VI. POLLUTION REDUCTION TECHNOLOGY PROGRAM FOR TURBOPROP ENGINES

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The Clean Air Act of 1970 charged the Environmental Protection Agency (EPA) with the responsibility to establish acceptable exhaust emission levels of carbon monoxide (CO), total unburned hydrocarbons (HC), oxides of nitrogen (NO_x), and smoke for all types of aircraft engines. In response to this charge, the EPA promulgated the exhaust emissions standards published in the Federal Register, Volume 38, Number 136, July 17, 1973 (ref. 1). Prior to the release of these standards, the aircraft engine industry, various independent research laboratories and universities, and the government were involved in research on and development of low-emission gas turbine engine combustors. Some of this research was used as a guide to set the levels of the EPA standards.

The Pollution Reduction Technology Program for turboprop engines covered by this report was a joint effort between NASA and Detroit Diesel Allison (DDA) directed toward the EPA class P2 engine category. The principal goal in this program was to reduce CO, HC, and smoke emissions while maintaining acceptable NO_x emissions without affecting fuel consumption, durability, maintainability, and safety. This program covered component combustor concept screening directed toward the demonstration of advanced combustor technology required to meet the EPA exhaust emissions standards for class P2 turboprop engines. The combustion system for the Allison 501-D22A engine was used as the basis for this program, and three combustor design concepts - reverse flow, prechamber, and staged fuel - were evaluated in the program.

The total program was conducted on the DDA single-burner combustor rig operating in the DDA combustion development facility. Combustors were operated to conditions corresponding to the power settings for the EPA landing/takeoff (LTO) cycle. Variations of fuel-air ratio and reference velocity were evaluated at takeoff and idle conditions to obtain further emissions definition of these limiting operating conditions.

Emissions measurements made on the baseline combustor configuration established that significant reductions of CO, HC, and exhaust smoke would be necessary to meet EPA regulations. Development variations of all three combustor design concepts met the projected EPA requirements with varying degrees of margin. Although these initial component development results indicated no significant compromises in steady-state performance, further component rig development is required before engine testing can proceed with assurance.

PROGRAM GOALS AND APPROACH

Emissions reduction requirements for this program were based on component rig test values obtained on a baseline combustion system in this program. Goals were established at 25 percent below the EPA regulation requirements to provide margin for engine development and production variations, as shown in table VI-1.

Three basic combustor designs were tested and then modified and retested to achieve the goals of the program. The program schedule is shown in figure VI-1. These designs were designated (1) the reverse-flow combustor, (2) the prechamber combustor, and (3) the staged-fuel combustor and are illustrated in figure VI-2. All configurations were designed for adequate cooling and structural integrity to provide satisfactory durability and the following minimal performance goals:

(1) Combustion efficiency greater than 99 percent at all operating conditions

(2) Combustor exit temperature pattern factor equal to or less than 0.25 at the takeoff power conditions

(3) Combustor pressure drop of 5 percent or less at takeoff power conditions

Test conditions were controlled to the exact values of flow, pressure, and temperature for the 501-D22A engine, as shown in table VI-2. The inlet temperature was obtained with direct-fired heaters, which provided nonvitiated inlet air to the component combustor test rig. Emissions measurements were obtained from 11 four-port sampling probes mounted in the combustor exit; and pressures, flows, and temperatures were measured with appropriate total and static pressure probles, thermocouples, and flow measurement orifices. Combustors were operated to conditions corresponding to the power settings for the EPA LTO cycle, and variations of fuel-air ratio and reference velocity were evaluated to takeoff and idle conditions in order to obtain further emissions definition at these limiting operating conditions.

ENGINE AND COMBUSTOR DESCRIPTION

The 501-D22A engine is one in a series of commercial model 501 engines; the T56 is their military counterpart. All engines in these series consist of an internal combustion gas turbine power section connected by extension shafting and a supporting structure to a single-reduction gear assembly that has a single propeller shaft, as shown in figure VI-3. In the 501-D22A, this shaft is offset above the power-section centerline. The power section contains six combustion chambers of the throughflow type assembled within a single-annular chamber and incorporates a 14-stage axial-flow compressor directly coupled to a four-stage aircooled turbine.

Engine operation is controlled by coordinated operation of the fuel, electrical, and propeller control systems. A characteristic of this turboprop engine is that changes in power are related not to engine speed but to turbine inlet temperature. During flight, the propeller maintains a constant engine speed, which is 100 percent of the engine's rated speed and is the design speed at which most power and best overall efficiency can be obtained. Therefore, fuel flow is changed to affect power requirements. An increase in fuel flow results in a higher turbine inlet temperature and a corresponding increase in available energy at the turbine. The turbine then absorbs more energy and transmits it to the propeller in the form of torque. The propeller, to absorb the increased torque, increases blade angle and maintains constant engine rotational speed.

Two specific performance ratings as a function of power setting for the 501-D22A turboprop engine are shown in table VI-3. The combustion system of the 501-D22A engine consists of six can-type combustion liners located in the annulus formed by the outer and inner casings, as shown in figure VI-3. The radial position of each can is set at the inlet end by a fuel nozzle centered within a flared fitting in the dome and at the exhaust end by the combustor transition engaging the turbine inlet vane assemblies. Axial positioning is accomplished by igniter plugs in two cans and dummy igniter plugs in the remaining four cans. Six crossover tubes interconnect the cans and provide flame transfer for starting. The six fuel nozzles are connected to a fuel manifold attached to the external surface of the outer case.

Production Liner

The combustion liner currently in production in the 501-D22A engine is shown in figure VI-4. Design features of this combustor are

(1) Dome air-entry holes backed by baffles to induce a circular flow pattern across the hot face of the dome
(2) Film cooling slots formed by overlapped wall segments
(3) Dome-center-mounted fuel nozzle
(4) Primary-zone trim holes
(5) Nonuniform dilution hole spacing for gas temperature-pattern control

The fuel injector used with the production liner is a dual-orifice, pressure atomizing type. An internal valve in the nozzle opens only the small pilot orifice for low fuel flows so that a high-quality spray pattern is obtained. For high flows the main section of the nozzle is operational in addition to the pilot.

Reverse-Flow Combustor Design

The low-emissions combustion system currently in production in the Allison model 501-K industrial engine formed the basis of the reverse-flow combustor - air-blast fuel injector system used in this program. The reverse-flow concept, shown in figure VI-5, incorporates a unique primary-zone flow system that increases the amount of recirculating products; improves the fuel and air mixing; and returns the partially burned products, which become trapped in the primary-zone cooling film, back into the reaction. This design operates with great stability over the fuel-air ratio range 0.004 to 0.022, which is typical of single-shaft industrial applications. Other features of the combustor were kept simple and conventional so that the low cost and durability of the original system were retained.

The air-blast fuel nozzle design uses the combustion liner differential air pressure to atomize the fuel. This is done by accelerating the air through a row of vanes and using the resulting high velocity for atomization. With this device, the fuel droplet diameters are reduced by approximately 1/3 and a modest degree of fuel-air premixing also occurs with the atomizing air. An important feature of this injector design is that droplet size remains small over the entire engine operating range. A pressure-atomizing pilot is used to retain good engine starting.

In this program, the 501-K industrial engine combustion system was redesigned so that its exhaust emissions would comply with the program emissions goal (75 percent of the EPA turboprop standard).

Prechamber Combustor Design

The prechamber where fuel and air mix is attached to a main combustion section having primary-zone trim holes and dilution holes. Details of the prechamber combustor designs and their modifications are shown in figure VI-6 and described here.

The features common to all the prechamber combustors are as follows:

(1) An air-blast fuel nozzle, which under certain conditions, incorporated a pressure-atomizing pilot

(2) A prechamber, employing an axial swirler at the inlet and a center-mounted fuel nozzle

(3) A radial swirler at the end of the prechamber, with the same swirl direction as the axial swirler and fuel nozzle air-blast swirler

(4) A trip between the radial swirler at the end of the prechamber and the main chamber, which, in conjunction with the swirler caused two distinct recirculation zones

(5) A secondary fuel system that placed fuel on the wall of the prechamber just upstream of the radial swirler, denoted as wall-film fuel injection
(6) A combustor exit transition section
(7) A variable-geometry band used to open and close the dilution holes

Staged-Fuel Combustor Design

The staged-fuel combustor was designed to provide maximum CO, HC, and smoke reduction with no attempt to reduce NO_x. Analysis of the 501-D22A production liner emissions over the LTO cycle shows that approximately 95 percent of the total CO and HC is emitted in the idle mode. Improvements must be made at the idle condition if program goals are to be met. The staged-fuel combustor is shown in figure VI-7. The following design features were incorporated in the pilot combustion zone specifically to reduce idle CO and HC:

(1) Slightly lean pilot zone for high reaction rates

(2) Low pilot-zone airflow loading: About 50 percent of the combustion air is admitted into a separate, main combustion zone.

(3) Low wall-quenching: A film-convection wall cooling system was employed. This provides excellent cooling performance with approximately 50-percent cooling flow reduction relative to conventional film cooling systems.

(4) Initial cooling step flow reversal: This feature is also used on the reverse-flow combustor to "recycle" CO and HC trapped in the cooling air close to the dome.

(5) Swirl prechamber: The fuel is introduced into a short axial prechamber to provide good initial fuel-air mixing and good stabilization and mixing patterns in the combustion region. The prechamber fuel-air mixing quality and the limited operating range required from the pilot zone allowed the use of the standard dual-orifice, pressure-atomizing fuel injector to obtain the required smoke reduction. The arrangement of two combustion chambers in series, the upstream chamber being the pilot zone and the downstream chamber the main zone, provides for extended residence time and combustor volume for emissions reduction at the critical idle and

approach conditions. Flame stabilization was accomplished by aerodynamic means; recirculation associated with geometric expansions was used to maintain pilot- and main-zone flames. In the main combustion chamber, flame stabilization was augmented by the hot pilot-zone gas mixing with the main-zone fuel-air mixture.

The fueling system was a key main-zone design feature. The main-zone fuel manifold was located close to the pilot-zone fuel nozzle to demonstrate the feasibility of obtaining pilot- and main-zone fuel from a single line. This capability would allow a staged-fuel combustor to be incorporated into the 501-D22A engine with only minor engine modifications and with no "buried" main fuel injectors or manifolds. The main fuel is injected from the main manifold into six fuel-air premixing tubes. Airflow in these tubes transports the fuel from the fuel manifold at the pilot-zone front end to the main combustion zone. Some fuel prevaporization occurs during transport. The degree of fuel prevaporization obtained is a function of many variables (fuel properties, pressure, temperature, residence time, etc.) and is probably small at the relatively low inlet temperature conditions of the 501-D22A. Higher inlet temperature cycles would have increased main fuel prevaporization. Six main prechambers were incorporated in the fuel-air premixing tubes at the inlet to the main combustion zone. Radial-inflow swirl air was introduced into these prechambers to centrifuge the remaining liquid fuel onto the tube walls in order to obtain good main fuel distribution and reduced preignition or flashback potential. An air-blast atomization rim was provided at the main prechamber exit to air-blast atomize the main fuel. The fuel-air mixture exiting each prechamber was directed in a swirling pattern to aid in main-zone stabilization and to assist mixing.

A dilution-zone, variable-geometry band was incorporated to readily accomplish airflow distribution changes during hot testing. This band allowed the dilution hole area to be adjusted from fully open to fully closed. The program objective, however, was to demonstrate low emissions and stable operation over the engine operating range in a fixed-geometry mode. The staged-fuel combustor design was tested with the three different pilot-zone fuel injectors. The first build employed the production 501-D22A dual-orifice pressure-atomizing nozzle.

TEST

The test equipment used in the performance of this contract consisted of (1) a test rig with instrumentation and readout equipment, and (2) a support facility supplying conditioned nonvitiated (neat) air at 501-D22A inlet conditions. An existing model 501-D combustion rig was modified and used to test the production and low-emission combustors. This rig is a single-burner configuration that simulates one-sixth of the 501-D can-annular combustion system. The airflow path of the 501-D rig simulates the engine in that the axial-station cross sections at all locations are the same as the dimensions of a 60° segment of the engine combustion system. Flowpath simulation also includes the compressor discharge passage and extends through the diffuser combustion section and into the turbine inlet. An overall view of the rig is shown in figure VI-8.

Flow and pressure level in the rig test section are regulated by an upstream control valve and a downstream backpressure valve, with final temperature trimmed by oil-fired heaters at the rig inlet. Flow is measured upstream near the test section; pressure and temperature are measured in the diffuser; and exhaust gas pressure, temperature, and emissions are measured just downstream of the test section. The test section of this rig included variable-geometry rod attachments and operators and 11 gas-sampling emission probes. The objective of the probe design is to obtain a representative sample, four holes per probe and 11 probes, and to maintain suitable probe tip temperatures for durability and suitable sample temperatures for accuracy of measurement. Electric heaters were used to regulate sample line temperature from the manifold to the instruments. The on-line instruments used to measure emissions are listed in table VI-4.

Analyzers used in this program were calibrated before and after the test program. The nitrogen oxides converter was checked weekly for efficiency with a model 100 Thermo Electron NO_x generator.

The emissions measurement system is shown in figure VI-9. An on-line verification of emissions measurement is employed whereby the fuel-air ratio from the measured exhaust gas composition is compared with the metered value. These values should be the same, within ±5 percent. Combustion efficiency is also calculated from the exhaust gas composition by the following equation:

$$\%\eta_b = 1 - \frac{fr_{CO}(-121\ 745) + fr_{HC}(A) - fr_{NO}(38\ 880) - fr_{NO_2}(12\ 654)}{(fr_{CO_2} + fr_{CO} + fr_{HC})\ (A)} \times 100$$

where A is a constant depending upon the fuel used: -273 070 for JP4, -258 843 for JP5, etc.; and fr is the fraction defining volume.

The smoke measurement system is shown schematically in figure VI-10.

Tests were conducted by establishing the desired test conditions, lighting the combustor with a spark igniter, and gradually increasing fuel flow to the required fuel-air ratio while carefully noting combustor skin thermocouple readings for excessive temperature in the combustor primary zone. After steady operation was established, data were recorded by the computer center and log entries were made of key readings. The test conditions were the four EPA parameter (EPAP) LTO cycle points - idle, approach, climbout, and takeoff - for the 501-D22A engine. Parametric tests were conducted on selected configurations to determine the effect of off-design-point operation and variations in fuel and air schedules.

The test time was significantly reduced in evaluating the primary-zone, equivalence ratio parameter by using variable-geometry dilution holes; a movable axial swirler; a variable-area radial swirler; and primary-zone, variable-area holes in selected combustors. With the variable-geometry techniques, the primary-zone equivalence ratio was changed while the test was in progress. Other provisions for reducing test time were separate pilot and main fuel lines to the air-blast nozzle, which allowed control of the pilot to main fuel split during the test; and separate fuel lines for the pilot and main combustion zones in the staged-fuel combustor to permit optimization of fuel splits at each EPAP LTO cycle condition.

RESULTS

Production Liner

All combustor designs on this program were tested at eight conditions, the four EPA LTO cycle points and two off-design fuel-air points at both idle and takeoff conditions. The results computed for the EPA LTO cycle expressed as EPA index values are compared with the program goals in table VI-5 for the 501-D22A production liner. As indicated, considerable reductions of HC, CO, and smoke are required. Nitrogen oxides are already below the program goal.

Reverse-Flow Combustor Design

Five configurations of the reverse-flow combustion system were tested for emissions and combustion system operating parameters. Exhaust emissions from all five reverse-flow designs were beneath the required contract goals, except for smoke from modification III, which was excessive at approach, climb, and takeoff. The results for the best of the five designs are shown in figure VI-11.

Prechamber Combustor Design

Six configurations of the prechamber combustion system were tested for emissions and combustion system performance. Exhaust emissions from all six prechamber designs were below the contract goals, except for smoke and CO from modifications I and II. The results for the best design are given in figure VI-12.

Staged-Fuel Combustor Design

The staged-fuel combustors were capable of being operated at various pilot to main fuel splits, and with various airflow splits as determined by the variable-geometry settings. Data were obtained for only a limited number of variable-geometry settings and pilot to main fuel splits in order to indicate emission trends.

The baseline combustor and modifications I to IV employed the original staged-fuel combustor design but with various pilot fuel injectors. Modifications V and VI employed a new staged-fuel combustor design with an air-blast pilot fuel injector. All EPAP values were computed from fixed-geometry data. The fuel flow split was allowed to vary in order to obtain low EPAP values. The low power points were always run with 100-percent pilot fuel. The climbout and takeoff conditions were generally tested with both pilot and main zones fueled. Main fuel flow ranged from 100 percent (no pilot flow) to about 50 percent. The fuel split at high power was generally selected for low NO_x emission.

Seven configurations of the staged-fuel combustion system were tested for emissions and combustion system performance. Exhaust emissions from all seven of the staged-fuel designs were below the contract goals except for smoke and NO_x on modification I and NO_x on modification II. The results for the best design are presented in figure VI-13. The emissions results from the best modification of each design concept are shown in figure VI-14, as compared with the production combustor and the program goals. All the design concepts showed significant emissions reductions and were well below the program goals.

Combustor outlet temperature distribution, liner maximum wall temperature, and combustion system pressure drop for the best low-emission combustors and the production combustor are compared in table VI-6.

CONCLUSIONS

The following conclusions are supported by the results obtained in the Pollution Reduction Technology Program:

1. All three low-emission combustor types - reverse flow, prechamber, and staged fuel - met the EPA 1979 class P2 aircraft regulations. The reverse-flow modification IV combustor design is the easiest to incorporate into the engine and the most durable and would require the least cost. Therefore, reverse-flow modification IV is the best candidate for further development into eventual use with the 501-D22A turboprop engine.

2. The reverse-flow combustion system met all program goals for emissions by large margins. Emissions from modification III are well below the goals established at the beginning of the program.

3. The prechamber combustion system met all program goals. Emissions from modification III are well below the program goals.

4. The staged-fuel combustion system met all program goals. Emissions from modification V are well below the program goals.

5. The experimental test program demonstrated that enriching the primary zone markedly improved idle emissions. The incorporation of an air-assist (external air source) fuel nozzle in place of an air-blast nozzle provided acceptable emissions at idle but failed to meet program smoke goals.

6. Large idle carbon monoxide and hydrocarbon reductions can be accomplished at some idle conditions by the use of air-blast or air-assist fuel injection.

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3. Aircraft Gas Turbine Engine Exhaust Smoke Measurement. SAE Aerospace Recommended Practice 1179, 1970.

4. Mularz, Edward J.: Results of the Pollution Reduction Technology Program for Turboprop Engines. NASA TM X-71911, 1976.

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PROGRAM GOALS

	EPA LTO CYCLE (LB/1000 HP-HR/CYCLE)		EMISSION INDEX G POLLUTANT/KG FUEL	
	REQUIREMENTS	GOALS	CONDITIONS	EI GOALS
TOTAL HYDROCARBONS	4.9	3.7	IDLE	5.4
CARBON MONOXIDE	26.8	20.1	IDLE	27.9
OXIDES OF NITROGEN	12.9	9.7	TAKEOFF	18.8
EXHAUST SMOKE	29.2	21.9		

Table VI-1.

MODEL 501-D22A COMBUSTOR INLET CONDITIONS

MODE	ENGINE SHAFT POWER (HP)	BURNER INLET TEMP. (°F)	BURNER OUTLET TEMP. (°F)	FUEL AIR RATIO	BURNER INLET PRESSURE (PSIA)	BURNER* AIR FLOW (LB/SEC)
TAXI/IDLE	155	335	1160	.0113	53.6	2.5
TAKEOFF	4368	639	1920	.0200	142.6	5.5
CLIMBOUT	3931	631	1825	.0185	138.9	5.32
APPROACH	1310	599	1275.	.0096	122.0	5.57

*FOR ONE COMBUSTOR

Table VI-2.

SPECIFIC PERFORMANCE RATINGS

STANDARD SEA-LEVEL STATIC CONDITIONS

POWER SETTING	TURBINE INLET TEMPERATURE °F	SPEED, RPM	EQUIVALENT SHAFT HORSEPOWER	SPECIFIC FUEL CONSUMPTION, LB/HR/ESHP	PROPELLER SHAFT HORSEPOWER	JET THRUST, LB
TAKEOFF (100 PERCENT)	1920	13 820	4680	0.502	4368	781
MAXIMUM CONTINUOUS (93 PERCENT)	1850	13 820	4364	.512	4061	760

Table VI-3.

EMISSIONS INSTRUMENTS

EMISSION	METHOD	INSTRUMENT	ACCURACY
OXIDES OF NITROGEN	CHEMILUMINESCENCE	THERMO ELECTRON (MODEL 10A WITH CONVERTER)	± 1%
CARBON MONOXIDE + WATER VAPOR	NONDISPERSIVE INFRARED	BECKMAN (MODEL 865)	± 2%
CARBON DIOXIDE	NONDISPERSIVE INFRARED	BECKMAN (MODEL 864)	± 1%
UNBURNED HYDROCARBONS	FLAME IONIZATION DETECTOR	BECKMAN (MODEL 402)	± 1%

Table VI-4.

EMISSION REDUCTION REQUIRED

	TOTAL HYDROCARBONS LB/1000 HP-HR/CYCLE	CARBON MONOXIDE LB/1000 HP-HR/CYCLE	OXIDES OF NITROGEN LB/1000 HP-HR/CYCLE	MAXIMUM SAE SMOKE NO.
EPA LIMITS CLASS P2	4.9	26.8	12.9	29
PROGRAM GOALS 75% OF CLASS P2	3.7	20.1	9.7	22
PRODUCTION LINER	15.0	31.5	6.2	59
REDUCTION REQUIRED, PERCENT BASED ON PROGRAM GOALS	75.5	36.1	0	62.7

Table VI-5.

COMBUSTOR PERFORMANCE SUMMARY SLS TAKEOFF

CONFIGURATION	PATTERN FACTOR	MAX. WALL TEMP.	$\frac{\Delta P}{P}$
PRODUCTION	.18	--	5.2%
REVERSE FLOW MOD. IV	.11	1614°F	5.2%
PRECHAMBER MOD. III	.14	1682°F	5.3%
STAGED FUEL MOD. V	.21	1489°F	5.7%

Table VI-6.

PROGRAM SCHEDULE

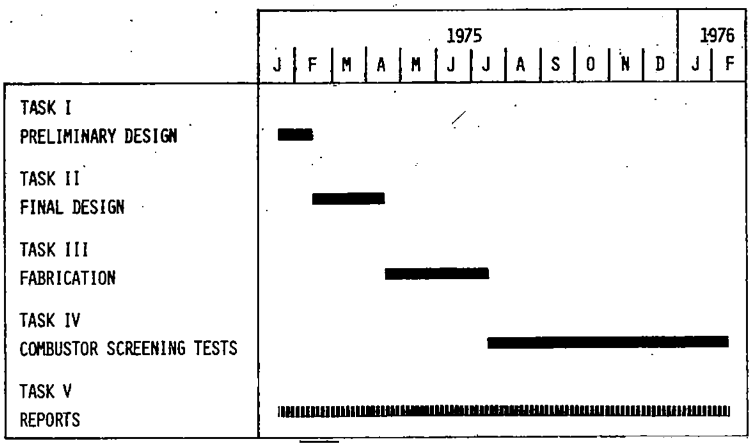


Figure VI-1.

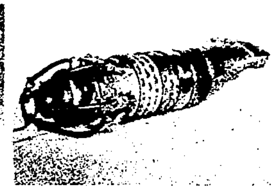
EMISSION REDUCTION CONCEPTS

501-D22A COMBUSTORS

PRODUCTION LINER

REVERSE FLOW

PRECHAMBER



STAGED FUEL

Figure VI-2.

MODEL 501-D22A ENGINE CUTAWAY

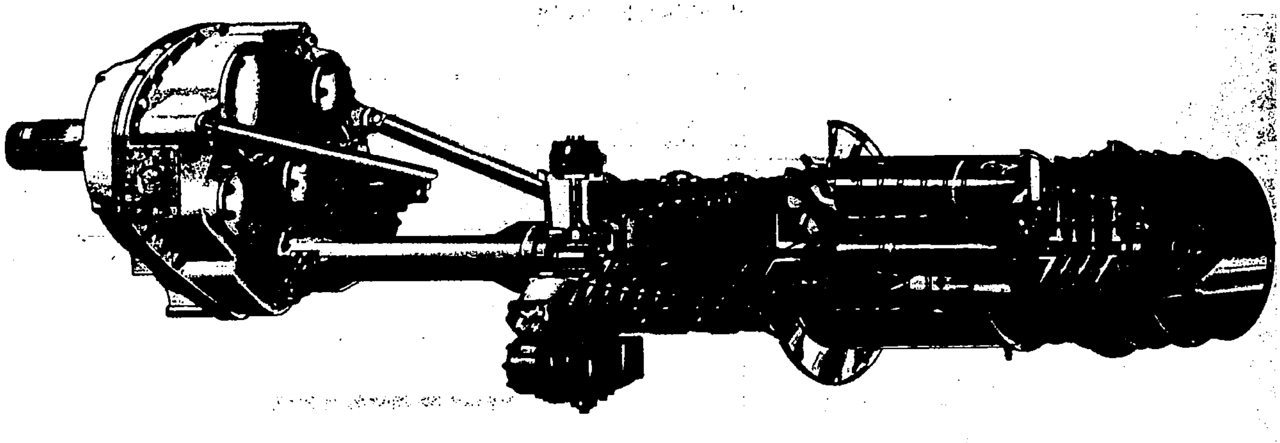


Figure VI-3.

MODEL 501-D22A PRODUCTION COMBUSTOR

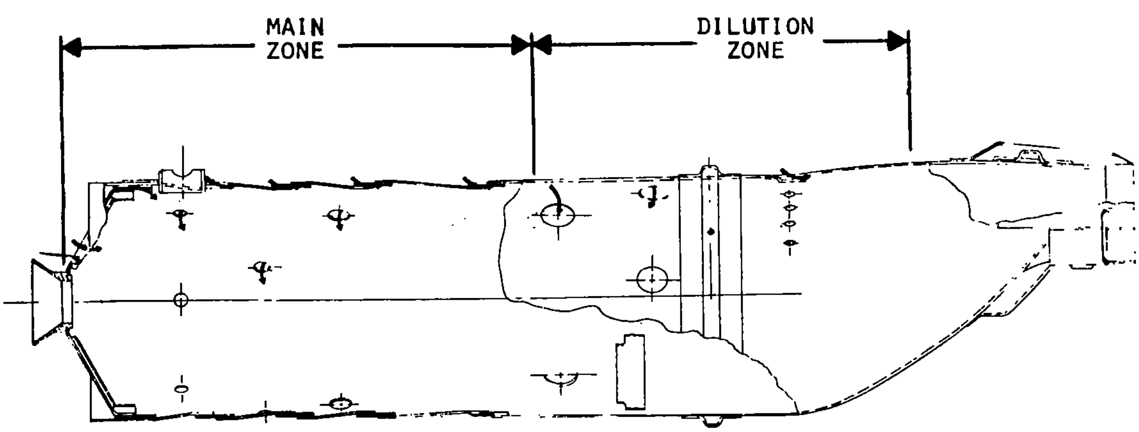


Figure VI-4.

MODEL 501-D22A REVERSE FLOW COMBUSTOR

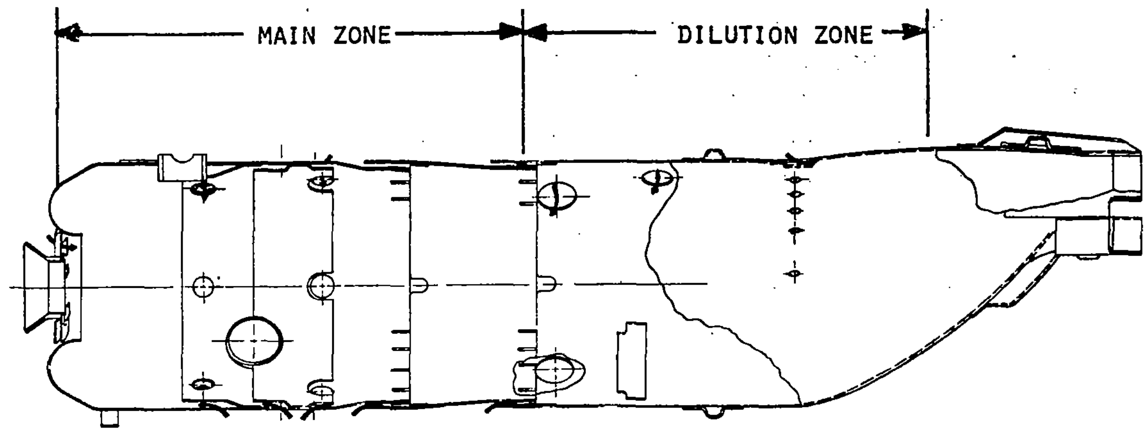


Figure VI-5.

MODEL 501-D22A PRECHAMBER COMBUSTOR

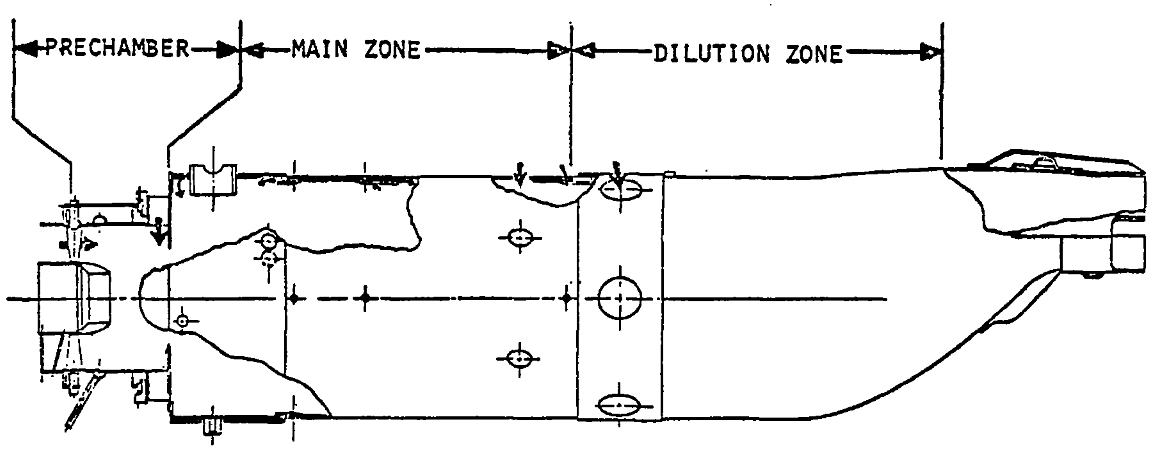


Figure VI-6.

MODEL 501-D22A STAGED FUEL COMBUSTOR

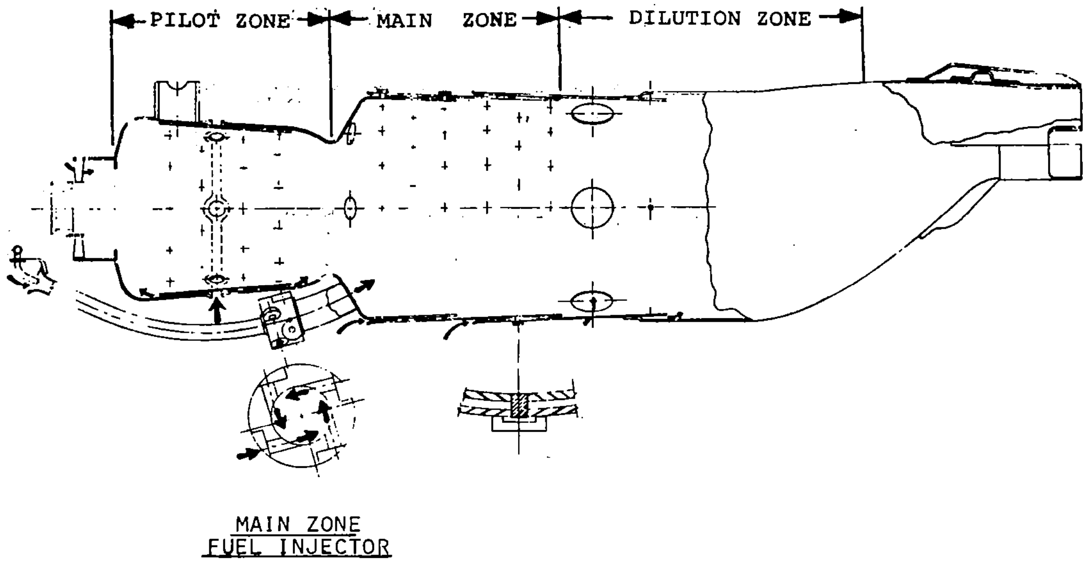


Figure VI-7.

MODEL 501-D22A COMBUSTOR TEST RIG

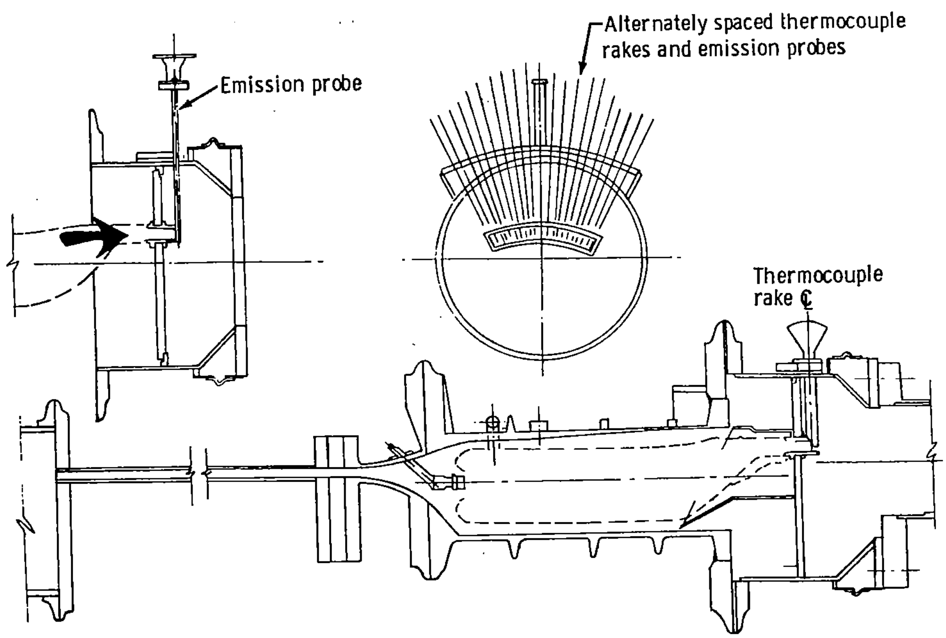


Figure VI-8.

EMISSION INSTRUMENTATION SYSTEM

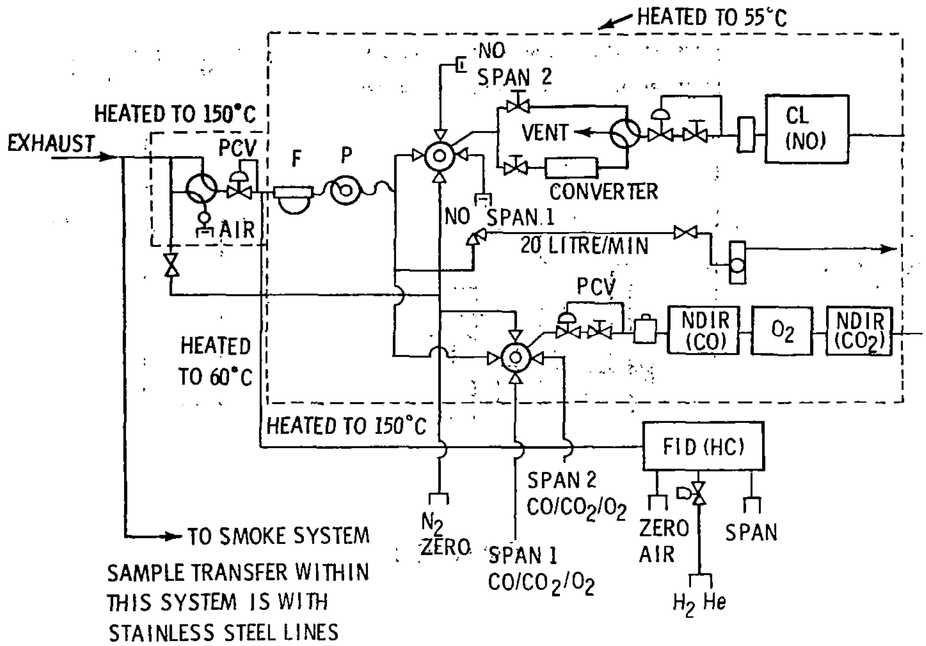


Figure VI-9.

SMOKE SAMPLING SYSTEM

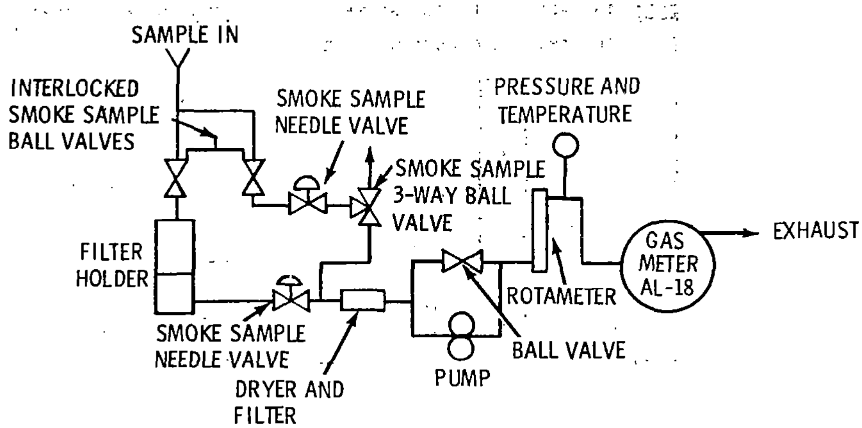


Figure VI-10.

EMISSIONS FROM FINAL DESIGN (MOD IV) REVERSE FLOW SYSTEM

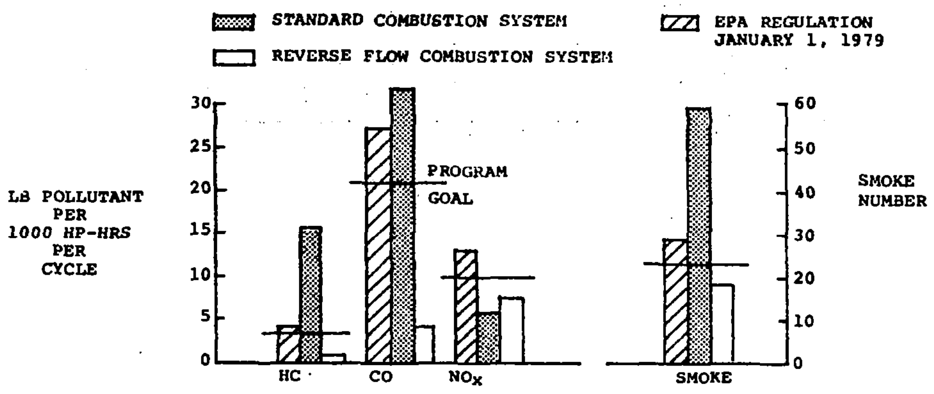


Figure VI-11.

EMISSIONS FROM MOD III DESIGN PRECHAMBER SYSTEM

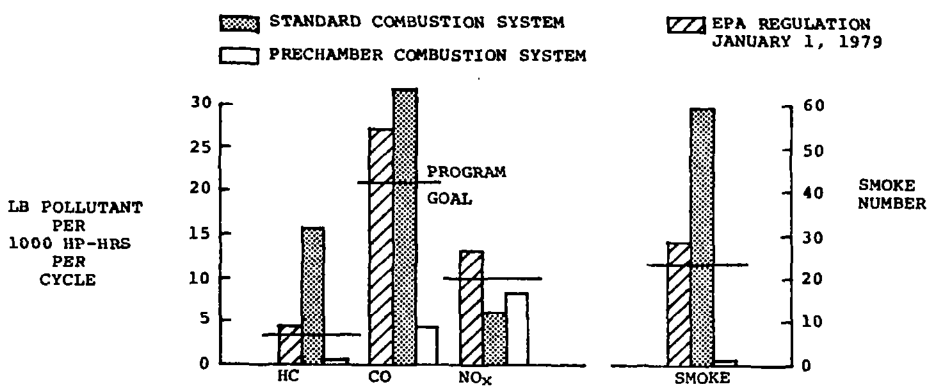


Figure VI-12.

EMISSIONS FROM MOD V DESIGN STAGED FUEL SYSTEM

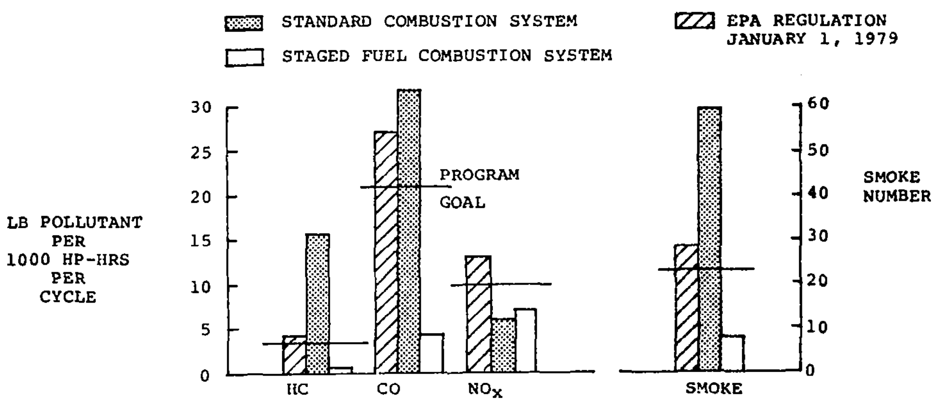


Figure VI-13.

EMISSIONS FROM MODEL 501-D22A COMBUSTORS

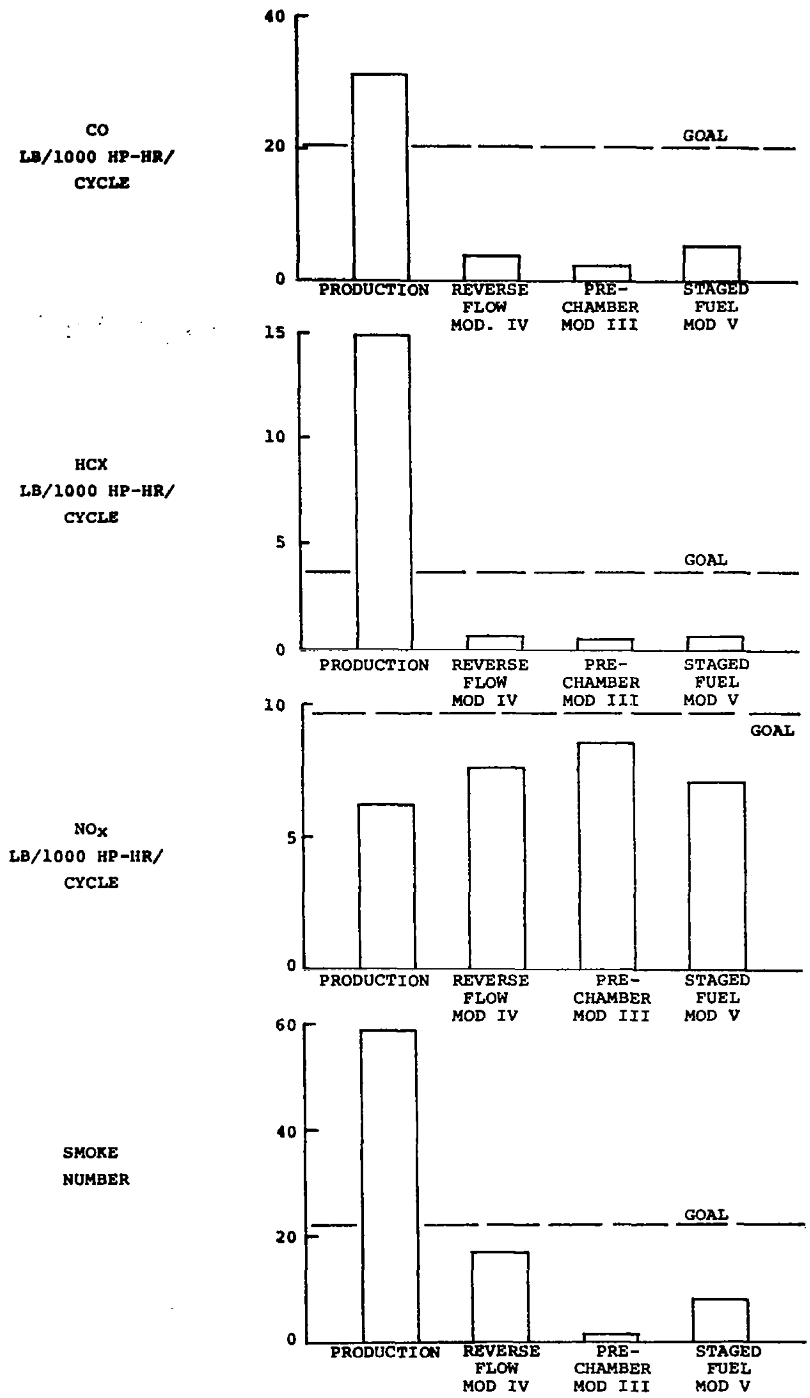


Figure VI-14.