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AIRCRAFT ENGINE POLLUTION REDUCTION

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Abstract

The effect of engine operation on the types and levels of the major aircraft engine pollutants is described and the major factors governing the formation of these pollutants during the burning of hydrocarbon fuel are discussed. Methods which are being explored to reduce these pollutants are discussed and their application to several experimental research programs are pointed out. Results showing significant reductions in the levels of carbon monoxide, unburned hydrocarbons, and oxides of nitrogen obtained from experimental combustion research programs are presented and discussed to point out potential application to aircraft engines. An experimental program designed to develop and demonstrate these and other advanced, low pollution combustor design methods is described. Results that have been obtained to date indicate considerable promise for reducing advanced engine exhaust pollutants to levels significantly below current engines.

Introduction

The understanding and reduction of aircraft engine pollution is being pursued through research and development aimed at the pollution source; the engine combustor. This paper describes some of the current efforts underway which are showing promise in understanding and reducing pollution formed during the burning of hydrocarbon fuels and a planned program for demonstrating some promising reduced pollution combustor designs in an engine environment.

As air traffic increases, the pollutants being emitted by aircraft engines will have an increasing influence on the air quality in both the vicinity of airports and in the upper atmosphere. The discharge of carbon monoxide (CO) and unburned hydrocarbons (HC) during idle and taxi operation and the discharge of the oxides of nitrogen (NO_x) and smoke at takeoff is a source of concern regarding air quality in the vicinity of airports. The discharge of these pollutants, in particular the oxides of nitrogen, into the upper atmosphere during aircraft cruise operation may also have a long term effect on global air quality. References 1 and 2 describe some of the current trends in air quality as affected by aircraft. Since the combustor is the source of these pollutants, extensive studies are underway to evaluate the causes and mechanisms involved in the formation of the pollutants. The effect of engine operating variables on the type and level of pollutant emissions was described in reference 3 through 5. The findings of these and other studies are just a partial description of the overall effort which is underway by both the government and the aircraft engine industry to evaluate the effects of aircraft engine pollution and to reduce the aircraft's detrimental contribution to air quality.

The NASA-Lewis Research Center, is actively involved in combustion research for aircraft engines. A significant part of this effort is directed toward the reduction of aircraft engine exhaust pollution. Experimental as well as analytical techniques are being employed to investigate the mechanisms involved in the formation of the various pollutants and to evaluate the effects of combustor design approaches on reducing these pollutants. Both small rig and full-scale annular combustor experiments are being employed in these studies. This paper summarizes some of the results of these studies including a description of the causes of the major pollutants, methods being investigated for reducing these pollutants, several promising experimental combustor design techniques for reducing pollutants and a planned program for demonstrating combustor technology for reducing pollution for advanced aircraft jet engines.

Jet Aircraft Pollution Characteristics

Both the character and level of engine exhaust emissions are governed to some extent by the mode of engine operation. Certain engine operating conditions tend to promote or reduce the levels of the various major pollutants being discharged. These effects are illustrated in Figure 1, where the variation in the three major gaseous pollutants resulting from burning hydrocarbon fuels is plotted as a function of engine power setting. The particular values shown on this figure are for a low pressure ratio engine (similar to those used in Boeing 707 and Douglas DC-8 type aircraft). The characteristic shape of the variations with power setting are similar for all current jet aircraft engines although the levels may vary considerably. The levels of pollutants are described in terms of an emission index which is defined as the ratio of grams of pollutant formed per kilogram of fuel burned. This index will be used to describe pollution levels throughout this paper. The levels of carbon monoxide (CO) and hydrocarbon (HC) emissions are greatest at low power or idle conditions which is representative of most ground type operation whereas the oxides of nitrogen (NO_x) are predominant at the high power or takeoff conditions. Although smoke is not shown on this figure, it is principally a high power or takeoff related pollutant.

Causes of the Major Pollutants

Although the pollutants can be described in terms of engine operation, the source of the pollution is, of course, the combustion chamber or combustor. A typical conventional type aircraft engine combustor is illustrated in Figure 2. It is composed of three basic zones; (1) a diffuser which decelerates the air discharging from the compressor to the low velocities necessary for good combustion, (2) a primary zone where fuel is mixed with a portion of the air and where the primary combustion process takes place, and (3) a secondary zone where diluent air is mixed with the primary gases to cool these gases to acceptable levels for entering the turbine and to control the temperature distribution to avoid excessive hot spots. Fuel is generally injected into the primary zone using pressure-atomizing-type nozzles. Even though the combustor can be considered as a separate engine component, its inlet and outlet conditions are governed by engine cycle requirements. The pressure and temperature of the air entering the combustor are functions of the compressor pressure ratio. As engine pressure ratio is increased, both the pressure and temperature (due to heat of compression) of the air entering the combustor are increased. Turbine inlet temperature requirements establish the combustor outlet temperature, thus setting the combustor temperature rise or fuel-air ratio requirements for various engine operating conditions.

The primary zone of the combustor is where the principle combustion processes are initiated. Hot gases are recirculated into this zone to mix with the fuel and "fresh" air to maintain the combustion process. Combustion in this zone should occur at a fuel-air ratio which is near "stoichiometric" in order to produce high temperatures for good efficiency. Theoretically, the highest flame temperature occurs at near "stoichiometric" which is defined as the exact mixture of fuel and air required for complete chemical combination of the reactants. Also, the residence (dwell) time of the fuel-air mixture in the hot primary zone should be long enough to permit the completion of chemical reactions which is also necessary for good efficiency. Since operating at near stoichiometric fuel-air ratios in the primary zone is desirable, increases in combustor inlet temperature (increasing compressor pressure ratio) will proportionately increase the flame temperature.

The oxides of nitrogen (NO_x) are formed when free nitrogen and oxygen not consumed in the combustion process react with each other. The rate at which this reaction occurs, increases with increasing temperature; thus flame temperature becomes an important variable in the formation of oxides of nitrogen in the primary combustion zone. Fortunately the reaction proceeds slowly, therefore, reducing the dwell time in the high temperature zone is helpful in reducing the amount of oxides of nitrogen formed. Unburned hydrocarbon (HC) emissions are the result of unreacted fuel passing through the combustion process due to poor mixing of fuel and air or lack of reaction time. Carbon monoxide (CO) emissions are the result of not allowing sufficient reaction time for the conversion of carbon monoxide to carbon dioxide in the combustion process. Both of these latter two processes are related to combustion efficiency. Smoke emissions are the result of carbon particles, formed by fuel-rich combustion, that are not consumed in the hot combustion zone. These major pollutant emissions including the corresponding engine operating conditions, and major causes are summarized in Figure 3. Most of the new high pressure ratio engines are low in smoke emissions (below the visibility level) and other engines (JT8D's) are being retrofitted with low smoke combustors. Because of these advances in smoke abatement, this paper will concentrate on the gaseous emission reduction technology only.

The variation in hydrocarbon (HC) and carbon monoxide (CO) emissions with combustion efficiency is shown in Figure 4 (reference 6). The curves shown on this figure represent an average variation of a band of results and are used only to illustrate the trends and not necessarily absolute values. Significant decreases in the emission index of these pollutants are indicated with increasing combustion efficiency. For example, improving efficiency from 94 percent to near 97 percent (typical high pressure ratio engine idle efficiency) would indicate a reduction in hydrocarbons emissions of approximately 75 percent and carbon monoxide by approximately 30 percent. Further increases in efficiency of up to 99 percent or higher at idle operating conditions may be possible with advanced combustor designs indicating further reductions in these two pollutants are possible.

As mentioned previously, the oxides of nitrogen (NO_x) increase with compressor pressure ratio. This effect is illustrated in Figure 5. The emission index is expressed in terms of nitrogen dioxide (NO_2) even though most of the engine effluent is nitric oxide (NO). This is done because all of the nitric oxide eventually combines with oxygen to form nitrogen dioxide as the jet disperses in the atmosphere. As a point of reference the current conventional aircraft jet engines fall in the 10-15 pressure ratio range at takeoff and the engines for the wide body aircraft are in the 20 - 25 pressure ratio range. Advanced future aircraft may use engines with takeoff pressure ratios of 30 or higher. This trend toward higher pressure ratios will increase the combustor inlet temperature that has to be coped with in controlling oxides of nitrogen emissions. Also as higher takeoff pressure ratios are realized, cruise pressure ratios may become high enough to produce significant levels of oxides of nitrogen being discharged into the upper atmosphere.

The foregoing characteristics indicate that advanced technology must be generated to improve the engine pollutant emission levels at both low and high power operating conditions. The trend toward higher pressure ratio advanced engines will emphasize the importance of generating techniques for reducing the oxides of nitrogen. Techniques for reducing hydrocarbons and carbon monoxide are also necessary for these type of engines as well as for current and future low pressure ratio engines with primary emphasis on increase idle combustion efficiency.

Methods for Reducing Pollutants

The main techniques under investigation for reducing aircraft engine pollutants are listed in figures 6 and 7. The benefits to be gained by utilizing these techniques are currently under study by both Government agencies and the aircraft industry.

For reducing hydrocarbons and carbon monoxide, four techniques are currently under investigation. Both the air-assist fuel injection and improved fuel injector techniques are aimed at improving the atomization of fuel in the primary zone. Improving atomization improves combustion efficiency by reducing the amount of unreacted fuel in the primary zone thereby increasing combustion temperature, reducing unburned hydrocarbons, and also decreasing carbon monoxide. These two techniques are capable of possible retrofit in current engines but certainly would require development to insure that engine operational and performance constraints are satisfied. Both fuel staging (supplying fuel to only a few of the injectors) and airflow distribution control techniques are aimed at increasing the local fuel-air ratio thereby increasing local combustion temperature and improving combustion efficiency to reduce unburned hydrocarbons and carbon monoxide. These two techniques would be most applicable to new, advanced type engines because they would most likely require appreciable combustor design changes. Examples of pollutant reductions obtained with air-assist fuel injection and fuel staging will be shown subsequently.

The only technique that is capable of reducing the oxides of nitrogen without an appreciable combustion redesign is the use of water injection. Water injected into the primary zone mixes with the fuel and the air and acts as an inert fluid which replaces otherwise excess air during the combustion process. This presence of an inert fluid reduces the nitrogen and oxygen which is available for reacting thereby reducing the amount of oxides of nitrogen formed. This is an attractive technique that can be implemented without major combustor changes and also provides the added benefit of thrust augmentation. It can reduce the oxides of nitrogen by up to a factor of four when the water flow equals the fuel flow. The disadvantages of water injection are apparent: (1) it adds takeoff weight to the aircraft thereby reducing payload; (2) it can have an adverse effect on combustor life; (3) it is only a solution at takeoff because of the payload penalty, hence does not help for the cruise situation; and (4) it adds mechanical complexity to the engine and aircraft.

The other three items listed for reducing the oxides of nitrogen all require significant changes in combustor design. Reduced dwell-time can be accomplished by either shortening the combustor length, increasing the air velocity through the combustor, or using small burning zones. Reducing dwell time reduces the overall oxides of nitrogen formed during combustion as previously described.

Effective fuel prevaporization and fuel-air premixing would allow combustion in the primary zone to be accomplished at fuel-air ratios less than stoichiometric. This would reduce the flame temperature thereby reducing the formation rate of the oxides of nitrogen. These two techniques will require considerable development before use in an operational engine combustor. An example of an experimental combustor which utilizes some of these techniques will be discussed subsequently.

Selected Research Results

It is certainly not within the scope of this paper to cover all of the current research being directed toward the reduction of jet aircraft engine pollution. Considerable effort and accomplishment is being expended by both government and industry. The results presented herein will represent only a small, selected portion of the techniques being investigated at the NASA-Lewis Research Center and are experimental in nature. Considerable development effort will be required to apply these techniques to actual engine usage.

The results of one of the attractive minor modification type techniques which improves fuel atomization is shown in Figure 8. This figure illustrates the reductions in hydrocarbons and carbon monoxide that were obtained by using air-assist fuel injection in a dual-orifice nozzle, in a single J-57 engine combustor-can at simulated engine idle conditions. Increases in atomizer air pressure (delta p) represent increases in the air through one orifice of the fuel nozzle. Fuel is supplied through the other orifice. The addition of air through the nozzle improved fuel atomization with the main effect being a dramatic improvement in combustion efficiency. Attendant reductions of approximately 80 percent in hydrocarbons and 30 percent in carbon monoxide emission index levels were realized. More details on this technique, including a description of the nozzle configuration, are given in Reference 7.

An experimental combustor currently under test at the Lewis Research Center is shown schematically in figure 9 and a photograph is shown in figure 10. This combustor design embodies many of the features that are attractive for reducing exhaust pollutants. It has many (120) fuel injection inlets arranged in three concentric rows thereby allowing for effective fuel staging (using only a few of the available fuel injectors), it provides some premixing of the fuel and air, it has many small recirculation zones thus reducing dwell-time (the time that reactions between nitrogen and oxygen can occur to form oxides of nitrogen), and it avoids fuel-rich regions. Each of the fuel injectors is a small modular combustor consisting of a carburetor for premixing the fuel and air, a swirler to further mix the fuel and air and to impart a swirl to the mixture, and a flame stabilizer to provide a recirculation zone. Air flows through and around each of the modules providing the oxygen necessary for the combustion reaction in the module wake, and dilution to provide the desired turbine inlet temperature distribution. More details on the operation and performance of this combustor are given in Reference 8.

The effect of supplying fuel to the inner row of modules (fuel staging) is illustrated in Figure 11. The variation in efficiency with overall fuel air ratio is shown for the case of all modules supplied with fuel and only the inner row supplied with fuel, at a typical engine idle pressure and temperature condition. At a representative idle fuel-air ratio of 0.010, the efficiency was improved from approximately 50 percent to nearly 100 percent. The resultant hydrocarbon and carbon monoxide emissions were reduced by more than an order of magnitude. The very low efficiency with all modules fired would not be acceptable for an engine application; therefore, the magnitude of the pollutant reduction would not be this dramatic in an actual engine adaptation of fuel staging. However, the trend would be similar. The reasons for this improvement is that the fuel flow to the inner row of modules is increased, for a given overall fuel flow, thereby producing a more optimum local fuel-air ratio for better combustion efficiency. Reference 9 gives further details of this study and the subsequent discussion.

As previously mentioned, increasing flame temperatures, resulting from increasing combustor inlet temperature as engine pressure ratio goes up, produces higher emission levels for the oxides of nitrogen. This effect is illustrated in Figure 12 for a variety of current production engines and for the experimental swirl-can-modular combustor. The curve marked for the production engines represents a nominal characteristic drawn through data points of many engines operating at takeoff conditions. It does not represent one engine operating at a varying pressure ratio. For comparative purposes, the upper limit of the production engine curve represents an engine with a 25:1 pressure ratio whereas an engine with a pressure ratio of 13:1 would correspond to an inlet temperature of approximately 600°F. The swirl-can-modular combustor was run at the correct inlet temperature for direct comparison but not at the correct pressure. The effect of pressure on the formation of oxides of nitrogen, theoretically increases the kinetic reaction rate, could raise the values of the swirl-can modular results by up to a factor of 2. Even with this pessimistic correction, the swirl-can-modular combustor appears to be capable of significantly reducing the oxides of nitrogen compared to current production type combustors. Considerable development effort will be required, however, to adapt this unconventional design to actual engine application.

Clean Combustor Program

A program is being initiated by Lewis Research Center which will evaluate the ability of the NASA swirl-can modular combustor and several other unconventional contractor combustor designs to produce low exhaust pollutants as well as maintain the other performance parameters required for engine application. This program will be conducted under contract with several current high pressure ratio engine manufacturing companies. The applications, goals, and constraints of this program are listed in Figure 13. The main objective of the program is to develop and demonstrate the combustor technology to reduce exhaust pollutants for advanced jet aircraft engines. The high bypass ratio, high pressure ratio engine cycle is the prime concern of this program. The program emission goals are significantly lower than current levels of representative engines (JT9D's and CF6's) as illustrated on this figure. Of paramount importance in the program will be determining the necessary tradeoffs that may be required in emission performance in order to maintain altitude relight capability as well as good turbine inlet temperature distribution. The program will be conducted in three phases; (1) an initial series of screening tests where emission performance will be concentrated on; (2) a second series of tests where engine performance and durability considerations will be considered; and (3) the actual demonstration of the best designs in a high pressure ratio engine. The program is expected to encompass about a three-year period.

Concluding Remarks

The composition and the level of the major jet aircraft engine exhaust pollutants formed during the combustion of hydrocarbon fuel were pointed out to be unburned hydrocarbons, carbon monoxide, oxides of nitrogen and smoke. The level of these constituents varies as a function of engine operation and design pressure ratio. The trend toward higher engine pressure ratio for advanced jet aircraft will increase the importance of developing technology to cope with reducing the oxides of nitrogen formed during the combustion process. Developing technology to reduce hydrocarbons, carbon monoxide and smoke is also necessary for these advanced engines as well as for current engines. Encouraging results in reducing all forms of major jet aircraft engine exhaust pollutants have been obtained in experimental research programs and continued research will be conducted to explore all the known techniques for reducing pollutants. A main element that is needed, is to adapt the experimental concepts to actual engine constraints to determine what tradeoffs may be necessary to produce feasible low pollution combustors. The NASA - Lewis Research Center's "Clean Combustor Program" has this latter objective as its goal.

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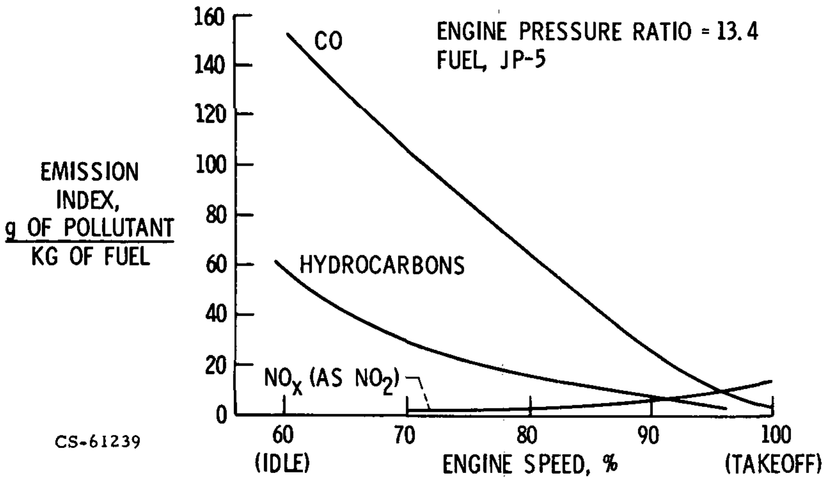


Figure 1. - Typical engine exhaust emission characteristics.

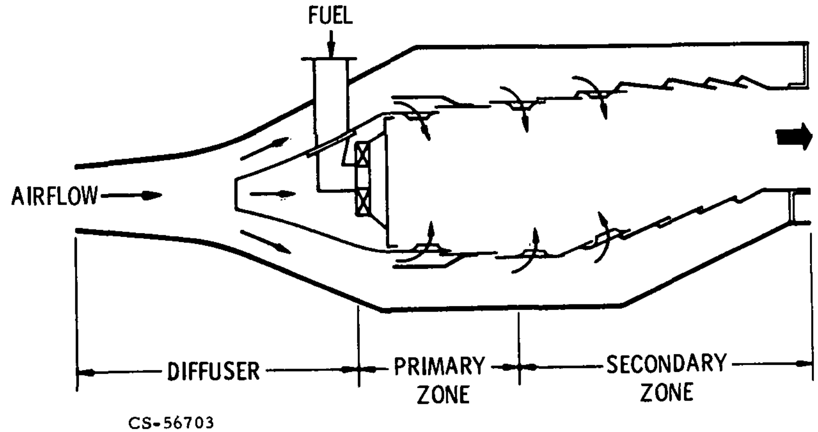


Figure 2. - Conventional annular combustor.

POLLUTANT	CAUSE	WHEN ENCOUNTERED
CO	INEFFICIENT COMBUSTION	ENGINE IDLE
HC		
NO_X	HIGH FLAME TEMP & LONG DWELL TIME	TAKEOFF
SMOKE	FUEL-RICH COMBUSTION	

CS-61107

Figure 3. - Major jet aircraft pollutants.

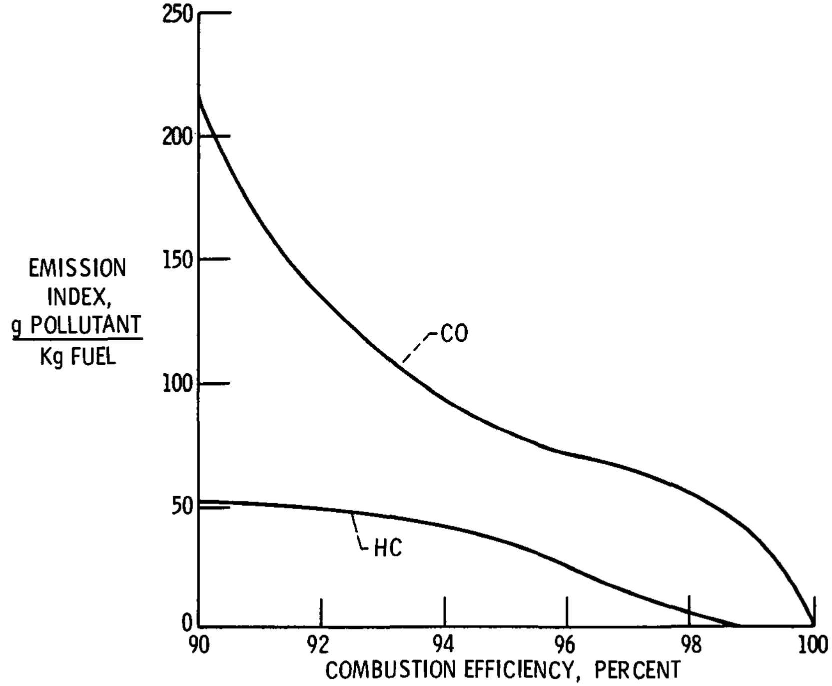


Figure 4. - Effect of combustion efficiency on pollutant levels of carbon monoxide and hydrocarbons.

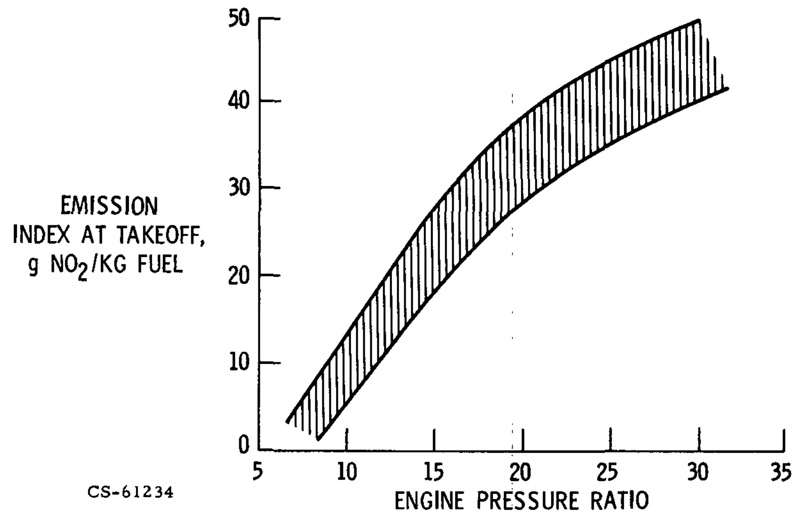


Figure 5. - Effect of engine pressure ratio on the emission of the oxides of nitrogen.

POLLUTANT	TECHNIQUES
HYDROCARBONS, CARBON MONOXIDE	AIR-ASSIST FUEL INJECTION IMPROVED FUEL INJECTORS FUEL STAGING AIRFLOW DISTRIBUTION CONTROL

CS-60904

Figure 6. - Methods to reduce idle emissions.

POLLUTANT	TECHNIQUES
OXIDES OF NITROGEN	REDUCED DWELL TIME FUEL PREVAPORIZATION FUEL-AIR PREMIXING WATER INJECTION
SMOKE	IMPROVED FUEL-AIR MIXING AVOID FUEL-RICH REGIONS

CS-60903

Figure 7. - Methods to reduce takeoff emissions.

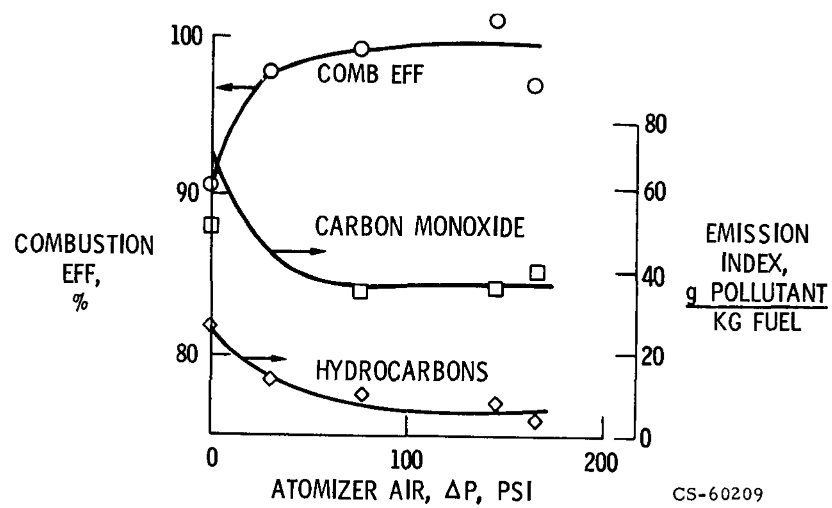
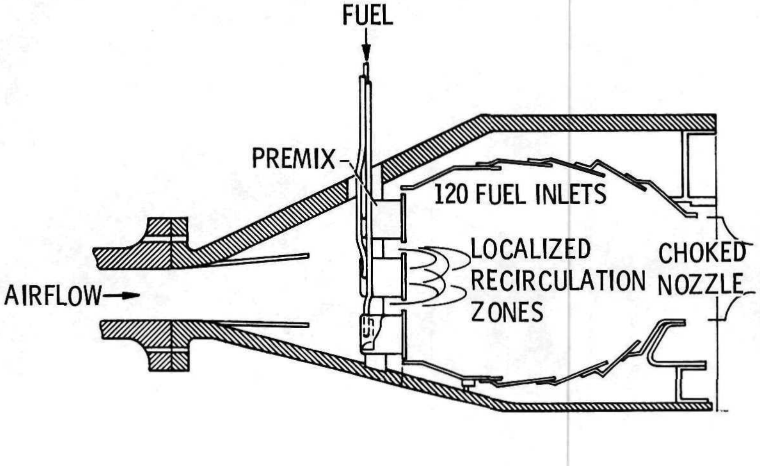
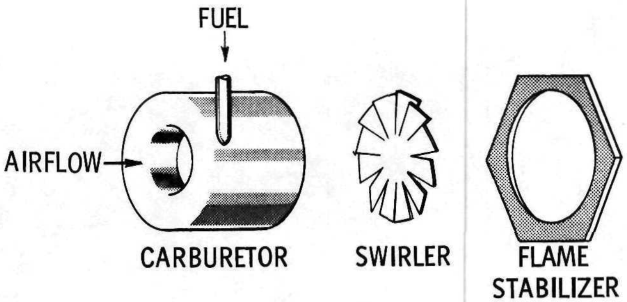


Figure 8. - Reduction in emissions at idle using air-assist fuel nozzle.

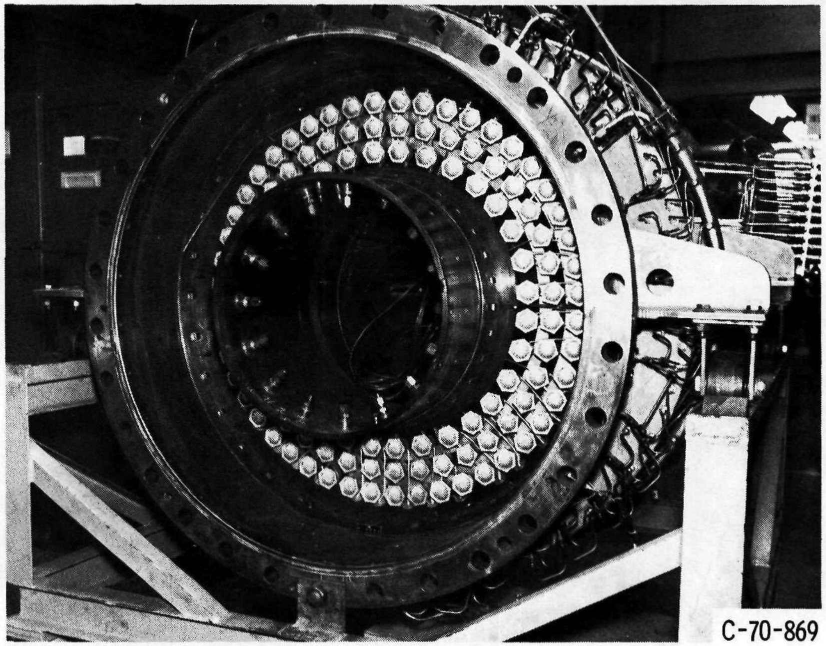


(a) CROSS-SECTIONAL VIEW. CS-56696



(b) MODULE COMPONENTS.

Figure 9. - Experimental modular combustor.



C-70-869

Figure 10. - Annular swirl-can-modular combustor.

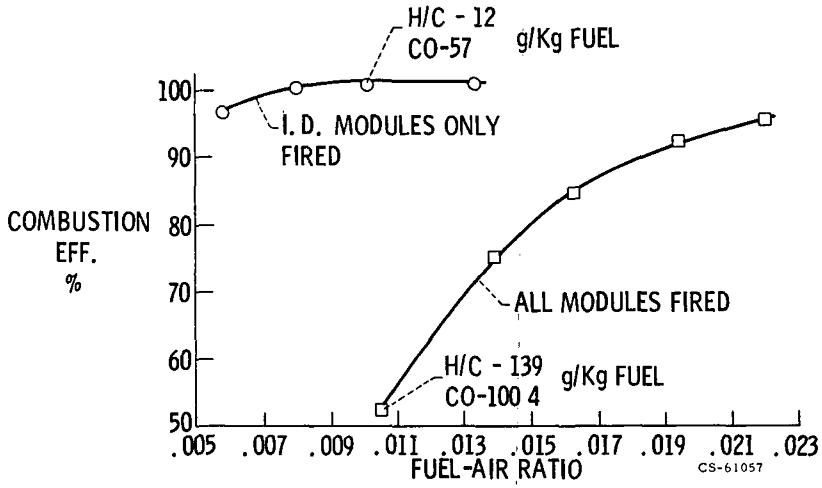


Figure 11. - Effect of fuel staging on idle emissions. Swirl-can-modular combustor.

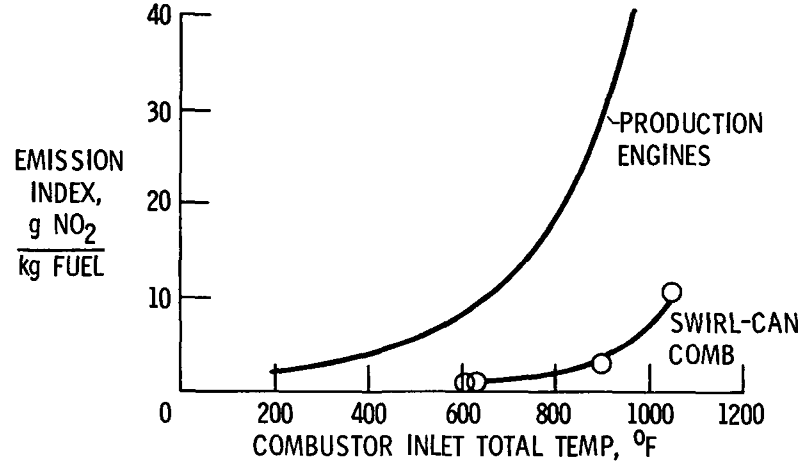


Figure 12. - Effect of inlet total temperature on emission index for oxides of nitrogen.

APPLICATIONS:
- ADVANCED COMMERCIAL CTOL AIRCRAFT WITH ENGINE PR OF 20 TO 35
- MILITARY ENGINES

POLLUTANTS:

	GOALS		CURRENT
NO_2	10	g/Kg FUEL	43
CO	20	g/Kg FUEL	70
HC	4	g/Kg FUEL	20
SMOKE	15	SAE SMOKE NO.	17

CONSTRAINTS:
- ADEQUATE RELIGHT
- PATTERN FACTOR

Figure 13. - Clean combustor program.