definition study. Inputs to this process consisted of key initial component aerodynamic and mechanical parameters, updated technology projections, materials updates, and initial engine design tables. The preliminary design process defined performance, engine/nozzle contours, and component and sub-system configurations. Because of the limited scope of this study contract, the aerodynamic, structural, and mechanical analyses summarized in Figure 5.1-1 concentrated on the hot section components, the main burner and the two turbine assemblies.

Complete and updated outputs of the preliminary design analyses were refined engine design tables, spool definitions, engine/nozzle system drawings, performance, weights, noise, and emissions estimates for the VSCE-515.

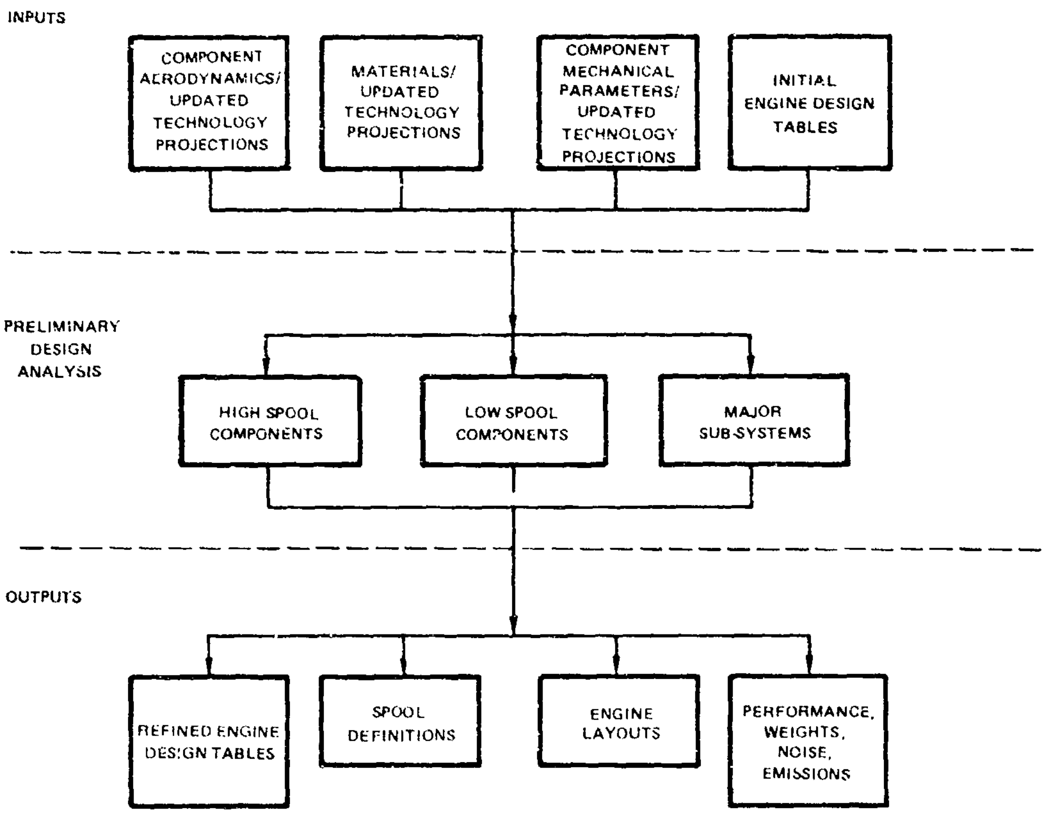
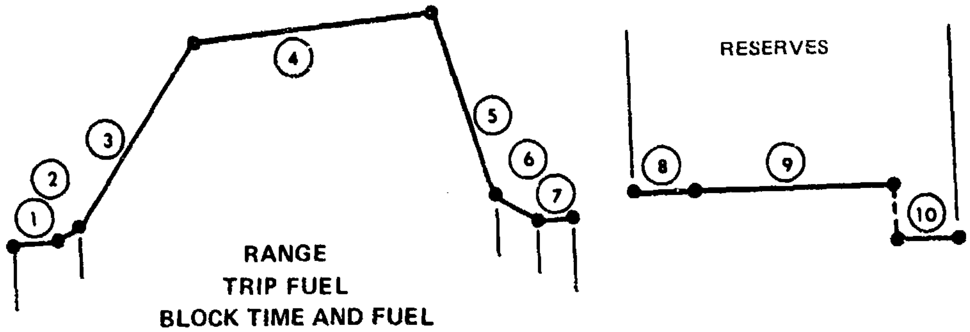


Figure 5.1-1 Primary Elements of the Preliminary Design Process Used in the VSCE Definition Study.

5.1.2 Design Requirements

Mission Life and Durability

Figure 5.1-2 shows a typical flight profile for an advanced supersonic transport, including reserve operating requirements. In establishing VSCE hot section mission life and durability design requirements, an assessment of various AST missions was made and reviewed in terms of operating time spent at the most severe temperatures and maximum rotor speeds.



1	TAXI	10 MIN, H = O, GROUND IDLE FUEL FLOW
2	TAKEOFF	TO H = 11M (35 FT)
3	ACCELERATE AND CLIMB TO BCA*	TO M = CRUISE
4	SUPERSONIC CRUISE	CLIMB CRUISE
5	DESCEND AND DECELERATE	FLIGHT IDLE FUEL FLOW
6	ILS APPROACH	TO TOUCHDOWN
7	ALLOWANCE	6% TRIP FUEL
8	SUBSONIC CRUISE TO ALTERNATE	M = 0.9, HP = 11521M (37,800 FT), R = 482 KM (260 NMI)
9	HOLD	30 MIN. HP = 4572M (15,000 FT), M = OPTIONAL
10	TAXI	5 MIN, H = O, GROUND IDLE FUEL FLOW

*BCA = BEST CRUISE ALTITUDE

Figure 5.1-2 AST Flight Profile and Reserves

Table 5.1-I summarizes the time (in minutes and in percent of total block time) for an all supersonic mission and for two mixed missions. The mission with the 556 Km (300 N.Mi) subsonic leg, with a block cycle time of 190.6 minutes, was selected as being most representative for establishing hot section design criteria. As indicated at the bottom of Table 5.1-I, 56% of the operating time is spent at the most severe temperature and stress condition.

TABLE 5.1-I

TIME BREAKDOWN FOR ADVANCED SUPERSONIC TRANSPORT VSCE MISSIONS

MISSION SEGMENT	ALL SUPERSONIC		556 Km (300 n.mi.) SUBSONIC LEG		1112 Km (600 n.mi.) SUBSONIC LEG	
(CET)	MIN.	%	MIN.	%	MIN.	%
TAXI (IDLE	10.0	5.6%	10.0	5.2%	10.0	4.8%
TAKEOFF 1204 to 1343°C (2200 to 2450°F)	0.7	0.4%	0.7	0.4%	0.7	0.3%
SUBSONIC CLIMB 1371°C (2500°F)	14.5	8.1%	17.4	9.1%	17.2	8.2%
SUBSONIC CRUISE 1094°C (2000°F)	-	-	18.5	9.7%	52.0	24.7%
*SUBSONIC CLIMB 1371 to 1482°C (2500 to 2700°F)	16.1	9.0%	14.7	7.7%	13.9	6.6%
*SUPERSONIC CRUISE 1482°C (2700°F)	104.4	60.2%	99.7	52.3%	87.0	41.3%
DESCENT (IDLE)	22.8	12.8%	22.8	12.0%	22.8	10.8%
APPROACH (LOW)	1.8	1.0%	1.8	0.9%	1.8	0.9%
TAXI (IDLE)	5.0	2.8%	5.0	2.6%	5.0	2.4%
MISSION TOTAL	178.3	100%	190.6	100%	210.5	100%
			REPRESENTATIVE MISSION			

* MAX. CET, MAX. N_2 + MAX. TCA TEMP = 52.3% + (7.7%/2)
= 56% Time at Most Severe Conditions

Corresponding to this representative mission, life limited parts are designed for 10,000 hours of operation, and, during this time, the hot section parts would experience maximum combustor exit temperature, maximum rotor speed and maximum cooling air temperatures, for approximately 5000 hours. This hot section design criteria was used to determine allowable stress/temperature levels for the VSCE-515 main burner, high pressure turbine, and low pressure turbine.

Critical Operating Conditions

Critical mission operating points were selected for consideration in design of the VSCE-515 engine component assemblies and are listed below. Also listed are the most significant operating requirements for each point.

Takeoff, sea level static, max. augmentation - high specific thrust, low noise

Takeoff, cutback power, 335 m (1,100 ft), 0.3Mn - low noise

Subsonic cruise, 1100 m (36,089 ft), 0.9Mn - low thrust, low fuel consumption, inlet flow-matching

Subsonic climb, 11125 m (36,500 ft), 1.3Mn - high thrust

Supersonic cruise, 16154 m (53,000 ft), 2.32Mn - high thrust, low fuel consumption

The following section provides a brief description of the VSCE-515 operating characteristics at these selected conditions.

Take-off - Figures 5.1-3a and 5.1-3b depict 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 close to its maximum design temperature as shown in Figure 5.1-3a. For climb out over the community, both streams are throttled back, and the inverted velocity profile is retained, as shown in Figure 5.1-3b. These take-off conditions set the cooling requirements for the duct-burner and nozzle system. Relative to military augmentor systems, the peak duct-burner temperatures for the VSCE are low.

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.

Subsonic Cruise - For subsonic cruise operation, the primary burner is throttled to a very low temperature, the duct burner is off, and the VSCE operates like a moderate bypass ratio turbofan cycle. Exhaust conditions for this third critical operating point are shown in Figure 5.1-3c. 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 designed strictly for subsonic operation

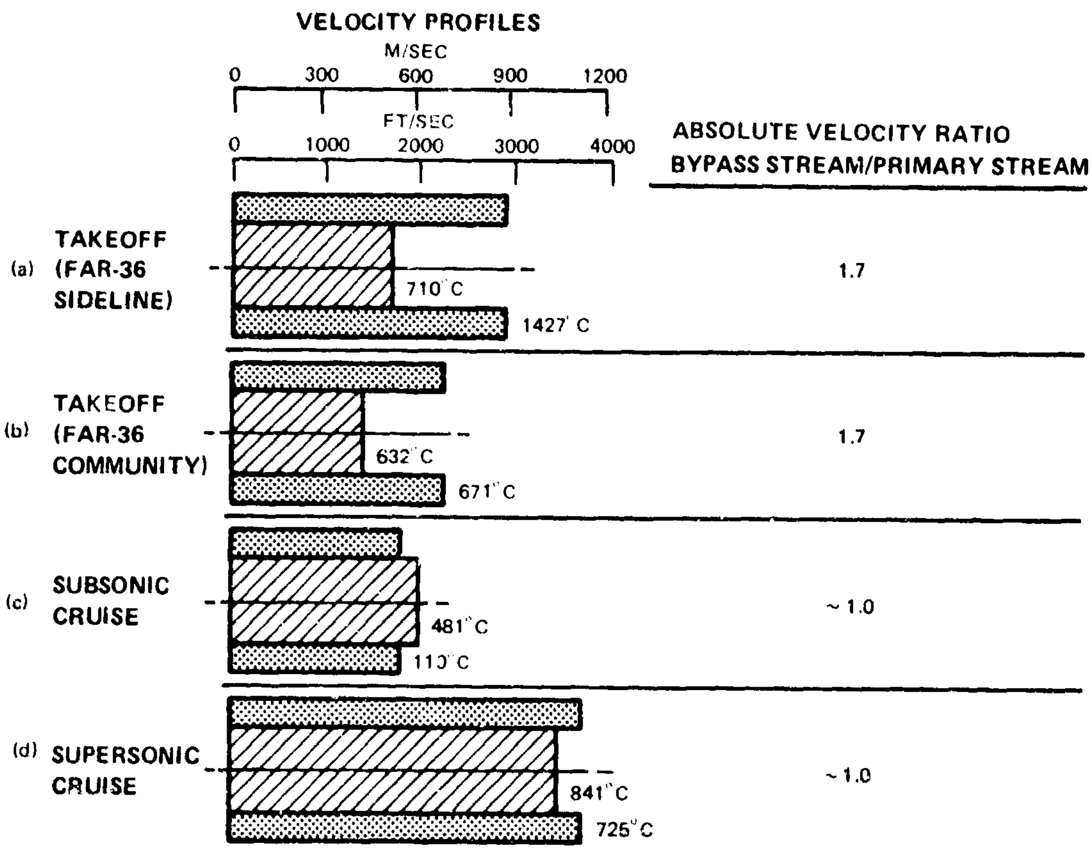


Figure 5.1-3 Variability of Exhaust Conditions for the VSCE-515

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 5.1-3, 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.

Transonic Climb

During transonic climb operation, the primary burner temperature is increased and high spool speed is increased relative to take-off. Duct augmentation is gradually increased from the dry subsonic climb condition to a fuel/air ratio in the vicinity of 0.03 at higher climb mach numbers. Actual fuel/air ratio in the duct burner would be tailored to meet specific aircraft/mission/thrust requirements as determined by the airframe companies.

For these critical conditions, design table information for the VSCE-515 was generated and is contained in Table 5.1-II. These tables specify engine pressures, temperatures, speeds, flows and efficiencies throughout the engine. This information, in conjunction with the specified design criteria, formed the basis for the mechanical/structural design of the VSCE-515 engine. The information contained in Table 5.1-II has been generated consistent with the engine station designations illustrated in Figure 5.1-4.

TABLE 5.1-II

VSCE - 515B

COMPONENT PERFORMANCE SUMMARY

	1	2	3	4	5	6	7
Operating Point	SLS (Design Point for Fan + Comp. + Partial Aug)	Takeoff (Reduced FPR, 1426°C Max Aug)	88% Takeoff (Reduced FPR-Cutback Power)	Subsonic Climb (Min AJE)	Subsonic Cruise	Supersonic Climb (Max CET)	Supersonic Cruise (Design Point for HPT + LPT Max CET)
TAMB °C	STD	+10	+10	+8	+8	+8	+8
ALT M	0	335	335	11000	11000	11125	16154
MN	0	0.3	0.3	0.9	0.9	1.3	2.32
CYCLE							
W2AR Kg/SEC	340.2	340.2	340.2	340.2	340.2	344.0	253.2
BPR	1.30	1.52	1.54	1.21	1.32	1.21	1.39
FPR	3.25	2.8	2.8	3.25	3.25	3.29	2.41
OPR	14.85	13.81	13.52	16.03	14.53	16.40	9.57
T4 °C	1115.7	1211.6	1189.3	1103.8	980.9	1308.4	1482.6
η Thermal	0.4045	0.4075	0.4031	0.5060	0.4863	0.5617	0.6397
η Propulsive	0	0.2448	0.2688	0.5260	0.5535	0.533	0.762
Customer Bleed (Kg/SEC)	0.4536	0.4536	0.4536	0.4536	0.4536	0.4536	0.4536
Power Extraction (WATTS)	149140	149140	149140	149140	149140	149140	149140
INLET							
% W2AR DES	100	100	100	100	100	101.1	74.4
η RAM	0.932	0.970	0.970	0.970	0.970	0.9535	0.931
W2A (Kg/SEC)	340.2	340.2	340.2	340.2	340.2	344.0	353.2
Mo	0	0.3	0.3	0.9	0.9	1.3	2.32
V airplane (M/SEC)	0	103.5	103.5	270.5	270.5	390.8	697.4
FAN AVERAGE							
W2AR	340.2	340.2	340.2	340.2	340.2	344.0	253.2
P23Q2A*	3.25	2.8	2.8	3.25	3.25	3.29	2.41
η AV*	85.7	78.9	78.9	85.7	85.7	85.4	86.3
UTIP/ $\sqrt{\phi}$ (M/SEC)	487.7	481.0	481.0	487.7	487.7	491.9	416.1
NLR2A (RPM)	6107	6022	6022	6107	6107	6159	5209
NL (RPM)	6107	6158	6158	5814	5814	6292	6622
No. Stages	3	3	3	3	3	3	3
FAN ENG. STREAM							
W2R (Kg/SEC)	147.9	135.2	133.7	153.5	146.6	155.6	106.1
* P23Q2	3.25	2.8	2.8	3.25	3.25	3.29	2.41
* η ID	0.857	0.789	0.789	0.857	0.857	0.854	0.863

* Includes FEGV

HIGH COMPRESSOR							
W23R23* (Kg/SEC)	55.1	57.8	57.1	57.2	54.6	57.4	50.5
P3Q23*	4.57	4.93	4.83	4.94	4.47	4.99	3.96
η HPC	0.889	0.886	0.887	0.886	0.890	0.886	0.896
NHR23 (RPM)	8073	8644	8424	8488	8025	8554	7749
NH (RPM)	9772	10574	10306	9786	9252	10599	11318
UTIP/ $\sqrt{\phi}$ 23 (M/SEC)	362.7	388.3	378.6	381.3	360.6	384.4	348.1
No Stages	5	5	5	5	5	5	5

* Includes 1.0% Intermediate Case & IGV Δ P/P

TABLE 5.1-II (Cont'd)

	1	2	3	4	5	6	7
Operating Point	SLS (Design Point for Fan + Comp. + Partial Aug)	Takeoff (Reduced FPR, 1426°C Max Aug)	88% Takeoff (Reduced FPR-Cutback Power)	Subsonic Climb (Min AJE)	Subsonic Cruise	Supersonic Climb (Max CET)	Supersonic Cruise (Design Point for HPT + LPT Max CET)

MAIN BURNER	1	2	3	4	5	6	7
T3 (°C)	397.1	426.8	422.2	352.2	333.4	446.7	642.2
T4 (°C)	1115.7	1211.6	1189.3	1103.8	980.9	1308.4	1482.6
Δ T (°C)	718.6	784.8	767.1	751.6	647.6	861.8	840.4
W3R3 (Kg/SEC)	123.6	117.5	116.2	52.7	50.3	78.8	88.9
W4R4 (Kg/SEC)	123.6	117.5	116.2	52.7	50.3	78.8	88.9
Δ P/P* 4/3	0.052	0.050	0.051	0.049	0.053	0.048	0.054
η B	100	100	100	100	100	100	100

* Includes Diffuser

HIGH TURBINE	1	2	3	4	5	6	7
P45Q4	2.29	2.31	2.31	2.26	2.30	2.26	2.27
η HPT	0.9171	0.9217	0.9199	0.9180	0.9168	0.9191	0.9203
T4 ~ °C	1115.7	1211.6	1189.3	1103.8	980.9	1308.4	1482.1
T45 ~ °C	855.3	932.6	914.3	846.2	740.5	1020.3	1170
No. Stages	1	1	1	1	1	1	1
NH (RPM)	9772	10574	10306	9786	9252	10599	11318
% NH DES	86.3	93.4	91.1	86.5	81.7	93.6	100
TCATOT (%) (Includes LPT)	10.2	10.2	10.2	10.2	10.2	10.2	10.2

LOW TURBINE	1	2	3	4	5	6	7
P49Q45	3.42	3.38	3.52	2.92	3.57	2.91	3.06
η LPT	0.9222	0.9198	0.9196	0.9192	0.9218	0.9197	0.9195
T45 °C	855.3	932.6	914.3	846.2	740.5	1020.3	1170
T49 °C	574.3	638.6	616.3	596.7	476	740.3	854.1
No. Stages	2	2	2	2	2	2	2
NL (RPM)	6107	6158	1658	5814	5814	6292	6622
% NL DES	92.2	93.0	93.0	87.8	87.8	95.0	100

LPT EXIT CASE + TIP	1	2	3	4	5	6	7
M49 - Axial	0.579	0.581	0.691	0.441	0.676	0.441	0.483
Exit Swirl (°) (0° is Axial)	28.73	29.83	34.52	19.68	33.23	19.25	23.77
M5 - Axial	0.600	0.598	0.659	0.473	0.658	0.473	0.514
Δ P/P EGV	0.018	0.020	0.038	0.0098	0.033	0.0098	0.011
Δ P/P* T/P	0.014	0.014	0.017	0.0087	0.017	0.0087	0.010
Cooling Air (% WAE)	0.04	0.04	0.04	0.04	0.04	0.04	0.04

* Includes Probe Loss

DUCT BURNER	1	2	3	4	5	6	7
F/A 17	0.024	0.040	0.027	0	0	0.030	0.010
T13 (°C)	148.74	157.79	157.79	157.80	157.80	168.99	341.10
T17 (°C)	967.37	1425.24	1075.59	113.28	112.99	1159.39	700.58
W13 (Kg/SEC)	179.2	198.9	200.4	71.850	74.572	106.7	137.8
W17 (Kg/SEC)	183.5	206.9	205.9	71.850	74.572	109.9	139.1
Δ P/P							
Struts + Diffuser	0.015	0.026	0.026	0.014	0.015	0.014	0.014
Cold	--	--	--	0.045	0.051	--	--
Hot	0.081	0.201	0.162	--	--	0.078	0.057
M13	0.115	0.159	0.154	0.106	0.111	0.112	0.110
M17	0.209	0.368	0.303	0	0	0.215	0.141
η Thrust Effective	0.9442	0.9350	0.9401	0.920	0.920	0.938	0.960

TABLE 5.1-II (Cont'd)

	1	2	3	4	5	6	7
Operating Point	SLS (Design Point for Fan + Comp. + Partial Aug)	Takeoff (Reduced FPR, 1426°C Max Aug)	88% Takeoff (Reduced FPR-Cutback Power)	Subsonic Climb (Min AJE)	Subsonic Cruise	Supersonic Climb (Max CET)	Supersonic Cruise (Design Point for HPT + LPT Max CET)
NOZZLE							
CD8	1.01	1.00	1.03	0.99	0.99	0.99	0.99
CD18	0.98	0.98	0.98	0.98	0.98	0.98	0.98
CV9	0.984	0.983	0.985	0.982	0.983	0.979	0.982
CV19	0.984	0.983	0.985	0.982	0.983	0.979	0.982
V9 M/SEC	463.2	495.8	451.2	733.4	594.7	903.4	1112.9
V19 M/SEC	787.2	842.9	767.3	525.8	525.2	1137.7	1092.3
V19/V9	1.7	1.7	1.7	0.717	0.883	1.259	0.981
A8 (M^2)	0.631	0.626	0.685	0.526	0.658	0.526	0.559
REL A8 % DES	1.0	1.0	1.05	0.85	1.06	0.85	0.90
A18 (M^2)	0.589	0.983	0.831	0.309	0.323	0.605	0.404
REL A18 % DES	1.85	3.10	2.62	0.974	1.02	1.91	1.27
A18/A8	0.933	1.570	1.224	0.588	0.491	1.151	0.722
AEXIT 9 + 19 (M^2)	1.266	1.636	1.541	1.124	1.225	2.266	3.019
PT8 (KN/M^2)	164.4	163.3	150.2	84.2	59.22	136.9	153.7
PT18 (KN/M^2)	278.1	221.6	231.2	113.1	112.3	174.9	270.4
P8QAMB	1.623	1.678	1.542	3.722	2.616	6.174	15.31
P18QAMB	2.745	2.277	2.374	5.00	4.963	7.881	26.93
T8 (°C)	573.76	637.97	1109.96	596.24	475.52	739.54	853.20
T18 (°C)	968	1426	1075.59	113.28	112.99	11161	701.2
WF8 Kg/SEC	2.554	2.699	2.599	1.134	0.912	2.023	2.332
WF18 Kg/SEC	4.259	8.042	5.475	0	0	3.202	1.370
WG8 Kg/SEC	139.9	135.4	131.9	59.83	56.88	89.72	101.2
WG18 Kg/SEC	183.5	206.9	205.8	71.85	74.57	109.9	139.1
DMAX (CM)	203.96	203.96	203.96	203.96	203.96	203.96	203.96
Boattail Drag (N)	0	266.4	254.8	3608.2	3165.2	3191.9	121.4
Ejector Position	OPEN	OPEN	OPEN	OPEN	OPEN	CLOSED	CLOSED
ENGINE PERF.							
FGCV9 (N)	65,879	67,276	60,390	44,653	34,396	82,795	114,731
FGCV19 (N)	146,775	177,319	160,342	38,466	39,827	127,773	154,803
FGCV (N)	212,654	244,595	220,732	83,120	74,224	210,568	269,535
FRAMTOT (N)	0	34,152	34,152	35,437	35,437	76,136	165,341
FNCV9 (N)	64,821	52,588	46,063	27,867	18,557	45,601	43,364
FNCV19 (N)	144,418	153,812	137,208	18,344	18,993	83,364	55,889
FNCV (N)	209,238	206,401	183,271	46,210	37,550	129,966	103,701
SFC CV Kg/HR-N	0.117	0.187	0.159	0.088	0.0873	0.1449	0.1342
Boattail Drag N	0	266.435	254.870	3608.2	3165.2	3191.9	121.430
FN INST N	209,238	206,134	183,017	42,603	34,383	126,772	99,133
TSFC INST Kg/HR-N	0.117	0.187	0.1584	0.0957	0.0953	0.1485	0.1344
LOCAL TEMPERATURE SUMMARY (°C)							
TAM	14.819	22.644	22.644	-48.618	-48.618	-48.618	-48.618
T2A	14.819	27.972	27.972	12.155	12.155	27.473	192.141
T23	148.74	157.787	157.787	109.613	109.613	168.99	341.10
T3	296.71	525.35	421.63	351.81	330.06	446.22	641.52
T4	1114.55	1210.40	1188.75	1102.67	979.96	1307.14	1481.07
T45	854.48	931.68	913.86	845.38	739.76	1019.31	1168.77
T5	573.76	637.97	616.05	596.24	475.52	739.54	853.20
T13	148.74	157.787	157.787	109.613	109.613	168.99	341.10
T17	968.	1426	1075.6	113.28	112.99	1161	701.2

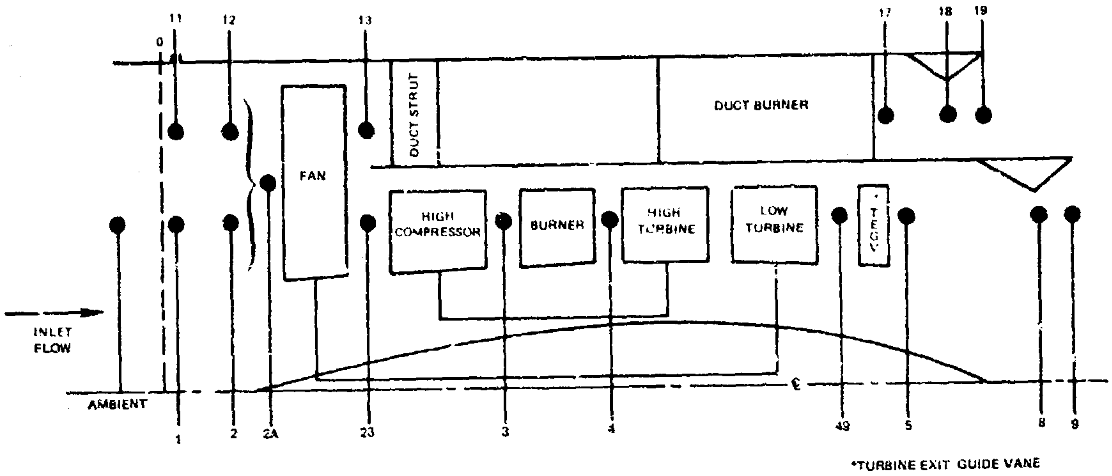


Figure 5.1-4 VSCE Station Designations

5.2 Preliminary Design Results

5.2.1 High Spool Components

5.2.1.1 High Pressure Compressor

Design Characteristics

The high pressure compressor is designed for maximum efficiency at supersonic cruise and to maintain adequate surge margin throughout the flight spectrum. The advanced supersonic transport mission results in the VSCE-515 operating at maximum speed and temperature for approximately 56% of the typical mission time. This causes the design criteria of the high compressor assembly to be primarily creep and/or burst margin related with a reduced effect from low cycle fatigue. The cycle selected for the VSCE-515 (see section 4.1.2.1) results in a maximum compressor discharge temperature of 649°C (1200°F) at this long time supersonic cruise condition. Disks, airfoils, and materials of the high pressure compressor were selected to provide durability consistent with commercial application and the aforementioned speeds and temperatures.

Technology Projections and Design Features

Abradable trench tip rubstrips and a low-volume inner cavity seal design are used to control endwall losses.

A constant outside diameter flowpath to maintain acceptable loadings and surge margin and provide desirable speed matching with the high pressure turbine was employed.

Construction is similar to the E^3 drum rotor type of design. The first stage blades have axially broached attachments to meet vibration design criteria while the remaining stages have dovetail attachments.

Advanced titanium alloy is utilized in the forward cool sections for high pressure compressor disks while the rear stage disks are fabricated from a nickel base superalloy-variable property material with capability of providing high strength at 629°C (1200°F).

High temperature titanium alloy is used for the blade and vane airfoils in the cooler front section while an advanced Nickel alloy is utilized in the hotter rear stages. This advanced nickel alloy is projected to have a 55°C (100°F) temperature advantage over current technology materials.

Airfoil coatings are used to preserve the smooth surface finish to maintain the high efficiency level.

Variable geometry is employed in the first two vane rows to provide flexibility in achieving desirable off-design performance characteristics.

Parametric Studies

A parametric study varying high compressor rotor speed and number of stages to optimize efficiency while maintaining adequate surge margin and airfoil loading characteristics was conducted early in the design phase of the VSCE-515. The initial studies, summarized in Figure 5.2-1, were conducted with a basic five stage machine with the following parameters.

inlet hub/tip ratio	0.7
exit hub/tip ratio	0.91
specific airflow	186 kg/sec m^2 (38 lb/sec ft^2)
average aspect ratio	1.3
axial exit mach number	0.48
exit swirl angle	65°
average gap chord	1.0

The exit mach number and swirl were based on an advanced high mach number design. Number of stages were then varied for this configuration while holding inlet and exit conditions. As Figure 5.2-1 illustrates, a 4 stage design, operating at 100% corrected design speed is near optimum for compressor efficiency, blade loading and surge margin. At this speed design, the high compressor was compatible with the optimized high pressure turbine design discussed in section 5.3.1.3. As indicated in Figure 5.2-1, a constant mean diameter compressor was also investigated for the 4 stage design and although slightly more efficient the increased rotor speed necessary to maintain desirable loading and surge margin characteristics made the design unattractive. This initial configuration resulted in high exit swirl and mach number. A

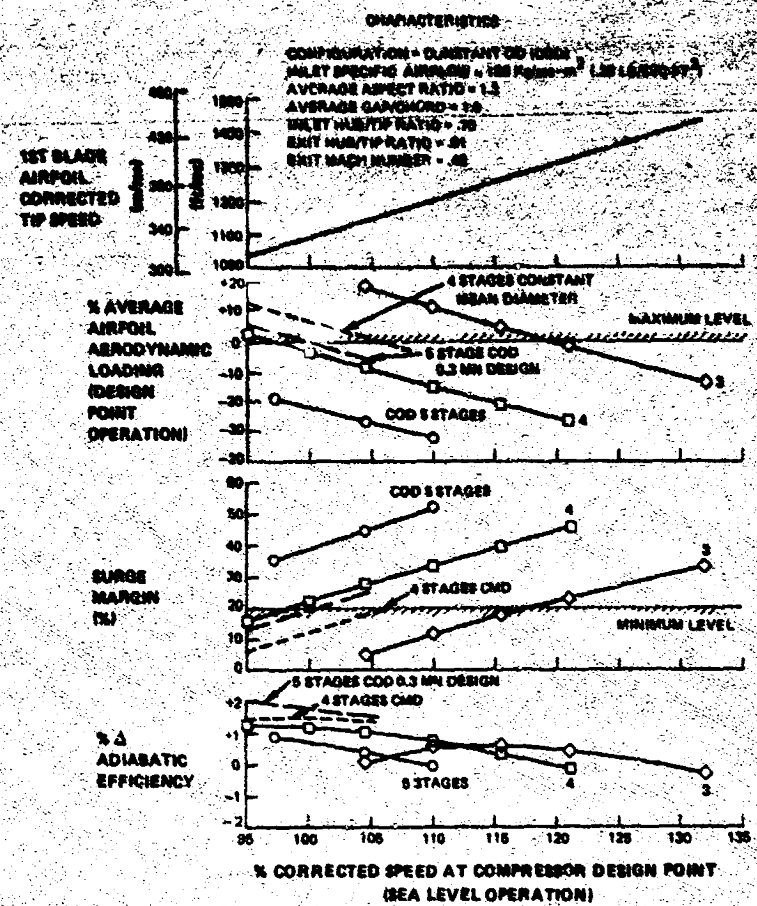


Figure 5.2-1 VSCE Constant Outer Diameter (COD) Compressor Designs

modification to the design consisting of a double row exit guide vane to remove the swirl and lower the exit mach number was evolved. The extra row of exit guide vanes resulted in an additional pressure loss of approximately 1% and nearly 2.54 cm (one inch) increase in length. The exit mach number remained above 0.4 resulting in increased diffuser length and loss than might be obtained with a more conventional exit mach number. This high exit mach number design compressor was included in the VSCE-515A definition shown in Figure 4.1-9.

An alternate high compressor design was composed which added a stage and altered the velocity and air angle distributions to lower the exit mach number to 0.3 with no swirl. As Figure 5.2-1 illustrates, this five stage design provides higher efficiency due to reduced Mach number losses and the elimination of the second exit guide loss. When a slight reduction in average gap/chord was made to keep aerodynamic loading within acceptable limits, this design mated equally well to the optimum high pressure rotor speed. This five stage design provided improved efficiency and lower losses in the diffuser region and was incorporated in the VSCE-515 definition.

High Pressure Compressor Configuration

As discussed above, two compressor configurations were evolved for this updated VSCE definition. The first a 5 stage conventional low exit mach number design was incorporated in the VSCE-515 and the second a four stage high mach number design was incorporated in the VSCE-515A. The following data defines each compressor configuration at the aerodynamic design point.

Configuration	VSCE-515A Constant Outer Diameter	VSCE-515 Constant Outer Diameter
Number of Stages	4	5
Total corrected airflow	54.8 kg/sec (120.9 lb/sec)	54.8 kg/sec (120.9 lb/sec)
Pressure ratio	4.57	4.57
Inlet hub/tip ratio	0.7	0.7
Exit hub/tip ratio	0.91	0.87
Corrected tip speed	363 m/sec (1190 ft/sec)	363 m/sec (1190 ft/sec)
Exit Mach number	0.48	0.3
Adiabatic efficiency (%)	88.2	88.9
Surge margin (%)	>20	>20
Average aspect ratio	1.3	1.3

The flowpath for each configuration is shown in Figure 5.2-2.

5.2.1.2 Main Burner

Design Considerations

- o Chemical efficiency $\geq$ 99.9% at all critical operating points
- o Pattern factor $\left(\dfrac{\Delta T\ max - \Delta T\ avg}{\Delta T\ average}\right) \leq 0.3$
- o Design life = 10,000 hours total/3400 cycles
  = 5,000 hours at supersonic cruise conditions
- o Emissions - EPAP's for advanced supersonic engines (EPA Class T5 engines) are:

Pollutant	EPAP $\left(\dfrac{\text{LBm}}{\text{1000 Lbf - cycle - hr.}}\right)$
NO_x	5.0
CO	7.8
THC	1.0

- o Accessibility for inspecting fuel nozzles, turbine inlet guide vanes and other critical elements of the hot section.

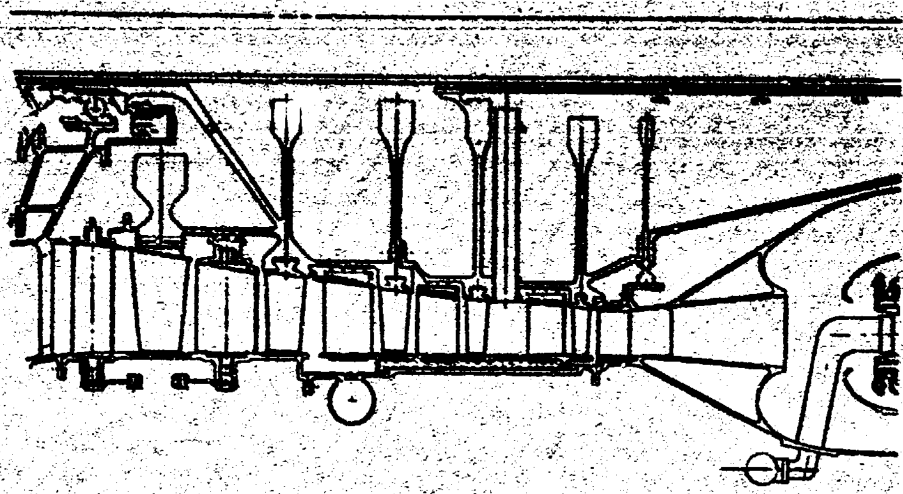


Figure 5.2-2(a) Five Stage Low Exit Mach Number Compressor Design

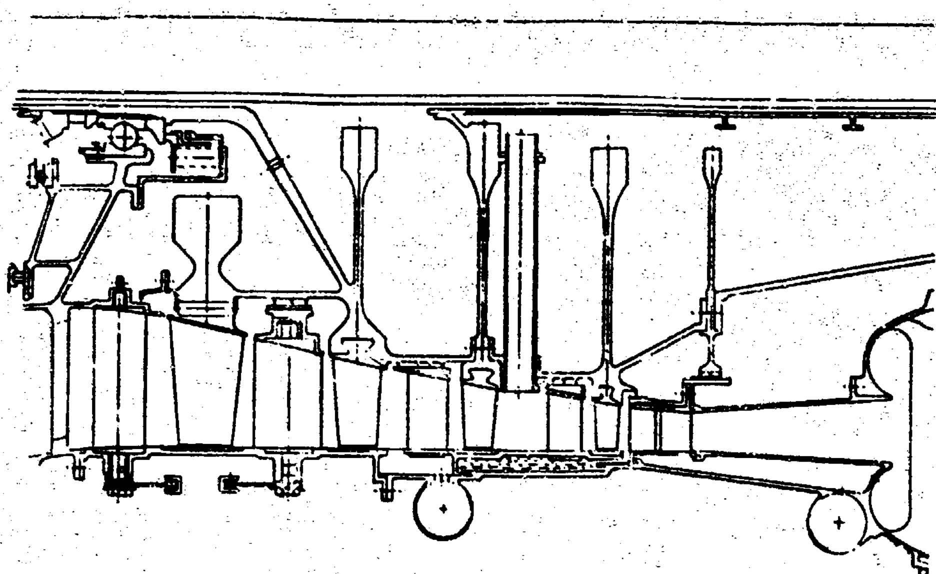


Figure 5.2-2(b) Four Stage High Exit Mach Number Compressor Design

Burner Liner Concepts

Because of the severe thermal environment at supersonic cruise, the liner, which is directly exposed to the high combustion temperature, is the most critical element of the burner concepts and configurations described in this section. Four liner configurations (one current technology and three advanced) and three materials (one current and two advanced) were considered. The construction for each advanced configuration consists of a segmented concept in which a lower temperature frame positions and supports the higher temperature liner segments. This concept reduces the severity of thermal strain in the burner liner and improves its low cycle fatigue life. Table 5.2-I summarizes the features and problems associated with each combination of liner segment configuration and material. The combinatins of materials and cooling configurations within the heavy broken line indicates which of these has the potential to meet the AST-VSCE life requirements. Of the twelve combinations, the four with ceramic materials are considered to be beyond the late 1980's technology readiness period, especially in the advanced configurations. Of the three potential candidates, the combination of Oxide Dispersion Strengthened (ODS) Nickel Alloy for the liner material, combined with the Impingement/Transpiration cooling configuration was selected as the prime design for the VSCE-515 liner segments. A Hastelloy X frame, which is exposed to lower temperatures, supports the high temperature segments. A thermal barrier coating applied to the outer (hot) surface of these liner segments may offer improved life capability and/or reduced cooling air requirements. Lowering the liner cooling will provide flexibility for optimizing the overall burner design for emissions, performance and temperature profiles entering the turbine. Figure 5.2-3 shows this frame and segment configuration. This selected combination, or any of the other advanced cooling configurations and materials are compatible with the diffuser-burner configurations described in the following sections.

Diffuser-Burner Configurations

Three main burner configurations were defined for the VSCE-515; one based on a conventional, single-stage configuration with aerating nozzles (VSCE-515B), and the other two derived from the two-stage VORBIX concept evaluated in the NASA-P&WA Experimental Clean Combustor Program (ECCP), and in particular from the Phase III JT9D test program. All three are annular designs. The two VORBIX types were designed to match the two compressor configurations described in section 5.3.1.1 that have different levels of exit Mach number. One has a conventional Mach number leaving the compressor and entering the diffuser of the main burner (VSCE-515) and the other has a higher exit Mach number leaving the compressor and entering the diffuser of the main burner (VSCE-515A). The more conventional burner was defined to serve as a baseline for comparing the VORBIX configurations.

TABLE 5.2-I

MATRIX OF MATERIALS AND CONFIGURATIONS
EVALUATED FOR MAIN BURNER LINER SEGMENTS

LINER SEGMENT Configuration	Material Hastelloy X	- - - Acceptable Oxide Dispersion Strengthened Ni Alloy	Ceramic
Louver (current technology)	1) Requires excessive cooling	1) Marginal cooling flow 2) Unacceptable life (creep relaxation is the limiting factor)	1) Acceptable cooling 2) Life unknown
Advanced Impingement Transpiration Segments	1) Marginal cooling flow 2) Adequate LCF life 3) Requires oxidation resistant coating	1) Acceptable Cooling 2) Acceptable LCF life	1) Acceptable cooling 2) Life unknown
Advanced Counter-Parallel Finwall Segments	1) Acceptable cooling flow 2) Adequa^e LCF life 3) Requires oxidation resistant coating	1) Unacceptable LCF life acceptable cooling flow 2) Questionable ability to fabricate	1) Acceptable cooling flow 2) Life unknown
Advanced Counter-Flow Film Cooled Segments	1) Acceptable cool.ng flow 2) Unacceptable LCF life 3) Requires oxidation resistant cooling	1) Unacceptable LCF life at acceptable cooling flow 2) Questionable ability to fabricate	1) Acceptable cooling flow 2) Life unknown

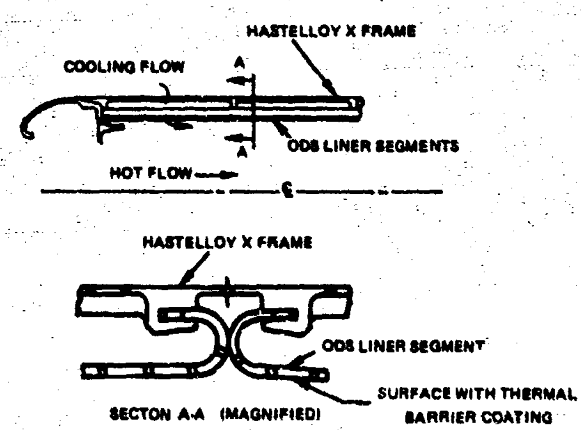


Figure 5.2-3 Frame and Segment Construction for Advanced Impingement/Transpiration Cooled Burner Liner

Figure 5.2-4 and 5.2-5 show flowpaths of the two ECCP VORBIX configurations. Based on these flowpaths, the more detailed burner designs were developed as shown in the VSCE cross-sections (Figures 4.1-9 and 4.1-10). Table 5.2-II summarizes the geometry and pressure loss characteristics of both configurations. The lengths of both diffuser-burner assemblies are almost identical at 88.9 cm (35 inches). However, the pressure loss is about 2.6 points higher for the high Mach number design due to the higher losses in the compressor exit guide vane, the pre-diffuser itself, and in the diffuser dump. Both VORBIX configurations have the same residence time in the combustion chamber. Table 5.2-III compares the operational and design characteristics of these VSCE VORBIX burners with the JT9D ECCP burner from which they were derived.

Figure 5.2-6 illustrates the diffuser-burner flowpath for the more conventional single-stage configuration. This design was incorporated into the VSCE-515B cross-section shown in Figure 4.1-8. It is 10.2 cm (4 inches) shorter than the VORBIX designs. This length reduction, combined with the less complex, single-stage fuel manifolding and liner contour provide a lighter weight design.

TABLE 5.2-II

VSCE-515 Two-Stage Vorbix Burner
Geometry and Pressure Loss Characteristics

	Low Mn Comp.	High Mn Comp.
Diffuser Length/Inlet Height	3	5.5
Diffuser Area Ratio	1.5	1.8
Total Diffuser-Burner Length	88.9 cm (35.0 in)	88.65 cm (34.9 in)
Pressure Losses (% $\Delta P/P$)		
- Compressor Exit Guide Vane	Base	+1.0
- Diffuser Loss	.3	.7
- Dump Loss	1.6	2.8
- Shroud Loss	.3	.3
- Burner Liner Loss	3.0	3.0
Total Pressure Loss	5.2	7.8

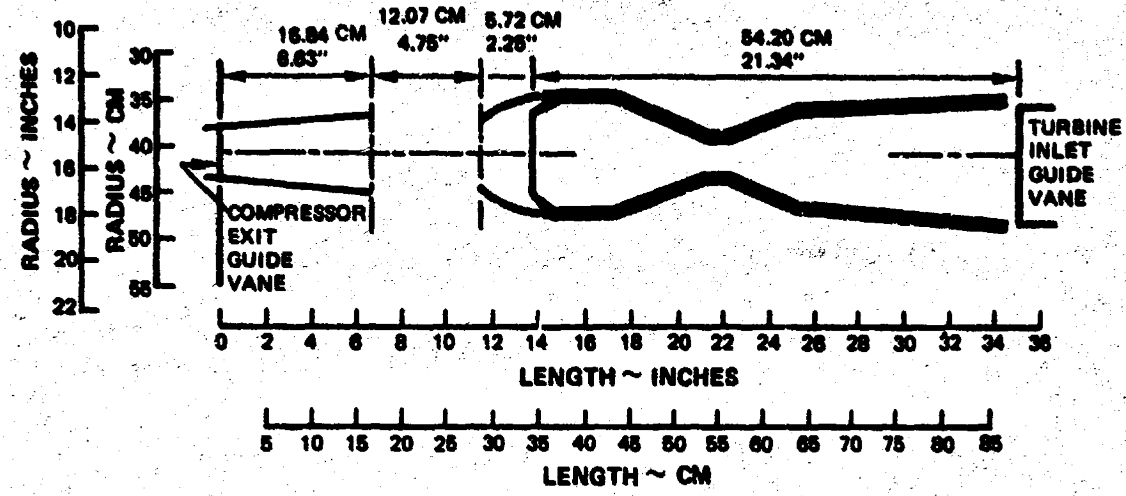


Figure 5.2-4 Two Stage Vorbix Burner Flowpath for Conventional Exit Mach Number Compressor or (VSCE-515)

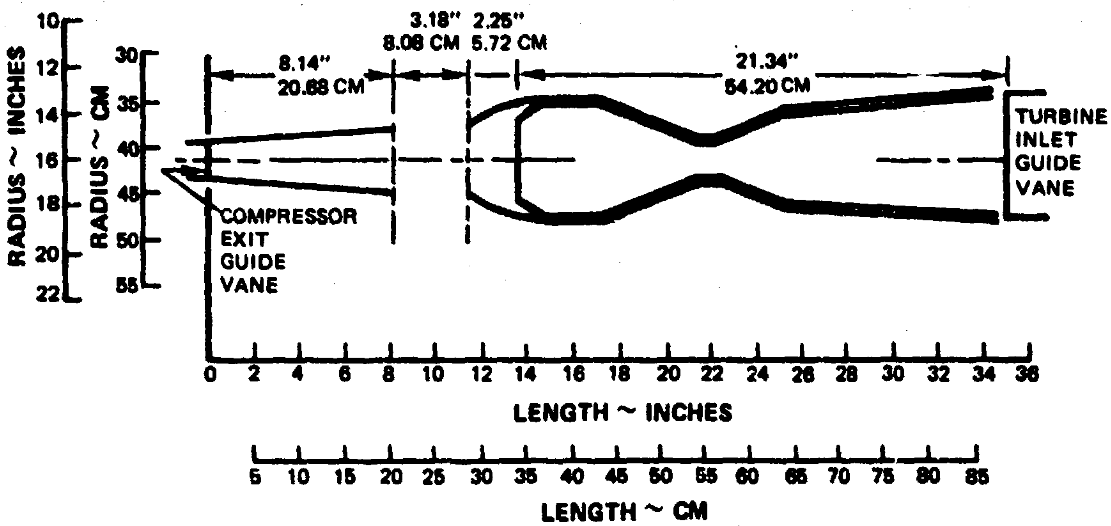


Figure 5.2-5 Two Stage Vorbix Burner Flowpath for High Exit Mach Number Compressor VSCE-515A

TABLE 5.2-III

ECCP AND VSCE-515 VORBIX MAIN BURNER
OPERATIONAL AND DESIGN CHARACTERISTICS
(SLTO Std Day)

	JT9D-ECCP Phase III Vorbix Burner	VSCE-515
Relative Airflow (%)	--	+33.0
HPC Discharge Total Pressure	2212.9 KN/m^2 (321 psia)	1416.7 KN/m^2 (205.4 psia)
HPC Discharge Total Temperature	764°K (1375°R)	683°K (1230°R)
Fuel/air ratio	.0222	.0224
Volumetric heat release Rate		6.0 x 10^6/BTU/ Hr-atm-ft^3
Residence Time (sec.)	.0072	.0080
Volume	.065m^3 (2.3 ft^3)	0.136m^3 (4.80 ft^3)
Combustion Chamber Length (in.)	38.86 cm (15.3)	54.20 cm (21.34)
Mean Radius (in.)	39.70 cm (15.63)	40.65 cm (16.00)
Overall Diffuser/Burner Length (in.)	60.33 cm (23.75)	88.98 cm (35.0)

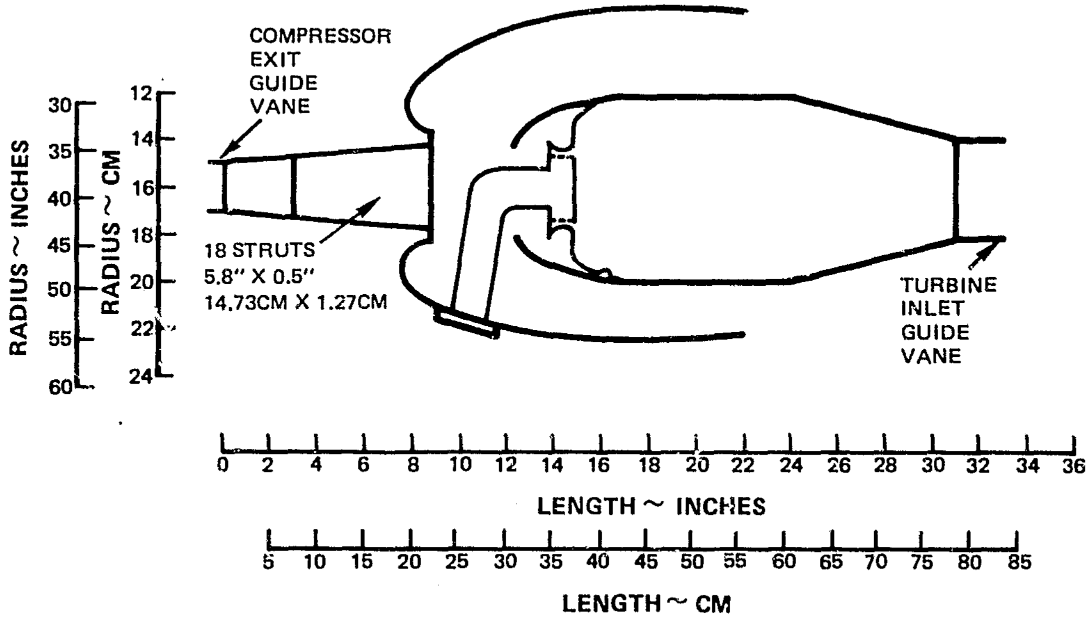


Figure 5.2-6 Single Stage VSCE-515B Flowpath Main Burner

The various liner cooling configurations and materials summarized in Table 5.2-I coupled with overall burner configurations described in this section illustrate the broad choice of advanced technology elements that can be incorporated in the VSCE main burner. Extensive analysis and experimental evaluation are required to select the best combination of performance, durability and emissions levels for the VSCE-515. The recommended VCE-HTV program described in Section 4.3 includes the most critical element -- the burner liner cooling configuration and material. It should be noted that all of the other candidate AST engines (Inverted Flow Engines, Low Bypass Engines and other VCE concepts) will also require the same type of advanced technology main burner.

Emission characteristics of the VSCE-515 are summarized in Section 4.2.4.

5.2.1.3 High Pressure Turbine

Design Considerations

The VSCE-515 operating requirements are unusual in that maximum turbine temperatures and rotor speeds occur during the long time cruise portion of the mission. This causes the major criteria of the high pressure turbine design life to be creep and/or oxidation related and a reduced effect from low cycle fatigue. Maximum combustor exit temperature of 1482°C (2700°F) and compressor discharge temperature of 649°C (1200°F) occur simultaneously at supersonic cruise and establish material and cooling flow requirements for the preliminary design of this turbine. Advanced cooling techniques coupled with material improvements are necessary to achieve durability consistent with commercial application and minimum cooling flow to avoid large penalties to the engine cycle and turbine efficiency. The following table summarizes the design criteria utilized in establishing the VSCE-515 durability goals.

A. Engine Cycle Conditions

VSCE-515
16,154 m (53,000 ft), 2.32 MN, STD + 8°C (14.4°F)
Nominal Values

Compressor Discharge Temperature	(T_{t3})	645°C/1192°F
Combustor Discharge Temperature	(T_{t4})	1482°C/2700°F
HPT Exit Temperature	($T_{t4.5}$)	1211°C/2212°F
Max High Rotor Speed	(N_2)	11193 RPM

B. Design Mission

4 hours
2 hours of hot time per mission

C. Design Life

The high pressure turbine assembly was designed to cause less than 5% Unscheduled Engine Removals (UER) in 10,000 hours of operation.

Technology Projections & Design Features

To attain high adiabatic efficiency while meeting the durability requirements of the VSCE mission profile outlined in Section 5.2.2, technology advancements in aerodynamics, cooling effectiveness and materials must be achieved. The following section reviews these technology projections and design features for this unique high pressure turbine.

The HPT is a single stage design with airfoil aerodynamic loading 17% higher than the E^3 loading. This increased HPT loading is projected for late 1980's technology low solidity turbines operating at the current level of aerodynamic losses.

A 10% reduction in profile loss and 15% reduction in endwall or secondary losses relative to E^3 technology are assumed, based on improved airfoil and endwall shapes as well as tailoring of spanwise velocity distributions.

The use of improved single crystal or RSRDR alloys is projected for both the vanes and the blades. The vane alloy will provide a (175°F) 92°C advantage and the blade alloy a (150°F) 83°C advantage over current engine alloys. These advantages provide increased creep strength for the blade and improved oxidation resistance for the vane at elevated temperatures.

The use of increased strength single crystal or RSRDR alloys provides the potential for improved turbine performance by accommodating increased airfoil root stresses. The improved turbine performance was obtained by increasing turbine annulus area 44% relative to E^3 which had a net effect of reducing aerodynamic losses but with increased blade root stress. The VCE HPT design has an average blade root stress of 413640 kn/m^2 (60ksi) which is 20% higher than the E^3 design. Airfoil load coefficient is varied radially by blade taper to minimize blade pull stress.

Thermal barrier coatings will provide insulative protection of 111 - 167°C (200 - 300°F) for both the VSCE turbine airfoil and platform designs. The use of electron beam deposited coatings with smooth surface finish and low thermal conductivity offers both aerodynamic and heat transfer advantages.

Oxidation/corrosion protection for both the airfoils and platforms is expected to be 55.5 - 111°C (100 - 200°F) better than current metallic coatings with the use of advanced metallic and ceramic overlay type coatings.

An internal heat transfer coefficient increase of 20% relative to the state-of-the-art convective cooling systems is included. This results in an airfoil cooling effectiveness improvement of approximately 10%. This increase in effectiveness will be accomplished through development of advanced trip strips, pedestal optimization, or wavy wall criss cross trailing edge configurations. These more complex internal configurations require advanced fabrication techniques - such as multipiece bonded airfoil or wafer designs.

An advanced tangential on-board injector (TOBI) is utilized to supply 1st blade/disc cooling air with minimum parasitic losses.

A compact, lightweight air/air heat exchanger is incorporated to minimize the 1st vane cooling air requirements. Fan air is used as the cooling medium for this heat exchanger.

Finally, a nickel base superalloy-variable property material with a 27.8°C (50°F) increased rim temperature capability relative to current disk materials was used in the HPT disk to accomodate the higher turbine temperatures while retaining high hub strength.

Parametric Studies

The VSCE-515 preliminary design table information provided a base for turbine parametric studies. The effects of load factor, annulus area, and rotor speed on turbine efficiency were investigated to determine an optimum performance level.

The initial investigation involved sizing the VSCE-515 HPT to the E^3 load factor and AN^2, resulting in the aerodynamic characteristics shown below. The data presented also includes the 502B cycle for reference. This aerodynamic design is conservative, mainly because of the reduced pressure ratio of the VSCE-515 high compressor for this cycle relative to E^3 and the VSCE-502B.

	EEE	VSCE-502B	VSCE-515
Blades-Gas Turning (Avg.)	119	92	90
Relative Exit Mach No.	1.20	1.11	0.93
HPT Pressure Ratio	4.0	3.0	2.3

To obtain a more aggressive design, a parametric study of 16 high pressure turbine configurations was conducted to identify a VSCE configuration which: (1) would achieve high efficiency, (2) satisfy VSCE flowpath geometrical constraints, and (3) represent the best match for the VSCE HPC. To meet the efficiency objective, three independent turbine parameters - turbine annulus area, rotor speed (N), and load factor (L.F.) - were varied from the parametric 502B base values. The turbine efficiencies and related results for the 16 turbine configurations are listed in Table 5.2-IV. The increasing trend in turbine efficiency resulting from the increased average blade root stress (AN^2) with

TABLE 5.2-IV

PARAMETRIC TURBINE CONFIGURATION SUMMARY

SCHEME NO.	LOAD FACTOR	$\frac{AN^2}{AN^2_{502B}}$	N_2 RPM	HPT η	1ST VANE EXIT ANGLE	1ST BLADE TURNING	1ST BLADE CONVERGENCE	EXIT AXIAL MACH NUMBER	EXIT SWIRL	HPT PRESSURE RATIO	1ST BLADE U_{RIM} (M/SEC)	$\frac{\text{AXIAL VELOCITY}}{\text{WHEEL SPEED}}$
502B	1.607	1.0	10120	.8722	18.37	94.57	1.294	.657	14.85	3.008	452.	.687
1A	1.623	1.0	10120	.8819	18.56	94.69	1.345	.642	16.2	2.97	452.	.677
1B		1.2		.907	15.36	107.07	1.61	.466	23.7	2.87	442.	.513
1C		1.3		.9117	14.16	111.65	1.696	.418	26.7	2.85	437.	.464
1D		1.4		.9142	13.13	115.66	1.767	.380	28.9	2.84	432.	.425
2A		1.0	9200	.9046	15.25	107.4	1.609	.463	23.9	2.88	452.	.51
2B		1.2		.9135	12.66	117.5	1.796	.364	30.0	2.84	442.	.41
2C		1.3		.9163	11.67	121.5	1.867	.331	32.7	2.83	437.	.373
2D		1.4		.9124	10.83	125.0	1.929	.304	35.1	2.82	437.	.373
3A	1.344	1.0	10120	.8919	18.58	85.8	1.518	.623	8.38	2.95	507.	.599
3B		1.2		.915	15.39	96.7	1.859	.465	13.49	2.85	498.	.457
3C		1.3		.919	14.18	101.0	1.985	.421	15.35	2.84	493.	.414
3D		1.4		.922	13.18	104.8	2.098	.387	17.13	2.83	489.	.379
4A		1.0	9200	.910	15.18	97.0	1.863	.462	13.56	2.86	507.	.454
4B		1.2		.9187	12.69	106.6	2.148	.373	17.85	2.83	498.	.365
4C		1.3		.921	11.70	110.5	2.267	.343	19.74	2.82	493.	.333
4D		1.4		.922	10.86	114.0	2.371	.318	21.48	2.81	489.	.307

annulus area at constant rotor speed is shown in Figures 5.2-7 and 5.2-8 for load factors of 1.62 and 1.34, respectively. Most of the efficiency change at constant rotor speed results from the decrease in airfoil exit mach numbers with increasing annulus area. An additional increase in turbine efficiency is obtained from the increased turbine annulus at constant rotor speed which increases airfoil turning, aspect ratio, and convergence ratio. The higher aspect and convergence ratios outweigh the adverse effect of increased turning on the endwall loss coefficient, and results in a net decrease in endwall loss coefficient. Although the profile loss coefficient also increases with increased airfoil turning, its effect on the 16 configurations is smaller compared to the decrease in loss due to Mach number and endwall effects. The upper curve in Figure 5.2-8 (LF = 1.34, N = 9200 RPM) does show, however, a tendency for an efficiency trend reversal with further increases in annulus area due to the increase of profile loss coefficient.

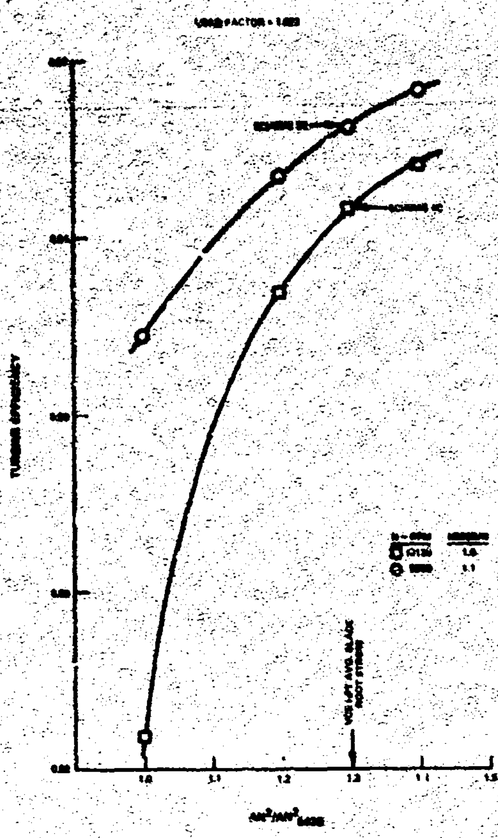


Figure 5.2-7 Configuration Study, Turbine Efficiency Versus Annulus Area X Speed^2

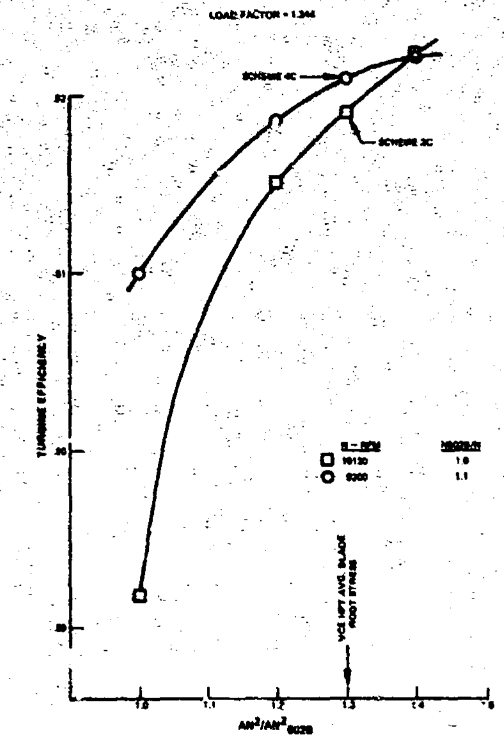


Figure 5.2-8 Configuration Study, Turbine Efficiency Versus Annulus Area X Speed^2

The gain in efficiency with decrease in load factor for constant annulus area and rotor speed is noted by comparing corresponding points from Figures 5.2-7 and 5.2-8. The load factor decrease to 1.34 in Figure 5.2-8 results from increasing the mean turbine diameter by 10% for the constant rotor speeds given in Figure 5.2-7. This increase in mean turbine diameter causes a decrease in airfoil turning (reduces profile loss) with an increase in convergence ratio (reduces endwall loss). The increase in turbine mean diameter also decreases airfoil aspect ratio (increases endwall loss) and increases blade tip leakage area (increases tip loss). Within the limits of the two load factors studied, the net gain in efficiency results primarily from the reduction in profile loss due to decreased turning and reduced Mach number.

Candidate turbines which potentially meet the efficiency objective for the VCE high pressure turbine were selected from the matrix summarized in Table 5.2-IV for further consideration. The efficiencies of four turbine configurations are indicated in Figures 5.2-7 and 5.2-8 according to scheme number from Table 5.2-IV. The two reduced load factor turbines shown in Figure 5.2-8 are from 0.3 to 0.9% higher in efficiency than those in Figure 5.2-7. One turbine was selected for each combination of rotor speed, load factor and AN^2 ratio equal to 1.3. The AN^2/AN^2 502B ratio of 1.3 is equivalent to an average blade root stress of 413640 kn/m^2 (60 ksi) which is 20% higher than E^3, using the E^3 airfoil taper ratio for these VSCE study turbines. An average blade root stress of 413640 kn/m^2 (60 ksi) was selected as being representative of the advanced turbine materials capability for the VSCE.

Further consideration of the four configurations shown in Figure 5.2-9 indicates that the HPT/LPT geometric envelopes are restricted by the LPT exit dimensions. Scheme 4C is the least favorable design because it results in the steepest ID wall angle for the LPT. Scheme 1C results in the least difficulty for the LPT design based on the fixed LPT exit dimensions, but is significantly lower in efficiency (from 0.4 to 0.9%) than the other three schemes. Another consideration is the effect of rotor speed on high pressure compressor efficiency which favors both Schemes 1C and 3C. From the 16 configurations summarized in Table 5.2-IV, Schemes 1C, 2C and 3C represent the most promising HPT/LPT designs, and were used to guide more detailed study of the HPT.

Further analysis of the effect of load factor variation at maximum AN^2 of 3.7×10^7 m^2/min^2 (5.77×10^{10} in^2/min^2) (equivalent to $1.3 \times AN^2$ of the VSCE-502B) was conducted. The data from this study are indicated in Figure 5.2-10 and resulted in a load factor of 1.49 being the maximum which would ensure that blade suction surface Mach numbers remained subsonic, thereby reducing pressure losses, and providing cooled efficiency levels capable of meeting the design goal.

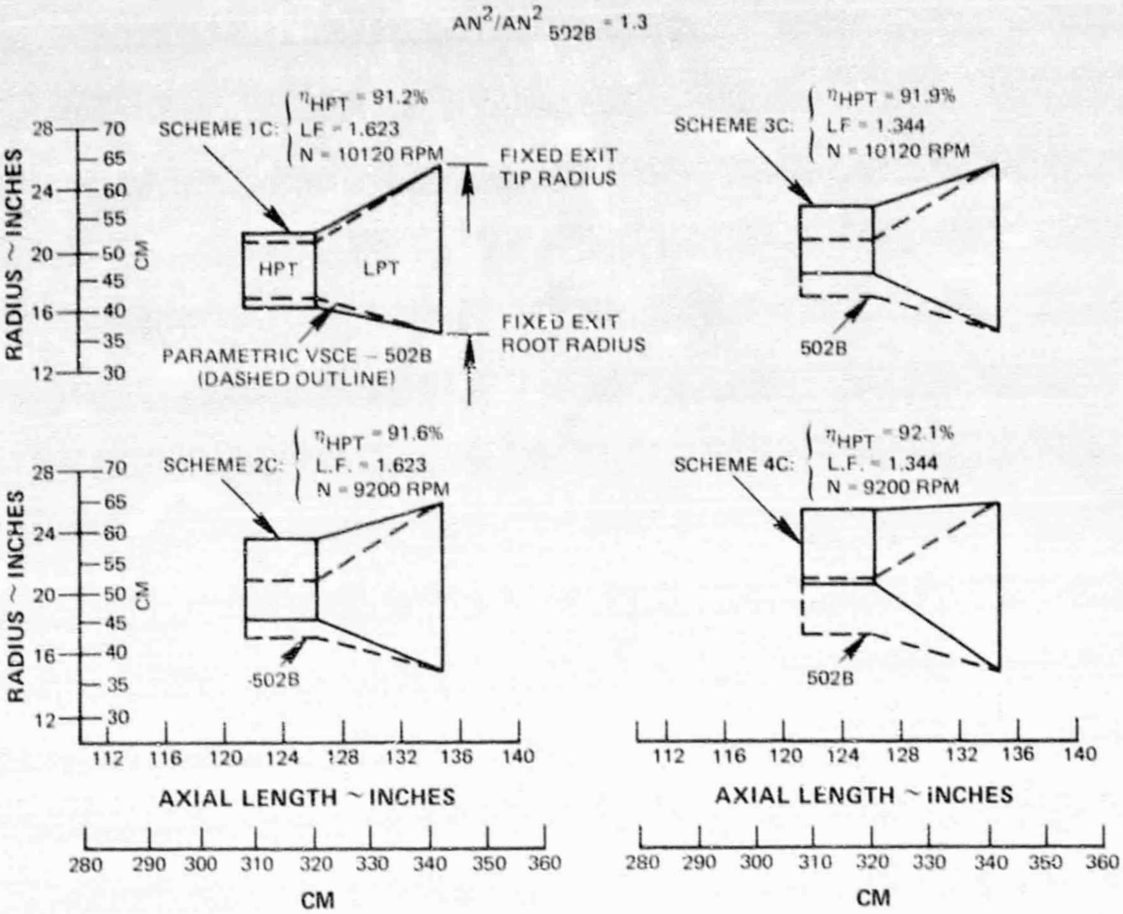


Figure 5.2-9 High Pressure Turbine Configuration Study Max Blade Root Stress = 60 Ksi

A study was then conducted to determine the optimum AN^2 and wheel speed combination for the turbine. Several assumptions were made for this study.

Reaction = 39 percent
Tip clearance = 0.051 cm (0.02 in.)
Trailing edge thickness = 0.137 cm (0.054 in.)
Number of airfoils set by aerodynamic loading

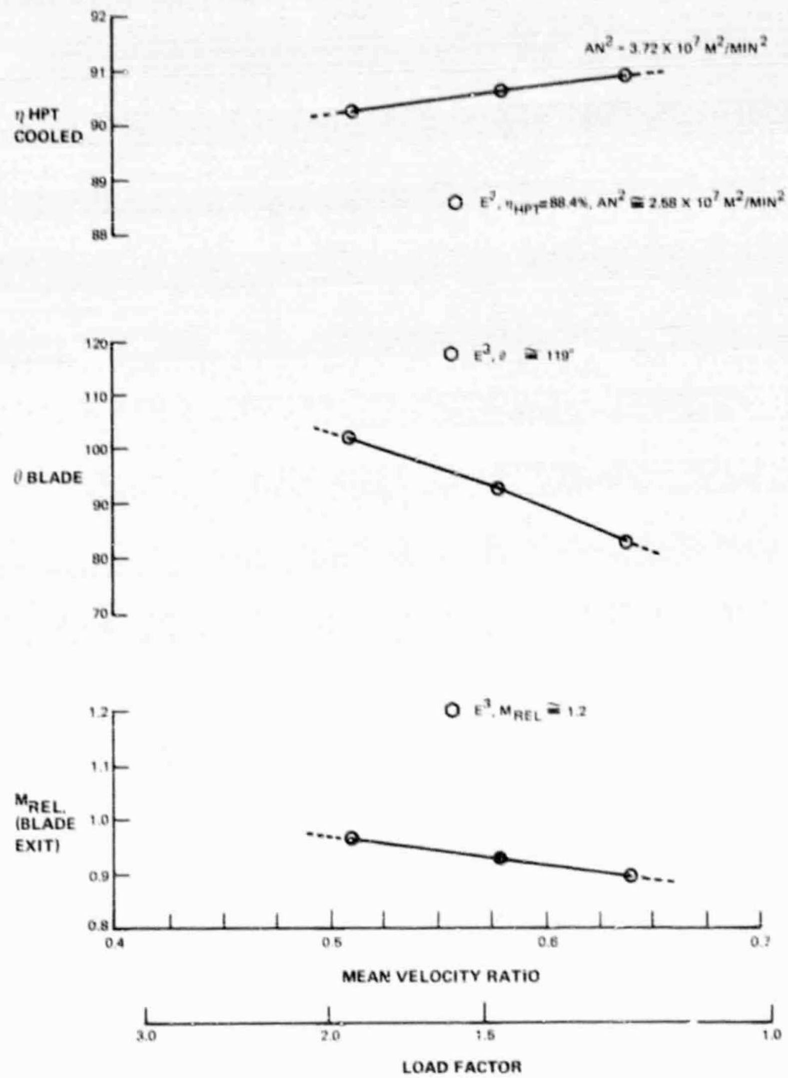


Figure 5.2-10 Parametric Study Load Factor Variation at Maximum AN^2

Preliminary cooling flows were estimated and cooling losses were scaled from E^3 results. A series of turbines were evaluated over a range of AN^2 when turbine velocity ratio, reaction, and work are held constant. As indicated on Figure 5.2-11, turbine efficiency is improved at any given spool speed as turbine annulus area is increased. Also, at the maximum AN^2 of 3.7 x 10^7 m^2/min^2 (5.77 x 10^{10} in^2/min^2), changes in wheel speed had minor impact on turbine efficiency, thereby allowing compressor design considerations to influence the design rotor speed selection of 11193 rpm.

Figure 5.2-12 shows turbine elevation, axial spacing and foil count for the resultant HPT flowpath.

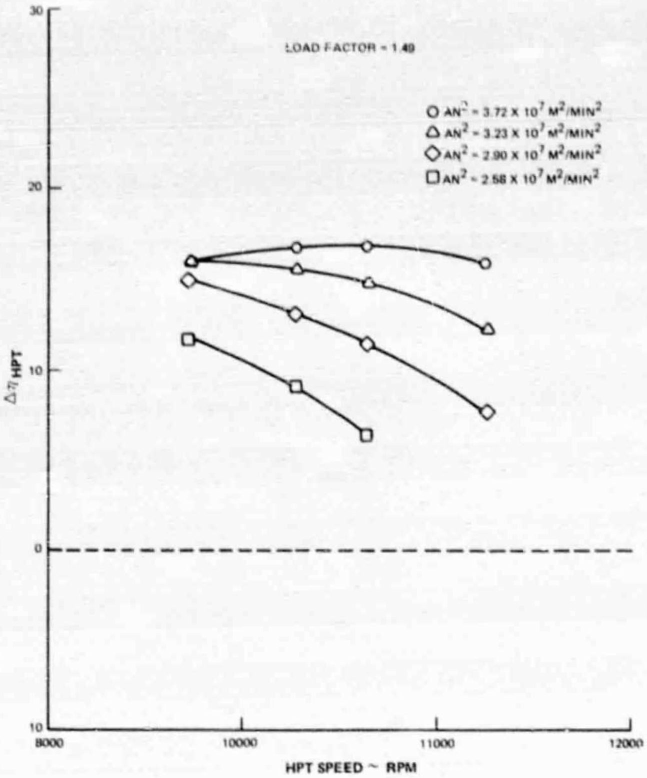


Figure 5.2-11 VSCE Parametric Study High Pressure Turbine Efficiency Vs. RPM

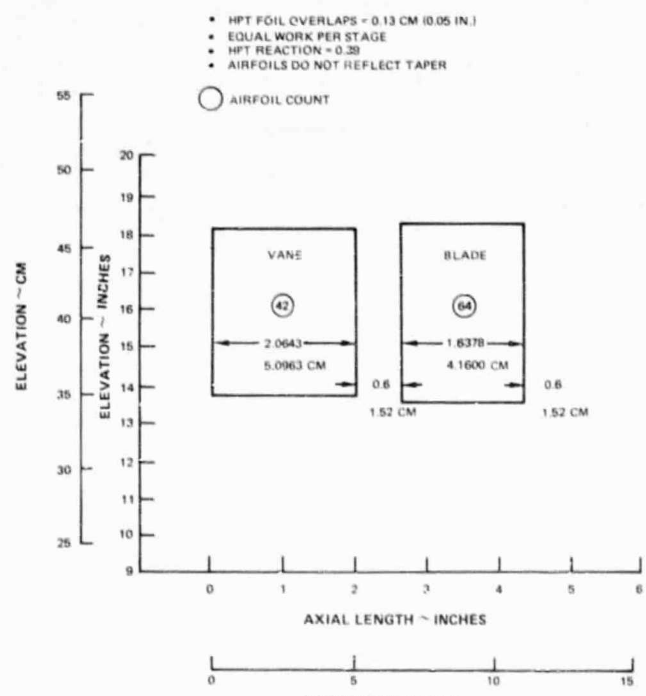


Figure 5.2-12 VSCE High Pressure Turbine Flowpath

Turbine Configuration

These parametric studies resulted in a single stage, unshrouded air cooled turbine aerodynamic design with relatively high velocity ratio and a large annulus area to reduce airfoil mach numbers without large increases in turning. The aerodynamic parameters are summarized in the following table at the supersonic cruise operating point.

No. of stages	1
Mean velocity ratio	0.58
Mean load factor	1.49
Expansion ratio	2.29
Axial velocity/wheel speed	0.6
AN^2	3.74×10^7 m^2/min^2 (5.8×10^{10} in^2/min^2)
Turbine exit Mach No.	0.49
Average Airfoil Inlet Mach No.	0.35
Average airfoil exit Mach No.	0.89
Cooled Efficiency	91.6
Speed RPM	11193
Average blade turning	91^o
Mean stage reaction	0.39

As indicated a cooled adiabatic efficiency of 91.6% was predicted for this turbine stage and is developed as follows. Efficiencies shown include cooling, leakage, and pumping effects. Note that this level of efficiency does not include the effects of precooling the turbine cooling air, described later in this section.

Efficiency

Current Technology	including AN^2, velocity ratio, pressure ratio effects	91.0%
Advanced technology	profile & secondary loss reductions	+0.6%
	TOTAL	91.6%

Figure 5.2-13 illustrates the preliminary design configuration for the HPT.

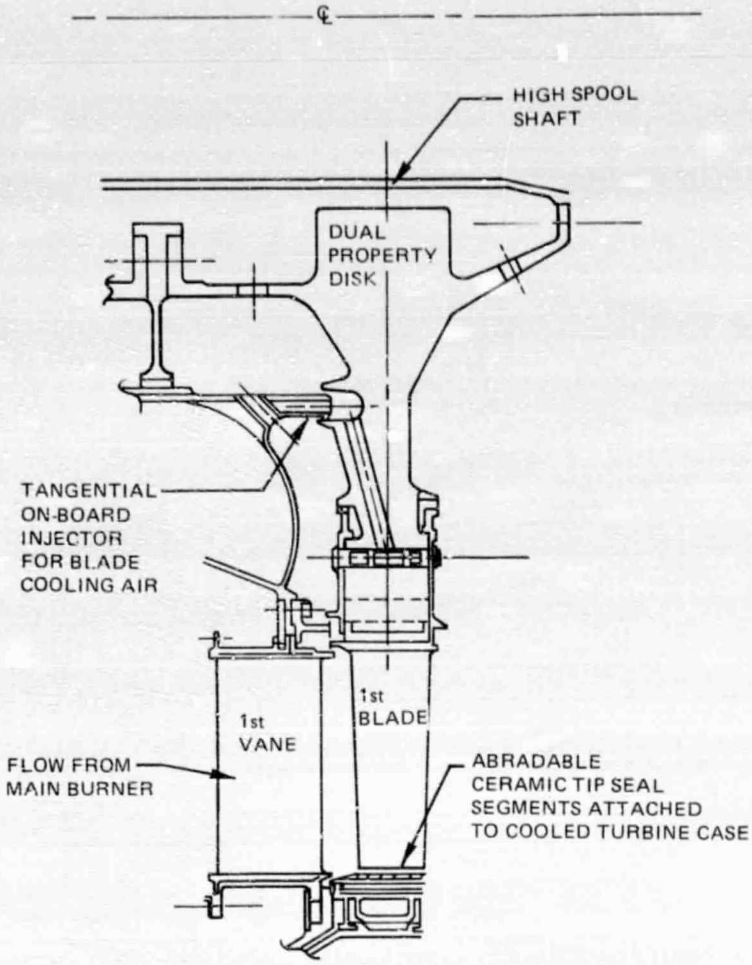


Figure 5.2-13 VSCE-515 High Pressure Turbine Cross Section

A tangential on-board injector (TOBI) for efficient transfer of blade cooling air from the static to rotating reference is utilized to minimize parasitic losses. The inlet guide vanes are also air cooled. Initial cooling scheme estimates use high compressor exit air in a dual feed to the vane (OD and ID) utilizing approximately 4.0% of core engine flow. This cooling configuration is illustrated in Figure 5.2-14 showing the foil cooling paths, leakage paths, and disc cooling provisions in the high pressure turbine area. Table 5.2-V indicates the turbine cooling bleed source and sink locations in addition to the cooling flow rate. It should be noted that the levels of cooling flow shown in Figure 5.2-14 and Table 5.2-V were preliminary in that they were recalculated to reflect the full potential of the advanced technology projections for the high pressure turbine, the single crystal or RSRDR alloy, the thermal barrier coating and the precooled cooling air resulted in the final cooling levels summarized in Table 4.1-III.

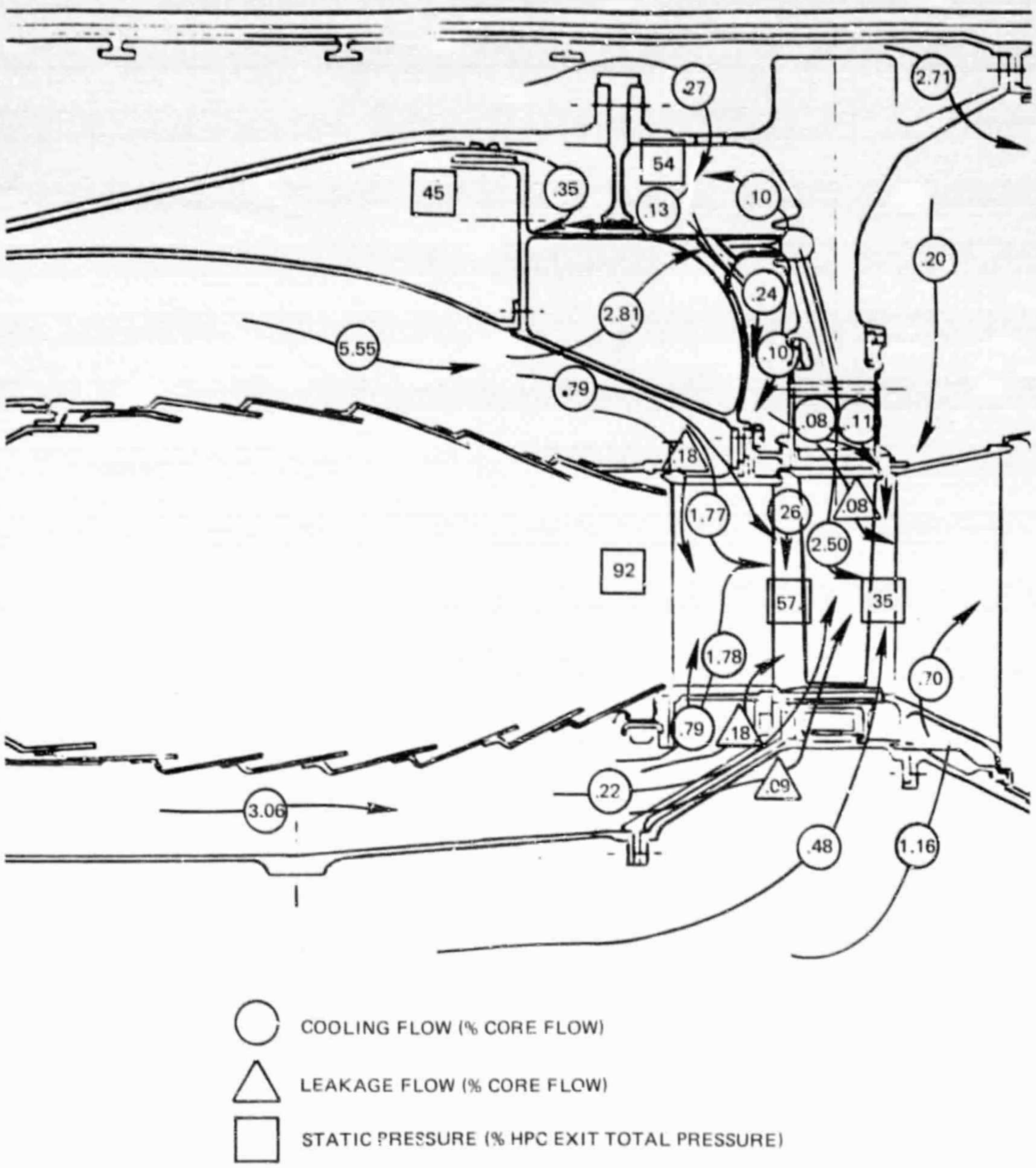


Figure 5.2-14 VSCE High Pressure Turbine Cooling Flow Map

TABLE 5.2-V

VSCE-515 HIGH PRESSURE TURBINE
COOLING FLOW

Compressor Bleed Source Location	Flow % Wae		Bleed Release Location
7th Blade	0.20		Disk Rear Flow
I.D. Rear	0.06		Disk Front Flow
	0.03		Blade Platform Leak
	0.13		Disk Rear Dump
	0.05		Disk Thru Flow
HPC O.D.	1.78		Vane O.D. Foil Cooling
Exit	0.79		Vane O.D. Platform Cool
(Burner)	0.06		Vane Front O.D. Leakage
	0.06	.18	Vane O.D. F/S Leakage
	0.06		Vane Rear O.D. Leakage
	0.09		OAS Front Cooling
	0.13	.22	OAS Rear Cooling
	0.09		OAS Leakage

Compressor Bleed Source Location	Flow % Wae	Bleed Release Location
HPC I.D.	2.50	Blade Foil Cooling
Exit	0.79	Vane I.D. Platform Cooling
(Burner)	0.02	Vane I.D. Front Leakage
	0.05	Vane I.D. F/S Leakage
	0.11	Vane I.D. Rear Leakage
	0.05	Blade Platform Leak
	1.77	Vane Foil Cooling
	0.20	Disk Front Flow
	0.06	Disk Thru Flow
HPC I.D. Exit	0.35	Blade Rear Dump

A parametric study was then conducted to examine the potential benefits of employing an air/air heat exchanger to precool the turbine cooling using fan air as a cooling medium. The heat exchanger core designs consist of arc segments located in the annular space between the bypass duct and the engine core over the compressor case. Cross flow heat exchanger operation is assumed with the cold side flow from the bypass duct flowing axially and the hot side compressor discharge bleed flowing circumferentially. Trade studies, assessing the impact of reduced turbine cooling flow, turbine efficiency gains and heat exchanger weight were made for two systems. The first in which vane cooling air only is precooled and the second in which the TOBI air (1st blade cooling) is precooled. For each case the engine cycle was optimized and evaluated at supersonic conditions to take full advantage of the resultant cooling flow and turbine efficiency changes. The most promising precooling system for each airfoil is listed in Table 5.2-VI. For reference, the VSCE-515 base is also tabulated. The case numbers refer to the different heat exchanger systems that were evaluated and are summarized in Figures 5.2-15 and 5.2-16. Relative to the VSCE-515

TABLE 5.2-VI

VSCE-515 PRECOOLED TURBINE COOLING AIR EVALUATION

	Reference (No Precooling)	HPT Vane Precooling	HPT Blade Precooling
Case No. (Fig. 1 & 2)	Base	2	4
Turbine Cooling Airflow (% Wae)			
Total	12.1	10.1	11.1
HPT Vane	4.2	2.2	4.2
HPT Blade	2.5	2.5	1.5
Heat Exchanger Weight	0 0	27 Kg (60 Lbs)	7 Kg (16 Lbs)
HPT Efficiency (%)	91.58	92.05 (+.47)	91.7 (+.12)
CET at Takeoff	1130°C (2066°F)	1116°C (2040°F)	1122°C (2052°F)
Wae_3	105.7 Kg/sec (233.0 lb/sec)	1C6.1 Kg/sec (233.9 lb/sec)	105.9 Kg/sec (233.5 lb/sec)
TSFC at Supersonic cruise (%)	--	-.42	-.25

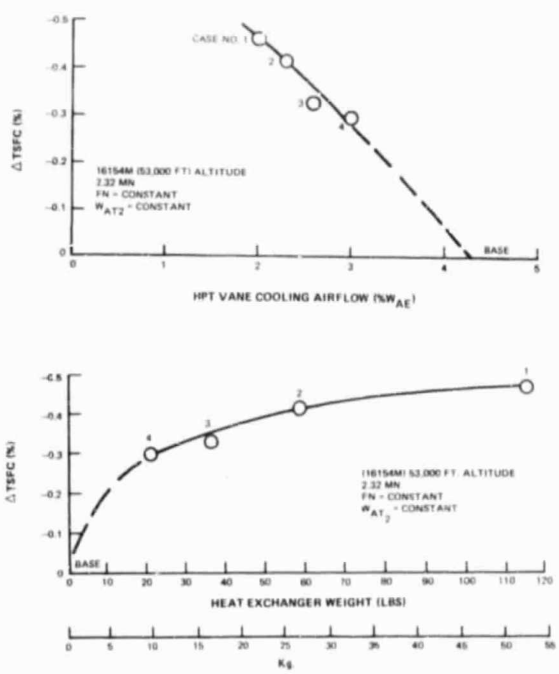


Figure 5.2-15 Parametric Evaluation of Cooling-515 High Pressure Vane Cooling Air

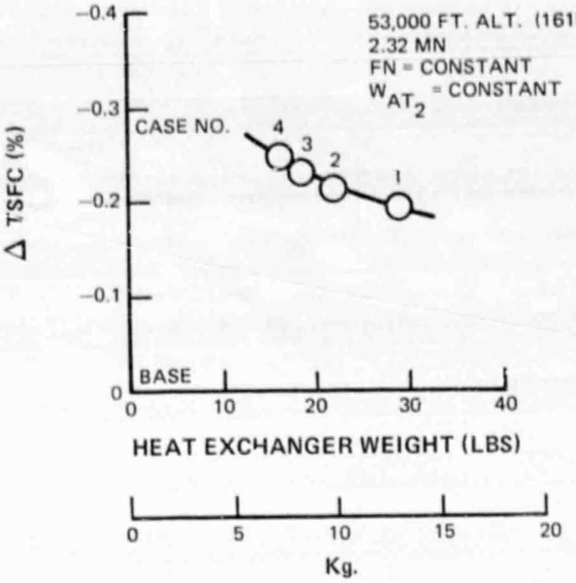


Figure 5.2-16 Parametric Evaluation of Cooling VSCE-515 High Pressure Turbine Blade Cooling Air

base, case no. 2 for vane precooling has a 27.2 kg (60 lb) heat exchanger weight, and provides a 2% Wae reduction in vane cooling, a 0.40% increase in turbine efficiency, and allows a small increase in core high-flowing at supersonic cruise to improve dry specific thrust, and augmented TSFC by -0.40%. This high-flowing rematch is indicated in Table 5.2-VI by the reduction in take-off Combustor Exit Temperature (CET) and the 0.41 Kg/sec (+0.9 lb./sec.) increase in core flow at supersonic cruise. Figure 5.2-15 shows the matrix of four cases that were evaluated for vane precooling. As the heat exchanger size (weight) is increased, the TSFC improves, but at a diminishing rate. Case 2 was selected as having most of the TSFC benefit for a small, 27.2 kg (60 lb.), heat exchanger weight penalty. Another 18.1 kg (40 lbs.) is added to allow for the ducting of the cold side of the precooler system, making a total weight increase of 45.4 kg (100 lbs). The plumbing and ducting systems for the vane precooler are located outside the primary stream flowpath in the region over the compressor case, thereby minimizing the added complexity to the secondary flow system.

The third column in Table 5.2-VI summarizes the effects of precooling the blade. The blade precooler is in series with and upstream from the tangential injector system which expands the blade cooling air through convergent nozzles to match the rotational speed of the disk that receives the cooling air. As the level of precooling is increased, and the heat exchanger pressure loss increases, the effective work of this tangential injector system on the turbine rotor decreases, and the net effect on engine performance is the reverse slope shown in Figure 5.2-16. From the matrix shown in this figure, Case 4 was selected as the representative blade precooling system, and is summarized in Table 5.2-VI. Although the blade precooling system is a good trade in terms of weight versus TSFC, it was rejected for the VSCE-515 mainly because it excessively complicates the secondary flow system in the region of the tangential injector and in the plumbing system that crosses the primary flowpath going to and from the heat exchanger. More detailed design studies are required to determine the overall merit versus complexity of the blade precooling system.

Based on these results, the VSCE-515 performance was modified to include the effects of precooling the first vane.

5.2.2 Low Spool Components

5.2.2.1 Fan

Design Considerations

The VSCE fan design emphasizes high efficiency at supersonic cruise, compatibility with supersonic inlets (especially stability, flow matching and choking for noise reduction), compatibility with the duct burner, and low noise generation. The basic fan design provides a relatively low exit Mach number to meet the fan duct burner compatibility requirements. In addition to being compatible with inlet choking for noise attenuation, the fan tip speed design must be consistent with low noise generation as well as stress limitations in the low pressure turbine. Spacing between the stages must adhere to generating low aft end noise. To meet nacelle envelope dimensions established by the SCR airplane contractors for good installed performance, as well as to provide space for packaging accessories around the fan case, the fan must be designed to have low elevation and hence low hub/tip ratios.

Technology Projections and Design Features

A high diffusion, low elevation, 3 stage fan design was incorporated in the VSCE-515 design. The fan has graduated spacing between the blades and vanes of the three stages --- 50%, 75%, and 100% front to back axial gap at the outer diameter relative to the axial chord of the upstream airfoil.

The flowpath was altered from the constant mean diameter design used for the parametric 502B definition by increasing the outside diameter of the back end to maintain surge margin/loading capability consistent with the technology time frame.

Advanced aerodynamic controlled diffusion airfoil contours are used to provide high efficiency and minimize losses.

Variable camber inlet and exit guide vanes are employed to reduce the incidence range in the first and last stages and provide high efficiency at subsonic cruise in addition to supersonic cruise.

Low aspect ratio unshrouded blade airfoils fabricated from boron/aluminum material were assumed for the first two stages. The higher temperature environment required the 3rd stage blades to be made from titanium. Stators in all rows are fabricated from advanced aluminum alloy.

An overspeed capability for trim and deterioration allowance consistent with current production engine philosophy has been provided.

Configuration Definition

An advanced 3 stage fan design was evolved for incorporation in the VSCE-515 definition and is illustrated in Figure 5.2-17. The following discusses the configuration definition of this fan assembly.

The fan inlet case structure provides front support for the low rotor system, a variable area inlet to the fan and a mounting structure for the engine. The basic structure consists of an inner ring structure joined by 18 struts, with separate variable area trailing edges, to an outer case section with an engine mounting ring.

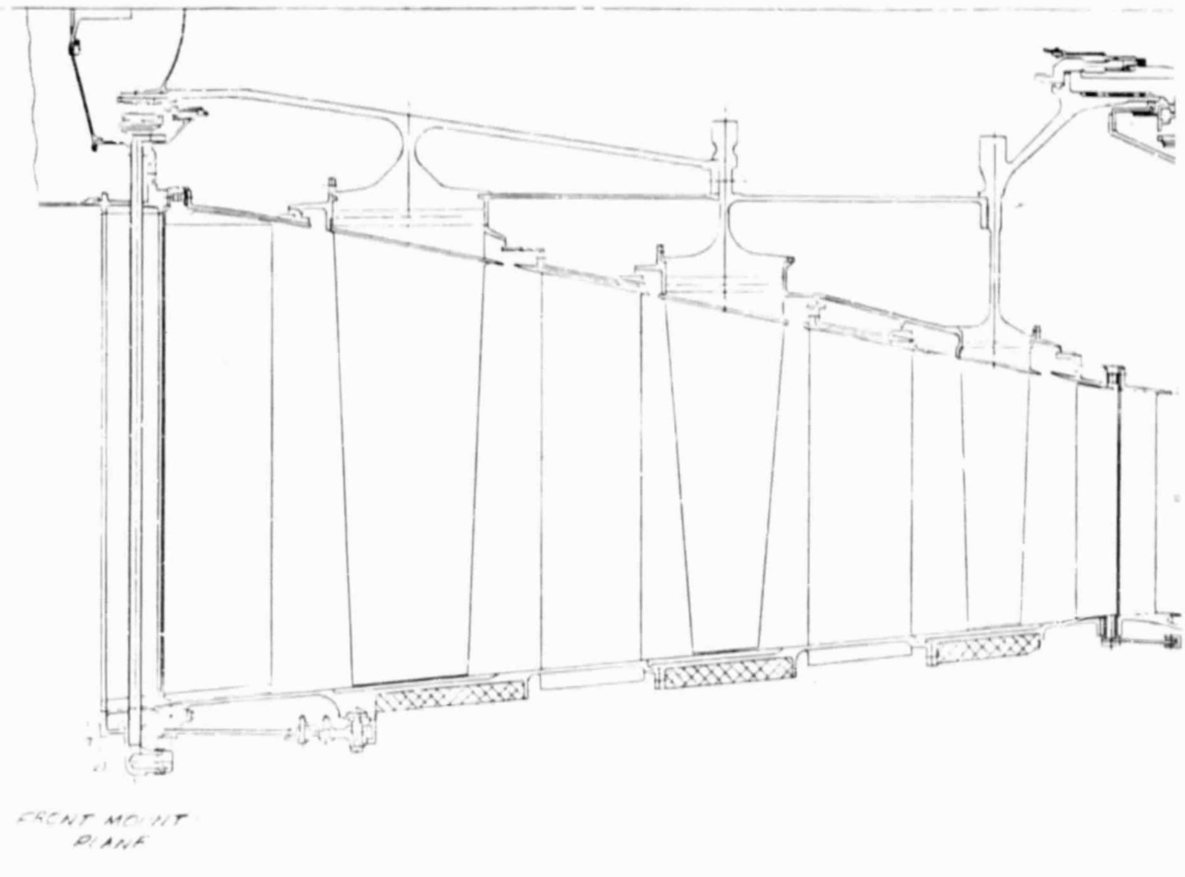


Figure 5.2-17 Advanced Three Stage Fan Design Utilized in the VSCE-515 Definition

Fan containment designated on the VSCE-515 configuration drawing (Figure 5.2-17) by cross hatched areas external to the fan case is an advanced composite material.

The material candidate selected for the case is an advanced aluminum alloy. However, due to the critical nature of the mounting system, it is recommended that the material selection be reviewed as more information on the mounting system is defined.

The following data characterizes the fan section at the sea level aerodynamic design point.

Design Pressure Ratio	3.3:1
Number of Stages	3
Design Corrected Airflow Size	340 kg/sec (750 lb/sec)
Design Corrected Specific Airflow	210 kg/sec-m^2 (43 lb/sec-ft^2)
Design Corrected Rotational Speed (rpm)	6107
Design Corrected Tip Speed	48.8 m/sec (1600 ft/sec)
Exit Axial Mach No.	0.40
Inlet Hub/Tip Ratio	0.33
Exit Hub/Tip Ratio	0.64
Adiabatic Efficiency (%)	85.7
Surge Margin (%)	20

Rotor root chord lengths are set by the material limited aspect ratio, number of blades are chosen to maintain reasonable distributions of both gap-chord ratio and chord taper ratio. Stators are all constant chord designs with aspect ratio and number of vanes adjusted to give reasonable gap-chord ratios while avoiding having rows with the same number of blades or vanes for noise considerations. A summary of the airfoil definition is provided in the following table.

Stage No.	-	1	1	2	2	3	3
Airfoil	IGV	R_1	S_1	R_2	S_2	R_3	S_3
Number of Airfoils	18	24	40	34	42	50	65
Root Aspect Ratio	3.0	2.8	3.8	2.8	2.8	3.0	3.0
Root Gap/Chord	0.44	0.40	0.42	0.44	0.44	0.50	0.49
Root Chord cm	18.3	17.5	11.4	14	12.2	9.9	8.4
(inches)	(7.2)	(6.9)	(4.5)	(5.5)	(4.8)	(3.9)	(3.3)
Taper Ratio (Tip/Root Chord)	1.0	1.38	1.0	1.20	1.0	1.10	1.0
Variable Camber	X	-	-	-	-	-	X

As noted variable camber stators were incorporated in both the inlet and exit guide vanes of the fan section. Estimated swings in the angle of attack on the first rotor and exit vane rows from the aerodynamic design point to the supersonic cruise condition are significant and for the exit guide vane may be as much as 10° to 14°. Conventional airfoils do not have enough range for low loss operation at both conditions, consequently the exit guide vane features a variable leading edge flap and the inlet guide vane a trailing edge flap to minimize losses.

The intermediate case is a titanium structure which carries the thrust loads of the fan and high pressure compressor. The transition duct in the engine core section is a moderate aerodynamic flowpath design with approximately ten axially oriented structural struts crossing the flowpath. The fan duct section of the intermediate case is also assumed to have ten structural struts. The precise number of struts will be determined at some later detail design phase.

5.2.2.2 Low Pressure Turbine

Design Considerations

Design considerations for the low pressure turbine for the VSCE-515 are similar to the high pressure turbine in that maximum speed and temperatures occur during the long time cruise portion of the mission. Hence, durability goals for the low pressure turbine are similar to the high pressure turbine, but are reviewed here for convenience.

Engine Cycle Conditions

VSCE-515
16154 m (53000 ft) 2.32 Mn Std + 8°C (14.4°F) Day
Nominal Value

Compressor Discharge Temperature (Tt3)	645°C(1192°F)
Low turbine inlet temperature (Tt4.5)	1211°C(2212°F)
Low turbine exit temperature (Tt5)	839°C(1541°F)
Max low rotor speed (N_1)	6616 RPM

Design Mission

4 hours
2 hours of hot mission time

Design Life

The low pressure turbine assembly was designed to cause less than 5% unscheduled engine removals (UER) in 10,000 hours of operation.

Technology Projections & Design Features

Technology advancements in aerodynamics, cooling effectiveness, and materials must be achieved for the VSCE low pressure turbine to attain high adiabatic efficiency while meeting the durability requirements of the mission profile outlined in Section 5.2.2. The following section reviews these technology projections and design features.

An advanced two stage, air cooled, high speed design with high airfoil loading capability was defined and incorporated in the VSCE-515. The flowpath has a low profile to minimize the duct burner and engine

C-2

diameters in order to provide good installation characteristics, especially low boattail drag for the nozzle during subsonic cruise operation.

Inside and outside wall angles of 10 degrees and 25 degrees respectively for a combined angle of 35 degrees were selected to minimize weight and length and keep endwall losses to a minimum for the two stage design.

Similar to the high pressure turbine aerodynamic design, a 10% reduction in profile loss and a 15% reduction in endwall or secondary losses relative to E^3 technology were applied to the low pressure turbine design. These technology advances are based on improved airfoil and endwall shapes as well as tailoring of spanwise velocity distributions.

Airfoils are contoured to minimize the pressure loss effect of relatively high inlet Mach numbers.

The low pressure turbine assembly is close-coupled to the high pressure turbine without a high temperature transition duct and without hot struts. The same high strength single crystal or RSRDR alloys that were applied to the high pressure turbine are used to provide increased thermal fatigue strength for the low pressure turbine vanes and increased creep strength for the blades. The vane alloy will provide a 92°C (175°F) advantage and the blade alloy a 83°C (150°F) advantage over current engine alloys. Blade airfoils incorporate mini tip shrouds to allow high aspect ratio airfoils.

Oxidation/corrosion protection for both airfoils and platforms is projected to be 55.5 to 111°C (100 to 200°F) better than current metallic coatings with the use of advanced metallic and ceramic overlay type coatings.

Thermal barrier coatings will provide insulative protection of 111 to 167°C (200-300°F) for both turbine airfoil and platform design. The use of electron beam deposited coatings with smooth surface finish and low thermal conductivity offers both aerodynamic and heat transfer advantages.

Airfoil cooling effectiveness is improved 10% relative to current state-of-the-art convective cooling systems and will be accomplished through development of advanced trip strips, pedestal optimization, or wavy wall criss cross trailing edge configurations.

Supercritical airfoil design is used for the turbine exit guide vane. Elliptical leading edges are included in these vane designs to reduce sensitivity to air angle mismatches that occur at subsonic cruise and low power (cut-back) takeoff operation.

Disks selected for the low pressure turbine consist of a nickel base superalloy variable property material made from powder metallurgy fabrication. Disk profiles, as in the high pressure turbine, utilize the dual properties of the material at the bore and rim.

Parametric Studies

The initial step in defining the low pressure turbine was a parametric configuration study to ensure compatibility of the high and low pressure turbine designs. This initial survey is reviewed in section 5.2. A two stage low pressure turbine flowpath was composed for the VSCE-515 design speed of 6616 rpm which was set by the maximum allowable design stress of the second blade. For high efficiency, subsonic airfoil exit Mach numbers were achieved by means of a relatively large annulus area. This resulted in a last blade AN^2 of 3.84×10^7 m^2/min^2 (5.95×10^{10} in^2/min^2) which was acceptable based on utilizing the advanced superalloy single crystal or RSRDR materials for improved creep strength for the blades. Both blade rows required cooling. This two stage design has a cooled efficiency of 92%, a load factor of approximately 2.0 and an axial exit Mach number of 0.51.

For back-up considerations, a parametric study was conducted to evaluate the possibility of reducing the last blade AN^2 by adding a third stage, thereby reducing the last blade stress and cooling requirements. The resulting three stage machine reduced AN^2 by 17%, including a 10% reduction in mechanical low rotor speed, and was approximately 0.3 percent more efficient relative to the two stage design. Although cooling airflow distribution was different for the three stage machine, all blade airfoils required cooling, and total cooling requirements remained nearly equal to the two stage configuration.

The following table compares the cooling flow requirements for the two and three stage turbine configurations.

	Required Cooling Percent of Core Airflow	
	2 stage	3 stage
2nd vane platform	.2	.2
airfoil	.6	.6
2nd blade	1.32	.87
3rd vane	uncooled	.25
3rd blade	1.07	.83

4th vane	- - -	uncooled
4th blade	- - -	.38
TOTAL	3.19	3.13

The fact that the cooling flow requirements could not be significantly reduced, in conjunction with the lower wheel speed of the 3 stage design necessitating an additional fan stage to maintain fan surge margin, resulted in the selection of the two stage configuration for the VSCE-515 low pressure turbine. Figure 5.2-18 shows the flow path for this two stage configuration indicating elevations, axial spacing, and airfoil count. Aspect ratio definition of the foils is as follows.

2nd vane	2.28
2nd blade	3.75
3rd vane	4.29
3rd blade	5.32

As discussed above, the low pressure turbine selected for this preliminary design of the VSCE-515 consists of 2 stages with tip shrouded, air cooled blades. Cooling of the 2nd turbine vane and turbine exit guide vanes is also required. Aerodynamic design characteristics for the selected low pressure turbine design are shown below for the supersonic cruise design point.

Cooled Efficiency	92%
Rotor speed (RPM)	6616
Mean Load Factor	2.06
pressure ratio	3.25
AN^2 1st blade/2nd blade	$2.39 \times 10^7 / 3.84 \times 10^7$ m^2/min^2
hub/tip (last blade)	0.48
absolute mach number-exit	0.56
axial mach number-exit	0.51
stage work distribution	50%/50%
mean stage reaction	0.45
average axial velocity/wheel speed	1.04

As indicated, an aerodynamic efficiency of 92% has been predicted for this 2 stage machine and is derived from the current technology base as follows.

	Cooled Efficiency
Current Tchnology	90.7%
Technology Projections based on	+1.3%
o Airfoil contour	
o Profile loss reduction	
o Endwall/secondary loss reduction	
	92.0%

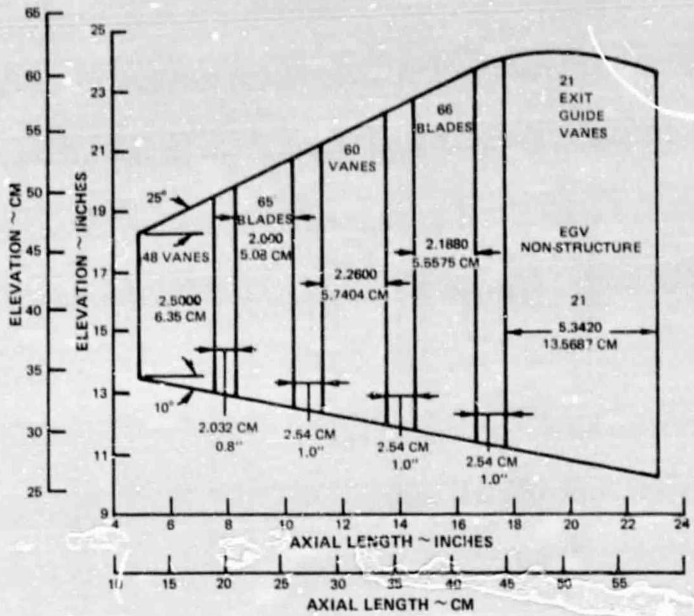


Figure 5.2-18 VSCE Low Pressure Turbine Flowpath

To complement this high efficiency design, the turbine exit guide vanes which house the radial supports for both rotors are based on a super-critical airfoil design. To provide high efficiency for off design operation (subsonic cruise) and to avoid the complication of having variable geometry in this hot region of the engine, elliptical leading edges are included in this vane design for reducing sensitivity to air angle mismatches. The following table illustrates the design parameters for the turbine exit guide vane at supersonic cruise conditions.

parameter	16154 m (53000 ft. 2.32 Mn)
inlet swirl	26°
inlet mach number	0.56
mach number exit	0.5
pressure loss	1.3%

Performance estimates for the VSCE-515, in addition to the 1.3% pressure loss for these exit guide vane, also include 0.5% pressure loss for the pressure instrumentation which would be included at this station to monitor engine pressure ratio.

Figure 5.2-19 illustrates the preliminary design configuration for this two stage turbine and shows the paths for airfoil and disk cooling and leakage. Table 5.2-VII details the source and sink locations for the various airfoil, leakage, and disk cooling paths.

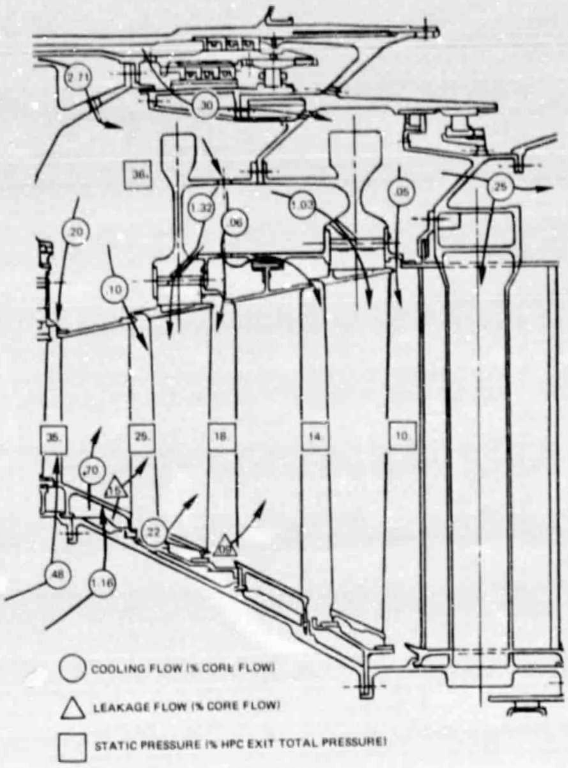


Figure 5.2-19 VSCE-515 Low Pressure Turbine Cooling Flow Map

TABLE 5.2-VII

VSCE-515 LOW PRESSURE TURBINE
COOLING AND LEAKAGE SECONDARY FLOW SYSTEM

Compressor Bleed Source Location	Flow % Wae	Bleed Release Location
7th Blade I.D. Rear	0.06	3T Blade I.D. Front
	0.10	2T Blade I.D. Front
	1.32	2T Blade Foil Cooling
	1.03	3T Blade Foil Cooling
5th Vane O.D. Rear	0.09	2T OAS Front Cooling
	0.13	2T OAS Rear Cooling
	0.09	2T OAS Leakage
	0.60	2T Vane O.D. Foil Cooling
	0.10	2T Vane O.D. Platform Cooling
	0.04	2T Vane O.D. F/S Leakage
	0.07	2T Vane O.D. Rear Leakage
	0.04	2T Vane O.D. Front Leak
LPC I.D. Exit	0.25	TEGV & Tailcone Cooling
	0.05	3T Blade Rear

5.2.3 Unique VSCE Components

The feasibility and overall competitiveness of the VSCE concept is dependent on the performance, environmental and operational characteristics of two critical and unique components - the duct burner and the coannular nozzle. The on-going VCE experimental programs are concentrating on research and substantiation of both components. Because these programs are not complete at the time of this writing, the refined VSCE-515 includes interim definition of these components. Furthermore, not all of the advanced technology requirements for these components have been established or projected, in particular in the durability area and in the operational features that make these components suitable for application to commercial engines. Further analytical and experimental work is required to refine these two components to the same degree of design definition as the other major VSCE-515 components.

5.2.3.1 Duct Burner

Design Requirements

- High chemical efficiency $\geq$ 99.5% to meet CO and THC emissions goals
- High thrust efficiency at supersonic cruise = 96%
- Maximum exit temperatures in the 1094 to 1427°C (2000 to 2600°F) range, depending on the noise goal and the requirements for programmed throttle scheduling
- Low emissions (EPAPs) in the airport vicinity (summarized in Section 4.2.4)
- Configuration must be compatible with commercial engine design, operational and installation requirements
- Design Life - 10,000 hours total for hot parts

Design Definition

Figure 5.2-20 shows a cross-section of the VSCE-515 duct burner. It is a simplified, two-stage version of the three-stage VORBIX design being tested in the VCE duct burner rig and testbed programs. By combining the pilot with the low power stage, the overall complexity is reduced by eliminating one complete fuel manifold assembly and associated hardware and control elements. This improvement is based on the VCE test results that show there are no significant pressure pulses or instabilities associated with the light-off and staging fuel/air ratios that correspond to a two-stage design. As was the case for the original three-stage design, the low power stage is tailored for high thrust efficiency at supersonic cruise (.010 to .015 fuel/air ratio, depending on the selected engine size), and the high power stage is designed for maximum fuel/air ratios (.030 to .040) for takeoff and supersonic climb. As an indication of the variation in fuel/air ratio that the

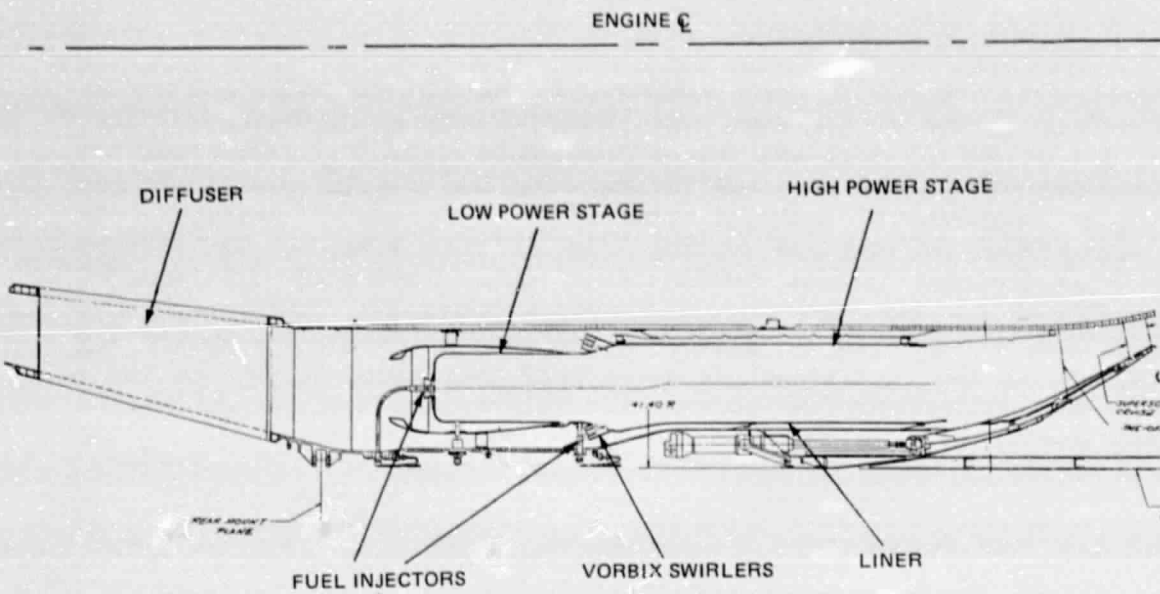


Figure 5.2-20 VSCE-515 Duct Burner Cross-Section - Simplified Two Stage Configuration

duct burner operates at over the complete flight spectrum, Table 5.2-VIII lists the fuel/air ratios at specific altitudes, Mach numbers and time for a full 7408 Km (4000 Nautical Mi.) mission. Table 5.2-VIII is based on a relatively small engine size (.00095 airflow/TOGW ratio) that does not meet noise constraints.

Figure 5.2-21 is a graph of thrust efficiency versus fuel/air ratio for the refined two-stage duct burner. It shows the peak level of 96% at the low fuel/air ratios that correspond to supersonic cruise. At the higher power levels where both stages are operating, the higher temperature rise causes the thermal profiles to increase slightly, and the thrust efficiency is reduced to 93.5% at the maximum fuel/air ratio of .040.

The pressure loss characteristics for the two-stage duct burner are shown in Figure 5.2-22. Two curves are plotted, one for operation on a reduced fan pressure ratio line which may provide a lower level of jet noise*, the other for normal operation. The higher pressure loss for the reduced operating line is caused by the increase in corrected airflow, and the increase in Mach number for this unique operating mode.

TABLE 5.2-VIII

RANGE OF DUCT BURNER FUEL/AIR RATIOS OVER COMPLETE FLIGHT SPECTRUM

	ALT FT.	ALT M	MN	(Min) TIME INTO MISSION	FUEL/AIR
Takeoff	(0)	0	0	0	.04
	(35)	11	.3	1.0	.04
Climb	(1500)	457	.4	1.73	.002
	(3000)	914	.5	2.99	0
	(20500)	6248	.8	12.12	0
	(24000)	7315	.85	14.72	.006
	(27500)	8382	.9	17.01	.0102
	(27900)	8504	.95	18.32	.0142
	(31000)	9449	1.00	19.61	.0224
	(32500)	9906	1.10	20.96	.0400
	(34500)	10516	1.20	22.14	.0400
	(36500)	11125	1.30	23.26	.0400
	(38000)	11582	1.40	24.29	.0400
	(39500)	12040	1.50	25.27	.0400
	(41500)	12649	1.60	26.34	.0370
	(43000)	13106	1.70	27.40	.0320
	(44500)	13564	1.80	28.46	.0292
	(46500)	14173	1.90	29.66	.0268
	(47700)	14539	2.00	30.80	.0240
	(50000)	15240	2.10	32.25	.0228
	(53000)	16154	2.30	35.97	.0160
	(53400)	16276	2.32	36.50	.0160
	(55267)	16845	2.32	37.18	.0160
Cruise	(55267)	16845	2.32	37.18	.0117
	(63370)	19315	2.32	185.11	.0120
Descent	(63370)	19315	2.32	185.11	——
	(1500)	457	0.23	207.9	——

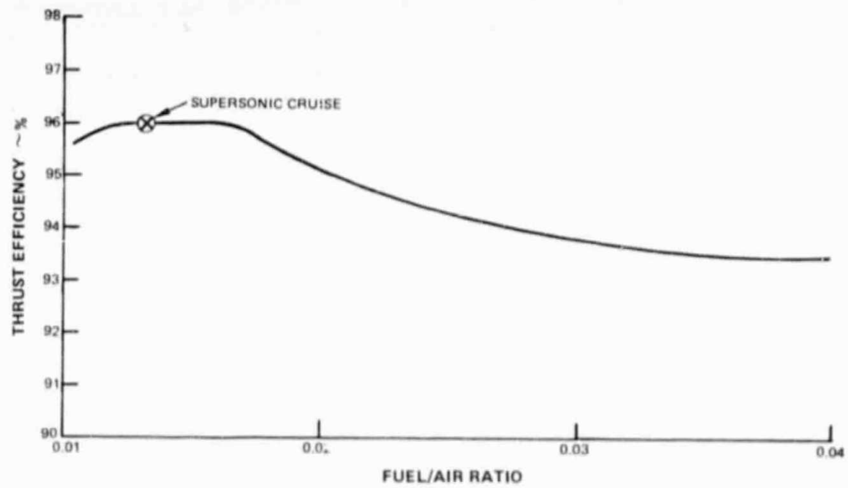


Figure 5.2-21 VSCE-515 Duct Burner Thrust Efficiency Versus Fuel/Air Ratio

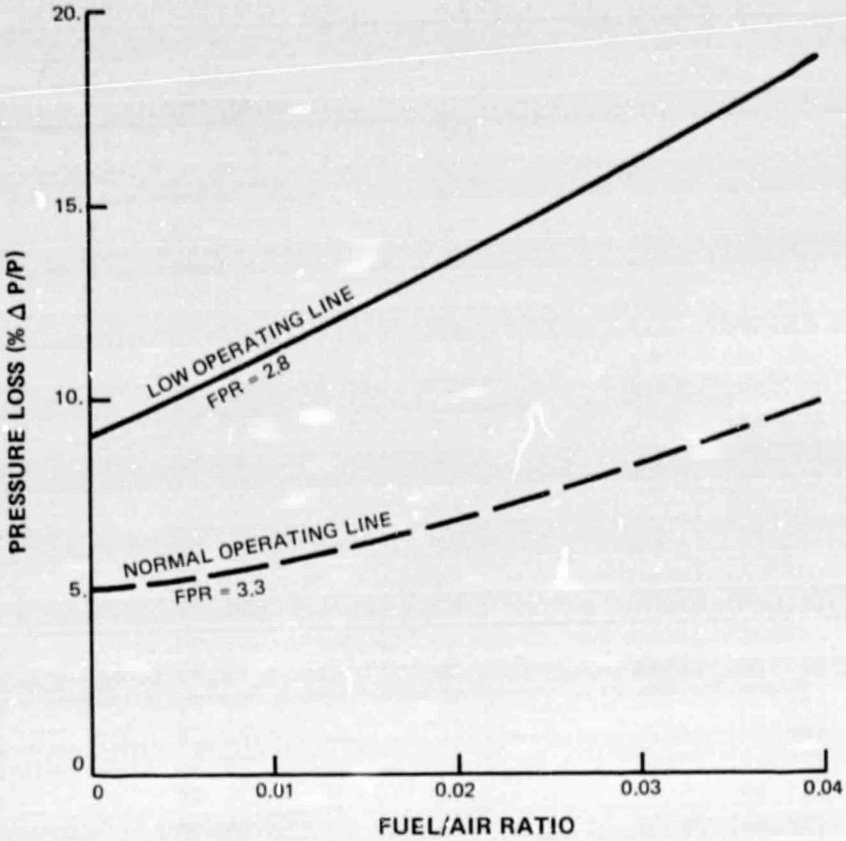


Figure 5.2-22 VSCE-515 Duct Burner P/P Versus Fuel/Air Ratio

The thrust efficiency levels of Figure 5.2-21 and the pressure losses of Figure 5.2-22 are projected from the duct burner rig test and from the testbed program which provide experimental data that is directly applicable to the VSCE-515 duct burner. In contrast, the duct burner definition for the parametric VSCE-502B was extrapolated from main burner and augmentor systems that were designed for other engine applications and had different design requirements. Therefore, the VSCE-515 duct burner definition has a more substantial base, and completely supercedes the VSCE-502B design, even though further work is required to fully establish its performance, environmental and durability characteristics.

* (Footnote) The VCE testbed acoustic test may provide data to determine the effects of fan operating line on jet noise.

The VSCE-515 emissions estimates are summarized in section 4.2.4.

5.2.3.2 Coannular Nozzle/Reverser System

Design Requirements

- o High Performance at Critical Operating Points
  - Supersonic Cruise, $C_F = 0.98$
  - Subsonic Cruise, $C_F = 0.94$
  - Takeoff, $C_F = 0.98$
- o Thrust reversing effectiveness = 40% of maximum dry takeoff thrust
- o Variable Area Capability

	ENGINE NOZZLE AREA CM^2 (in^2)	BYPASS NOZZLE AREA CM^2 (in^2)
Takeoff-maximum augmentation	6252 (969) = +20%	9703 (1504) = +216%
Takeoff-cutback	6794 (1053) = +31%	8155 (1264) = +165%
Subsonic climb	5265 (816) = + 1%	3071 (476) = minimum
Subsonic cruise	6581 (1020) = +26%	3200 (496) = + 4%
Supersonic climb	5258 (815) = + 1%	6045 (937) = +99%
Supersonic cruise	5200 (806) = minimum	4077 (632) = +33%

Design Description

Figure 5.2-23 shows a cross-section of the VSCE-515 coannular nozzle/reverser system. This definition is significantly different from the parametric VSCE-502B nozzle design because of two special requirements: an increase in the area change requirement, and to improve subsonic performance. The increase in area change is required for the engine nozzle (the inner stream of the coannular nozzle) so that the cycle matching flexibility can meet the VCE operating conditions, especially in providing the low noise inverted velocity profile during low power flyout over the community. This increase in area change eliminated the possibility of using a variable geometry splitter between the coannular streams which was the type incorporated in the VSCE-502B. Instead a translating plug is used, shown in Figure 5.2-23. An improved flowpath is required for the ejector stream to meet the performance level required for subsonic cruise. The need for this improvement was made evident from the results of initial model testing of ejector nozzles conducted in a separate NASA-P&WA program. Although the coannular nozzle configuration shown in Figure 5.2-23 is considered to be an improvement over the earlier VSCE-502B definition, more quantitative design analysis, followed by wind-tunnel model tests will be required to verify and refine the coannular nozzle/ejector/reverser system design. At the time of this writing, a nozzle design study is being conducted under a separate NASA-P&WA nozzle design-analytical contract. Results were not available for incorporation into the refined VSCE-515 definition.

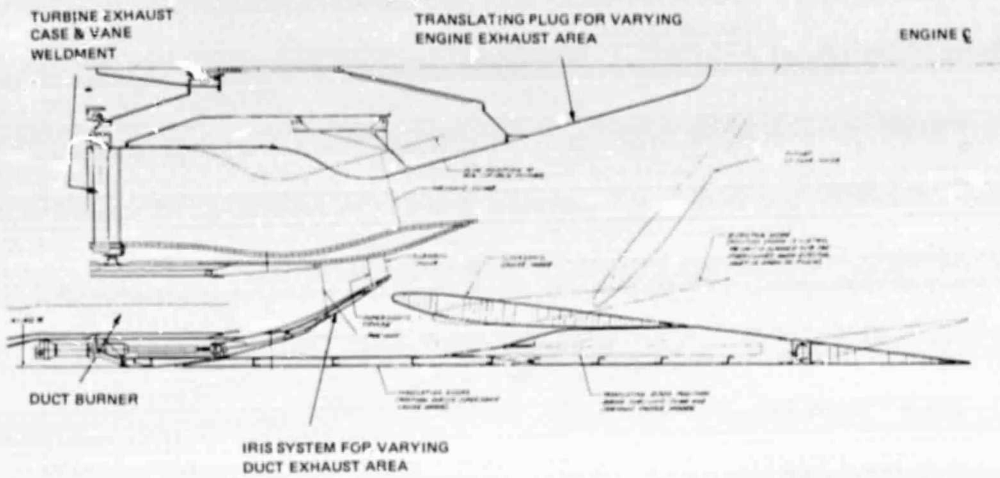


Figure 5.2-23 VSCE-515 Coannular Nozzle/Reverser System Cross-Section

LIST OF ABBREVIATIONS

AN^2	Annulus Area Times Revolutions Per Minute Squared
AST	Advanced Supersonic Technology
BCA	Best Cruise Altitude
BPR	Bypass Ratio
CET	Combustor Exit Temperature
COD	Constant Outer Diameter
C	Centerline
CMD	Constant Mean Diameter
dB	Decibel
D_{max}	Maximum Diameter
CO	Carbon Monoxide
C_x	Velocity Axial Direction
EEE	Energy Efficient Engine
ECCP	Experimental Clean Combustor Program
EGA	Extra Ground Attenuation
EGV	Exit Guide Vane
EPAP	Environmental Protection Agency Parameter
EPNdb	Effective Perceived Noise - Decibels
EPNL	Effective Perceived Noise Level
FAR	Federal Aviation Regulations
F_N	Net Thrust
h	Enthalpy
HP	Horsepower

HPC	High-Pressure Compressor
HPT	High-Pressure Turbine
IFE	Inverted Flow Engine
IGV	Inlet Guide Vane
ITS	Inverse Throttle Schedule
IVP	Inverted Velocity Profile
LB_f	Pounds Force
LB_n	Pounds Mass
LBE	Low Bypass Engine
LPT	Low-Pressure Turbine
M	Meters
NASA	National Aeronautics and Space Administration
NO_x	Oxides of Nitrogen
ODS	Oxide Dispersion Strengthened
OPR	Overall Pressure Ratio
PR	Pressure Ratio
RPM	Revolutions Per Minute
RSRDR	Rapid Solidification Rate Directional Recrystallization
SCAR	Supersonic Cruise Airplane Research
TCA	Turbine Cooling Air
TEGV	Turbine Exit Guide Vane
THC	Total Hydrocarbons
TSFC	Thrust Specific Fuel Consumption
TOBI	Tangential On-Board Injector

VCE-HTV	Variable Cycle Engine-High Temperature Validation
U	Wheel Speed
UER	Unscheduled Engine Removals
V_{REL}	Relative Velocity
VSCE	Variable Stream Control Engine
V	Velocity
VCE	Variable Cycle Engine
VCEE	Variable Cycle Experimental Engine
W_{AE}	Engine Core Airflow
W_g	Engine Airflow & Fuel Flow

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