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METHODS FOR REDUCING POLLUTANT EMISSIONS FROM JET AIRCRAFT

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ABSTRACT

The purpose of this paper is to define the problem of pollutant emissions from jet aircraft and to review NASA-Lewis combustion research aimed at reducing these emissions. The problem of smoke formation and results achieved in smoke reduction from commercial combustors are discussed. Experimental results of parametric tests performed on both conventional and experimental combustors over a range of combustor-inlet conditions are presented. Combustor design techniques for reducing pollutant emissions are discussed. Improved fuel atomization resulting from the use of air-assist fuel nozzles has brought about significant reductions in hydrocarbon and carbon monoxide emissions at idle. Diffuser tests have shown that the combustor-inlet airflow profile can be controlled through the use of diffuser-wall bleed and that it may thus be possible to reduce emissions by controlling combustor airflow distribution. Emissions of nitric oxide from a short-length annular swirl-can combustor were significantly lower than those from a conventional combustor operating at similar conditions.

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SUMMARY

The purpose of this paper is to define the problem of pollutant emissions from jet aircraft and to review NASA-Lewis combustor research aimed at reducing these emissions. It is shown that pollutant emissions from aircraft are most pronounced in the vicinity of commercial airports. During idling and taxiing, the principal pollutants are unburned hydrocarbons and carbon monoxide while during landing and take-off, the main pollutants are oxides of nitrogen and smoke.

Reductions in smoke levels from commercial engines have been effected through the use of leaner primary zones. In experimental combustors tested at Lewis, low smoke numbers were achieved through improved mixing of fuel and air and through increased primary-zone airflow.

Parametric tests conducted with a single-can J-57 combustor showed that emissions of hydrocarbons and carbon monoxide increased with decreasing combustor-inlet temperature and pressure and with increasing combustor reference velocity. Oxides of nitrogen increased with increasing combustor-inlet temperature and pressure and with decreasing reference velocity. Similar results were obtained from limited tests conducted with an experimental swirl-can combustor.

Tests have shown that significant reductions in hydrocarbon and carbon monoxide emissions can be effected by improving fuel atomization through the use of air-assist fuel nozzles. Additional experimental designs aimed at optimizing local primary-zone fuel-air ratios through diffuser-wall bleed or through the use of staggered fuel nozzles also

suggest that reductions in idle emissions can be realized. Further research is being carried out to determine the effectiveness of the above techniques. Emissions of nitric oxide from a short-length annular combustor featuring partial premixing of fuel and air were shown to be significantly lower than those from a conventional combustor operating at similar conditions.

INTRODUCTION

Products of combustion from all sorts of heat or power generating devices constitute a large source of environmental pollution. Although, at the present time, the contribution of aircraft is small on a nationwide basis, the projected increase in aircraft usage over the next decade and the anticipated reduction in automotive emissions could alter this picture appreciably. On a local basis, the pollutant emissions from jet aircraft are most pronounced in the vicinity of commercial airports (ref. 1) where ambient pollutant concentrations often equal or exceed those in the nearby industrial communities.

The main pollutants from aircraft engines are unburned hydrocarbons, carbon monoxide, oxides of nitrogen, and smoke. Oxides of sulfur are not a major problem because the sulfur content of aircraft fuels is generally quite low. Carbon monoxide is toxic and prolonged exposure to high ambient concentrations could present severe health problems. Unburned hydrocarbons combine with oxides of nitrogen in the presence of sunlight to form photochemical smog which is injurious to plants and human life and can cause severe visibility problems. Aldehydes and other oxidants also contribute to the formation of photochemical smog. Smoke, which consists largely of carbon particles is objectionable from an aesthetic standpoint. In addition to these readily identifiable pollutants the odor of exhaust gas is objectionable to many people.

As previously pointed out, pollutant emissions from jet aircraft are of concern mainly in the vicinity of commercial airports. There is also growing concern over the contribution of high-flying aircraft to pollution of the upper atmosphere and thus on weather patterns; however, the information existing at the present time is too meager to draw any valid conclusions. Research now being planned by NASA and other agencies should shed considerable light on this problem of upper atmospheric pollution.

Exhaust emissions at the airport are mainly a function of the mode of operation of the aircraft (ref. 2), as shown in figure 1. The term emission index, grams of pollutant per kilogram of fuel burned, is used instead of the more familiar volumetric concentration term, parts per million, in order to normalize emissions on the basis of fuel flow. During idling and taxiing, exhaust emissions consist primarily of carbon monoxide and unburned hydrocarbons whereas, during take-off and landing, large amounts of smoke and oxides of nitrogen are formed. During cruise, the only significant pollutants are oxides of nitrogen.

Emissions at idle result from low combustion efficiencies caused by (1) poor fuel atomization at low fuel flow rates, (2) low fuel-air ratios, and (3) low combustor-inlet pressures and temperatures. Formation of oxides of nitrogen is enhanced by the high combustor-inlet temperatures and pressures encountered during take-off and cruise. Smoke, which is most pronounced at take-off and landing, is the result of high combustor-inlet pressures and rich primary-zone fuel-air ratios.

Combustor-inlet parameters such as temperature, pressure and overall fuel-air ratio are fixed by the engine design. Thus the only means readily available to the combustor designer to combat pollutant emissions are the method of fuel atomization, the mixing of fuel and air, and the general geometry of the combustor. The purpose of this paper is to review the progress that has been achieved to date by employing some of these expedients and to discuss the schemes by which additional reductions in pollutant emissions can be brought about.

Smoke

Because smoke plumes from jet aircraft are readily visible, they have become the targets of attack of regulatory agencies, and, as a result, the problem of smoke formation has received a great deal of attention in the past few years. Smoke consists of about 96 percent carbon and is the result of rich fuel-air mixtures in the primary zone of the combustor.

On the test stand, smoke in the exhaust is determined by a stained-filter technique (ref. 3) whereby a metered volume of exhaust gas is passed through a paper filter with resultant deposition of the carbon on the filter paper. The darkness of the stain is a measure of the amount of smoke and is assigned a value called a "smoke number." At the present time no reliable method exists for correlating smoke numbers, as determined on the test stand, with visibility of the smoke plume. Smoke plume visibility depends on many factors such as the size and numbers of exhaust nozzles, background and viewing angle, and wind conditions. However, within these limitations, a rough correlation shown in reference 4 suggests that for small engines a smoke number of 40 represents an approximate visibility threshold while for large engines a smoke number of 25 can be considered the visibility threshold.

Considerable progress in smoke reduction has been made as shown in figure 2. The data shown in the upper band are typical of early combustors which were purposely designed with rich primary zones to improve the altitude relight characteristics of the engine. Lately, Pratt & Whitney has succeeded in reducing the smoke level of the JT8D engine to values below the visibility threshold by leaning out the primary zone. Whenever these engines are scheduled for overhaul, retrofit modifications to reduce smoke are made. Similarly, more recent engines like the JT9D, CF6, and RB 211 have been designed with leaner primary zones in order to reduce smoke formation. As shown in figure 2, these engines have smoke numbers at or below the visibility threshold. The JT8D is the powerplant for the 727, 737, and DC-9 airplanes while the

JT9D and CF6 engines power the 747 and DC-10 airplanes, respectively. Increased primary zone airflow and increased mixing intensity are primarily responsible for the low smoke levels exhibited by the experimental combustors being tested at Lewis. However, these experimental combustors exhibit poor altitude relight characteristics and additional work would be required to improve their relight capabilities.

Hydrocarbons and Carbon Monoxide

As shown in figure 1, the principal contributors toward ground-level pollution at airports are the idling and taxiing modes of operation of the aircraft although other vehicles, such as automobiles and auxiliary units may contribute as much as the aircraft itself. Aircraft combustors are designed for maximum performance at take-off and cruise conditions and operation at off-design points generally results in lower combustion efficiencies and, as a result, in higher pollutant emissions.

To determine the effect of changes in combustor-inlet conditions on pollutant emissions a parametric study was conducted at Lewis with a single-can installation of a J-57 combustor (ref. 4). In general, combustion efficiencies decreased with decreasing pressure and temperature and with increasing velocity. As combustion efficiency decreased, emissions of hydrocarbons and carbon monoxide increased.

The effect of combustor-inlet total pressure on emissions of carbon monoxide and hydrocarbons is shown in figure 3. As pressure decreased below about 4 atmospheres, emissions of carbon monoxide and hydrocarbons increased markedly. Decreases in pressure at constant velocity and temperature are accompanied by corresponding decreases in air and fuel flows and hence low fuel nozzle pressure drops. The resulting poor fuel atomization is considered to be primarily responsible for the large increases in carbon monoxide and hydrocarbon emissions.

The effect of combustor-inlet temperature is shown in figure 4. Both hydrocarbon and carbon monoxide emissions increased with decreasing combustor-inlet temperature. Decreases in temperature decrease the rate of fuel vaporization and the rate of chemical reaction and hence tend to increase emissions of products of incomplete combustion. The effect was most pronounced at the high reference velocity and at low pressures.

The effect of reference velocity on emissions is shown in figure 5. Reference velocity is a yardstick commonly used in combustor design and is defined as the total combustor airflow divided by the product of combustor-inlet density and the maximum cross-sectional area of the combustor. Hydrocarbon emissions reached a minimum at a reference velocity of 75 feet per second while carbon monoxide emissions increased with increasing velocity. The increase in emissions with increasing reference velocity may be attributed to a reduction in flame stability and dwell time. The increase in hydrocarbon emission at the low velocities is probably caused by poor mixing or by poor fuel atomization as the result of reduced fuel nozzle pressure drops.

The results of the parametric tests show that emissions of hydrocarbons and carbon monoxide are greatly affected by changes in combustor-inlet pressure, temperature, velocity, and overall fuel-air ratio. These parameters are generally fixed by the engine design. However, there are some expedients that are available to the combustor designer. It was pointed out earlier that the idling and taxiing modes contribute heavily to the ground-level pollution at airports. Low combustor-inlet temperatures and pressures, lean primary-zone fuel-air ratios, and poor fuel atomization caused by low fuel flows are directly responsible for inefficient combustion at idle conditions.

A number of ways to improve idle efficiencies and hence to reduce pollutant emissions have been suggested. Of these expedients, the use of air-assist fuel nozzles to improve fuel vaporization and fuel-air mixing and the use of diffuser-wall bleed to increase primary-zone fuel-air ratios appear quite promising. Recent combustor tests at Lewis (ref. 5) with air-assist fuel nozzles have shown significant increases in combustion efficiency as shown in figure 6. These tests were conducted with a J-57 single-can combustor using conventional dual-flow nozzles in which the secondary flow passages were supplied with air from an auxiliary compressor to improve fuel atomization. Airflows less than 0.5 percent of the total combustor airflow and differential discharge pressures as low as 4 atmospheres were required for the air assist. With this mode air-assist operation would be employed only at idle and at all other conditions the normal dual-flow operation would be resumed.

Figures 7 and 8 show that the increases in combustion efficiency brought about by the use of air-assist fuel nozzles were accompanied by large reductions in hydrocarbon and carbon monoxide emissions. At a fuel-air ratio of 0.008 hydrocarbon emissions were reduced from 26 to 3 grams per kilogram of fuel while carbon monoxide emissions were reduced only slightly. However, at fuel-air ratios lower than 0.008 the reductions were more pronounced.

It was stated before that increases in primary-zone fuel-air ratios could be effected by diverting a portion of the combustion air away from the primary zone through diffuser wall bleed. A sketch of a typical combustor employing this principle is shown in figure 9. The combustor would be designed with a skewed inlet profile to give a fuel-rich primary zone at idle. Diffuser-wall bleed would then be employed at cruise and take-off to flatten the inlet profile and lean out the primary zone. The bleed air could be used for turbine cooling or other purposes. Diffuser tests conducted at Lewis have shown that the combustor-inlet airflow profile can be controlled through diffuser-wall bleed and arrangements have been made to incorporate this principle into an experimental full-scale annular combustor being tested at Lewis. In addition to decreasing pollutant emissions at idle, this mode of operation could provide the rich primary zones required for good altitude relight capability. Smoke formation at idle is very low, hence enriching the primary zone at idle presents no problem.

Oxides of Nitrogen

Emission of oxides of nitrogen is of primary importance only at take-off conditions. Formation of nitric oxide is the result of high-temperature combustion and reaches a maximum near stoichiometric fuel-air ratios. As a rule, turbojet combustors are designed with primary combustion zones at or near stoichiometric fuel-air ratios to impart maximum stability to the flame. Thus the obvious approach toward reducing NO_x formation would be to operate the combustor with either very rich or very lean primary zones. However, rich primary zones tend to form excessive amounts of carbon monoxide, hydrocarbons, and smoke while lean primary zones present severe combustion stability problems.

Tests were conducted at Lewis with a single-can J-57 combustor installation (ref. 4) to determine the effects of variations in combustor-inlet conditions on NO_x formation. The results are shown in figure 10. Increases in combustor-inlet pressure and temperature increased nitric oxide formation while increases in reference velocity tended to decrease NO_x formation. The effect of combustor-inlet temperature was the most pronounced because of its direct influence on flame temperature.

The formation of nitric oxide is controlled by the kinetics of the reaction and fortunately, the reaction proceeds quite slowly compared to the oxidation of hydrocarbons. Of the combustor-inlet parameters investigated only the reference velocity and possibly the primary-zone fuel-air ratio are within the control of the combustor designer. Because turbojet engines must perform effectively over a wide range of overall fuel-air ratios, control of primary-zone fuel-air ratios requires some sort of mechanical or aerodynamic control which is difficult to achieve. Increases in velocity, which can be brought about by reducing combustor diameter, decrease the dwell time of the reactants in the hot combustion zone and thus, since the reaction is kinetics - controlled, tend to reduce NO_x formation. However, there are practical limitations since increases in velocity tend to increase pressure loss and to enhance formation of unburned hydrocarbons and carbon monoxide.

Another way to decrease residence time is to shorten the combustor length. Tests have been conducted at Lewis with an experimental full-scale combustor designed for operation at combustor-exit temperatures as high as 3500° F. This combustor is about 30 percent shorter than conventional combustors and is made up of 120 discrete combustor elements featuring partial premixing of fuel and air. Results of comparison tests (ref. 6) with a J-57 single-can combustor, presented in figure 11, show that even at the more severe operating conditions NO_x emissions from the short-length experimental Lewis combustor were considerably lower than those from the J-57 combustor.

Another possible approach to nitric oxide reduction is the use of water injection to reduce flame temperature. However, this expedient would present a severe logistics problem. Research to determine the effectiveness of water injection is being considered at the present time.

Odors

Another pollution problem which is receiving attention is the odor of aircraft engine exhaust gases. Considerable work on exhaust from automotive Diesel engines has been done in the past and some progress toward identifying the mal-odorous chemical species has been made. Although some sophisticated analytical chemical methods have been developed, the principal method of rating the intensity of odors has been through the use of human panels trained to detect odor intensities by sniffing diluted exhaust gases. A program is being initiated at Lewis to study the odor characteristics of jet engine exhaust gases under various operating conditions. The method of approach will be patterned after the Diesel odor projects and it is hoped that the experience gained in the Diesel field will be applicable to the odor problem of jet engine exhaust.

CONCLUDING REMARKS

In summary it has been shown that the major contribution of jet aircraft to atmospheric pollution occurs in the vicinity of commercial airports. The principal offenders are the idling and taxiing modes which contribute large amounts of unburned hydrocarbons and carbon monoxide while landing and take-off are primarily responsible for emissions of smoke and oxides of nitrogen. Results obtained so far indicate that improvements can be made. Reductions in smoke levels from commercial engines have already been accomplished through the use of leaner primary zones. In tests conducted at Lewis substantial reductions in hydrocarbon and carbon monoxide emissions have been realized through the use of air-assist fuel nozzles. Over a wide range of operating conditions emissions of oxides of nitrogen from the short-length experimental Lewis combustor were substantially lower than those from a longer-length production-model combustor.

However, despite the fact that improvements have been made, it must be remembered that the gains were often made at the expense of some other performance parameter and that trade-offs are generally necessary to achieve the desired goals.

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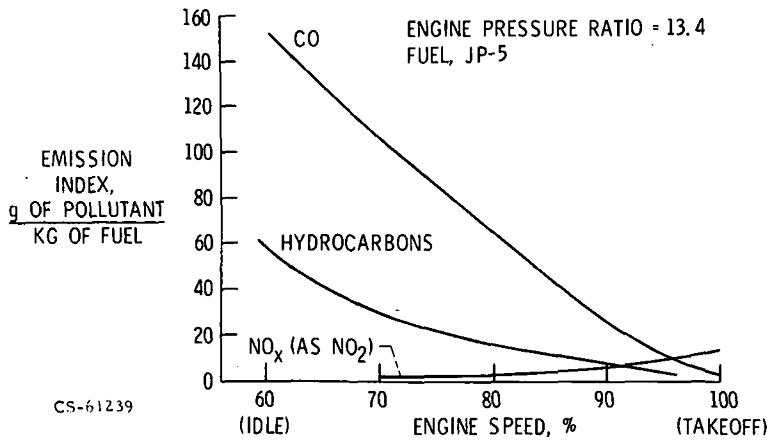

Figure 1. - Typical engine exhaust emission characteristics.

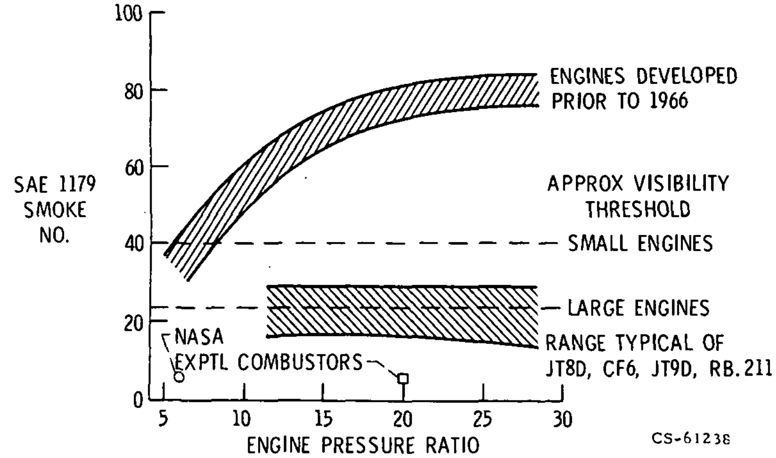

Figure 2. - Comparison of peak engine smoke emission characteristics.

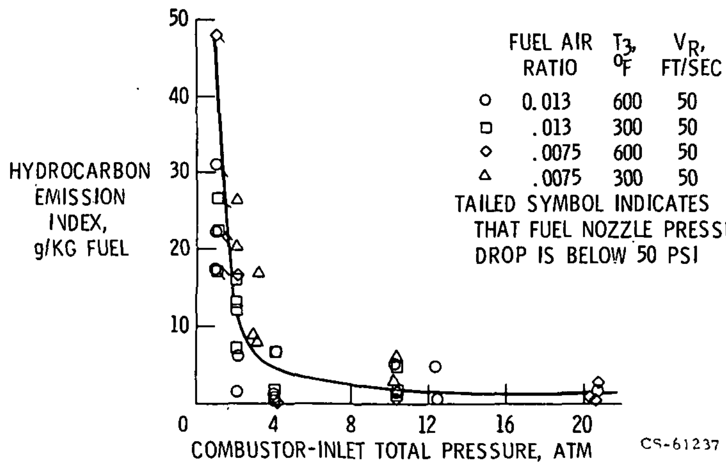

Figure 3(a). - Effect of combustor-inlet total pressure on hydrocarbon emissions of J57 combustor.

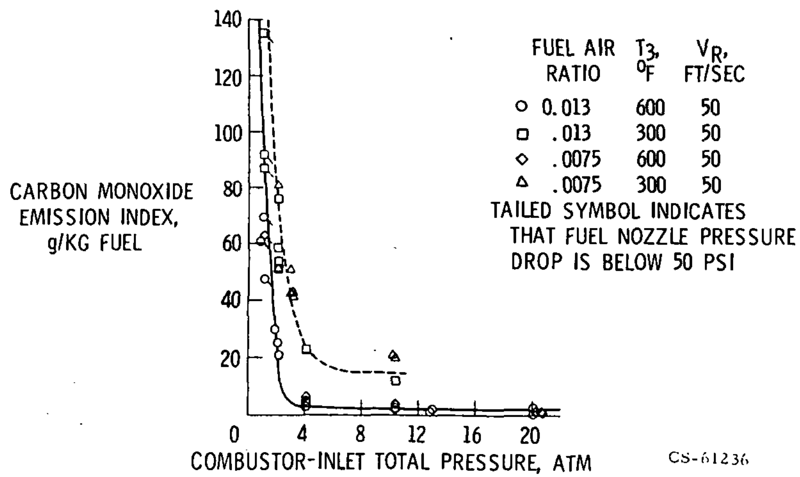

Figure 3(b). - Effect of combustor-inlet total pressure on carbon monoxide emissions of J57 combustor.

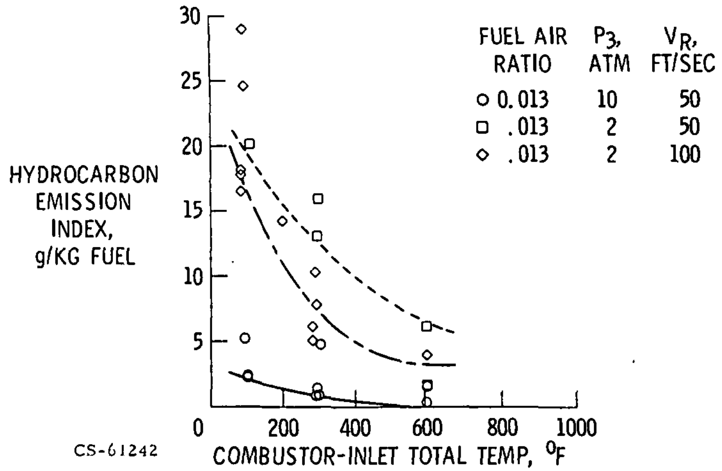

Figure 4(a). - Effect of combustor-inlet total temperature on hydrocarbon emissions of J57 combustor.

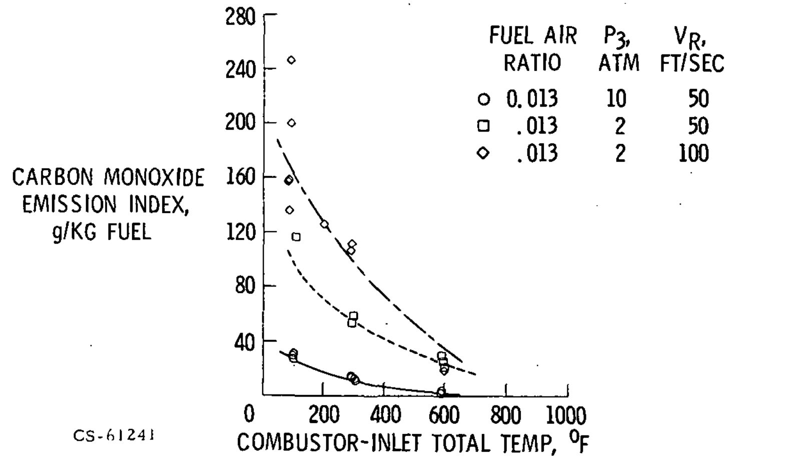

Figure 4(b). - Effect of combustor-inlet total temperature on carbon monoxide emissions of J57 combustor.

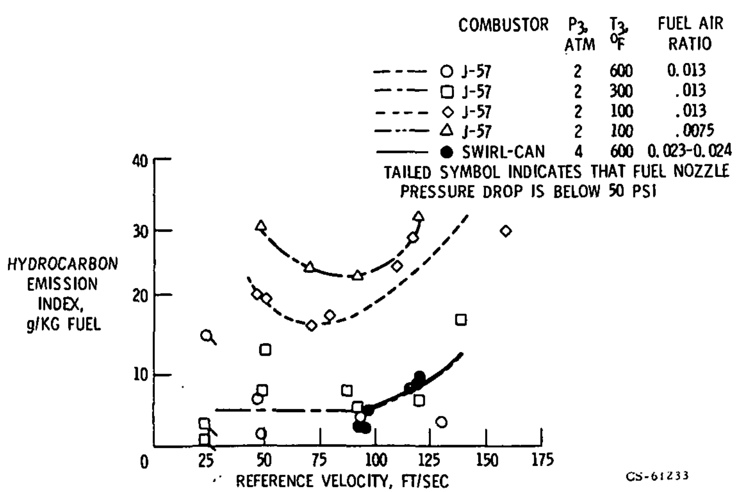

Figure 5(a). - Effect of reference velocity on hydrocarbon emissions of J57 combustor.

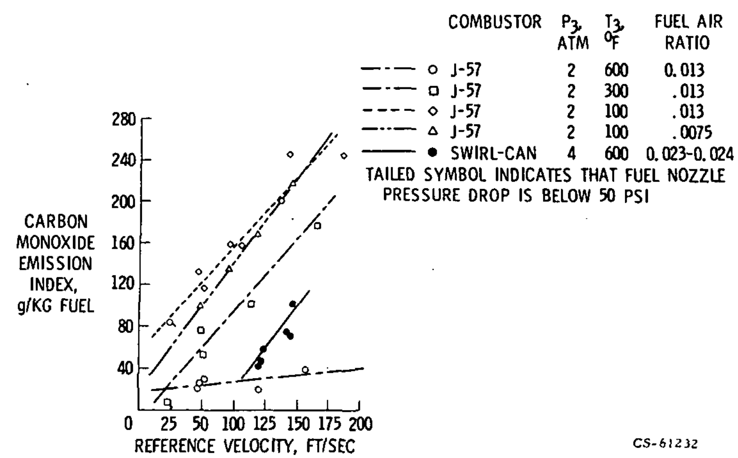

Figure 5(b). - Effect of reference velocity on carbon monoxide emissions of J57 combustor.

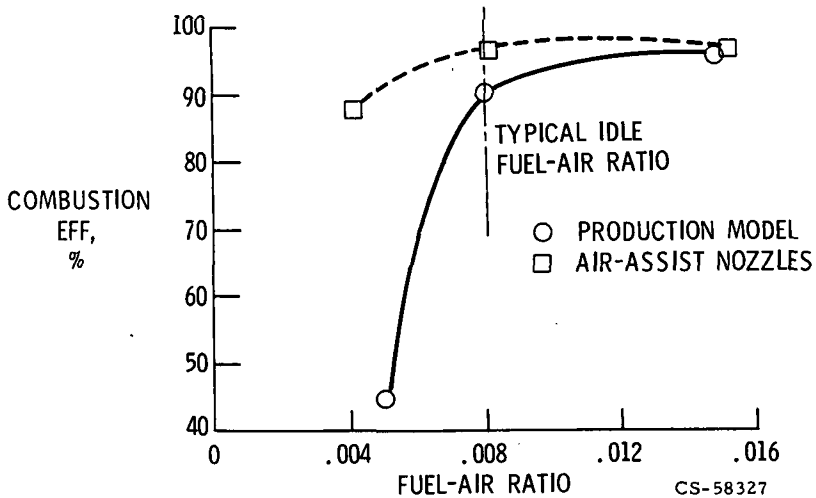

Figure 6. - Effect of air-assist nozzles on combustion efficiency of J57 combustor.

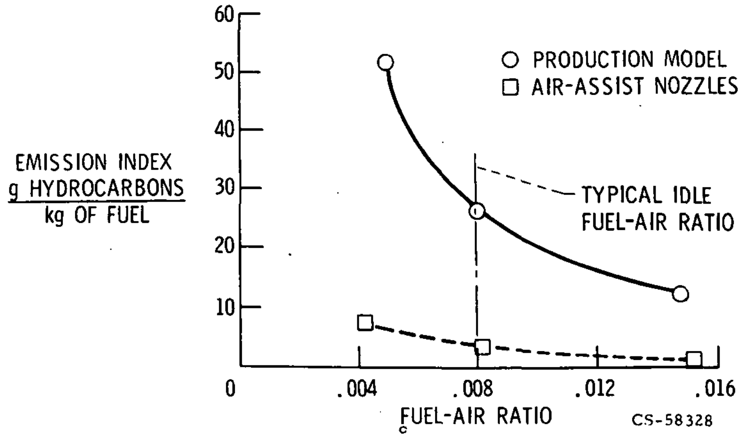

Figure 7. - Effect of air-assist nozzles on hydrocarbon emissions of J57 combustor.

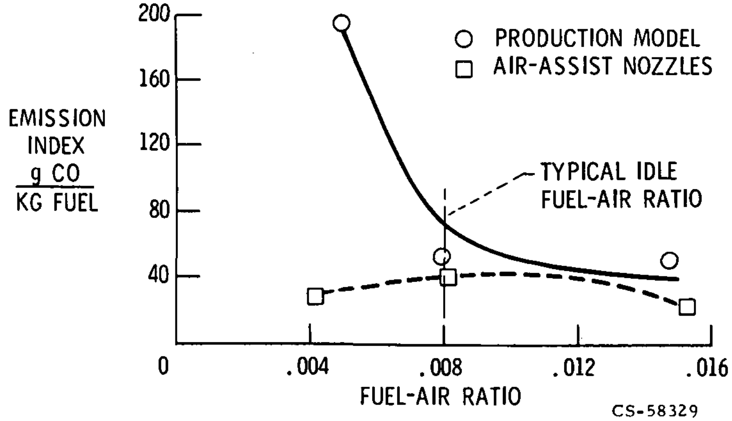

Figure 8. - Effect of fuel-air ratio on carbon monoxide emissions of J57 combustor.

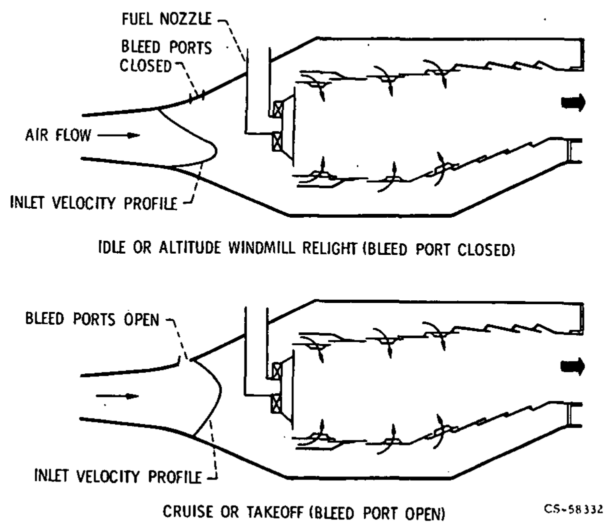

Figure 9. - Use of diffuser wall bleed to control combustor airflow distribution.

INCREASES IN PARAMETER	EFFECT ON NO_X
COMBUSTOR-INLET TEMP	GREAT INCREASE
COMBUSTOR-INLET PRESSURE	INCREASE
COMBUSTOR REFERENCE VELOCITY	DECREASE

Figure 10. - Effect of combustor-inlet conditions on NO_X formation.

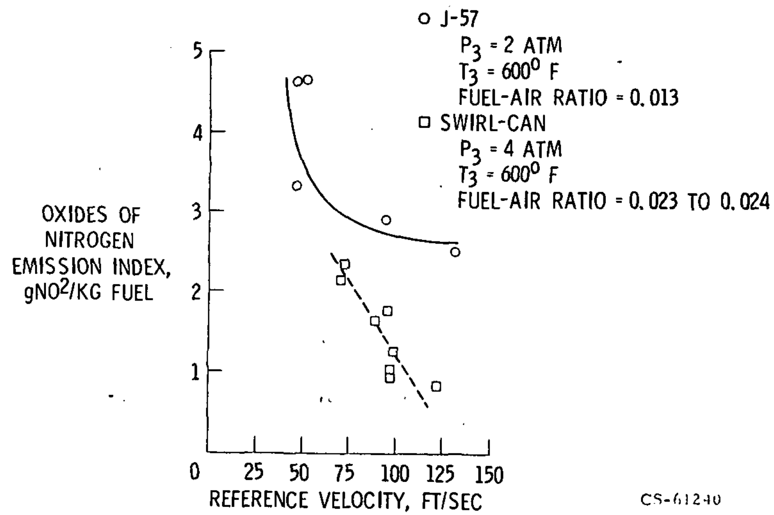

Figure 11. - Effect of combustor reference velocity on emission index for oxides of nitrogen.