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THE EXPERIMENTAL CLEAN COMBUSTOR PROGRAM - DESCRIPTION AND STATUS

by Richard W. Niedzwiecki and Robert E. Jones
Lewis Research Center
Cleveland, Ohio

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ABSTRACT

The "Experimental Clean Combustor Program" is a contract effort with primary objectives including the generation and demonstration of technology for development of advanced commercial CTOL aircraft engines with lower exhaust emissions than current aircraft, and the demonstration of this technology in full scale engines in 1976. The program is being conducted in three phases. These consist of screening of low pollutant combustors, refinement of the best combustors and engine demonstration of the best combustors. The combustor screening phase was initiated in December 1972 and is currently in progress. Contracts were awarded to Pratt & Whitney Aircraft and the General Electric Company to evolve combustors for the JT-9D and the CF6-50 engines respectively. Pollution goals are emission index values of 20 and 4 for carbon monoxide and unburned hydrocarbons respectively at engine idle conditions, and an oxides of nitrogen emission index level of 10 at engine takeoff conditions. Pollution reduction approaches which are being investigated include multiple burning zone combustors, investigations of improved fuel distribution and preparation and the staging of combustor airflow.

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INTRODUCTION

This paper describes the "Experimental Clean Combustor Program" including its objectives, program plan, schedule, pollution and performance goals, program approaches to pollution reduction, and status to date. Also described are advanced supersonic transport and combustion noise program addendums.

While considerable progress has been made in reducing the smoke levels of gas turbine engines, no combustors for current aircraft incorporate design features specifically for the reduction of gaseous pollutants. The Environmental Protection Agency has published standards which require substantial reduction of gaseous pollutants by 1979. The pollutants in question are oxides of nitrogen formed primarily during high power engine operation and, carbon monoxide and total unburned hydrocarbons formed primarily during low power engine operation.

It appears that substantial reduction of pollutants can be attained. The concepts for pollution reduction now exist. However, although the mechanisms of pollution production as well as techniques for reducing pollutants are generally known, application of these techniques

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to specific combustor-engine designs have not yet demonstrated the anticipated pollutant reductions without compromising other combustor parameters. Thus additional technology is needed to apply these concepts. The "Experimental Clean Combustor Program" was initiated since no other program aimed at timely evolution of clean combustors existed.

The program aim is to develop this required po ion reduction technology. This will be accomplished by evaluating the most promising pollution reduction techniques through combustor component testing, solving interface and performance problems which low pollutant combustor designs create for engine installation, and demonstrating the pollution reductions in a high pressure ratio CTOL engine in 1976.

PROGRAM DESCRIPTION

General

The "Experimental Clean Combustor Program" is a multi-year contract effort administered by the NASA Lewis Research Center. The program's primary objectives are the following:

1. To generate and demonstrate the technology required to develop advanced commercial CTOL aircraft engines with lower exhaust pollutant emissions than are possible with current technology.

2. To demonstrate the emission reductions in full-scale engines in 1976.

The program is aimed at generating technology primarily applicable to advanced commercial engines with overall compressor pressure ratios of 20 to 35. This technology should also be applicable to military engines. Specifically, the program emphasizes pollution reduction through combustor design. Gaseous pollutant reductions are emphasized since commercial engines currently produce smoke emissions which are below visible thresholds.

Program Plan

The program is being conducted in three sequential, individually funded phases. Program phases consist of the following:

Phase I: Combustor screening. - Phase I consists of screening various combustor designs to determine the most promising combustor configurations based on pollutant emission characteristics and combustor performance. Combustor evaluations will be based results of combustor testing, design modifications and retests. Phase I is an eighteen month effort and is currently in progress.

Two concurrent addendums have been included in the Phase I effort. The objective of the first addendum is to develop technology for reducing oxides of nitrogen concentrations for advanced supersonic aircraft engines at supersonic cruise conditions. The objective of the second addendum is to record combustion noise. Subsequent sections of this report discuss Phase I and the addendums more fully.

Phase II: Combustor refinement and optimization. - Phase II shall consist of refinement and optimization of the best Phase I combustor designs in order to establish required overall combustor performance, durability and engine adaptability. Combustor evaluations will be made based on results of test series, design modifications and retests. Phase II will be a fifteen month effort.

Phase III: Combustor-engine testing. - Phase III will consist of tests of the best Phase II combustor(s) as part of a complete engine. Modifications and retests are not anticipated and will be undertaken only if required. Phase III will be a twelve month effort.

Program Schedule

The planned program schedule is shown in Table I. Phase I contracts were awarded in December 1972 to the Pratt & Whitney Aircraft Company and the General Electric Company to evolve low pollutant combustors for the JT-9D and the CF6-50 engines, respectively. Phase I combustor testing is scheduled for completion by June 1974. The anticipated initiation data for Phase II is July 1975. Phase III is scheduled for completion by June 1976.

Program Goals

Inasmuch as smoke emissions have been reduced to below the visible threshold on current commercial engines, program focus is directed towards reduction of gaseous pollutants of oxides of nitrogen, total unburned hydrocarbons, and carbon monoxide. However, further reductions in smoke and particulate emissions are also sought. These pollutant reductions must be accomplished with a minimum and acceptable sacrifice of conventional combustor performance parameters.

Pollution goals. - Criteria used for selecting pollution goals were the following: The goals represent optimistic projections of achievable pollutant reductions. The program purpose is technology generation, gaseous pollutant reduction, not verification of existing technology. The goals are currently beyond combustor design state-of-the-art, and, in order to be achieved, require pollutant reductions by factors of three to five for the CF6-50 and the JT-9D engines.

Combustor exhaust pollutant goals in terms of engine operating modes are listed in Table II. Gaseous pollutant goals for oxides of nitrogen or NO_x ($NO_x = NO + NO_2$), carbon monoxide and total unburned hydrocarbons are expressed in terms of emission index. Emission index is the ratio of grams of pollutant formed per kilogram of fuel consumed. Smoke and particulate concentrations are expressed in terms of the S.A.E. smoke number. Idle and takeoff operating modes represent standard day engine operating conditions. Pollution data obtained during combustor component testing (program Phases I and II) at simulated engine conditions of reduced pressure, require extrapolation to indicate concentrations at engine conditions.

For comparative purposes, the Environmental Protection Agency Standards for T-2 class engines, estimated on an emission index basis, are also included in Table II. T-2 class engines have been defined by the Environmental Protection Agency as turbofan or turbojet engines with 8 000 pounds thrust or greater, excluding the JT-3D and the JT-8D model families as well as supersonic transport engines. The NO emission index value was computed by assuming that NO_x emission index values at taxi-idle and approach conditions are unchanged and that climb-out values equal 75 percent of the computed takeoff value. A comparison of standards and program pollutant values show that the idle pollutant values are quite close. The major variance occurs in the NO_x value where the program goal is lower, ten as opposed to thirteen for the 1979 EPA standards.

Also contained in Table II are engine emissions data for the JT-9D and the CF6-50 engines. These data indicate that reductions by factors of 3 to 5 are required to achieve program goal values.

Supersonic cruise addendum pollutant goal values are also contained in Table II. These goals are applicable only to the AST cruise point. Even though the cruise NO_x goal is one-half the CTOL goal, both goals are of approximate equal severity since combustor pressure is lower and reference velocity higher at the cruise condition. Additional pollutant reduction is not required to achieve the carbon monoxide and total unburned hydrocarbon supersonic cruise goals. Rather, these values represent limits up to which these pollutants can be increased in pursuit of the NO_x goal.

Performance goals. - Key combustor performance goals are listed in Table III. With the exception of combustion efficiency, these goals represent values achievable with current aircraft. Thus, these goals again represent limits up to which these values can be increased in pursuit of the pollution goals. With current aircraft, combustion efficiencies of 99 percent are not achieved at the taxi-idle condition. Combustion efficiencies of 99 percent or higher are required at all engine conditions to achieve the program pollution goals.

Program Approaches to Pollution Reduction

The greatest concentrations of gas turbine pollutants are formed at the two extremes of the engine operating power range. Thus pollutant control involves minimizing pollutant formation at both low power conditions as typified by engine taxi-idle as well as at high power or takeoff. If pollutant formation can be significantly reduced at the extreme engine operating modes, then corresponding reductions in pollutants will be realized at intermediate engine operating modes such as descent, cruise and climb-out. For the above reasons, pollution goals were selected at and combustor evaluations will be conducted primarily at simulated engine idle and takeoff conditions.

Idle pollutants. - Incomplete combustion is the principal cause of idle pollutants. The principal pollutants at idle are carbon monoxide and hydrocarbons, either as raw fuel or as partially oxidized fuel. The latter are primarily responsible for the characteristic odor common to all jetports (ref. 1). Aircraft combustors are designed for maximum performance at takeoff and cruise conditions. Operation at low power conditions generally results in lower combustion efficiencies and, as a result, in higher pollutant emissions. Typical combustion efficiencies at idle vary between 88 and 96 percent; the actual values are dependent on engine size, type, and age as well as operational procedures such as the amount of power extracted and the amount of compressor air bleed used.

Low combustion efficiency at idle results primarily from the poor burning conditions encountered. Low combustor inlet air temperatures, typically 366° to 466° K cause quenching to occur thus terminating combustion before completion. Low pressures, typically 2 to 4 atmospheres, reduce burning intensity. The low fuel-air ratios required at idle, typically 0.010 to 0.012, result in low primary zone equivalence ratios reducing burning intensity as well as causing poor fuel atomization and distribution. In addition, the low volatility of commercial aircraft kerosene fuel further aggravates the problem.

High power pollutants. - Combustor pressure, inlet air temperature and fuel-air ratio increase as the power level of a gas turbine engine is increased. At full power the combustion efficiency is nearly 100 percent and negligible levels of carbon monoxide and unburned hydrocarbons exist. However, the higher temperature and pressure levels within the combustor lead to the generation of smoke and oxides of nitrogen.

Reduction of smoke and particulate matter has received a great deal of attention in recent years and new gas turbine engines generate little if any visible smoke. Smoke reduction was accomplished principally by reducing combustor primary zone fuel-air ratio thereby eliminating large, fuel-rich zones.

Redesigning gas turbine combustors so they produce significantly reduced oxides of nitrogen levels is a difficult task. Oxides of nitrogen are natural combustion products forming during all combustion processes involving air. The formation of oxides of nitrogen in combustors is relatively well understood and has been the subject of many technical reports (refs. 2 to 4). The amount formed is controlled by the chemical reaction rate and is a function of the flame temperature, residence time of combustion gases at the highest temperatures, the concentrations of oxygen and nitrogen present, and, to a lesser extent, the combustor pressure.

Program pollution reduction approaches. - Although the mechanisms of pollution production as well as techniques for reducing pollutants are generally known, the application of these techniques to specific combustor-engine designs have not yet demonstrated the anticipated pollutant reductions without compromising combustor performance or increasing other pollutants. Thus implementation of these techniques is required. The aim of the "Experimental Clean Combustor Program" is to investigate the most promising of these techniques, determine which ones are most effective in reducing pollutants, and demonstrate the pollutant reductions in a T-2 class engine.

Table IV highlights some of the difficulties that are encountered in applying pollution reduction techniques. Because of the large changes in combustor environment between low power and high power engine operating modes, and also because of differences in mechanisms for production of the pollutants at these operating modes, techniques which reduce pollutants at one condition can increase pollutants at the other condition. An exception is improvement in fuel preparation and distribution which could produce better control of the combustion reactions thereby reducing pollutants at both power modes.

Three main pollution reduction approaches are being pursued in this program. Each approach appears to contain the potential for reducing pollutants at both low and high power operating conditions. The approaches are being investigated individually and in combination. The approaches are:

Multiple Burning Zones: In this approach combustion is split into two burning zones, a primary burner optimized for low power operation and a secondary burner optimized for high power operation. Primary burner equivalence ratios are near 1 with mixing of combustion gases with diluent air delayed. Secondary burner equivalence ratios are 0.5 to 0.8 with increased and quick mixing of combustion gases and diluent air.

Only the primary burner is fired during operation at low power conditions. Both burning zones, with fuel reduced to the primary burner, are fired during high power operation.

Two types of multiple burning zone combustors are being investigated. In one type, each burning zone operates independently of the other. In the other type, burners are coupled. For example, hot gases from the primary burner are used to increase combustion stability and vaporize fuel for the secondary burner.

Improved Distribution and Preparation of Fuel: The purpose of fuel distribution and preparation studies are to provide fuel systems which better control fuel-air mixture uniformity as well as mixture strength. The following methods are being employed:

1. Increased number of fuel sources.
2. Advanced fuel-air atomization techniques.
3. Premixing of fuel and air upstream of the burning zones.
4. Prevaporization of fuel upstream of the burning zones.

Program applications of these techniques are described in the next section of this report.

Fuel staging is also being investigated. Fuel is being staged radially, axially and in combustor sectors at low power conditions. Staging fuel consists of supplying fuel to some but not all of the fuel sources. Staging fuel improves atomization, increases local burning intensities and minimizes quenching interfaces between combustion gases and diluent air.

Combustor-Air Staging: Effects of combustor-air staging are being determined by simulating variable geometry for a conventional combustor. This is being accomplished by proportionating airflow with combustor blockage to produce optimum pollution reduction conditions at either low or high engine power conditions. If pollutants are significantly reduced by this method, efforts will be undertaken to develop variable geometry combustor hardware.

CURRENT CONTRACTED EFFORTS - PHASE I AND ADDENDUMS

The "Experimental Clean Combustor Program" was initiated in December 1972. Phase I contracts were awarded to Pratt & Whitney Aircraft and the General Electric Company to screen low pollutant combustor concepts for the JT-9D and the CF6-50 engines, respectively. Two addendums have also been incorporated into each Phase I effort.

Contract Items

Phase I. - Phase I efforts are divided into two program elements. Element I consists of designing, fabricating and testing swirl-can combustor designs. Swirl-can combustors originated at the Lewis Research Center and have previously demonstrated the potential for low pollutant formation, especially the oxides of nitrogen (refs. 5 and 6). Element II consists of designing, fabricating and testing the contractors' own low-pollutant combustor designs.

All combustor designs fit within the contractors' combustor-engine envelope. Combustor evaluations are being performed in combustor component test facilities at test conditions identical to engine conditions except for pressure which is limited by facility capabilities. As testing proceeds, allocations of test time and program resources will be proportioned to pursue the most promising combustor designs.

Phase I addendums. - Two addendums have been included in the Phase I contract efforts. Addendum items include the following:

Supersonic Cruise Addendum: The AST addendum objective is to develop technology for reducing oxides of nitrogen concentrations for advanced supersonic aircraft engines at supersonic cruise conditions. This will be accomplished by testing selected Phase I combustor configurations at simulated supersonic cruise conditions, and by evaluating several combustor modifications specifically designed for oxides of nitrogen reduction at supersonic cruise conditions. Testing will be concurrent with Phase I testing. In addition, each contractor is also required to utilize the data to prepare a conceptual combustor design capable of low oxides of nitrogen formation as well as meeting supersonic cruise mission requirements.

Combustion Noise Addendum: Objectives of this addendum are to obtain combustion noise data for Phase I combustors and, ultimately, to correlate this data with far-field engine noise measurements. Sound spectra data are being recorded upstream and downstream of selected combustor configurations.

Combustor Configurations

JT-9D Combustor applications. - Pratt & Whitney is evaluating three combustor designs in a 90°-sector test facility. The combustors are shown in figure 1.

Swirl-can Combustor: As in all swirl-can combustors, all combustor airflow exclusive of liner coolant air, passes either through or around the combustor modules and thus through the combustor primary burning zone. Each swirl-can consists of three major components; a carburetor, swirler, and a flame stabilizer. In operation, fuel and air enter the carburetor, mix in passing through the swirler and burn in the wake of the flame stabilizer.

The Pratt & Whitney adaptation of the swirl-can combustor consists of a three row array simulating 120 modules for the entire annulus. Module diameters vary between rows with the largest modules placed on the outer row. This arrangement will provide maximum stability and corresponding minimum carbon monoxide and unburned hydrocarbon emissions during low power operation where only the outer module row is fueled.

Combustor modifications include variations in the three module components as well as variations in fuel entry techniques and swirl-can equivalence ratios.

Staged Premix Combustor: This combustor consists of multiple burning zones; a primary or low power burner and a secondary burner. Each burner has its own fuel injectors, premix passage, flameholder and combustion volume. The main pollution reduction features contained in this combustor are the premix passages. Their purpose is to control mixture uniformity and strength.

Idle power is furnished by supplying fuel to only the primary burner. Both burners are fueled at high power. The two premix passages and combustion zones are axially displaced with the primary zone located upstream of the secondary zone. This placement avoids rapid quenching of the primary zone combustion gases by secondary zone air.

Combustor modifications emphasize staging of fuel and air between the combustion zones as well as varying the diluent air.

Swirl Combustor: This combustor also employs two burning zones, a primary and a secondary zone, located along the combustor axis. Air and fuel splits between zones are configured so that the primary burner only is fueled at idle conditions. At high power conditions, secondary burner fuel is introduced at the exit of the pilot zone where it is vaporized. Air required for secondary zone burning is introduced through swirlers located on both combustor liners.

Modifications of this combustor design emphasize fuel and air splits between burning zones as well as location and number of secondary zone fuel sources.

CF6-50 Combustor applications. - General Electric is evaluating four advanced combustor designs. In addition, specialized tests are also being made with the standard CF6-50 combustor. Tests are being performed in a full-annular test facility. The combustors are shown in figure 2.

Single Annulus-Lean Dome Combustor: The standard CF6-50 combustor was modified to produce extremely lean primary zone equivalence ratios. This was accomplished by eliminating the diluent air and passing all of the combustor airflow through the primary zone. It is anticipated that the lean primary zone equivalence ratio will produce low oxides of nitrogen levels.

Specialized testing of the standard CF6-50 combustor was also undertaken for the following reasons: First, the combustor was used to validate test facility pollutant sampling techniques by comparing facility data to engine data. Second, the combustor is being used to assess how effective various fuel and air staging techniques are in reducing low power pollutants.

The lean primary zone tests, along with the standard CF6-50 tests described above, will evaluate the potential of incorporating variable geometry into standard combustor designs. If these tests are successful, variable geometry features could be incorporated into combustor designs during latter program phases.

NASA Swirl-can Combustor: A two-row swirl-can combustor is being evaluated by General Electric. Combustor description and features are similar to the Pratt & Whitney design differing principally only in the reduced number of swirl-can modules in the array. General Electric is evaluating arrays consisting of 60, 72 and 90 modules. Combustor modifications emphasize module number effects, module equivalence ratio variations, and flame stabilizer geometry.

Radial/Axial Staged Combustor: This combustor also incorporates multiple burning zones; a primary burner of conventional design and a secondary burner incorporating a premix passage. Combustor operation is staged with only the primary burner fueled at low power conditions and both burners fueled at high power conditions. Secondary zone burning is stabilized by V-gutter type chutes located at the end of the premix passage. Combustion gases from the primary burner are also utilized to enhance secondary burner combustion stability permitting operation to low secondary zone equivalence ratios.

Initial configurations of this combustor pass all of the combustor airflow through the burning zones. Modifications emphasize the incorporation of dilution air, fuel and airflow splits and secondary zone fueling techniques.

Double Annular Lean Dome Combustor: This combustor incorporates two parallel burning zones. In operation, only the outer annulus is fueled at low power conditions. Both annuli are fueled at high power conditions.

Initial configurations of this design pass all of the combustor airflow through the burning zones. Configurational changes emphasize equivalence ratio variations in the two annuli as well as variations in airflow distributions.

CONCLUDING REMARKS

At the present time, the Phase I program is approximately 50 percent completed. All test hardware has been obtained and the programs are in the midst of the combustor screening tests. Combustor testing is scheduled for completion by June 1974.

Preliminary test results obtained to date indicate the ambitious nature of the program pollution goals, especially the oxides of nitrogen goal. Both contractors have approached the idle pollutant goals with several combustor configurations. All combustor designs, with sufficient additional effort, appear capable of achieving the idle pollutant goals. Regarding the oxides of nitrogen, reductions of approximately 50 percent have been realized to date. Further reductions have been obtained but at the expense of increasing combustion inefficiencies at both low and high power conditions. Additional oxides of nitrogen reductions of 50 percent or more will be sought.

Upon completion of Phase I testing, contractor and NASA Lewis Research Center reports will be forthcoming which will enumerate program progress and test results.

REFERENCES

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5. Richard W. Niedzwiecki, and Robert E. Jones, "Pollution Measurements of a Swirl-Can Combustor." NASA TM X-68160, December 1972.
6. Richard W. Niedzwiecki, and Robert E. Jones, "Parametric Test Results of a Swirl-Can Combustor." NASA TM X-68247, June 1973.

[redacted]

TABLE I. - PROGRAM SCHEDULE

CONTRACT EFFORT	1972	1973	1974	1975	1976
PHASE I: COMBUSTOR SCREENING					
SUPERSONIC CRUISE ADDENDUM					
COMBUSTION NOISE ADDENDUM					
PHASE II: COMBUSTOR REFINEMENT					
ADDENDUMS					
PHASE III: COMBUSTOR-ENGINE TESTING					
ADDENDUMS					

▽ CONTRACT AWARD
◇ TESTING COMPLETE
▼ CLOSED SYMBOLS INDICATE COMPLETED ITEMS
▽ ◇ OPEN SYMBOLS INDICATE PLANNED COMPLETION DATE

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TABLE II. - POLLUTION GOALS

	POLLUTANT	ENGINE MODE	PROGRAM GOAL	1979 EPA STANDARD	JT-9D ENGINE EMISSIONS DATA P.R. 22:1	CF6-50 ENGINE EMISSIONS DATA P.R. 30:1
CTOL POLLUTANTS	OXIDES OF NITROGEN AS NO_2 - E. I.	TAKEOFF	10	13	36	36
	CARBON MONOXIDE E. I.	IDLE	20	22.5	43	67
	UNBURNED HYDROCARBONS TOTAL - E. I.	IDLE	4	4.5	12	27
	SMOKE - SAE	TAKEOFF	15	19	15	15
SUPERSONIC CRUISE POLLUTANTS	OXIDES OF NITROGEN AS NO_2 - E. I.	AST CRUISE	5	----	--	--
	CARBON MONOXIDE E. I.	AST CRUISE	5	----	--	--
	UNBURNED HYDROCARBONS E. I.	AST CRUISE	1	----	--	--

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TABLE III. - PERFORMANCE GOALS

PARAMETER	ENGINE MODE	PROGRAM GOAL
COMBUSTION EFF	ALL	99%+
PRESSURE LOSS	CRUISE	6%
PATTERN FACTOR	TAKEOFF CRUISE	0.25
ALTITUDE RELIGHT	WINDMILLING	ENGINE RELIGHT ENVELOPE
DURABILITY	ADEQUATE AT ALL ENGINE CONDITIONS	

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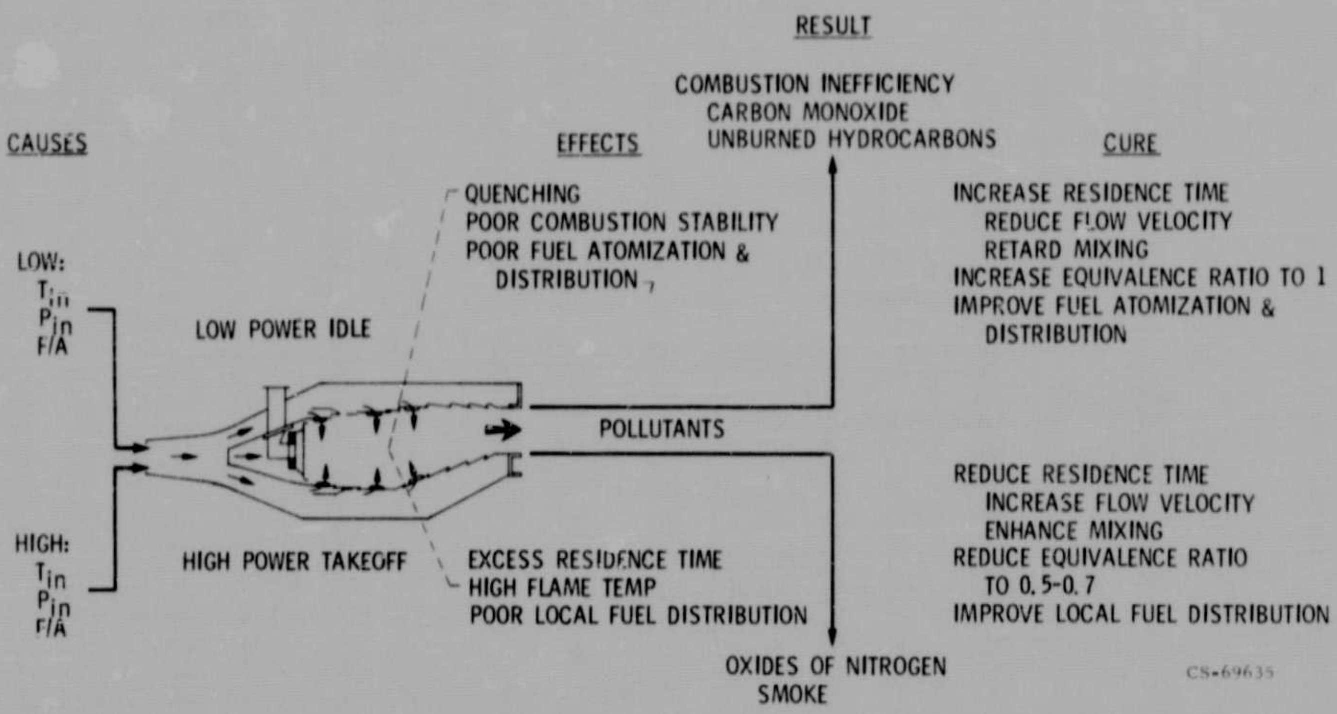
TABLE IV. - POLLUTION CONSIDERATIONS



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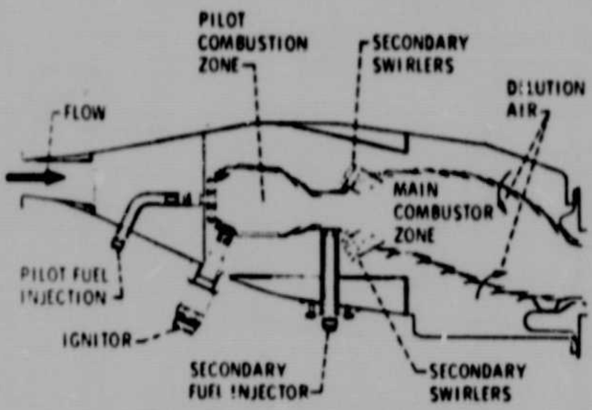
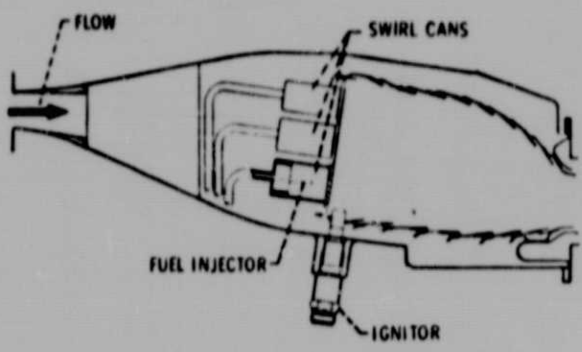
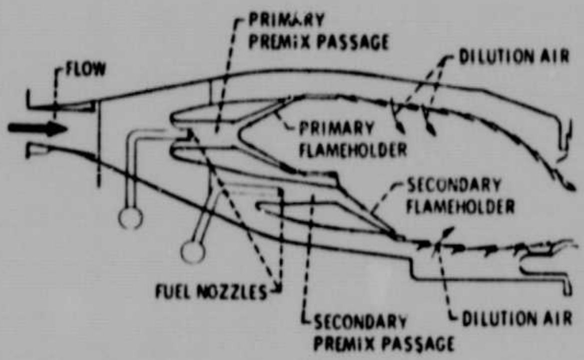


Swirl combustor for JT9D engine.



NASA swirl-can modular combustor, for JT9D engine.



Staged premix combustor, JT9D engine.

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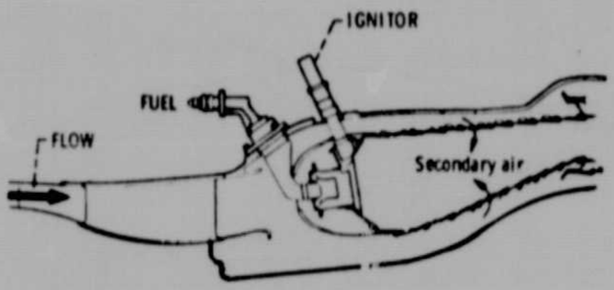
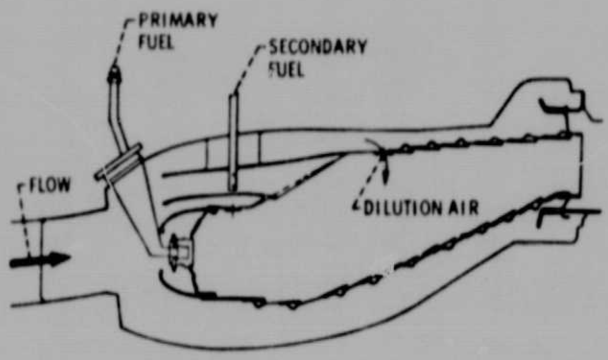
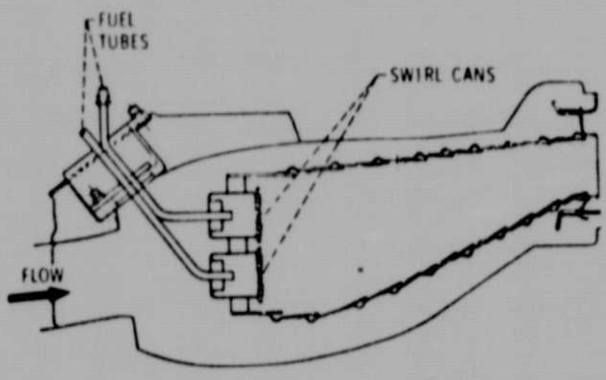
Figure 1. - Combustor concepts for the JT9D engine.



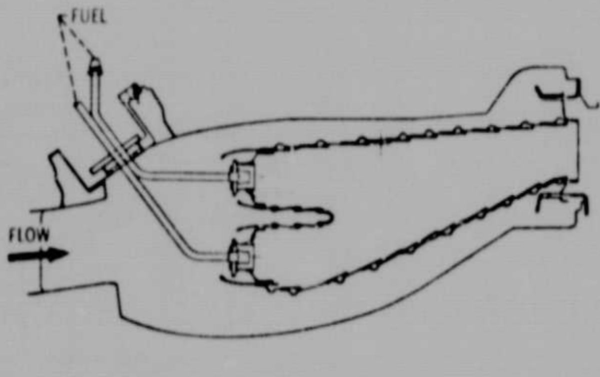
Single annulus - lean dome combustor, CF6 engine.



Radial/axial staged combustor, CF6 engine.



NASA swirl can modular combustor for CF6 engine.



Double-annular lean dome combustor, CF6 engine.

Figure 2. - Combustor concepts for the CF6 engine. CS-67656