VARIABLE STREAM CONTROL ENGINE CONCEPT FOR ADVANCED SUPERSONIC AIRCRAFT – FEATURES AND BENEFITS

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SUMMARY

The Variable Stream Control Engine being studied for advanced supersonic cruise aircraft shows potential for significant environmental and performance improvements relative to first-generation supersonic turbojet engines. This engine concept has two separate flow streams – each with independent burner and nozzle systems. By unique control of the exhaust temperatures and velocities in these two coannular streams, significant reduction in jet noise may be obtained. This engine has the potential for other major improvements, including matching the engine flow schedule with the inlet airflow at critical operating points, improved stability, and a less severe thermal environment for the thrust augmentor and nozzle/reverser systems. Technology programs are required to qualify and demonstrate these potential improvements. The most critical programs are: expanded configuration testing and large-scale noise tests of coannular nozzles, and experimental evaluation of advanced combustor concepts for the duct burner.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) is engaged in studies of advanced technology for future supersonic commercial aircraft, with emphasis on improving environmental and economic characteristics. As part of this overall program, Pratt & Whitney Aircraft (P&WA) is conducting advanced propulsion studies which are directed toward three basic objectives:

- Evaluation of a variety of conventional and unconventional engine types, in terms of environmental and economic factors,
- Identification of engine concepts that warrant further study. These studies include engine/airframe integration evaluation, and an assessment of the impact of advanced technology,
- Direction of critical technology programs so that a data base can be established for guiding future supersonic engine design decisions.

The time frame for this study program is consistent with advanced technology projections that would provide the capability for a U.S. entry into the commercial supersonic aircraft market by the late 1980's or early 1990's. The engine definitions and related technolgy requirements described herein would, therefore, be applicable to second-generation supersonic cruise aircraft.

The approach for this on-going study program has been to conduct broad parametric studies of many types of conventional and unconventional engine concepts. These parametric engines were evaluated, compared, and screened on the basis of environmental and economic characteristics. The most promising concepts were then selected for further evaluation including refinement studies and preliminary design.

Over 100 different engine types and configurations have been studied and evaluated in this program. The broad scope of the study is indicated by the general types of configurations illustrated in figure 1. Shown are cross-sections (top half only) of some of the conventional and unconventional engines that were evaluated. Several of the variable cycle engine configurations have very significant improvements relative to first-generation supersonic engines. The advanced engine configuration identified as having the greatest potential is the Variable Stream Control Engine (VSCE).

The potential improvements provided by the advanced VSCE concept relative to first-generation supersonic engines are shown in table 1. The 8 dB reduction in take-off noise results from the use of a coannular nozzle with an inverted velocity profile. The 25 percent 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 also from advanced technology components. The 20 percent 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 three percent higher than that of the turbojet because of cycle differences.

The overall potential of the VSCE on advanced supersonic aircraft performance is very significant, as shown in figure 2. The VSCE offers both a 25 percent improvement in airplane range, and an 8 dB reduction in noise during take-off. Significant improvements in the enonomic characteristics of advanced supersonic aircraft will also be provided by the VSCE.

DESCRIPTION OF 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 take-off and high performance at both subsonic and supersonic cruise. Figure 3 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 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 require low emissions, 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 take-off. This noise reduction characteristic is based on an inverse velocity profile, where the bypass stream jet velocity is 60 to 70 percent higher than the primary stream velocity. Results from a P&WA model nozzle test program 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 dB) 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 take-off 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 variability 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: take-off, supersonic cruise, and subsonic cruise.

Take-Off

Figure 4a depicts the unique inverted velocity profile for take-off 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 take-off thrust, and the inverse velocity profile, the duct-burner is operated at its maximum design temperature of approximately 1430°C (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 take-off), and the high spool speed and flow rate are matched to the higher primary burner temperature. This 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 they require for 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 thrust augmentation required for the duct-burner during supersonic operation can therefore be reduced. At this condition, the exhaust temperature from the coannular streams are almost equal and, as shown in Figure 4b, the velocity 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 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 (< 1090°C (< 2000°F)), and the VSCE operates like a moderate bypass ratio turbofan. Exhaust conditions for this third critical operating point are shown in figure 4c. 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 reduces boat-tail 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.

INLET/ENGINE AIRFLOW MATCHING

A special feature of the VSCE concept is its capability to match inlet/engine airflow at critical operating points. Figure 5 shows the mass flow ratio for a representative, axisymmetric, mixed-compression inlet as a function of Mach number. Also shown is a band that represents various engine airflow schedules for the VSCE. 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 SCAR program. The various engine schedules indicated by the band in figure 5 allow each installation to be optimized for the best balance between subsonic and supersonic characteristics. The bottom half of the band in figure 5 corresponds to engines with high ratios of supersonic/subsonic airflow. The top half corresponds to low ratios. Relative to an engine that is matched exactly to the inlet airflow schedule, the bottom of the band represents an engine match that reduces fuel consumption at supersonic cruise (more engine airflow - less augmentation). However, this improvement is gained at the expense of subsonic performance (larger inlet resulting in a small installation loss). The top half of the band represents an engine matched for a more efficient airplane design at supersonic cruise (higher lift-to-drag ratio – reduced thrust requirements), but with some additional complexity to the inlet (such as the requirement for more variable geometry) to accommodate the relative increase in engine flow requirements at subsonic cruise.

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 figure 5. The subsonic airflow schedule differences between these two engines is shown in figure 6 over a range of thrust levels. The VSCE schedule maintains higher levels of airflow as it is throttled back to part-power operation, such as for subsonic cruise. As indicated in figure 6, the VSCE can handle significantly higher airflow than the first-generation turbojet engine at subsonic cruise. This improves installed performance of the VSCE by essentially eliminating inlet spillage at subsonic cruise.

The high-flow capability shown in figure 6 is also beneficial during take-off when designing the system for low jet noise. By maintaining maximum engine airflow at part-power take-off 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 take-off.

VSCE STABILITY FEATURES

The VSCE concept includes design features which 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 control accuracy and logic provide high performance for the fan and compressor, including surge line and operating line control, self-trim, 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 two-zone fuel flow distribution systems. The fuel flow zone split varies with power setting to provide smooth lighting, continuous zone transfer, and low emissions. An augmentor light-off/flame-out detector in conjunction with integrated Mach number control of the augmentor fuel flow and duct nozzle provides improved stability during both augmented and non-augmented operation.

Continuously variable primary and duct nozzles provide improved stability, in addition to matching the engine with the inlet airflow, and controlling jet noise. This variable nozzle geometry, in conjunction with improved sensors, provides sufficient flexibility to tune the propulsion system for component variations associated with manufacturing tolerances or from deterioration and transient effects.

Because of the extensive use of variable geometry components, a full authority digital electronic control system is a critical requirement for the VSCE concept. Current technology hybrid hydromechanical/supervisory electronic control systems are not adequate for this engine. The advanced electronic control system provides computational capability, closed-loop feed-back safety and accuracy, and self trim/test capability.

This 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 insure adequate stability margins, and automatic recovery from distrubances caused by transients or other operational problems.

CRITICAL TECHNOLOGY REQUIREMENTS AND PROGRAMS

To realize the potential benefits shown in figure 2 for the VSCE concept, the critical technologies listed in table 2 will be required. The programs needed to substantiate these technologies over the next ten years are shown in figure 7. There are five basic programs:

1. Feasibility demonstration of those components most critical to the success of the VSCE using small-scale rig tests. These components include the low-emissions duct burner, the main burner, and the coannular nozzle.

2. Evaluation of the critical technology duct burner and coannular nozzle in large-scale tests in an engine environment.

3. Substantiation testing of demonstrator engine components.

4. Substantiation of the VSCE concept by demonstrator engine testing.

5. Studies of the integrated propulsion system, involving both the airplane and engine manufacturers.

Programs 1 through 4 would be conducted sequentially, with the small rig tests preceding the large-scale component and engine tests. This is a low risk approach where the preliminary testing and screening is accomplished in relatively inexpensive component rigs. The integration study must be conducted by both the airplane and engine manufacturers concurrent with the engine technology programs. This is necessary to ensure that all of the interfaces are appropriately understood and resolved, and that the propulsion system design is tailored to give the best overall airplane performance and economics. These technology programs would bring us to the point where a full-scale supersonic engine development program could be initiated.

CONCLUSION

In conclusion, the advanced VSCE concept with its coannular nozzle has been identified as having the best combination of performance and noise characteristics. This engine has promise of making significant environmental and economic improvements to advanced supersonic aircraft. Establishing technology readiness for this engine is a formidable challange, both technically and financially, and NASA-sponsored programs will have a dominant effect on the eventual timing and success of advanced supersonic aircraft.

TABLE 1

IMPROVEMENT PROVIDED BY VARIABLE STREAM CONTROL ENGINE RELATIVE TO FIRST-GENERATION SUPERSONIC TURBOJET ENGINE

Take-off noise	8 dB reduction
Engine weight	25 percent reduction
Specific fuel consumption at	
Subsonic cruise	20 percent reduction
Supersonic cruise	3 percent increase

Note: Comparisons made by scaling first-generation turbojet engine to flow size of variable stream control engine

TABLE 2

CRITICAL TECHNOLOGY REQUIREMENTS FOR VSCE CONCEPT

- Low noise – high performance coannular nozzle
- Low-emissions – high efficiency burner systems
- Variable geometry components
    - Nozzle/ejector/reverser
    - Inlet
    - Fan
    - Compressor
- High temperature burners and turbines with commercial life
- Integrated propulsion system
- Electronic control system

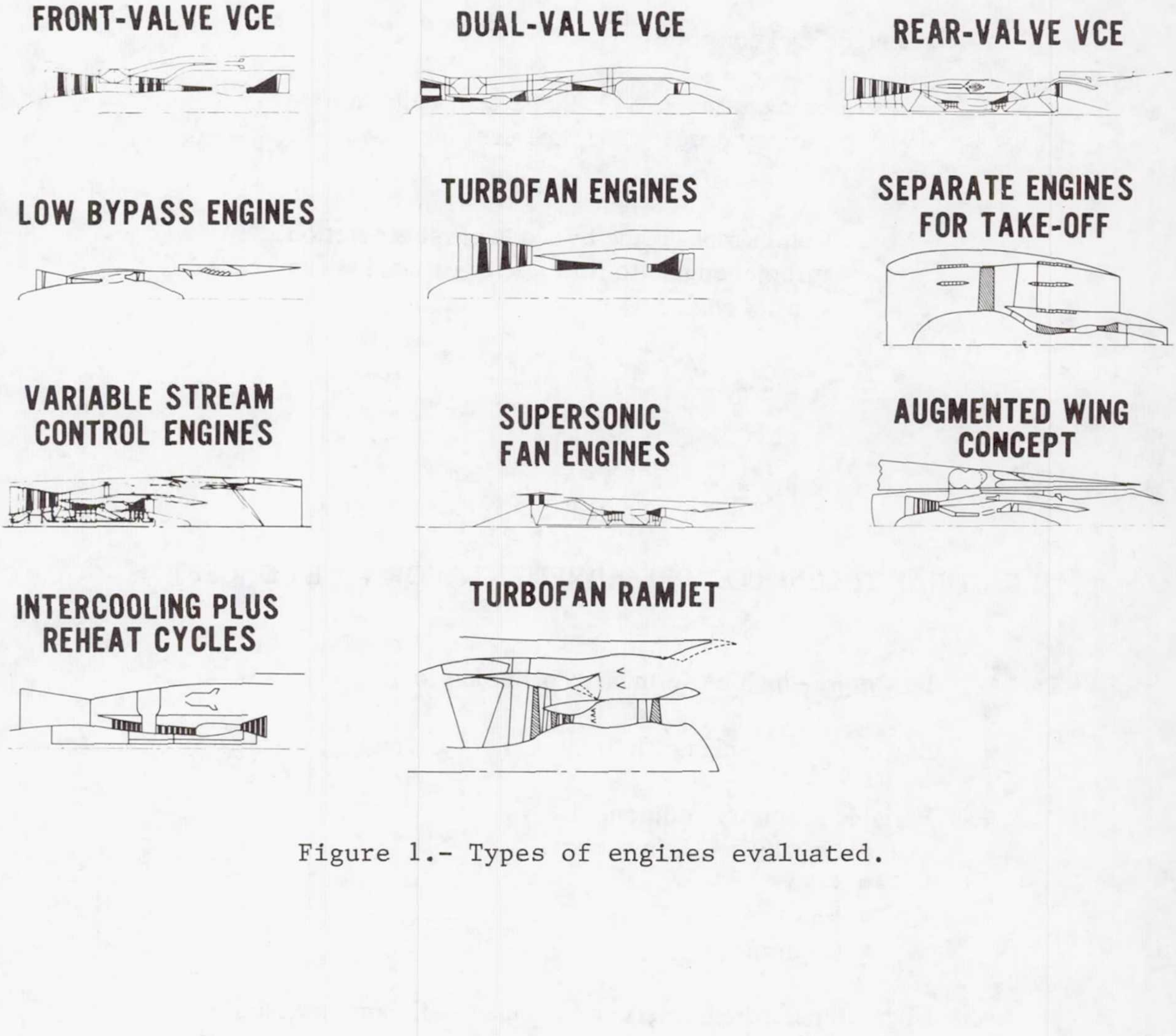


Figure 1.- Types of engines evaluated.

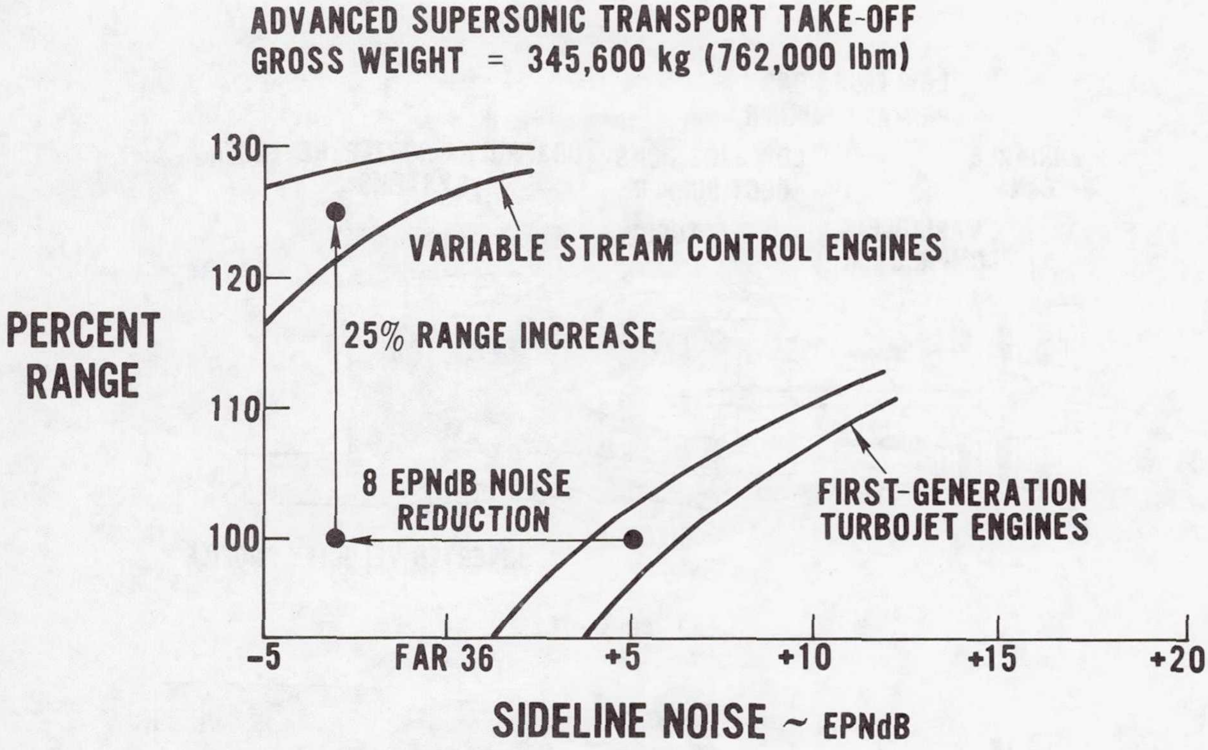


Figure 2.- Potential impact of advanced supersonic technology on aircraft range and noise.

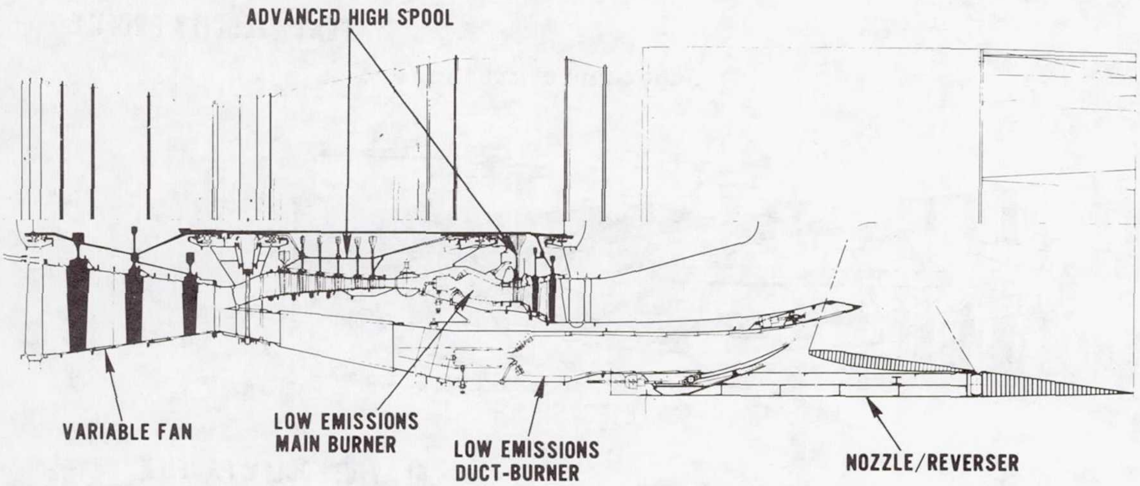
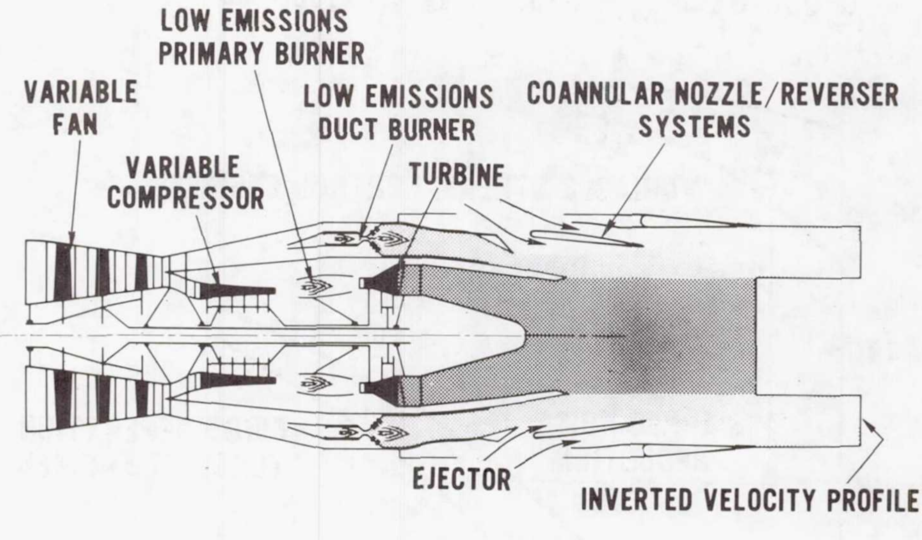
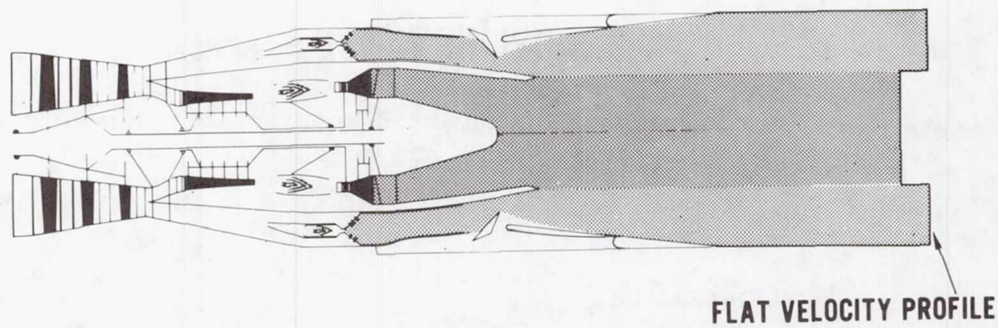


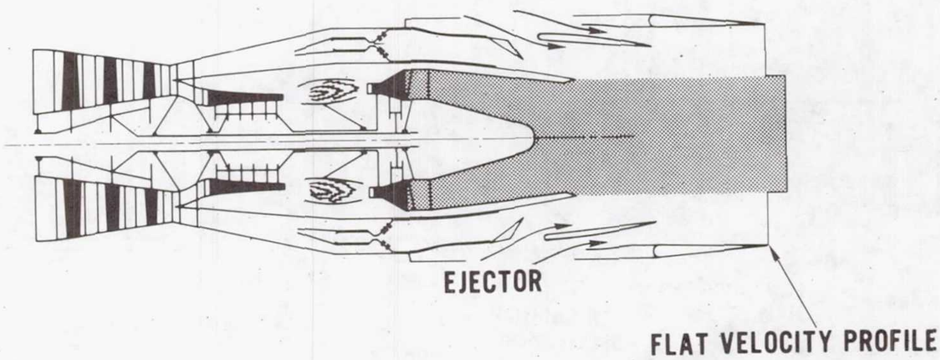
Figure 3.- Variable stream control engine cross-section.



(a) Take-off.



(b) Supersonic cruise.



(c) Subsonic cruise.

Figure 4.- Variable stream control engine at critical operating conditions.

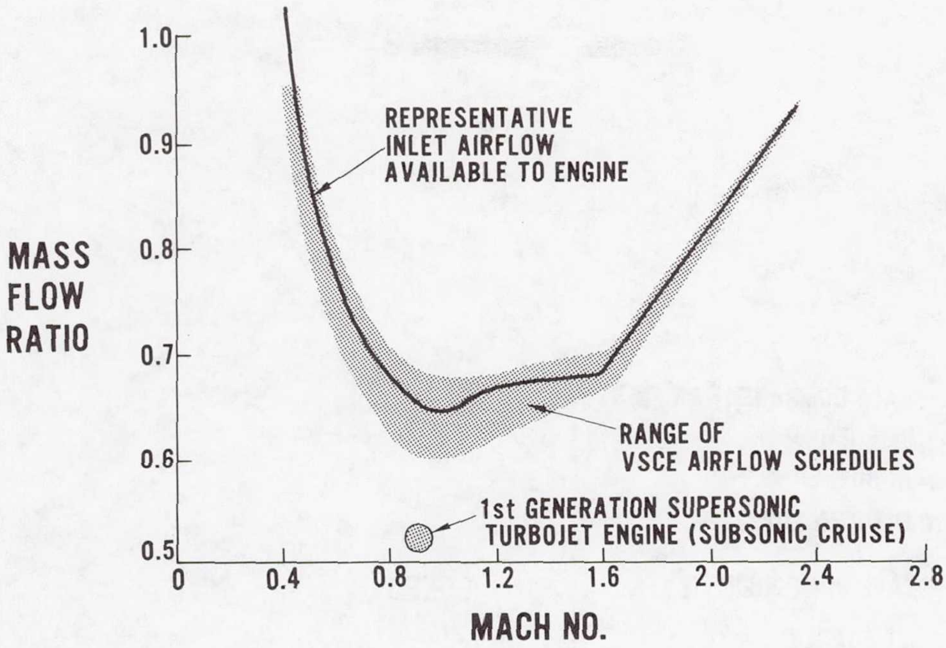


Figure 5.- Mass flow ratio versus Mach number for a representative supersonic inlet and for the VSCE.

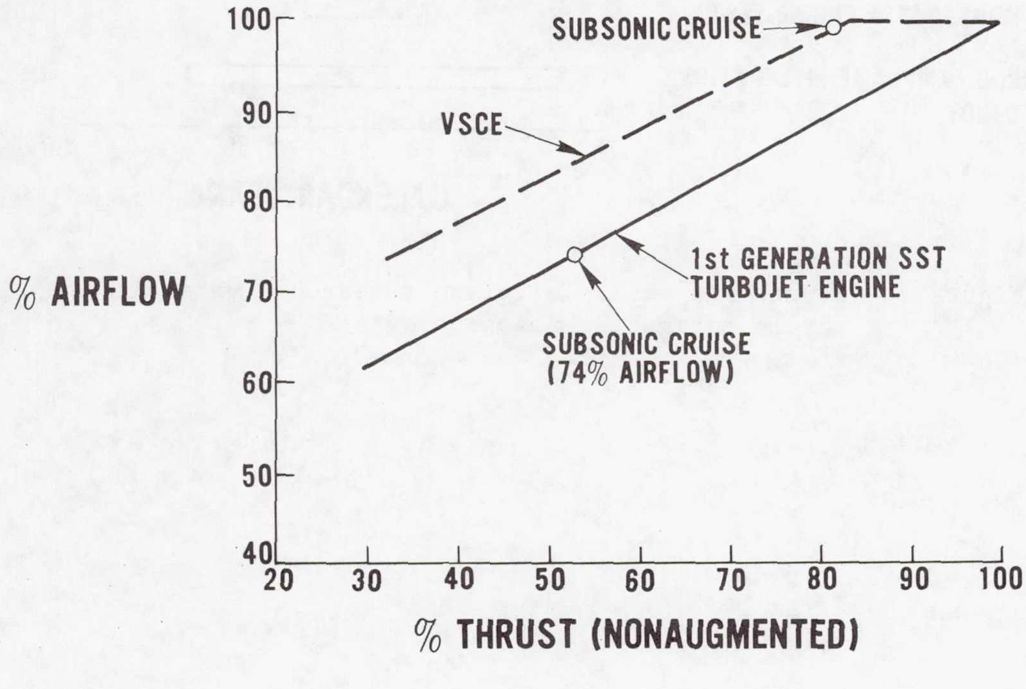


Figure 6.- High-flowing capability of VSCE relative to first-generation supersonic turbojet engine.

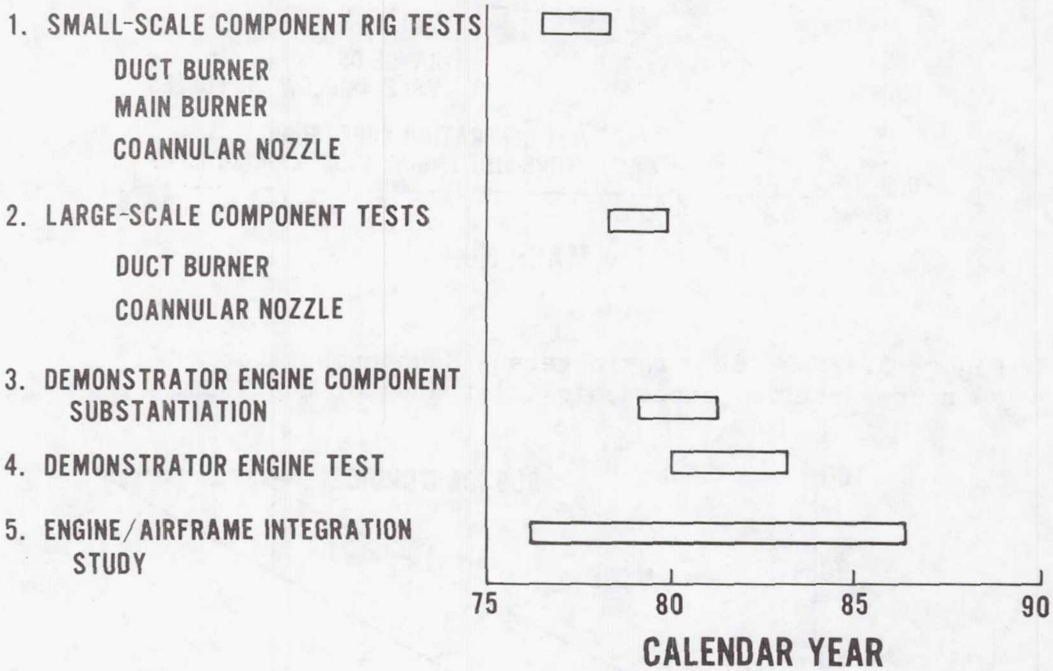


Figure 7.- Supersonic cruise airplane research - variable cycle engine technology programs.