COMPONENT TEST PROGRAM FOR VARIABLE-CYCLE ENGINES

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SUMMARY

The NASA Lewis Research Center supersonic cruise aircraft research program (SCAR) involves propulsion study contracts with the General Electric Company (G.E.) and Pratt & Whitney Aircraft (P&WA). Through these contracts, promising variable-cycle engine (VCE) concepts for a supersonic cruise aircraft have been identified. These VCE concepts incorporate unique critical components and flow path arrangements that provide good performance at both supersonic and subsonic cruise and appear to be economically and environmentally viable.

Certain technologies have been identified as critical to the successful development of these engine concepts and require considerable development and testing. To assess the feasibility and readiness of the most critical VCE technologies, the Lewis Research Center has begun a VCE component test program through a series of contracts to the two engine companies. Large-scale test hardware will be integrated with existing high-technology core engines.

In their variable-stream-control engine (VSCE) component test program, P&WA will test and evaluate an efficient low-emission duct burner and a quiet coannular ejector nozzle at the rear of a rematched F100 engine.

In their component test program G.E. will, in addition to evaluating a quiet, coannular, high-radius-ratio plug nozzle, simulate the double-bypass engine (DBE) cycle concept using modified YJ101 hardware. The fan will be split into two blocks to provide the second bypass stream required by the double-bypass concept. Variable-geometry features will be added to the engine to provide the control necessary to demonstrate a mode-switching capability.

INTRODUCTION

Advanced supersonic cruise aircraft will be required to operate efficiently over a wide variety of flight conditions without significant impact to the environment. This creates conflicting requirements on the propulsion system that can be met most effectively by a variable-cycle engine (VCE) (ref. 1). Typically, a VCE has two or more distinct operating modes, each tailored to provide a high level of efficiency at one or more major flight conditions such as takeoff, subsonic cruise, and supersonic cruise.

After screening numerous engine cycles, including preliminary design of the better concepts, NASA and the engine companies have identified two promising engine cycles from the supersonic cruise aircraft research (SCAR) studies. These engine concepts are the General Electric double-bypass, variable-cycle engine (DBE) (ref. 2) and the Pratt & Whitney Aircraft variable-stream-control engine (VSCE) (ref. 3). Each of these concepts represents a significant advance over conventional engines. They may be viewed as VCE's because of extensive flow modulation either through variable components, valving, novel control techniques, or combinations of these features. Both engine concepts use high airflow for takeoff. They take advantage of coannular flow to reduce jet noise, bypass flow to reduce engine weight and improve off-design subsonic cruise performance, and high turbine inlet temperatures to provide good supersonic performance with bypass flow.

To demonstrate the feasibility, readiness, and performance of some of the most critical technologies peculiar to these engine concepts, the Lewis Research Center has begun a component test program for variable-cycle engines through a series of contracts to the two engine companies. Phase I of this program consists of further component concept screening and rig testing directed toward achieving the goals established in the SCAR propulsion studies. Phase II will consist of modifying an existing high-performance core engine to simulate, to the extent practical, these VCE concepts. Many other technologies need further development before a VCE can be put into commercial service. However, these technologies are not unique to VCE; they are common to many other advanced engine applications.

PROGRAM OBJECTIVES AND STRUCTURE

Program Objectives

The specific objectives of the VCE component test program are as follows:

(1) Demonstrate coannular jet noise reduction in large scale and in a real engine environment. Thus far, this noise reduction has been verified only with small-scale models having diameters about one-tenth of the full size.

(2) Evaluate the performance of selected unique VCE components. Pratt & Whitney will evaluate a coannular ejector nozzle and a low-emission, high-efficiency duct burner. General Electric will evaluate a unique coannular plug nozzle together with a variable-geometry, split-flow fan and flow control valves.

(3) Provide the technical basis for future experimental VCE's. Successful completion of the current program should enable us to confidently proceed into an experimental engine program. Such a program could provide complete cycle simulation, allowing performance testing at simulated climb/acceleration and cruise conditions as well as at takeoff.

Program Structure

The overall structure of the VCE component test program is illustrated in figure 1. Results of the SCAR studies, the acoustic model tests, and the component rig testing will be used in an engine and program definition study. During this phase of the program, both contractors will continue model tests of the coannular nozzle and will refine the aerodynamic lines of the exhaust systems. Candidate duct-burner configurations will be selected and rig tested by P&WA. A variable-flow front fan will be designed and rig tested by G.E. However, because of the lengthy development time, the fan will not be incorporated in the test-bed engine. The engine and program definition study will define the details of the test-bed engine configuration and the components to be used in this program.

The two branches at the bottom of figure 1 show the test-bed engines to be built. The P&WA test-bed engine will use a rematched military F100 engine with its exhaust flow separated to provide exhaust conditions similar to those of the VSCE. An advanced high-efficiency duct burner and coannular ejector nozzle will be added. Pratt & Whitney will evaluate duct-burner emissions as well as jet noise.

The G.E. test-bed engine will be based on a military YJ101 core engine. The fan will be split into two blocks to provide the two bypass streams necessary to the double-bypass concept. Variable-geometry features will be added to provide the control necessary to demonstrate a mode-switching capability. A high-radius-ratio coannular plug nozzle will be installed to verify the jet noise suppression predicted by the model tests. This will be the first test of the systems compatibility and stability of the double-bypass VCE concept.

ENVIRONMENTAL CONSIDERATIONS

Jet Noise

An important characteristic of supersonic cruise engines is the need for high specific thrust to overcome drag at supersonic conditions with minimum weight penalty and low installation losses. Engines designed for efficient supersonic operation would therefore normally also have high takeoff jet velocities and require noise suppression to meet FAR 36 limits. The upper band of data in figure 2 shows sideline noise relative to the FAR 36 limit as a function of fully expanded jet velocity for conventional mixed-flow nozzles sized with the area variation needed to produce a constant thrust. It can be seen that the turbojet engine planned for the U.S. supersonic transport (SST) in 1970 would have required about 15 EPNdB of suppression to meet the FAR 36 sideline noise limit. It is questionable whether such a retractable mechanical suppressor could have been built. At any rate, it would have been heavy and inefficient.

Model tests of coannular nozzles by P&WA and G.E. in the SCAR and VCE programs (refs. 4 to 6) have shown that an inherent noise reduction can be obtained when the outer annulus jet velocity V_j is appreciably higher than that of the inner stream, as shown in the nozzle sketch in the lower right corner of figure 2. This reduction can be as much as 8 to 10 EPNdB, as shown by the lower band of data in figure 2, relative to a conventional mixed-flow nozzle having a jet velocity equal to that of the outer annulus of the coannular system with an inverted velocity profile. A conventional turbojet engine would require a 45-percent reduction in jet velocity to meet the FAR 36 sideline noise limit without suppression. The weight penalty involved in oversizing a conventional turbojet to obtain the needed takeoff thrust with such a low jet velocity would be prohibitive. An adverse performance mismatch with the airplane would also occur, especially at subsonic cruise. By using bypass flow in a turbofan engine to increase takeoff thrust, the weight penalty can be reduced at these lower jet velocities. With the coannular inverted exhaust velocity profile, the annulus jet velocity can be raised to a value about 40 percent higher than for the conventional engine at the same noise level. This therefore reduces the total airflow (or engine size) requirement. The subsonic cruise performance match with the airplane is also improved with the bypass engine sized in this way.

Emissions

The development of variable-cycle engines to meet acceptable exhaust emission standards will face many of the same problems currently being addressed in on-going research for low-emissions combustors. However, in addition to the main combustor, both candidate VCE's employ low levels of augmentation during certain critical stages of operation. The environment for the duct burner and afterburner is entirely different than for the main combustor, and the pressure, temperature, and velocity conditions are less compatible for efficient low-emission burning.

Since the VCE will cruise well into the stratosphere, major concern focuses on the oxides-of-nitrogen (NO_x) emissions and their effect on the ozone layer. At this condition, the pressure and temperature into the duct burner of the VSCE favor lower NO_x emissions relative to the main combustor.

Figure 3 compares the normalized performance of several combustor concepts in terms of the relative NO_x emission index at supersonic cruise. The normalizing factor may vary from 20 to 50 grams per kilogram of fuel, depending on the cruise Mach number and the engine operating condition. Since the emission index scale presented is relative, it may, as a first approximation, be applied to augmentors as well as main combustors. The clean-combustor concepts being developed in the NASA/industry experimental clean-combustor program (ECCP) (refs. 7 and 8) show the possibility of a 50-percent reduction in NO_x emissions in burner-rig experiments. However, the emissions goal for the duct-burner application is 1 gram of NO_x per kilogram of fuel. This extremely low level, as well as operational considerations, may require even more advanced techniques to be applied. Further combustion improvements are predicted for such concepts as premix combustion. Results based on small-scale, idealized laboratory experiments are encouraging and indicate potential reductions of tenfold at supersonic cruise conditions. However, any appreciable reduction in NO_x emissions below the ECCP level will require extensive and costly research and development programs to determine if they can be adapted to meet SST burner requirements.

Stringent EPA goals have been proposed for carbon monoxide (CO), total unburned hydrocarbons (THC), and NO_x for future airport environments. During takeoff (sideline and cutback) the duct burner presents a more difficult problem than the main combustor relative to CO and THC. The cycle parameters (low pressure and temperature) that tend to help relieve the cruise NO_x problem become detrimental during takeoff and result in a somewhat lower combustion efficiency. Advanced techniques such as staged combustion and variable geometry may be required to raise combustor efficiency and lower emissions.

COMPONENT TEST PROGRAM

Variable-Stream-Control Engine

VSCE engine concept. - The P&WA VSCE engine concept (ref. 3) is shown schematically in figure 4. It features a coannular ejector exhaust nozzle and uses a duct burner in the bypass stream to obtain the coannular inverted velocity profile. Therefore, at takeoff the turbine inlet temperature is restricted to achieve the inverted velocity profile needed for low noise. However, at supersonic conditions this temperature must be as high as the state of the art allows to obtain good specific fuel consumption (sfc) at the high thrust levels needed. Despite this high temperature, duct burning must be used to obtain adequate thrust at supersonic cruise. Also with bypass flow, some duct burning is desirable from an sfc or propulsive efficiency standpoint to equalize the jet velocities of the two streams. A higher level of duct burning is required in supersonic climb/acceleration to obtain optimum thrust margins.

A variable-area, duct-stream nozzle is required to accommodate changes in the duct-burner temperature setting. Variable geometry in the fan and compressor is used in conjunction with the variable geometry in both exhaust nozzles to schedule airflow and shaft speed in order to match engine airflow with inlet airflow and minimize the supersonic bypass ratio.

VSCE component test bed. - Figure 5 shows schematically the test-bed concept to be used in testing the two most critical and unique components of the PW&A VSCE: (1) the coannular exhaust nozzle with the inverted velocity profile, and (2) the low-emissions, high-efficiency duct burner. An existing high-technology F100 turbofan engine will be used to provide the proper gas conditions into the duct burner and primary nozzle, similar to those of the conceptual VSCE at takeoff conditions. The exhaust flow from the F100 will be kept separated by an add-on bypass duct downstream of the turbines. Although the duct burner in this test will be farther downstream than it would be in an actual flight engine, this should not have a major impact on the jet noise tests or the duct-burner emissions tests. Every attempt will be made to keep costs low by using existing hardware wherever possible. Not only is an existing F100 engine being used as the gas generator, but an existing TF30 iris nozzle is planned for the duct nozzle throat.

The duct-burner design will be selected on the basis of results from duct-burner conceptual screening and rig testing currently underway in the VCE program. The exhaust nozzle will include an acoustically lined ejector based on results from SCAR and from VCE small-scale acoustic model tests. The F100 engine will be rematched for a lower turbine inlet temperature, a higher bypass ratio, and a lower overall pressure ratio to better simulate the exhaust conditions of the VSCE.

Table I compares the cycle characteristics of the rematched F100 test bed and the conceptual VSCE. As shown, the test-bed engine airflow will be about ¼ scale. However, this is about 25 times the airflow used in the acoustic model tests. Large-scale testing is important for the verification of the scaling laws that have been used to extrapolate model test data to full size. The bypass ratio of the test-bed engine is somewhat lower than that of the conceptual VSCE, and there are also some slight differences in the other parameters.

The duct-stream jet velocity can be varied by changing the duct-burner temperature through adjustment of the fuel-air ratio. Less flexibility is available in varying the core-stream jet velocity. For the duct-stream velocity indicated, the ratio of duct-stream to core-jet velocity of 1.7 should produce maximum inherent suppression. Noise measurements will be taken at both higher and lower duct-burner temperatures for a range of duct-stream to core-stream velocity ratios.

<u>VSCE schedule</u>. - A contract was awarded to P&WA in mid-1976 to begin the first phase of component test program. The definition study is in progress and will extend over a 1-year period, as shown by the schedule in figure 6. Technical results from the individual critical-component technology programs will be incorporated in the design of the large-scale test hardware.

A contract was also awarded to P&WA to analytically screen duct-burner concepts for the VSCE. The synthesis of 8 to 12 duct-burner concepts has been completed. These configurations were ranked and four were selected for further study and design. Follow-on segment rig tests will be made in early 1977 to select the most promising duct-burner configuration to be incorporated in the test-bed engine.

Pratt & Whitney will continue aeroacoustic model tests of coannular nozzles to identify the most promising configuration for the VSCE. Results of this technology program will be used in the design of a large-scale nozzle configuration for the F100 engine test bed. The environmental and performance tests of the duct burner and the coannular nozzle installed on the test-bed engine are scheduled to begin in early 1979.

Double-Bypass Engine

<u>DBE engine concept</u>. - The G.E. double-bypass VCE concept (ref. 2) is shown schematically in figure 7. It also uses a coannular exhaust nozzle with an inverted velocity profile for low jet noise. In this concept, fan discharge flow is crossducted at takeoff to the plug centerbody to get the low-energy exhaust stream on the inside, as required by the inverted velocity profile. Bypass air is also used to increase the total flow at takeoff for increased thrust at the reduced jet velocities. The maximum state-of-the-art turbine inlet temperature is used with this turbofan cycle at takeoff as well as at supersonic conditions. The high temperature is required for takeoff thrust as well as for providing the high annulus velocity.

The fan is split into two blocks to provide two bypass streams - hence the terminology "double bypass." The outer bypass airflow can be controlled to give the turbofan cycle additional flexibility. It is desirable in takeoff to have the maximum bypass ratio and total airflow for sufficient thrust at low noise. At subsonic cruise, the higher bypass ratio is also desirable from a propulsive efficiency standpoint. However, at supersonic flight conditions, the bypass ratio must be kept low, and the outer bypass flow is therefore eliminated. In this mode of operation, the engine behaves as a low-bypass-ratio, mixed-flow turbofan engine. Extensive variable geometry is required in the turbomachinery components to accommodate these flow swings and changing work requirements.

An afterburner is required for supplying additional thrust during climb/acceleration. It may or may not be required during supersonic cruise, depending on the outcome of continuing engine/airplane sizing and integration studies.

DBE component test bed. - Figure 8 illustrates the test-bed engine for the double-bypass concept. In addition to demonstrating the coannular suppression benefit in large scale with a plug nozzle, this test bed will also demonstrate the system compatibility and stability of the double-bypass concept. The test bed is to be built around the advanced-technology military YJ101, a minibypass turbojet engine. The fan will be split into two blocks to get the extra bypass stream. Variable geometry components will be added to control the bypass flow split. The turbine work split will be changed to better serve the demands of the new fan arrangement.

Table II compares some of the cycle parameters between the conceptual double-bypass study engine and the test-bed engine. The top line shows that the test-bed airflow is approximately 15 percent that of the conceptual DBE. The dual values shown for each engine represent high/low flow conditions. The second line shows that at sea-level-static conditions the high-mode bypass ratio is about double the low-mode bypass ratio. Subsequent lines in the table compare pressure ratios and combustor exit temperatures. The bottom two lines indicate that, despite slight differences in some of the cycle characteristics for the two engines, the fully expanded jet velocities are similar and provide a valid large-scale test of the inverted velocity profile desirable for inherent noise suppression. These velocities are obtained in the high-flow mode where the exhaust is separated into two distinct streams. In the low-flow mode, the exhaust would be mixed and a high jet noise condition would result. Although the test bed will be tested in both modes on the test stand, a flight engine at takeoff would be operated only in the high-flow, low-noise mode.

DBE schedule. - A contract was awarded to G.E. in the fall of 1976 to begin the component test program definition study for the double-bypass-cycle test bed. The study will extend over a 9-month period, as shown on the schedule in figure 9. Technical results from the on-going technology programs will be factored into the design of the test-bed engine as they become available.

The two critical components being studied in the technology program are the variable-flow fan and the low-noise, coannular plug nozzle. A contract was awarded in mid-1976 to screen concepts and to conduct design and performance studies of variable-flow fans. A follow-on contract will provide for design and fabrication in late 1977 and rig testing of the most-promising fan concept beginning in late 1978.

A contract was also awarded to G.E. in early 1976 to evaluate the effect of key design variables on the aeroacoustic performance of high-radius-ratio, ventilated plug nozzles. Results from this technology effort will be factored into the selection of a large-scale nozzle configuration for the test-bed engine. Evaluation of the noise and performance characteristics of the engine should begin in early 1979.

CONCLUDING REMARKS

The variable-cycle engine (VCE) component test program addresses only certain unique and critical components necessary to assess the feasibility of the concept and to evaluate the potential of the cycle for supersonic cruise applications. Test-bed engines are a next logical step following model and laboratory investigations. The current schedule calls for testing to begin in early 1979, with tests to be conducted at sea-level-static conditions approximating those encountered at takeoff. The variable-cycle test-bed engines will use existing high-technology core engines with approximately a 15- to 25-percent airflow relative to the flight engines.

Successful completion of the component test program with the two test-bed engines described in this paper will allow us to proceed confidently to an experimental variable-cycle-engine program. However, performance and environmental acceptability of a VCE depend on attaining predicted levels of technology in other areas not addressed in the component test program. Many other technologies need further development before a VCE can be considered for commercial service.

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TABLE I. - COMPARISON OF CONCEPTUAL VARIABLE-STREAM-CONTROL ENGINE WITH TEST-BED SIMULATION

[Takeoff conditions.]

Characteristic	Conceptual VSCE	Test-bed engine
Engine:		
Relative total airflow	1.00	0.27
Bypass ratio	1.5	0.85
Fan pressure ratio	2.8	3.1
Overall (fan plus compressor) pressure ratio	18.6	19.5
Combustor exit temperature, K(°F)	1600 (2420)	1520 (2280)
Duct-burner temperature, K(°F)	1710 (2610)	1390 (2040)
Nozzle:		
Duct-stream jet velocity, m/sec (ft/sec)	885 (2900)	805 (2640)
Ratio of duct-stream to core-stream jet velocity	1.7	1.7

TABLE II. - COMPARISON OF CONCEPTUAL DOUBLE-BYPASS VARIABLE-CYCLE ENGINE WITH TEST-BED SIMULATION

[Takeoff conditions.]

Characteristic	Conceptual double-bypass VCE[a]	Test-bed engine[a]
Engine:		
Relative total airflow (high/low)	1.20/1.00	0.19/0.15
Overall bypass ratio	0.8/0.4	0.7/0.4
Pressure ratio, front fan block	3.2/2.7	3.1/2.4
Pressure ratio, rear fan block	1.2/1.5	1.2/1.4
Overall fan pressure ratio	3.8/4.0	3.7/3.2
Overall (fan plus compressor) pressure ratio	17	17
Combustor exit temperature, K(°F)	1870/1700 (2900/2600)	1730/1700 (2650/2600)
Nozzle:		
Hot exhaust jet velocity, m/sec (ft/sec)	750 (2450)	690 (2250)
Ratio of hot to cold exhaust jet velocity	1.58	1.45

[a]Dual values represent high/low flow conditions.

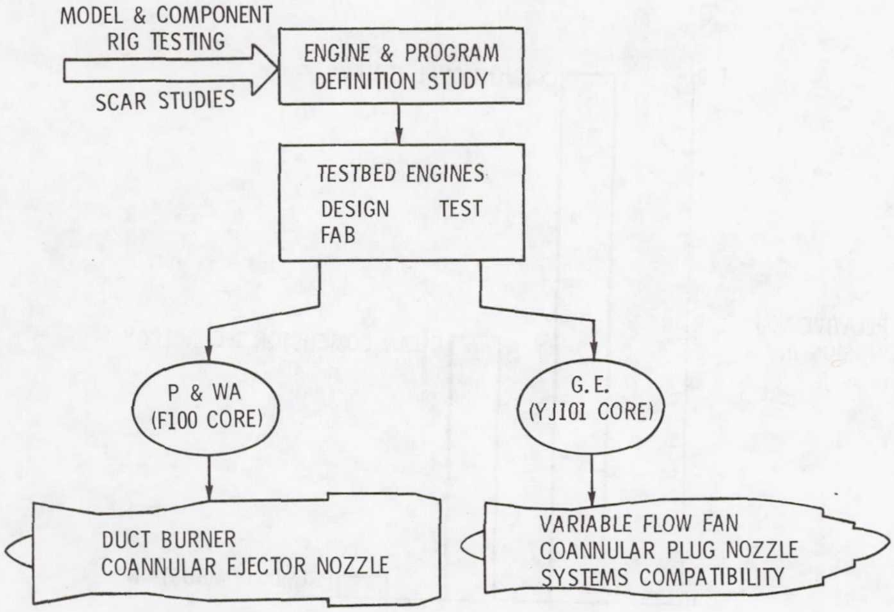

Figure 1.- Variable-cycle engine component test program.

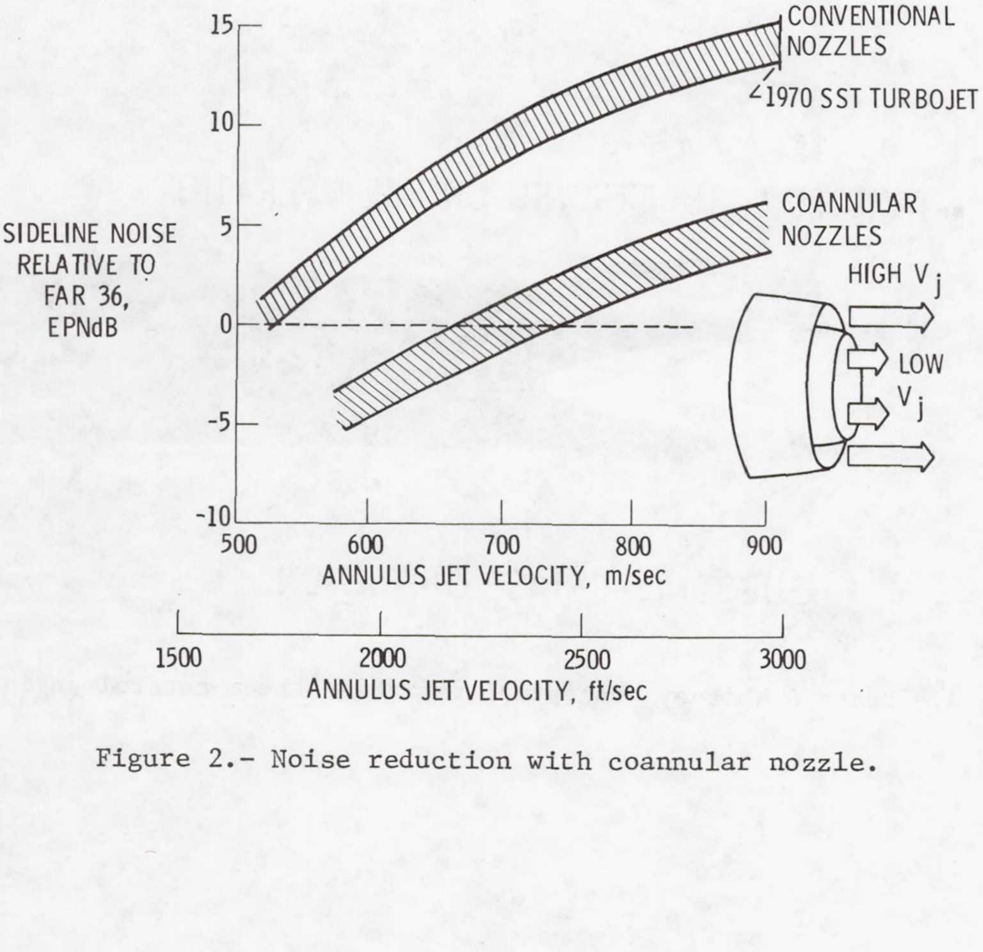

Figure 2.- Noise reduction with coannular nozzle.

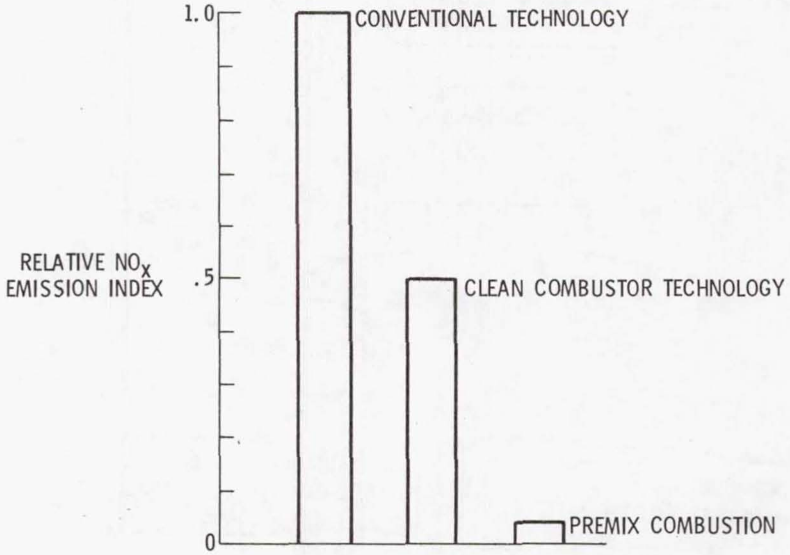

Figure 3.- Status of oxides-of-nitrogen emissions at supersonic cruise.

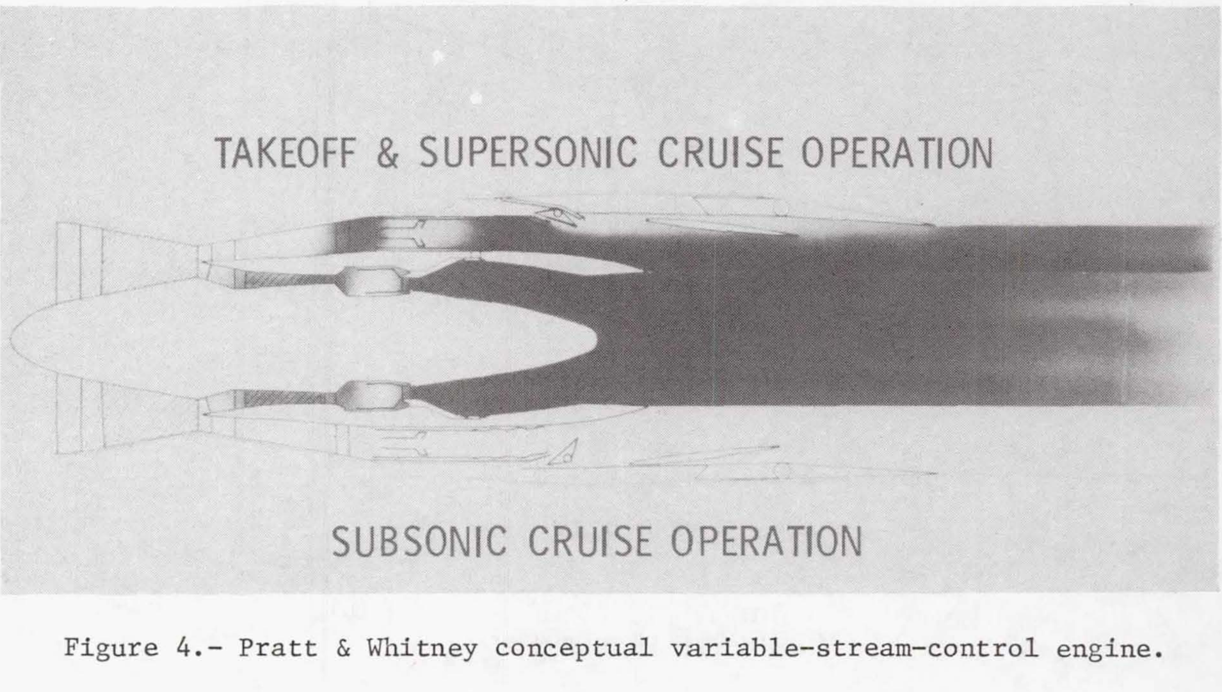

Figure 4.- Pratt & Whitney conceptual variable-stream-control engine.

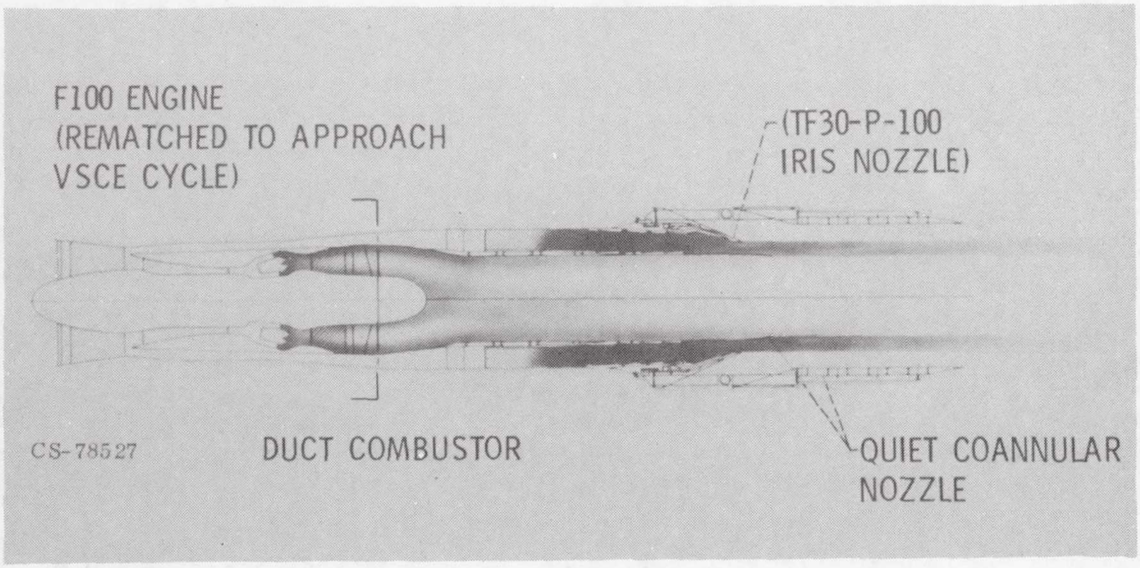

Figure 5.- Pratt & Whitney test-bed variable-stream-control engine.

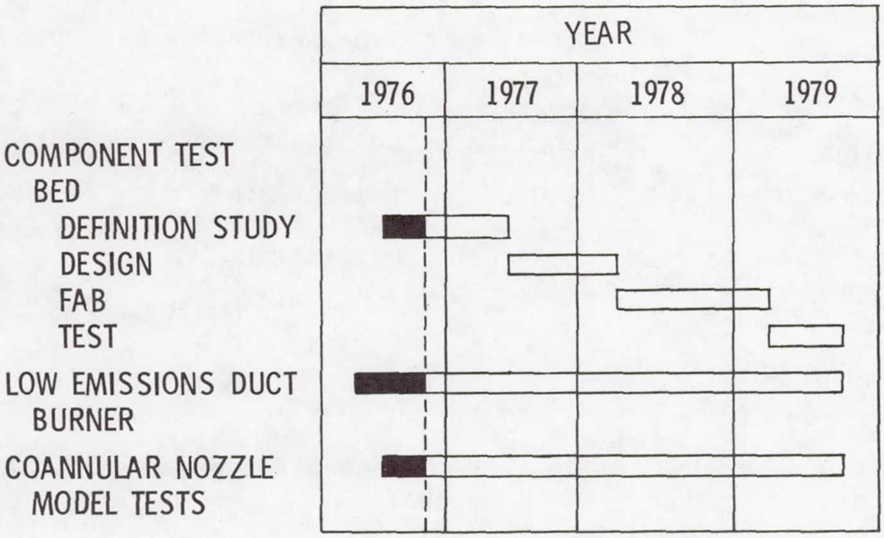

Figure 6.- Schedule of component test program for
Pratt & Whitney variable-stream-control engine.

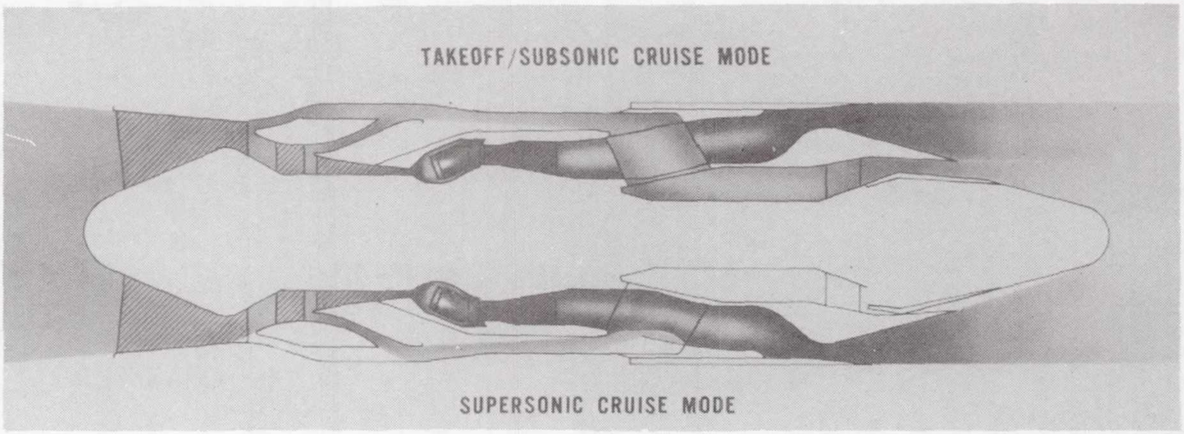

Figure 7.- General Electric conceptual double-bypass, variable-cycle engine.

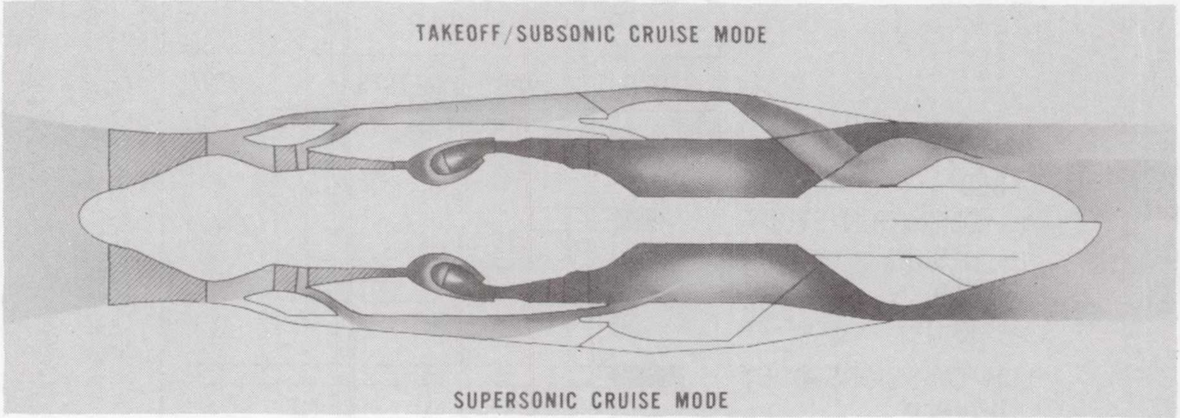

Figure 8.- General Electric test-bed, double-bypass, variable-cycle engine.

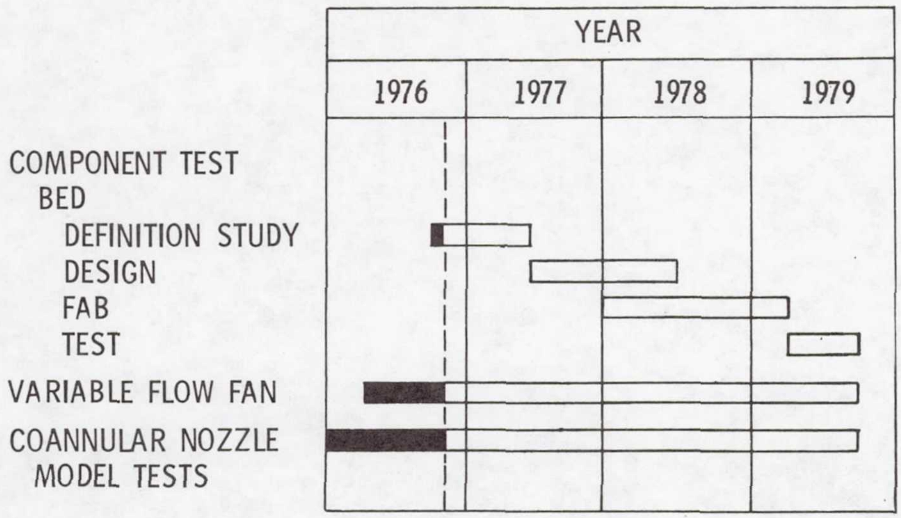

Figure 9.- Schedule of component test program for G.E. double-bypass, variable-cycle engine.