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ADVANCED TECHNOLOGY FOR REDUCING AIRCRAFT ENGINE POLLUTION

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ABSTRACT

The proposed EPA regulations covering emissions of gas turbine engines will require extensive combustor development. The NASA is working to develop technology to meet these goals through a wide variety of combustor research programs conducted in-house, by contract, and by university grant. In-house efforts using the swirl-can modular combustor have demonstrated sizable reduction in NO_X emission levels. Testing to reduce idle pollutants has included the modification of duplex fuel nozzles to air-assisted nozzles and an exploration of the potential improvements possible with combustors using fuel staging and variable geometry. The Experimental Clean Combustor Program, a large contracted effort, is devoted to the testing and development of combustor concepts designed to achieve a large reduction in the levels of all emissions. This effort is planned to be conducted in three phases with the final phase to be an engine demonstration of the best reduced emission concepts.

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SUMMARY

This paper describes combustor research programs whose purpose is to demonstrate significantly lower exhaust emission levels. The proposed EPA regulations covering the allowable levels of emissions will require a major technological effort if these levels are to be met by 1979. Pollution reduction technology is being pursued by the NASA through a combination of in-house research, contracted programs, and university grants. In-house research with the swirl-can modular combustor and the double-annular combustor has demonstrated significant reduction in the level of NO_X emissions. This work is continuing in an attempt to further reduce these levels by improvements in module design and in air-fuel scheduling. Research on the reduction of idle emissions has included the conversion of conventional duplex fuel nozzles to air-assisted nozzles and an exploration of the potential improvements possible with fuel staging and variable combustor geometry.

A major contracted effort is the Experimental Clean Combustor Program. The Clean Combustor Program objective is to evaluate the potential emissions reduction of a wide variety of combustor designs. The program goal is a 75+ percent reduction in the level of NO_X emissions at take-off and a 50 percent reduction in the level of idle pollutants from the present day levels for large turbofan engines. This effort is planned to be conducted in three phases consisting of combustor concept screening, combustor development, and full engine demonstration of the emissions reduction possible.

INTRODUCTION

This paper describes the research efforts conducted and sponsored by the NASA to develop new low emissions combustor technology. While considerable progress has been made in reducing the smoke levels of gas turbine engines, no combustors at present incorporate design features specifically for the reduction of gaseous pollutants. The Environmental Protection Agency will have standards that require reduced aircraft combustor emissions by 1979. The time available for combustor development is short if substantially reduced emission levels are required by 1979. But the technological approaches are available to design new combustors. The NASA has taken a major role in sponsoring the study and development of new combustor concepts.

The problems of gaseous pollutant production are reasonably well understood. The pollutants are known and the mechanism of their production is understood. In general the techniques that can be employed to reduce pollutants are universally agreed to. However, the application of these techniques to specific combustor designs that will prove to be most effective in controlling emissions have yet to be demonstrated. The NASA is attempting to solve this problem through a wide variety of research efforts conducted in-house, by contracts with aircraft engine manufacturers and by grants to universities.

This paper summarizes the NASA in-house research and the Clean Combustor Program contract work that are aimed towards reduction of aircraft combustion emissions.

POLLUTANT GENERATION

The problem of controlling gas turbine pollutant generation is divided into two regions of interest. These are the pollutants generated at engine idle (low power) conditions and those generated during takeoff and high power conditions.

Idle Pollutants

Aircraft combustors are designed for maximum performance at takeoff and cruise conditions. Operation at off-design points 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 other factors such as the amount of power extracted and the amount of compressor air bleed used. The principal pollutants at idle are carbon monoxide and hydrocarbons, either as raw fuel or as partially oxidized fuel fragments. The latter are primarily responsible for the characteristic odor common to all jetports (ref. 1).

Attaining levels of idle combustion efficiency that may be required to meet the EPA standards will require a substantial effort. Engine operating conditions at idle result in low combustor-inlet temperatures (366 to 466 K) and pressure (typically about 2 to 4 atm). In addition, the low fuel-air ratios required at idle result in poor fuel atomization and distribution. The low volatility of commercial aircraft kerosene fuel further aggravates this problem.

High Power Pollutants

As the power level of a gas turbine engine is increased, the combustor pressure and inlet-air temperature are increased. At full power the combustion efficiency is nearly 100 percent and almost negligible levels of carbon monoxide and unburned hydrocarbons exist. Unfortunately the higher temperature and pressure levels within the combustor lead to the generation of smoke and oxides of nitrogen. The problem of smoke reduction has received a great deal of attention for many years and new engines generate little if any visible smoke. In general the smoke reduction was accomplished by reducing the fuel-air ratio in the primary zone of the combustor to avoid locally overrich pockets. This results in locally higher flame temperatures.

The trend in gas turbine engine development toward higher pressure ratio also caused increased production of oxides of nitrogen. The formation of oxides of nitrogen in combustors is relatively well understood and has been the subject of many technical reports (e.g., refs. 2 to 4).

While the levels of idle pollutants can be affected by many factors related to the way engines are operated and by the way in which aircraft traffic is managed in and around the terminals, significant reductions in NO_X levels can come about only through redesign of the gas turbine combustor. Expedients such as water injection into the primary zone of the combustor can reduce NO_X emissions, but have the disadvantage of requiring increased engine maintenance and the handling of large quantities of demineralized water. At the present time the NASA is exploring many new and radical combustor designs that have the potential to reduce NO_X levels.

The EPA proposed emission standards as of December 12, 1972 for the T3 class of gas turbine engines (engines with thrust levels exceeding 29 000 lbs) for the 1979 time period are shown in table I, reference 5. The values in the second column are integrated values for a Landing-Takeoff-Cycle and are presented in terms of pounds of pollutant per 1000 pounds of thrust per hour per cycle. The third column gives values of emission index in terms of pounds of pollutant per 1000 pounds of fuel consumed. The values shown for CO and THC were computed by assuming that the combustor is 100 percent efficient at all operating conditions other than taxi-idle. This allows one to then estimate the required value of minimum combustion efficiency. The minimum value of combustion efficiency at taxi-idle that will meet the standards in table I for CO and THC combined is 99.52 percent. If some combustion inefficiency occurs at other operating modes within the Landing-Takeoff-Cycle then the computed value of combustion efficiency at idle must increase in order to keep the total weight of emitted pollutants within the standard. The allowable emission index for NO_X at takeoff was calculated by assuming that any change in combustor geometry would not alter the presently measured values of NO_X at idle and approach and that the level of NO_X produced during climb-out was 75 percent of the allowable NO_X index at takeoff.

Table II compares the goals of the NASA Clean Combustor Program with the proposed EPA standards in table I on an emission index basis. The primary differences are that the Clean Combustor Program is allowing combustion efficiency at idle to be as low as 99 percent but is imposing a lower level on NO_X emissions. Table III compares the present day performance of the T3 class engines (JT9D and CF6-6) with the goals of the NASA Clean Combustor Program. Idle emissions of CO and THC will have to be reduced by half while emissions of NO_X must be reduced by 75 percent. The performance of these engines already meets or exceeds the proposed smoke goal. The primary focus of the NASA combustor research programs is on NO_X reductions. Once proven techniques of NO_X reduction are developed in practical combustors then more effort will be devoted to the control of idle emissions.

PROGRESS IN NO_X REDUCTION

Swirl-Can Combustor

One unique combustor concept that has demonstrated substantial potential for lower NO_X emissions is the swirl-can combustor. Figure 1 is a cross-sectional sketch and photograph of this combustor. The combustor is of annular design, 0.514 m long and 1.067 m in outer diameter. The combustor consists of 120 individual swirl-can modules which distribute combustion uniformly across the annulus. The modules are arranged in three concentric rows with fuel flow independently controlled to each row.

There are 48 modules in the outer row, 40 in the center, and 32 in the inner row.

The combustor module design is shown in ifgure 2. Each module premixes fuel with air in the carburetor, swirls the mixture, stabilizes combustion in its wake, and provides interfacial mixing areas between the bypass air through the array and the hot gases in the wake of the module. More detailed information on swirl-can combustors can be found in references 6 to 8.

Figure 3 compares the NO_X emissions of the swirl-can combustor with NO_X emissions of present day combustors (ref. 9). The curves for the swirl-can and advanced annular combustor were obtained by increasing the measured NO_X values by multiplying by the square root of the pressure ratio. The figure shows the variation of the NO_X emission index with inlet-air temperature or engine pressure ratio. The trend of greatly increased NO_X emission with increasing engine pressure ratio is evident. Although NO_X emissions from the swirl-can combustor are considerably lower than those from conventional combustors, the goal of 75 percent reduction in NO_X levels has yet to be met. Attempts to reduce the level of NO_X have concentrated on changes in the design of the flame stabilizer plate. These flame stabilizers have been modified in an attempt to increase the rate of mixing of the module bypass air with the combustion products. This should result in minimizing the residence time of gases in the hottest part of the recirculation zone. Some of the various flame stabilizers tested are shown in figure 4 and their performance in reducing emissions of NO_X is shown in figure 5. The contra-swirl plates are the only flame stabilizers tested so far that seem to have any potential for further NO_X reduction. Although the measured values of NO_X are reduced from levels shown for the previously reported flat plate flame stabilizers, the overall combustion efficiency was also slightly reduced. This was largely accounted for by a large increase in the level of unburned hydrocarbons which indicates that fuel is being sprayed through the recirculation zone before reaction can take place. If a way can be found to retain the fuel in the reaction zone, thereby improving efficiency, then the quick mixing caused by the opposed swirlers may be successfully utilized.

Experimental Clean Combustor Program

The Experimental Clean Combustor Program is a contracted program with both the Pratt & Whitney Aircraft and the General Electric companies. The primary emphasis of this effort is to design, test and evaluate combustors aimed at significantly reducing NO_X emissions as well as idle emissions. The emissions goals for this program are given in tables II and III. This program effort consists of three planned phases: the first phase is a screening of several combustor concepts; the second phase consists of further development testing of the most promising concepts and the third phase will be a demonstration of the emissions reduction possible with these combustors installed in a JT9D or CF6-50 engine. At present only the first phase of this effort is underway.

Figures 6 through 12 are sketches of the various combustors being tested. Figure 6 is a sketch of a two-row swirl can combustor installed in a CF6 combustor passage. Combustors consisting of 60, 72, and 90 modules will be tested. Figure 7 shows a three row swirl-can combustor consisting of 120 modules of varying diameter mounted in a JT9D combustor. Each row contains 40 modules. Each contractor will study swirl-can combustors by evaluating many variations in swirler, flame stabilizer design, fuel injection techniques, and flow through the swirl-can.

Figure 8 is a sketch of the fully premixed combustor designed for the JT9D engine. This combustor consists of two premix passages. The primary burner supplies all power during engine idle operation. Both burners are employed for operation at higher power levels. Another version of a staged premix combustor is shown in figure 9. This combustor designed for the CF6-50 engine uses a pressure atomizing nozzle in the primary passage and employs premixing in only the secondary or full power passage. Figure 10 is a sketch of a modified CF6-50 combustor that incorporates a pressure atomizing fuel nozzle and a high dome air flow rate such that the entire primary zone operates at a low overall value of equivalence ratio. Variable geometry will be simulated with this combustor by varying the primary and secondary air flow splits. Figure 11 is a cross-sectional sketch of a swirl type combustor designed for the JT9D engine. In this combustor concept, combustion is initiated in the pilot combustion zone which is the only zone operating at idle conditions. For higher power operation, fuel is added through the secondary fuel injectors and combustion occurs in the secondary combustion zone. NO_X emissions may be minimized by the intense stirring caused by air admitted to this zone through rows of secondary air swirlers. The final combustor configuration being investigated is a double annular combustor designed for use in the CF6 engine and shown in figure 12. This configuration employs the lean dome concept similar to the one shown in figure 10. The use of a double-annular concept allows for radial staging of the fuel during idle operation while the overall fuel lean primary zones should result in low NO_X

at full power operation.

CONTROL OF IDLE POLLUTANTS

Since idle emissions are exclusively due to combustion inefficiency, the remedy is to improve combustion efficiency. Many varied approaches all offer some partial improvement in idle emissions. The use of engine bleed to increase the combustor operating fuel-air ratio at idle can improve idle emissions. Fuel staging in multizone combustors also will improve idle emissions. One approach that has been investigated has potential as a retrofit to existing engines as well as a design feature for future engines. This technique is the conversion of the usual duplex fuel nozzle to an air-assisted fuel nozzle at idle conditions.

Air-Assisted Fuel Nozzle

The air-assisted fuel nozzle conversion of a conventional duplex fuel nozzle is illustrated in figure 13. During idle operation fuel is injected using only the primary fuel nozzle, the secondary fuel flow being cut in during higher power operation. Conversion of a conventional duplex nozzle to an air-assisted nozzle is relatively simple. A small amount of air would be drawn off the compressor, passed through a small supercharger and then ducted to the secondary fuel passage of the duplex nozzle. The effectiveness of this approach in reducing idle emissions has been illustrated in reference 10 and is shown in figure 14. These tests were conducted on a single JT3D combustor can operated at a typical idle condition. The figure illustrates that as the quantity of air-assisted flow increases the overall combustion efficiency increases with simultaneous decreases in the levels of CO and THC. While the improvements demonstrated are significant, some emissions at idle still exist and may not meet the proposed standards for this class of engine. Figure 15 illustrates the same technique applied to a JT8D combustor at simulated idle conditions. At an air assisted flow of 0.00318 kilogram per second or 0.25 percent of the total combustor air flow CO emissions are reduced by a factor of 3.5 to 1 and hydrocarbons by a factor of 8 to 1. The emission of NO_X is increased slightly as expected due to the increase in flame temperature with improving efficiency.

Variable Geometry

It is generally agreed that reduction of idle emissions to the very low values proposed by the EPA will probably require some use of variable combustor geometry. A combustor incorporating variable geometry could have a primary zone optimized for low emissions at idle and then by admission of more air during high power operation achieve low NO_X production. Combustor geometry changes simulating variable geometry have been tested. Figure 16 is a cross-sectional sketch of the double-annular ram-induction combustor. Detailed descriptions and performance of this combustor can be found in references 11 to 16. This particular version has a snout attached to the headplate of the combustor. The open area of the snout was varied by attaching punched plates with holes of varying diameter. Varying the snout air flow changed the amount of air admitted to the combustor primary zone through the swirlers and central scoops. In order to maintain a reasonable combustor pressure loss as well as assure the desired air flow distribution, a portion of the transition liner on the outer diameter was opened. This allowed the air that cannot be accepted by the snout to bypass the combustor by being admitted further downstream. The arrangement presented may be neither optimum nor practical but is intended to illustrate the potential of the variable combustor geometry concept for idle emissions reduction. Figure 17 shows the variation in idle pollutant levels for two variations of combustor geometry. Test results are also shown with only the outer annulus burning. With this type of combustor fuel can be staged to either annulus during idle operation, thus locally increasing the fuel-air ratio in that annulus with resulting improvements in combustion efficiency. With combustion in both annuli CO and THC emissions were significantly lower than the base-line model for both variable geometry configurations. Combustion in the outer annulus gives markedly less THC emissions than when both annuli are burning. In this mode the lowest emissions occur with the open liner configuration. The open liner-plus-blocked snout configuration gives slightly higher levels of CO and THC indicating that the primary zone is too fuel rich. A configuration having a lower snout blockage than that tested is probably more optimum.

CONCLUDING REMARKS

Research on most of the combustor concepts mentioned will be continuing in an attempt to better understand ways of minimizing combustor generated pollutants. The goals that have been established for future gas turbine engines will require the development of new technology in combustor design. Several trends and approaches for pollutant reduction have been determined, but with the exception of exhaust smoke have yet to be demonstrated on flight engines. This demonstration is the goal of the NASA Experimental Clean Combustor Program.

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TABLE I. - 1979 EPA STANDARDS

(As of Dec. 12, 1972, Ref. 5)

T3 Class Engines

Pollutant	LTO-cycle #/hr - 1000 #/cycle	Emission index #/1000 # fuel
CO	1.7	[a]10.3
THC	0.4	[a]2.4
NO_X	3.0	[b]12.9
Smoke (SAE no.)	20	----

[a]Assumes 100 percent combustion efficiency at all LTO cycle modes except "Taxi-Idle."

[b]NO_X emission index at takeoff. Computed by assuming that NO_X emission index values at Taxi-Idle and Approach are unchanged and that Climb-Out value equals 75% of the computed takeoff value.

TABLE II. - COMPARISON OF 1979 EPA STANDARDS

WITH CLEAN COMBUSTOR GOALS

Pollutant	Mode	EPA	Clean combustor
CO	Idle	[a]10.3	[a]20
THC	Idle	2.4	4
NO_X	Takeoff	12.9	10
Smoke (SAE no.)	Takeoff	20	15

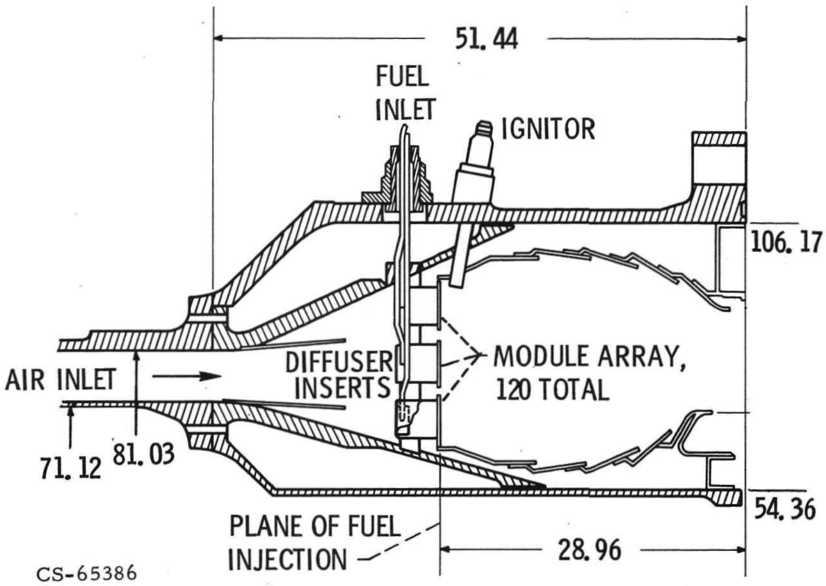
[a]Comparison based on emission index values.

TABLE III. - COMPARISON OF PRESENT T3 CLASS ENGINE

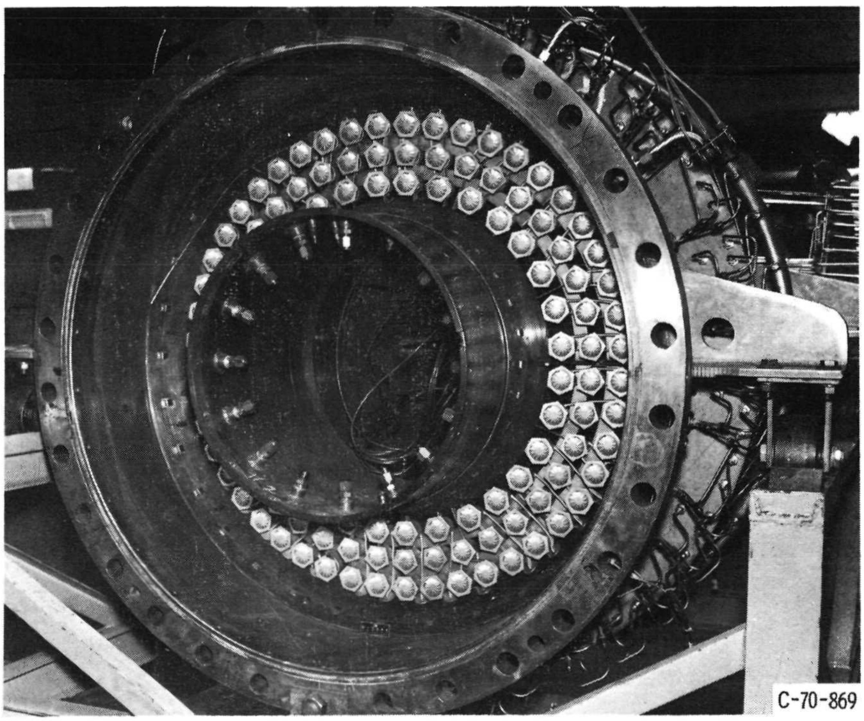
EMISSIONS WITH CLEAN COMBUSTOR GOALS

Pollutant	Mode	T3 engines	Clean combustor goal
CO	Idle	[a]50-60	[a]20
THC	Idle	10-20	4
NO_X	Takeoff	40-50	10
Smoke (SAE no.)	Takeoff	10-15	15

[a]Emission indices.



(a) CROSS-SECTIONAL SKETCH OF SWIRL-CAN COMBUSTOR.



(b) SWIRL-CAN COMBUSTOR.

Figure 1. - Full annular model of swirl-can combustor. (Dimensions in centimeters.)

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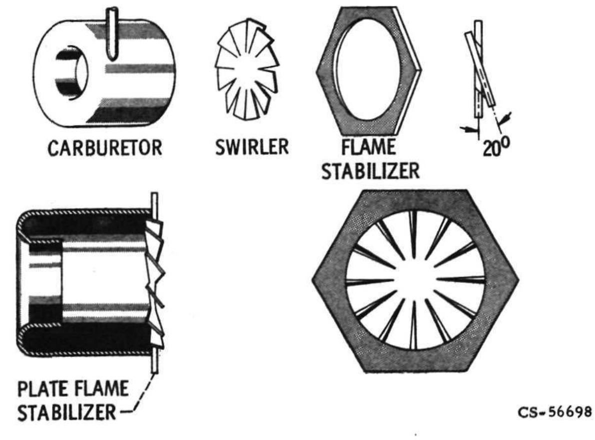

Figure 2. - Combustor module details.

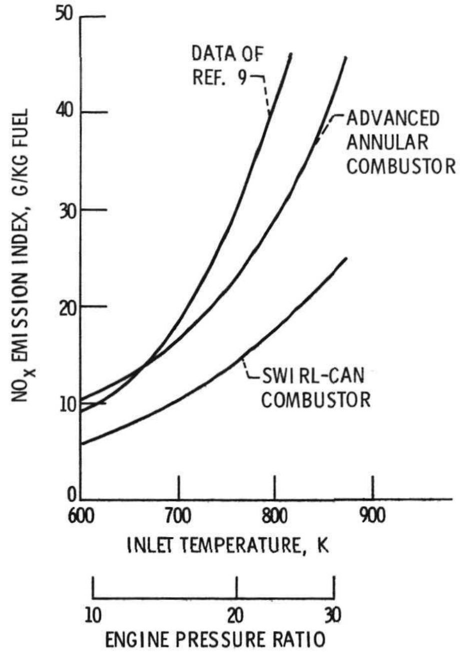

Figure 3. - Comparison of NO_x emissions of swirl-can combustors with more conventional combustors.

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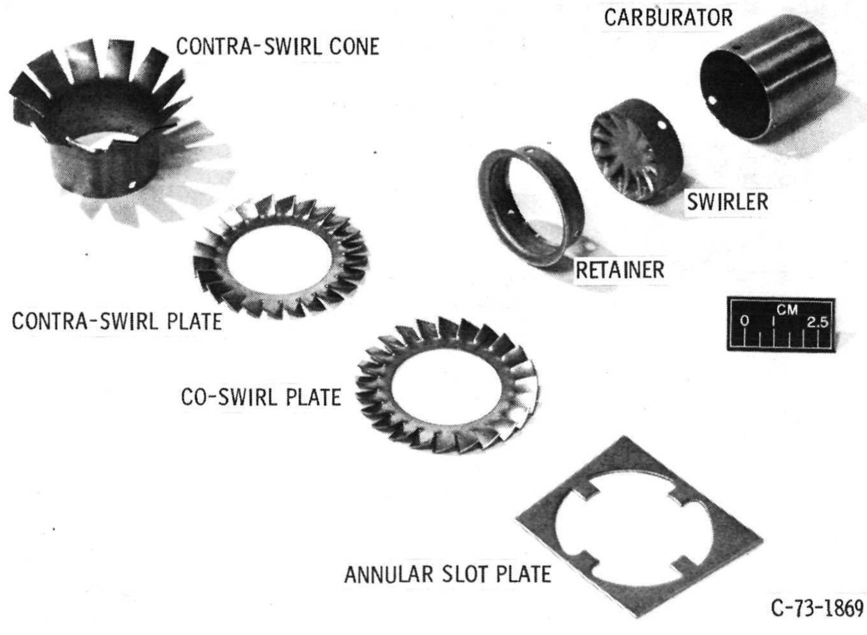

Figure 4. - Swirl-can module and various flame stabilizers.

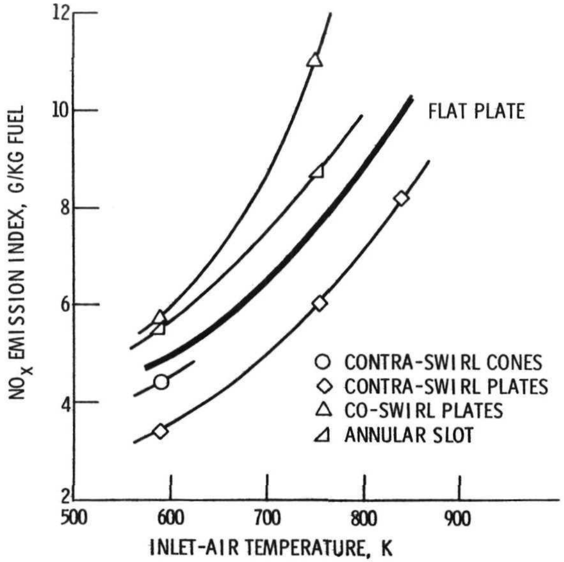

Figure 5. - Effect of flame stabilizer geometry on NO_x emissions at various inlet-air temperatures and a pressure of 61.9 N/cm^2.

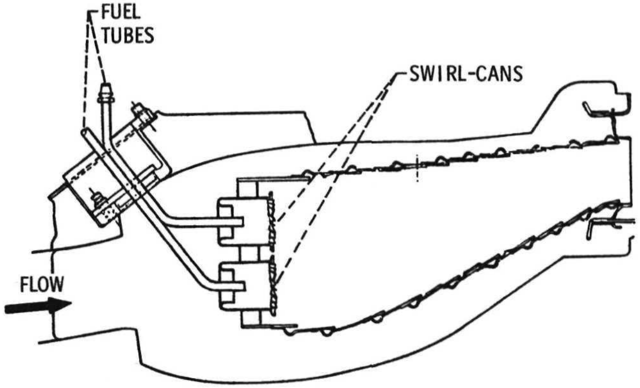

Figure 6. - NASA swirl-can-modular combustor for CF6 engine.

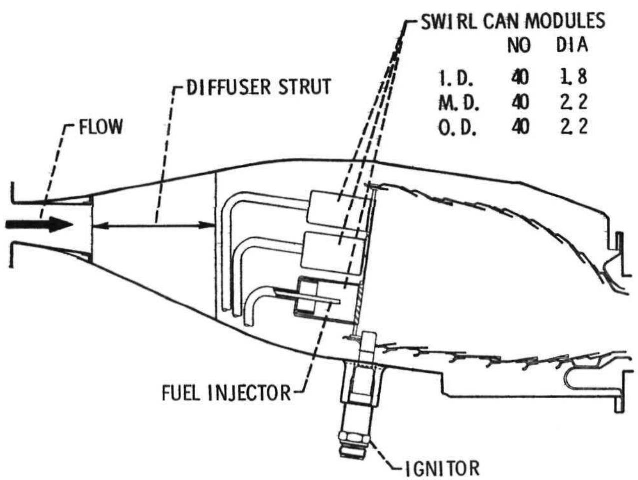

Figure 7. - NASA swirl-can modular combustor, for JT9D engine.

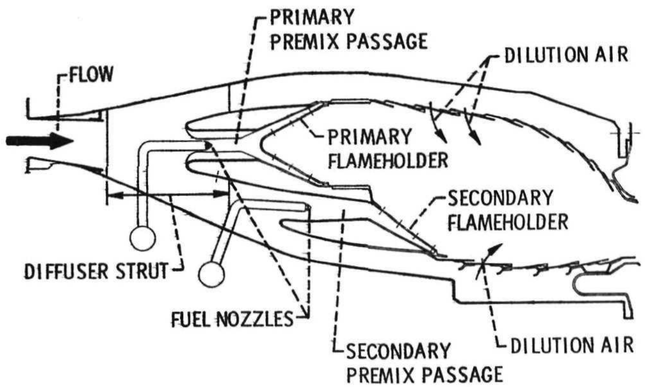

Figure 8. - Staged premix combustor, JT9D engine.

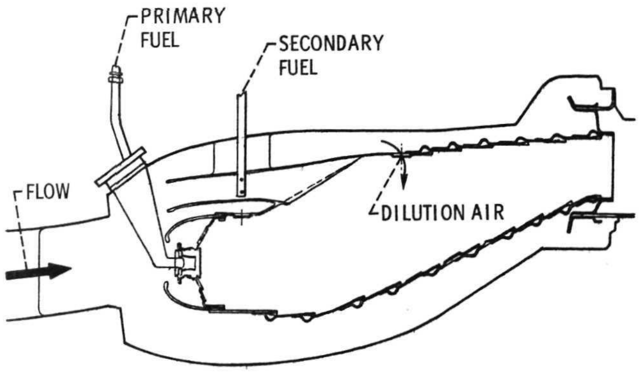

Figure 9. - Radial/axial staged combustor, CF6 engine.

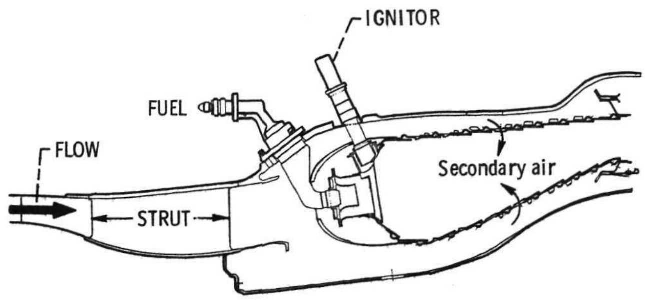

Figure 10. - Single annulus - lean dome combustor, CF6 engine.

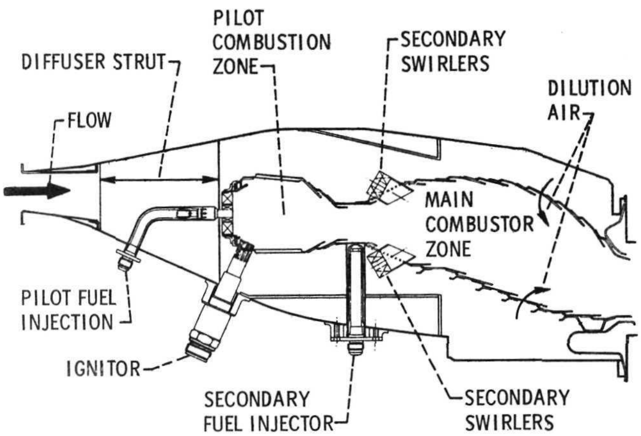

Figure 11. - Swirl combustor for JT9D engine.

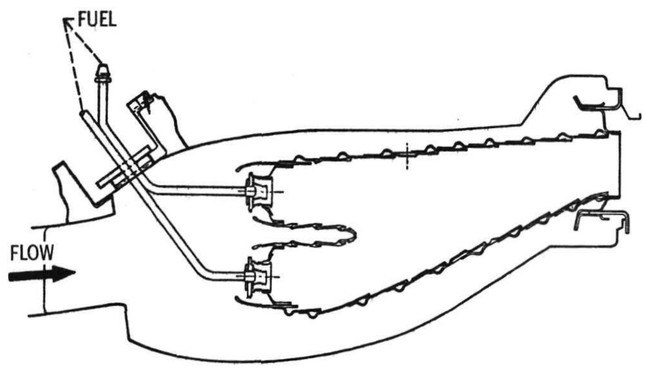

Figure 12. - Double-annular lean dome combustor, CF6 engine.

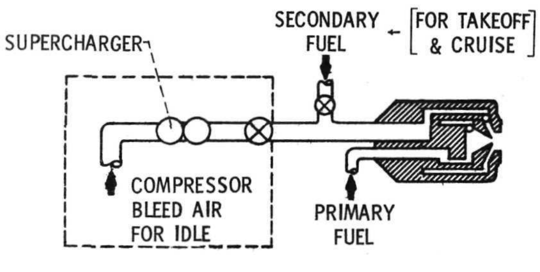

Figure 13. - Air-assist fuel injection.

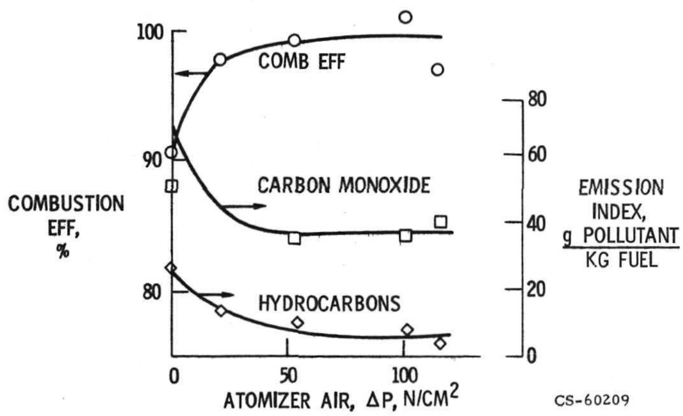

Figure 14. - Reduction in emissions at idle using air-assist fuel nozzle.

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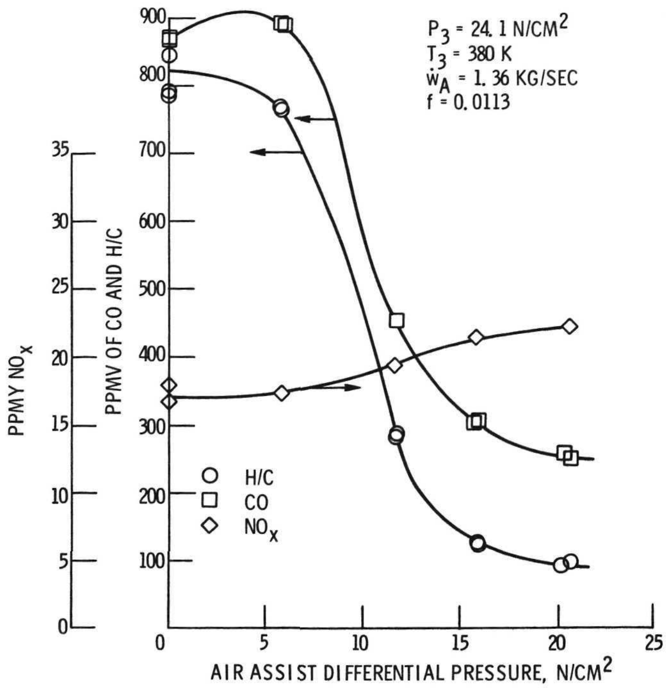

Figure 15. - JT8D air-assist idle emissions.

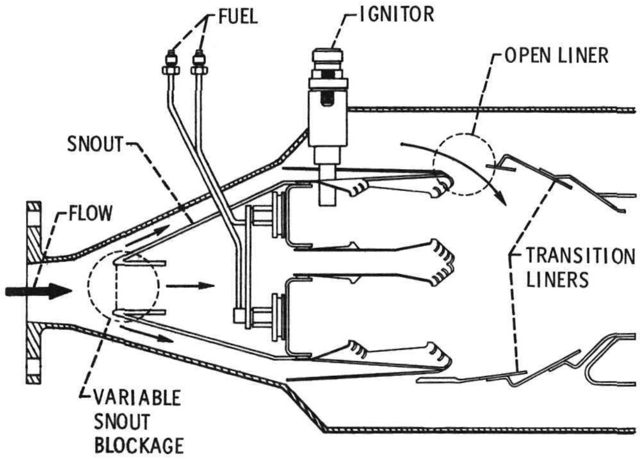

Figure 16. - Cross-sectional sketch of double-annular ram-induction combustor showing variable geometry features.

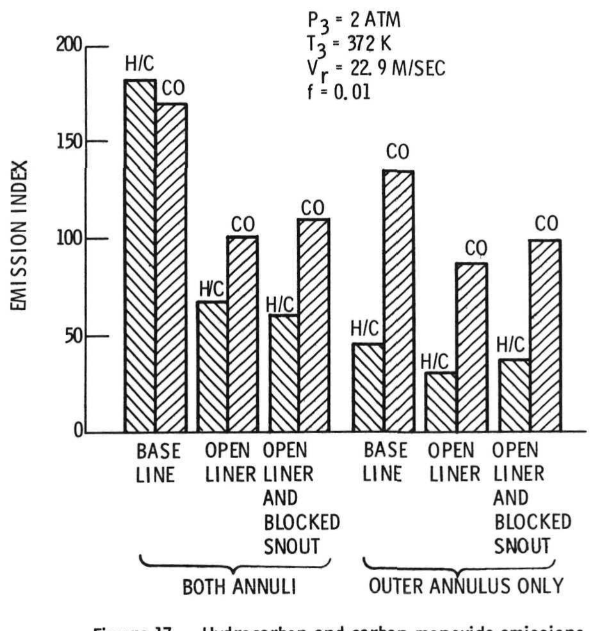

Figure 17. - Hydrocarbon and carbon monoxide emissions for variable geometry combustor with combustion in both annuli and in outer annulus only.