NASA TECHNICAL MEMORANDUM

NASA TM X- 68064

NASA TM X- 68064

(NASA-TM-X-68064) REVIEW OF JET ENGINE EMISSIONS J. Grobman (NASA) 1972 17 p CSCL 21E

N72-24830

Unclas

G3/28 29431

REVIEW OF JET ENGINE EMISSIONS

by Jack Grobman
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER presented at the Department of Transportation Survey Conference: Climatic Impact Assessment Program
Cambridge, Massachusetts, February 15-16, 1972

ABSTRACT

The purpose of this presentation is to provide a brief tutorial review on the subject of the emission characteristics of jet engines. The sources and concentrations of the various constituents in the engine exhaust and the influence of engine operating conditions on emissions are discussed. Cruise emissions to be expected from supersonic engines are compared with emissions from subsonic engines. The basic operating principles of the gas turbine combustor are reviewed together with the effects of combustor operating conditions on emissions. The performance criteria that determine the design of gas turbine combustors are discussed. Combustor design techniques are considered that may be used to reduce emissions.

E-6938

E-6938

REVIEW OF JET ENGINE EMISSIONS

by Jack Grobman

Lewis Research Center

SUMMARY

A considerable amount of data has been reported in the literature describing the emission characteristics of commercial subsonic jet aircraft for operating modes below an altitude of 900 meters (3000 ft), which include idle, takeoff, climbout, descent, and landing. These data were obtained by ground-based sampling of the exhaust from jet engines tested over a range of engine speeds to simulate the various operating modes. Virtually no data are presently available on the emissions of either subsonic or supersonic aircraft at cruise conditions. The constituents in the exhaust from the engine are mainly a function of the combustor operating conditions including combustor inlet total temperature and pressure, combustor reference velocity or reaction dwell time, and fuel-air ratio. Cruise emissions from either subsonic or supersonic jet aircraft may be predicted from a knowledge of combustor operating conditions during cruise using typical combustor emission data correlations obtained over a range of combustor operating conditions.

The constituents in the exhaust may be divided into five categories including the unreacted constituents in the air, the products of complete combustion, the products of incomplete combustion, oxides of nitrogen, and constituents due to trace elements in the fuel. During cruise, the products of incomplete combustion, carbon monoxide and hydrocarbons, are relatively low in concentration because gas turbine combustors operate at a combustion efficiency near 100 percent at cruise conditions. The concentrations of carbon monoxide and hydrocarbons in the exhaust of an afterburning turbine engine would be expected to be slightly higher than those of an unaugmented engine because afterburners tend to burn less efficiently than main combustors.

Nitric oxide is considered to be the most significant emission product formed during altitude cruise. The quantity of nitric oxide formed in the combustor is a strong function of flame temperature which increases with increasing combustor inlet total temperature. Combustor inlet total temperature increases with increases in either compressor pressure ratio or flight Mach number. Altering gas turbine combustor designs in order to make substantial reductions in oxides of nitrogen will be an extremely difficult task. Research is in progress to develop and evaluate experimental combustors that reduce oxides of nitrogen without compromising on engine performance.

INTRODUCTION

The purpose of this presentation is to provide a brief tutorial review on the subject of the emission characteristics of jet engines, particularly during high altitude cruise. Many recent reports (refs. 1 to 3) have discussed the relative contribution of jet aircraft emissions from ground and low altitude maneuvers to urban pollution. Even though the overall contribution of aircraft to urban pollution is small, the air quality in the vicinity of commercial airports is considered to be significantly affected by jet aircraft emissions. During idling and taxiing, the principal pollutants are unburned hydrocarbons and carbon monoxide while during landing and takeoff, the main pollutants are oxides of nitrogen and smoke. Emission data for a number of commercial jet engines for subsonic aircraft have been documented in reference 4. These data apply mainly to the emissions from jet aircraft during idle, takeoff, and landing operations. Similar data on cruise emissions from subsonic and supersonic aircraft are presently not documented. We are just beginning to obtain the necessary cruise emission data to help determine the nature of the global problem.

This paper discusses the sources and concentrations of the various constituents in the engine exhaust and the influence of engine operating conditions on emissions. Predictions are made of cruise emissions to be expected from supersonic and subsonic engines based on existing data relating emissions with combustor operating conditions. A brief review is made of the basic operating principles and performance criteria that determine the design of gas turbine combustors. A brief survey is made of recent reports (refs. 5 to 9) that consider combustor design techniques that may be used to reduce emissions.

CONSTITUENTS IN JET ENGINE EXHAUST

The various constituents in jet engine exhaust during typical takeoff or cruise conditions are tabulated in figure 1. Each constituent has been grouped into five different categories determined by its source. These include (1) inerts and unreacted oxygen from air, (2) products of complete combustion of fuel, (3) products of incomplete combustion, (4) oxides of nitrogen formed during the heating of air, and (5) elements or compounds derived from sulfur and trace metals present in kerosene fuel. The concentration of the components in the air and products of complete combustion were determined for an overall fuel-air ratio of 0.014 using commercial Jet A-1 kerosene fuel. The overall fuel-air ratio during cruise generally has a range of 0.01 to 0.03. The products of incomplete combustion include carbon monoxide, unburned fuel, partially oxidized hydrocarbons such as aldehydes, hydrogen, and particulates (soot) consisting mainly of carbon. Combustors for gas turbine engines are designed to operate with maximum performance during cruise, and the estimated concentrations of the products of incomplete combustion shown in the table are equivalent to an overall combustion inefficiency of about 1 percent or less. Afterburners for gas turbine engines tend to be less efficient than the main comubstor; and therefore, the concentrations of the products of incomplete combustion are generally several times greater for augmented engines.

Oxides of nitrogen are formed from the reactions of oxygen and nitrogen at elevated temperatures generated in the reaction zone of the combustor. These oxides of nitrogen (NO_X) generally consist of about 90 to 95 percent nitric oxide (NO) with the remainder being nitrogen dioxide (NO_2). The quantity of nitric oxide formed is affected by a number of factors including engine compressor pressure ratio, flight Mach number, fuel-air ratio, and combustor design.

Commercial specifications for Jet A-1 kerosene require that the sulfur concentration in the fuel not exceed a value of 0.3 percent by weight. In practice, the sulfur concentration is generally less than 25 percent of this value. The sulfur in the fuel is converted into mostly sulfur dioxide (SO_2) and lesser amounts of sulfur trioxide (SO_3). A variety of trace metals are present in the fuel such as aluminum, iron, manganese, nickel, sodium, potassium, and vanadium. The total concentration of the trace metals in jet engine exhaust is estimated to be about 5 to 20 ppb (parts per billion).

The remaining discussion on the constituents in jet engine exhaust will be limited to the products of incomplete combustion and nitric oxide. The factors affecting the formation and control of these exhaust components will be covered.

TYPICAL JET ENGINE EMISSION CHARACTERISTICS

Figure 2 illustrates the carbon monoxide (CO), total hydrocarbon, and nitrogen oxide (NO_X) emissions over a range of engine speeds for a typical gas turbine engine for a subsonic aircraft with a compressor pressure ratio of 13.4 using JP-5 fuel (similar to commercial Jet A-1 fuel). 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. At a fuel-air ratio of 0.015, an emission index of unity is equivalent to either 15 ppm CO, or 30 ppmC total hydrocarbons, or 10 ppm NO_X. The NO_X emission index is calculated by assuming the conversion of all nitric oxide (NO) in the exhaust to nitrogen dioxide (NO_2). At low engine speeds corresponding to idle operation, the CO and hydrocarbon emissions are at their highest whereas nitrogen oxide emissions are at their lowest. At an engine speed of 100 percent corresponding to takeoff conditions, the nitrogen oxide emissions are highest, whereas CO and hydrocarbon emissions approach their minimum. For a subsonic aircraft the CO and hydrocarbon emission levels at cruise would be expected to be similar to the levels during takeoff, but NO_X emissions would be lower than at takeoff.

Figure 3 shows a tabulation of the main emission products, together with their major causes. A range of emissions at either idle or takeoff is shown for typical subsonic commercial engines. High hydrocarbon and CO emissions that occur only during idle are due to inefficient combustion. Inefficient combustion is caused by a combination of poor fuel atomization at low fuel flow rates, lean reaction zone fuel-air ratios, and low combustor-inlet pressure and temperatures. Higher NO_X emissions during takeoff are caused by the increased reaction rates of oxygen and nitrogen at higher flame temperatures as a result of higher combustor inlet temperatures. Smoke density is higher at takeoff because of higher combustor pressures and richer reaction zone fuel-air ratios. Only nitric oxide is formed in any significant quantities during subsonic cruise, but the NO_X emission index during cruise is less than that during takeoff because the combustor-inlet temperature and pressure are lower.

COMPARISON OF SUBSONIC AND SUPERSONIC ENGINES

Figure 4 shows a drawing of a typical turbofan engine used on subsonic aircraft. The main engine components include a fan, compressor, combustor, and turbine. A portion of the air passing through the fan enters the compressor, while the remaining air is by-passed around the core engine to provide additional thrust. The flowrate and total temperature and pressure of the air entering the combustor from the compressor discharge are established by the overall fan and compressor pressure ratio, flight altitude, and flight speed. The fuel-air ratio is determined by the combustor temperature rise required to obtain the designed turbine inlet temperature. The frontal area of the combustor generally does not exceed the required frontal area of the compressor or turbine in order to avoid unnecessary engine drag. The overall length of the combustor is kept as short as practical to minimize engine shaft length and bearing requirements. The combustor shown in the drawing is of the can-annular type in which a number of tubular combustion liners are arranged within a common annular housing. Most recent engines use an annular type combustor in which a continuous annular combustion liner is installed within an annular housing.

A schematic drawing of a conventional annular combustor is shown in figure 5. The combustor consists of three main parts: A diffuser, the primary (reaction) zone, and the secondary (dilution) zone. The diffuser is used to diffuse the relatively high velocity airflow discharging from the compressor to a high static pressure. Lower combustor velocities are necessary to obtain stable combustion and to avoid excessive combustor pressure loss. Fuel is generally injected by pressure atomizing nozzles and combustion is initiated and stabilized in the primary zone. Enough air is introduced into the primary zone through swirlers around the fuel nozzles or through openings in the liner wall to maintain a near stoichiometric mixture of fuel and air. Air by-passing the primary zone is injected into the secondary zone through additional openings in the liner and mixes with the hot gases from the primary zone to achieve a desired turbine inlet temperature distribution. The remaining airflow is used to film cool the walls of the chamber. Most of the chemical reactions are completed prior to dilution in the secondary zone. Consequently the emission products are essentially frozen near the exit of the combustor.

A drawing of one type of engine suitable for powering a supersonic aircraft is shown in figure 6. The main differences between the afterburning turbojet shown in this figure and the turbofan engine shown in a previous figure are: (1) incorporation of an inlet diffuser (not shown) to slow the air to subsonic speeds before it enters the engine, (2) omission of fan and by-pass duct, (3) addition of afterburner to provide thrust augmentation, and (4) installation of a supersonic exhaust nozzle. Afterburning turbojet engines similar to that shown in figure 6 are used on the Concorde SST and were to be used on the Boeing SST Other engine types could be considered for future SST designs. Recent studies (ref. 10) have shown that an afterburning turbofan engine may offer advantages in reducing jet noise.

The afterburner consists of an inlet diffuser to slow down the turbine discharge gases, an array of fuel-spray bars followed by an array of flameholders, and a combustion chamber that is air cooled and accoustically damped to prevent screech. From a combustion point of view, the operating conditions in an afterburner are generally more severe than in the main combustor, and therefore, the afterburner combustion efficiency tends to be lower.

A comparison of the cruise operating conditions of representative subsonic turbofan and supersonic afterburning (AB) turbojet engines is shown in figure 7. The flight conditions chosen for the supersonic engine were those for the GE-4/Boeing SST. A combustion efficiency of nearly 100 percent is achieved during cruise for either of these engines; and, thus a minimum quantity of hydrocarbons and CO is formed. The afterburner combustion efficiency would be expected to be several percent less than that of the main combustor; however, the quantity of fuel burned in the afterburner during cruise amounts to only about 22 percent of the total fuel burned in the engine. The main factor affecting the formation of nitric oxide in either engine is the combustor inlet total temperature. Increasing either the compressor pressure ratio or the flight speed results in an increase in combustor inlet total temperature. Preliminary data (ref. 11) indicate that afterburning does not significantly add to nitric oxide emissions from supersonic aircraft.

EFFECT OF OPERATING VARIABLES ON EMISSIONS

Hydrocarbons and Carbon Monoxide

Combustion efficiency can be defined as the ratio of the actual enthalpy rise to the theoretical enthalpy rise attainable for the amount of fuel used. The theoretical enthalpy rise assumes that the combustion reaction proceeds to completion to form gaseous products of combustion in equilibrium at the combustor exit temperature. Previous studies (ref. 12) have correlated combustion efficiency against a combustion parameter composed of inlet total pressure, (P_{inlet} or P_3), multiplied by inlet total temperature, (T_{inlet} or T_3), and divided by reference velocity (V_R) where reference velocity is equal to the combustor airflow rate divided by the product of the air density at the combustor inlet and the maximum cross-sectional flow area of the combustor. A typical combustion efficiency correlation is shown plotted in figure 8. The figure shows that combustion efficiency increases as inlet pressure and inlet temperature increase and decreases as combustor velocity increases. Typical values of the correlating parameter for takeoff and cruise fall far to the right of the bend in the curve. Therefore, there are not any significant problems in obtaining good combustion efficiency for takeoff and cruise. At engine idle conditions, the value for the correlating parameter is low, and in addition fuel flow is low; therefore, obtaining good combustion efficiency is a difficult problem. As expected, the emission indices for CO and total hydrocarbons decrease with increasing values for the correlating parameter. A plot of the CO emission index against the correlating parameter for a typical combustor obtained from reference 13 is shown in figure 9. The correlation plot for the hydrocarbon emission index follows a similar trend.

Oxides of Nitrogen

Figure 10 obtained from reference 2 shows the effect of engine pressure ratio on NO_X emissions at takeoff. The increase in the NO_X emission index with engine pressure ratio is mainly due to increasing combustor inlet temperature. For a given subsonic engine, the combustor inlet temperature during cruise is less than at takeoff because the ambient temperature is lower at the cruise altitude and because corrected engine speed is lower; and therefore, NO_X emissions at cruise are less than at takeoff. For a supersonic aircraft, the combustor inlet total temperature increases significantly with increases in flight Mach number, and thus, can result in increases in NO_X emissions. Combustor inlet total pressure is lower during cruise than at takeoff for both subsonic and supersonic engines. Preliminary data indicate that nitric oxide emissions tend to be lower as combustor pressure is reduced.

The effect of combustor operating variables on NO_X formation is summarized in figure 11. The strong influence of combustor inlet temperature on NO_X formation is the result of the fact that increasing combustor inlet temperature increases the flame temperature and hence the reaction rate. Increasing combustor inlet pressure also tends to increase the formation of NO_X, but the effect is not as significant as the effect of inlet temperature. The effect of pressure might be attributed to either chemical kinetics or fuel-air mixing. Increasing combustor reference velocity tends to reduce reaction zone dwell time thus reducing the quantity of NO_X formed since the formation of NO_X is reaction rate limited.

In general, increasing the overall fuel-air ratio has been observed to increase NO_X formation. Theoretically, the local fuel-air ratio in the primary (reaction) zone should have a very significant effect on NO_X formation by its effect on flame temperature. Flame temperature should be near a maximum at stoichiometric conditions and should be lower for fuel-air mixtures that are either leaner or richer than stoichiometric. Gas turbine combustors are generally designed so that the primary zone fuel-air ratio is near stoichiometric in order to optimize combustion performance. Operating with a primary zone that is lean in fuel leads to unstable combustion while operating on the fuel rich side causes excessive carbon formation. Even if the reaction zone were operated either leaner or richer than stoichiometric, factors that affect the homogeneity of the reactants such as the fuel-air mixing intensity, fuel droplet size distribution, and fuel evaporation rate tend to be as important an effect on NO_X formation as the average local fuel-air ratio in the reaction zone.

COMBUSTOR DESIGN TECHNIQUES TO REDUCE EMISSIONS

Combustor operating variables such as combustor inlet total pressure and temperature, and overall fuel-air ratio are fixed by the engine design. Factors affecting engine design are discussed in reference 10. Combustor reference velocity must be limited to prevent excessive pressure losses. Thus the only means readily available to the combustor designer to control emissions are the method of fuel atomization, the mixing of fuel and air, and the general geometry of the combustor. Preliminary research on the subject of emission reductions in gas turbine combustors is discussed in references 5 to 9. Hydrocarbon and CO emissions were shown to be mainly a problem during idle while smoke is mainly a takeoff problem, and since this paper is mainly concerned with emissions in the upper atmosphere, the discussion in this section will be limited to methods to reduce nitric oxide emissions.

The two principal methods for reducing nitric oxide emissions are to reduce the reaction zone temperature (flame temperature) and to reduce the reaction zone dwell time. The reaction zone temperature may be reduced either (1) by operating with either a fuel-rich or fuel-lean reaction zone, (2) by operating with a more homogeneous fuel-air mixture, or (3) by introducing inerts into the reaction zone. The reaction zone fuel-air ratio may be shifted by altering the combustor airflow distribution. However, rich reaction zones tend to form excessive amounts of carbon monoxide, hydrocarbons, and smoke while lean reaction zones present severe combustion stability problems. If this approach is to be used, variable geometry might be required to continuously control combustor airflow distribution to avoid poor combustion efficiency and the emission products due to incomplete combustion.

The fuel-air mixture could be made more homogeneous either by increasing mixing intensity, by premixing the fuel and air before they enter the reaction zone, by prevaporizing the fuel before it enters the reaction zone, or by increasing the number of fuel injection points. Inerts that might be used to reduce flame temperature include water or recirculated combustion products. Water injection would be impractical during cruise because of payload penalties. A significant increase in the amount of combustion products that are already recirculated in the reaction zone might require excessive pressure losses.

The reaction zone dwell time could be reduced either by shortening the length of the reaction zone or by increasing the number of local burning zones in order to reduce the recirculation path length. One experimental combustor being studied at NASA-Lewis that incorporates many of the above approaches is shown in the photograph of figure 12. This annular combustor which is about 30 percent shorter than conventional combustors incorporates 120 small individual burners, referred to as swirl-cans, into a modular array arranged in three concentric annular rows as shown in the cross-sectional sketch in figure 13. The modular combustor has no well-defined primary or secondary zone as in the conventional combustor. Nearly all the airflow, except for that required to cool the liner, passes directly through or around the modules. The details of each swirl-can element are illustrated in figure 14. Each swirl-can, which is about 5 centimeters (2 in.) in diameter, consists of a carburetor, swirler, and flame stabilizer. The carburetor premixes the fuel with a portion of air entering an orifice in the upstream end of the chamber. The swirler acts to further mix the fuel and air and to impart a swirl to the mixture. Combustion is initiated and maintained at the flame stabilizer. The air flowing around the outside of the module mixes with the hot combustion gases in the wake of each module. There the combustion reaction is completed and mixing of the gases to the desired turbine inlet temperature distribution is achieved. Further details on the operation and performance of the swirl-can combustor are described in references 14 and 15.

The main advantages of this type of combustor are that fuel and air are partially premixed prior to burning and that burning and mixing downstream of each module is very rapid. Nitric oxide emission data for the experimental swirl-can combustor are compared to those from a more conventional combustor in figure 15. The NO_X emission index is plotted against combustor inlet total temperature. Even though these results are quite preliminary and even though there are a number of problems remaining to be solved before such a combustor may be incorporated into an actual engine, the swirl-can concept appears to be a promising approach for obtaining reduced nitric oxide emissions.

CONCLUDING REMARKS

Nitric oxide appears to be the only pollutant emission product that is formed during high altitude cruise that has a significant concentration. A great deal of research is currently in progress to develop methods of reducing nitric oxide emissions from gas turbine combustors. Other research being performed to determine the constituents and chemical reactiors in the upper atmosphere may provide a clearer answer to whether or not reductions in cruise emissions are required, and if so, how large a reduction is required. It is fairly clear, however, that whether the approaches described herein or some similar approach is required to reduce nitric oxide emissions, a significant modification will be required to conventional gas turbine combustors. Furthermore, a considerable effort will be required to accomplish these emission reductions without compromising on other combustor performance requirements.

REFERENCES

1. Platt, M.; Baker, R. C.; Bastress, E. K.; Chng, K. M.; and Siegel, R. D.: The Potential Impact of Aircraft Emissions Upon Air Quality. Rep 1167-1, Northern Research and Eng. Corp , Dec. 29, 1971.

2. Anon.: A Study of Aircraft Gas Turbine Engine Exhaust Emissions. Aerospace Industries Association of America, Aug. 1971.

3. Sawyer, R. F.: Atmospheric Pollution by Aircraft Engines and Fuels. AGARD-AR-40, Mar. 1972.

4. Bogdan, Leonard; and McAdams, H. T.: Analysis of Aircraft Exhaust Emission Measurements. CAL-NA-5007-K-1, Cornell Aeronautical Lab., Oct. 1971.

5. Butze, Helmut F.: Methods for Reducing Pollutant Emissions from Jet Aircraft. NASA TM-X-68000, 1971.

6. Bastress, E. K.; et al.: Assessment of Aircraft Emission Control Technology. Rep. 1168-1, Northern Research and Eng. Corp., July 1971.

7. Norster, E. R.; and Lefebvre, A. H.: Effects of Fuel Injection Methods on Gas Turbine Combustor Emissions. Presented at General Motors Research Lab Symposium, Warren, Mich., Sept. 27-28, 1971.

8. Bahr, D. W.: Control and Reduction of Aircraft Exhause Emissions from Aircraft Turbine Engines. Presented at General Motors Research Lab Symposium, Warren, Mich., Sept. 27-28, 1971.

9. Grobman, Jack: Effect of Operating Variables on Pollutant Emissions from Aircraft Turbine Engine Combustors. Presented at General Motors Research Lab Symposium, Warren, Mich., Sept. 27-28, 1971.

10. Beheim, Milton A.; Cummings, Robert L.; Dugan, James F., Jr.; Feiler, Charles E.; Grobman, Jack S.; and Stewart, Warner L.: Subsonic and Supersonic Propulsion. Vehicle Technology for Civil Aviation: The Seventies and Beyond. NASA SP-292, pp. 107-156.

11. Diehl, Larry A.: Preliminary Investigation of Gaseous Emissions from Jet Engine Afterburners. NASA TM X-2323, 1971.

12. Childs, J. Howard; Reynolds, Thaine W.; and Graves, Charles C.: Relation of Turbojet and Ramjet Combustion Efficiency to Second-Order Reaction Kinetics and Fundamental Flame Speed. NACA Rep. 1334, 1957.

13. Briehl, Daniel; Papathakos, Leonidas; and Strancar, Richard J.: Effect of Operating Conditions on the Exhaust Emissions from a Gas Turbine Combustor. NASA TN D-6661, 1972.

14. Niedzwiecki, Richard W.; Juhasz, Albert J.; and Anderson, David N.: Performance of a Swirl-Can Primary Combustor to Outlet Temperatures of 3600° F (2256 K). NASA TM X-52902, 1970.

15. Grobman, Jack; Jones, Robert E.; Marek, Cecil J.; and Niedzwiecki, Richard W.: Combustion. Aircraft Propulsion. NASA SP-259, 1971, pp. 97-134.

E-6938

ENGINE EXHAUST CONSTITUENTS

CONSTITUENTS	SOURCE	ESTIMATED CONCENTRATION
N_2	AIR	77% (VOL)
O_2	AIR	16.6% (VOL)
A	AIR	0.9% (VOL)
H_2O	EFF COMBUSTION	2.7% (VOL)
CO_2	EFF COMBUSTION	2.8% (VOL)
CO	INEFF COMBUSTION	10-50 PPM
UNBURNED HC	INEFF COMBUSTION	5-25 PPMC
PARTIALLY OXIDIZED HC	INEFF COMBUSTION	
H_2	INEFF COMBUSTION	5-50 PPM
SMOKE (PARTICULATES)	INEFF COMBUSTION	0.4-50 PPM (MASS)
NO, NO_2	HEATING OF AIR	50-400 PPM
SO_2, SO_3	FUEL	1-10 PPM
TRACE METALS	FUEL	5-20 PPB

CS-...

Figure 1.

TYPICAL ENGINE EXHAUST EMISSION CHARACTERISTICS

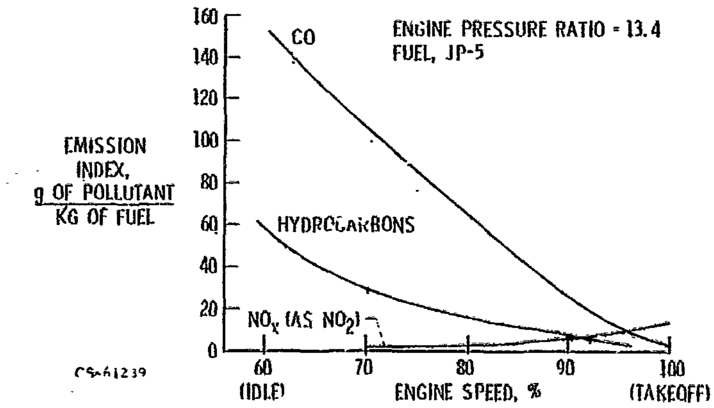


Figure 2.

JET AIRCRAFT EMISSIONS

POLLUTANT	CRITICAL OPERATING CONDITION	TYPICAL EMISSION LEVELS, g/KG FUEL	MAJOR CAUSES
HYDROCARBONS	IDLE	7-75	POOR FUEL ATOMIZATION LEAN FUEL-AIR RATIOS LOW COMBUSTOR PRESSURE AND TEMPERATURE
CARBON MONOXIDE	IDLE	30-77	
OXIDES OF NITROGEN	TAKEOFF	13-40	HIGH FLAME TEMPERATURE
SMOKE	TAKEOFF	SAE SMOKE NUMBER 20-65	HIGH PRESSURE RICH FUEL-AIR RATIOS

Figure 3.

TURBOFAN ENGINE

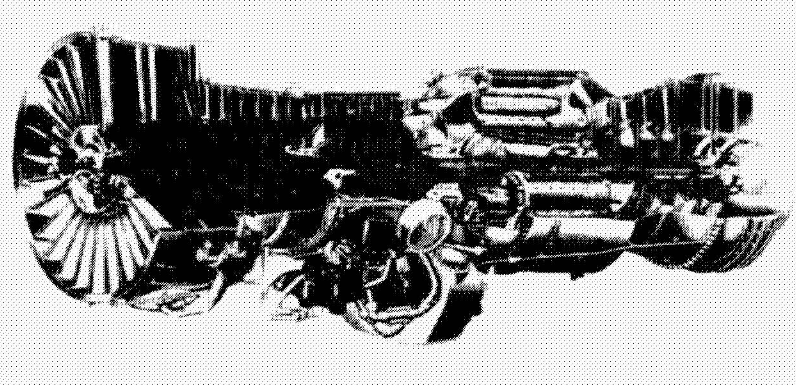


Figure 4.

E-6938

CONVENTIONAL ANNULAR COMBUSTOR

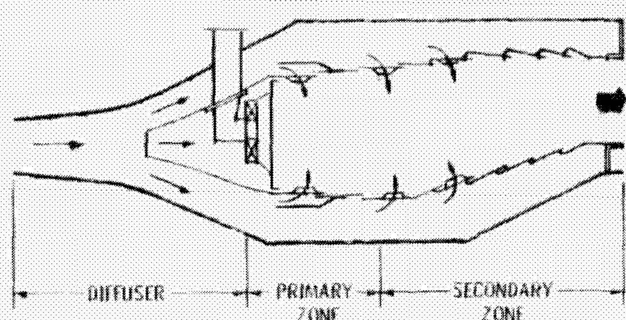


Figure 5.

TURBOJET ENGINE WITH AFTERBURNER

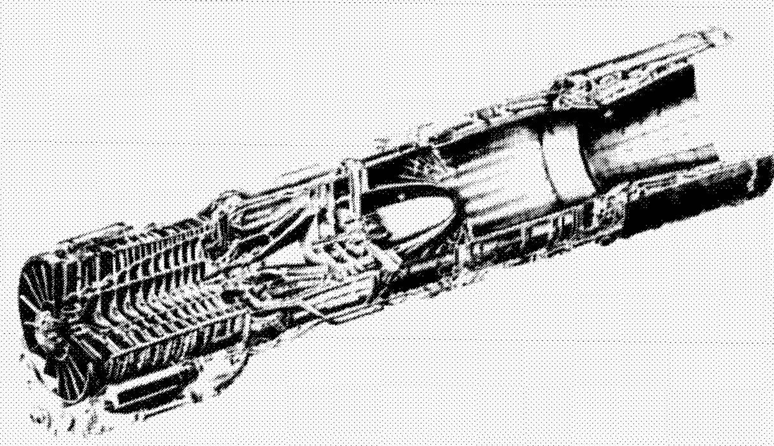


Figure 6.

E-6938

CRUISE OPERATING CONDITIONS

	TURBOFAN	AB TURBOJET
CRUISE MACH NO.	0.85	2.7
CRUISE ALTITUDE, FT	35 000	65 000
COMBUSTOR INLET TEMP, °F	820	1100
COMBUSTOR INLET PRESSURE, PSIA	150	90
COMBUSTOR REF VELOCITY, FT/SEC	70	140
COMBUSTOR FUEL-AIR RATIO	0.02	0.018
AB INLET TEMP, °F	------	1600
AB INLET PRESSURE, PSIA	------	25
AB INLET VELOCITY, FT/SEC	------	500
AB FUEL-AIR RATIO	------	0.005
TOTAL FUEL FLOW, LB/HR (PER ENGINE)	5100	22 000

Figure 7.

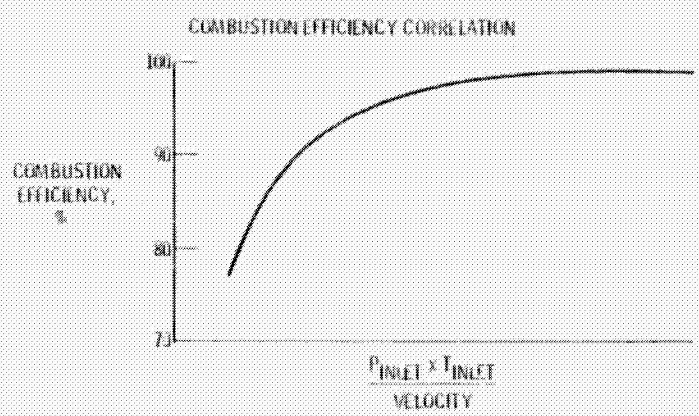


Figure 8.

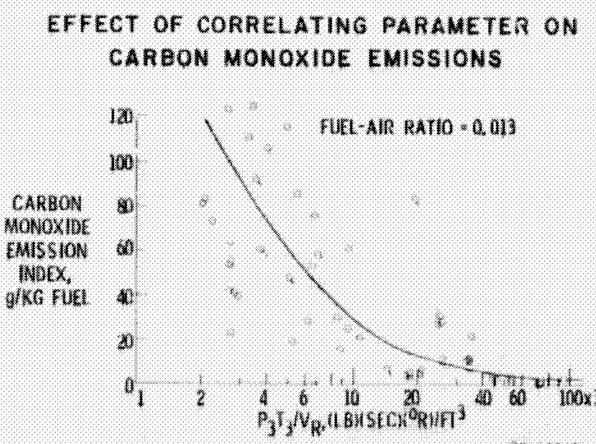
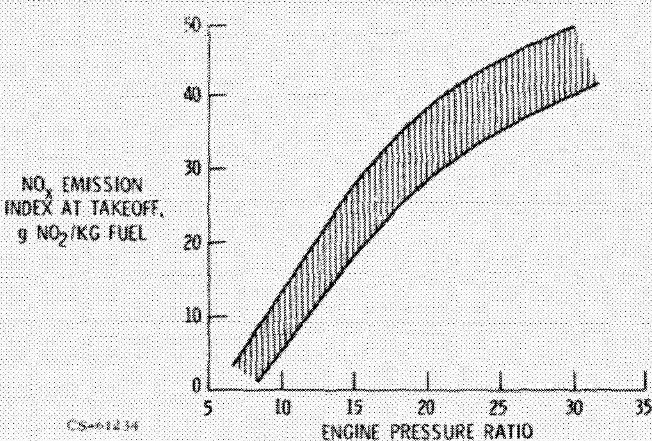


Figure 9.

E-6938

EFFECT OF ENGINE PRESSURE RATIO ON NO_x EMISSIONS



CS-61234

Figure 10.

EFFECT OF COMBUSTOR-INLET CONDITIONS ON NO_x FORMATION

INCREASES IN PARAMETER	EFFECT ON NO_x
COMBUSTOR-INLET TEMP	GREAT INCREASE
COMBUSTOR-INLET PRESSURE	INCREASE
COMBUSTOR REFERENCE VELOCITY	DECREASE
FUEL-AIR RATIO	INCREASE

Figure 11.

CS-61235

E-6938

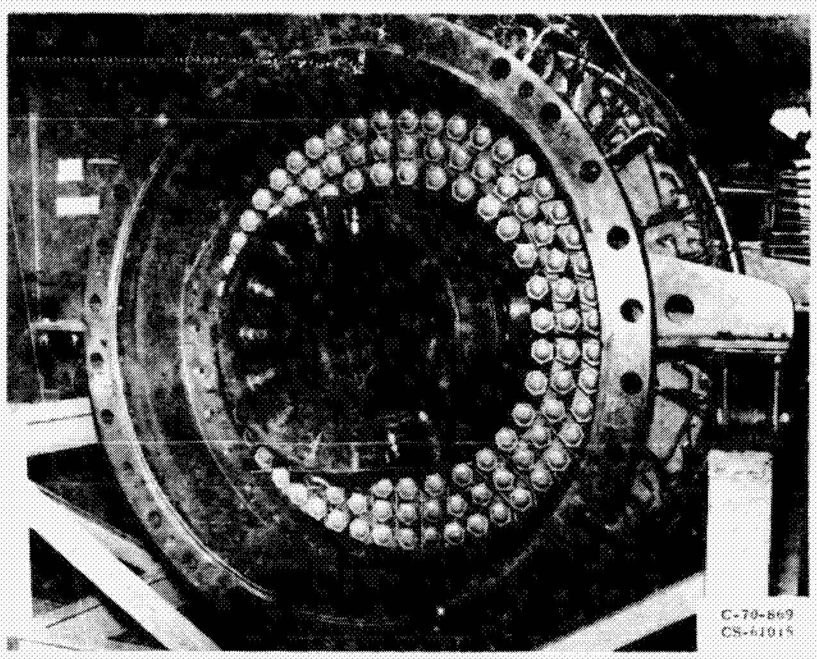


Figure 12.

CROSS-SECTIONAL SKETCH OF HIGH TEMPERATURE SWIRL-CAN COMBUSTOR

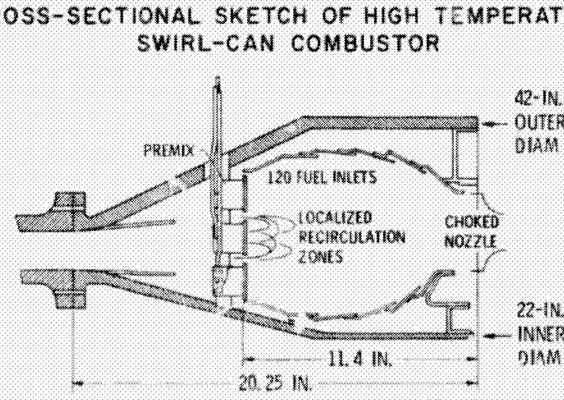


Figure 13.

COMBUSTOR MODULE DETAILS

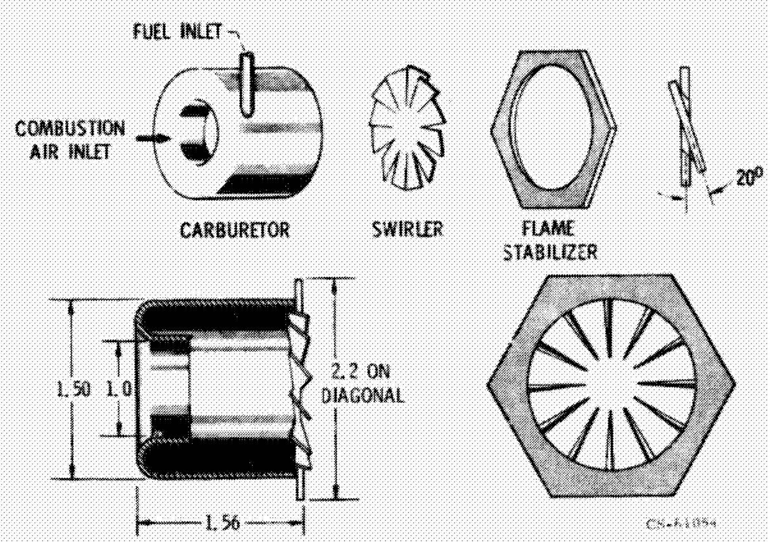


Figure 14.

EFFECT OF INLET TOTAL TEMPERATURE ON EMISSION INDEX FOR OXIDES OF NITROGEN

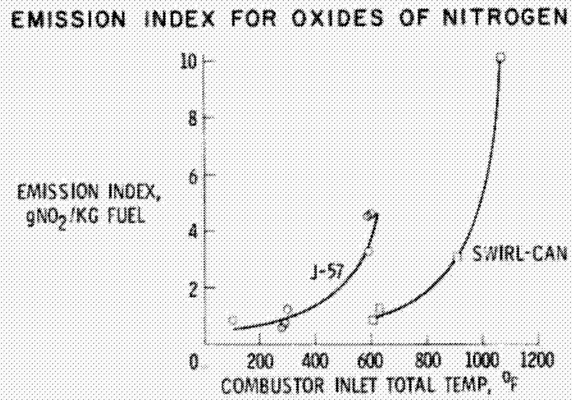


Figure 15.