MEASUREMENT OF GASEOUS EMISSIONS FROM A TURBOFAN ENGINE AT SIMULATED ALTITUDE CONDITIONS

by Larry A. Diehl and James A. Biaglow

Lewis Research Center
Cleveland, Ohio 44135
MEASUREMENT OF GASEOUS EMISSIONS FROM A TURBOFAN ENGINE AT SIMULATED ALTITUDE CONDITIONS

Larry A. Diehl and James A. Biaglow

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio 44135

National Aeronautics and Space Administration
Washington, D.C. 20546

Gaseous emissions from a TFE 731-2 turbofan engine were measured over a range of fuel-air ratios from idle to full power at simulated altitudes from near sea level to 13,200 m. Carbon monoxide and unburned hydrocarbon emissions were highest at idle and lowest at high power settings; oxides of nitrogen exhibited the reverse trend. Carbon monoxide and unburned hydrocarbon levels increased while oxides of nitrogen levels decreased with increasing altitude. Oxides of nitrogen emissions were successfully correlated by a parametric group of combustor operating variables.

Air pollution; Combustion; Combustion products; Exhaust gases; Exhaust products; Fuel combustion; Jet engines; Gas turbine engines; Turbofan engines

Unclassified - unlimited
Category 33

For sale by the National Technical Information Service, Springfield, Virginia 22151
MEASUREMENT OF GASEOUS EMISSIONS FROM A TURBOFAN ENGINE AT SIMULATED ALTITUDE CONDITIONS

by Larry A. Diehl and James A. Biaglow

Lewis Research Center

SUMMARY

Gaseous emissions from a TFE 731-2 turbofan engine were measured over a range of fuel-air ratios from idle to full power at simulated altitudes from near sea level to 13,200 meters and flight Mach numbers of 0.6 and 0.8. Gas samples were collected at the core engine exit and were analyzed for carbon monoxide, unburned hydrocarbons, oxides of nitrogen, and carbon dioxide.

Carbon monoxide and unburned hydrocarbon emissions were highest at idle and lowest at high power settings; oxides of nitrogen exhibited the reverse trend. As the altitude was increased, carbon monoxide and unburned hydrocarbons increased. Oxides of nitrogen emissions decreased with increasing altitude.

A correlating parameter consisting of combustor variables was successful in correlating the emissions of oxides of nitrogen to within an emission index value of ±0.5 for the range of test conditions investigated.

INTRODUCTION

The purpose of this report is to document the gaseous emissions from a turbofan engine at various simulated altitudes. Particular emphasis was placed on measurement of the oxides of nitrogen.

In preparation for formulating emissions standards for aircraft gas turbines the Environmental Protection Agency undertook an extensive program of engine emission testing. The results of these studies are presented in reference 1. As the primary purpose of these data was to assess the environmental impact of pollutant emissions in the vicinity of the airport, all data were gathered at ground level static conditions.

The effect of high-altitude vehicle flight on the environment and meteorology is also of concern. The Climatic Impact Assessment Program of the Department of
Transportation (ref. 2) addresses itself directly to this problem. For constant Mach number flight the anticipated effect of altitude on gaseous emissions is to increase carbon monoxide and unburned hydrocarbons and to decrease the oxides of nitrogen. Experimental data from recent studies (refs. 3 and 4) have exhibited this trend with turbojet engines. This report presents data from a turbofan engine.

Measurements of engine exhaust emissions were made on a TFE 731-2 turbofan engine tested in an altitude test cell. The test conditions included simulated altitudes from 640 to 13,200 meters and flight Mach numbers of 0.6 and 0.8. Additional data were taken at a constant engine inlet-air temperature of 294 K (70°F) with varying pressure altitudes. It was hoped that some correlation could be found between the two sets of data as all engine altitude test facilities do not have the required refrigerated air capacity to simulate wide ranges of altitude and flight Mach number. A successful correlation would obviate the requirements of conducting engine tests with refrigerated air. All tests were conducted with ASTM Jet-A fuel. Exhaust gas samples were continuously analyzed for oxides of nitrogen, unburned hydrocarbons, carbon monoxide, and carbon dioxide.

APPARATUS

Engine

The TFE 731-2, shown schematically in figure 1, is a twin-spool turbofan engine consisting of a geared fan and a four-stage axial compressor driven by a three-stage axial turbine and a single-stage centrifugal compressor driven by a single-stage axial turbine. The annular combustor is a reverse-flow design. The engine has a rated sea-level static thrust of 15,560 newtons (3500 lb) and a bypass ratio of 2.67. The fan and cycle pressure ratios are 1.54 and 15.09, respectively.

Facility

The engine was installed in the propulsion systems laboratory altitude chamber at the Lewis Research Center. This facility is capable of simulating altitudes from near sea level to 24,000 meters (80,000 ft) at airflow rates of 220 and 23 kilograms per second (480 and 50 lb/sec), respectively. Facility air handling equipment was available to supply sufficient flow rates at pressures and temperatures necessary to simulate the Mach number range from static to 1.5 at sea level. The thrust stand was not used for these tests.
The engine was instrumented to record and monitor the engine operating parameters. The measurements were recorded by the Lewis central automatic digital data acquisition system (ref. 5).

Gas Sample Probe

The uncooled stainless-steel probe used in these tests is shown in figure 2. It was located at the exit plane of the engine core. Four sampling holes of 0.15-centimeter (0.060-in.) diameter in each arm were spaced so that the sample was collected in four quadrants at the center of four equal annular areas of the core engine tailpipe. This design conforms to SAE recommendations (ref. 6). The four sampling arms were brought to a common manifold in the central mixing chamber.

Gas Sample System

Approximately 14 meters (45 ft) of 0.95-centimeter (3/8-in.) stainless-steel line was used to transport the sample to the analytical instruments. In order to prevent condensation of water and to minimize adsorption-desorption effects of hydrocarbon compounds, the line was heated with steam at 428 K (310° F). For the majority of test conditions a heated metal bellows pump was required to supply sufficient pressures, 69 kilonewtons per square meter (10 psig), to operate the analytical instruments. At the higher simulated altitude conditions the pump capacity was sufficient to provide a line residence time of about 5 seconds, while at lower simulated altitudes the line residence time was about 1 second.

The exhaust gas analysis system (fig. 3) is a packaged unit consisting of four commercially available instruments along with associated peripheral equipment necessary for sample conditioning and instrument calibration. In addition to visual readout, electrical inputs are provided to the IBM 360 computer for on-line analysis and evaluation of the data.

The hydrocarbon content of the exhaust gas is determined by a flame ionization detector hydrocarbon analyzer.

The concentration of the oxides of nitrogen is determined by a chemiluminescent analyzer. The instrument includes a thermal converter to reduce nitrogen dioxide (NO₂) to nitric oxide (NO) and was operated at 973 K (1290° F).

Both carbon monoxide (CO) and carbon dioxide (CO₂) analyzers are of the nondispersive infrared (NDIR) type. The CO analyzer has four ranges: 0 to 100 ppm, 0 to 1000 ppm, 0 to 1 percent, and 0 to 10 percent. These ranges of sensitivity are
accomplished by using stacked cells of 0.64- and 33-centimeter (0.25- and 13.5-in.) length. The CO₂ analyzer has two ranges, 0 to 5 percent and 0 to 15 percent, with a sample cell length of 0.32 centimeter (0.125 in.).

**ANALYTICAL PROCEDURE**

All analyzers were checked for zero and span prior to the test. Solenoid switching within the console allows rapid selection of zero, span, or sample modes. Therefore, it was possible to perform frequent checks to ensure the calibration accuracy without disrupting testing.

Where appropriate, the measured quantities were corrected for water vapor removed. The correction includes both inlet air humidity and water vapor from combustion. The equations used are given in reference 6.

The emission levels of all the constituents were converted to an emission index parameter EIₜ. The emission index is defined as

\[
EI_X = \frac{M_X}{M_e} \frac{1 + f}{f} [X] \times 10^{-3}
\]

where

- \( EI_X \): emission index for \( X \), g \( X \)/kg fuel burned
- \( M_X \): molecular weight of \( X \)
- \( M_e \): average molecular weight of exhaust gas
- \( f \): fuel-air ratio
- \([X]\): measured concentration of \( X \), ppm

The fuel-air ratio may be computed from the measured exhaust gas products as proposed in reference 6, or alternatively, the metered fuel-air ratio may be used, when it is accurately known. Both procedures yield identical results when the sample validity is good. For this report the value computed from the measured emissions was used.

**TEST CONDITIONS**

The engine test conditions are presented in table I. Facility limitations prohibit the operation of the engine with the altitude chamber at atmospheric pressure. Thus, true sea-level static operation was not obtained. The lowest simulated altitude was 640
meters. The engine was operated at simulated flight Mach numbers of 0.6 and 0.8, and the engine inlet-air temperature was controlled to match that of actual altitude ram conditions. At each of these conditions the fuel-air ratio was varied over a limited range.

Additional test data shown in table II were taken at varying pressure altitudes with a constant engine inlet-air temperature. At each of these pressure altitude conditions the fuel-air ratio was varied over a limited range.

RESULTS AND DISCUSSION

The emission data obtained during the test program are presented in tables I and II.

Carbon Monoxide Emissions

The carbon monoxide emission index is shown in figure 4 as a function of the combustor fuel-air ratio. Also shown for comparison are supplementary data taken at a constant engine inlet-air temperature of 294 K (70°F).

With increasing combustor fuel-air ratio carbon monoxide emissions decreased. The maximum emission levels occurred at engine idle, while the reduced emissions at higher fuel-air ratios corresponded to nominal cruise conditions. At a given altitude the small change in flight Mach number resulted in minor changes in combustor inlet temperature and pressure and hence negligible effect on combustor efficiency as manifest by CO emissions. Increasing altitude with a constant cruise power setting produced little effect until the 13200-meter condition was reached. At this altitude CO emissions were increased, as evidenced by the separate curve in figure 4. As shown in table I, it was not until this condition was reached that increasing altitude resulted in reduced combustor inlet temperature and pressure.

Unburned Hydrocarbon Emissions

The flame ionization detector used to measure hydrocarbons is calibrated to count carbon atoms, and the results are expressed as parts per million carbon (ppm C). In order to calculate a value for the emission index, it is necessary to make some assumption as to the structure of the unburned hydrocarbon molecule. The assumed form was CH₂.

The unburned hydrocarbon data are presented in figure 5 as a function of the combustor fuel-air ratio. In general, the emission values were quite low. The maximum
values occurred at idle and decreased with increasing throttle setting. At the cruise throttle setting all the emission index values were less than 0.2, which implies a combustion inefficiency due to unburned hydrocarbons of less than 0.02 percent. The variation shown in the data at these low levels was due to data scatter involved in making measurements of 6 ppm C or less.

At a constant cruise throttle setting the highest emission index value occurred at the 13 200-meter-altitude condition. However, care should be taken in placing too great a significance on this for the reasons just discussed.

Oxides of Nitrogen Emissions

Among other things, the production of oxides of nitrogen (NO\textsubscript{x}) is dependent on the water content (humidity) of the air. As proposed in reference 7, NO\textsubscript{x} data may be corrected to zero humidity by multiplying by the factor $e^{19H}$, where $H$ is grams of water per gram of air. For these tests the conditioned air had a humidity of 0.0005 gram of water per gram of air. The humidity correction may then be safely neglected with a consequent error of less than 1 percent. The remainder of this section discusses the engine NO\textsubscript{x} production in terms of the combustor operating conditions.

The oxides of nitrogen emission index is presented in figure 6. When plotted on semilogarithmic coordinates the data displayed the anticipated straight line relation, which indicates NO\textsubscript{x} formation is an exponential function of combustor inlet-air temperature. This result was first implied by Lipfert (ref. 8) and recently by more extensive correlations (refs. 7 and 9). For altitudes greater than 4570 meters there was a distinct decrease in NO\textsubscript{x} with increasing altitude. The NO\textsubscript{x} emissions were more sensitive to changes in combustor operating conditions than either carbon monoxide or unburned hydrocarbons. At a constant inlet-air temperature increasing altitude resulted in decreasing combustor pressure and increasing combustor reference Mach number (see table I). Both effects resulted in less NO\textsubscript{x} being formed.

As mentioned previously, the effect of combustor inlet-air temperature on NO\textsubscript{x} formation is exponential. Data taken from references 7 and 9 indicate that NO\textsubscript{x} emission index varies with combustor reference Mach number to the -1 power, and data taken from references 7, 9, 10, and 11 indicate that the NO\textsubscript{x} emission index varies with pressure to approximately the 0.5 power. In addition, the NO\textsubscript{x} correlation of references 7 and 9 indicates a dependence on combustor exit temperature. In view of these factors, an attempt was made to correlate the NO\textsubscript{x} emission data on the basis of the measured combustor operating parameters. In this case the parameters were grouped as follows:
\[
e^{0.5 - 1.5 \times 10^4} \frac{f}{M_3}
\]

where

\(\theta\) combustor inlet total temperature normalized to standard sea-level temperature of 288 K (518.68° R)

\(\delta\) combustor inlet total pressure normalized to standard sea-level pressure of 10.13 N/cm² (14.696 psia)

\(f\) fuel-air ratio (which is a measure of the exit temperature)

\(M_3\) combustor inlet Mach number

The results of correlating NO\(_x\) emissions with these parameters are shown in figure 7. Also shown for comparison are the data of table II, where the engine was run with nonrefrigerated air. The latter data appear to define a curve which lies above the rest of the data. However, the parameter does correlate the two sets of data within an emission index span of 1. The correlation of all the data was improved by increasing the dependence on the combustor inlet-air temperature. Increasing the exponential temperature dependence to a factor of 2 (ref. 7 has determined 1.14) improved the correlation of NO\(_x\) emissions, as shown in figure 8. This indicates that characterization of the engine NO\(_x\) emissions could be obtained without running refrigerated inlet air providing the correct correlating parameters are known. It is not clear whether this correlating parameter may apply to other engines. Additional test data for a variety of engines are required.

An attempt was made to correlate the carbon monoxide and unburned hydrocarbon emissions by using this parameter. The results are not significantly different from those presented in figures 4 and 5 as a function of combustor inlet-air temperature alone.

Figure 9 shows the nitric oxide fraction of the total oxides of nitrogen. Considerable scatter exists in the data at the low power conditions. An indicated average ratio NO/NO\(_x\) of 0.5 to 0.6 at idle and 0.9 to 0.95 at high power puts the data of this report in agreement with the data of references 4 and 12.

Comparison With Data From Reference 1

The data are compared in table III with data from an identical model engine presented in reference 1. Since the data presented in this report were taken at various altitudes and the data of reference 1 were taken in a sea-level test bed, only the 640-meter-altitude data were compared. The two sets of data compare very well with the largest
discrepancy occurring in the CO measurement at takeoff. At this condition the CO emission index was sensitive to instrument accuracy and to combustor inlet conditions (fig. 4).

Sample Validity

The measured values of CO, CO₂, and unburned hydrocarbons were used to compute an emission based fuel-air ratio, and this value was compared with the metered fuel-air ratio. The emission based fuel-air ratio was computed by the method suggested in reference 6. Results of this computation are shown in figure 10. At the high power settings the agreement was within ±10 percent. Sample validity at the low power settings was poor with the greatest discrepancy occurring at idle. In general, there is a high potential for sampling errors at idle with fixed position rakes because of the large concentration gradients in the plume at this condition.

SUMMARY OF RESULTS

Gaseous emissions from a TFE 731-2 turbofan engine were measured over a range of fuel-air ratios from idle to full power, at simulated altitudes from near sea level to 13,200 meters, and at flight Mach numbers of 0.6 and 0.8. Pollutant emissions obtained for carbon monoxide, unburned hydrocarbons, and oxides of nitrogen gave the following results:

1. Carbon monoxide and unburned hydrocarbon emissions were highest at idle and decreased with increasing throttle. At the highest altitude tested reduced combustor inlet temperature and pressure resulted in increased carbon monoxide and hydrocarbon emissions.

2. Oxides of nitrogen emissions were lowest at idle and increased with increasing throttle. Increasing altitude resulted in decreased oxides of nitrogen emissions. At idle the oxides of nitrogen consisted of 50 to 60 percent nitric oxide, which increased to 90 to 95 percent at high power levels.

3. Oxides of nitrogen were correlated to within an emission index value of ±0.5 by the parametric group \( e^{2\theta \delta} \delta^{0.5} f^{1.5} / M_3 \), where \( \Theta \) is combustor inlet total temperature normalized to standard sea-level temperature of 288 K (518.68° R), \( \delta \) is combustor inlet total pressure normalized to standard sea-level pressure of 10.13 newtons per square centimeter (14.696 psia), \( f \) is fuel-air ratio, and \( M_3 \) is combustor inlet Mach number. The correlation was successful for the range of altitude test conditions investigated and
also successfully correlated additional altitude data taken at a constant engine inlet-air temperature. It is not known if the correlation applies to other engine-combustor configurations.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 18, 1974,

REFERENCES


<table>
<thead>
<tr>
<th>Test condition</th>
<th>Altitude, m</th>
<th>Mach number</th>
<th>Fuel-air ratio</th>
<th>Combinator inlet temperature, $T_3$, K</th>
<th>Normalized combustor inlet total pressure, $\delta$</th>
<th>Oxides of nitrogen ppm g/kg fuel</th>
<th>NO/NO$_X$ ppm</th>
<th>Carbon monoxide ppm g/kg fuel</th>
<th>Hydrocarbons ppm g/kg fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idle</td>
<td>640</td>
<td>---</td>
<td>0.008</td>
<td>371</td>
<td>1.87</td>
<td>12.8</td>
<td>1.89</td>
<td>0.690</td>
<td>290</td>
</tr>
<tr>
<td></td>
<td></td>
<td>---</td>
<td>0.008</td>
<td>371</td>
<td>1.87</td>
<td>13.1</td>
<td>1.94</td>
<td>0.690</td>
<td>292</td>
</tr>
<tr>
<td></td>
<td></td>
<td>---</td>
<td>0.010</td>
<td>486</td>
<td>4.26</td>
<td>36.0</td>
<td>4.59</td>
<td>0.700</td>
<td>254</td>
</tr>
<tr>
<td></td>
<td></td>
<td>---</td>
<td>0.010</td>
<td>486</td>
<td>4.25</td>
<td>36.2</td>
<td>4.63</td>
<td>0.700</td>
<td>257</td>
</tr>
<tr>
<td>30 Percent power</td>
<td>640</td>
<td>---</td>
<td>0.016</td>
<td>656</td>
<td>11.2</td>
<td>133</td>
<td>13.3</td>
<td>0.934</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>---</td>
<td>0.016</td>
<td>656</td>
<td>11.1</td>
<td>133</td>
<td>13.3</td>
<td>0.934</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td></td>
<td>---</td>
<td>0.016</td>
<td>658</td>
<td>11.1</td>
<td>135</td>
<td>13.4</td>
<td>0.935</td>
<td>57</td>
</tr>
<tr>
<td>Takeoff</td>
<td>640</td>
<td>---</td>
<td>0.016</td>
<td>656</td>
<td>11.2</td>
<td>133</td>
<td>13.3</td>
<td>0.934</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>---</td>
<td>0.016</td>
<td>656</td>
<td>11.1</td>
<td>133</td>
<td>13.3</td>
<td>0.934</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td></td>
<td>---</td>
<td>0.016</td>
<td>658</td>
<td>11.1</td>
<td>135</td>
<td>13.4</td>
<td>0.935</td>
<td>57</td>
</tr>
<tr>
<td>Altitude</td>
<td>4570</td>
<td>0.6</td>
<td>0.005</td>
<td>407</td>
<td>2.15</td>
<td>11.2</td>
<td>2.04</td>
<td>0.828</td>
<td>393</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.010</td>
<td>665</td>
<td>10.01</td>
<td>152</td>
<td>14.6</td>
<td>0.956</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.010</td>
<td>666</td>
<td>10.01</td>
<td>151</td>
<td>14.5</td>
<td>0.956</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.016</td>
<td>646</td>
<td>9.26</td>
<td>124</td>
<td>12.6</td>
<td>0.952</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.016</td>
<td>648</td>
<td>9.24</td>
<td>124</td>
<td>12.7</td>
<td>0.952</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>1340</td>
<td>0.8</td>
<td>0.0105</td>
<td>538</td>
<td>3.62</td>
<td>45</td>
<td>5.88</td>
<td>0.845</td>
<td>236</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.0105</td>
<td>539</td>
<td>3.61</td>
<td>46</td>
<td>5.96</td>
<td>0.845</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.016</td>
<td>641</td>
<td>6.47</td>
<td>116</td>
<td>11.3</td>
<td>0.934</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.016</td>
<td>641</td>
<td>6.50</td>
<td>116</td>
<td>11.3</td>
<td>0.934</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.017</td>
<td>648</td>
<td>6.86</td>
<td>129</td>
<td>12.2</td>
<td>0.948</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.017</td>
<td>648</td>
<td>6.88</td>
<td>130</td>
<td>12.3</td>
<td>0.948</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.016</td>
<td>632</td>
<td>6.39</td>
<td>109</td>
<td>10.9</td>
<td>0.929</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.016</td>
<td>632</td>
<td>6.39</td>
<td>109</td>
<td>10.9</td>
<td>0.929</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>13200</td>
<td>0.8</td>
<td>0.016</td>
<td>607</td>
<td>3.13</td>
<td>83</td>
<td>8.32</td>
<td>0.931</td>
<td>136</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.016</td>
<td>607</td>
<td>3.12</td>
<td>84</td>
<td>8.40</td>
<td>0.932</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.015</td>
<td>591</td>
<td>2.87</td>
<td>73</td>
<td>7.72</td>
<td>0.933</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.015</td>
<td>591</td>
<td>2.88</td>
<td>73</td>
<td>7.98</td>
<td>0.932</td>
<td>173</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.015</td>
<td>586</td>
<td>2.79</td>
<td>70</td>
<td>7.45</td>
<td>0.928</td>
<td>182</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.015</td>
<td>586</td>
<td>2.79</td>
<td>70</td>
<td>7.59</td>
<td>0.928</td>
<td>188</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.017</td>
<td>632</td>
<td>3.51</td>
<td>103</td>
<td>9.53</td>
<td>0.944</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.017</td>
<td>632</td>
<td>3.51</td>
<td>103</td>
<td>9.62</td>
<td>0.944</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.018</td>
<td>622</td>
<td>3.15</td>
<td>98</td>
<td>9.04</td>
<td>0.951</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.018</td>
<td>621</td>
<td>3.14</td>
<td>98</td>
<td>9.04</td>
<td>0.951</td>
<td>105</td>
</tr>
</tbody>
</table>

[Inlet air humidity, 0.0005 g water/g air; all emissions corrected for water removed.]
TABLE II. - MEASURED GASEOUS EMISSIONS FOR TFE 731-2 AT ALTITUDE TAKEN AT
CONSTANT ENGINE INLET TEMPERATURE OF 294 K (70° F)

[All emissions corrected for water removed.]

<table>
<thead>
<tr>
<th>Altitude, m</th>
<th>Fuel-air ratio</th>
<th>Combustor inlet temperature, T3 K</th>
<th>Normalized combustor inlet total pressure, δ</th>
<th>Oxides of nitrogen ppm</th>
<th>NO/NOx g/kg fuel</th>
<th>Carbon monoxide ppm</th>
<th>Hydrocarbons g/kg fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>4150</td>
<td>.0045</td>
<td>416</td>
<td>2.33</td>
<td>10.5</td>
<td>2.43</td>
<td>0.420</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>.005</td>
<td>416</td>
<td>2.33</td>
<td>10.6</td>
<td>2.43</td>
<td>.430</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>.016</td>
<td>673</td>
<td>9.36</td>
<td>142</td>
<td>14.7</td>
<td>.947</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>.016</td>
<td>673</td>
<td>9.36</td>
<td>143</td>
<td>14.6</td>
<td>.947</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>.016</td>
<td>677</td>
<td>11.36</td>
<td>158</td>
<td>15.4</td>
<td>.938</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>.016</td>
<td>677</td>
<td>11.36</td>
<td>159</td>
<td>15.45</td>
<td>.938</td>
<td>48</td>
</tr>
<tr>
<td>9140</td>
<td>.0115</td>
<td>571</td>
<td>3.24</td>
<td>51.4</td>
<td>6.52</td>
<td>.938</td>
<td>181</td>
</tr>
<tr>
<td></td>
<td>.012</td>
<td>571</td>
<td>3.25</td>
<td>51.8</td>
<td>6.60</td>
<td>.938</td>
<td>183</td>
</tr>
<tr>
<td></td>
<td>.017</td>
<td>672</td>
<td>4.78</td>
<td>121</td>
<td>11.6</td>
<td>.949</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>.017</td>
<td>672</td>
<td>4.78</td>
<td>122</td>
<td>11.6</td>
<td>.744</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>.017</td>
<td>676</td>
<td>5.70</td>
<td>128</td>
<td>12.2</td>
<td>.925</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>.017</td>
<td>676</td>
<td>5.69</td>
<td>128</td>
<td>12.3</td>
<td>.925</td>
<td>84</td>
</tr>
<tr>
<td>13200</td>
<td>.0185</td>
<td>654</td>
<td>2.07</td>
<td>90.4</td>
<td>9.0</td>
<td>.914</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td>.018</td>
<td>655</td>
<td>2.04</td>
<td>87.2</td>
<td>8.85</td>
<td>.913</td>
<td>137</td>
</tr>
<tr>
<td></td>
<td>.017</td>
<td>662</td>
<td>2.60</td>
<td>97.1</td>
<td>9.42</td>
<td>.960</td>
<td>112</td>
</tr>
<tr>
<td></td>
<td>.017</td>
<td>662</td>
<td>2.60</td>
<td>97.8</td>
<td>9.50</td>
<td>.960</td>
<td>113</td>
</tr>
<tr>
<td></td>
<td>.017</td>
<td>645</td>
<td>2.38</td>
<td>83.6</td>
<td>8.6</td>
<td>.978</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td>.017</td>
<td>639</td>
<td>2.34</td>
<td>80.9</td>
<td>8.45</td>
<td>.963</td>
<td>141</td>
</tr>
<tr>
<td></td>
<td>.017</td>
<td>640</td>
<td>2.34</td>
<td>81.4</td>
<td>8.54</td>
<td>.963</td>
<td>136</td>
</tr>
</tbody>
</table>

TABLE III. - COMPARISON OF EXPERIMENTAL EMISSION INDEX DATA FOR ALTITUDE OF 640 METERS WITH THOSE OF REFERENCE 1

<table>
<thead>
<tr>
<th>Test condition</th>
<th>Oxides of nitrogen</th>
<th>Carbon monoxide</th>
<th>Unburned hydrocarbons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This report Ref. 1</td>
<td>This report Ref. 1</td>
<td>This report Ref. 1</td>
</tr>
<tr>
<td>Idle</td>
<td>1.92</td>
<td>1.89</td>
<td>51.0</td>
</tr>
<tr>
<td>Approach (30 percent power)</td>
<td>4.61</td>
<td>4.65</td>
<td>19.9</td>
</tr>
<tr>
<td>Takeoff</td>
<td>13.3</td>
<td>14.1</td>
<td>3.4</td>
</tr>
</tbody>
</table>
Figure 1. - TFE 731-2 turbofan engine.

Figure 2. - Uncooled gas sample probe.
Figure 3. - Gas sampling instrument console.
Figure 4. - Carbon monoxide emission index as function of combustor fuel-air ratio at various altitudes.
1 Percent combustion inefficiency due to unburned hydrocarbons

Figure 5. - Unburned hydrocarbon emission index as function of combustor fuel-air ratio at various altitudes.
Figure 6. - Oxides of nitrogen emission index as function of combustor inlet total temperature at various altitudes.

Figure 7. - Oxides of nitrogen correlation showing separation of data for refrigerated and non-refrigerated air cases.
Figure 8. - Refined oxides of nitrogen correlation showing improved fit of data.

Solid symbols denote altitude simulation by pressure only with constant engine inlet temperature of 294 K.

Figure 9. - Nitric oxide fraction of total oxides of nitrogen as function of combustor inlet total temperature at various altitudes.
Solid symbols denote altitude simulation by pressure only with constant engine inlet temperature of 294 K.

Figure 10. - Comparison of fuel-air ratios to check sample validity.
"The aeronautical and space activities of the United States shall be conducted so as to contribute ... to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—National Aeronautics and Space Act of 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons. Also includes conference proceedings with either limited or unlimited distribution.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include final reports of major projects, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546