XV. ADVANCED LOW-NO_x COMBUSTORS FOR SUPERSONIC HIGH-ALTITUDE GAS TURBINES

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The impact of gas-turbine-engine-powered aircraft on worldwide pollution can be defined within two major areas of contribution. First, the contribution of aircraft to the local air pollution of metropolitan areas and, second, the long-term effects on the chemical balance of the stratosphere of pollutants emitted from future generations of high-altitude, supersonic commercial and military aircraft.

Preliminary findings indicate that stratospheric oxides of nitrogen (NO_x) emissions may have to be limited to very low levels if, for example, ozone depletion with concomitant increases in sea-level radiation, are to be avoided. Although they are beyond the reach of any current combustor technology, theoretical considerations suggest that NO_x levels as low as 1.0 gram per kilogram of fuel and less should be attainable from a idealized premixed type of combustor. As a comparison, current commercial supersonic aircraft operate at cruise levels of approximately 18 to 20 g/kg fuel.

Experimental rig studies performed by the Solar Division of International Harvester under contract to the NASA Lewis Research Center, therefore, were intended to explore new combustor concepts designed to minimize the formation of NO_x in aircraft gas turbines and to define their major operational problems and limitations. The first program was begun in March 1974 and completed in June 1975. It defined the basic NO_x emission potential of two lean, premixed combustion systems at simulated cruise conditions and their operational range limitations. A follow-on effort was begun in November 1975 and is currently in the final stages. The same two combustor concepts have been reevaluated, with the major stress placed on screening of techniques that will allow these combustors to operate with satisfactory emis-

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sions at the engine idle condition and thus across the complete range of entire conditions.

This paper describes the combustor concepts investigated and summarizes the test results obtained during the follow-on program. Also future program efforts are outlined.

BACKGROUND

A review of the relevant background (ref. 1) will establish the basis for the program, the tests results of which are reported in this paper.

It was the primary goal of the first program to demonstrate that an NO_x emission index of 1.0 g/kg fuel could be achieved with maximum carbon monoxide (CO) and unburned hydrocarbon (THC) emission indices of 1.0 and 0.5 g/kg fuel, respectively, at a simulated supersonic cruise condition represented by a combustor inlet temperature and pressure of 1500° R and 5 atmospheres, with a combustor outlet temperature of 3200° R on Jet-A1 fuel.

Two separate types of lean, premixed combustion systems were evaluated. The design and operation of the two combustors, the jet-induced circulation (JIC) and the vortex air blast (VAB), are described in a subsequent section of this paper. The combustors differ in both the type of fuel-air preparation device used and the manner in which the reaction is stabilized. Oxides of nitrogen control is effected by minimizing the mean reaction-zone equivalence ratio and avoiding local equivalence ratio deviations, which can cause high NO_x levels.

Of the two combustor concepts evaluated, the vortex air blast demonstrated a superior emissions signature at the cruise condition, essentially meeting the cruise NO_x goal of 1.0 g/kg fuel. The jet-induced circulation combustor demonstrated an NO_x level of 2.1 g/kg fuel at the completion of the first program and in addition operated successfully at a higher reference velocity level, 100 feet per second as compared with the VAB combustor level of 50 feet per second. Subsequent improvements to the JIC mixing-tube system during the current program resulted in a further reduction of the JIC cruise NO_x level of 1.3 g/kg fuel.

An emissions signature of a VAB combustor obtained during the first contract study is shown in figure XV-1. The VAB combustor was configured as essentially a reaction zone with no dilution flow; hence, the temperature rise indicated on the abscissa refers to the reaction zone. Although the signature was obtained at a fairly low combustor inlet pressure, the 1495° R inlet temperature is representative of the supersonic cruise condition. The NO_x, CO, and THC characteristics depicted are typical of a well-stirred reactor, with the NO_x a strong exponential function of reaction temperature. The CO and THC characteristics are close to equilibrium levels over most of the operational range but increase sharply just prior to the lean stability point of the system. Because of the exponential NO_x dependency on reaction temperature, the liner cooling air must be maintained at a minimum level so that the effective reaction-zone equivalence ratio is as low as possible. If an upper limit of 1 g/kg fuel is set for the NO_x emissions and the VAB combustor is required to operate with a practical margin of stability and high combustion efficiency (i.e., on the horizontal section of the CO and THC characteristics), the allowable range of reaction temperatures is very limited.

Because such advanced combustors must ultimately operate across the complete engine condition range from idle to takeoff, a secondary program objective was to evaluate the emission performance of the two combustors at inlet temperatures representative of an idle point. The effect of low combustor inlet temperature can be seen in figures XV-2 and XV-3, which depict the CO and NO_x characteristics, respectively, obtained during the first program. These characteristics were obtained from the identical VAB combustor referred to in connection with figure XV-1. As the inlet temperature is reduced, both the NO_x and CO levels at a given reaction temperature progressively increase. This effect is due to a decrease in the driving force for the vaporization process resulting in a greater degree of nonuniformity, or "unmixedness," of the fuel-air charge entering the reactor. Upon combustion, the "unmixed" charge produces higher NO_x levels because the local equivalence ratio -' iations are higher than the weighted average.

The lea ..ability of the system, in terms of the minimum allowable reaction temperature before rapidly increasing CO levels occur, deteriorates as the combustor inlet temperature decreases. At an inlet temperature of 295° F, the lean limit of the combustor is at a combustor outlet temperature of approximately 2300° F; this is considerably higher than engine idle requirements, which are typically of the order of 1200° F.

Thus, a simple, lean, premixed, constant-geometry combustor designed for minimum NO_x at a cruise condition cannot operate satisfactorily across the complete range of engine conditions. The objective of the second program, the results of which are also presented in this paper, was therefore to define and develop techniques that could be used with the JIC and VAB combustors to allow satisfactory low-emission idle operation without compromise to the NO_x emissions at cruise.

COMBUSTOR CONCEPTS

The design of the two combustion systems was based on both the program operational constraints and Solar's background experience from the first program investigations. As in the first program, both model combustors were tested as reverse-flow can configurations. Both concepts were sized to give a cruise reference velocity of 50 feet per second at a total-pressure drop of 6.0 percent, resulting in a 4.5-inch-diameter reaction zone.

Jet-Induced Circulation (JIC) Combustor

A section through the JIC combustor is shown in figure XV-4 and displays the salient points of the design. To produce a reaction zone with a maximum degree of homogeneity, the reaction airflow and fuel flow are premixed for cruise operation in a system of four mixing tubes that are external to the reaction zone of the combustor and inclined at 30° to the combustor axis. The fuel is air-blast atomized at the entrance to each mixing tube from a multipoint injector rake 0.062 inch in diameter. The fuel is vaporized and mixed with the reaction air in the mixing tubes and emerges as a near-homogeneous jet into the reaction zone of the combustor. The four separate jets impinge toward the axis of the combustor, forming two derived jets. The major derived jet flows upstream into the reaction zone toward the combustor dome, impinges on the dome, and then flows rearward toward the entering mixing-tube jets. The resultant recirculation pattern is anchored by the mixing-tube jets, with a fraction of the reaction products being entrained into the mixing-tube jets to act as a continuous ignition source and the remainder of the products flowing out of the reaction zone between the mixing-tube jets. The minor derived jet flows rearward from the impingement point of the separate mixing-tube jets and is reacted partially in the dilution zone and partially by recirculation and entrainment into the mixing-tube jets.

The combustor design includes several features intended for potential use during idle operation, such as alternative fuel injection techniques and simulated variable geometry. The variable-geometry design consists of a translating-plug port system for reaction-zone and dilution-zone area control. No mechanism was provided, and the required areas were set before each test run. The reaction and dilution zones are convectively cooled and ignition is by torch igniter firing into the reaction zone of the combustor. For normal running purposes, the torch igniter was isolated after ignition.

Vortex Air Blast (VAB) Combustor

A section through the VAB combustor is given in figure XV-5 and shows the major features of the design. In the VAB combustor, premixing for cruise operation is accomplished within a radial inflow swirler rather than with a system of mixing tubes as for the JIC combustor. The swirler radial inlet has a set of 24 flat vanes set at a nominal angle of 45^{o}. The axial, annular discharge section communicates with the reaction zone. The fuel is air-blast atomized from 24 separate multipoint rakes situated within each vane channel slightly upstream of the vane leading-edge diameter. The fuel is vaporized and mixed with the reaction air in the swirler passage and enters the reaction zone of the combustor as a near homogeneous stream with a nominal outlet swirl cone included angle of 90^{o}. The radial static-pressure gradients produced in the vortex serve to drive the reaction-zone recirculation necessary for flame stabilization.

As in the JIC combustor, the VAB design includes several features intended for potential use during idle operation, such as alternative fuel injection techniques and simulated variable geometry. The variable-geometry design consists of the translating-plug port system for dilution-zone area control and variable-angle swirl vanes for reaction-zone area control. No mechanism was provided and the required areas were set before each test run.

The reaction and dilution zones are convectively cooled and ignition is by torch igniter firing into the reaction zone of the combustor. For normal running purposes the torch igniter was isolated after ignition. In both combustor concepts, the dilution-zone port area is zero at the cruise test condition; hence, the combustor operates as a reaction zone only.

TEST RESULTS

The simulated idle and cruise combustor test conditions and the program emission goals are shown in table XV-1. The following sections contain the principal emissions test results of the JIC and VAB combustor modifications.

Idle Test Condition

Several potential range control techniques for allowing satisfactory idle operation of the combustors were defined in the early program stages and included both fixed- and variable-geometry methods. For a fixed geometry the techniques are

(1) Fuel switching
(2) Vane angle change (VAB combustor)
(3) Pilot burner
(4) Axial fuel staging

For a variable geometry the techniques are

(1) Variable dilution
(2) Total variable geometry

Fuel switching. - As previously demonstrated, the basic JIC or VAB reaction zone using the premixed fuel injection techniques at cruise condition does not possess sufficient stability to operate at the idle test point. Variations in the type and positioning of the fuel injection system can, however, significantly improve the lean stability of the JIC and VAB reaction zones by deliberately introducing a greater degree of inhomogeneity in the reaction zone in terms of fuel-air distribution. This occurs at the expense of some increase in NO_x emissions, which are not normally excessive at reaction temperatures close to the lean stability point. For the JIC combustor, the alternative fuel injection positions and techniques evaluated are shown in figure XV-4 and consist of a dome pressure atomizer on the combustor axis and four inclined pressure atomizers mounted between the mixing tubes. In the VAB combustor shown in figure XV-5, a centerbody-mounted pressure atomizer and a multipoint air-blast atomizer were evaluated.

Most of these alternative fuel injection techniques improved the JIC and VAB reaction-zone lean stability to a varying degree, but none were successful in allowing operation of the reaction zone at engine idle with emissions within the program goals. This can be seen, for example, in figure XV-6, which depicts the variation of the limiting reaction-zone outlet temperature for various VAB configurations and fuel injection techniques. The limiting reaction-zone outlet temperature is defined as the temperature at which the CO emissions goal of 20.0 g/kg fuel is exceeded.

Variable dilution. - One range control technique that has been demonstrated is the use of variable geometry in the form of variable dilution ports. At the cruise and takeoff engine conditions, the dilution ports are fully closed; thus, the combustor is essentially a reaction zone alone and both the reaction-zone equivalence ratio and the NO_x production levels are minimized. At the engine idle condition, the variable dilution ports are fully open, so that the reaction-zone equivalence ratio is matched at a point where acceptable emissions and stability are attained.

Variable-area dilution ports are depicted in the schematic of a VAB can combustor shown in figure XV-5, where the area control is attained by a translating plug moving in and out of the port. By opening the dilution ports to their full extent, satisfactory idle operation can be attained, as shown by the emissions characteristic of figure XV-7. The combustor operates at the required outlet temperature of 1190° F with CO and THC levels of 3.5 and 0.6 g/kg fuel, respectively. Similar results were attained with the JIC combustor.

A potential problem area with this approach results from the wide range of movement required of the dilution ports in order to establish an acceptable reaction-zone equivalence ratio. This produces combustor total-pressure drops at the idle condition that can be lower than 1.0 percent (depending on the design-point pressure drop). The use of such low pressure drop levels means low velocity in the JIC mixing tube and a potential for flashback. The low pressure drop also means a degeneration in atomization quality when an air-blast injection system is used and poor dilution mixing although the exhaust pattern factor is not normally an important consideration at the idle condition.

Total variable geometry. - An extension of the variable dilution technique is total variable geometry. Here the scheme involves modulation of both the dilution ports and the primary airflow register. For the JIC combustor this means reducing the mixing-tube inlet area by means of translating plugs (fig. XV-4); for the VAB combustor it means varying the swirl vane angle (fig. XV-5).

Total variable geometry allows the idle pressure drop to be maintained at levels higher than are possible with variable dilution alone. These higher levels can enhance dilution air penetration, mixing, and fuel atomization but still will result in low mixture velocities in the fuel preparation device because most of the pressure drop is taken across the translating area modulation plug (JIC) or vane throat (VAB). Some potential problem areas of the simple variable dilution techniques can therefore be avoided at the expense of mechanical complexity.

The results of a series of simulated total-variable-geometry tests are shown in figure XV-8, where, with a constant dilution port setting, the reaction area of a JIC combustor was varied from a full-open setting to a modulating plug position gap of 0.04 inch. The limiting CO outlet temperature is defined as that temperature at which the idle CO emissions goal of 20 g/kg fuel is exceeded. The characteristic shows that the combustor can operate at idle with satisfactory CO emissions when the primary port setting is less than approximately 0.065 inch but is only one possible characteristic of a complete map depending on the chosen idle combustor pressure drop.

Similar results were demonstrated for the VAB combustor.

Fuel switching plus variable dilution. - By taking advantage of the lean limit augmentation effect obtained from fuel switching (fig. XV-6), a variable dilution system can be operated at idle that requires less dilution turn-down than the simple variable dilution technique without fuel switching. This results in higher combustor pressure drop levels at idle without incurring an excessive cruise pressure drop. The effect of matching a VAB reaction zone at various equivalence ratios by varying the dilution port setting is shown in figure XV-9 for two types of fuel injection: a centerbody pressure atomizer and a centerbody air-blast atomizer. Similar results were demonstrated for the JIC combustor.

Again, therefore, as with total variable geometry, some potential problem areas associated with the simple variable dilution system can be avoided by the addition, in this case, of fuel injection system complexity.

Axial fuel staging. - To evaluate the concept of axial fuel staging, the dilution zones of the JIC and VAB combustors were replaced by a secondary reaction/dilution zone of the JIC type. The resulting arrangements are shown in figures XV-10 and XV-11, depicting the axial fuel-staged JIC and VAB combustors, respectively.

The operation of the system is as follows. At the idle condition, the secondary JIC mixing tubes are unfueled and act as a conventional dilution system with fuel switching in the primary reaction zone, either JIC or VAB. At the cruise condition, both the primary reaction zone and the secondary JIC mixing tubes are fueled, with the flow split normally such as to produce a uniform equivalence ratio throughout the combustor. The system thus completely avoids the use of variable geometry.

A typical idle emissions characteristic of the VAB axial fuel-staged combustor where primary-zone fuel switching was used is shown in figure XV-12. Although the axial fuel-staged configurations possess the inherent simplicity of a fixed-geometry system, the combustor length is somewhat greater than the equivalent single-stage system length for the same reference velocity. This might be a significant disadvantage in some installations.

Cruise Test Condition

The test results at the cruise condition were obtained by closing the dilution ports completely and thus minimizing the reaction-zone equivalence ratio. Only low-pressure results are available at this time; the full cruise pressure of 14 atmospheres has not yet been evaluated.

JIC combustor - single stage. - A typical JIC reaction-zone emission characteristic at the cruise inlet temperature and a pressure of 3 atmospheres is shown in figure XV-13. The CO and THC emissions at the design outlet temperature are well within the program goals, but the NO_x emission level is almost 1.2 g/kg fuel. Although slightly higher than the program goal of 1.0 g/kg fuel, the NO_x result is lower than that obtained during the first contract program because of an increase in the mixing-tube length. A very preliminary assessment of the NO_x dependency on combustor pressure up to 5 atmospheres was made and is shown in figure XV-14.

VAB combustor - single stage. - A typical VAB reaction-zone emission characteristic at the cruise inlet temperature and a pressure of 5 atmospheres is shown in figure XV-15. As with the JIC combustor, the CO and THC emissions at the design outlet temperature are well within the program goals, but the NO_x level is 2.6 g/kg fuel. This level is considerably higher than the first-program result of 1.1 g/kg fuel and is considered to be due to differences in the design and performance of the fuel preparation system. Further tests are scheduled in an attempt to resolve the discrepancy. The preliminary results of the NO_x dependency on combustor pressure are shown in figure XV-16, where an exponent of 0.65 is obtained. This is also a deviation from the results of the first program, where the VAB combustor demonstrated an NO_x level that was not a function of pressure between 2 and 5 atmospheres.

Axial fuel-staged VAB combustor. - The two-stage VAB combustor was tested at the cruise inlet temperature and a pressure of 3 atmospheres. The primary reaction-zone equivalence ratio was maintained constant across the characteristic as the secondary reaction-zone equivalence ratio was modulated. At the design-point outlet temperature, the stages were operating at equal equivalence ratios. The emission characteristic is shown in figure XV-17.

The design-point NO_x of 1.1 g/kg fuel essentially meets the program goal although the pressure effects are unknown at the time of writing. Further tests are scheduled.

ANNULAR COMBUSTORS

Both of the NASA/Solar programs to date have been conducted with small can-combustor models and have served to demonstrate both the basic low-NO_x potential of the lean, premixed combustion system and a number of possible techniques for meeting a major limitation of the lean, premixed system; that is, the relatively narrow low-emissions operating range.

The next logical step in the development of a practical lean, premixed combustion system for an aircraft gas turbine is to transfer the technology available into an effort to demonstrate a configuration representative of current and future aircraft engine practice. The objective of a future NASA/Solar program will therefore be to develop and demonstrate a full-size, annular, low-emissions premixed combustor capable of operating across the full range of engine conditions, from idle through cruise to takeoff.

The program will investigate the two concepts of lean, premixed combustion that formed the basis for the two previous programs: the vortex air blast (VAB) combustor, where fuel preparation takes place within a swirler channel and reaction stabilization occurs in the resulting vortex recirculation; and the jet-induced circulation (JIC) combustor, where fuel preparation takes place within a mixing-tube system and reaction stabilization is the result of the multiple mixing-jet impingement.

The principal annular combustor features can be seen in figure XV-18, which illustrates preliminary concepts of the JIC and VAB combustors, respectively. Both combustors will incorporate fuel switching and variable geometry, which have been demonstrated as being required, in various combinations, to allow satisfactory operation across the total range of engine conditions.

SUMMARY OF RESULTS AND CONCLUSIONS

It has been demonstrated that certain available design techniques allow a premixed type of combustor to operate at idle conditions within the Experimental Clean Combustor Program emissions goals. Idle performance was generally limited by the carbon monoxide (CO) goal; no exhaust smoke was monitored at idle with the CO level less than the program goal of 20.0 g/kg fuel.

The optimum system for idle operation will ultimately be determined by such factors as size, mechanical reliability, control sophistication, and fuel injection complexity. The work presented in this paper was intended merely to define as many potential techniques as possible rather than a single optimum design. The successful systems demonstrated were

(1) Axial fuel staging (fixed geometry)

(2) Variable dilution

(3) Total variable geometry

(4) Variable dilution plus fuel switching or circumferential fuel staging

All these techniques are applicable to an annular combustor configuration.

The cruise oxides of nitrogen (NO_x) performance of the jet-induced circulation (JIC) combustor has essentially repeated the results of the first NASA/Solar program for the same available mixing tube length. Extending the effective mixing-tube length within an acceptable combustor size envelope results in complex tube curvatures, and further work is required to ensure that the NO_x improvements thus obtained are not at the expense of an operational limitation such as autoignition.

The cruise NO_x emissions of the vortex air blast (VAB) combustor are in excess of the levels recorded during the first NASA/Solar program, and a distinct pressure effect on NO_x is noticeable, which is also a deviation from the findings of the first program. At the time of writing, this deviation is thought to be due to the difficulty of scaling the VAB fuel preparation system in terms of atomization quality and the available vaporization/mixing residence time profiles in the swirler channel. Subsequent work on the program may serve to reduce the discrepancy in results between the two VAB combustion system designs.

The operational limitations imposed by autoignition at the cruise condition have not been adequately defined during the program investigations, and further work is required in that important area.

The axial fuel-staged VAB and JIC combustor systems can demonstrate good performance at idle conditions, and the cruise NO_x of the VAB appears to be at least as good as the equivalent single-stage system. The overall systems are, however, somewhat longer than the single-stage combustors, which is a distinct disadvantage. This must be weighed against the advantage of relative simplicity for the fixed-geometry system.

REFERENCE

1. Roberts, P. B.; et al.: Advanced Low NO_x Combustors for Aircraft Gas Turbines. AIAA Paper 76-764, July 1976.

PROGRAM GOALS AND TEST CONDITIONS

IDLE		CRUISE	
P_{in}	= 3atm	P_{in}	= 14atm
T_{in}	= 760°R	T_{in}	= 1500°R
T_{out}	= 1650°R	T_{out}	= 3200°R
CO	= 20.0 gm/kg fuel	NO_x (as NO_2)	= 1.0 gm/kg fuel
UHC	= 4.0 gm/kg fuel	CO	= 1.0 gm/kg fuel
		UHC	= 0.5 gm/kg fuel
		SAE smoke number	= 15.0

Table XV-1.

VAB REACTION ZONE EMISSIONS CHARACTERISTIC - HIGH INLET TEMPERATURE

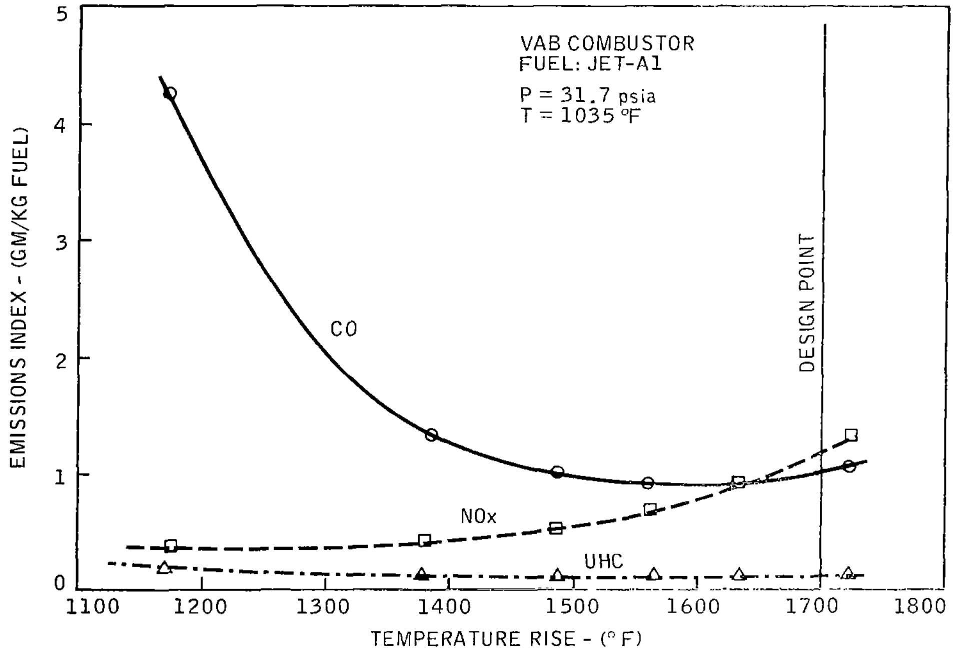

Figure XV-1.

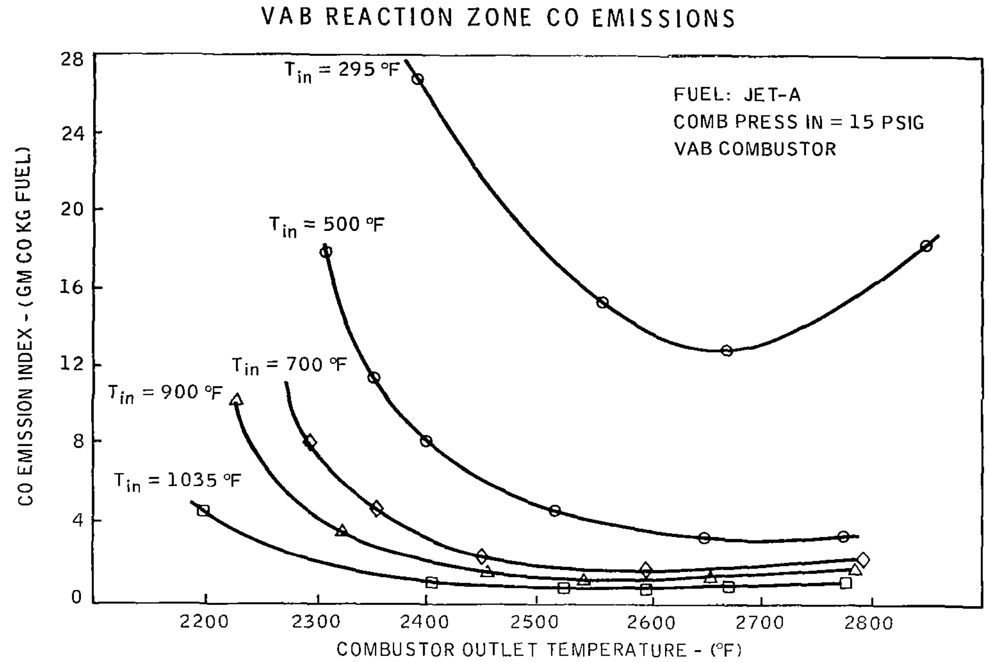

Figure XV-2.

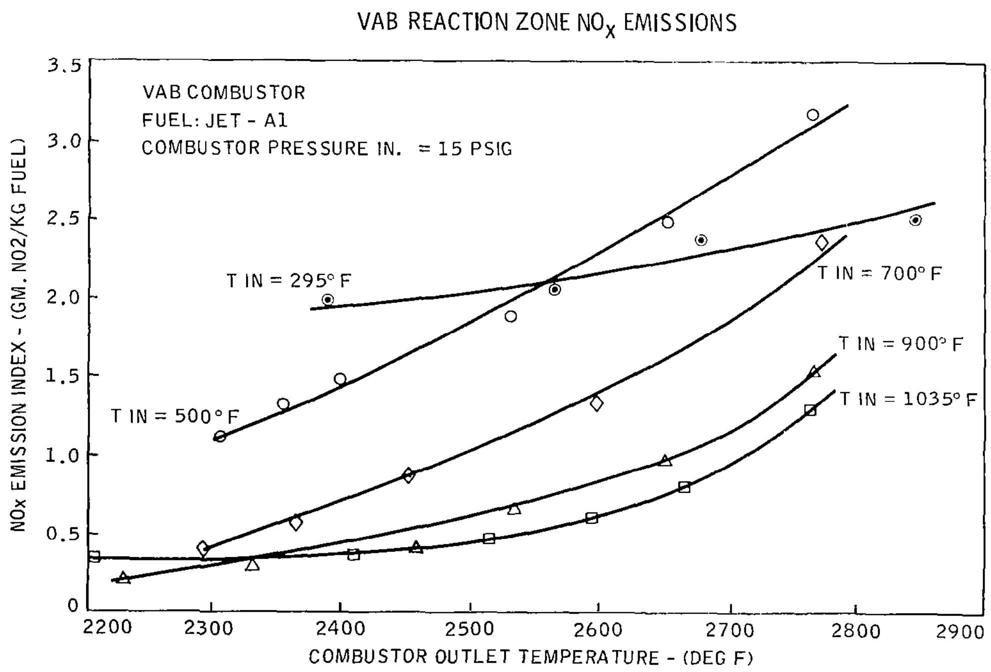

Figure XV-3.

JIC COMBUSTOR DETAILS

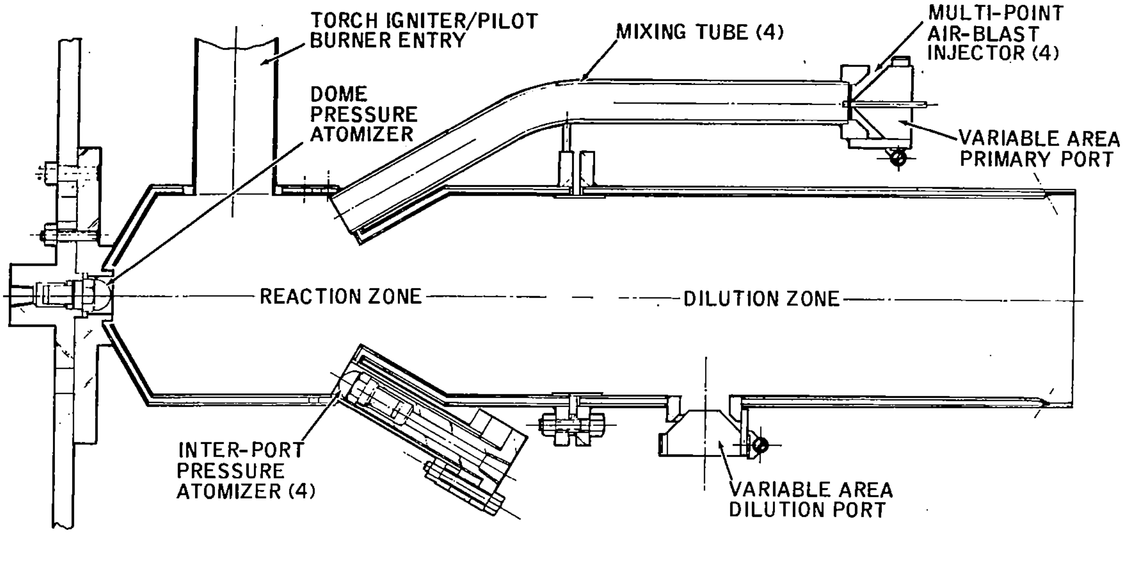

Figure XV-4.

VAB COMBUSTOR DETAILS

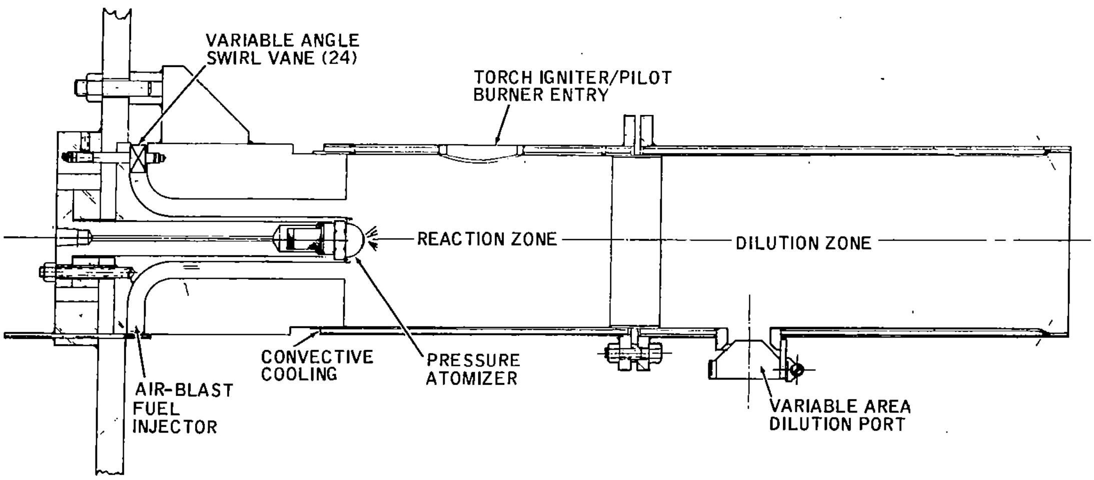

Figure XV-5.

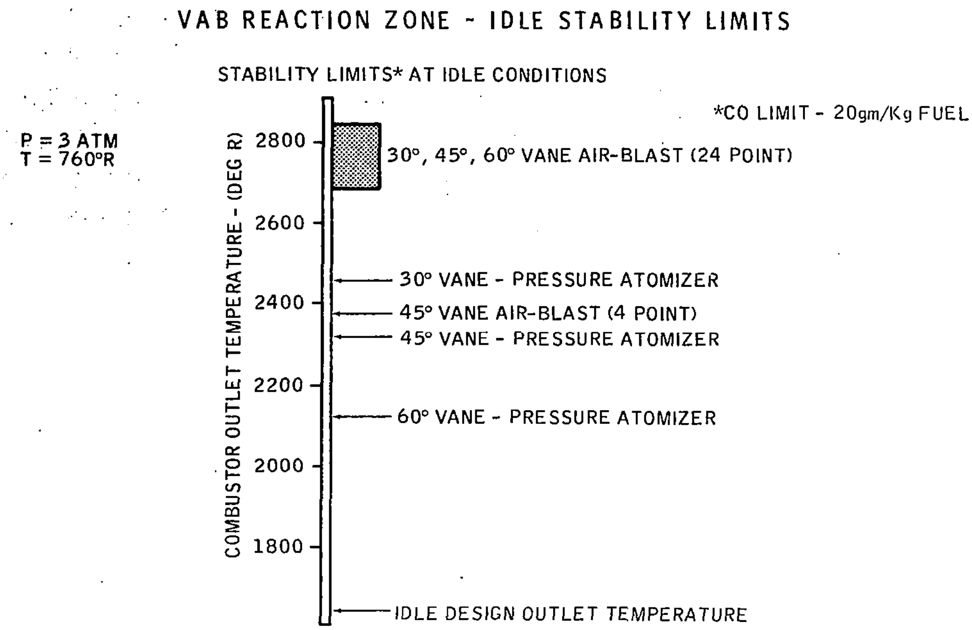

Figure XV-6.

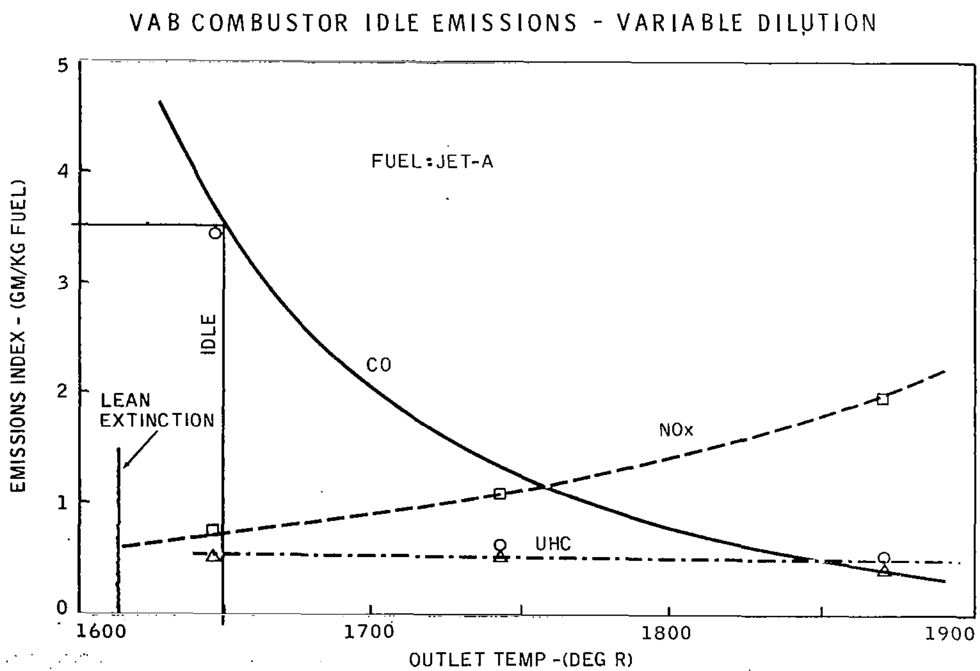

Figure XV-7.

JIC COMBUSTOR IDLE CO EMISSIONS - TOTAL VARIABLE GEOMETRY

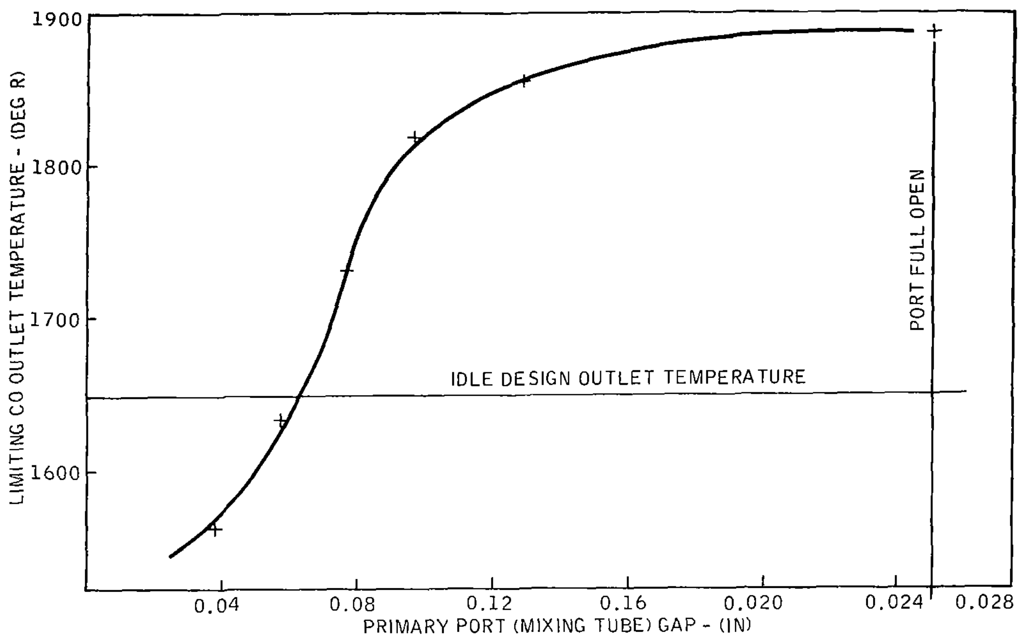

Figure XV-8.

VAB COMBUSTOR IDLE CO EMISSIONS - VARIABLE DILUTION PLUS FUEL SWITCHING

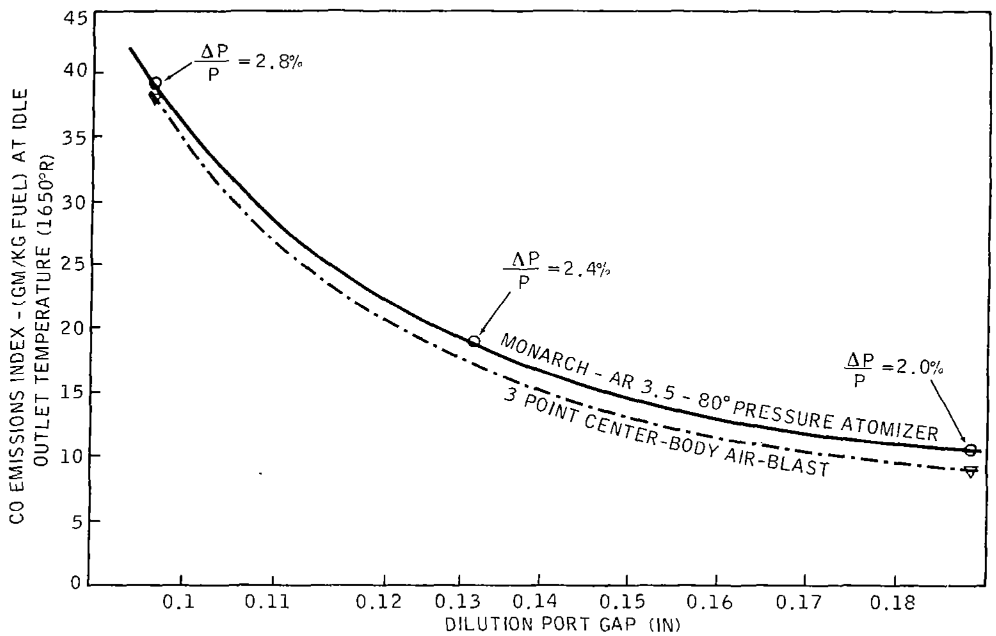

Figure XV-9.

JIC AXIAL FUEL-STAGED COMBUSTOR DETAILS

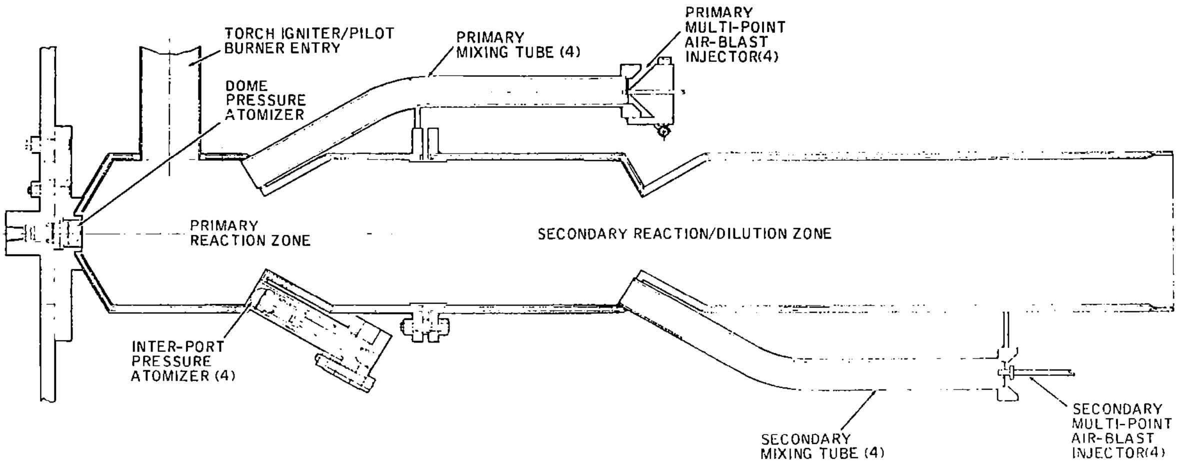

Figure XV-10.

VAB AXIAL FUEL-STAGED COMBUSTOR DETAILS

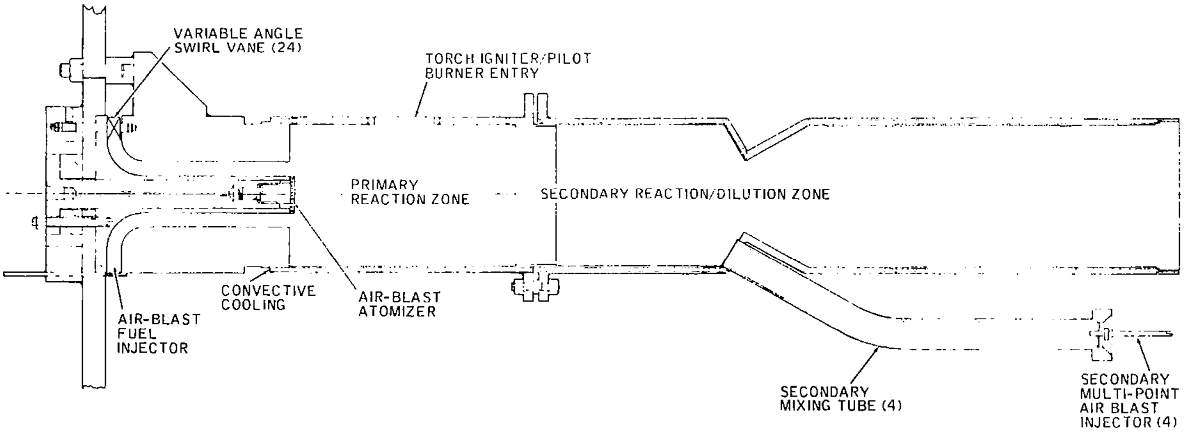

Figure XV-11.

VAB AXIAL FUEL STAGED COMBUSTOR IDLE EMISSIONS

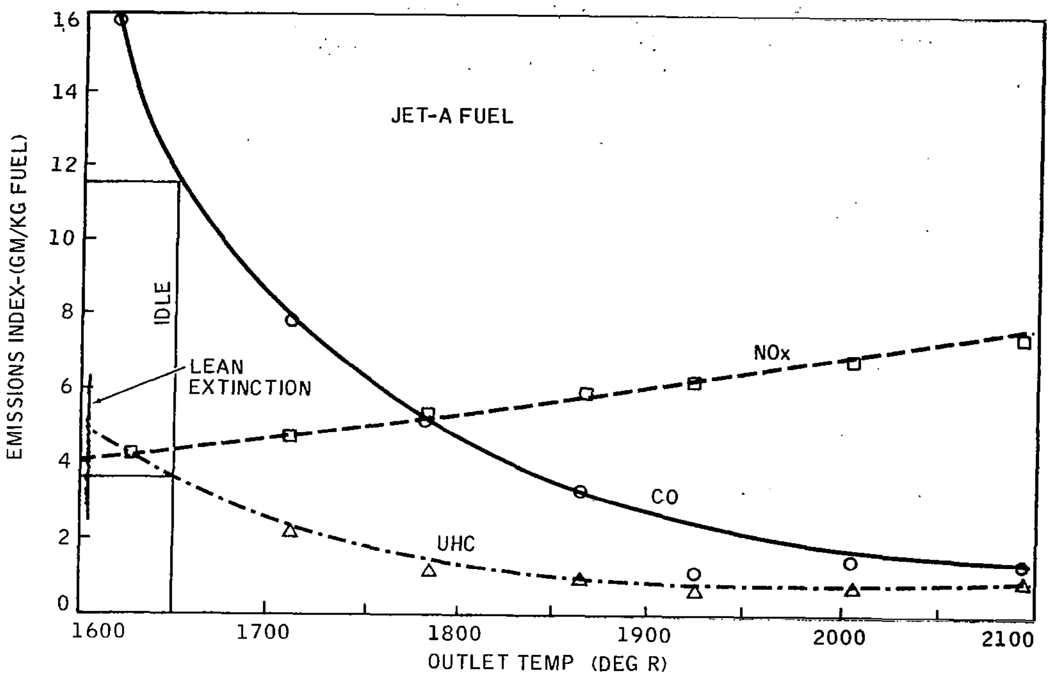

Figure XV-12.

JIC COMBUSTOR (REACTION ZONE) CRUISE CONDITIONS

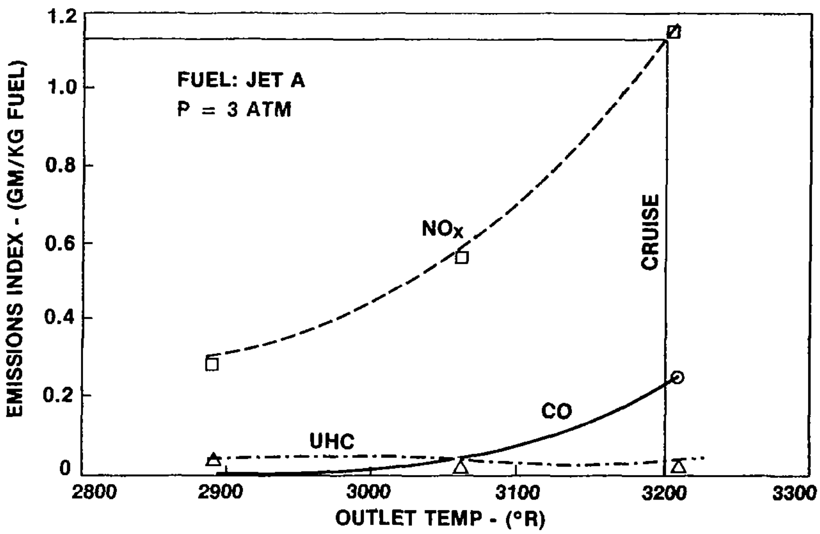

Figure XV-13.

JIC REACTION ZONE CRUISE NO_X PRESSURE DEPENDENCY

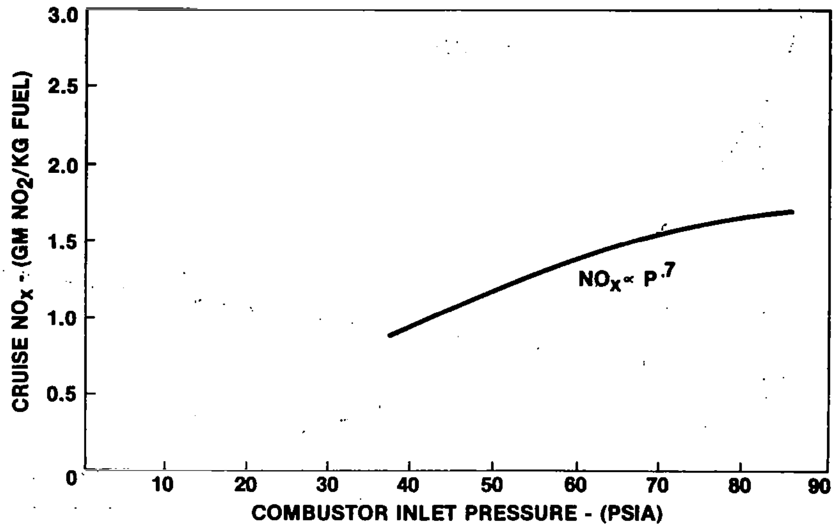

Figure XV-14.

TYPICAL VAB REACTION-ZONE EMISSION CHARACTERISTIC

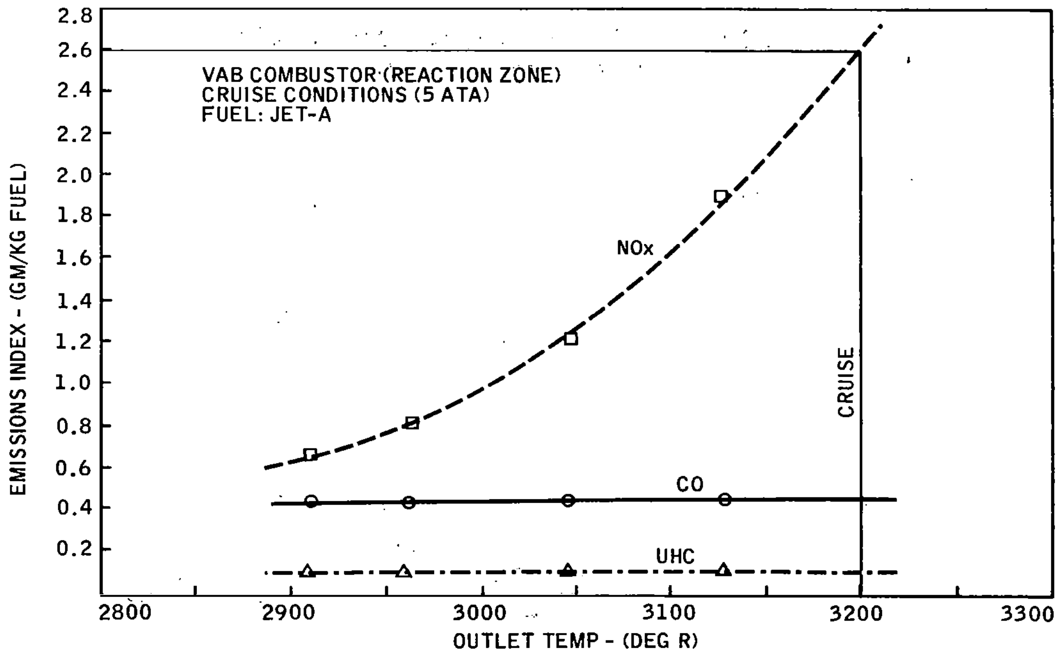

Figure XV-15.

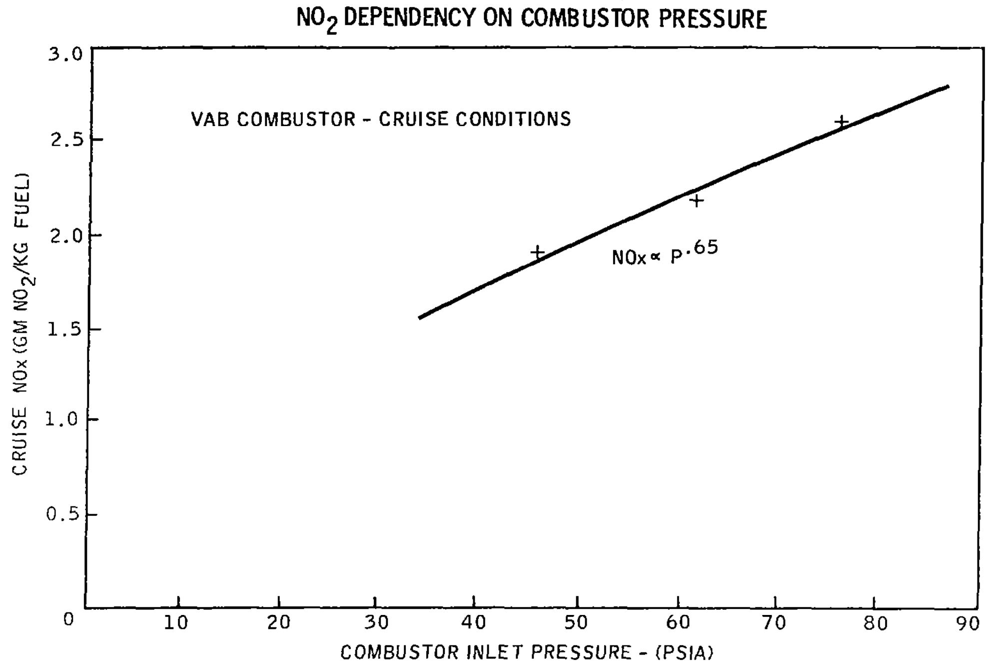

Figure XV-16.

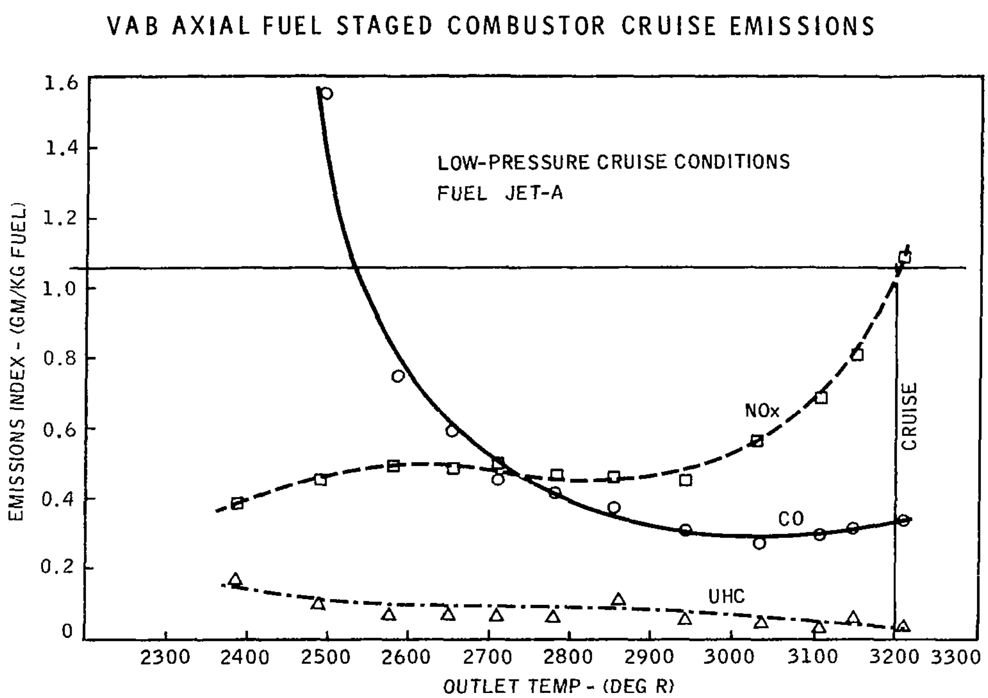

Figure XV-17.

VAB AND JIC ANNULAR COMBUSTOR SCHEMES

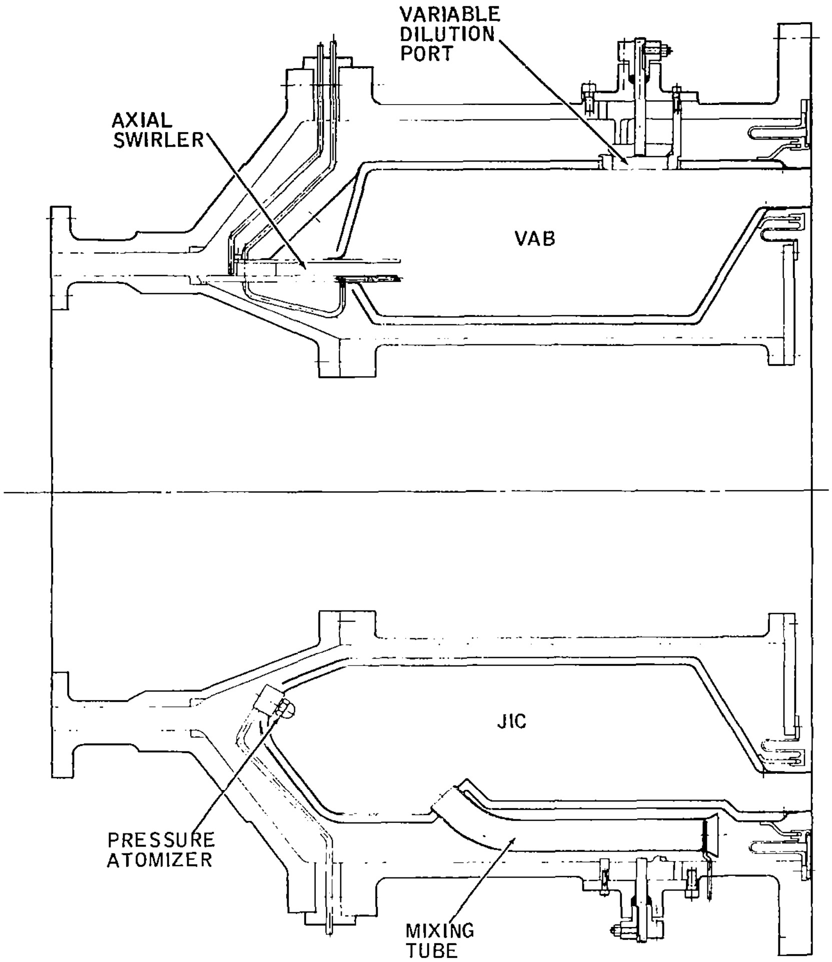

Figure XV-18.