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Engine Exhaust Emission Levels

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As a part of the U.S. Department of Transportation's Climatic Impact Assessment Program (CIAP), the exhaust emission products from a YJ93-GE-3 afterburning turbojet engine were measured under simulated flight conditions. The results show that the emission indices for both the formation of carbon monoxide (CO) and total unburned hydrocarbons (THC) increase with increasing altitude at constant Mach number; both decrease with increasing Mach number at constant altitude. The results also show that the emission index for nitric oxide (NO) formation increases with increasing Mach number at constant altitude and decreases with increasing altitude at constant Mach number.

Introduction

THE United States Department of Transportation is conducting a Climatic Impact Assessment Program (CIAP). The objective of this program, as defined by its director, Dr. A. J. Grobecker, is "to assess, by report in 1974, the impact of the environmental and meteorological changes due to a world high-altitude vehicle fleet as projected to 1990."[1] During the initial planning for CIAP the primary concern was directed toward the impact of supersonic aircraft. However, as reported by W. B. Beckwith[2] and J. F. Leach et al.[3], it has become apparent that there is already a significant number of subsonic aircraft flights in the stratosphere. Consequently, CIAP is now concerned with any and all vehicles that may be operating in the stratosphere in 1990.

The measurement of the exhaust emissions from several existing engines under simulated flight conditions is included in the various projects of CIAP. This paper presents and discusses some of the results of one of the measurement tests.

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Test Description

The test covered herein was conducted in July 1972 in the Engine Test Facility at the U.S. Air Force Arnold Engineering Development Center (AEDC) near Tullahoma, Tennessee. A General Electric YJ93-GE-3 engine, originally used in the XB-70 supersonic bomber, was used for the test. The YJ93-GE-3 engine is an afterburning turbojet engine designed for cruise at a Mach 3 flight speed.

Exhaust emission measurements were made over a range of altitudes from sea level to 75,000 ft and a range of flight speeds from zero to Mach 2.6. Two power settings were used at almost all altitudes. These power settings were: 1) maximum nonafterburning or military power, and 2) partial afterburning power simulating a supersonic cruise condition. At sea level a variable engine rpm test was conducted. At several conditions variable afterburner fuel/air ratio tests were run.

The test was conducted at AEDC in altitude cell J-2, which is 20 ft in diam. In the cell, the engine inlet and exhaust conditions are controlled to simulate the conditions of temperature, pressure, and airflow equivalent to what the engine would experience in flight.

On-line instrumentation was used to measure the exhaust products of interest in this study. The exhaust gas sampling system was designed insofar as practicable to meet the requirements of SAE Aerospace Recommended Practice (ARP) 1256, "Procedures for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines." A single-point sampling probe

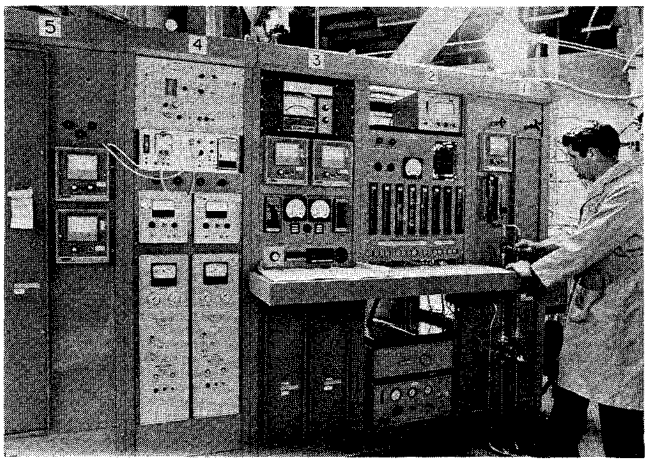

Fig. 1. AEDC engine exhaust emissions instrument package.

was mounted on a traversing mechanism that permitted the probe to be positioned to any location in the engine exhaust stream. The plane of the sampling probe was approximately 5 in. downstream of the engine exhaust nozzle. The probe was connected to the instruments, which were located outside the test cell, by a 50-ft sampling line. The line temperature was maintained at 150°C in accordance with ARP 1256. The line was sized to ensure a residence time of the gas sample in the line of not more than 2 sec. The probe and all but 6 ft of the line were made of Type 316 stainless steel. The 6-ft section was of Teflon to provide the required flexibility at the probe traversing mechanism.

Instruments were available to measure the substances listed in Table 1 even though satisfactory measurements were not obtained with all instruments all the time. The commercially available instruments obviously were not ideally suited for use under the conditions of this test. In fairness to the manufacturers of the instruments, it must be acknowledged that none of the instruments were designed for those conditions. By giving careful attention to detail in the design, installation, and operation of the instrument package (Fig. 1), having infinite patience, and calibrating the instruments at frequent intervals, the people at AEDC were able to obtain good data with the available instruments. A complete description of the instrumentation arrangement has been given by J. L. Grissom.[4]

Results and Analysis

The quantity of data obtained was large, including more than 150 data points, with measurements of several substances at each point. A preliminary report of the test results was presented by D. L. Davidson and J. L. Neely.[5]

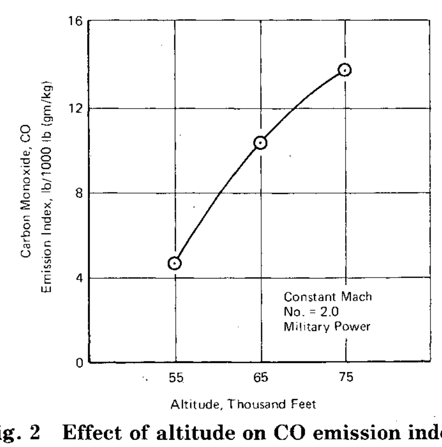

Fig. 2 Effect of altitude on CO emission index.

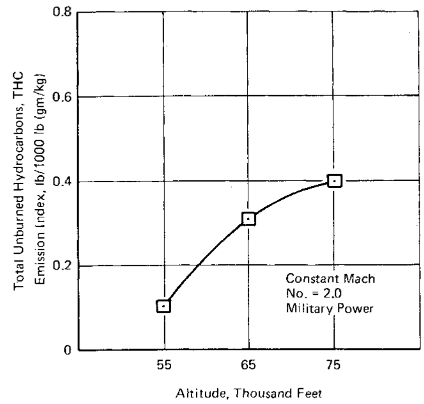

Fig. 3 Effect of altitude on THC emission index.

Final corrected data have not been available long enough at the time of this writing to permit complete analysis; the intent is to cover a few points considered to be of particular interest.

In 1971 the Federal Aviation Administration made arrangements with the Naval Air Systems Command to measure the emissions from a TF30 engine. J. L. Palcza reported the results of that test. That report concludes, "Test results indicated that, within areas of efficient engine component operation, altitude and Mach number effects on emission level were negligible."[6] The results of the YJ93 test do not confirm that conclusion.

Figures 2 and 3 show the YJ93 test results at three different altitudes and constant Mach number for carbon monoxide (CO) and total unburned hydrocarbons (THC) respectively. It can be observed that the emission indices for CO and THC increase with increasing altitude. This

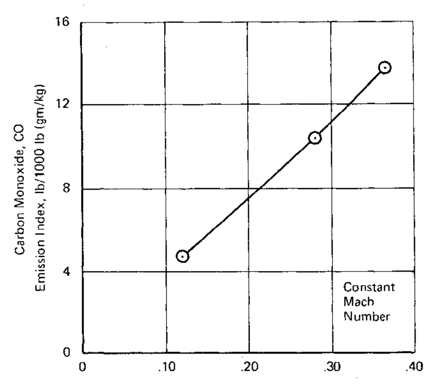

Fig. 4 Effect of combustion inefficiency on CO emission index.

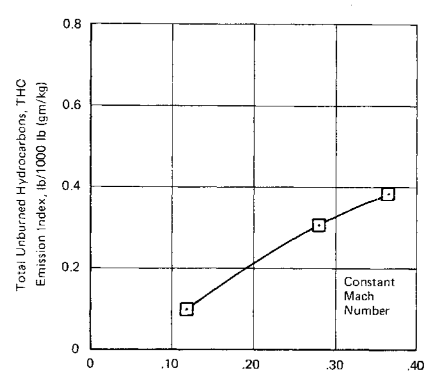

Fig. 5 Effect of combustion inefficiency on THC emission index.

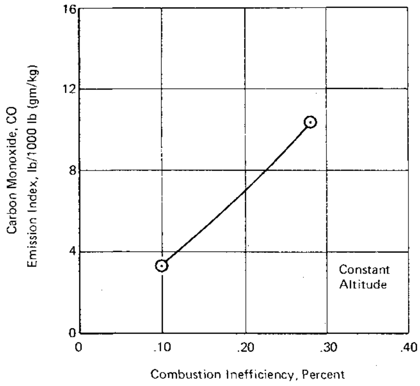

Fig. 6 Effect of combustion inefficiency on CO emission index.

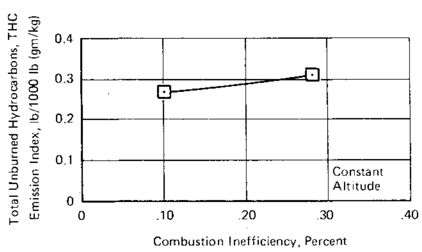

Fig. 7 Effect of combustion inefficiency on THC emission index.

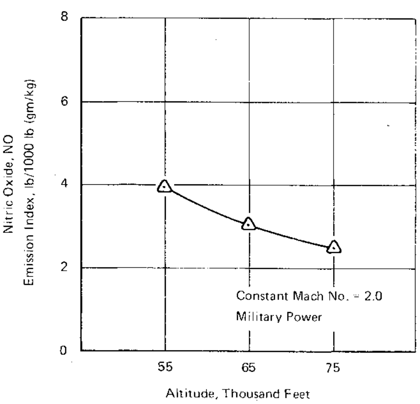

Fig. 8 Effect of altitude on NO emission index.

result is expected. The amount of CO and THC in the exhaust of an aircraft gas turbine is a function of the combustion efficiency. There is a slight reduction in the combustion efficiency in the YJ93 engine with increasing altitude above 55,000 ft. This reduction is best shown in Figs. 4 and 5, where the CO and THC are plotted against combustion inefficiency. These two curves clearly show the significant increase in CO and THC with increasing combustion inefficiency. Figures 6 and 7 show the CO and

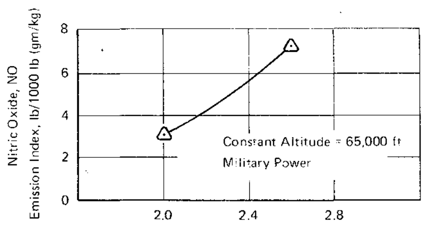

Fig. 9 Effect of Mach number on NO emission index.

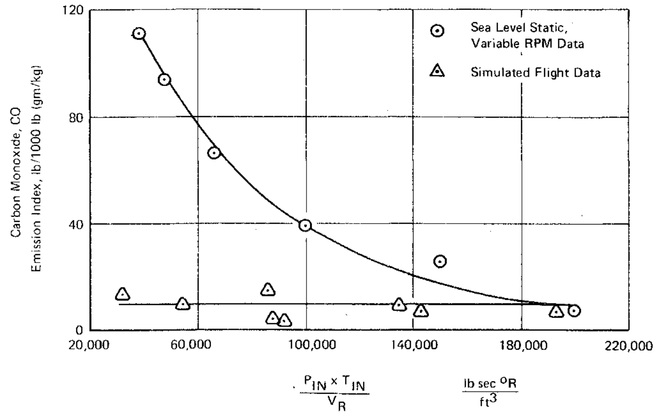

Fig. 10 Correlation of CO emission index with NASA combustor inlet parameter.

THC emission indices, respectively, plotted against combustion inefficiency for two different Mach numbers at constant altitude. Increasing the Mach number decreases slightly the combustion inefficiency with a consequent reduction in the CO and THC emission indices.

Figure 8 shows the change in the nitric oxide (NO) emission index with increasing altitude at constant Mach number. It can be observed that for NO there is a reduction in the emission index with increasing altitude. This result too is expected. The NO emission index decreases with the decreasing combustion chamber pressure, which occurs with increasing altitude at constant Mach number. Figure 9 shows the effect of a change in Mach number at constant altitude on the NO emission index. Again the results are as expected. The combustion chamber pressure and temperature increase with increasing Mach number. Both these changes cause an increase in the NO emission index.

The National Aeronautics and Space Administration (NASA) has published some emission data with the CO

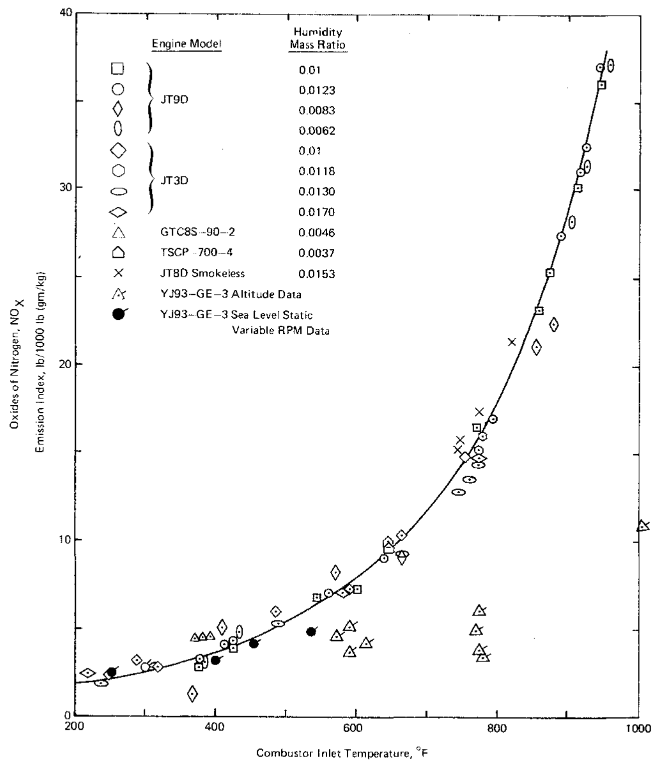

Fig. 11 Correlation of NO_x emissions data with combustor inlet temperature.

Table 1 Engine exhaust emissions instruments

Species	Type of instrument
Carbon monoxide (CO)	Nondispersive infrared (NDIR)
Carbon dioxide (CO_2)	Nondispersive infrared (NDIR)
Nitric oxide (NO)	Nondispersive infrared (NDIR)
Nitric oxide (NO)	Chemiluminescence (CID)
Nitrogen dioxide (NO_2)	Nondispersive untraviolet (NDUV)
Oxides of nitrogen (NO_x)	Chemiluminescence plus thermal converter (CID+)
Total unburned hydrocarbons (THC)	Flame ionization detector (FID)

emission index plotted against a parameter consisting of the product of combustion chamber inlet temperature and pressure divided by an airflow reference velocity.[7] Figure 10 shows the results of the YJ93 test plotted against that same parameter. The sea level static variable rpm data correlate with the NASA parameter, but the altitude data plot, for all practical purposes, is a horizontal straight line. There appears to be no value in using this parameter for altitude correlations.

W. S. Blazowski and R. E. Henderson have plotted additional data[8] to that presented in the Cornell report of L. Bogdan and H. T. McAdams[9] to the F. W. Lipfert correlation[10] of the NO_x emission index with combustion chamber inlet temperature. Figure 11 shows data from the YJ93 test also plotted against combustion chamber inlet temperature. Again a fair correlation is observed for the sea level static variable rpm run but not for the data obtained at altitude.

Conclusions

Although there is still a great deal of analysis and study to be made of the data obtained during this test, some conclusions are evident at this point.

1) Altitude and Mach number do have measurable effects on the emission levels of the YJ93-GE-3 engine.

2) Emission levels cannot be directly correlated to altitude and Mach number, but apparently they can be correlated to combustion conditions.

3) Some correlation parameters useful for sea level static conditions are of no value for altitude conditions.

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