VARIABLE STREAM CONTROL ENGINE FOR ADVANCED SUPERSONIC AIRCRAFT DESIGN UPDATE*

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SUMMARY

The Pratt & Whitney Aircraft study engine concept for a second-generation supersonic transport, the Variable Stream Control Engine (VSCE), has been updated in terms of mechanical design definition and estimated performance. The design definition reflects technology advancements projected for the late 1980 time period that improve system efficiency, durability and environmental performance. On the basis of the design update, technology requirements were established. The components unique to the VSCE concept, a high performance duct burner and a low noise coannular nozzle, and the high temperature components are identified as critical technologies. Technology advances for the high temperature components (main combustor and turbines) are not exclusive to the VSCE, but are equally applicable to any advanced supersonic propulsion system whether a low bypass engine, inverted flow engine or other variable cycle engine configuration. To address the requirements in this area, the technical approach for undertaking a High Temperature Validation Program has been defined. The multi-phased effort would include assorted rig and laboratory tests, then culminate with the demonstration of a flight-type main combustor and single-stage high-pressure turbine at operating conditions envisioned for a VSCE.

INTRODUCTION

For the past seven years, Pratt & Whitney Aircraft has been conducting analytical and experimental technology programs under NASA sponsorship in the area of advanced supersonic technology. A result of earlier parametric cycle studies (refs. 1-4) was identification of the Variable Stream Control Engine (VSCE) concept as having the greatest potential to meet performance, environmental and economic requirements for a second-generation supersonic cruise vehicle. The Variable Stream Control Engine is based on two unique components -- a high performance duct burner for thrust augmentation and a low noise coannular nozzle.

As this engine concept has evolved (refs. 5-7), substantial progress has been made in refining the basic mechanical configuration as well as system aerothermodynamic and environmental performance. The VSCE design history is illustrated in Figure 1 showing progress made since its inception to the most recent study configuration, the VSCE-515.

* Work performed under NASA Contract NAS3-21389

The VSCE-515 reflects the latest technology projections in the areas of advanced aerodynamics, materials and structure-mechanics. As defined, the technology in the VSCE-515 could be attainable to be commensurate with an engine development program in the late 1980 time period. This could lead to engine certification in the mid 1990's.

This paper describes the VSCE-515 and also outlines plans for a future technology program, the High Temperature Validation Program, which is a major step in realization of a mid 1990 certification date.

VARIABLE STREAM CONTROL ENGINE - AN OVERVIEW

The Variable Stream Control Engine is an advanced, moderate bypass ratio turbofan configuration that uses duct burner thrust augmentation, along with a coannular nozzle for jet noise reduction. A distinctive operating feature is the independent control of both core and fan stream temperature and velocity levels for in-flight cycle matching. Cycle matching is further enhanced by a technique referred to as the inverse throttle schedule. The inverse throttle schedule offers the following advantages:

- o Meeting the unique thrust schedule of advanced supersonic cruise aircraft over the entire flight spectrum,
- o Provides low core exhaust velocity at takeoff to obtain the inverted velocity profile and associated noise benefit, and
- o Minimizing fuel consumption at supersonic cruise by high flowing the core engine to control the cycle bypass ratio.

Thus, the inverse throttle schedule is a feature that enables sizing the VSCE for optimum supersonic cruise performance, while also meeting FAR (Federal Aviation Regulation) Part 36 noise levels at the other end of the operating spectrum by means of the coannular noise benefit. Figure 2 illustrates the in flight flexibility of the VSCE with the inverse throttle schedule at three key flight conditions -- takeoff, subsonic cruise and supersonic cruise.

As indicated during takeoff, the main burner is throttled to an intermediate power setting so that jet noise from the core stream is low. However, the duct burner is operated at a moderate temperature level to provide both the required takeoff thrust and inverted velocity profile. For climb out over the community, both streams are throttled back, and the inverted velocity profile is retained. Relative to military afterburner systems, the peak duct burner temperatures are low for the VSCE.

At the takeoff power settings corresponding to FAR Part 36 sideline and community noise levels, the variable components (fan, high-pressure compressor, nozzle exhaust system) and throttle settings are matched to "high flow" the engine. High flowing is the capability to maintain maximum design flow during part power operation for low noise. This capability complements the coannular noise benefit to enhance overall noise characteristics of the VSCE.

The engine operates as a moderate bypass ratio turbofan during subsonic cruise. As a result, it has fuel consumption characteristics that are significantly improved relative to a turbojet cycle at this condition. Figure 2b shows the engine configuration that achieves a flat exit velocity profile for the attendant fuel economy benefits. The main burner operates at a low exit temperature and there is no duct augmentation. 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. In turn, installation losses, including boattail drag, are reduced.

At supersonic cruise, fuel consumption characteristics approach those of a cycle designed exclusively for supersonic operation. The main burner temperature is increased (relative to takeoff), and the high spool speed is also increased. This is accomplished with the inverse throttle schedule by matching the variable engine components to a higher main burner temperature and high-pressure spool flow rate. The high flow condition reduces the cycle bypass ratio so the level of duct burner thrust augmentation required during supersonic operation can be decreased. As shown in Figure 2c, 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.

VARIABLE STREAM CONTROL ENGINE DESIGN UPDATE

Updating the Variable Stream Control Engine design definition involved surveying projected technology advancements that offer improvements in cycle efficiency, weight, durability and environmental performance. The technology projections were based on the following:

- Test results and experience acquired from the current NASA sponsored VCE Technology Programs -- the Duct Burner Segment Rig Program, the Coannular Nozzle Model Program and the VCE Testbed Program
- A technology forecast that extends component technology levels in the areas of aerodynamics, materials/cooling and structure mechanics five years beyond that in the NASA/Pratt & Whitney Aircraft Energy Efficient Engine Program.
- Technology readiness attainable by the late 1980 time period with engine certification to follow in the mid 1990's.

Engine General Description

The updated Variable Stream Control Engine, study designation VSCE-515, retains the same basic configuration as the preceding engine definition, the VSCE-502B. A cross-sectional view of the VSCE-515 is presented in Figure 3. The dual spool configuration is designed for an inlet mass flow of 340 kg/sec (750 lb/sec) at sea level static conditions. All components are arranged in a close-coupled manner to provide an optimum flowpath by avoiding transition ducts in either the core or fan stream. Structurally, the low-pressure spool is supported by three main bearings and the high-pressure spool is supported by two. This five bearing arrangement povides a short, stiff rotor system for optimum blade tip clearance control.

In the mechanical design, the low-pressure spool contains a three-stage fan driven by a two-stage turbine. The high-pressure spool uses a single-stage turbine to drive a five-stage compressor. The main combustor is an annular, staged system similar in concept and operating principle to the duct burner. Both combustion systems are based on the Vorbix (vortex burning and mixing) technology demonstrated under the NASA/Pratt & Whitney Aircraft Experimental Clean Combustor Program. The exhaust nozzle system is a coannular configuration that includes an ejector with acoustic treatment and a thrust reverser. Management and control of integrated engine/aircraft operating functions is accomplished with a full-authority electronic control system. Components with variable geometry capability are the fan, the high-pressure compressor and the coannular nozzle. A more detailed description of the individual component designs is presented in a subsequent section of this paper.

VSCE-515 Performance Relative to First-Generation Supersonic Propulsion System

The performance improvements offered by the VSCE-515 relative to the first-generation supersonic transport engine are presented in Table I. The reduction in takeoff noise by 8 dB results from the jet noise suppression produced by the coannular exhaust nozzle. For a constant engine flow size, a 23 percent weight reduction results from the two-stream engine configuration where as much airflow bypasses the core as passes through it, thereby reducing core size and weight. Also, the advanced component designs and materials contribute substantially to this weight improvement.

The capability of a VSCE to operate as a conventional turbofan during subsonic cruise offers a significant 20 percent improvement in fuel efficiency compared to first-generation engines. These improvements in subsonic fuel consumption, noise, and engine weight are obtainable while still maintaining good supersonic fuel consumption characteristics. Improvements in subsonic fuel consumption are particularly important with respect to meeting environmental performance goals since VSCE-powered aircraft will be capable of cruising subsonically over land without a loss in range where supersonic cruising is prohibited by noise constraints.

The overall effect of VSCE characteristics, based on the level of technology in the updated engine, is very significant on advanced supersonic airplane performance, as shown in Figure 4. The VSCE-515 offers both a 25 percent improvement in airplane range and an 8 dB reduction in takeoff noise. Thus, this engine configuration provides the potential for practical airplane range while maintaining acceptable noise levels.

VSCE-515 Component Definition

Fan

The fan in the VSCE-515 is an advanced three-stage unit, and the design concept emphasizes high efficiency at supersonic cruise, compatibility with supersonic inlets and compatibility with the duct burner. Compatibility with the duct burner necessitates high diffusion capability. The aerodynamic design is based on a low elevation (low hub to tip ratio) to meet nacelle envelope dimensions established by the Supersonic Cruise Research (SCR) airplane contractors for good installed performance and provide space for packaging accessories around the case. A tip speed of approximately 487 m/sec (1600 ft/sec) has been established as optimum on the basis of low-pressure turbine blade stress considerations, in addition to the emphasis for high efficiency and low noise.

In the mechanical design, the first two rotating stages contain low aspect ratio blades made of an advanced composite material. The high strength properties of composite materials eliminate the requirement for part span shrouds. Conventional titanium material blades are required in the third stage because of the higher temperature environment. The trailing edge of the inlet guide vane and leading edge of the fan exit guide vane are variable. For noise suppression, axial spacing between the blades and vanes in each stage is increased in a graduated manner.

High-Pressure Compressor

The high-pressure compressor in the VSCE-515 is unique compared to other advanced subsonic commercial engines because it operates at a high exit temperature of 649°C (1200°F) during supersonic cruise as well as at a low pressure ratio and high rotational speed. As defined, the compressor is a five-stage, drum-type rotor with integral abradable trench tip rubstrips. The blades are multiple circular arc controlled-diffusion airfoils and the vanes in the first two stages have variable geometry capability. All airfoils are coated with an advanced erosion resistant coating. Interstage cavities are designed for low volume and multiple knife-edge seals provide effective interstage sealing to reduce recirculation losses.

Main Combustor

Because of environmental constraints, compounded by prolonged high temperature operation at supersonic cruise, design requirements for the main combustor in a VSCE reflect a substantial departure from requirements for current subsonic applications. A combustor configuration considered for the VSCE-515 is an annular two-stage design, based on the Vorbix operating principle. However, another design concept, derived from more conventional low emissions combustion systems, was also considered as part of this design update.

In the two-stage configuration, the first stage is a pilot premixing zone where combustion is initiated. Combustion is completed in the second stage or main combustion zone. Each stage has a separate fuel supply system, and air for combustion is introduced into the main combustion zone through a series of swirler tubes.

The liners are a double wall structure with an efficient impingement transpiration cooling scheme. For additional thermal protection, the interior liner surfaces are coated with a thermal barrier ceramic coating.

High-Pressure Turbine

The high-pressure turbine, as in preceding generations of VSCEs, is an advanced single-stage system. This configuration is designed for sustained high temperature operation at high rotational speeds and high mechanical loadings.

The design concept specifically addresses effective coolant management and the use of advanced materials with high temperature capability. Airfoils, both rotating and stationary, are designed with internal cooling passages to promote a high heat transfer rate and cooled with advanced convective and film cooling techniques. One feature of the turbine cooling system is the use of a heat exchanger to reduce the coolant temperature so that a smaller percentage of cooling air is required. The heat exchanger uses fan air as the cooling medium of the turbine coolant.

The airfoils are made from materials that offer superior creep strength properties, along with a good resistance to thermal fatigue. Both the vanes and the blades are coated with a dual coating that consists of a high grade ceramic material for added thermal protection, plus a substrate oxidation coating.

Low-Pressure Turbine

Many of the design features used in the high-pressure turbine have been adapted for the low-pressure turbine. Basically, the low-pressure turbine is designed for efficient operation at a high rotational speed. The high speed capability allows a two-stage configuration and provides a low elevation flowpath for the three-stage fan. The flowpath also has a low profile to minimize the duct burner diameter. This is a key design consideration since the low-pressure turbine and duct burner together set the maximum nozzle diameter.

Both stages are air cooled. However, like in the high-pressure turbine design, cooling losses are minimized by the application of advanced materials, coatings and cooling air management techniques. Interstage sealing is accomplished with conventional platform single knife-edge seals. The blade tips, which incorporate mini shrouds, also have a knife-edge sealing arrangement.

Duct Burner

The duct burner, one of the unique components in the Variable Stream Control Engine concept, is a simplified two-stage version of the three-stage configuration currently undergoing experimental testing in the Duct Burner Rig

Technology Program and VCE Testbed Program. Results from these efforts will be instrumental in improving the design definition.

The aerothermal definition is based on the Vorbix technology, and the design employs many of the technology features in the main combustor. The first combustion zone, or pilot/low power stage, is a double wall geometry. This stage is enclosed by a hood to ensure positive air management for combustion and dilution. The second zone, the high power stage, resembles the primary combustion zone in the main burner. The liner is also a double wall construction, and a series of aerodynamically-designed swirler tubes introduces the combustion air. An insulating ceramic coating is used in this stage for additional temperature capability.

Exhaust Nozzle System

The exhaust nozzle is the other unique component in a VSCE. The nozzle is comprised of three main components: the nozzle proper, the ejector and the reverser. If a mechanical jet noise suppressor is required, it will be included only in the duct stream and the main engine stream will be designed with a low exit velocity which will not require suppression. Progress from the present analytical effort and from anticipated follow-on model tests will have a large influence in optimizing the aerodynamic and acoustic design of the exhaust nozzle system.

The nozzle is coannular in design with variable geometry capability in both fan and core streams. An iris system is employed for varying the fan stream exit area. In the core stream, area variations are achieved by a translating plug. The nozzle is constructed from a lightweight material, and a small percentage of cooling is used to maintain acceptable metal temperature levels. The ejector and reverser are also constructed from a lightweight material. For added noise suppression, the ejector is lined with an acoustic treatment.

Electronic Control System

All engine operating functions such as air and fuel flows are coordinated and controlled by a full-authority electronic control system. The use of electronics, in comparison to hydromechanical units, enables responsive and accurate management of the engine components to match the operating requirements of the flight condition. In addition, the physical size and weight of the unit are greatly reduced. Input for control is provided by advanced sensing devices which monitor key operating parameters. Sensing redundancy is provided to ensure failsafe operation.

TECHNOLOGY REQUIREMENTS AND FUTURE PROGRAM CONSIDERATIONS

VSCE Technology Requirements

Technology requirements for a VSCE propulsion system are identified in Figure 5. Of these requirements, the duct burner, coannular nozzle and high temperature components -- the turbines and combustor -- are the areas most critical. At present, work under NASA sponsorship is proceeding with the components unique to the VSCE concept. Efforts have been successful in demonstrating the design feasibility and performance potential of both the duct burner and coannular nozzle. However, the demonstration of technology should be expanded to include the high temperature components.

To indicate the necessity for advancements in the area of main engine high temperature technology, Figure 6 presents a comparison of VSCE operating temperatures with another advanced engine design, the Energy Efficient Engine, which is representative of the next generation of subsonic engines. The temperature levels correspond to cruise operation which comprises at least 50 percent of the total engine operating time. As shown, VSCE hot section temperatures are elevated appreciably over the Energy Efficient Engine levels. For further comparison, Figure 7 shows the contrast among the VSCE, the Energy Efficient Engine and a current technology subsonic engine, the JT9D. In addition to elevated turbine and cooling air temperatures, the VSCE is matched to high-flow the core during supersonic cruise for low fuel consumption. However, this produces the maximum rotational speeds and attendant stress levels. Thus, the combination of operating at high temperatures, high stress levels and extended operating times makes high temperature technology a critical requirement.

Future Program Considerations

Continued work in the Duct Burner Technology Program, Coannular Nozzle Technology Program, and VCE Testbed Program is required. Because of the importance of high temperature technology, a High Temperature Validation Program has been defined as the next major technology program. The following paragraphs present an overview of the High Temperature Validation Program.

High Temperature Validation Program

The overall objective of the High Temperature Validation Program is to substantiate the critical technology for a main combustor and single-stage high pressure turbine that reflects the requirements for a second-generation, commercial supersonic propulsion system. This objective would be accomplished by first verifying individual concepts in the areas of materials/cooling, aerodynamics and structures through a series of component rig evaluations, followed by a collective demonstration of the different technologies in real engine environment using a high-pressure spool as the testbed. As planned, the program is organized into three phases, as indicated in Figure 8.

The initial phase of the program involves the concept selection and the preliminary design definition. As part of this effort, advanced component concepts for the combustor and turbine would be evaluated analytically in terms of design feasibility, performance potential, technical risk, fabricability, and overall cost.

Phase II starts the design verification and component refinement process. Technologies selected for High Temperature Validation Program would be combined and rig tested for overall compatibility and suitability. Material characterization testing would be conducted first. This would be followed by a series of specialized cascade and rig tests to demonstrate specific aerodynamic and cooling technologies.

The third phase of the program focuses on a technology validation test. In this effort, the configuration of the main combustor and single-stage high-pressure turbine, as derived from the preceding work, would be tested in a high-pressure spool arrangement. Testing would be completed over a range of operating conditions, including simulated high altitude, envisioned for a VSCE. The test program would consist of a series of diagnostic evaluations to assess all aspects of performance as well as durability.

CONCLUDING REMARKS

The battery of studies completed during the past several years has corroborated the economic and environmental attractiveness of the Variable Stream Control Engine concept for a second-generation supersonic cruise vehicle. In addition the technology requirements have been established. This leads to the next logical step, technology demonstration as the prerequisite to achieving technology readiness.

In this respect, technology development has been limited to the unique components in the VSCE configuration, namely the duct burner and coannular nozzle system. Although continuing these efforts, particularly the work under the VCE Testbed Program, is essential, work should be expanded to other key areas if engine certification by the mid 1990's is a realistic goal.

On the basis of technology requirements, the main combustor and turbines should be the next area of concentration. High temperature technology, since it is noncommittal to any particular engine configuration, has a wide application and offers the greatest return in technology for a given program investment. For example, the High Temperature Validation Program, as outlined in this paper, would address VSCE requirements but also provide the technology base for other advanced supersonic engine concepts such as the low bypass engine and inverted flow engine. Also, the technical achievements would be applicable to advanced commercial transport and military engines.

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TABLE I - IMMPROVEMENTS PROVIDED BY VSCE
RELATIVE TO FIRST-GENERATION SUPERSONIC TURBOJET ENGINES

Takeoff Noise	8 EPNdB Reduction
Specific Fuel Consumption	
Subsonic Cruise	20 Percent Reduction
Supersonic Cruise	1 Percent Increase
Engine Weight	23 Percent Reduction

Note: Comparisons made by scaling first generation turbojet engine to flow size of VSCE

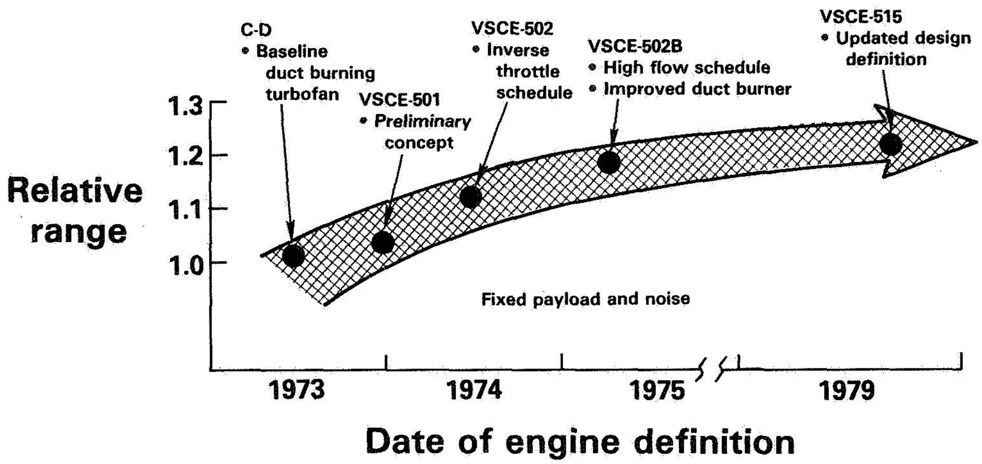

Figure 1.- Variable stream control engine evolution.

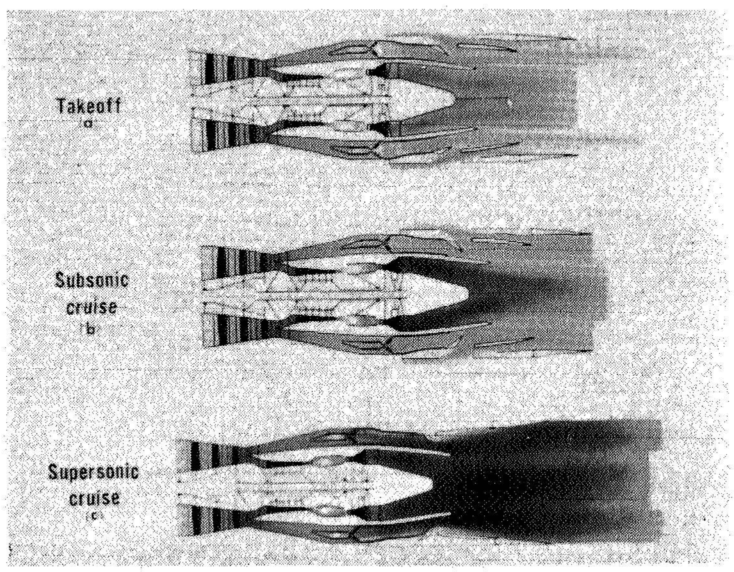

Figure 2.- VSCE with inverse velocity profile at critical flight conditions.

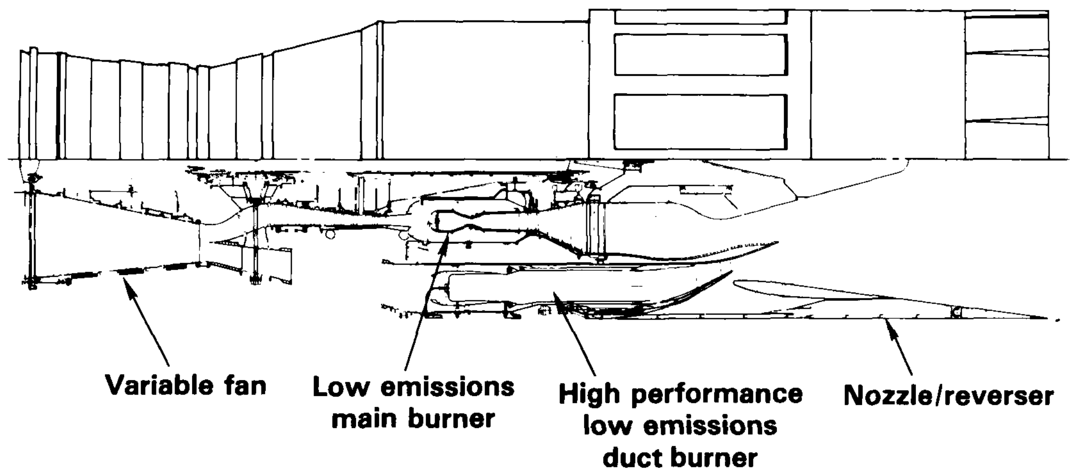

Figure 3.- Cross sectional view of the VSCE-515.

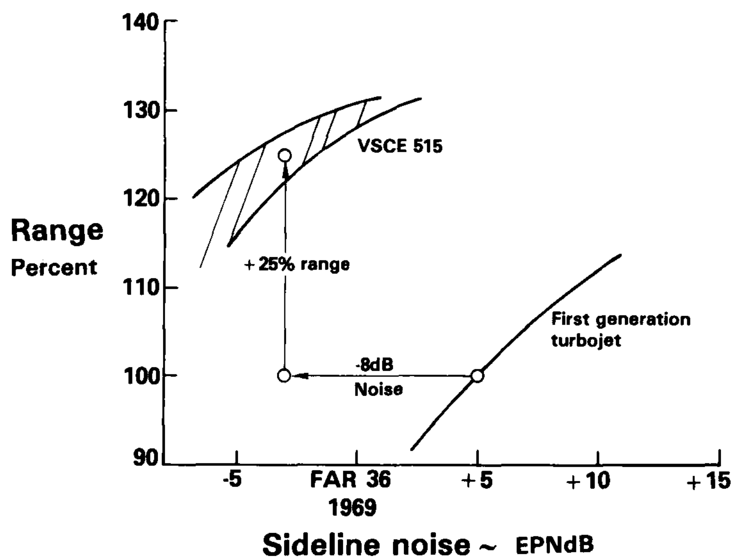

Figure 4.- VSCE performance improvement relative to first-generation turbojet.

- **Duct burner**
- **Coannular nozzle**
- **High temperature components**
  - Main combustor
  - Turbines
- **Stowable jet noise suppressor**
- **Variable geometry components**
  - Fan
  - Compressor
- **Integrated electronic control system**

Figure 5.- VSCE critical technology requirements.

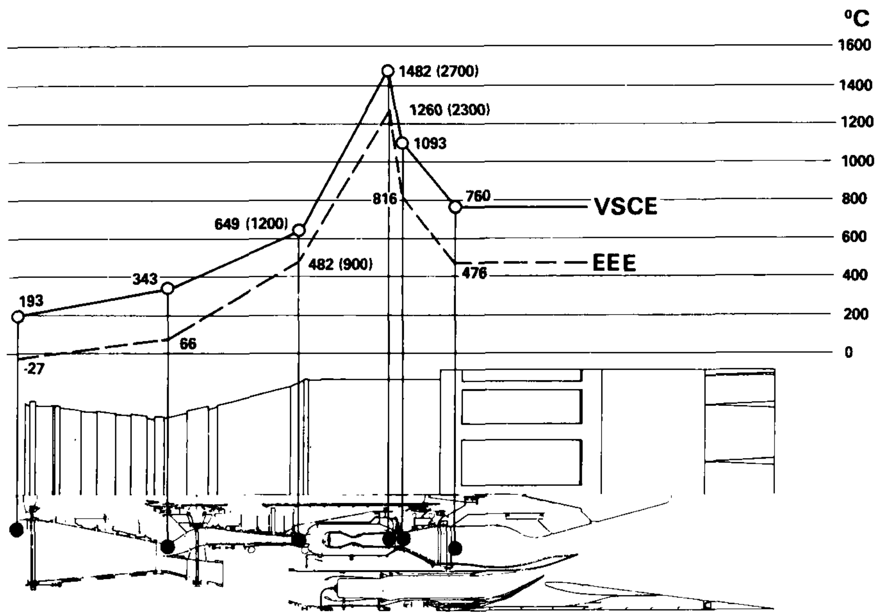

Figure 6.- VSCE operating temperature levels compared to the advanced technology energy efficient engine.

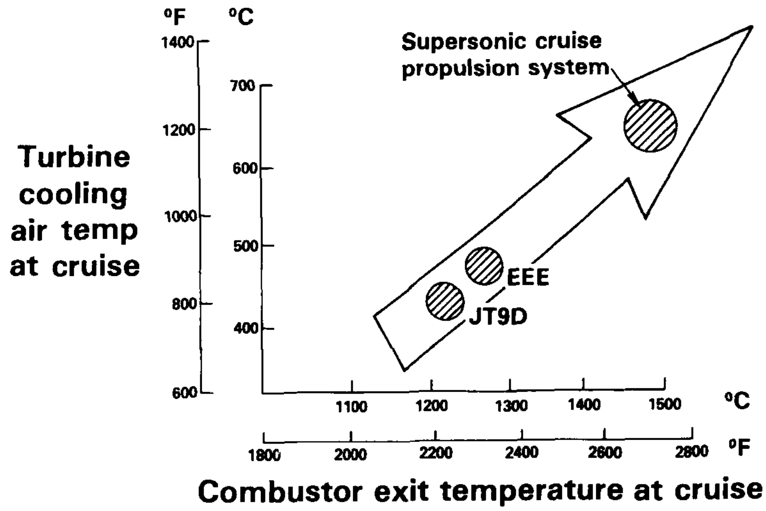

Figure 7.- Temperature levels at cruise.

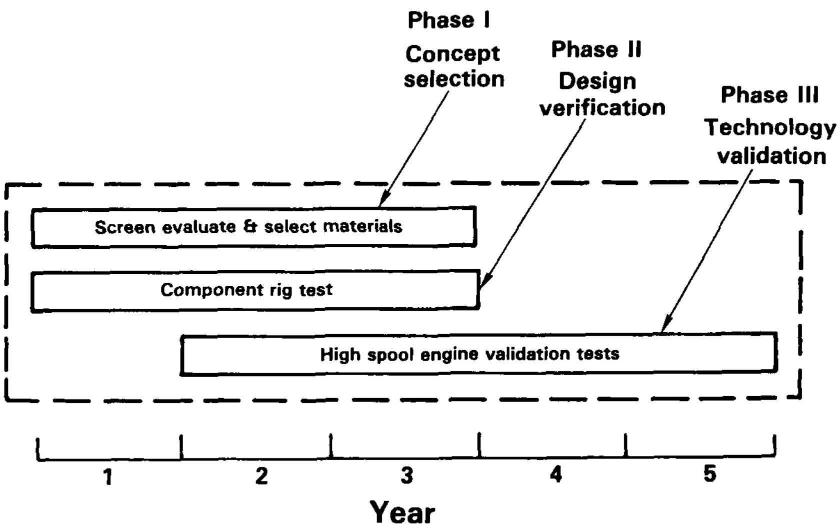

Figure 8.- High temperature validation program schedule.