EFFECT OF AIR TEMPERATURE AND RELATIVE HUMIDITY AT VARIOUS FUEL-AIR RATIOS ON EXHAUST EMISSIONS ON A PER-MODE BASIS OF AN AVCO LYCOMING 0-320 DIAD LIGHT AIRCRAFT ENGINE

VOLUME I - RESULTS AND PLOTTED DATA

by Michael Skorobatckyi, Donald V. Cosgrove, Phillip R. Meng and Erwin E. Kempke, Jr.
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SUMMARY

A carbureted four-cylinder air-cooled 0-320 DIAD Lycoming aircraft engine was tested to establish the effects of ambient air temperature and relative humidity at various fuel-air ratios on exhaust emissions on a per-mode basis (idle, taxi, takeoff, climb, and approach). The test conditions included carburetor leanout for each of the five modes, air temperatures of 50, 59, 80 and 100°F and relative humidities of 0, 30, 60, and 80%. Combinations of these parameters resulted in over 800 different test conditions.

Fuel-air ratio (calculated on the dry basis) showed the strongest single influence on CO, HC and NOx exhaust emissions. The results agree well with known general characteristics of spark ignition piston engines operating over the same range of fuel-air ratio. Ambient conditions influence emissions in two ways. Change in air temperature and/or humidity induces a change in fuel-air ratio due to the variation of air density and displacement of air by water vapor. This results in a dependent change in emissions. In addition, for a constant fuel-air ratio, hot/humid ambient air conditions had a significant further influence on the HC and NOx emissions due to chemical effects on the combustion process. At a rich fuel-air ratio and higher air temperature and relative humidity, the HC emissions increased by as much as 130% in the lower power modes and the NOx emissions decreased by as much as 90% in the higher power modes; whereas the CO emissions were essentially independent of ambient conditions. For any fixed fuel-air ratio and zero humidity, higher air temperature had virtually no effect on CO, HC and NOx emissions in any of the test modes, except for the 20% increase in CO emissions in climb.

The report is presented in two volumes. Volume I (herein) contains the results, plotted data, and microfiche film of the data taken at each of the individual test points. Volume II contains a compilation of the data taken at each of the individual test points. Volume II is included on microfilm at the back of this volume.
INTRODUCTION

NASA is involved in a research and technology program aimed at improving general aviation engines. One major objective of the program is to establish and demonstrate the technology which will safely reduce general-aviation piston-engine exhaust emissions to levels consistent with the EPA 1979 emissions standards.

One element of the above program was a joint FAA/NASA General Aviation Piston Engine Emissions Reduction effort. Funded studies have been completed by the two primary engine firms building general aviation piston engines: Avco-Lycoming and Teledyne-Continental. Each contractor tested five different engine models to experimentally characterize emissions and to determine the effects of variation in fuel-air ratio and spark timing on emissions levels and other operating characteristics such as cooling, misfiring, roughness, power, acceleration, etc. The FAA used its NAPEC facility to perform independent checks on each of the engines the contractors tested. It was recognized early in the program that the tests would be conducted under essentially uncontrolled induction air conditions at widely different geographical locations and that a better understanding of temperature and humidity effects would enhance the ability to make a correlation and better comparison of these data. It was also recognized that such understanding would be extremely useful in future emissions compliance testing. Therefore, NASA-Lewis Research Center has undertaken a series of aircraft engine tests to develop such a correlation. Two engines, models identical to ones in the FAA/NASA program, were selected for testing. The engines were: (1) Lycoming model 0-320 D1AD 4-cylinder, naturally-aspirated carbureted engine; and (2) a Teledyne Continental Model TSIO-360-C, a 6-cylinder turbocharged, fuel injected engine.

The exhaust emissions for the Lycoming 0-320 engine over the EPA emissions test cycle for a range of test conditions were reported in Reference 1. A summary of these baseline cycle test results can be best described by comparing the temperature and humidity results at 100°F and 80 percent humidity with those at 50°F and no humidity, and which shows that with the increased temperature and humidity, CO emissions increased by a factor of 1.6, HC emissions increased by a factor of 2.2, and NOx emissions decreased by a factor of 3.5. Present-day aircraft engines do not use a temperature-density compensated fuel system. Hence, the cited changes in the exhaust emissions are primarily the result of richer-fuel-air ratios, which occur at the higher air temperatures and humidities.

Ambient conditions can also affect the induction vaporization and basic combustion process, thereby influencing the emissions. Therefore, a series of tests were performed to establish these direct effects for different engine operating conditions (load and fuel/air ratio) and ambient conditions. The results are reported herein. This report is printed in two volumes: Volume I contains the plotted test results and microfiche copies of all of the individual test points. Volume II contains the individual data test points in tabular form.
APPARATUS AND PROCEDURE
Test Facility

The aircraft engine is shown schematically in Figure 1 and photographically on the test stand in Figure 2. The engine was coupled to a 300 hp dynamometer through a fluid coupling in the drive shaft which was located under a safety shield. Engine cooling and induction air were both supplied by a laboratory air distribution system. The cooling and induction air system, as shown in Figure 3, can be controlled to deliver air to the engine over a temperature range of from 50\(^\circ\) to 120\(^\circ\) F and over a range of relative humidity from 0 to 80 percent. The cooling air was always at the same conditions as the induction air and was directed down over the engine by an air distribution hood. This hood was the same as that which was used by the engine manufacturer in their engine testing. The engine cooling air was removed from the test cell by a high capacity exhaust system which had the inlet located beneath the engine. An additional cell exhaust fan was used to maintain a slightly negative pressure in the test cell. This was done to vent off any combustible or toxic gases which may have been present in the test cell during engine operation.

The engine exhaust was manifolded together in a standard configuration with the emission sample probe located downstream of the manifold. The exhaust was then ducted out of the cell through the roof as shown in Figure 2. Care was taken to insure that the exhaust system was leak-proof. A leak-proof system was necessary to prevent air dilution of the gas sample which would result in erroneous emission measurements.

Engine Description. The 0-320 DIAD is a horizontally opposed, four cylinder, direct drive, air-cooled engine. The engine has a bore of 5.125 inches and a stroke of 3.875 inches with the resulting total piston displacement being 319.8 cubic inches. The compression ratio is 8.50:1. The engine is rated 160 bhp at 2700 rpm and 0.51 BSFC. Fuel metering is performed by a Marvel-Schebler MA4SPA carburetor using grade 100/130 aviation gasoline. A carburetor intake air box was used to insure uniform pressure distribution across the throat. The carburetor was calibrated for full-rich operation at the factory, typical of what might be expected as the rich limit of production engines. The carburetor, at this calibration, constituted the baseline for the engine. The fuel used was standardized reference fuel conforming to the requirements of the ASTM Committee on Aviation Reference Fuels and Certification. Ignition was supplied by a dual Bendix magneto timed to 25\(^\circ\) BTDC. The engine is further described in AVCO Lycoming Specification 2283-C (Ref. 2).

Engine Exhaust System. There are two major areas of consideration that can affect the accuracy of emission measurements. These are the leak tightness of the engine exhaust system and the handling of the exhaust gas sample through the gas analyzer.

In order to obtain a representative exhaust gas sample for emissions analysis the individual cylinder exhaust tubes were brought together under the engine to a common header. Allowing for proper mixing, the gas sample probe was located approximately 5 ft.
downstream in the common header. Great care was taken in the
design, fabrication and installation of the exhaust system so that
it would not leak air into the exhaust gas upstream of the gas
sample probe. It was found that the combination of exhaust gas
temperature and engine vibration necessitated a number of changes in
the exhaust system before an acceptable leak proof system was
obtained.

Exhaust Gas Sample Handling. The criteria for exhaust gas
analysis were twofold. The sample had to be representative of a
complete mixing from all cylinders and the temperature of the gas
sample at the analyzer had to be at least 300°F. The sample line
from the exhaust gas manifold to the gas analyzer was heated to
300°F using an electrical tape type heater. The Scott analyzer (see
Fig. 4) contained the following five analysis meters:
1. Beckman Model 864 Infrared CO Analyzer
2. Beckman Model 864 Infrared CO₂ Analyzer
3. Scott Model 125 Chemiluminescent NO/NOₓ Analyzer. The
Scott NO/NOₓ Analyzer was modified at NASA-Lewis as
discussed in reference 3.
4. Scott Model 415 Flame Ionization Detector for HC
5. Scott Model 250 Paramagnetic O₂ Detector.
Careful daily monitoring of these sensors indicated a
need for frequent adjustments. It was necessary to zero and span
these instruments with known gases at least once for each
hour of operation. A complete console calibration was carried out
at least once a month.

Instrumentation. The engine instrumentation and control panel
is shown in Figure 5. The major measured parameters and estimated
system accuracies for this investigation are listed below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Instrumentation</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Flow</td>
<td>Hydraulic Wheatstone Bridge Flow Meter</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>Induction Air Flow</td>
<td>Turbine-type Flow Meter</td>
<td>± 0.6%</td>
</tr>
<tr>
<td>Induction Air Press.</td>
<td>Absolute Transducer</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>Cooling Air Flow</td>
<td>Orifice AP Transducer</td>
<td>± 1.5%</td>
</tr>
<tr>
<td>Cooling Air Press.</td>
<td>Absolute Transducer</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>Dew Point</td>
<td>Temp. Controlled Mirrored</td>
<td>± 0.7°F</td>
</tr>
<tr>
<td></td>
<td>Photoelectric Sensor</td>
<td></td>
</tr>
<tr>
<td>Engine Torque</td>
<td>Shaft Mounted Rotary Transformer Type</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>Dyno. Torque</td>
<td>Load Cell</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>Speed</td>
<td>Magnetic Pickup</td>
<td>± 0.25%</td>
</tr>
<tr>
<td>Exh. Gas Temp.</td>
<td>Chrome-Alumel Thermocouple</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>Cyl. Hd. Temp.</td>
<td>Iron Constantan Thermocouple</td>
<td>± 0.5%</td>
</tr>
</tbody>
</table>

All instrumentation was connected to the "CADDE" (Central Automatic
Digital Data Encoder) Central Data Acquisition System and the data
processed on an IBM 360/67 time-sharing computer.
TEST PROCEDURE

The engine leanout tests at various temperatures and relative humidities were conducted for the modes shown below:

<table>
<thead>
<tr>
<th>Mode</th>
<th>Mode Description</th>
<th>Power Level</th>
<th>Speed</th>
<th>Time in Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Idle-Out</td>
<td>----</td>
<td>600</td>
<td>1.0 min.</td>
</tr>
<tr>
<td>2</td>
<td>Taxi-Out</td>
<td>----</td>
<td>1200</td>
<td>11.0 min.</td>
</tr>
<tr>
<td>3</td>
<td>Takeoff (Full Power)</td>
<td>2700</td>
<td></td>
<td>0.3 min.</td>
</tr>
<tr>
<td>4</td>
<td>Climb</td>
<td>80%</td>
<td>2430</td>
<td>5.0 min.</td>
</tr>
<tr>
<td>5</td>
<td>Approach</td>
<td>40%</td>
<td>2350</td>
<td>6.0 min.</td>
</tr>
<tr>
<td>6</td>
<td>Taxi-In</td>
<td>----</td>
<td>1200</td>
<td>3.0 min.</td>
</tr>
<tr>
<td>7</td>
<td>Idle-In</td>
<td>----</td>
<td>600</td>
<td>1.0 min.</td>
</tr>
</tbody>
</table>

These modes were divided into two distinct test operations. Takeoff, climb, and approach modes were run separately from the idle and taxi modes. In the takeoff, climb, and approach modes, cooling air flow was supplied across the engine at a differential pressure of three inches of water (approximately 2100 CFM). Approach and climb mode tests were run at a constant engine power over the matrix of variables. Takeoff mode tests were conducted at "wide-open throttle" position and consequently the engine power did vary at the various temperature, humidity and fuel-air ratio test conditions. Fuel flow to the engine was varied by adjusting the carburetor mixture control during these three modes.

The idle and taxi modes were conducted with no cooling air flow over the engine. During these two modes, the fuel-air ratio was varied by manually adjusting the "idle mixture screw" on the carburetor. Idle out, taxi out, taxi in, and idle-in were run sequentially at one setting of the carburetor "idle mixture screw". If abnormally rough operation appeared due to prolonged low power operation, the engine speed was increased to 2000 rpm at 150 ft-lbs torque for "clearing".

Emissions data was not recorded, in any of the modes, until the desired temperature and relative humidity was established in the induction and cooling air system and the engine achieved a stabilized operating condition for that mode.

Data Reduction

The LeRC emissions data reduction procedures are as specified by the EPA in the Federal Register (ref. 4). Shown in figure 6 is the flow diagram outlining the data reduction process. Some of the intermediate steps used in the raw emissions data reduction which are not explicitly defined in the Federal Register are summarized below and presented in Appendix A.

Five exhaust products are measured by the emissions analyzer. HC and NOx are measured on a "wet" basis. The other three, CO, CO2 and O2, are measured on a "dry" basis and as a result their
volumetric percentages must be corrected for the water removal. The water correction factor \( K_W \) used for this conversion is defined as:

\[
K_W = 1 - (\text{H}_2\text{O})
\]

where \( \text{H}_2\text{O} \) represents the total water vapor contained in the products of combustion. The water correction factor is based on a chemical reaction including water vapor, oxygen and carbon balance, measured fuel-air ratio and water-dry air mass ratio. This factor as used was obtained from Teledyne Continental Motors and is included in appendix A.

The Federal Register (ref. 4) states that the total engine exhaust volume flow rate is to be used in the computation of the pollutant emission rate. Appendix A contains the procedure used in obtaining the exhaust volume flow rate. Primarily, it is based on the total intake mass flow rate and the exhaust gas density. The exhaust gas density is calculated from the exhaust molecular weight, air molecular weight and air density at 68°F and 760 mm Hg pressure. The pollutant emission rate and mass per mode is then calculated per the Federal Register (ref. 4).

The time in mode value used in this calculation (lbs/mode emission rate) was stated in the test procedures. The idle out and idle-in emissions were plotted as separate points on the same plots after the calculated emissions values of lbs/mode for both idles were multiplied by a factor of two to normalize them to two minutes. The two minutes represents the total idle time of the emission test cycle. The taxi-out and taxi-in emissions values of lbs/mode for both taxis were normalized to fourteen minutes. The fourteen minutes represents the total taxi time of the emission test cycle. The remaining three modes takeoff, climb, and approach were plotted as calculated (per the Federal Register, ref. 4).

To verify the exhaust gas products concentrations, the Spindt procedure (ref. 5) was used. In this procedure, the fuel-air ratio is based on the measured exhaust gas products. This calculated fuel-air ratio, as presented in appendix A, is then compared to the measured fuel-air ratio. The percent difference between the measured to calculated is defined as:

\[
\text{Percent Difference} = \frac{\text{Calculated fuel-air ratio} - \text{Measured fuel-air ratio}}{\text{Measured fuel-air ratio}}
\]

DATA AND RESULTS

As mentioned previously, higher air temperature and humidities affect emissions in two ways; (1) indirectly, by increasing the fuel-air ratio, (2) directly, by modifying the combustion process. The tests described herein were performed to establish the latter effort.

The leanout emissions data were taken for the following values of temperature and relative humidity:

Air temperature, °F: 50, 59, 80, 100
Relative humidity, %: 0, 30, 60, 80

6
Combinations of the above temperatures and humidities at various fuel-air ratios for the five modes tested (idle, taxi, takeoff, climb and approach) resulted in over 800 test conditions.

Comparison of Emissions Data Generated at the Two Extreme Test Conditions

The modal leanout exhaust emissions obtained at the two extreme ambient test conditions (50°F, 0% relative humidity and 100°F, 80% relative humidity) are compared in Figures 7a through 7o.

The CO, HC and NO\textsubscript{x} emissions (lb/mode) are shown on the respective figures as solid lines for the 50°F, 0% relative humidity and as broken lines for the 100°F, 80% relative humidity over the various fuel-air ratios tested. At any one fuel-air ratio, the difference in the emissions values between the solid and broken lines represents ambient conditions direct effect on the emissions.

The two extreme ambient test condition effects on CO emissions are shown in figure 7a-e for each of the five engine test modes and various fuel-air ratios. The CO emissions showed some increase at the 100°F, 80% relative humidity condition in all the modes except takeoff. The takeoff mode (fig. 7c) shows a slight decrease in CO emissions. Figure 7f-7j are plots of HC emissions for each of the five test modes. The HC emissions were higher at the 100°F, 80% relative humidity conditions in all the modes except takeoff. The takeoff mode (fig. 7h) shows that the HC emissions were lower at the richer fuel-air ratio and higher in the leaner fuel-air ratio at the 100°F, 80% relative humidity as compared to the 50°F, 0% relative humidity test condition. The emissions in lbs/mode are directly related to the total mass flow through the engine (Appendix A). Therefore the decrease in emissions (CO and HC) in takeoff as temperature and humidity increases is in part attributed to the lower mass flow rate due to the elevated air temperatures at wide open throttle conditions.

The NO\textsubscript{x} emissions (fig. 7k-7o) versus fuel-air ratio show a decreased in NO\textsubscript{x} emissions at the 100°F, 80% relative humidity for all the modes and all fuel-air ratios tested. This decrease in NO\textsubscript{x} emissions was more pronounced at leaner fuel-air ratios.

The data from figures 7a - 7o was used to quantify the variation in emissions (expressed as a % difference) as ambient conditions are changed from cool, dry to hot, moist and is presented as a function of engine operating mode and fuel-air ratio (figs. 8-10). For CO emissions (fig. 8) the climb mode had the largest percent difference with an increase of over 40% occurring at a fuel-air ratio of .07. The only mode showing a decrease in CO emissions was the takeoff mode. It showed a negative percent difference of 16% at a fuel-air ratio of .085.

The percent difference in HC emissions are shown in figure 9. The idle and taxi modes showed increases of over 130 percent difference in HC emissions at rich fuel-air ratios. The percent difference in HC at the approach mode showed the least sensitivity to fuel-air ratio. Again, only the takeoff mode resulted in negative percent differences of HC emissions. This occurred between fuel-air ratio of .080 - .085.
Figure 10 shows that the largest decrease in NOX emissions as ambient conditions changed from cool, dry to hot, moist was obtained in the climb mode. It showed a fairly constant reduction of about 90% over all the fuel-air ratios tested. The taxi mode was also fairly insensitive to fuel/air reduction ratio. The other modes were strongly affected by fuel/air ratio, and of course, all five modes consistently exhibit negative percent differences.

**Effects of Humidity on Modal Emissions at Four Temperatures**

For the convenience of those having a further interest in ambient effects on emissions, the following sixty figures contain the emissions test data of over 800 test points. Figures 11 through 14 are divided into four sets by the inlet air temperatures of 50, 59, 80 and 100°F with relative humidities of 0, 30, 60 and 80%. Each set contains fifteen figures lettered "a through o" which show the lbs/mode of CO, HC and NOX emissions at one temperature and four relative humidities for each of the five engine test mode conditions and at the fuel-air ratios tested.

All of the figures (11 through 14) each contain a list of the reading numbers of the test data plotted. The test data are divided into groups of identical ambient conditions with a symbol to the right of each group. The symbol not only defines the specific ambient test condition but also represents the emission value point plotted on the figure.

The CO emission appeared to be insensitive to humidity at each of the tested temperatures. At the lower air temperature of 50°F and 59°F, relative humidity had essentially no effect on the HC and NOX emissions. The bulk of the effect of relative humidity on HC and NOX emissions occur at the higher temperature.

**Effects of Air Temperature for Zero Humidity Modal Emissions**

To evaluate if temperature alone had any effect on emissions a comparison was made between the (fig. 11 and 14) emissions at 50°F and 100°F air temperature at 0% humidity. Air temperature had little effect on the formation of CO emissions for any given fuel-air ratio in the idle, taxi, takeoff and approach modes. In the climb mode, the test data results showed a constant 20% increase in CO emissions over the fuel-air ratios tested. The effect of air temperature on the formation of HC and NOX emissions for the five test modes at any of the fuel-air ratios was insignificant.

**Comparison of Modal Emissions**

The variation in the mode time, exhaust volume flow, and the engine combustion process which occur throughout the EPA cycle, result in substantial differences in the contributions by mode to the total cycle emissions. Mode lean-out curves for the three emissions (CO, HC and NOX) are graphically shown in figures 15-17 for 59°F air temperature and 60% relative humidity. (The EPA
standard day conditions). Each figure displays one of the emissions expressed in lb/mile versus fuel-air ratio for the five modes of engine operation. From each figure, it is evident that the climb, approach, and taxi modes are the highest contributors of emissions.

**Comparison of Constructed Modal Cycle and Baseline Cycle Emissions**

The comparison of the cycle emissions constructed from the modal emissions data with the experimental baseline full rich cycle test results (obtained from ref. 1) is shown in Figure 18. Modal fuel-air ratio values corresponding to those of the baseline full rich cycle were used in the construction of the cycle emissions over the range of temperatures and humidities. The comparison of the CO emissions resulted in a relatively close agreement with the percent difference ranging from +8 to -13 percent. At the lower three operating temperatures of 50, 59 and 80°F and for all four of the humidities the percent difference between the constructed cycle and baseline cycle HC emissions (obtained from ref. 1) was less than ±12 percent. This difference increased up to -24% at the 100°F temperature and 30% relative humidity conditions. The percent difference in NOX emissions varied from -11 to +63 percent. The largest percent difference occurred at the test condition in which very low NOX values were generated. Thus, the poor agreement is probably related to computing percent differences of small values having experimental inaccuracies. Overall, however, it was shown that leanout data can be used to construct optimum baseline cycles based on leaner fuel schedules and the data thereby provide a quick and simple method for assessing the benefit of tailored fuel schedules.

**CONCLUDING REMARKS**

A carbureted four-cylinder air-cooled 0-320-DIAD Lycoming aircraft engine was tested to establish the fuel vaporization and combustion effect of air temperature and humidity on exhaust emissions. The test conditions included carburetor leanout at four air temperatures and four values of relative humidity at each temperature for each of the five different engine operating modes. The following conclusions are based on the data obtained and the plots thereof presented in the report.

The general shape of the CO, HC and NOX emissions vs. fuel-air ratio curves for a given mode is consistent with well known general emission characteristics for spark-ignition piston engines. From these curves, it is apparent that the exhaust emissions are strongly influenced by fuel-air ratio. In addition, hot/humid ambient inlet air conditions which affect the induction vaporization and basic combustion process are seen as significantly influencing the emissions. At a fixed fuel-air ratio with higher air temperatures and relative humidities, the HC emissions increased by as much as 130% and the NOX emissions decreased by as much as 90% in certain modes.
Lean out curves for each of the emissions illustrated that the climb mode followed by the approach mode were the largest contributors of the CO and NOx to the EPA cycle emissions, whereas the taxi mode was the largest contributor of the HC emissions. The comparison of the EPA cycle emissions (ref. 1) to the constructed seven mode cycle data resulted in reasonably good agreement. Thus, leanout data from these curves can be used to construct optimum cycle based on leaner fuel schedules and thereby provide a quick and simple method for assessing the benefits of tailored fuel schedules.

The results reported herein are based on tests conducted on one carbureted naturally-aspirated engine. A Continental turbocharged and fuel-injected TSIO-360-C engine has been investigated over the same range of test conditions as the Lycoming engine described herein. A least-squares regression technique of the data from each engine is being planned to study generalized representation of engine emission trends for ambient condition.
APPENDIX A

INTERMEDIATE EQUATIONS USED IN THE RAW EMISSIONS DATA REDUCTION

The basic computational procedures on emission data reduction are specified in the Federal Register (ref. 4). Presented are only those equations and calculations which are not explicitly defined in the Federal Register.

SYMBOLS

\begin{align*}
A & \quad \text{air flow, lb/hr} \\
Ar & \quad \text{argon} \\
a & \quad \text{mole of air} \\
C_{e_{H}} & \quad \text{molecular formula of the fuel} \\
c & \quad \text{mass fraction of carbon in the fuel} \\
D & \quad \text{density of exhaust products, lb/ft}^3 \\
E & \quad \text{exhaust molecular weight, lb/(lb-mole)} \\
F & \quad \text{fuel flow, lb/hr} \\
f & \quad \text{mole of fuel} \\
h & \quad \text{mass fraction of hydrogen in fuel} \\
M & \quad \text{molecular weight of air, 28.96 lb/(lb-mole)} \\
m_n & \quad \text{mole fraction of the compound } n \\
P & \quad \text{equals } (\text{CO}) + (\text{CO}_2)/[(\text{CO}) + (\text{CO}_2) + (\text{HC})] \\
Q & \quad \text{equals } (\text{O}_2)/(\text{CO}_2) \\
R & \quad \text{equals } (\text{CO})/(\text{CO}_2) \\
V & \quad \text{exhaust volume flow rate, ft}^3/\text{hr} \\
W & \quad \text{water flow rate, lb/hr} \\
\rho & \quad \text{density of air at 68}^0 \text{ F and 760 mm Hg pressure, 0.075 lb/ft}^3
\end{align*}
Subscripts:

b  number of hydrogen atoms in one molecule of fuel

d  measured on the "dry" basis water removed

e  number of carbon atoms in one molecule of fuel

n  identifies the individual constituent fraction

I. Water Correction Factor

The chemical reaction including water vapor in the air may be written as:

\[ fC_{eH_b} + a(O_2 + 3.72744 N_2 + 0.04451 \text{ Ar}) \]

\[ + WH_2O + m_1H_2O + m_2CO_2 + m_3CO + m_4NO + m_5O_2 \]

\[ + m_6HC + m_7H_2 + m_8N_2 + m_9\text{Ar} \]

An oxygen balance results in equation (1).

\[ m_1 = 2a + w - 2m_2 - m_3 - m_4 - 2m_5 \]  \( (1) \)

A carbon balance results in equation (2).

\[ f = \frac{m_2 + m_3 + m_6}{e} \]  \( (2) \)

The fuel-air mass ratio may be defined as

\[ \frac{F}{A} = \frac{f(12.01 e + 1.008 b)}{a(138.2689)} \]  \( (3) \)

The water-dry air mass ratio may be defined as

\[ \frac{W}{A} = \frac{w(18.016)}{a(138.2689)} \]  \( (4) \)

Substituting equations (2) to (4) into equation (1) and rearranging

\[ m_1 = \left(2.0 + 7.67478 \frac{W}{A}\right) \left[\frac{(m_2 + m_3 + m_6) \left(12.01 + 1.008 \frac{b}{e}\right)}{138.2689 \frac{F}{A}}\right] \]

\[ -2m_2 - m_3 - m_4 - 2m_5 \]  \( (5) \)

For clarity equation (5) may be written using chemical symbols to represent the mole fraction for each constituent
\[ (H_2O) = \left(2.0 + 7.67478 \frac{W}{A} \right) \left[ \frac{(CO_2) + (CO) + (HC) \left(12.01 + 1.008 \frac{b}{e} \right)}{138.2648 \frac{F}{A}} \right] \]

\[-2(CO_2) - (CO) - (NO) - 2(O_2) \quad (6)\]

The above equation (6), represents the total water vapor contained in the products of combustion with each constituent measured on a "wet" basis. Since CO, CO\(_2\), and O\(_2\) are measured dry and since the water correction factor is defined as

\[ K_w = 1.0 - (H_2O) \quad (7)\]

equation (6) may be written in terms of dry measurements as

\[ \frac{H_2O}{(H_2O)} = \left(2.0 + 7.67478 \frac{W}{A} \right) \]

\[ \times \left\{ \frac{(CO_2)_d + \frac{(HC)}{1 - (H_2O)_d} \left[\left(12.01 + 1.008 \frac{b}{e}\right)\right]}{138.2648 \frac{F}{A}} \right\} \]

\[-2(CO_2)_d - (CO)_d - \frac{NU}{1 - (H_2O)} - 2(O_2)_d \quad (8)\]

The solution to equation (8) for H\(_2\)O is an iteration process since HC and NO are measured wet. The water correction factor is then calculated using equation (7).

II. Exhaust Volume Flow Rate

The exhaust volume flow rate can be equated as:

\[ V = \frac{A + W + F}{D} \]

The exhaust density can be expressed as

\[ D = \frac{PXe}{M} \]

Figure A1 shows the relation between the exhaust molecular weight and F/A ratio obtained from "computer program for calculation of complex chemical equilibrium composition" NASA SP-273 (ref. 6). The pollution production rate is then calculated as specified in the Federal Register (ref. 4).
FIGURE A4: EXHAUST MOLECULAR WEIGHT AS A FUNCTION OF FUEL/AIR RATIO FOR AVIATION GASOLINE

GASOLINE H/C RATIO = 2.25
III. Fuel Air Ratio Based on Exhaust Gas Components and Procedure of Spindt (ref. 5)

The F/A ratio can be expressed as:

\[
\frac{F}{A} = \frac{1}{P \left[ 11.492 \, c \left( 1.0 + \frac{\frac{R}{2} + Q}{1 + R} \right) + \left( \frac{120h}{3.5 + R} \right) \right]}
\]
APPENDIX B

TEST DATA

The data from individual test points, which were taken on a carbureted, four-cylinder, 0-320 DIAD Lycoming light-aircraft engine, have been microfilmed and are contained in the pocket at the back of this volume. These data points represent all of the environmental and engine conditions tested in the individual seven modes in the EPA emissions test cycle as discussed in Volume I. The test data presented herein, representing over 800 data points (readings), were taken at air temperatures of 50º, 59º, 80º, and 100º F at values of 0, 30, 60, and 80 percent relative humidity over a range of fuel-air ratios from 0.06 to 0.113. The data points included in this appendix are all of those for which the exhaust emissions are plotted on a per-mode basis in Volume I of this report. Data point reading number listings are included in tabular form for each series of test conditions and the data symbols which were used for the curves plotted in Volume I. Because of the large number of data points, the data points are arranged numerically by reading number for easy reference.
REFERENCES


FUEL ---> ENGINE

EXHAUST GAS SAMPLE

POLLUTANT CONCENTRATION "DRY"

WATER CORRECTION FACTOR

EXHAUST VOLUME FLOW RATE

POLLUTANT PRODUCTION RATE

POLLUTANT CONCENTRATION "WET"

CALCULATE FUEL AIR RATIO

COMPARE CALCULATED & MEASURED F/A RATIO

EXHAUST EMISSION DATA REDUCTION FLOW CHART

FIGURE 6
Figure 7a

Idle Emissions Ø-320-DIAD

- Temp. 50°F, Rel. Hum. 0%
- Temp. 100°F, Rel. Hum. 80%

Fuel Air Ratio vs. CO Lbs./Mode
TAXI EMISSIONS Ø-32Ø-DIAD

**Figure 7b**

- Temp. 50°F, Rel. Hum. 0%
- Temp. 100°F, Rel. Hum. 80%
TAKE OFF EMISSIONS B-328-DIAD

FUEL AIR RATIO

FIGURE 7c
APPROACH EMISSIONS 0-320-DIAO

- Temp. 50°F, Rel. Hum. 0%
- Temp. 100°F, Rel. Hum. 80%

FIGURE 7e
TAXI EMISSIONS Ø-32Ø-DIAO

FUEL AIR RATIO

Fig. 7g

--- Temp. 50°F, Rel. Hum. 0%
--- Temp. 100°F, Rel. Hum. 80%
Figure 7h
CLIMB EMISSIONS B-320-DIAD

- Temp. 50°F, Rel. Hum. 0%
- Temp. 100°F, Rel. Hum. 80%

FIGURE 7i
Figure 7k

Idle Emissions 8-320-D1AD

Temp. 50°F, Rel. Hum. 0%

Temp. 100°F, Rel. Hum. 80%
TAXI EMISSIONS $\theta$-320-D1AD

\begin{align*}
\text{Temp. } &50^\circ\text{F, Rel. Hum. } 0\% \\
\text{Temp. } &100^\circ\text{F, Rel. Hum. } 80\%
\end{align*}

FIGURE 71
TAKE OFF EMISSIONS Z-320-DIAE

---

**Figure 7m**

- Temp. 50°F, Rel. Hum. 0%
- Temp. 100°F, Rel. Hum. 80%
CLIMB EMISSIONS O-320-DIAD

--- Temp. 50°F, Rel. Hum. 0%
--- Temp. 100°F, Rel. Hum. 80%

FIGURE 7n
APPROACH EMISSIONS  B-320-DIAJ

Figure 70

- Temp. 50°F, Rel. Hum. 0%
- Temp. 100°F, Rel. Hum. 80%

FUEL AIR RATIO

NOX LBS/MODE
CO EMISSIONS (PERCENT DIFFERENCE)

\[
\frac{(CO_{100^\circ F, 40\% RH}) - (CO_{50^\circ F, 0\% RH})}{(CO_{50^\circ F, 0\% RH})} \times 100
\]
HC EMISSIONS
(Percent difference between 50°F, 0% R.H. and 100°F, 80% R.H.)
for various fuel-air ratios
and engine operating modes.
\[ \text{NOx Emissions} = \left( \frac{\text{NOx at } 100^\circ F \text{ and } 100\% \text{ RH}}{\text{NOx at } 50^\circ F \text{ and } 0\% \text{ RH}} \right) \times 100 \]
NASA LEAN-OUT DATA

TEMP. 50°F REL. HUM. 0, 30, 60, 80%

TAXI EMISSIONS Ø-320-DIAD

CO LBS/MODE

FUEL AIR RATIO

FIGURE 11b
NASA LEAN-OUT DATA

TEMP. 50°F REL. HUM. 0, 30, 60, 80%
CLIMB EMISSIONS B-32G-DIAI

CO LBS/MODE

FUEL AIR RATIO

FIGURE 11a
## NASA LEAN-OUT DATA

**TEMP. 50°F REL. HUM. 0, 30, 60, 80%**

### REL. HUMIDITY

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### OUT OF RANGE

**TAKE-OFF EMISSIONS 0-320-DIG**

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### ORIGINAL PAGE DE POOR QUALITY

**FUEL AIR RATIO**

![Graph](image)

**FIGURE 11n**
NASA LEAN-OUT DATA

TEMP. 50°F REL HUM. 0, 30, 60, 80%

CLIMB EMISSIONS B-32B-DIAD

REL. HUMIDITY

OUT OF RANGE =

FUEL AIR RATIO

FIGURE III

RDG. 2433
NASA LEAN-OUT DATA

TEMP. 50°F REL. HUM. 0, 30, 60, 80%

APPROACH EMISSIONS 8-320-DIA 0

REL. HUMIDITY

OUT OF RANGE =

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</table>

FUEL AIR RATIO

FIGURE 113
NASA LEAN-OUT DATA

TEMP. 50°F REL. HUM. 0, 30, 60, 80%

IDLE EMISSIONS B-320-DIAD

REL. HUMIDITY

TEMP. DEG.F

OUT OF RANGE

FUEL AIR RATIO

FIGURE 11k
# NASA LEAN-OUT DATA

TEMP. 50°F REL. HUM. 0, 30, 60, 80%

**TAXI EMISSIONS 0-320-D-1A1**

<table>
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**FIGURE 111**
NASA LEAN-OUT DATA

TEMP. 50°F REL. HUM. 0, 30, 60, 80%

CLIMB EMISSIONS 8-328-DIAD

OUT OF RANGE -

FUEL AIR RATIO

FIGURE 11n
NASA LEAN-OUT DATA

TEMP. 500°F REL. HUM. 0, 30, 60, 80%

APPROACH EMISSIONS Ø-320-DIAD

REL. HUMIDITY

TEMP. DEG. F

65 60 60
69 1 0 0
85 2 A Y
180 3 M Z

OUT OF RANGE

NOX LBS/MODE

FUEL AIR RATIO

FIGURE 110

APPROACH

2434 2637
2441 2546
2447 2450
2547 2553
2660 2662
2496 3561
3562 3563
3564 3565
3566 3567
3568 3559
3570 3571
3638 3642
3645 3648
3651 3654
3657 3660
3663 3665
3670 3673
3676 3679
3685 3688
3691 3694
3697

RDG. 2434
NASA LEAN-OUT DATA

TEMP. 59°F REL HUM. 0, 30, 60, 80%

IDL E E M I S S I O N S Ø-320-DIAB

REL. HUMIDITY

OUT-OF-RANGE

FUEL AIR RATIO

FIGURE 12a
NASA LEAN-OUT DATA

TEMP. 59°F REL. HUM. 0, 30, 60, 80%

TAXI EMISSIONS Ø-32Ø-DIAD

REL. HUMIDITY

TEMP. DEG. F

OUT OF RANGE

CO- LBS/MODE

FUEL AIR RATIO

FIGURE 12b
NASA LEAN-OUT DATA

TEMP. 59°F REL. HUM. 0, 30, 60, 80%

TAKE-OFF EMISSIONS D-320-DIAO

REL. HUMIDITY

OUT OF RANGE

TAKE-OFF

Fig. 12c
NASA LEAN-OUT DATA
TEMP. 59°F REL. HUM. 0, 30, 60, 80%

APPROACH EMISSIONS 0-328-DIAD

REL. HUMIDITY
58 58 58 60 60
59 59 59 x
68 68 68
100 100 100

OUT OF RANGE

APPROACH
2726
2733 1
2740
2746
2752
2758
2787
2793 0
2799
2804
2815
2822
2837
2843
2847
2879
2953
2956
2988
2992
2998
3016
3021
3027 x
3034
3064

APPROACH
2736
2737 1
2743
2749
2756
2783
2790
2796 0
2802
2808
2814
2825
2840
2846
2852
2859
2882
2899
2900
2917
2924
2930 x
2940
2946

CC LBS./MOLE

FUEL AIR RATIO

FIGURE 12e
NASA LEAN-OUT DATA

TEMP. 59°F REL. HUM. 0, 30, 60, 80%

IDLE EMISSIONS Ø-328-DIA

REL. HUMIDITY

OUT OF RANGE -

HC LBS/NODE

FUEL AIR RATIO

FIGURE 12E
FIGURE 12g
NASA LEAN-OUT DATA

TEMP. 59°F REL HUM. 0, 30, 60, 80%

TAKE OFF EMISSIONS Ø-32Ø-DIAD

REL. HUMIDITY

OUT OF RANGE

TAKE-OFF

2724

2731

2738

2744

2750

2778

2784

2788

2794

2800

2806

2819

2835

2841

2848

2877

2883

2890

2896

2902

2915

2919

2925

2931

2941

FUEL AIR RATIO

FIGURE 12h

HC-LBS/MODE
NASA LEAN-OUT DATA

TEMP. 59°F REL. HUM. 0, 30, 60, 80%

CLIMB EMISSIONS Ø-320-DIAD

REL. HUMIDITY

TEMP. DEG.F

59 69 79 89

69 1 0 2

79 2 1 3

89 3

OUT OF RANGE

HC LBS/MODE

FU0L AIR RATIO

CLIMB
2725
2732
2739
2745
2751
2779
2786
2792
2798
2804
2810
2820
2836
2842
2849
2852
2855
2873
2879
2892
2906
2920
2926
2932
2942

FiGURE 12
NASA LEAN-OUT DATA

TEMP. 59°F REL. HUM. 0, 30, 60, 80%

APPROACH EMISSIONS Ø-32Ø-DIAD

FUEL AIR RATIO

FIGURE 12j
NASA LEAN-OUT DATA

TEMP. 59°F REL. HUM. 0, 30, 60, 80%

IDLE EMISSIONS 0-32°DIAD

REL. HUMIDITY

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<td>X</td>
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OUT OF RANGE

<table>
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<tbody>
<tr>
<td>0.06 0.07 0.09 0.10 0.11 0.12</td>
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</tbody>
</table>

FIGURE 12k
FIGURE 121
NASA LEAN-OUT DATA

TEMP. 59°F REL. HUM. 0, 33, 60, 80%

CLIMB EMISSIONS 8-320-DIAO

REL. HUMIDITY

TEMP. DEG.F

59 1 O = X
59 2 A = Y
100 3 X = Z

OUT OF RANGE —

FUEL AIR RATIO

FIGURE 12n
NASA LEAN-OUT DATA

TEMP. 59°F REL. HUM. 0, 30, 60, 80%

APPROACH EMISSIONS Ø-32Ø-DIAD

REL. HUMIDITY

TEMP. DEG. F

59 60 65

REL. HUMIDITY

59 0 0

60 1 0

65 2 0

OUT OF RANGE

OF POOR QUALITY

ORIGINAL PAGE IS

FIGURE 12°
NASA LEAN-OUT DATA

TEMP. 80°F REL. HUM. 0, 30, 60, 80%

IDL EMISSIONS 8-320-DIAD

REL. HUMIDITY

OUT OF RANGE

CO LBS/MODE

FUEL AIR RATIO

FIGURE 13a
NASA LEAN-OUT DATA
TEMP. 80°F REL. HUM. 0, 30, 60, 80%
TAXI EMISSIONS 0-320-DIAD

Figure 13b
NASA LEAN-OUT DATA

TEMP. 80°F REL. HUM. 0, 30, 60, 80%

TAKE OFF EMISSIONS Ø-32Ø-DIAD

REL. HUMIDITY

TEMP. °C/G.F.

OUT OF RANGE -

FUEL AIR RATIO

FIGURE 13c
NASA LEAN-OUT DATA
TEMP. 80°F REL. HUM. 0, 30, 60, 80%
CLIMB EMISSIONS θ-328-DIAD

REL. HUMIDITY

OUT OF RANGE

CO LBS/MODE

FUEL AIR RATIO

FIGURE 13a
NASA LEAN-OUT DATA

TEMP. 80°F REL. HUM. 0, 30, 60, 80%

APPROACH EMISSIONS Ø-32Ø-DIAD

CO LBS/MODE

FUEL AIR RATIO

FIGURE 13e
NASA LEAN-OUT DATA
TEMP. 80°F REL. HUM. 0, 30, 60, 80%

IDLE EMISSIONS B-320-DIAB

REL. HUMIDITY

OUT OF RANGE

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FUEL AIR RATIO

FIGURE 13e
NASA LEAN-OUT DATA

TEMP. 80°F REL. HUM. 0, 30, 60, 80%

TAKE OFF EMISSIONS 0-320-DIAD

FUEL AIR RATIO

FIGURE 13n
NASA LEAN-OUT DATA

TEMP. 80°F REL. HUM. 0, 30, 60, 80%

IDLE EMISSIONS Ø-32Ø-DIAD

FUEL AIR RATIO

FIGURE 13
NASA LEAN-OUT DATA
TEMP. 80°F REL. HUM. 0, 30, 60, 80%
TAXI EMISSIONS 8-320-UIAD

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OUT OF RANGE

FIGURE 131
NASA LEAN-OUT DATA

TEMP. 80°F REL. HUM. 0, 30, 60, 80%

TAKE OFF EMISSIONS Ø-320-DIAD

REL. HUMIDITY

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<td>Δ</td>
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OUT OF RANGE -

NOX LBS/MODE

FUEL AIR RATIO

TAKE-OFF

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FIGURE 13m
NASA LEAN-OUT DATA

TEMP. 80°F REL. HUM. 0, 30, 60, 80%

APPROACH EMISSIONS 9-320-DIAD

REL. HUMIDITY

TEMP. DEG. F

0 35 65 88

0.58 0.6 0.62 0.64

OUT OF RANGE -

APPROACH

3262
3268
3277 2
3283
3289
3381
3387
3393 Δ
3399
3405
3502
3508
3514
3520
3527
3472
3478
3484
3490 2
3496

APPROACH

3265
3274
3280 2
3286
3378
3384
3390
3396 Δ
3402
3499
3505
3511 Δ
3517
3523
3569
3475
3481 Y
3487 Y
3493

FUEL AIR RATIO

FIGURE 130

RDQ. 3262
NASA LEAN-OUT DATA

TEMP. 100° F REL. HUM. 0, 30, 60, 80%

IDLE EMISSIONS Ø-32Ø-OIAD

REL. HUMIDITY
58  0  60  88
59  1  61  89
88  2  1  69
188  3  2  89

OUT OF RANGE

FUEL AIR RATIO

FIGURE 14a
NASA LEAN-OUT DATA

TEMP. 100°F REL. HUM. 0, 30, 60, 80%

TAXI EMISSIONS Ø-320-DIAD

REL. HUMIDITY

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OUT OF RANGE

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FLOW AIR RATIO

FIGURE 14b
NASA LEAN-OUT DATA

TEMP. 100°F REL. HUM. 0, 30, 60, 80%

APPROACH EMISSIONS 8-320-DIAO

REL. HUMIDITY

OUT OF RANGE

APPROACH
3013
3019
3026
3034
3040
3043
3125
3128
3131
3134
3137
3140
3143
3146
3149
3152
3211
3219
3226
3235
3244
3278
3078
3084
3098
3104
3113
3116

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1.0
2.0
3.0
4.0
5.0

CO - LBS/MODE

FUEL AIR RATIO

FIGURE 14e
NASA LEAN-OUT DATA

TEMP. 100°F REL. HUM. 0, 30, 60, 80%

TAKE-OFF EMISSIONS Ø-328-DIAD

OUT OF RANGE

TAKE-OFF
3010
3017
3024
3032
3038
3121
3126
3132
3138
3144
3150
3212
3220
3229
3239
3247
3079
3085
3099
3105

FUEL AIR RATIO

FIGURE 14h
NASA LEAN-OUT DATA
TEMP. 100°F REL. HUM. 0, 30, 60, 80%

CLIMB EMISSIONS 0-320-01AD

HC LBS/MODE

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FIGURE 141
NASA LEAN-OUT DATA

TEMP. 100°F REL. HUM. 0, 30, 60, 80%

TAXI EMISSIONS O-320-DIAD

REL. HUMIDITY

TEMP. DEG. F

OUT OF RANGE

FUEL AIR RATIO

FIGURE 141
NASA LEAN-OUT DATA

TEMP. 100°F REL. HUM. 0, 30, 60, 80%
TAKE-OFF EMISSIONS Ø-32Ø-D\1AD

FIGURE 14m
NASA LEAN-OUT DATA

TEMP. 100°F REL. HUM. 0, 30, 60, 80%

CLIMB EMISSIONS 0-320-CIAO

CLIMB

3529
3532
3534
3537
3122
3127
3133
3139
3145
3153
3176
3227
3247
3237
3070
3089
3106
3111

CLIMB

3531
3533
3536
3538
3124
3130
3136
3142
3151
3215
3218
3227
3236
3077
3087
3097
3106
3109
3112

FUEL AIR RATIO

FIGURE 14n
NASÁ LEAN-OUT DATA

TEMP. 100°F REL. HUM. 0, 30, 60, 80%

APPROACH EMISSIONS 0–320° DIAD

REL. HUMIDITY

5% 2 3% 4% 5% 8%
5% 1 0 8% +
8% 2 Δ + 8% X
10% 3 △ 8% Z

OUT OF RANGE -

FUEL AIR RATIO

NOX LBS/MODE

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FIGURE 140
CO MODAL EMISSIONS
VERSUS FUEL-AIR RATIO

AIR TEMPERATURE - 59°F
RELATIVE HUM - 60%  

○ - IDLE  
□ - TAXI  
△ - TAKE OFF  
△ - CLIMB  
△ - APPROACH  

FUEL-AIR RATIO

FIGURE 15
HC MODAL EMISSIONS
VERSUS FUEL- AIR RATIO

AIR TEMPERATURE - 59°F
RELATIVE HUM. - 60 %

○ - IDLE
□ - TAXI
◆ - TAKE-OFF
△ - CLIMB
△ - APPROACH

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FIGURE 16
NO\textsubscript{x} MODAL EMISSIONS
VERSUS FUEL-AIR RATIO

AIR TEMPERATURE 59°F
RELATIVE HUM. 60%

○ - IDLE
□ - TAXI
◇ - TAKEOFF
△ - CLimb
◇ - APPROACH

FUEL-AIR RATIO
FIGURE 17
A carbureted four-cylinder air-cooled 0-320 DIAD Lycoming aircraft engine was tested to establish the effects of air temperature and humidity at various fuel-air ratios on the exhaust emissions on a per-mode basis. The test conditions included carburetor lean-out at air temperatures of 50°, 59°, 80°, and 100° F at relative humidities of 0, 30, 60, and 80 percent. Temperature-humidity effects at the higher values of air temperature and relative humidity tested indicated that the HC and CO emissions increased significantly, while the NOx emissions decreased. Even at a fixed fuel-air ratio, the HC emissions increase and the NOx emissions decrease at the higher values of air temperature and humidity. The report is divided in two volumes: Volume I contains the results and plotted data, and Volume II contains the data taken at each of the individual test points. (The data of Volume II are included on microfilm in a pocket at the back of Volume I.)