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COMBUSTOR CONCEPTS FOR AIRCRAFT GAS TURBINE LOW-POWER EMISSIONS REDUCTION

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Abstract

Three combustor concepts have been designed and tested to demonstrate significant reductions in aircraft engine idle pollutant emissions. Each concept used a different approach for pollutant reductions: the Hot Wall Combustor employs a thermal barrier coating and impingement cooled liners, the Recuperative Cooling Combustor preheats the air before entering the combustion chamber, and the Catalytic Converter Combustor is composed of a conventional primary zone followed by a catalytic bed for pollutant cleanup. The designs are discussed in detail and test results are presented for a range of aircraft engine idle conditions. The results indicate that ultra-low levels of unburned hydrocarbons and carbon monoxide emissions can be achieved with this technology.

Introduction

This paper summarizes the results of a program to evolve and demonstrate combustor technology directed toward reducing pollutant emissions from aircraft gas turbine engines during idle operation.

E-9608

Concern over air pollution has drawn the attention of combustion engineers to the quantities of exhaust emissions produced by aircraft 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 (CO) during idle and taxi, and oxides of nitrogen (NO_x) and smoke during takeoff and landing. Oxides of nitrogen formed during altitude cruise of an aircraft are also considered pollutants of concern. 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 (EPA) 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. These emission standards for Class T2 engines are shown in table I in terms of the EPA parameter, which is a weighted integration of emissions over a prescribed landing-takeoff cycle. In response to these EPA standards, Lewis Research Center generated the Experimental Clean Combustor Program (ECCP) and the Pollution Reduction Technology Programs to develop technology which could be used in future gas turbine combustor designs. These programs are now nearly all completed and have demonstrated that significant reductions in pollutant emissions are possible

The EPA also promulgated standards for newly certified aircraft gas turbine engines with a compliance date being January 1, 1981. These emission standards are also shown in table I, indicating a further reduction in HC and CO from the 1979 standards. Since most of the HC and CO pollutants over the landing-takeoff cycle occur during the idle mode of the engine, further significant reductions of HC and CO are required at idle conditions than were demonstrated during the ECCP program. To investigate methods of further improvement at idle, therefore, Lewis Research Center awarded a contract entitled the Aircraft Gas Turbine Engine Low-Power Emissions Reduction Technology Program (LOPER).

This paper summarizes the results of the LOPER program. Details of the combustor designs and a comprehensive listing of the data has been omitted. Rather, the purpose of this paper is to discuss the techniques used for pollution reduction and to highlight the major results of the program. More detailed information may be found in reference 2.

Loper Program Description

The purpose of the LOPER program was to evolve advanced aircraft gas turbine engine technology capable of reducing low power emissions of CO and HC to levels significantly lower than that which can be achieved with current technology. The emission goals of the program are shown in table II. These emission index values are representative of the levels required at the engine idle condition in order to meet the 1981 EPA standards. For comparison purposes, the idle emission goals of the ECCP program are also shown along with idle emissions from two current commercial aircraft engines. One can see from the table that the LOPER program goals for CO and HC are much lower than the ECCP program goals, and require large reductions in the emission values of the current engines. These CO and HC emission index goals would result in a combustion efficiency at idle of 99.7 percent.

Although this program does not focus on NO_x reduction, a goal is specified for NO_x at idle conditions in order that NO_x - CO tradeoffs are not used. Such tradeoffs could reduce CO at idle to the detriment of the NO_x limitations imposed by the EPA standards at idle and other operating conditions.

Three combustor concepts were to be designed and tested at the operating conditions given in table III. A single design condition was specified as shown and is representative of the engine idle condition of an advanced gas turbine. In addition, testing was to be performed at two other sets of inlet pressure and temperature, 2 atmospheres, 366 K, and 4 atmospheres, 478 K, as well as at a total of 3 reference velocities and a range of fuel-air ratios in order to more completely document the idle performance of each combustor concept.

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This program was performed under contract to General Electric and was performed by their Aircraft Engine Group, Evandale, Ohio.

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.

Combustor Designs

Three combustor concepts were designed and fabricated for testing in a 60° sector combustor rig. All three combustors are annular designs; they are shown in cross-section in figure 1. The combustors were sized to be typical of those used in large turbofan engines. The overall length of the original designs were 34.4 cm, with an annular height between inner combustor liner walls of 7.6 cm. See reference 2 for more detail. The three concepts employed many common parts in order to better compare their performance (e.g., combustor aft section). Each concept uses a distinct technique for achieving the low pollutant emissions goals. At the same time low pollutant features such as air blast fuel nozzles and air impingement cooled liners are common to all three concepts. The major design features of each concept are shown in table IV.

Concept No. 1, the Hot Wall Combustor (fig. 1(a)), uses a thermal barrier coating along the inside combustor liner. This allows combustion gases near the wall to be at higher temperatures, minimizing wall quenching of the combustion kinetics. The thermal barrier coating employed was a 1.3 mm thick thermally sprayed yttria-stabilized zirconia. This material has been used previously in a combustor, but with a much thinner coating, by Butze and Liebert in reference 3. The combustor liners do not employ the conventional film cooling technique but rather are double wall construction with the outer wall drilled with equally spaced holes for high velocity air impingement cooling. A schematic of this double wall construction is shown in figure 2. The cooling air, after impinging off the back of the inner liner, flows between the liner walls until it reaches the series of dilution air thimbles. Then it passes into the combustor as a coannular dilution jet. This wall cooling technique is an effective way of protecting the combustor liners and also minimizes wall quenching effects.

Concept No. 2, the Recuperative Cooling Combustor, (fig. 1(b)), sends all the primary combustion air first through the annular passage of the combustor liners before being admitted into the combustor through the air swirlers of the fuel injectors or the primary dilution holes. Thus the combustion air is first used to cool the liners and in this way picks up heat before entering the combustor. This effected an air temperature rise of about 50 to 100 K depending on operating conditions. This increase in air temperature reduces pollutant emissions by increasing combustion reaction rates. The secondary air dilution thimbles were sized as shown in figure 1(b) to prevent cooling air from passing into the combustor as a coannular jet. A cover is attached to the cowls of the combustor dome as shown in figure 2 to block air from flowing directly into the air swirlers from the diffuser. The pressure drop of the air swirlers was reduced to provide an overall combustor pressure drop comparable to Concept 1.

Concept No. 3, the Catalytic Converter Combustor, (fig. 1(c)), consists of a standard combustor primary zone followed by a ceramic honeycomb catalyst bed. The fuel is first burned in front of the catalyst bed using approximately 50 percent of the airflow. This lean burning results in an average equivalence ratio at the face of the catalyst bed of 0.30 at the idle design condition. The catalyst acts as a cleanup reactor for the unburned HC and CO products in the combustion gas. The burning of the fuel in front of the catalyst bed raises the bed temperature to a level where it can operate efficiently at consuming the residual CO and HC gases. The lean equivalence ratio of this preburner protects the catalyst bed from overtemperature and also lowers the NO_x formation rates. The catalyst bed was manufactured under subcontract by Engelhard Minerals and Chemicals Corp., the Engelhard Industries Division. The catalyst type, designated by the manufacturer as DXD - 222, was chosen from screening tests on a number of candidates. The bed is composed of three annular sections of substrate cemented together to form one rigid 60° annular segment. Further details on the catalyst design may be found in reference 2.

All three concepts were designed for idle operation only. Concepts 1 and 2 were designed for a primary equivalence ratio close to stoichiometric at the design condition, and this would result in a very rich primary zone at higher power operating conditions. The purpose of these designs was to demonstrate that this technology could achieve ultra-low levels of CO and HC emissions. The application of this technology to a practical combustor system could be realized through variable geometry schemes or by using the design as the pilot stage of a multistaged combustor. This application is beyond the scope of this present program.

Photographs of combustor hardware are shown in figure 3. The smooth inner combustor liners and the deep plunged dilution hole thimbles are significant features shown in figures 3(a) and (b). Figure 3(c) shows the triple wall construction of the combustor dome. The four tubes in between the five fuel injector barrels admit air to the impingement cooling holes for the combustor dome.

Test Facility and Instrumentation

The combustor tests were conducted at General Electric in a facility which provides unvitiated, preheated air at required pressures to the test combustor. The combustor test rig is shown in figure 4. The rig consists of an inlet plenum, a central section containing the diffuser and combustor casing flow path, and an exit instrumentation section. The rig provides a good simulation of the flow conditions inside a typical gas turbine engine. Some of the major design features of the test rig are listed in table V. Five fuel nozzles are equally spaced in the 60° sector central section. The combustor reference velocity is defined in terms of a reference area based on the 7.6 cm inner dome height. The burning length of the original combustor designs are shown to be comparable to combustors of other engines. One distinct difference between these combustor designs and conventional combustors is that the combustor liners are cylindrical rather than conical. This combustor shape was provided for ease of installation of the honeycomb catalyst bed.

Standard instrumentation was provided for the combustor tests. A photograph of the combustor inlet and exit airflow rakes are shown in figure 5. There were seven fixed exit rakes in the sector annular exhaust section. These rakes provided temperature and gas sampling data simultaneously. And pressure information was also obtained by momentarily stopping the gas sample flow. Gas sampling was measured online during the tests using the standard gas sampling equipment and following the procedure of reference 4. Smoke was not measured since it was not considered to be significant at these idle conditions. For further information on the instrumenation and data analysis, see reference 2.

Combustor Test Results

Seven configurations of each combustor concept were tested during the program. The emissions of the most promising configuration of each concept are presented in figures 6, 7, and 8, and a discussion of these results follows.

Hot Wall Combustor

Emissions from configuration H4 of the Hot Wall Combustor are shown in figure 6. The emissions were well below the program goal at the 3 atmosphere, 422 K inlet condition. In fact, even at the more severe inlet condition of two atmospheres, 366 K, the emissions performance was below the program goals. Total combustor pressure drop at the design point of table III was 5.4 percent, very close to the design goal. A major modification from the original design of this concept was an improved set of air blast fuel nozzles as indicated on figure 9(a). The original fuel nozzles tended to inject large drops of fuel into the combustor due to fuel wetting the swirler barrel wall. The modified fuel nozzle eliminated this fuel-wetting and lowered the HC and CO emissions. In addition the primary dilution holes were staggered at two axial positions resulting in NO_x emissions below the program goal.

Recuperative Cooling Combustor

Emissions from configuration R7 of the Recuperative Cooling Combustor are shown in figure 7. At the design condition of 3 atmospheres and 422 K, the concept met all the emissions goals between fuel-air ratios of 0.0067 and 0.0075. At the design fuel-air ratio of 0.0105 the HC and CO emissions were below the goal values, but the NO_x emissions exceeded the goal. At the more severe conditions of 2 atmospheres, 366 K, all the emissions were below the goals over a range of fuel-air ratios from 0.006 to 0.010. The main modifications to the original design of this configuration was an improved set of air blast fuel nozzles similar to those of concept 1, as indicated in figure 9(b); and the primary dilution air was relocated further downstream from the combustor dome. Total combustor pressure drop at the design point of table III was 6.4 percent, very close to the design goal. The higher NO_x emissions of this concept is inherent in the design since the combustion air temperature has been heated before entering the combustion chamber.

Catalytic Converter Combustor

Emissions from configuration C7 of the Catalystic Converter Combustor are shown in figure 8. The data are at the design inlet condition of three atmospheres, 422 K, at two different reference velocities. At the design fuel-air ratio the HC and CO emissions were well below the program goals and the NO_x emissions were at the program goal. This configuration reflects a number of major modifications from the original design. As shown in figure 9(c), the front end of the combustor was lengthened from 8.3 to 19.4 cm to reduce peak temperatures at the front of the catalytic bed. Previous tests with the original design resulted in hot spots in the catalyst which limited the allowable fuel-air ratio to less than the design value. The longer front end allowed more mixing of combustion gases to take place, reducing the peak temperatures. Also, a set of nonwall-wetting fuel injectors were used that were the same as that of concept 2. Finally, two rows of dilution holes were located further downstream from the dome than the single row of holes of the original design. All these features were effective in reducing the levels of HC and CO gases entering the catalyst bed and, with the conversion efficiency of the catalyst, very low levels of HC and CO emissions at the combustor exhaust resulted. The total combustor pressure drop at the design point of table III was 4.6, slightly lower than the design value.

Comparison of Combustor Emissions

A direct comparison of the emissions of the combustor concepts is shown in table VI at the combustor design point. All three concepts demonstrated very low pollutant emissions. Carbon monoxide emissions were well below the program goal for all three concepts. Hydrocarbon emissions were below the goal for all three, and all but the Recuperative Cooling Concept were below the NO_x program goals. Higher NO_x emissions are inherent in the recuperation cooling concept since the actual inlet-air temperature into the combustor was increased by as much as 100 K, but further combustor development might lower the NO_x emissions to the goal value.

All three concepts were successful in demonstrating substantially lower pollutant emissions at engine idle. The results of this program are compared in figure 10 with ECCP program results using demonstrator engines and with current CF6 and JT9D engine idle emissions. The hydrocarbon and carbon monoxide emissions comparisons are dramatic. The NO_x emissions from concepts 1 and 3 are quite comparable with current engine emissions. Please note, however, that we are comparing combustor rig data with engine data, and slight differences in emissions can be expected between rig and engine tests of the same combustor. Nevertheless, figure 10 does point out the potential emissions reduction by using these advanced technology concepts.

Evaluation of Concepts

The chief characteristics of each concept are shown in table VII. The Hot Wall Combustor is the simplest design of the three and interestingly enough had the lowest emissions. There was no ceramic coating deterioration during the tests, but the durability of the coating could not be judged with so few test hours.

The Recuperative Cooling Combustor exhibits more complex aerodynamics than Concept 1. Since all the primary combustion air must first pass through the liner walls, there is less pressure drop available for the fuel atomization process. This results in a less efficient fuel atomizer than the one used in Concept 1. Nevertheless, emissions were quite low, and approached or were lower than the program goals. The temperature of the inlet air was significantly increased by this design. For example, at the design condition of table III, the temperature increase of the air was 74 K.

The Catalytic Converter Combustor also exhibits more complex aerodynamics than Concept 1. The temperature of the gases approaching the catalyst bed must be carefully controlled to prevent catalyst bed damage. The combustor length had to be increased in order to better control these gas temperatures, although further work might result in a shorter length. Once again less pressure drop was available for fuel atomization than with Concept 1, because of the required pressure drop of the catalyst bed. In spite of these features, the emissions were very low, well below the program goals, and this Concept does warrant further interest. During the tests there were some problems with catalyst bed durability. Local hot zones caused bed deterioration in small spots which did not affect overall performance. And the initial design of the bed support resulted in cracking of the bed in early tests. No bed cracking was evident using a modified design of the bed support.

Summary of Results

A program which focused on reducing aircraft engine idle pollutant emissions was performed with the goal of demonstrating advanced technology which can later be applied to future combustion systems. Three combustor concepts were designed and tested at idle conditions typical of current and future aircraft gas turbines. Each concept used a different approach for pollutant reductions: A thermal barrier coating of the liners, preheating the combustion air, and a catalytic clean up device. Final test results indicate that all three concepts demonstrated the ability to achieve substantial reductions in idle emissions. All three concepts exhibited emissions of unburned hydrocarbons, carbon monoxide, and oxides of nitrogen which met or were below the program goal values which correspond to current EPA 1981 emission standards. Of the three concepts, the Hot Wall Combustor, which employs a thermal barrier coating and impingement cooled liners, demonstrated the lowest emissions. At the design condition of an inlet temperature of 422 K, an inlet pressure of 304 kPa, a reference velocity of 23 m/sec, and a fuel-air ratio of 0.0106, the emissions were: HC = 0.5 g/kg fuel, CO = 1.3 g/kg fuel, and NO_x = 2.6 g/kg fuel. The simplicity of this concept makes it particularly attractive for development into future gas turbine engines.

The Recuperative Cooling Combustor and the Catalytic Converter Combustor also exhibited pollutant emissions which achieved the program goals. Both of these concepts are more complex than the Hot Wall Combustor, but warrant further consideration for their pollution reduction potential.

Acknowledgement

This program was performed under NASA contract NAS 3-20580 by the Aircraft Engine Group of General Electric. Mr. A. L. Meyer was Program Manager and Mr. D. W. Bahr served as Technical Program Manager for the contractor. The program was directed out of the Combustion and Pollution Research Branch of the Airbreathing Engines Division at the Lewis Research Center.

References

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. Gleason, C. C., Dodds, W., and Bahr, D. W., "Final Report, Aircraft Gas Turbine Engine Low-Power Emissions Reduction Technology Program," NASA Contract No. NAS 3-20580, to be published.

3. Butze, H. F. and Liebert, C. H., "Effect of Ceramic Coating of JT8D Combustor Liner on Maximum Liner Temperatures and Other Combustor Performance Parameters," NASA TM X-73581, 1976.

4. "Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines," Aerospace Recommended Practice 1256. SAE, 1971.

5. Gleason, C. C., Rogers, D. W., and Bahr, D. W., "Experimental Clean Combustor Program, Phase II," General Electric Co., Cincinnati, Ohio, R76AEG422, Aug. 1976 (NASA CR-134971).

6. Roberts, R., Peduzzi, A., and Vitti, G. E., "Experimental Clean Combustor Program, Phase II," Pratt and Whitney Aircraft, East Hartford, Conn., PWA5418, Nov. 1976 (NASA CR-134969).

TABLE I. - CURRENT EPA EMISSION STANDARDS FOR T2 AIRCRAFT ENGINES

[Over a prescribed taxi/idle-takeoff-climbout-approach-taxi/idle cycle: lb/1000 lb thrust-hr/cycle.]

	1979 Standards	1981 Standards
Unburned hydrocarbons	0.8	0.4
Carbon monoxide	4.3	3.0
Oxides of nitrogen (as NO_2)	3.0	3.0

TABLE II. - POLLUTANT EMISSIONS GOALS AT ENGINE IDLE CONDITIONS

[In terms of emission index, g/kg fuel.]

	Program goals	ECCP goals	Current CF6-50*	Current JT9D-7+
Total hydrocarbons, HC	1	4	30	22
Carbon monoxide, CO	10	20	73	47
Oxides of nitrogen, NO_x	≤ 4	--	2.5	3.9

*Ref. 5.
+Ref. 6.

TABLE III. - COMBUSTOR OPERATING CONDITIONS

	Design condition	**Parametric test conditions**		
Inlet pressure, atm	3	2	3	4
Inlet temperature, K	422	366	422	478
Reference velocity, m/sec	22.9	15.2,	22.9,	30.5
Fuel-air ratio	0.0105	0.006	to	0.0134
Combustor pressure drop, $\Delta P/P$ (percent)	5.0	-----	----	------

TABLE IV. - LOW EMISSION COMBUSTOR DESIGN CONCEPTS

1. Hot wall concept
    - Refractory coated surfaces
    - Minimized wall quenching

2. Recuperative cooling concept
    - Preheated primary air
    - Increased combustion reaction rates

3. Catalytic converter concept
    - Precombustion and catalytic cleanup
    - Rapid residual CO and HC consumption
    - Catalyst bed defined and fabricated under subcontract with Engelhard M & C Corp.

4. All concepts
    - Impingement cooled liners, no film cooling
    - Air blast fuel injectors
    - Near Stoichiometric primary zone equivalence ratio
    - Dilution air admitted far down combustor length
    - Common dome assembly
    - Common aft dilution-transition assembly

TABLE V. - TEST RIG DESIGN DETAILS

- 60° Sector combustor rig (5 nozzle CF6-50/ECCP)
- 7.62 cm (3.0 in.) dome height
- Reference velocity defined by:
    Combustor airflow divided by the combustor inner dome area and the inlet air density:

$$Vr = \frac{W_{comb}}{A_{dome}\,\rho_3}$$

With this definition:

$$\left.\begin{array}{l}\text{CF6-50} = 23.5 \text{ m/s (77 fps)} \\ \text{CFM56} = 16.5 \text{ m/s (54 fps)}\end{array}\right\} \text{At idle}$$

- 29.2 cm (11.5 in.) burning length
  Compared with:
    CF6-50 = 33.3 cm (13.1 in.)
    CFM56 = 22.9 cm (9.0 in.)
- Cylindrical combustor walls (for catalyst configuration)
- Five element fixed exit rakes
    Spaced in-line and between fuel nozzle locations (7 total)
    Combination pressure/temperature/gas sample

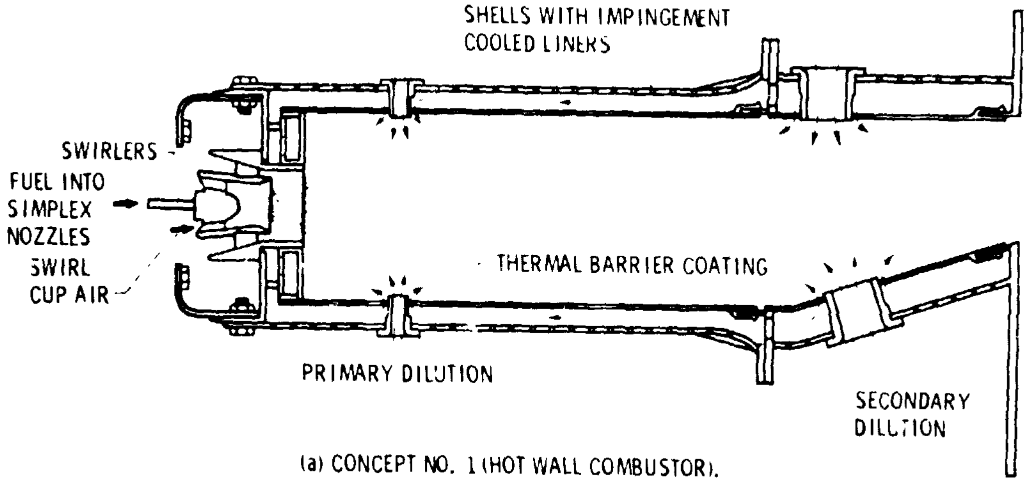
TABLE VI. - CONCEPT EMISSIONS COMPARISON

(NO_x corrected to std. humidity 6.3 g/kg)

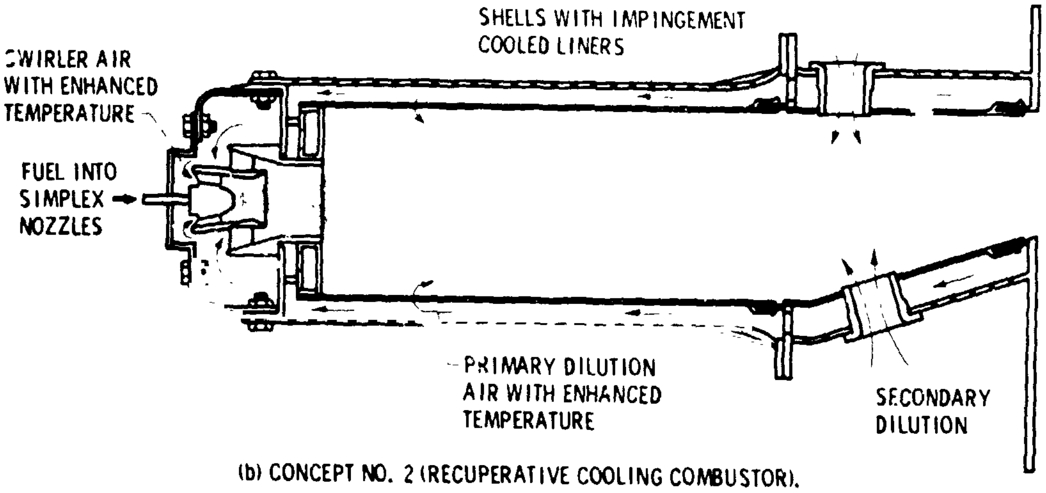
	At design point (422 K, 304 kPa, 23 m/s, f/a = 0.0105)		
	HC (g/kg fuel)	CO (g/kg fuel)	NO_x (g NO_2/kg fuel)
Hot wall (H4)	0.5	1.3	2.6
Recuperative (R7)	.5	9.0	5.4
Catalytic (C7)	.3	1.3	4.0
Goal	1.0	10.0	4.0

TABLE VII. - COMBUSTOR CHARACTERISTICS

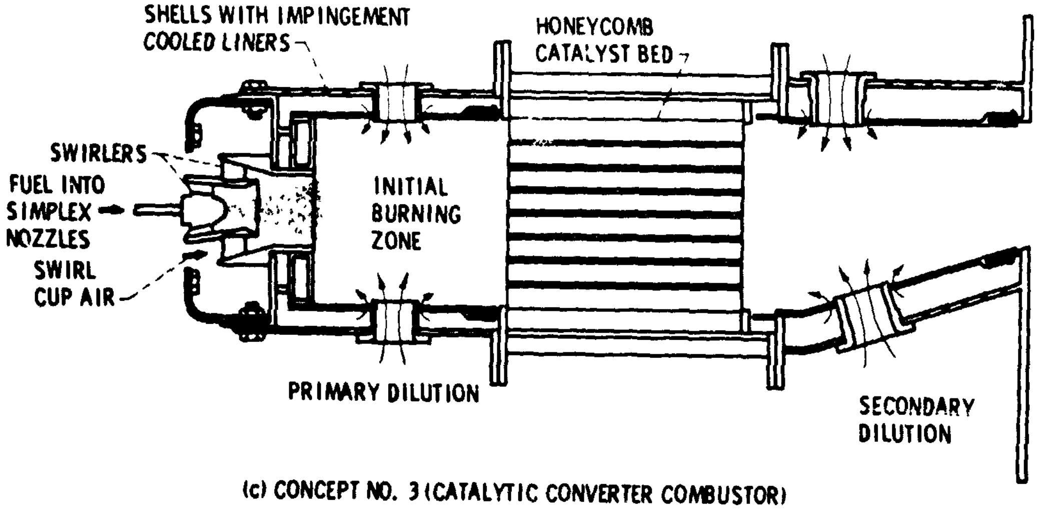
Hot wall combustor	Simplest aerodynamically Lowest emissions (below program goals) No ceramic deterioration
Recuperative cooling combustor	Complex aerodynamics Emissions approach program goals Low swirler pressure drop - less efficient atomization and mixing Inherently higher NO_x because of increased swirler/primary dilution temperature
Catalytic converter combustor	Complex aerodynamics Emissions below program goals Transient operation not addressed (lightoff, sub-idle operation) Requires extended length or increased dome complexity Low swirler pressure drop - less efficient atomization and mixing Problems with catalyst durability



(a) CONCEPT NO. 1 (HOT WALL COMBUSTOR).



(b) CONCEPT NO. 2 (RECUPERATIVE COOLING COMBUSTOR).



(c) CONCEPT NO. 3 (CATALYTIC CONVERTER COMBUSTOR)

Figure 1. - Schematic of three combustor concepts.

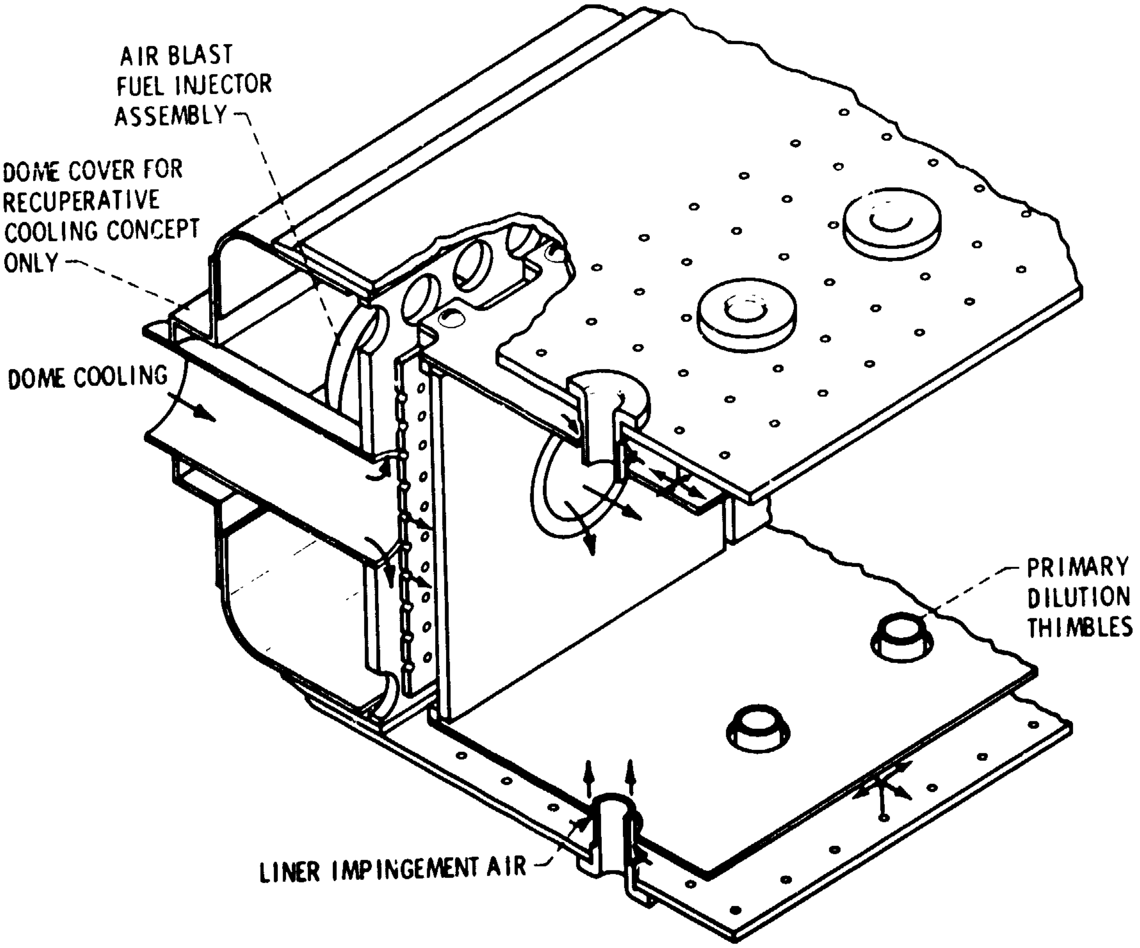


Figure 2. - Impingement cooling circuit

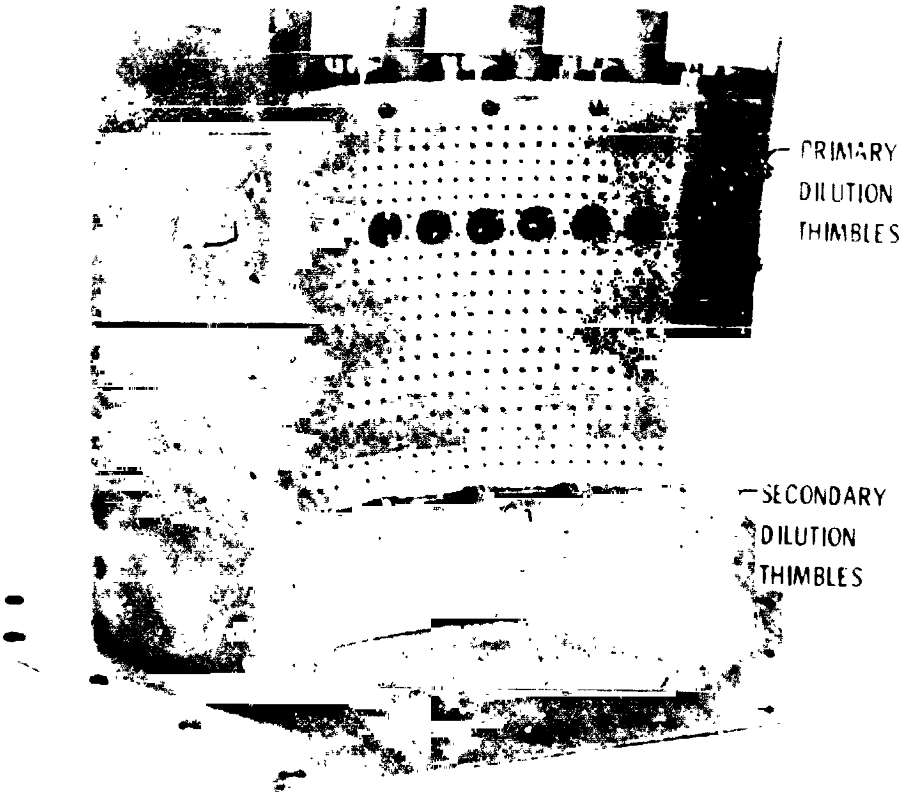


Figure 3a. - Combustor assembly, exterior view.

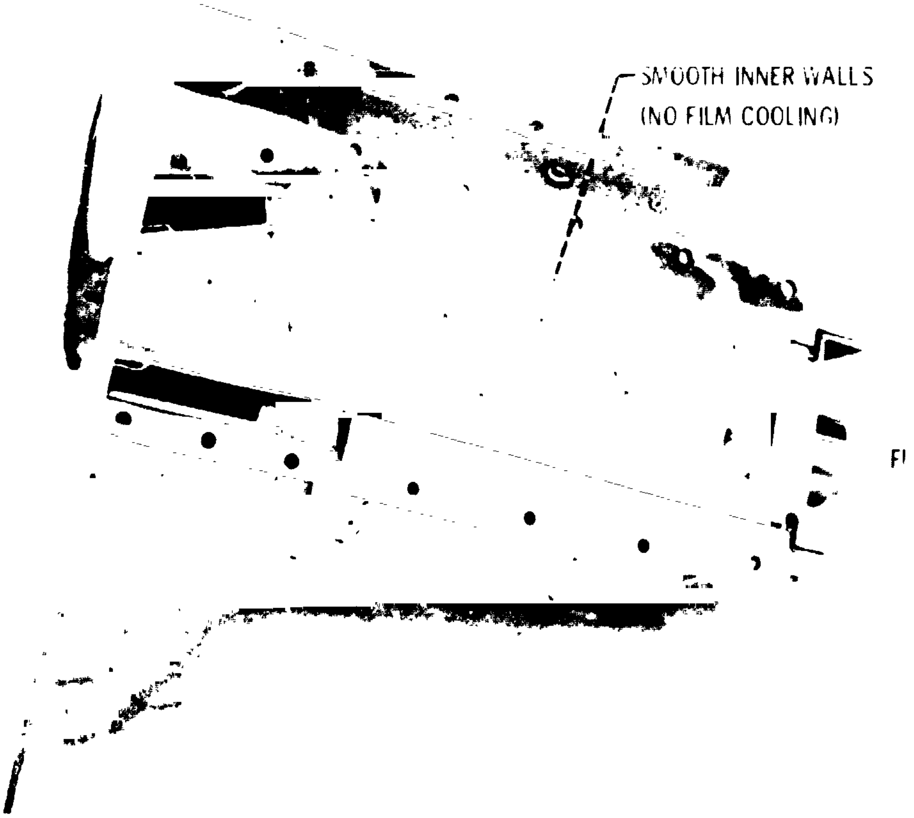


Figure 3b. - Combustor assembly with end plate removed.

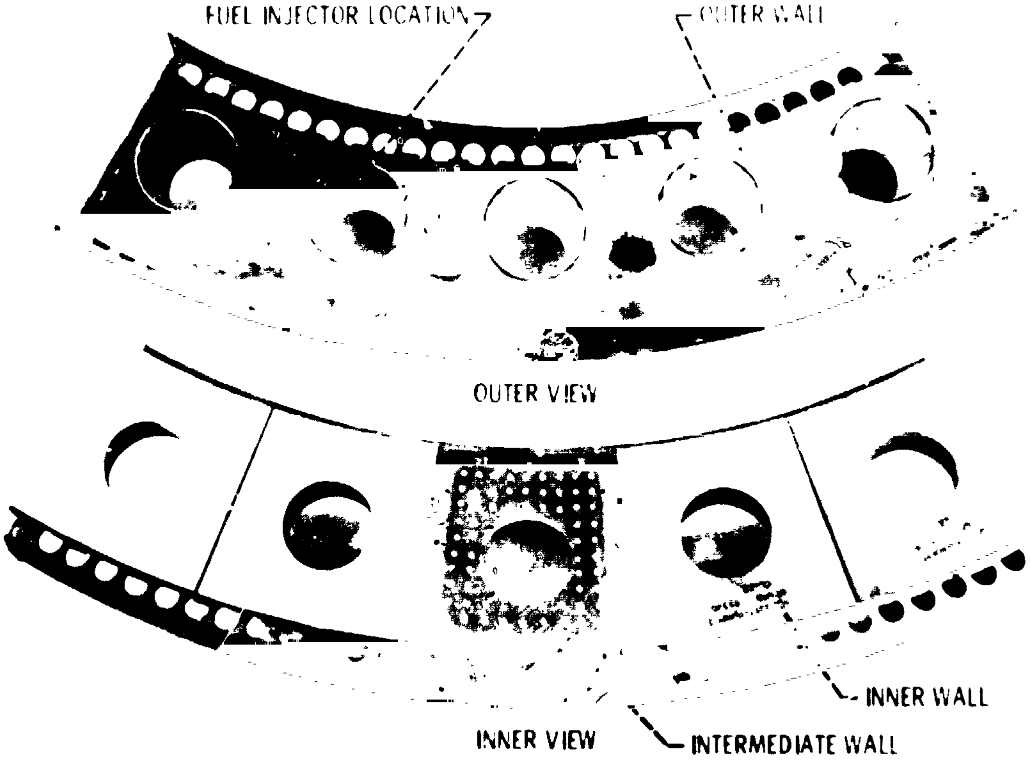


Figure 3c. - Combustor dome, showing triple wall construction.

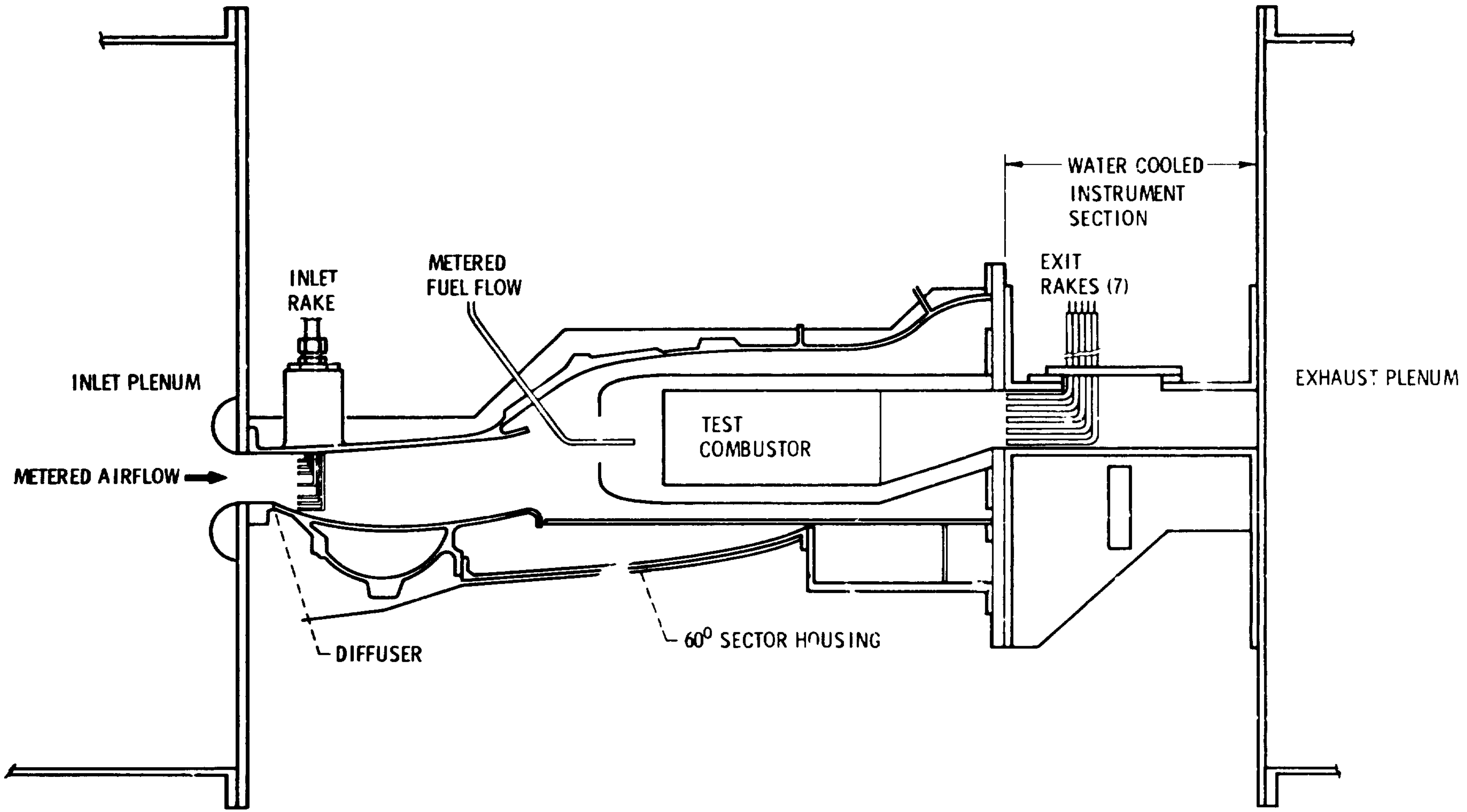


Figure 4. - Combustor test rig assembly.

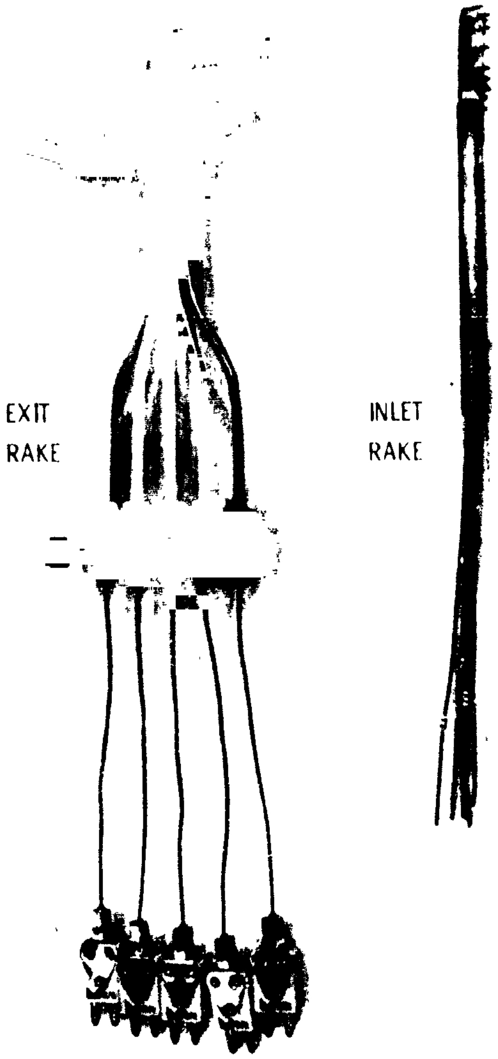


Figure 5. - Typical combustor exit rake (thermocouple/pressure/gas sample) and inlet rake (thermocouple/pressure).

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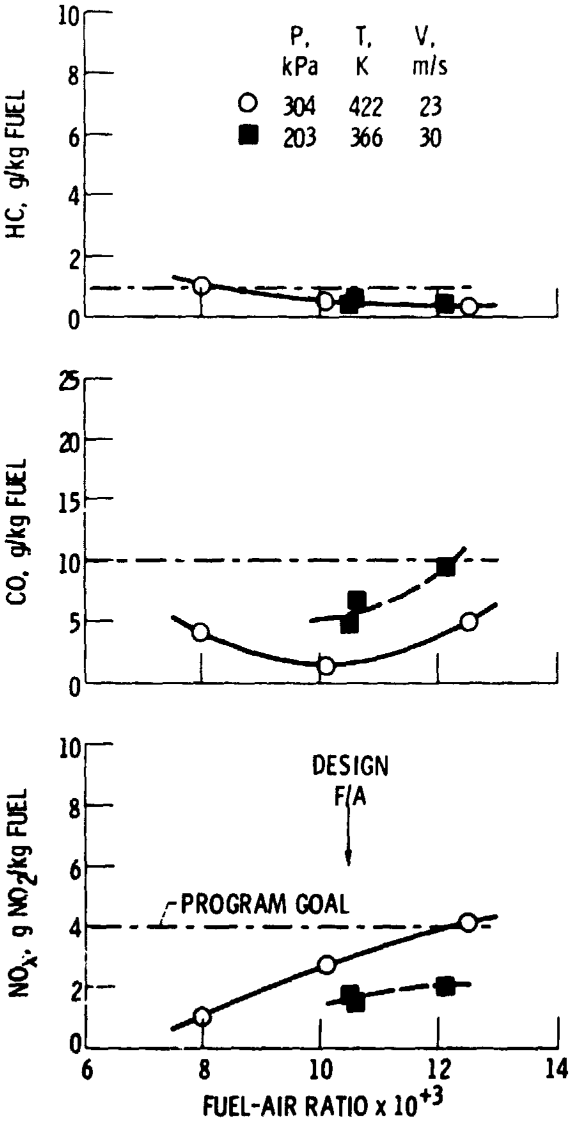

Figure 6. - Pollutant emissions from hot-wall combustor (H4).

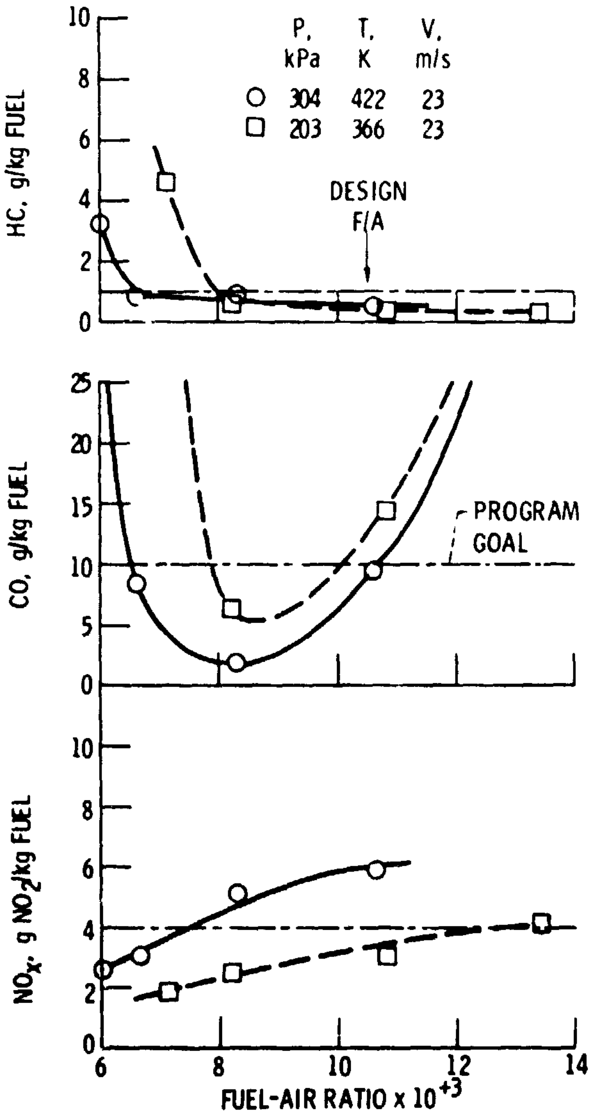

Figure 7. - Pollutant emissions from recuperative cooling combustor (R7).

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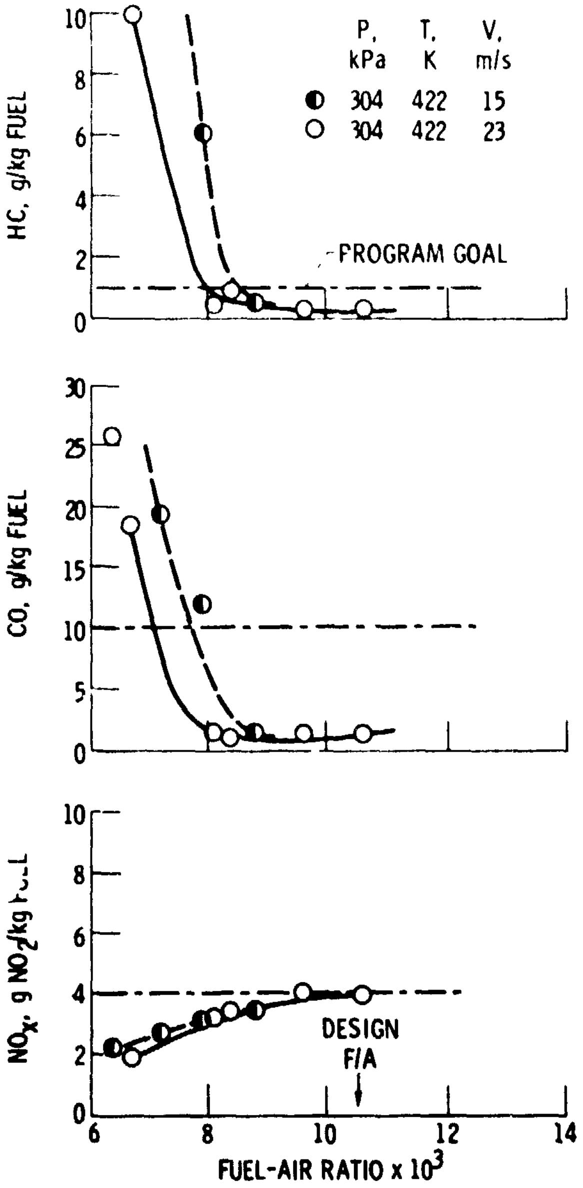
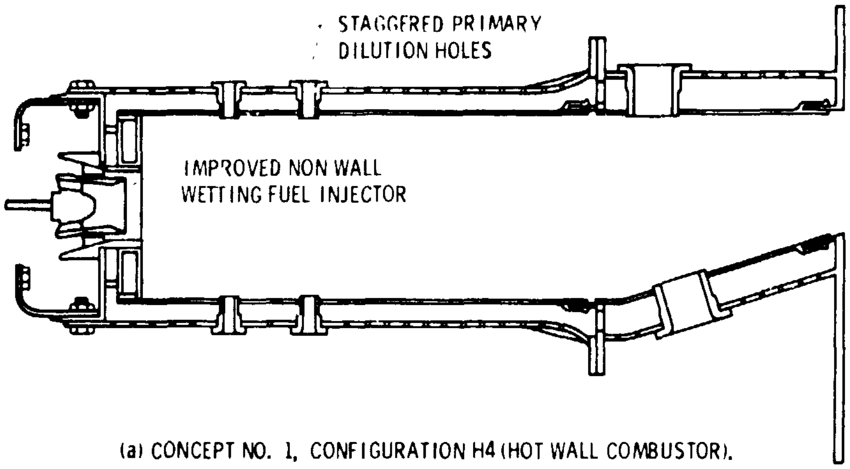
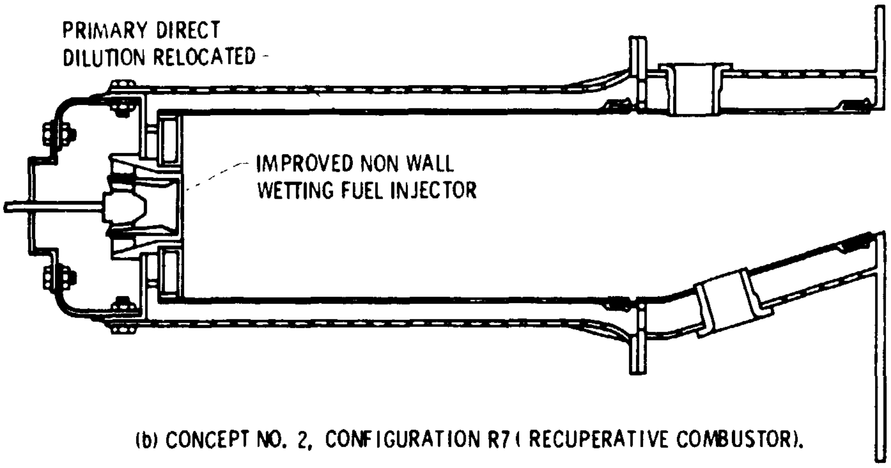


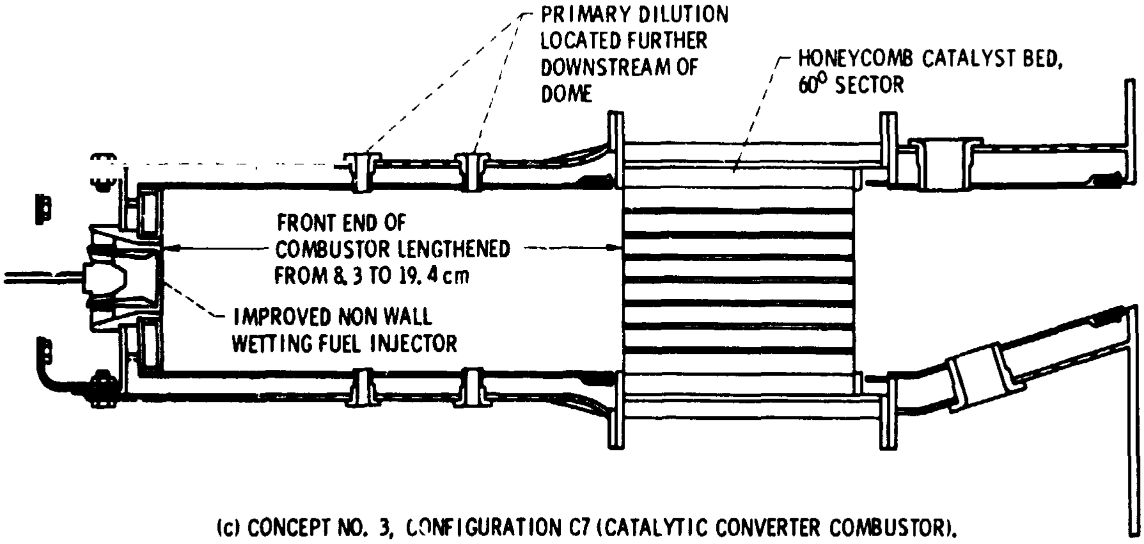
Figure 8. - Pollutant emissions from catalytic converter combustor (C7).



(a) CONCEPT NO. 1, CONFIGURATION H4 (HOT WALL COMBUSTOR).



(b) CONCEPT NO. 2, CONFIGURATION R7 (RECUPERATIVE COMBUSTOR).



(c) CONCEPT NO. 3, CONFIGURATION C7 (CATALYTIC CONVERTER COMBUSTOR).

Figure 9. - Final configuration of each combustor concept exhibiting best emissions results.

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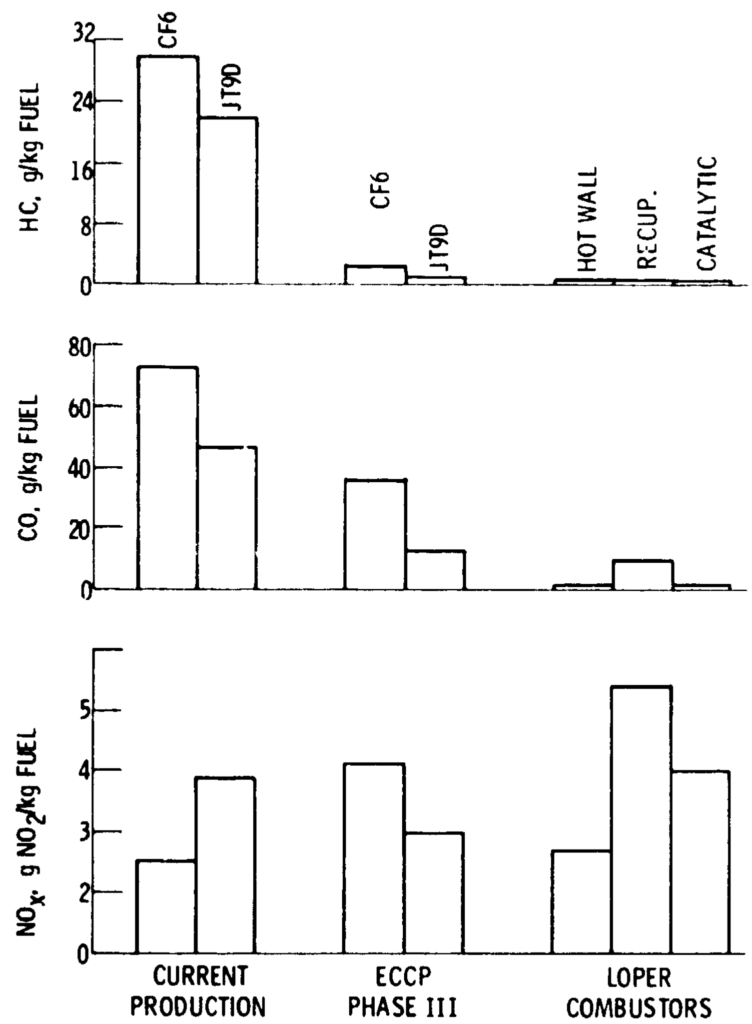

Figure 10. - Comparison of idle emissions of current production engines and Experimental Clean Combustor Program engines with combustor rig emissions of LOPER combustors at nominal idle design condition: 304 kPa, 422 K, $V_{REF} = 23$ m/sec, fuel-air ratio = 0.0105.