Variable Stream Control Engine for Supersonic Propulsion

Richard W. Hines*
United Technologies Corporation, East Hartford, Conn.

The objective of this paper is to review one of the most promising propulsion systems, the variable stream control engine (VSCE), for supersonic commercial transport application. The VSCE concept employs variable geometry components and a unique throttle schedule for independent control of the fan stream and the primary stream. The benefits of advanced propulsion technology, as applied to the VSCE, are presented on an overall systems basis showing the full impact on a supersonic transport airplane from an environmental, performance, and economic viewpoint. Takeoff noise levels for the VSCE are approximately 8 EPNdB lower than those for a first generation SST turbojet. The VSCE has 20% lower fuel consumption at subsonic cruise and 0-3% higher fuel consumption at supersonic cruise than a first generation SST turbojet. The VSCE offers a weight reduction of 25% and a direct operating cost reduction of 20% relative to a single-stream engine operating at the same airflow and thrust level. The realization of potential VSCE benefits is contingent on extensive research and evaluation in many advanced technology areas.

Introduction

FOR the past five years, Pratt & Whitney Aircraft (P&WA) has participated with NASA in a program of advanced technology aimed at future supersonic commercial transports, with emphasis on improving environmental and economic characteristics. During this period, over 100 different engine concepts and cycle configurations were studied and evaluated. One of the most attractive engine configurations identified from this matrix was the variable stream control engine (VSCE). The VSCE is a conceptual engine that was defined based on propulsion studies conducted during the past few years[1-3] This study engine concept[4,5] shows the potential of a very significant improvement relative to the first-generation supersonic transport (SST) engines, such as the Rolls Royce Olympus-type engine. The variable stream control engine, as shown in Fig. 1, employs concentric jet exhaust streams and variable geometry components. (The engine cycle is selected to provide a fan stream jet velocity that is significantly higher than the primary engine stream velocity during takeoff, which is very important in providing effective and efficient noise suppression). Also, this concept, through appropriate control of the fan and primary stream components, achieves the performance of a moderate bypass ratio turbofan engine at subsonic speeds and closely approaches the best achievable supersonic cruise fuel consumption of nonaugmented turbojet engines.

Variable-Stream Control Engine (VSCE)

The advanced VSCE concept employs variable-geometry components and a unique throttle schedule for independent control of two flow streams to provide reduced jet noise at takeoff and high performance at both subsonic and supersonic cruise. Figure 1 shows the basic arrangement of the major engine components. It has a twin-spool configuration similar to a conventional turbofan engine. The low spool consists of an advanced-technology, multi-stage, variable-geometry fan and a low-pressure turbine. The high spool consists of a variable-geometry compressor driven by an advanced single-stage, high-temperature turbine. The primary burner and the duct burner utilize low-emission, high-efficiency combustor concepts. The nozzle is a two-stream, concentric, annular (coannular) design with variable throat areas in both streams and an ejector/reverser exhaust system.

The independent temperature and velocity control for both primary and bypass streams provides an inherent reduction in jet noise during takeoff. This noise reduction characteristic is based on an inverse velocity profile, where the bypass stream jet velocity is 50-70% higher than the primary stream velocity. Results from a P&WA model nozzle test program[6] sponsored by NASA indicate that noise levels measured for coannular nozzles with this inverted velocity profile are approximately 8 EPNdB (effective perceived noise level in decibels) lower than a single-stream nozzle operating at the same airflow and thrust levels. These results are based on both static tests and wind-tunnel tests simulating takeoff flight conditions. Based on these model tests, the coannular noise benefit represents a breakthrough in jet noise control. Further evaluation (a large-scale demonstration of this noise benefit) is in the planning stage.

Critical Operating Conditions

The flexibility of the VSCE concept to meet the diverse requirements of low jet noise and good fuel consumption at both supersonic and subsonic cruise can be illustrated best by describing the three most critical operating conditions: takeoff, supersonic cruise, and subsonic cruise.

Takeoff

Figure 2a depicts the unique inverted velocity profile for takeoff operation. 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 takeoff thrust and the inverse velocity profile, the duct burner is operated at its maximum design temperature of approximately 1500-2600°F. It is this condition that sets the cooling requirements for the duct burner and nozzle system. Relative to military engine augmentor systems, which approach stoichiometric combustion, the peak duct-burner temperatures for the VSCE are relatively low and will not compromise the life capability of this commercial engine.

Supersonic Cruise

For supersonic operation, the VSCE primary burner temperature is increased (relative to takeoff) , and the high

Presented as Paper 77-831 at the AIAA/SAE 13th Propulsion Conference, Orlando, Fla., July 11-13, 1977; submitted Aug. 18, 1977; revision received Dec. 27, 1977.

Index categories: Airbreathing Propulsion; Engine Performance.

*Manager of Advanced NASA Programs, Commercial Products Division, Pratt & Whitney Aircraft Group.

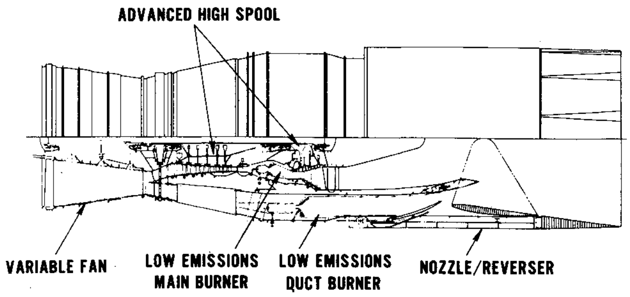

Fig. 1 Variable stream control engine.

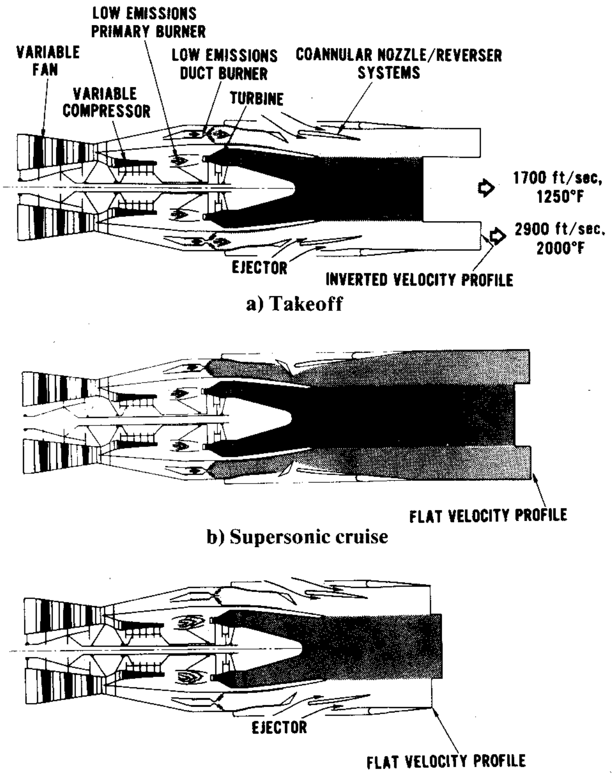

Fig. 2 Variable stream control engine at critical operating conditions.

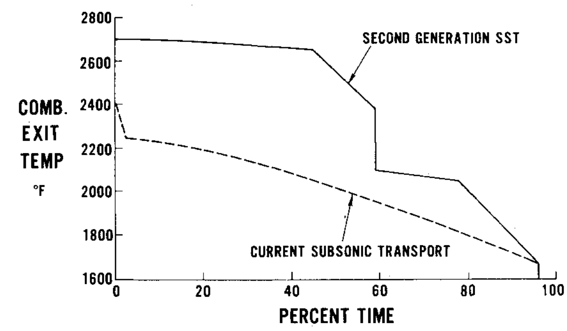

Fig. 3 Temperature/operating-time comparison.

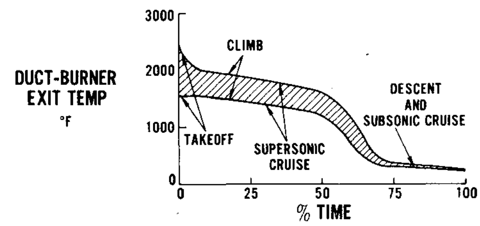

Fig. 4 Duct burner temperature/operating-time for two noise levels.

spool speed and flow rate are matched to the higher primary burner temperature. This matching technique is referred to as the inverse throttle schedle (ITS): inverse relative to conventional subsonic engines that cruise at much lower temperatures and spool speeds than they require for takeoff 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 thrust augmentation required for the duct burner during supersonic operation can therefore be reduced. At this condition, the exhaust temperatures from the coannular streams are almost equal, and, as shown in Fig. 2b, the velofity profile is flat to provide optimum propulsive efficiency. 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[7] noise levels at the other end of the operating spectrum by means of the coannular noise benefit.

Subsonic Cruise

For subsonic cruise operation, the main burner is throttled to a low temperature (2000°F), and the VSCE operates like a moderate bypass ratio turbofan. Exhaust conditions for this third critical operating point are shown in Fig. 2c. The variable-geometry components are matched to "high-flow" the engine, so that the inlet airflow and the engine airflow can be matched almost exactly. 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 reduced boattail drag. In this subsonic mode of operation, the VSCE has low fuel consumption that approaches performance levels of turbofan engines designed strictly for subsonic operation.

Hot-Section Operating Requirements

Based on operating histories of commercial engines, the hot-section components (consisting of the primary burner and the turbine assemblies) constitute a critical area of the engine regarding overall reliability and maintainability characteristics. The thermal environment in the hot section for second-generation SST engines compounds the criticality of these components, necessitating advanced materials, more effective sealing and cooling systems, and related design innovations.[8] Projected maximum combustor exit temperatures for these advanced engines are in the 2600-2700°F range. At supersonic cruise, the turbine and burner liner cooling air temperatures are in the 1200-1300°F range. Relative to current technology engines for subsonic transports, the SST engines will spend a higher percentage of operating time at supersonic cruise (Fig. 3), where the turbine blades are at maximum stress levels.[2,3] These integrated stress/time/temperature conditions require advanced material having high creep strength and oxidation resistance for turbine airfoils, turbine disks, and burner liners. Improvements in cooling effectiveness for the turbine airfoils and burner liners are also required to improve performance and meet reliability and maintainability requirements for commercial operation. The duct burner for second-generation SST engines could also be considered a hot-section component. However, the low jet noise requirement restricts the maximum exit temperatures (Fig. 4) to levels well below the design temperatures of military engine augmenters (3500°-4000°F.). With these relatively mild temperatures, emphasis for advanced augmenter technology and related design considerations can be placed on providing stability, high efficiency, and low noise and emissions rather than on very-high-temperature capability. Duct-burner design concepts that will facilitate inspection and maintenance of the augmenter itself, as well as the other engine components, will also be required.

Inlet/Engine Airflow Matching

A special feature of the VSCE concept is its capability to match inlet/engine airflow at critical operation points. The middle lines in Fig. 5 show the corrected airflow of three representative, axisymmetric, mixed-compression inlets as a function of Mach number. Also shown is a band that represents various engine airflow schedules to which the VSCE engine can be matched. These different schedules can be obtained with only minor changes to the engine design. This band of engine airflow schedules indicates the flexibility of the engine to match installations for the advanced airplane designs being evaluated in the NASA Supersonic Cruise Airplane Research (SCAR) Program. The various possible engine schedules, indicated by the band in Fig. 5, allow each installation to be optimized for the best balance between subsonic and supersonic characteristics.

As an indication of the improvement in the inlet/engine flow-matching capability of the VSCE, the subsonic cruise airflow level for the first-generation supersonic turbojet engine is also shown in Fig. 5. The VSCE schedule maintains higher levels of airflow as it is throttled back to part-power operation, such as for subsonic cruise, than the first-generation turbojet. This improves installed performance of the VSCE by essentially elminiating inlet spillage at subsonic cruise.

The high-flow capability of the VSCE shown in Fig. 5 is also beneficial during takeoff when designing the system for low jet noise. By maintaining maximum engine airflow while reducing power for low noise during takeoff operation, jet velocity (which is directly proportional to the ratio of thrust/airflow) can be minimized. In this manner, high flowing complements the coannular noise benefit during takeoff.

VSCE Stability Features and Control Requirements

The VSCE concept includes design features that provide the potential for improved stability characteristics of the overall propulsion system. The VSCE compression system incorporates variable fan and compressor stators for optimizing performance while maintaining stability margins over the entire flight envelope. Improved sensors and increased accuracy and logic provide high performance for the fan and compressor, including surge line and operating line control, and efficiency. A key stability and performance feature of the compressor is an active tip clearance control system.

The primary burner and duct burner have multizone fuel flow distribution systems. The fuel flow zone split varies with power setting to provide smooth lighting, continuous zone transfer, and low emissions. An augmenter light-off/flame-out detector in conjunction with integrated Mach number control of the augmenter fuel flow and duct nozzle provides improved stability during both augmented and nonaugmented operation. Continuously variable primary and duct nozzles provide improved stability, in addition to matching the engine with the inlet airflow and controlling jet noise. Variable nozzle areas are also required to maximize performance during supersonic and subsonic cruise conditions.

Because of the extensive use of variable-geometry components, a full-authority digital electronic control system is a critical requirement for the VSCE concept. There may be as many as 10 control system variables: 1) variable-geometry inlet, 2) variable fan stators, 3) variable compressor stators, 4) primary full flow (multizones), 5) augmenter fuel flow (multizones), 6) variable primary nozzle, 7) variable duct nozzle including an ejector, 8) reverser, 9) noise suppressor, and 10) active tip clearance controls. In contrast, current technology subsonic commercial engines have only three control system variables. Current technology hybrid hydromechanical/supervisory electronic control systems are not adequate for these engines. The advanced electronic control system provides computational capability, closed-loop, feedback safety and accuracy, and self trim/test capability.

The advanced electronic control will be integrated with the aircraft control system to realize total aircraft performance, stability, and safety advantages. Features of this integration will include performance-seeking control modes to minimize cruise fuel consumption, propulsion control resets for varying flight conditions to ensure adequate stability margins, and automatic recovery from disturbances caused by transients or other operational problems.

Improvements Relative to First-Generation SST Engine

Fuel Consumption

To compare fuel consumption characteristics of the advanced VSCE concept with first-generation turbojets such as the Rolls Royce Olympus engine, the representative turbojet was scaled to the flow size that provides the required level of supersonic thrust without operating the afterburner. The VSCE concept was sized for the same flow and then augmented with duct burning to provide the same supersonic thrust. Fuel consumption was determined for representative thrust levels of the advanced supersonic airplane at supersonic and subsonic cruise conditions. This approach yields a realistic comparison of fuel consumption characteristics of these engines.

Figure 6 shows the fuel consumption and thrust levels of the first-generation turbojet and the VSCE at subsonic cruise. The curve representing each engine shows relative fuel consumption versus relative thrust for various power settings obtained by controlling fuel flow to the primary burner. The maximum thrust available for each engine without augmentation is indicated by the point located to the right of each curve. The broken vertical line indicates the nominal thrust requirement for the advanced supersonic transport. As shown, the turbojet has excessive thrust capability and must be throttled back to 40% of its maximum nonaugmented thrust. The nonaugmented maximum thrust of the VSCE is approximately 50% lower than the turbojet, and consequently

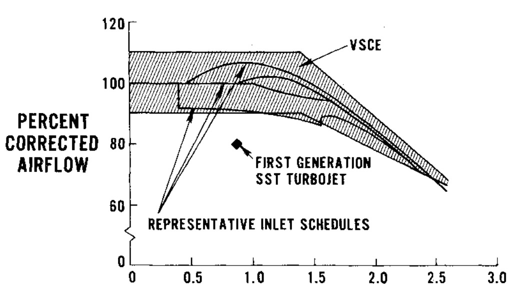

Fig. 5 Airflow schedules.

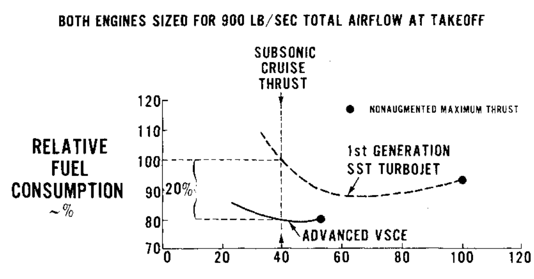

Fig. 6 Performance comparison at subsonic cruise.

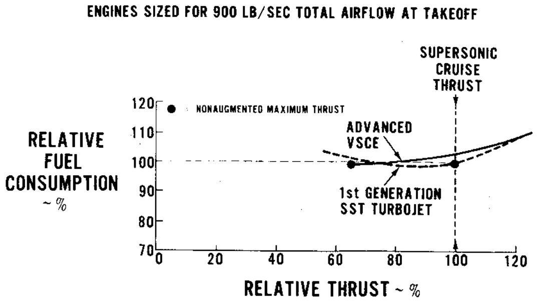

Fig. 7 Performance comparison at supersonic cruise.

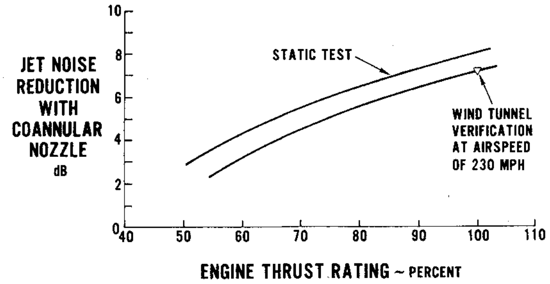

Fig. 8 Coannular noise reduction relative to single-flow nozzle based on scale-model tests.

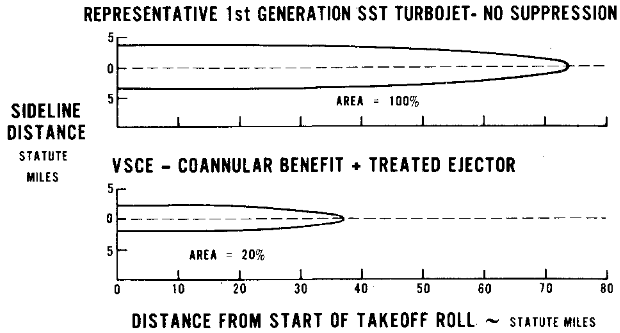

Fig. 9 Comparison of 90-EPNdB noise contours for representative turbojet and VSCE (takeoff with cutback).

the VSCE has a much better thrust match at subsonic cruise. Because of this match, and also because the VSCE concept is a more efficienct cycle with its bypass stream and unique throttle control schedule, it has 20% lower fuel consumption at subsonic cruise. This advantage has special significance when considering a potential sonic-boom restriction over inhabited land, resulting in significant flight time at subsonic conditions. The low subsonic fuel consumption minimizes the impact of this flight restriction. Another factor that amplifies the significance of subsonic fuel consumption is the effect it has on fuel reserves. A significant portion of the reserve fuel requirement is based on subsonic fuel consumption characteristics of the engines. By minimizing the amount of reserve fuel required, the VSCE improves the overall airplane design. A third factor associated with improved subsonic fuel consumption is the flexibility that it provides to operate more economically between intermediate-range city pairs or between city pairs that require a long subsonic leg. This may be a significant improvement in utilization of advanced supersonic transports.

The supersonic cruise performance characteristics are shown in Fig. 7. As a result of the sizing technique, the turbojet provides the required thrust without augmentation and is close to its minimum level of fuel consumption. Being sized for the same airflow as the turbojet, the nonaugmented thrust of the VSCE concept is lower than the required level. Duct burning is required to provide the additional thrust. For the turboject shown in Fig. 7, the region to the left of the maximum nonaugmented point represents different power settings (fuel/air ratios) for the primary burner. To the right of this point, the curve for both engines represents increasing levels of thrust augmentation with a constant primary burner setting. As shown, the fuel consumption characteristics of these engines are very close at supersonic cruise. At the nominal thrust level indicated in the figure, the VSCE fuel consumption is 3% higher than the turbojet. The VSCE shows the potential of substantial improvements in engine weight, noise, and subsonic fuel consumption without any significant compromise to supersonic fuel consumption.

Jet Noise Benefits

Pratt & Whitney Aircraft has been conducting noise and performance tests on small-scale models of the VSCE coannular nozzle under NASA sponsorship. Results from the static tests of the model nozzles showed that an inherent reduction in jet noice occurred when the outer fan stream (Fig. 2a) was operated at the high jet velocities of the VSCE cycle. This noise reduction was achieved without the use of additional parts and the thrust losses usually associated with jet noise suppressors. With encouragement from these early tests, NASA sponsored testing of the nozzle models in a wind tunnel to verify the noise reduction under simulated flight conditions. The resulting data substantiated the data obtained statically, as shown in Fig. 8. These results substantiated in small scale that the coannular nozzle would provide noise reductions of approximately 8 dB relative to a single-stream turbojet operating at the same airflow and thrust level.[6] This is a real technical breakthrough.

Whether this 8-dB reduction in jet noise will be sufficient to meet future noise requirements and still have an overall economically attractive system is not clear at this time. However, the VSCE concept has two additional advantages relative to the first-generation SST engines in regard to jet noise. For very low noise levels, the duct burner and main burner temperatures can be lowered and the engine scaled up with a lower weight penalty than a conventional turbojet. The VSCE has an inherent engine weight advantage at any given airflow size. Since jet noise is proportional to thrust per pound of airflow, once the thrust and noise requirements are selected the engine airflow is also determined. The VSCE's bypass ratio of approximately 1.3 relative to 0 for the turbojet results in much lighter engine weight for a given total airflow or jet noise level. The VSCE cycle can also be reoptimized for a lower fan pressure ratio and higher bypass ratio in order to minimize oversizing the engine. Another advantage for the VSCE is that, if a mechanical jet noise suppressor is necessary, it only has to be included in the duct portion, as the VSCE engine primary stream is designed low enough not to need suppression. This concept makes it easier to store any mechanical suppressors during cruise operation when the suppressor is no longer deployed.

The VSCE concept allows the use of programmed throttle scheduling (variable engine power setting) to make use of extra ground attenuation (EGA) and engine shielding to permit higher thrust during takeoff and for the initial climbout to the takeoff noise measuring station. The object is to achieve a higher cutback altitude for reduced community noise or, for a given noise level, to reduce the engine size and achieve greater airplane range. The basic requirement to accomplish this programmed throttle noise benefit is that the engine must have the capability for high specific thrusts. Of the various types of engines that have been studied, only the variable stream control engine has this capability for high specific thrust. By use of programmed throttle schedule, the noise footprints (90 EPNdB contour) can be reduced by over 50% relative to a conventional constant throttle schedule.

A total benefit of the VSCE relative to the first-generation SST engine in jet noise is shown in Fig. 9 in terms of takeoff community noise footprints.[5] When both engines are sized

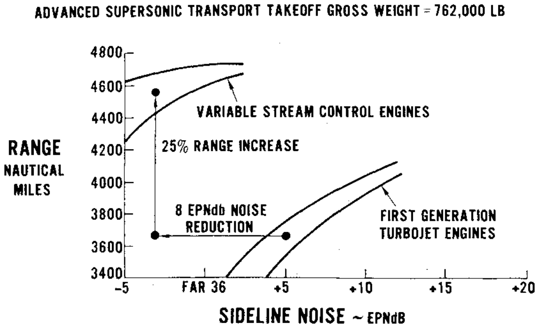

Fig. 10 Potential impact of advanced supersonic technology on aircraft range and noise relative to FAR part 36 noise levels.

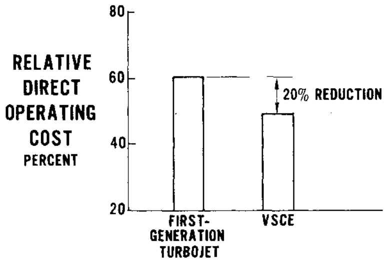

Fig. 11 Potential impact of advanced supersonic technology on economics.

for equal airflow, the turbojet subjects a much larger ground area (five times greater) at a 90-EPNdB noise level than the VSCE. Most of this reduction is attributed to the coannular noise benefit.

Total VSCE Improvements

The improvements provided by the VSCE study engine relative to the first-generation SST engine are as follows: jet noise, −8 dB (unsuppressed); engine weight, −25% (equal flow size); fuel consumption for subsonic cruise, −20%; and fuel consumption for supersonic cruise, +3%. The 8-dB takeoff nose reduction results from the coannular nozzle jet noise suppression. The 25% weight improvement results from the two-stream engine configuration, where as much airflow bypasses the engine core as passes through it, thereby reducing the size and weight of the engine core, and from the use of advanced technology components. The 20% lower fuel consumption at subsonic cruise is due to the VSCE engine operating as a conventional turbofan at these conditions. The improvement in subsonic fuel consumption provided by the VSCE is particularly important, since the VSCE-powered supersonic aircraft will be capable of cruising substantial distances over land, where supersonic operation may be prohibited by sonic boom noise constraints, without a loss in range capability. At supersonic cruise conditions, the VSCE fuel consumption is approximately 3% higher than that of the turbojet because of cycle differences.

The overall effect of the VSCE characteristics on supersonic transport airplane performance is very significant, as shown in Fig. 10. The VSCE offers both a 25% improvement in airplane range and a 8-dB reduction in noise during takeoff. Consequently, practical airplane range with acceptable noise levels appears possible with this advanced technology engine.

The estimated economic benefits of the VSCE are illustrated in Fig. 11. The VSCE offers a 20% reduction in direct operating cost relative to a comparable airplane using scaled first-generation SST engines. This large improvement is due to the increase in airplane size in addition to the improvement in aircraft and powerplant technology. This improvement may be sufficient to permit the SST to compete effectively with the wide-body subsonic aircraft for the first class and full economy fare long-range passenger business.

Technology Requirements for Advanced VSCE

The realization of the potential benefits of the VSCE propulsion system, relative to the first-generation Olympus-type engine, is contingent on extensive research and evaluation in many advanced technology areas. The most critical of these technology requirements are the following: 1) low-noise/high-performance coannular nozzle, 2) low-emission/high-efficiency burner systems, 3) variable-geometry components (nozzle/ejector/reverser, inlet, fan, compressor), 4) high-temperature burners and turbines with commercial life, 5) electronic control system, and 6) integrated propulsion system. The first two areas, the low-noise coannular nozzle and the clear combustor systems, are critical for both environmental and economic characteristics. The variable-geometry components contribute to low noise and also to performance improvements. The high-temperature materials affect engine weight and cooling air requirements for the hot sections of these engines which, in turn, affect performance. An electronic control system complements the variable-geometry components by providing accurate closed-look control with a lighter system than can be obtained with conventional hydromechanical controls. The last item, the integrated propulsion system, represents a broad area of design interfaces between the engine and airplane (inlet/engine, nozzle/reverser, and engine/airframe interfaces). It includes structural and aerodynamic considerations to ensure structural and aerodynamic compatibility between advanced VSCE concepts and advanced supersonic airplanes. These integration features influence installed performance characteristics as well as operational characteristics such as inspection and servicing of the complete propulsion system.

References

[1] "Advanced Supersonic Propulsion Study," Final Rept.—Phase I, NASA CR-134633, Jan. 1974.

[2] "Advanced Supersonic Propulsion Study," Final Rept.—Phase II, NASA CR-134904, Sept. 1975.

[3] "Advanced Supersonic Propulsion Study," Final Rept.—Phase III, NASA CR-135148, Dec. 1976.

[4] Howlett, R.A., "Variable Stream Control Engine Concept for Advanced Supersonic Aircraft—Features and Benefits," *Proceedings of the SCAR Conference,* Pt. 1, Session III, No. 15, NASA CP-001.

[5] Howlett, R.A. and Kozlowski, H., "Variable Cycle Engines for Advanced Supersonic Transport," Society of Automotive Engineers, Paper 751086, Nov. 1975.

[6] "Aero-Acoustic Tests of Duct-Burning Turbofan Exhaust Nozzles," Final Rept.—NASA CR-2628, July 1976.

[7] "Noise Standard: Aircraft Type Certification," Federal Aviation Regulation as defined in Federal Register, Nov. 18, 1969.

[8] Howlett, R.A., "Engine Design Considerations for Second Generation Supersonic Transports," Society of Automotive Engineers, Paper 750628, May 1976.