NASA TECHNICAL MEMORANDUM

NASA TM X-71911

NASA TM X-71911

(NASA-TM-X-71911) RESULTS OF THE POLUTION REDUCTION TECHNOLOGY PROGRAM FOR TURBOPROP ENGINES (NASA) 13 p HC $3.50 CSCL 21E

N76-23267

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TECHNICAL PAPER to be presented at
Twelfth Propulsion Conference cosponsored by
the American Institute of Aeronautics and Astronautics and the Society of Automotive Engineers
Palo Alto, California, July 26-29, 1976

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E-8713

ABSTRACT

A program was performed to evolve and demonstrate advanced combustor technology aimed at achieving the 1979 EPA standards for turboprop engines (Class P2). The engine selected for this program was the 501-D22A turboprop manufactured by Detroit Diesel Allison Division of General Motors Corporation. Three combustor concepts were designed and tested in a combustor rig at the exact combustor operating conditions of the 501-D22A engine over the EPA landing-takeoff cycle. Each combustor concept exhibited pollutant emissions well below the EPA standards, achieving substantial reductions in unburned hydrocarbons, carbon monoxide, and smoke emissions compared with emissions from the production combustor of this engine. Oxides of nitrogen emissions remained well below the EPA standards, also.

INTRODUCTION

Three gas turbine combustor concepts were designed and tested in a combustor rig to determine their emissions of unburned hydrocarbons, carbon monoxide, oxides of nitrogen, and smoke at the combustor operating conditions of the 501-D22A turboprop engine.

Concern over air pollution has drawn the attention of combustion engineers to the quantities of exhaust emissions produced by gas turbine engines. Two general areas of concern have been expressed: Urban pollution in the vicinity of airports and pollution of the stratosphere. The principal urban pollutants are unburned hydrocarbons (HC) and carbon monoxide during idle and taxi, and oxides of nitrogen (NO_x) and smoke during takeoff and landing. Oxides of nitrogen are also considered to be the most predominant gaseous emission products formed during altitude cruise of an aircraft. NASA Lewis Research Center is engaged in in-house research, university grants, and industry contracts to reduce the levels of these pollutants.

In 1970, the Clean Air Act charged the Environmental Protection Agency with the responsibility to establish acceptable exhaust emission levels of these pollutants for all types of aircraft engines. In response to this charge, the EPA promulgated the standards described in reference 1, with the first compliance date being January 1, 1979. One of the programs generated by Lewis Research Center in response to these EPA standards was the Pollution Reduction Technology Program for Turboprop Engines. The purpose of this program was to evolve and demonstrate advanced combustor technology aimed at achieving the EPA standards applicable to turboprop engines (EPA Class P2). The technology generated from this program is primarily applicable to the commercial sector, but it also has applicability to military turboprop and turboshaft engines. This effort focused on reducing emissions of HC, CO, NO_x and smoke, without seriously affecting combustor performance requirements such as combustion efficiency, total pressure loss, exit temperature pattern factor, and altitude relight capability. This paper presents the results of this program.

The combustors were tested at the following spans of operating conditions: at combustor inlet pressures of 37.0 to 113.8 N/cm^2, combustor inlet air temperatures of 441 to 666 K, fuel-air ratios of 0.007 to 0.02, and at reference velocities of 18.3 to 36.6 m/sec.

The U.S. Customary system of units was used for primary measurements and calculations. Conversion to SI units (System International d'Unites) is done for reporting purposes only. In making the conversion, consideration is given to implied accuracy and may result in rounding off the values expressed in SI units.

CONTRACTOR AND ENGINE SELECTION

The contractor was chosen for this program through a competetive RFP. The program was conducted by Detroit Diesel Allison (DDA) a Division of General Motors Corporation. The program was a cost sharing contract and was conducted at the DDA facilities at Indianapolis, Indiana. The contract duration was thirteen months, and the various tasks and their duration are shown in table I.

The engine selected for combustor redesign was the Model 501-D22A turboprop. This engine, shown in a cutaway view in figure 1, has a 9.2:1 compression ratio, and utilizes six cylindrical combustor cans in an annulus. The engine is rated at 4680 equivalent shaft horsepower at standard static sea-level conditions. The engines' use in the commercial field is with the L-382 (Hercules) and the L-188 (Electra) aircraft manufactured by Lockheed and used as cargo and passenger transport. Various military aircraft also use this engine.

PROGRAM GOALS

The major goal of the program was to produce a combustor which, when operated at conditions of the 501-D22A turboprop engine, would exhibit pollutant emissions 25 percent below the EPA requirements for 1979 for turboprop engines. The 25 percent margin was to allow for possible pollutant emission increase during combustor final development and also for possible engine to engine variations. The pollutant goals are shown in table II and are compared with the EPA limits and with current 501-D22A engine data from reference 2. The emission values are in terms of the EPA parameter as specified in reference 1. The current engine requires a substantial reduction in unburned hydrocarbons and smoke emissions. On the other hand, the oxides of nitrogen emissions are well within the goal; so the effort was focused on reducing idle emissions and smoke while minimizing NO_x emissions. An increase in NO_x emissions might be expected due to higher flame temperatures which are associated with improvements in combustion efficiency at idle.

TEST FACILITY

The 501-D22A combustor operating conditions are shown in table III for the EPA landing-takeoff cycle modes. Except for the taxi-idle mode, the engine runs at constant speed which results in combustor

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inlet temperature, combustor inlet pressure, and airflow rate varying only slightly among the takeoff, climbout, and approach modes. Increased torque is generated by an increase in fuel-air ratio and is absorbed by the propeller by changing the pitch of the blades.

In the test facility for this program, the combustor operating conditions exactly duplicated the combustor conditions inside the engine for all modes of operation. Therefore, it was possible to obtain measured data at the specific conditions of table III without any extrapolation of inlet pressure or temperature. The combustor test rig is shown in figures 2 and 3. The rig exactly duplicates a 1/6 annular segment of the 501-D22A engine, including diffuser, combustor annulus, and turbine inlet annulus.

Exhaust instrumentation consisted of ten thermocouple rakes and eleven gas sampling probes alternatively spaced as shown in figure 3. Each thermocouple probe had three thermocouples; each gas sample probe had four sampling ports. The gas sample was steam traced to maintain a temperature of about 420 K. The procedure of reference 3 was followed in obtaining gas sampling data. The gas sample was manifolded to one line from the eleven probes, and was continuously analyzed by the following instruments: carbon monoxide and carbon dioxide analyzers were both of the nondispersive infrared (NDIR) type (Beckman Instruments Model 315A). The concentration of oxides of nitrogen was determined by a Thermo Electron Corporation Chemiluminescent Analyzer with NO_2 converter. The hydrocarbon content of the gas was determined by a flame ionization detector (FID): a Beckman Instruments Model 402 Hydrocarbon Analyzer. Smoke analysis was also performed on gas samples drawn from the same eleven gas sampling probes. The smoke sampling procedure as recommended in reference 4 was followed.

COMBUSTOR DESIGNS

Three combustor concepts were designed to reduce pollutant emissions from the 501-D22A turboprop engine. All of these concepts were burner cans which fit within the combustor envelope of the current engine. Photographs of the three combustor concepts as well as the 501-D22A production combustor are shown in figure 4. These combustors will now be briefly described.

A schematic of the production combustor is shown in figure 5. The burner is approximately 14.0 cm in diameter and 62.8 cm long. The main features of this design are: dome air-entry holes backed by baffles to give the incoming air a swirling motion; dilution holes not evenly positioned around the circumference but placed as required to give a suitable gas temperature distribution; primary-zone air entry holes; and a dual-orifice, pressure-atomizing fuel injector.

The first combustor concept, the reverse flow combustor, is shown in figure 6. The initial design plus four modifications of this design were tested. The main features of this combustor concept are: the primary zone equivalence ratio was increased over the value of the production combustor by reducing airflow through the combustor front end; two reversed louvers in the front end of the combustor sweep air along the liner in the upstream direction, enhancing the recirculating zone and preventing fuel from hitting the wall and passing downstream without burning; an air assist fuel nozzle was used in one configuration; an airblast nozzle consists of a pressure atomizing pilot and an airblast main section. Maximum fuel flow to the pilot is 27.2 kg/hr. In two of the reverse flow combustor configurations the fuel flow to the pilot was shut off and all the fuel passed through the airblast section.

The second combustor concept, the prechamber combustor, is shown in figure 7. The initial design and five modifications of this design were tested. The main features of this combustor concept are: a chamber in front of the combustor primary zone in which fuel and air is mixed prior to combustion (prechamber); the use of remotely operated variable geometry to alter airflow distribution and observe results during testing to obtain optimum performance; and an air blast fuel nozzle which was described previously. The variable geometry hardware consisted of a variable vane-angle axial swirler in the prechamber, a selection of location of the primary-zone air entry holes in either a fore or aft position, and a set of variable-area dilution holes around the combustor. The size of the prechamber was also enlarged for two of the combustor designs.

The third combustor concept, the staged fuel combustor, is shown in figure 8. The initial design and six modifications of this design were tested. The main features of this combustor concept are: a two-stage in-series combustion system consisting of a pilot zone for low-power operation, and a main combustion zone which is used in combination with the pilot zone at higher power conditions; the fuel for the main zone is premixed with air in six equally-spaced tubes and is then air-blast injected into the combustor; advanced wall cooling consisting of film and convection cooling, allowing more air to be used for quick mixing with hot combination gases; variable geometry dilution air entry ports. Three different fuel nozzles for the pilot zone were tested: the production combustor pressure atomizing nozzle, an air assist nozzle, and an airblast nozzle which was described previously.

The three combustor concepts vary in complexity and in potential for pollutant reduction. The reverse flow combustor was simplest in design and the staged fuel combustor was most complex with the most potential, it was felt, for low pollutant emissions.

COMBUSTOR TEST RESULTS

A total of 19 combustor configurations were tested, including the production combustor for direct comparison with the 18 test combustors. An abbreviated description of each configuration is given in table IV. Over 400 data points were taken at the EPA cycle conditions and at idle or takeoff with parametric variations of fuel-air ratio, inlet pressure, inlet temperature, and reference velocity. For a complete analysis of the data, see the final report of the program, reference 5.

Pollutant Emissions

The pollutant emissions of the 19 combustor configurations are summarized in table V for data taken over the landing-takeoff cycle. The gaseous pollutants are in terms of the EPA parameter and the smoke number is the highest value recorded over all the landing-takeoff cycle conditions. The three combustor concepts achieved the program goals in 13 of the 18 configurations.

The combustor configurations that exhibited the lowest pollutant emissions for each concept were the reverse flow mod IV combustor, the prechamber mod V combustor, and the staged fuel mod V combustor. The emissions of these three combustors are compared with the baseline production combustor in figures 9 through 12. The hydrocarbon emissions, shown in figure 9, were reduced substantially by the three combustor concepts and are all well below the program goal. The carbon monoxide emissions in figure 10 also show a substantial reduction for the three combustor concepts over the baseline production combustor. Again the emission levels are well within the program goals. The oxides of nitrogen emissions of figure 11 show the expected rise for the three combustor concepts compared with the production combustor, but this increase is very moderate and still remains well below the program goal. Finally, the maximum values of smoke for the three combustor concepts are substantially below the production combustor in figure 12, and are also below the program goal.

Thus, all three combustor concepts produced exhaust pollutant emissions which met the program goals of 25 percent below the EPA standards. Substantial reductions in unburned hydrocarbons, carbon monoxide, and smoke were achieved compared with the production combustor with only slight increase in oxides of nitrogen emissions. From an emissions point of view, all three combustors qualify as candidates for development into the 501-D22A turboprop engine.

Performance

A summary of combustor performance for the three best combustor concept designs is shown in table VI. Pattern factors compare quite favorably with the production combustor for all three combustor concepts. Combustor pressure drop was adequate for all three designs as far as this program was concerned. However, the prechamber mod V and the staged fuel mod V exhibited pressure drop values higher than the production combustor and a further development of these combustors might require reducing these levels. The combustor liner temperatures recorded by skin thermocouples indicate no major problem areas; however, it must be pointed out that more rigorous testing would be required to ensure proper combustor durability and would be part of further development of any of these combustors. Altitude relight tests were not within the scope of this program and were not performed. A complete altitude relight map would be required for further combustor development.

Based on the performance results and on relative combustor complexity, the reverse flow mod IV combustor is judged to be the best candidate for further development into eventual use with the 501-D22A turboprop engine. In this program it has demonstrated pollutant emissions well below the 1979 EPA standards, is quite simple in design, and has shown excellent combustion efficiency, pattern factor, and combustor pressure drop.

CONCLUDING REMARKS

A program was undertaken to evolve and demonstrate advanced combustor technology aimed at achieving the 1979 EPA standards for the 501-D22A turboprop engine. As a result of this program three can-type combustor concepts were designed and tested. Each concept exhibited pollutant emissions well below the EPA standards, achieving substantial reductions in unburned hydrocarbons, carbon monoxide, and smoke emissions from the production combustor of the 501-D22A engine. Based on performance results, pollutant emissions, and combustor complexity, the reverse flow mod IV combustor is judged to be the best candidate for further development into eventual use with the 501-D22A turboprop engine.

ACKNOWLEDGEMENTS

This program was performed under NASA contract number NAS3-18561. The author wishes to acknowledge the Detroit Diesel Allison Division of General Motors Corporation for the professional and expert execution of this program. Specific recognition is extended to the DDA Program Manager Mr. J. G. Tomlinson, the Technical Director Mr. R. D. Anderson, and to combustor engineers A. S. Herman, J. M. Vaught, and A. J. Verdouw for their technical management and support.

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1. "Control of Air Pollution for Aircraft Engines - Emission Standards and Test Procedures for Aircraft," Federal Register, Vol. 38, July 17, 1973, pp. 19088-19103.
2. Vaught, J. M., Johnsen, S. E. J., Parks, W. M., and Johnson, R. L., "Collection and Assessment of Aircraft Emissions Base-Line Data, Turboprop Engines (Allison T56-A-15)," EDR-7200, General Motors Corp., Indianopolis, 1971.
3. "Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines," Aerospace Recommended Practice 1256, SAE, 1971.
4. Aircraft Gas Turbine Engine Exhaust Smoke Measurement. Aerospace Recommended Practice 1179, SAE, 1970.
5. Tomlinson, J. G.; and Anderson, R. D.: Final Report, Pollution Reduction Technology Program, Turboprop Engines - Phase I, Combustor Screening, NASA Contract No. NAS3-18561, to be published.

TABLE I. - SCHEDULE FOR THE POLLUTION REDUCTION TECHNOLOGY PROGRAM FOR TURBOPROP ENGINES

	1975				1976
	1	2	3	4	1
TASK I Preliminary design					
TASK II Final design					
TASK III Fabrication					
TASK IV Combustor screening tests					
TASK V Reports					

TABLE II. - POLLUTANT EMISSION VALUES

	EPA limits P2	Program[a] goals	501-D22A engine	Reduction required %
Total hydrocarbons	4.9[b]	3.7	9.7	62
Carbon monoxide	26.8[b]	20.1	19.0	0
Oxides of nitrogen	12.9[b]	9.7	5.4	0
Smoke	29[c]	22	55	60

[a]75% of EPA limits

[b]lb/1000 HP-HR-cycle

[c]SAE smoke no.

TABLE III. - COMBUSTOR OPERATING CONDITIONS FOR 501-D22A ENGINE

Mode	Engine shaft power (kW)	Combustor inlet temperature (K)	Combustor outlet temperature (K)	Combustor inlet pressure (N/cm^2)	Fuel-air ratio	Combustor airflow (kg/sec)	
						Total	Per comb.
Taxi/idle (out)	116	441	900	37.0	.011	6.80	[a]1.13
Takeoff	3257	610	1322	98.3	.020	14.97	2.49
Climbout	2931	606	1269	95.8	.0185	15.01	2.50
Approach	977	588	964	84.1	.0096	15.15	2.53
Taxi/idle (in)	116	411	900	37.0	.011	6.80	1.13

[a]Single combustor rig operated to these exact conditions.

TABLE IV. - ABBREVIATED DESCRIPTION OF EACH COMBUSTOR CONCEPT AND THEIR MODIFICATIONS

Reverse flow combustors	Prechamber combustors	Staged fuel combustors
Baseline - Initial design with airblast fuel nozzle Mod. I - Baseline combustor with airblast nozzle operated with zero pilot flow Mod. II - Baseline combustor with modified 2nd flow reverser and production airblast fuel nozzle Mod. III - Mod. II combustor and air assist fuel nozzle Mod. IV - Mod. II combustor with airblast fuel nozzle with zero pilot flow	Baseline - Initial design with a short prechamber, 10° axial swirler, aft located primary holes, and 14.2 cm^2 dilution area Mod. I - A second design with a long prechamber, 20° axial swirler, forward located primary holes, and 14.2 cm^2 dilution holes Mod. II - The same combustor as Mod. I but with the dilution adjusted to 12.9 cm^2 Mod. III - The baseline combustor modified for improved cooling, and the same dilution area of 14.2 cm^2 Mod. IV - The Mod. III combustor with reduced radial swirler flow area Mod. V - The Mod. IV combustor with optimum variable geometry settings	Baseline - Initial design of pilot and main combustion chambers in series and a pressure atomizing pilot nozzle and variable-area dilution holes full open Mod. I - Baseline combustor tested with an air assist pilot nozzle and dilution holes open Mod. II - Mod. I configuration dilution holes partly closed Mod. III - Mod. II configuration but with an airblast nozzle and dilution holes open Mod. IV - Mod. III configuration but with dilution holes partly closed Mod. V - This is a rebuilt configuration tested with an airblast fuel nozzle. Prechamber variable geometry open, primary zone variable geometry open, dilution holes 2.0 cm closed Mod. VI - Mod. V but dilution holes 1.3 cm closed

TABLE V. - SUMMARY OF COMBUSTOR EMISSIONS

Combustor	EPA Parameter, lb/1000 Hp-Hr/cycle			Maximum smoke
	HC	CO	NO_x	
Conventional (501-D22A)	15.03	31.46	6.24	54.9
Reverse flow baseline	2.48	4.99	7.80	9.0
Reverse flow Mod. I	.74	3.53	7.66	8.0
Reverse flow Mod. II	1.27	9.22	6.83	15.0
Reverse flow Mod. III	.99	5.55	7.35	29.0
Reverse flow Mod. IV	.29	4.57	7.30	17.0
Prechamber baseline	1.58	3.99	6.10	1.0
Prechamber Mod. I	2.27	21.67	6.53	52.0
Prechamber Mod. II	.85	37.49	6.40	29.0
Prechamber Mod. III	.39	2.05	8.50	1.0
Prechamber Mod. IV	.27	4.83	7.93	1.0
Prechamber Mod. V	.20	4.71	6.39	5.0
Staged fuel baseline	1.92	11.25	8.13	15.0
Staged fuel Mod. I	.67	11.74	9.98	33.0
Staged fuel Mod. II	.61	9.20	9.76	17.1
Staged fuel Mod. III	.42	10.60	8.63	13.0
Staged fuel Mod. IV	.37	8.38	8.06	3.0
Staged fuel Mod. V	.56	5.73	7.17	8.0
Staged fuel Mod. VI	.59	4.26	9.03	9.0
Program goals	3.7	20.1	9.7	22.0

TABLE VI. - SUMMARY OF COMBUSTOR PERFORMANCE

Configuration	Pattern factor	Max wall temp., K	ΔP/P, %
Production	0.18	----	5.2
Reverse flow Mod. IV	.11	1152	5.2
Prechamber Mod. V	.17	1190	7.6
Staged fuel Mod. V	.21	1083	6.0

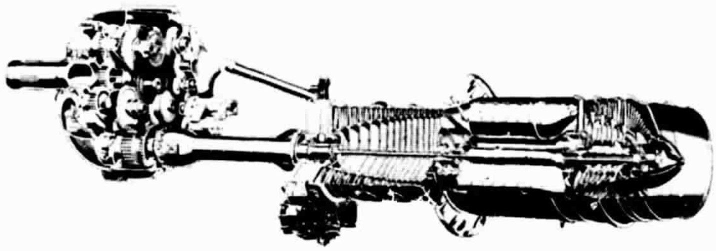


Figure 1. - Cutaway view of the Detroit Diesel Allison 501-D22A turboprop engine.

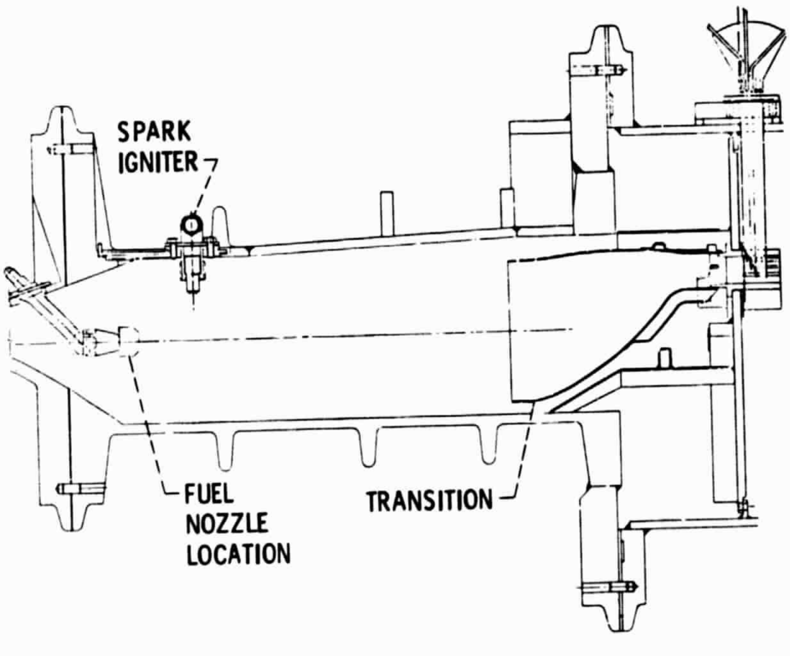


Figure 2. - Detailed sketch of combustor test rig.

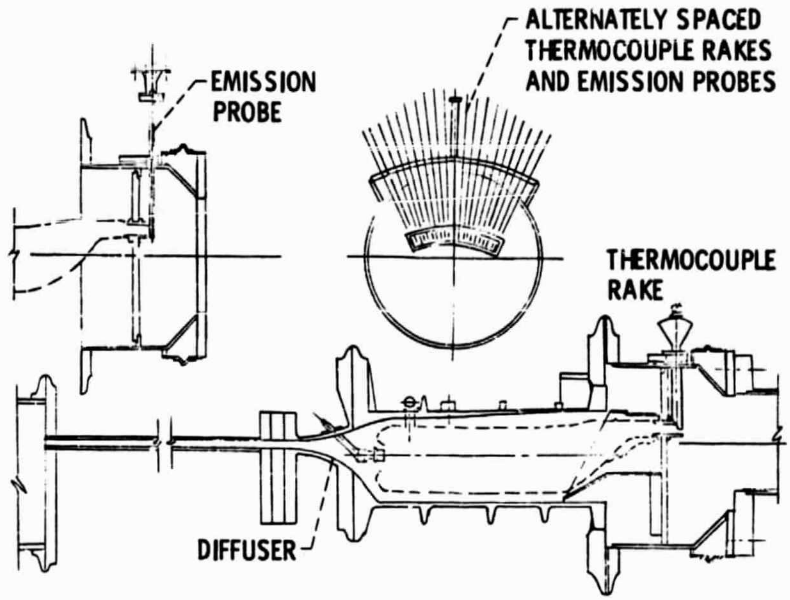
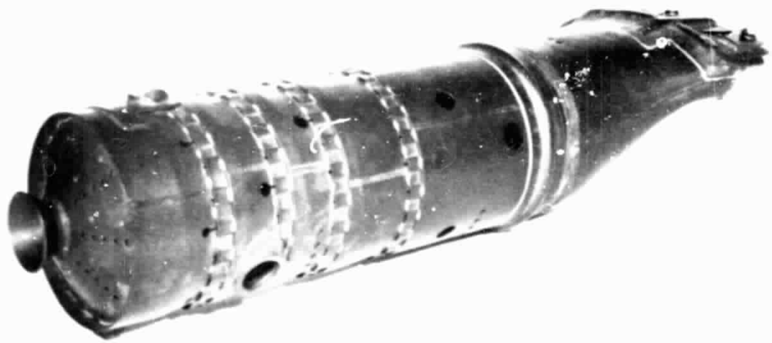
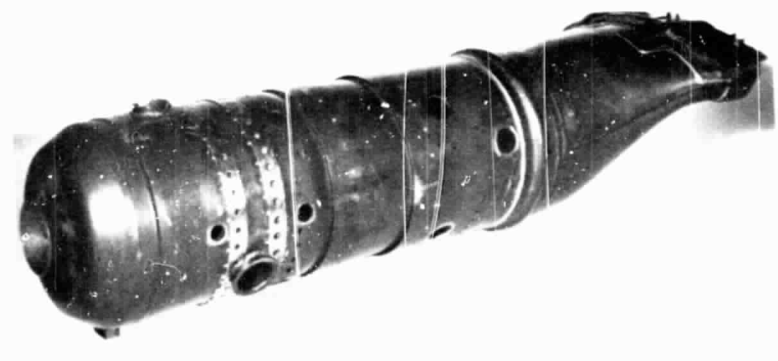


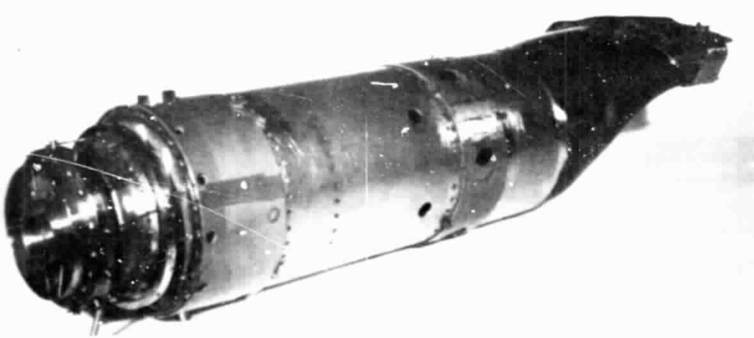
Figure 3. - Overall combustor test rig showing exhaust instrumentation location.



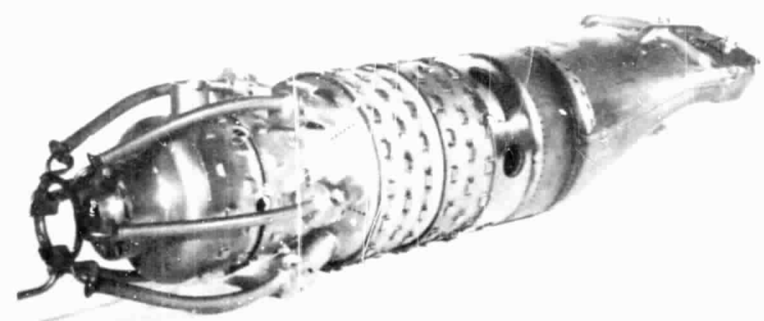
501-022A PRODUCTION COMBUSTOR



REVERSE FLOW COMBUSTOR



PRECHAMBER COMBUSTOR



STAGED FUEL COMBUSTOR

Figure 4. - Combustors of program.

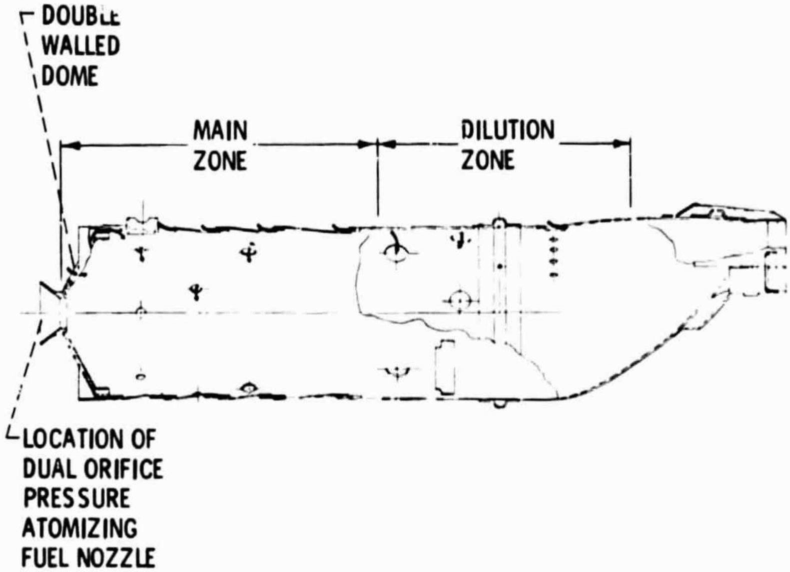


Figure 5. - Schematic of 501-D22A production combustor.

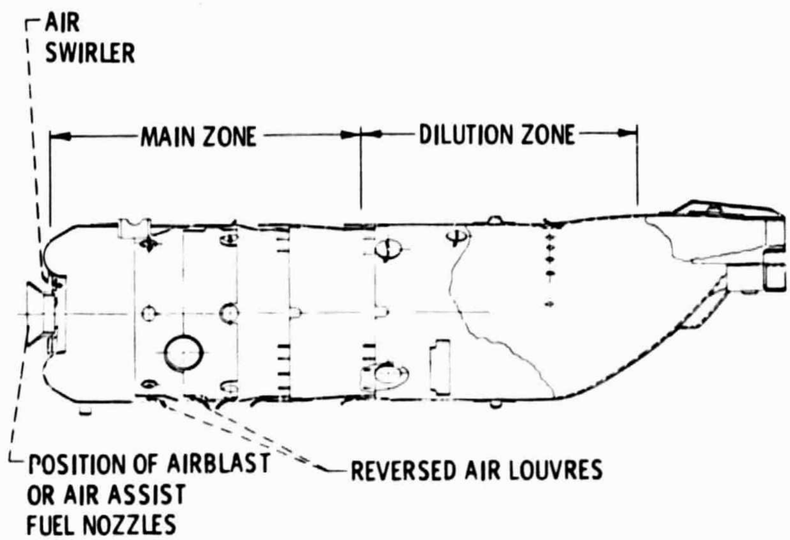


Figure 6. - Reverse flow combustor design.

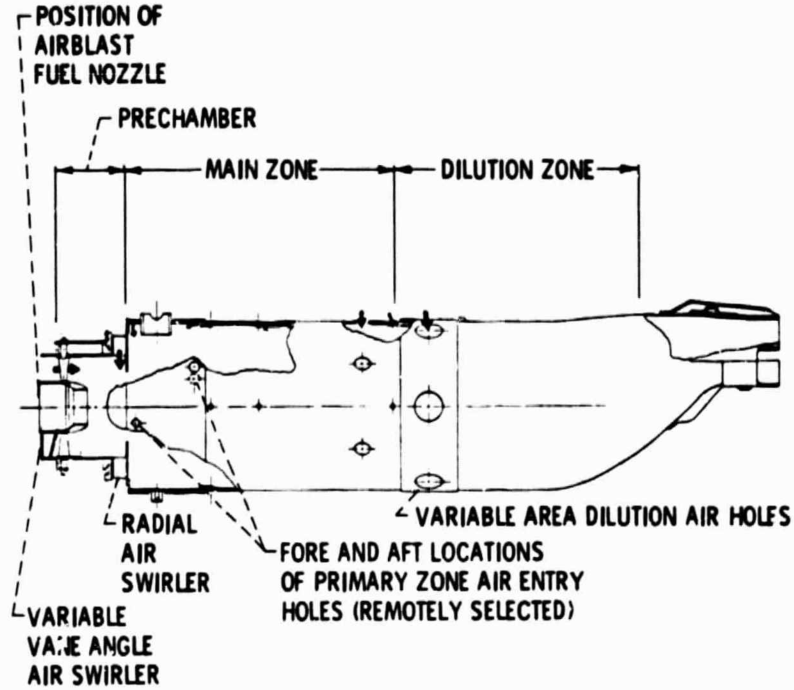


Figure 7. - Prechamber combustor design.

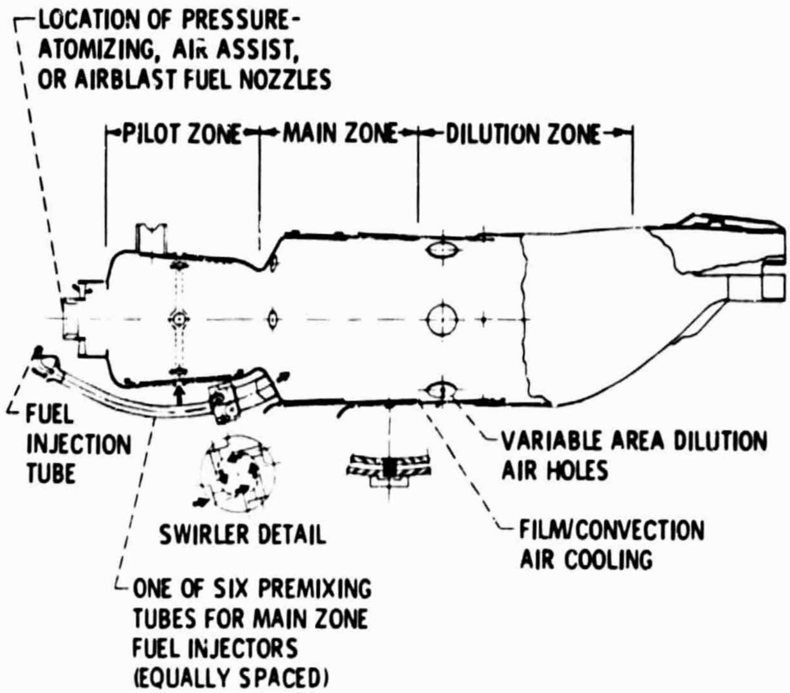


Figure 8. - Staged fuel combustor design.

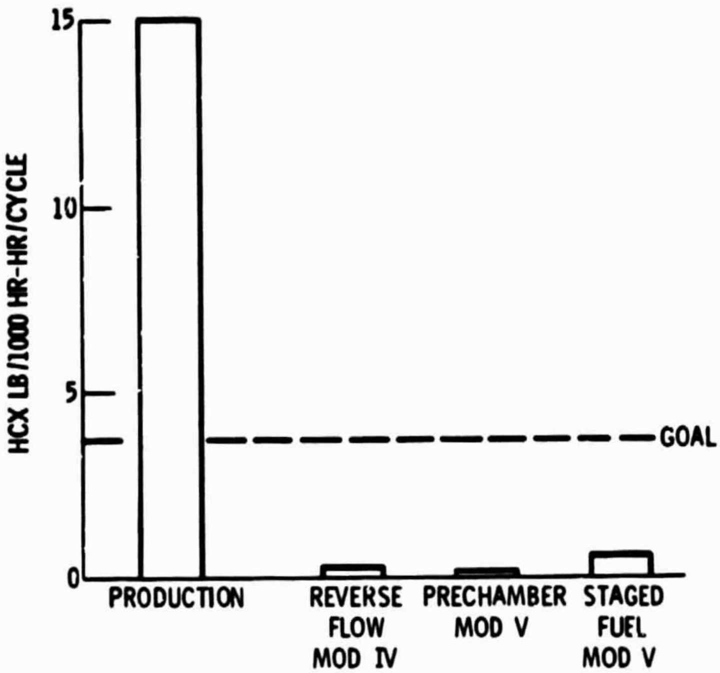


Figure 9. - Comparison of hydrocarbon emissions from best combustor concepts and from production combustor.

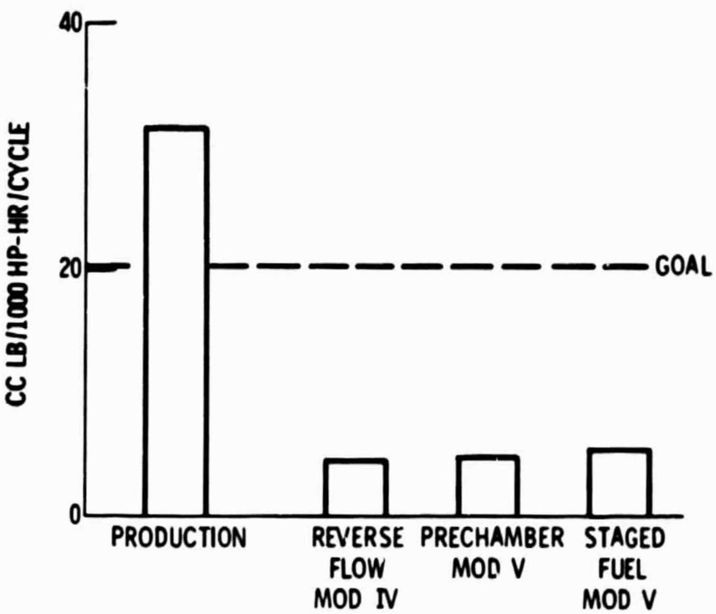


Figure 10. - Comparison of carbon monoxide emissions from best combustor concepts and from production combustor.

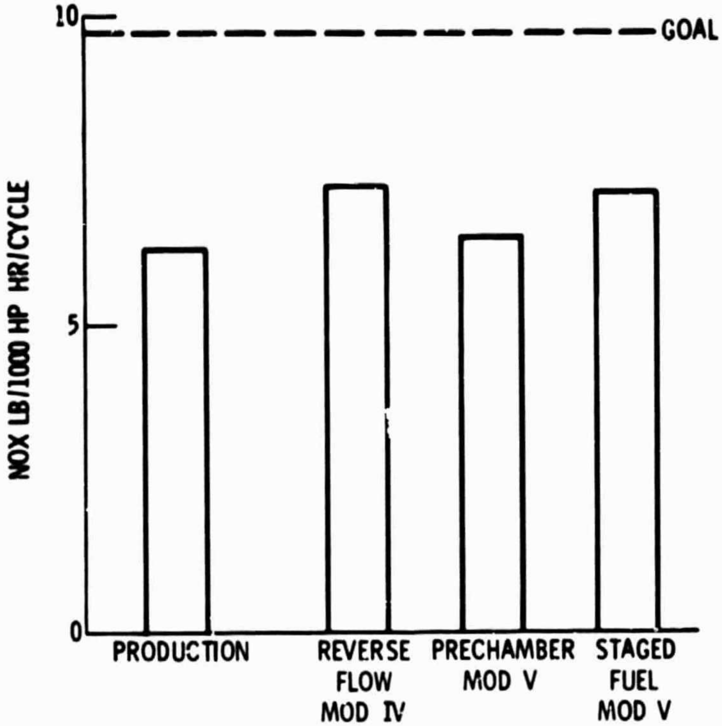


Figure 11. - Comparison of oxides of nitrogen emissions from best combustor concepts and from production combustor.

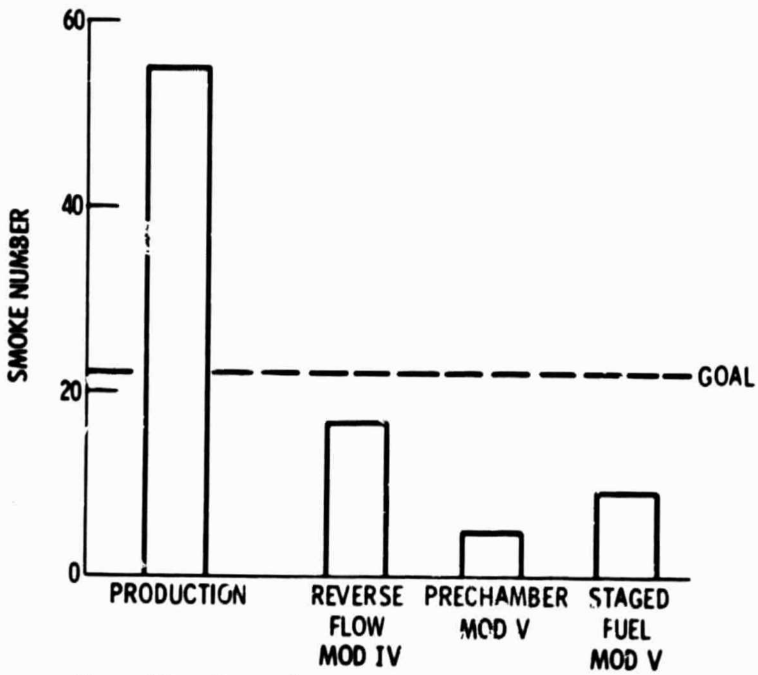


Figure 12. - Comparison of smoke emissions from best combustor concepts and from production combustor.