PROGRESS WITH VARIABLE CYCLE ENGINES*

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SUMMARY

Under NASA sponsorship, Pratt & Whitney Aircraft has been evaluating and substantiating two of the most critical and unique components of an advanced propulsion system for a future supersonic cruise vehicle. These components, a high performance duct burner for thrust augmentation and a low jet noise coannular exhaust nozzle, are part of the Variable Stream Control Engine (VSCE). Studies have identified this engine as having the greatest potential for an advanced supersonic commercial cruise vehicle, when considering the overall environmental and economic requirements. An experimental test program involving both isolated component and complete engine tests has been conducted for the high performance, low emissions duct burner with excellent results. Nozzle model tests have also been completed which substantiate the inherent jet noise benefit associated with the unique velocity profile possible of a coannular exhuast nozzle system on a Variable Stream Control Engine. Additional nozzle model performance tests have established high thrust efficiency levels at takeoff and supersonic cruise for this nozzle system. Large scale testing of these two critical components is being conducted using an F100 engine as the testbed for simulating the Variable Stream Control Engine.

INTRODUCTION

For the past six years, Pratt & Whitney Aircraft has participated in a series of NASA-sponsored programs aimed at establishing the technology base for a future supersonic cruise transport, with special emphasis on improving environmental and economic characteristics. During this period, over 100 different engine concepts and cycle configurations were studied, including Variable Cycle Engines (refs. 1-4). The most attractive engine configuration identified from this matrix was the Variable Stream Control Engine (VSCE). This concept shows the potential for very significant improvements in range, noise and emissions relative to the first-generation supersonic transport (SST) engines. Figure 1 shows the basic mechanical arrangement of this engine. The latest update of this engine concept, including its mode of operation, is contained in reference 5.

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Attaining the potential benefits of the Variable Stream Control Engine is contingent on extensive research and evaluation in many areas of advanced technology. The most critical of these technology requirements are the following: (1) low noise/high performance coannular nozzle, (2) low emissions/ high performance burner systems, (3) high temperature component technology, (4) variable-geometry components (nozzle/ejector/reverser, inlet, fan, compressor), (5) electronic control system, and (6) an integrated propulsion system.

Concentrating on the two most unique components in the VSCE -- a low noise, variable geometry coannular nozzle and a low-emissions, high performance duct burner -- experimental component technology programs are being conducted by Pratt & Whitney Aircraft under NASA direction. The programs include a Coannular Nozzle Model Technology Program and a Duct Burner Rig Technology Program. Results from this work have provided the basis for the VCE Testbed Program, which involves large scale testing of these components at realistic VSCE conditions. This paper reviews the technical accomplishments and progress made in these programs.

COANNULAR NOZZLE MODEL TECHNOLOGY PROGRAM

Overview

The purpose of the Coannular Nozzle Model Technology Program is to identify and investigate aerodynamic and acoustic nozzle technology for an advanced powerplant in a second-generation supersonic cruise vehicle. More specifically, the major areas of the overall program, which have been completed or are in progress, include:

- Establishing aerodynamic and acoustic performance characteristics of both unsuppressed and suppressed coannular nozzle models over a large range of operating conditions.
- Determining the effect of flight velocity on coannular jets.
- Developing an aerodynamic/acoustic prediction procedure for refining coannular jet nozzles with inverted velocity profiles.
- Calibrating model data with acoustic data to be obtained from the VCE Testbed Program, and evaluating the performance of two supersonic coannular nozzle systems that combine low noise and high aerodynamic performance.

Effort in the first three areas of the program (refs. 6-8) was completed during or prior to 1977, and the significant results of this work will be discussed briefly. Experimental model testing on the fourth area has just been completed, and work for a follow-on effort has started.

Early Efforts

During the first phase of the program, scale models representing unsuppressed and suppressed coannular exhaust systems were evaluated statically under varying exhaust conditions. Ejectors with both hardwall and acoustically-treated inserts were also evaluated. The unsuppressed coannular configurations were found to be as much as 11 PNdB quieter than predictions of that time when scaled to a 2.62 m (50 in) equivalent diameter size. At typical VSCE operating conditions, noise reductions of approximately 8 PNdB were demonstrated.

In Phase II, wind tunnel tests showed that jet noise levels of the coannular nozzles were reduced, due to the simulated flight speed, by approximately the same amount as found for single stream nozzles. Thus, the coannular noise benefits identified during the preceding Phase I static test were essentially retained in the simulated flight environment. The noise reduction resulting from flight effects was a function of nozzle stream velocities and simulated flight speed.

The third part continued the experimental and analytical work mentioned above and was directed towards identifying and investigating aerodynamic/acoustic technology relating to the coannular nozzle design. This effort was directed toward the acquisition of static acoustic and aerodynamic performance data which were combined with existing data to support an aerodynamic/acoustic prediction procedure for inverted velocity profile coannular jet nozzles. A procedure was developed to predict jet noise sound pressure level spectra for coannular nozzles with inverted velocity profiles at all angles as a function of nozzle geometry, operating condition and flight velocity.

Recent Work

The recently completed effort involved two programs. In one program, a scale model of the VCE testbed nozzle system was fabricated and tested for acoustic performance. In the other, two potential supersonic nozzle systems for the VSCE study engine were evaluated over a wide range of operating conditions in the NASA-Lewis 8 x 6 foot supersonic wind tunnel.

The purpose of testing the VCE testbed nozzle model was to obtain model acoustic data that can be scaled directly to large scale engine data at the same aerothermodynamic conditions and so permit definition of scaling effects while at the same time provide test data for evaluation of the current acoustic prediction procedure. A one-sixth scale model of the testbed exhaust nozzle system with a fan to primary jet area ratio of 0.65 and 0.82 fan radius ratio was fabricated and tested in the Pratt & Whitney Aircraft Anechoic Jet Noise Test Chamber. This test facility, as shown in Fig. 2, is lined with acoustic absorbent wedges to provide an anechoic environment at frequencies above 150 Hz. The model was designed for testing both with or without an ejector. Acoustic data were obtained at operating conditions that bracket the testbed engine operating points.

The testbed model acoustic test results are consistent with the existing prediction procedure, as shown in Fig. 3, indicating that the results are similar to data obtained with models tested previously. With the inverted velocity profile, characteristic double hump spectra are present. The high frequency region is controlled largely by the fan stream, while the low frequency region is controlled by the merged fan and primary jet stream.

The second aspect of the program involved an evaluation of the two potential VSCE nozzle systems shown in Fig. 4. The main difference between the two configurations is that one uses a short flap nozzle for the fan stream with an isotropic splitter, while the other employs an iris fan nozzle with a conical splitter. Both configurations have plugs in the primary stream.

Six one-tenth scale models of the two exhaust systems were fabricated and tested in the NASA-Lewis 8 x 6 foot wind tunnel. In Fig. 5, one of the models is shown installed in the wind tunnel. The models simulated actual flight designs at takeoff, subsonic cruise and Mach 2.0 supersonic cruise. Over 200 data points were acquired at wind tunnel Mach numbers of 0.36, 0.9 and 2.0 for a wide range of nozzle operating conditions. Fan and primary nozzle areas were varied to match desired operating conditions, while fan to primary pressure levels were varied along with the ejector inlet area and clamshell reverser position. In addition, the supersonic configuration was tested with 0, 2 and 4 percent corrected secondary flow, which was released behind the duct throat in the gap formed by the reverser buckets.

Both nozzle configurations produced similar results at the same operating conditions. At takeoff and supersonic cruise, nozzle performance approached or met the desired performance goals (Fig. 6). However, subsonic cruise performance fell short of the target. Diagnostic tests of the subsonic cruise configurations showed that lower performance was a result of ejector inlet flow separation. The follow-on work is addressing this effort.

In evaluating the nozzles, the addition of secondary flow in the amount of 2 and 4 percent improved nozzle performance by approximately 2.5 and 3.8 percent. The effect of varying the fan to primary pressure ratio was negligible.

Future Program Plans

In future work, the nozzle designs will be refined by applying knowledge gained from the preceding phases. Work is also planned to improve analytical techniques. This involves modifying existing computer programs for supersonic flow fields so they can be applied to coannular nozzle geometries. Ultimately, integrated airframe nozzle configurations will have to be studied, designed and tested.

DUCT BURNER RIG TECHNOLOGY PROGRAM

Overview

The objective of the Duct Burner Rig Technology Program is to identify and substantiate the required technology to evolve a duct burner configuration with the necessary high performance and low emissions for second-generation supersonic propulsion systems. The efforts conducted under this program are directed at the duct burner application in the VSCE study engine. Three augmented operating conditions were established as being most critical to the duct burner design: (1) supersonic cruise at which the duct burner fuel/air ratio is low, but pressure loss and thrust efficiency are most critical to fuel consumption; (2) a climb condition at which a modest level of augmentation would be required to accelerate through the transonic flight regime; and (3) the takeoff condition at which the aircraft would be subject to airport vicinity noise and emissions regulations.

Critical performance goals established for this program include thrust efficiency at supersonic cruise equal to 94.5 percent, fan duct total pressure loss at supersonic cruise equal to 4.5 percent and a maximum ignition fuel/air ratio of 0.002.

The low ignition fuel/air ratio is dictated by operational constraints. Experience with conventional thrust augmentors indicates that if ignition occurs at a fuel/air ratio of 0.002 or lower, the pressure pulse is sufficiently low to avoid pressure pulsing the engine.

Exhaust emissions goals established for this program by NASA are listed in Table I. The goals for carbon monoxide (CO) and unburned hydrocarbons (THC) emissions indices are representative in that they are typical of those necessary to achieve the more general combustion efficiency goal. These goals are intended only as a standard for comparison and are not related to any proposed or established regulations for advanced supersonic aircraft.

Under the first phase of the Duct Burner Rig Technology Program, an analtyical screening and definition study was completed. At present, experimental rig development testing is continuing under the second and third phases of the program.

Early Effort

The first phase of the program was conducted under NASA Lewis Research Center Contract NAS3-19781 (ref. 9). The objective of this study was, through systematic analytical screening of combustor concepts, to identify duct burner concepts with the potential for high performance and low emissions. Combustion concepts were considered that ranged from improved versions of current state-of-the-art duct burners through the technology levels demonstrated in the NASA-sponsored Experimental Clean Combustor (ref. 10) and Pollution Reduction Technology Programs, to such advanced concepts as variable geometry premixed-prevaporized combustors. The concepts were used to define a number of duct burner configurations.

As the study progressed, it became evident that technology derived from advanced, low-emissions main combustor programs such as the NASA/P&WA Experimental Clean Combustor Program would be required to achieve the desired high performance and low emissions levels over the entire operating range. Analyses indicated that a three-stage Vorbix (vortex mixing and burning) duct burner concept has the potential to meet the overall engine requirements, including pressure loss, thrust efficiency and ignition margin and is compatible with the geometry of the VSCE. A schematic of the three-stage configuration in the fan duct of a VSCE is presented in Fig. 7.

In the basic mechanical configuration the pilot secondary stages are enclosed by a hood to ensure a positive air management for combustion. Air enters the pilot secondary stage through a row of swirler tubes that promotes rapid mixing of air with combustion gases exiting the prechamber stage. The rapid turbulent mixing produced by the swirling jets enhances complete combustion to reduce exhaust pollutants. A similar arrangement is used in the third combustion zone or high power stage. The fuel injectors for the secondary high power stages are located at the exit of the previous stage so that fuel may be rapidly vaporized in these hot combustion products. Combustor liners in both low and high power stages are a conventional louvered design.

Recent Effort

In the current rig test effort under NASA Lewis Research Center Contract NAS3-20602, tests are being conducted to substantiate and refine emissions and performance characteristics of the three-stage Vorbix duct burner as well as resolve any potential operational problems in the VCE Testbed Program. For this work, the test rig was sized to duplicate a 60-degree sector of the annular burner configuration required for the VCE Testbed Program. An exploded view of the duct burner rig is shown in Fig. 8.

A total of thirteen duct burner configurations have been tested. Data were obtained for emissions, smoke, and total pressure loss at both simulated sea level takeoff and supersonic cruise. Also, measurements were made to evaluate lighting and blowout characteristics and determine emissions characteristics at other operating conditions. This work has successfully substantiated the three-stage configuration. Some of the more important results and observations from recent testing are presented in the following paragraphs.

Historically, acoustic instability -- primarily high frequency screech associated with radial oscillatory modes -- has been a concern in the design of augmentors. No such instability was encountered during rig testing.

The ability to ignite the duct burner at low fuel/air ratios is necessary to avoid pressure pulses that might adversely affect operating stability. A very low ignition fuel/air ratio of 0.002 was established as a light off goal based on experience from other augmentor programs. This goal was surpassed during ignition tests with fuel/air ratios of 0.0014 to 0.0018.

As a tool strictly for technology evaluation, the duct burner rig does not incorporate commercial life-related design features and materials. Thus, minor cooling and buckling problems with liner high temperatures encountered during initial tests were eliminated in subsequent stages of testing. Inadequate liner cooling occurred in limited areas immediately downstream of the swirler tubes in the pilot secondary and high power stages. This was attributed to marginal film integrity on the louver caused by high turbulence generated by the swirling flow. A double louver scheme was incorporated in these areas to improve film integrity. Typical louver temperatures such as those indicated in Fig. 9 are used to help evaluate characteristics of the duct burner. In this case, a comparison is shown which illustrates the influence of swirler orientation on liner temperature.

Table II presents the duct burner emissions characteristics. These results indicate that the combustion efficiency exceeds both the NASA contract goals and predicted levels at all operating conditions. While NO_x emissions are above the goal and predicted levels, they are consistent with the projected emissions characteristics. It should be noted that the potential exists for tradeoffs between combustion efficiency and NO_x emissions by reducing residence time, i.e., the length, of the duct burner.

The SAE smoke number was well below the goal, on the order of 2, during high fuel/air ratio operation with all configurations evaluated.

Despite the external pressure distribution around the duct burner and the airflow distribution being close to the design intent, the overall total pressure loss across the duct burner was initially higher than projected. Analyses and flow visualization studies identified the mechanism causing the higher losses, and subsequent tests with a revised swirler geometry demonstrated a substantial reduction in pressure loss without significantly altering emissions or other performance characteristics.

Thrust efficiency is related to the uniformity of the gas temperature distribution at the duct nozzle exit plane. Test results have demonstrated minimal circumferential variation of the gas temperature at the duct burner exit. Typical radial temperature profiles are shown in Fig. 10. The profile at supersonic cruise is extremely uniform, thereby conducive to a high thrust efficiency required at this condition. Analysis of these profiles, including the effect of assumed nozzle cooling air and the existing circumferential variations, indicates that in a flight engine the thrust efficiency at supersonic cruise would be in the 96-98 percent range -- well above the 94.5 percent goal. At the higher fuel/air ratios of takeoff and transonic climb, the thrust efficiency is computed to be 92 to 94 percent, which also exceeds the projected levels.

Future Program Plans

Further experimental testing is scheduled with the duct burner rig. Future tests would be conducted in an effort to reduce the total pressure loss to the design level, optimize the emissions characteristics, investigate reductions in stage length, and reduce burner sensitivity to the fuel spray characteristics of the high power stage fuel injectors. Additional efforts are planned to assess a simplified version of the three-stage design.

VCE TESTBED PROGRAM

Overview

The VCE Testbed Program, being conducted under NASA Lewis Research Center Contract NAS3-20048, provides an effective method to evaluate and verify the VSCE unique duct burner and coannular nozzle technologies. By testing a large scale duct burner and coannular nozzle in a realistic operating environment, the program will demonstrate:

- The coannular noise benefit with inverted velocity profile
- A high performance and low emissions duct burner
- Effectiveness of acoustic treatment on the ejector
- VSCE characteristics (inverted throttle schedule)

In addition, the testbed provides the opportunity to evaluate:

- Duct burner combustion noise
- Fan/duct burner noise interactions
- Fan/duct burner/nozzle stability
- Fan and core noise sources
- Validity of noise prediction based on model test data
- Improvements to advanced supersonic vehicle jet noise prediction

The VCE testbed configuration is shown in Fig. 11. A Pratt & Whitney Aircraft F100 engine was selected as the gas generator for the testbed since it has the potential to simulate the desired exhaust conditions of the VSCE study engine. Furthermore, it did not require extensive modification to incorporate the duct burner, a variable exhaust nozzle and an ejector that can accommodate both a hard wall surface and acoustic treatment.

The program plan includes two major series of tests: a duct burner emissions and performance evaluation, and a comprehensive aero/acoustic evaluation. Three different test sites are being employed for conducting these and other associated tests. Calibration of the F100 engine was performed at the Pratt & Whitney Aircraft Government Products Division in Florida. A checkout of the F100/testbed system and emissions evaluation is being performed at the Pratt & Whitney Aircraft Commercial Products Division in Connecticut. The Boeing Boardman facility in Oregon was selected as the site for completing the aero/acoustic test.

Design Philosophy

Since the intent of this program is to evaluate critical concepts and demonstrate VSCE operational characteristics, the testbed does not represent flight type hardware nor is it designed for long life. Standard cooling techniques and available materials were employed in the duct burner and nozzle systems, realizing that future programs would be required to develop long term cooling methods and structural approaches.

Duct Burner

The duct burner for the testbed is based on the aerothermal and mechanical concepts described in the previous discussion of the Duct Burner Rig Technology Program. In the design process, particular emphasis was placed to ensure a similarity as close as possible between the testbed and the design concept for the flight engine. Design parameters that are identical to the VSCE study engine include:

- Local velocities and Mach numbers
- Stage lengths
- Mixing zone parameters such as the ratios of swirler diameter to radial height and fuel injector spacing to radial height
- Percent airflow and fuel/air ratios at end of stages.

The major variations between the testbed and a possible flight engine duct burner are the reduction in duct height and mean diameter by approximately 50 percent to match the F100 engine size.

Coannular Nozzle

The exhaust nozzle system used in the VCE testbed to evaluate the coannular noise effect is similar to the nozzle considered for the VSCE study concept. The axial orientation of the duct burner and primary nozzles in the testbed is nearly identical to that in the flight concept. Also, the ejector system is nearly the same.

One dissimilarity, however, is in the primary nozzle configuration. The study engine shows the potential for a variable throat, convergent divergent nozzle system, while the testbed utilizes a fixed convergent primary nozzle. This difference, however, will not produce any significant effects on the experimental data desired in the program. Several different sizes of fixed primary nozzles are used during testing to permit attainment of a variety of primary stream exit velocities.

Testbed Control System

The control system in the VCE testbed was designed to maintain control of all F100, duct burner and nozzle control variables in order to obtain the desired operating points for acquisition of aero/acoustic and emissions data. For repeatability of operating points, it was desirable that the system regulate the engine and testbed components such that actual duct airflow variations were accurate to 1 percent of the set point.

In addition, the control is capable of independently metering the duct burner fuel flow to the three combustion stages as well as sequencing the stage operation. Finally, the control system protects the test vehicle from control system failures such as sensor malfunction and permits ease of operation to establish operating points for data acquisition.

Recent Effort

Testing accomplished to date includes a checkout of the integrated F100/testbed system and a series of evaluations to demonstrate duct burner aerothermal/mechanical performance and acquire emissions data. Aero/acoustic testing is planned in 1980.

The testbed demonstrator vehicle became operational during mid 1978. The test configuration is shown in Fig. 12 installed in a test stand at the Commercial Products Division prior to emissions testing. The high performance/low emissions duct burner, initially demonstrated in the companion rig program, has been substantiated through testbed operation. Also, the VSCE concept, in which the exit velocity profiles are varied and controlled, has been demonstrated while maintaining good engine/duct burner/nozzle stability characteristics.

Approximately 100 hours of testing has been completed, and no major problems have been encountered with respect to duct burner operation. A photograph of the testbed exhaust plume with the duct burner operative is presented in Fig. 13. Velocity ratios (fan velocity/primary velocity) between 1.0 and 1.9 have been obtained at steady-state conditions. The development breadboard control system, which is computer controlled, has successfully maintained safe and stable operation of the test vehicle throughout the operating range.

An element related to VSCE operation is fan/duct burner/nozzle stability. At duct burner light off, upstream pressure pulses were expected to be on the order of 1 to 3 percent, but, in fact, instabilities have not been observed during testing. Moreover, intentional variation of the fan nozzle area did not produce any instabilities in the system. Also, a variation in fuel flow to any of the duct burner stages has been limited by wall temperatures and not stability problems. The transition from one to two to three combustion zones over a variety of fuel flow splits has proven the stability of the integrated engine, duct burner, and nozzle system.

For an accurate characterization of duct burner exhaust emissions, gas sampling instrumentation is especially critical. The emissions sampling system designed for this program is comprised of four probes located at the duct burner exit plane. Three of the probes are fixed and each of these contains nine sampling elements. The fourth probe is a traversing unit with a single sensing element capable of both radial and circumferential movement.

All probes in the system are steam cooled. As emissions samples are extracted by the probe sensing elements, the samples are passed through heated tubes to a collection chamber that is external to the test vehicle. From this point, the sample is transferred to the Pratt & Whitney Aircraft mobile emissions laboratory for analysis. The gas sampling system design addressed the mounting and positioning of sensors, in addition to quenching the sample without condensation through the switching and mixing prior to analysis in the mobile laboratory. Sampling probes and emissions sampling equipment were designed to conform with the specifications described in Federal Register Vol. 38, No. 136, Part II, July 17, 1973, "Control of Air Pollution from Aircraft and Aircraft Engines".

For emissions assessment, the testbed has been operated over a wide range of overall fuel/air (f/a) ratios from 0.005 to 0.030*. Various operating conditions were evaluated as the operating range and limits of the duct burner were investigated. Also, different pressure levels were run at various representative points in order to duplicate the nozzle model acoustic data that were discussed previously.

Typical emissions results for CO, THC and NO_x are shown in Fig. 14. Also shown are results from the companion rig program and the predicted data scatter band that is based on Pratt & Whitney Aircraft's burner experience. The testbed results tend to duplicate rig data, thereby corroborating the high overall performance of the basic duct burner design. As demonstrated during rig testing, the higher than expected combustion efficiency due to the excellent mixing characteristics yielded low CO and THC levels. A comparison of the testbed duct burner combustion and thrust efficiency at the three fuel/air ratios versus the predicted efficiency is presented in Table III. The results are based on data available at the time of this writing. Further work is expected to improve these initial emissions and performance characteristics.

Future Program Plans

Acquisition of acoustic data and the evaluation of the coannular effect are planned. Also the testbed demonstrator will be used to test and evaluate design refinements from the companion rig program. Follow-on plans may include testing the VCE testbed in a wind tunnel to evaluate flight effects on the coannular nozzle acoustic results and testing a simplified duct burner configuration.

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* Fuel/air ratio refers to the fuel passing through eitner all or a particular set of nozzles ratioed to the total airflow passing through the burner, including air that actually bypasses the burner and is used to cool the nozzle.

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TABLE I - DUCT BURNER EMISSIONS GOALS

Pollutant	Emissions Index (g pollutant/kg fuel)
NO_x	1.0
CO	30.0
THC	2.5
Smoke (SAE No.)	15.0

Note: Combustion efficiency at all operating conditions = 99 percent

TABLE II - DUCT BURNER RIG EMISSIONS CHARACTERISTICS

	CO (EI) gm/kg	THC (EI) gm/kg	COMB. EFFIC.	NOx (EI) gm/kg
Supersonic Cruise				
Meas.	1.6	0.03	99.9	5.7
Anal.	30	3	99.0	2.8
Goal	30	3	99.0	1.0
Transonic Climb				
Meas.	7.4	0.04	99.8	4.0
Anal.	225	22.5	92.5	1.2
Goal	30	3.0	99.0	___
Takeoff				
Meas. (f/a = 0.035)	13.7	0.001	99.7	2.7
Pred. (f/a = 0.0385)	30	3	99.0	1.8
Goal	30	3	99.0	1.0

TABLE III - VCE TESTBED DUCT BURNER COMBUSTION AND THRUST EFFICIENCY

	Combustion efficiency		Thrust Efficiency	
	Meas.	Pred.	Meas.	Pred.
Fuel/Air Ratio .013	99.6	99.0	97.3	94.5
Fuel/Air Ratio .019	98.5	--	96.0	--
Fuel/Air Ratio .030	99.3	99.9	96.8	86.0

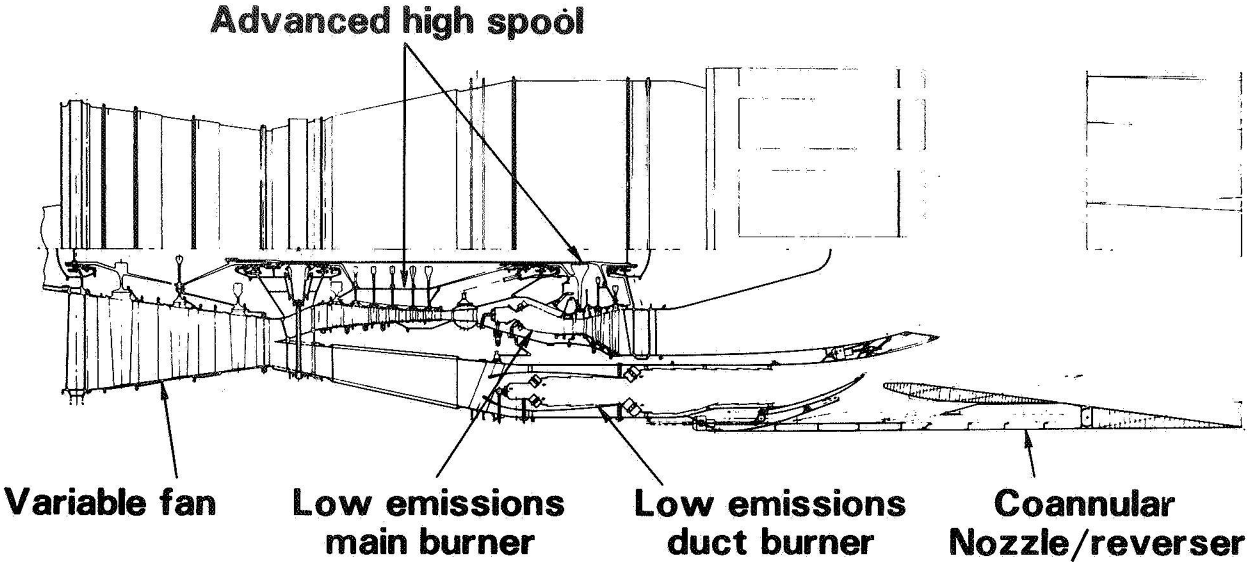


Figure 1.- Conceptual configuration of Variable Stream Control Engine (VSCE).

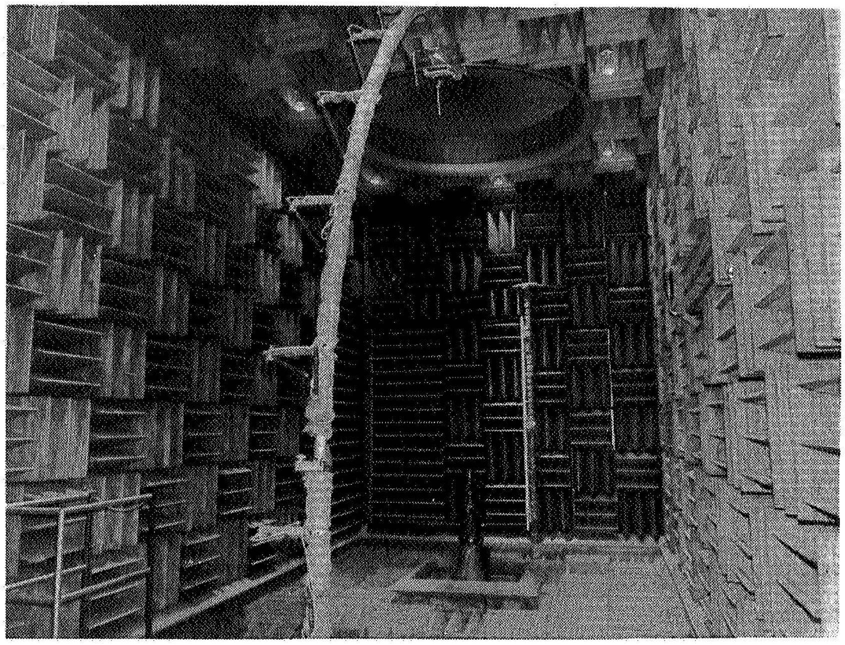


Figure 2.- Test nozzle model installed in Anechoic Jet Noise Facility.

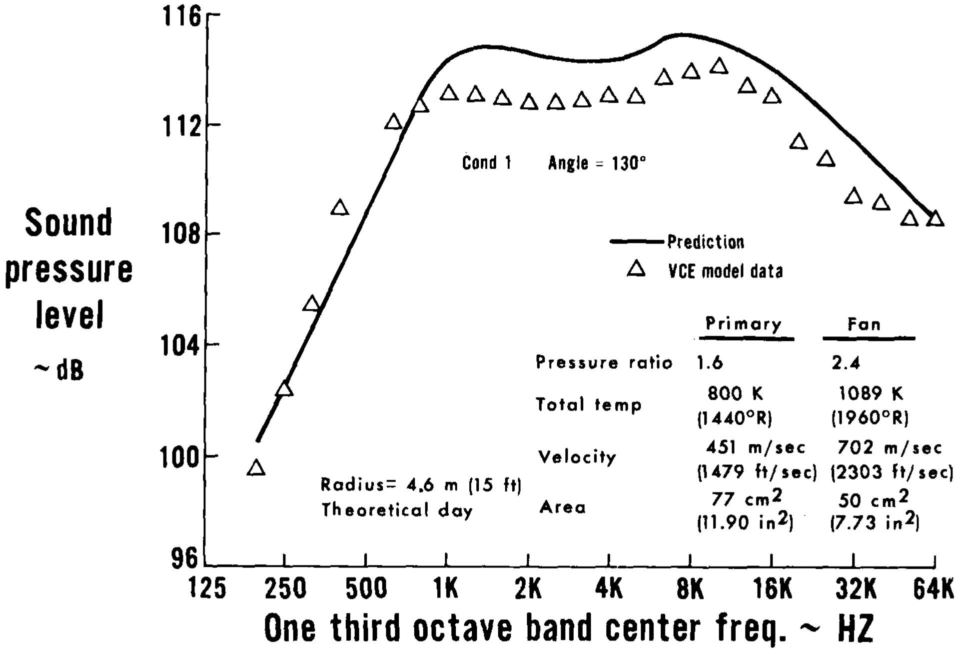
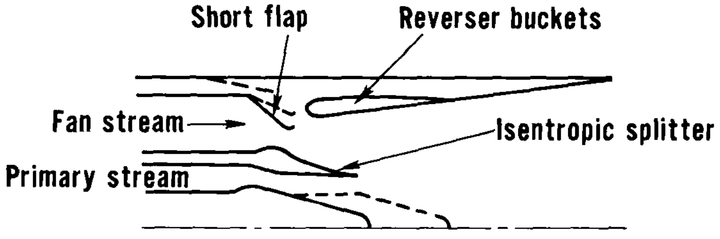
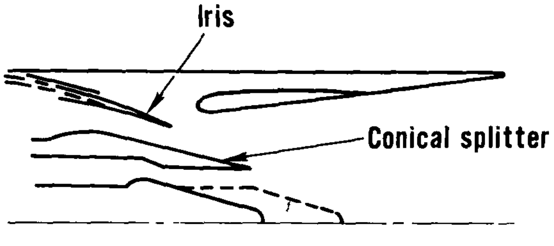


Figure 3.- Comparison of VCE coannular nozzle model test prediction and test data.



Short flap ejector



Iris flap ejector

Figure 4.- Cross sections of potential VSCE nozzle configurations evaluated for aero/acoustic performance during Phase IV Program.

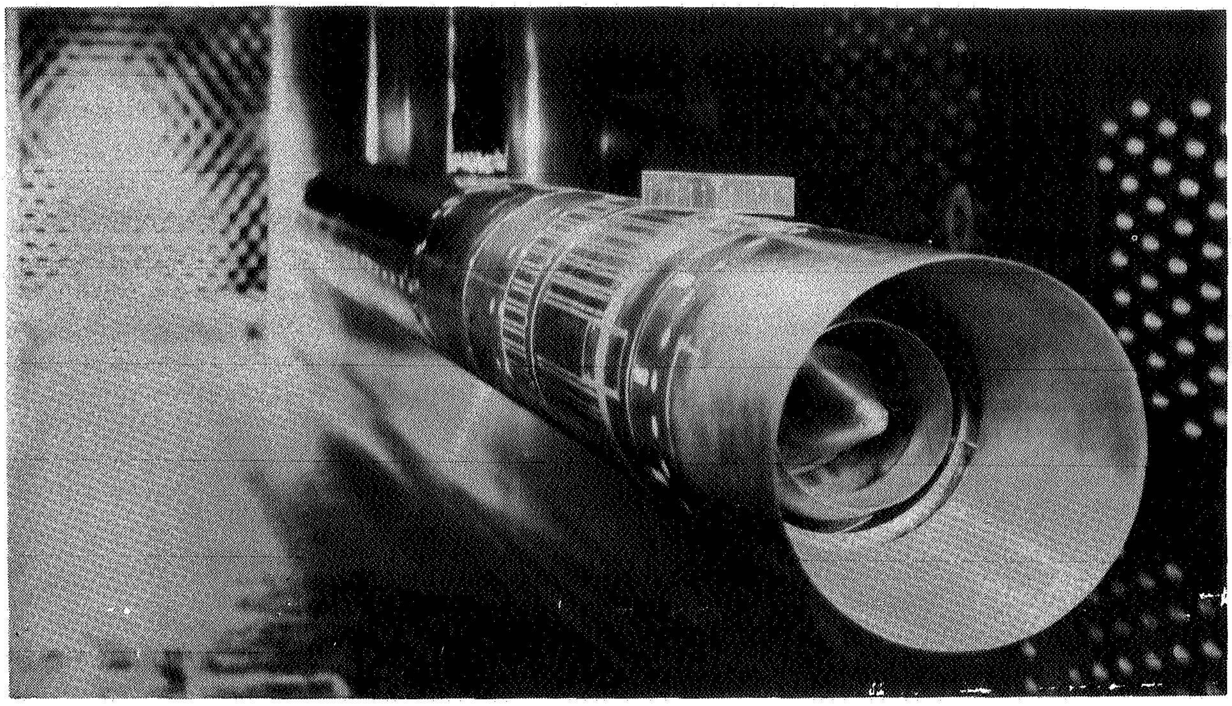


Figure 5.- Test nozzle installed in NASA-Lewis wind tunnel.

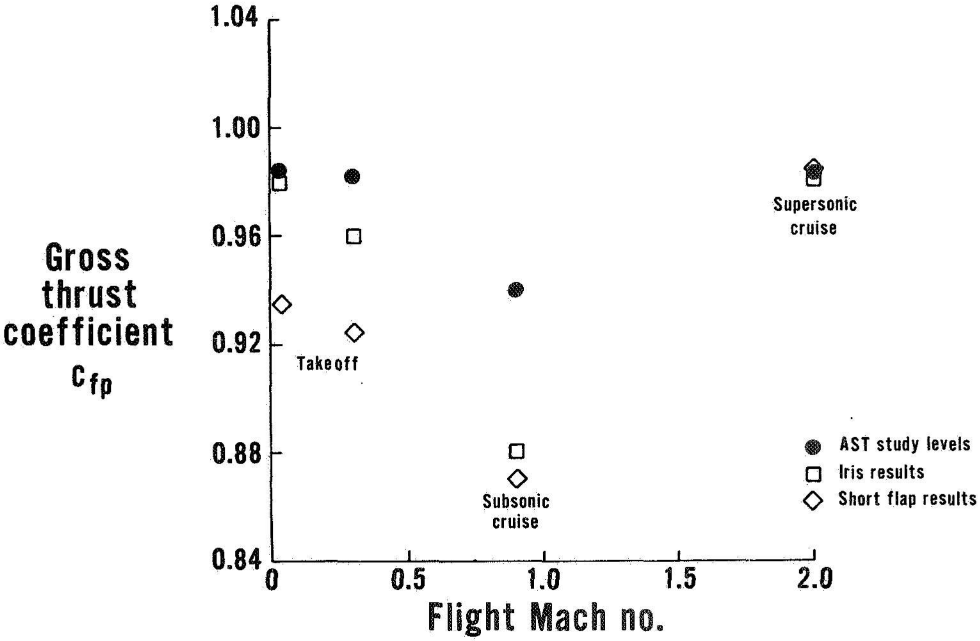


Figure 6.- Comparison of test results with advanced supersonic propulsion study nozzle performance.

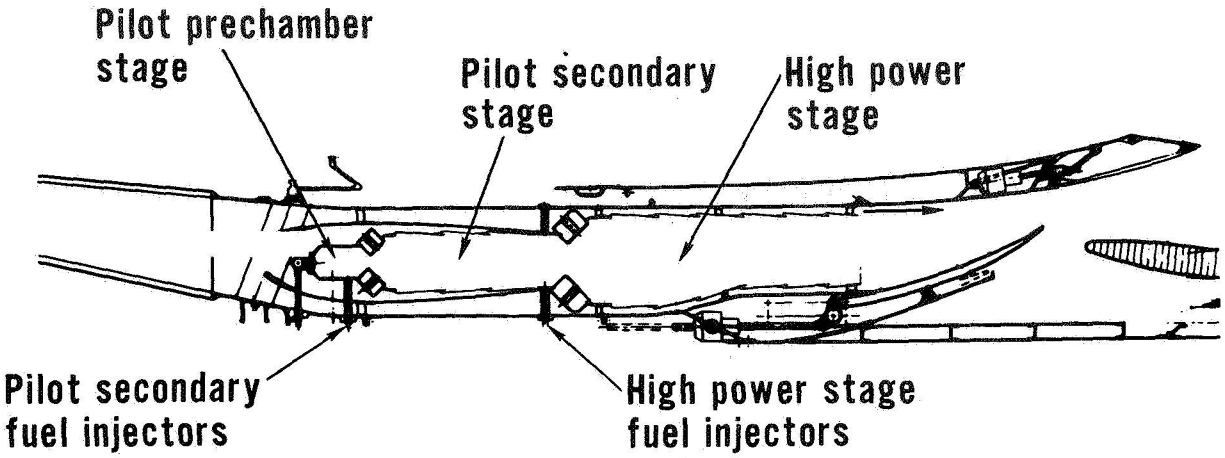


Figure 7.- Three-stage Vorbix duct burner configuration shown with fan exhaust nozzle.

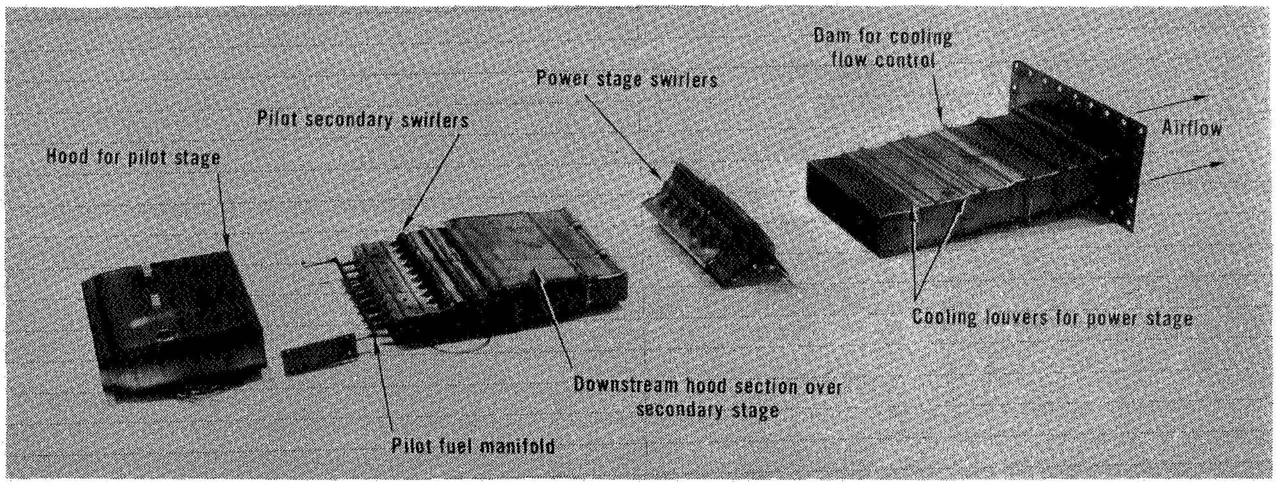


Figure 8.- Exploded view of duct burner rig.

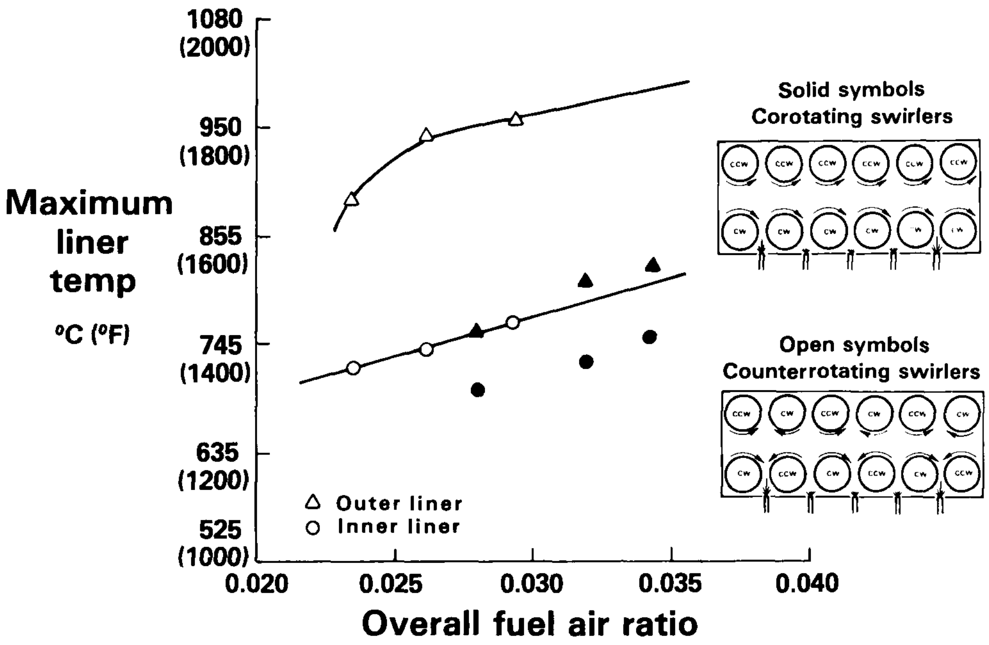


Figure 9.- Influence of swirler orientation on liner temperature.

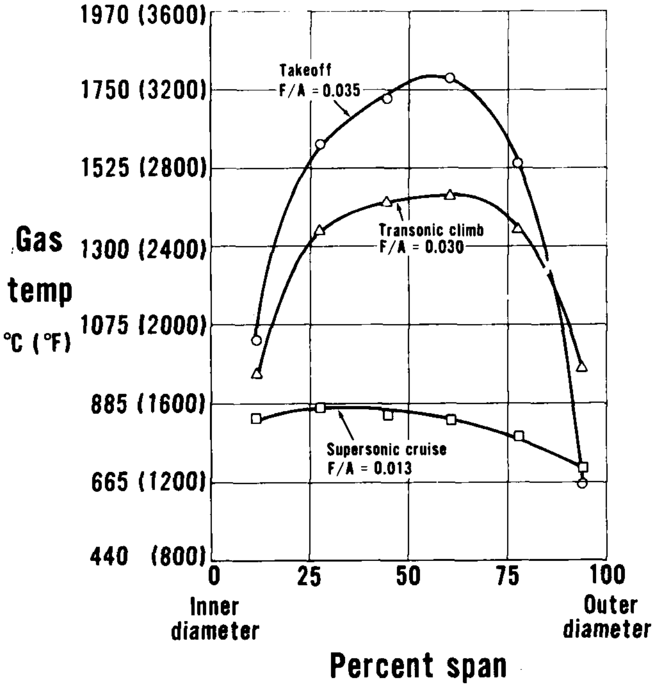


Figure 10.- Typical radial temperature profiles at duct burner exit plane for selected operating conditions.

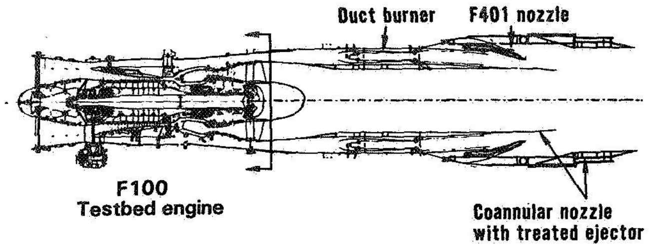


Figure 11.- VCE testbed demonstrator configuration using a Pratt & Whitney Aircraft F100 engine as gas generator to develop proper environment of testbed components - the duct burner and coannular nozzle.

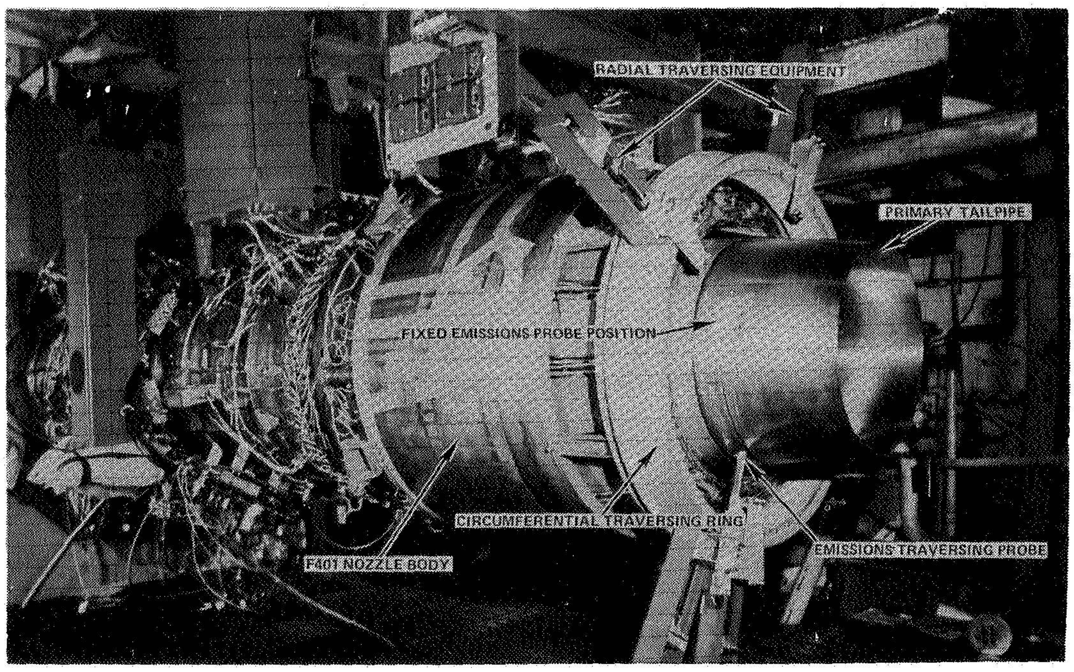


Figure 12.- VCE testbed demonstrator installed in test stand at Pratt & Whitney Aircraft Commercial Products Division in East Hartford, Connecticut.

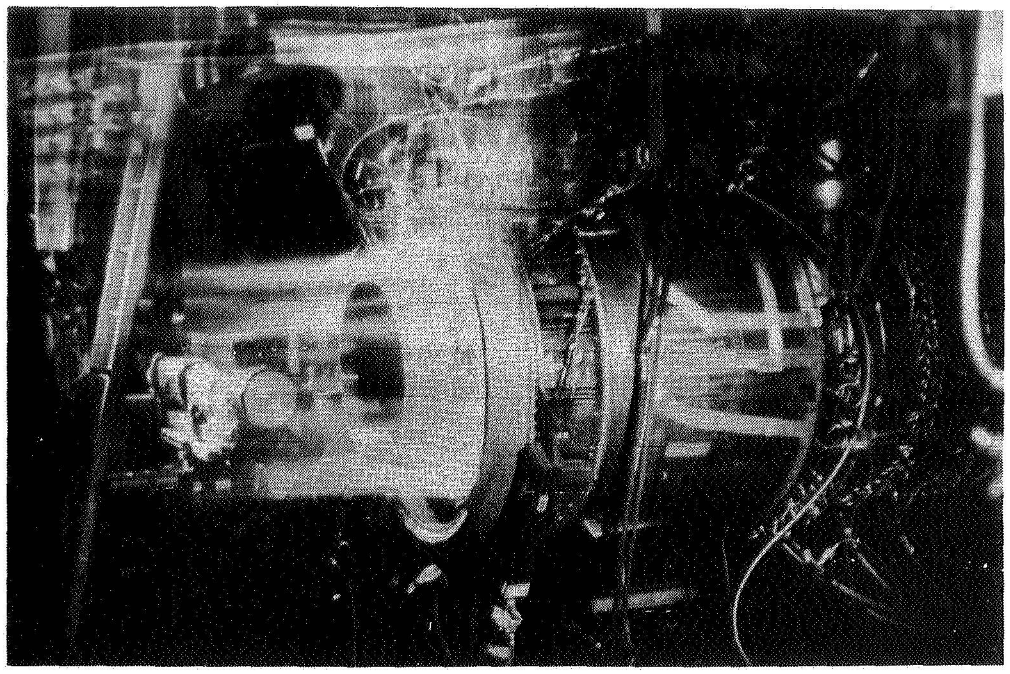


Figure 13.- VCE testbed demonstrator exhaust plume at duct burner augmentation.

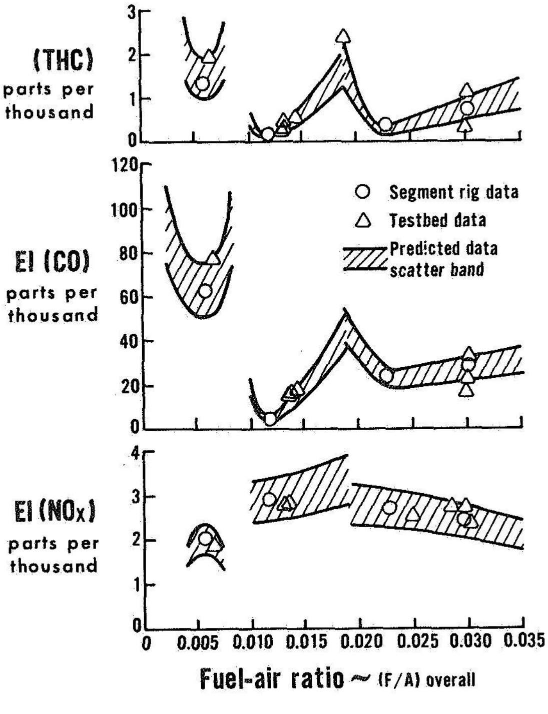


Figure 14.- Typical emissions results acquired from VCE testbed emissions testing.