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COMBUSTOR EXHAUST-EMISSIONS AND BLOWOUT-LIMITS WITH DIESEL NUMBER 2 AND JET A FUELS UTILIZING AIR-ATOMIZING AND PRESSURE-ATOMIZING NOZZLES

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COMBUSTOR EXHAUST-EMISSIONS AND BLOWOUT-LIMITS

WITH DIESEL NUMBER 2 AND JET A FUELS

UTILIZING AIR-ATOMIZING AND PRESSURE-ATOMIZING NOZZLES

Robert D. Ingebo and Carl T. Norgren

ABSTRACT

Experimental tests with diesel number 2 and Jet A fuels were conducted in a combustor segment to obtain comparative data on exhaust emissions and blowout limits. An air-atomizing nozzle was used to inject the fuels. Tests were also made with diesel number 2 fuel using a pressure-atomizing nozzle to determine the effectiveness of the air-atomizing nozzle in reducing exhaust emissions. Test conditions included fuel-air ratios of 0.008 to 0.018, inlet-air total pressures and temperatures of 41 to 203 newtons per square centimeter and 477 to 811 K, respectively, and a reference velocity of 21.3 meters per second.

Smoke number and unburned hydrocarbons were twice as high with diesel number 2 as with Jet A fuel. This was attributed to diesel number 2 having a higher concentration of aromatics and lower volatility than Jet A fuel. Oxides of nitrogen, carbon monoxide, and blowout limits were approximately the same for the two fuels. The air-atomizing nozzle, as compared with the pressure-atomizing nozzle, reduced oxides-of-nitrogen by 20 percent, smoke number by [illegible]0 percent, carbon monoxide by 70 percent, and unburned hydrocarbons by 50 percent when used with diesel number 2 fuel.

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SUMMARY

Diesel number 2 and Jet A fuels were tested in an experimental combustor segment. Exhaust emissions and blowout data were obtained and compared on the basis of the aromatic content and volatility of the two fuels. An air-atomizing splash-groove fuel nozzle was used to inject each fuel. Tests were also made with diesel number 2 fuel using a pressure-atomizing nozzle to determine the effectiveness of the air-atomizing nozzle in reducing exhaust emissions. Test conditions included fuel-air ratios of 0.008 to 0.018, inlet-air total pressures of 41 to 203 newtons per square centimeter, inlet-air temperatures of 477 to 811 K, and a reference velocity of 21.3 meters per second.

In comparing diesel number 2 with Jet A fuel on the basis of exhaust emissions and blowout conditions, the following results were obtained: (1) Smoke numbers at simulated engine-takeoff conditions were reduced approximately 30 percent by using an air-atomizing fuel injector instead of the conventional pressure-atomizing type, but smoke numbers were approximately twice as high with diesel number 2 fuel as with Jet A. (2) Unburned hydrocarbons emission-indices at simulated engine-idle conditions were reduced nearly 50 percent by using an air-atomizing injector in comparison with the pressure atomizing type, but the values were approximately twice as high with diesel number 2 fuel as with Jet A. (3) Carbon monoxide emission-indices at simulated engine-idle conditions were reduced 70 percent by using an air-atomizing injector instead of the pressure-atomizing type, and carbon monoxide values were approximately the same for diesel number 2 and Jet A fuels. (4) Oxides-of-nitrogen emission-indices at simulated engine-takeoff conditions were reduced by approximately 20 percent by using an air-atomizing fuel injector in preference to the pressure-atomizing type, and the values were approximately the same for diesel number 2 fuel as with Jet A. (5) Combustor blowout limits were approximately the same for diesel number 2 and Jet A fuels when injected with the air-atomizing fuel nozzle at an inlet-air temperature of 311° K.

INTRODUCTION

An investigation was conducted to obtain combustor exhaust-emission and blowout-limit data for diesel number 2 and conventional Jet A fuels using air-atomizing nozzles, and to obtain emission data for diesel number 2 fuel using pressure-atomizing nozzles for comparison.

At present, diesel number 2 fuel is used in ground-power gas-turbine engines. However, with the demand for fuels increasing, it is being investigated as an alternate fuel for turbojet-engine powered aircraft. In a recent study it was compared with other alternate fuels such as oil-shale-derived JP-5 in tests using a single-can JT8D combustor with conventional pressure-atomizing fuel nozzles (ref. 1). An increase in emissions was observed due to its relatively high aromatic content and its low volatility as compared with Jet A fuel. Thus, the acceptability of diesel number 2 as a fuel for turbojet engines may depend on improved combustor design such as the development of fuel injectors capable of producing low emissions. In references 2 and 3 it was found that air-atomizing fuel nozzles were effective in reducing emissions of experimental combustors below those obtained with a pressure-atomizing type.

The purpose of the present investigation was to determine the combined effect on combustor exhaust emissions as a result of using diesel number 2 fuel and air-atomizing nozzles. Also, combustor blowout conditions were determined for diesel number 2 and Jet A fuels with air-atomizing nozzles. Test conditions included fuel-air ratios of 0.008 to 0.018, inlet-air total pressures of 41 to 203 newtons per square centimeter, inlet-air temperatures of 477 to 811 K, and a reference velocity of 21.3 meters per second.

APPARATUS AND PROCEDURE

The combustor segment was mounted in the closed-duct test facility shown in figure 1. Combustor air drawn from the laboratory high-pressure supply system was indirectly heated to 811 K in a counterflow U-tube heat exchanger at combustor inlet-air pressures up to 203 newtons per square centimeter. The temperature of the air flowing out of the heat exchanger was automatically controlled by mixing the heated air with varying amounts of bypassed air. The test facility is described in more detail in reference 4.

Test Combustor

The test combustor, shown in figure 2, had a rectangular cross section which simulated an annular combustor segment. The overall combustor length of 45.6 centimeters included a diffuser length of 14.0 centimeters and a burner length of 31.6 centimeters, consisting of a primary-zone length of 7.6 centimeters and a secondary-zone length of 24.0 centimeters. The combustor cross section was 5.3 by 30.5 centimeters at the diffuser inlet and 5.1 by 30.5 centimeters at the combustor exit. The maximum cross section was 15.3 by 30.5 centimeters. The inlet snout open area was 40 percent of the combustor inlet area. A detailed description of the airflow in the primary and secondary mixing zones is given in the discussion of combustor model 3 in reference 4.

Fuel Injectors

The fuel injector tested, shown in figure 3, was an air-atomizing splash-groove nozzle designed to improve the uniformity of fuel distribution in the combustor primary zone. It contained forty-two 0.051-centimeter-diameter orifices and was used with diesel number 2 and Jet A fuels. At a fuel flow rate of 0.0152 kg/sec (120 lb/hr), it gave a pressure drop of 7 and 12 newtons per square centimeter with Jet A and diesel number 2 fuels, respectively. A conventional pressure-atomizing nozzle was used only with diesel number 2 fuel and it gave a flow rate of 0.0152 kg/sec (120 lb/hr) at a pressure drop of 42 newtons per square centimeter.

Instrumentation

Combustor instrumentation stations are shown schematically in figure 2, and detailed locations are given in reference 2. Inlet-air total temperature was measured at station 1 in the diffuser inlet with eight Chromel-Alumel thermocouples. Inlet-air pressure was measured at the same location with four stationary rakes consisting of three total-pressure tubes connected to differential-pressure strain-gage transducers balanced by wall static-pressure taps located at the top and bottom of the duct. Combustor exhaust temperatures and pressures and smoke samples were obtained with a traversing probe mounted at the combustor exit, station 2. The probe consisted of 12 elements: five aspirating platinum-platinum-13-percent-rhodium total-temperature thermocouples, five total-pressure tubes, and two wedge-shape static-pressure tubes. Smoke samples were withdrawn through the aspirating thermocouple lines. A detailed description of the probe is given in reference 2.

Sharp-edge orifices installed according to ASME specifications were used to measure airflow rates. Jet A fuel-flow rates were measured with pairs of turbine flowmeters connected in series to cross check their accuracy. Three pairs of flowmeters were required to cover the flow range.

Gaseous-Exhaust-Emission Measurement

Exhaust gas samples were obtained according to the procedure recommended in reference 5. Exhaust gases were withdrawn through the air-cooled stationary probe mounted approximately 92 centimeters downstream of the traversing probe and in the center of the exhaust gas stream (fig. 1). Concentrations of oxides of nitrogen, carbon monoxide, unburned hydrocarbons and carbon dioxide were determined with the gas-analysis equipment described in reference 6. The gas sample temperature was maintained at approximately 423 K in the electrically heated sampling line. Most of the gas sample entered the analyzer oven, while excess flow was bypassed to the exhaust system. To prevent fuel accumulation in the sample line, a nitrogen purge was used just before and during combustor ignition.

After passing through the analyzer oven, the gas sample was divided into three parts, and each was analyzed. Concentrations of oxides of nitrogen, carbon monoxide and carbon dioxide and unburned hydrocarbons were measured by the chemiluminiscence, nondispersed-infrared, and flame-ionization methods, respectively. Gas samples used to determine oxides of nitrogen and carbon monoxide were passed through a refrigerated dryer and analyzed on a dry basis. Readings for oxides of nitrogen and carbon monoxide were corrected so that they could be reported on a wet basis, as were those for unburned hydrocarbons.

Carbon dioxide concentrations in the gas samples were determined, and fuel-air ratios calculated from a carbon balance agreed to within 15 percent with values obtained from fuel-flow and airflow-rate measurements. Thus, representative exhaust-gas samples were obtained with the stationary probe, and emission values agreed with average values obtained with the traversing probe at the combustor exit.

Smoke-Number Measurement

Smoke samples were obtained according to the procedure recommended in reference 7 by withdrawing exhaust gases through the probe while it traversed the combustor exit (fig. 1). The sample flow rate at standard conditions was 236 cubic centimeters per second. Smoke numbers determined with the smoke meter described in reference 6 were based on 1.623 grams of gas per square centimeter of filter tape. A reflective densitometer was used to measure comparative reflectance of the smoke stain, and a Welch Gray Scale was used for instrument calibration. The smoke number, as defined in reference 7, was determined from the following expression:

$$\text{smoke number} = 100\ (1 - r)$$

where r is the ratio of the percent of absolute reflectivity of the smoke stain to that of the clean filter paper.

RESULTS AND DISCUSSION

Combustor exhaust-emission data for diesel number 2 and Jet A fuels were obtained at fuel-air ratios of 0.008 to 0.018, a reference velocity of 21.3 meters per second, and the combustor inlet-air conditions given in Table I.

One of the problems anticipated in the use of diesel number 2 fuel is that of high smoke concentrations due to its high aromatic content which is approximately twice that of Jet A as shown in the tabulation of properties given in Table II. In figure 4, smoke number is plotted against fuel-air ratio at a combustor inlet-air temperature and pressure of 700^o K and 101 newtons per square centimeter, respectively. At the simulated engine-takeoff conditions (0.018 fuel-air ratio), diesel number 2 fuel gave a smoke number of 28 with a pressure-atomizing nozzle which was reduced to a value of 20 (nearly 30 percent) by using the air-atomizing nozzle. Also, the smoke number for diesel number 2, which is twice as high in aromatics, was approximately twice as high as the smoke number for Jet A.

In view of the relatively high boiling-point constituents in diesel number 2 as shown in Table II, it was anticipated that exhaust emissions might be relatively high for unburned hydrocarbons. Figure 5 shows the variation in unburned-hydrocarbons emission-index with combustor inlet-air temperature. At the simulated engine-idle condition (477 K 41 newtons per square centimeter and 0.008 fuel-air ratio), diesel number 2 gave an unburned hydrocarbon emission-index of 58 (a combustion inefficiency of 6 percent due to unburned hydrocarbons) with the pressure-atomizing nozzle. This value was reduced to approximately 28 (a combustion inefficiency of 3 percent) by using the air-atomizing nozzle, but it was considerably above the value of 12 obtained with Jet A fuel. Thus, unburned hydrocarbons for diesel number 2 were reduced 50 percent with the air-atomizing nozzle.

The variation of the CO emission-index with combustor inlet-air temperature is shown in figure 6. At simulated engine-idle conditions (477^o K, 41 newtons per square centimeter, and 0.008 fuel-air ratio), diesel number 2 gave a CO emission-index of 130 (or a combustor inefficiency of approximately 3 percent due to CO) with a pressure atomizing nozzle. This was reduced to a value of 35 (or a combustor inefficiency of approximately 1 percent) with the use of an air-atomizing nozzle. This value was approximately the same as that obtained with Jet A fuel. Thus, CO emissions did not appear to be as much of a problem as unburned hydrocarbons in using diesel number 2 as an alternate fuel.

The variation of the oxides-of-nitrogen emission-index with combustor inlet-air pressure is shown in figure 7. At simulated engine-takeoff conditions (700^o K, 203 newtons per square centimeter, and 0.018 fuel-air ratio) diesel number 2 gave a NO_x emission index of 21 with a pressure-atomizing nozzle that was reduced to a value of 17 with the air-atomizing nozzle. This was somewhat less than the value of 19 obtained with Jet A fuel, and indicates that the problem of reducing oxides-of-nitrogen is not appreciably increased by using diesel number 2 as an alternate fuel for turbojet combustors.

Combustor blowout tests were made with diesel fuel to determine the effect of its decreased volatility, as compared with Jet A fuel, on combustor blowout limits. As shown in figure 8, the minimum inlet-air total pressure at which steady burning could be maintained in the combustor was approximately the same for diesel number 2 and Jet A fuels with the air-atomizing nozzle. The data were obtained at an inlet-air temperature of 311° K and no tests were made with pressure-atomizing nozzles. Lower inlet-air temperatures would be more useful in demonstrating the effect of fuel volatility on blowout limits. However, these data indicate that diesel number 2 fuel does have reasonable good blowout performance that is approximately the same as that of Jet A fuel when used with the air-atomizing fuel injector at an inlet-air temperature of 311° K.

SUMMARY OF RESULTS

The effect of fuel properties on exhaust emissions and blowout limits of a high-pressure combustor segment was determined using a splash-groove air-atomizing fuel injector and a pressure-atomizing simplex fuel nozzle to burn both diesel number 2 and Jet A fuels. Exhaust smoke number and emission indices for oxides of nitrogen, carbon monoxide, and unburned hydrocarbons were determined for comparison. Also, combustor blowout conditions were determined for diesel number 2 and Jet A fuels. Test conditions included fuel-air ratios of 0.008 to 0.018, inlet-air temperatures and pressures of 477 to 811 K and 41 to 203 newtons per square centimeter, respectively, and a reference velocity of 21.3 meters per second.

In using an air-atomizing fuel nozzle and comparing diesel number 2 with Jet A fuel on the basis of exhaust emissions and blowout conditions, the following results were obtained (as summarized in Table III): (1) Smoke numbers at simulated engine-takeoff conditions were reduced approximately 30 percent by using an air atomizing fuel injector instead of the pressure-atomizing type, but smoke numbers were approximately twice as high with diesel number 2 fuel as with Jet A. (2) Unburned hydrocarbons emission-indices at simulated engine-idle conditions were reduced nearly 50 percent by using an air-atomizing injector in comparison with the pressure atomizing type, but unburned hydrocarbons were approximately twice as high with diesel number 2 fuel as with Jet A. (3) Carbon monoxide emission-indices at simulated engine-idle conditions were reduced 70 percent by using an air-atomizing injector instead of the pressure-atomizing type, and carbon monoxide values were approximately the same for diesel number 2 and Jet A fuels. (4) Oxides-of-nitrogen emission-indices at simulated engine-takeoff conditions were reduced by approximately 20 percent by using an air-atomizing fuel injector in preference to the pressure-atomizing type, and the values were approximately the same for diesel number 2 and Jet A fuels. (5) Combustor blowout limits were approximately the same for diesel number 2 and Jet A fuels when injected with the air-atomizing fuel nozzle at an inlet-air temperature of 311° K.

In comparing fuel properties, the higher concentration of aromatics and lower volatility of diesel number 2 as compared to Jet A appeared to have the most detrimental effect on exhaust emissions. However, the use of air-atomizing nozzles was effective in reducing exhaust emissions obtained with diesel number 2 fuel.

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7. Aircraft Turbine Exhaust Smoke Measurement. Aerospace Recommended Practice 1179 SAE, May 1970.

TABLE I. - COMBUSTOR TEST CONDITIONS

Inlet-Air Total Pressure, N/cm^2	Inlet-Air Total Temperature	
	K	^oR
41	[a]477	[a]859
	589	1060
	700	1260
	811	1460
101	589	1060
	700	1260
203	589	1060
	[b]700	[b]1260

[a]Simulated engine idle condition, 0.008 fuel-air ratio.

[b]Simulated engine takeoff condition, 0.018 fuel-air ratio.

TABLE II. - PHYSICAL AND CHEMICAL

PROPERTIES OF TEST FUELS

Property	Fuel	
	Jet A	Diesel number 2
Boiling point, K (^{o}R)		
Initial	442 (796)	450 (810)
Final	544 (980)	607 (1093)
Distillation point, K (^{o}R)		
(10 percent)	460 (828)	490 (882)
Lower heating value,		
J/g (BTU/lb)	43000 (18600)	42600 (18464)
Hydrogen-carbon ratio	0.160	0.150
Aromatics, vol. %	16.8	30.5

TABLE III. - TABULATION OF RESULTS

FUEL	Diesel Number 2		Jet A
INJECTOR	Pressure-Atomizing	Air-Atomizing	Air-Atomizing
[a]Smoke Number	28	20	10
Emission-Index			
[b]Unburned Hydrocarbons (gCH_2/kg fuel)	58	28	12
[b]Carbon Monoxide (gCO/kg fuel)	130	35	33
[a]Oxides of Nitrogen (g NO_x/kg fuel)	21	17	19
[b]Combustion Inefficiency, percent	9	4	2
Blowout Limit			
Inlet-Air Total Press. (N/cm^2)	-	4.5	4.5

[a]Simulated Takeoff Conditions

[b]Simulated Idle Conditions

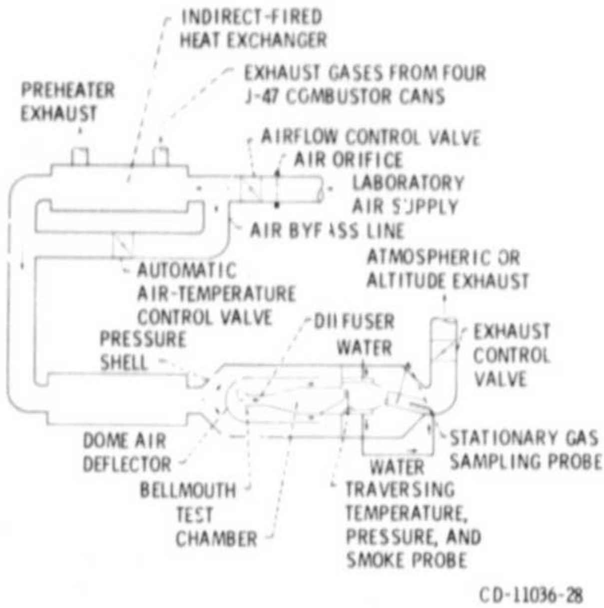

Figure 1. - Test facility and auxiliary equipment.

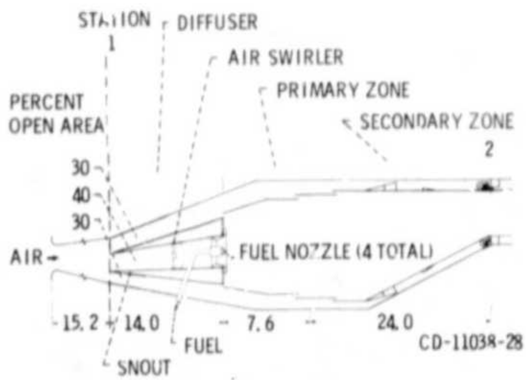

Figure 2. - Test combustor. (Dimensions are in centimeters.)

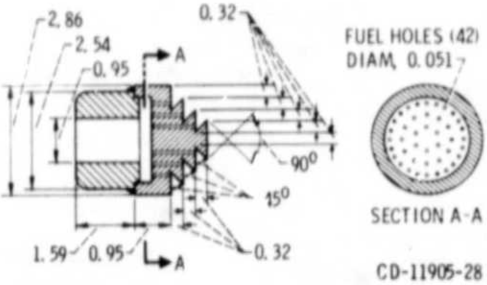

Figure 3. - Schematic diagram of splash-groove fuel injector. (Dimensions are in centimeters)

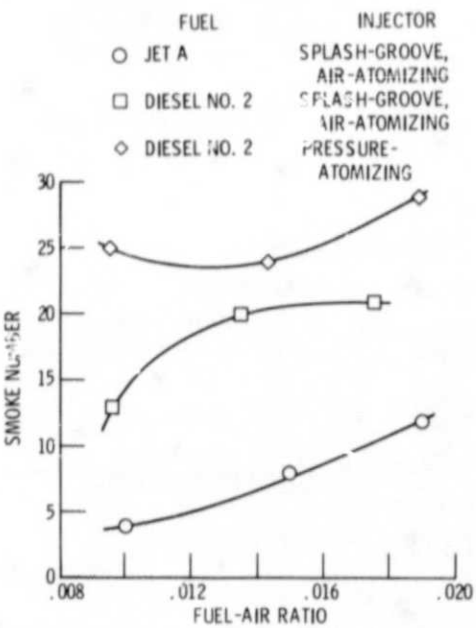

Figure 4. - Variation of exhaust smoke number with fuel-air ratio. Inlet-air temperature, 700 K; inlet-air pressure, 101 N/cm^2; reference velocity, 21.3 m/sec.

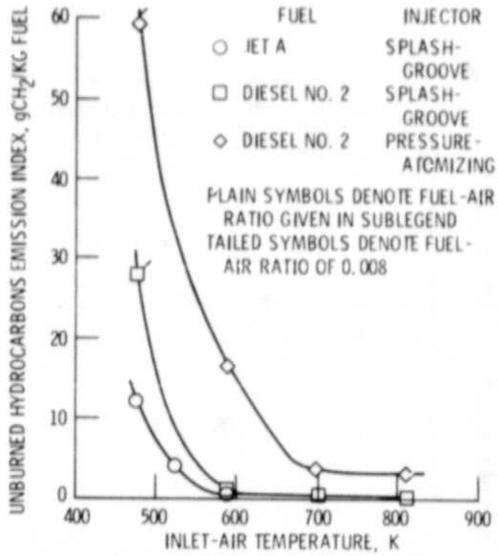

Figure 5. - Variation of unburned hydrocarbons with inlet-air temperature. Fuel-air ratio, 0.0 0; inlet-air pressure, 41 N/cm^2; reference velocity, 21.3 m/sec.

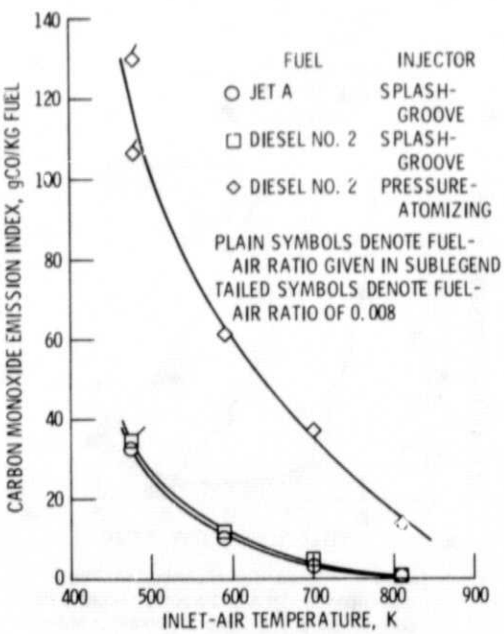

Figure 6. - Variation of carbon monoxide with inlet-air temperature. Fuel-air ratio, 0.010; inlet-air pressure, 41 N/cm^2; reference velocity, 21.3 m/sec.

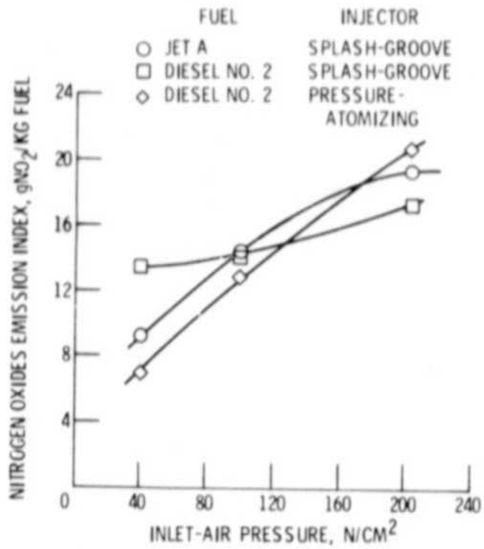

Figure 7. - Variation of nitrogen oxides emission index with inlet-air pressure. Fuel-air ratio, 0.018; inlet-air temperature, 700 K; reference velocity, 21.3 m/sec.

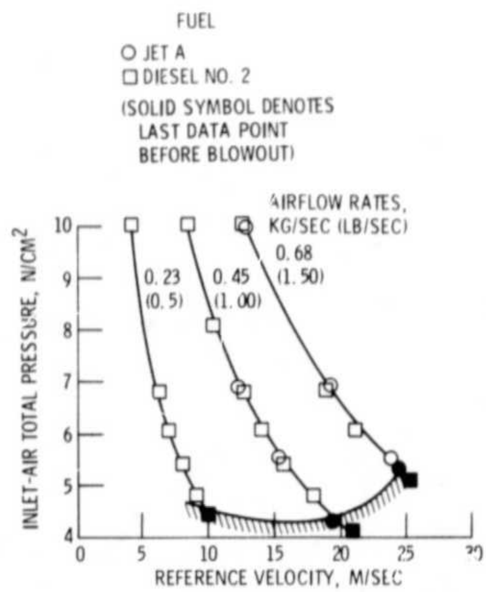

Figure 8. - Comparison of combustor blowout conditions for Jet A and diesel oil no. 2 fuels with splash-groove injector. Inlet-air temperature, 311 K; fuel-air ratio, 0.020.