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EFFECTS OF AIR INJECTION ON A TURBOCHARGED TELEDYNE CONTINENTAL MOTORS TSIO-360-C ENGINE

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ABSTRACT

A fuel-injected, turbocharged, six-cylinder air cooled Teledyne Continental Motors TSIO-360-C aircraft engine was operated over a range of test conditions to investigate factors influencing the effectiveness of air injection in reducing exhaust emissions. The test program included the standard EPA five-mode baseline cycle revised to a seven-mode cycle and engine fuel-air ratio leanout tests. All tests were carried out using induction and cooling air at a temperature of 59° F and a relative humidity of 60%. Such factors as composition and temperature of the reacted mixtures were evaluated by varying the engine fuel-air ratio and exhaust tube air injection flow rates for various engine loads. No attempt was made to optimize the location of the point of air injection. The standard exhaust system was not modified other than to weld air injection couplings below the cylinder heads in the exhaust tubes. Air was injected into the exhaust tube of each cylinder for all modes and an exhaust gas analysis was made for hydrocarbons, oxides of nitrogen, and carbon monoxide content. For the revised seven-mode EPA baseline cycle it was found that as the amount of injection air was increased both carbon monoxide and hydrocarbons showed a marked decrease while the oxides of nitrogen changed only slightly. When sufficient air was injected to lower the pollutant levels to meet the Environmental Protection Agency (EPA) standards it was found that the temperature of the exhaust gas mixture as it entered the turbine exceeded the maximum recommended temperature of 1650° F by approximately 225° F while operating in the high power modes. Leanout data on a mode basis showed that, in the lower power modes of idle and taxi, air injection was more effective in reducing hydrocarbons and carbon monoxide at the richer fuel-air ratios. At the higher power modes of takeoff, climb, and approach air injection was more effective at the leaner fuel-air ratios. In combining air injection at various rates of flow and leaning the engine mixutre through fuel management it was found that the EPA standard could be met while not exceeding a turbine inlet temperature of 1650° F.

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NASA IS INVOLVED in a research and technology program aimed at improving general aviation intermittant combustion engines. One major objective of the program is to establish and demonstrate the technology which will safety reduce piston engine exhaust emissions to levels consistent with the formerly proposed EPA 1979 emission standards. The present program encompasses in-house and contracted efforts to meet this objective. This report presents the results of an in-house investigation of factors influencing the effectiveness of air injection in reducing exhaust emissions of a representative current production general aviation turbocharged engine. The feasibility of adding supplementary air to the exhaust gases to provide an oxidizing environment for incompletely oxidized carbonaceous species, CO and HC, is a well proven concept and has had widespread use in controlling automotive emissions (4-7).* However aircraft engines are designed to operate at rich fuel-air ratios and, if turbocharged, the exhaust gas temperatures (EGT) must be maintained below the allowable limit of the turbocharger turbine inlet temperature (TIT). Therefore when operated at the rich fuel-air ratio typical of current general aviation engines during the landing-takeoff (LTO) cycle the exhaust gas temperature may be too low during the low power modes to achieve significant after reaction with injected air. Furthermore, during the higher power modes, the EGT is restricted to 1650° F or below. This report presents the results of tests which were performed to establish the effects of exhaust manifold injection air flow rate on emissions and exhaust gas temperature (EGT) - turbine inlet temperature (TIT) for a range of engine operating conditions (speed, torque, and fuel-air ratios) of a Teledyne Continental Motors (TCM) TSIO-360-C engine.

APPARATUS AND PROCEDURE

TEST FACILITY - The aircraft engine installation is shown schematically in Fig. 1 and photographically in Figs. 2 and 3. The engine was coupled to a 300-hp dynamometer through a fluid coupling in the drive shaft which was located under a safety shield. Both engine cooling and induction air were supplied by a centralized laboratory air distribution system. The cooling and induction air system, as shown in Fig. 4, can be controlled to deliver air to the engine over a temperature range of from 50° to 120° F and over a range of relative humidity from 0 to 80%. The cooling air 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 performance testing. The engine cooling air was removed from the test cell by a high capacity, facility altitude 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 standard engine exhaust system that is supplied by the manufacturer for this engine was used. An extension pipe was welded to the exhaust gas outlet downstream of the turbocharger and ducted from the test cell through the roof. The gas sample probe was located in this extension pipe approximately 4 feet downstream of the turbocharger. Care was taken to insure that the exhaust system was leak-proof. This was necessary to prevent air dilution of the gas sample which result in erroneous emission measurements.

Air for injection, as shown in Fig. 5, was supplied by a central control system. The air temperature entering the exhaust manifold was 80° F.

Engine Description - The Continental TSIO-360-C is a horizontally opposed, six cylinder, direct-drive, turbocharged, air-cooled engine. The engine has a bore of 4.438 inches and a stroke of 3.875 inches with the resulting total piston displacement being 360 cubic inches. The compression ratio is 7.50:1. The engine is rated 225 bhp at 2800 rpm and 0.65 bsfc. The engine has a continuous flow fuel injection system using grade 100/130 aviation gasoline. The fuel system was calibrated for full-rich operation at the factory, typical of what might be expected as the rich limit of production engines. The fuel system, at this calibration, constituted the baseline power and emissions data for the engine. The fuel used was standardized reference fuel conforming to the requirements of the ASTM Com-

*Numbers in parentheses designate References at end of paper.

mittee on Aviation Reference Fuels and Certification (ASTM D910). Ignition was supplied by a magneto timed to 20° BTDC.

Engine Exhaust System - Two major areas of consideration that can effect the accuracy of emission measurements 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 sampling probe was located far enough downstream of the turbocharger to insure a homogeneous exhaust gas mixture. Bellows were installed around all exhaust slip-fit joints so that air could not enter the system and dilute the gas sample. Great care was taken in the design, fabrication, and installation of the exhaust system so that it would not leak.

Exhaust Gas Sample Handling - The main criteria for exhaust gas analysis were as follows. The sample had to be representative of complete mixing of gases from all cylinders and the temperature of the gas sample at the analyzer had to be at least 300° F to preclude condensation of moisture. 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. 6) contained the following five analysis meters:

1. Beckman Model 864 Infrared CO_2 Analyzer
2. Beckman Model 864 Infrared CO Analyzer
3. Scott Model 125 Chemiluminescent NO/NO_x Analyzer
4. Scott Model 415 Flame Ionization Detector for HC
5. Scott Model 250 Paramagnetic O_2 Detector

Careful daily monitoring of these sensitive instruments indicated a need for frequent adjustments. It was necessary to zero and span calibrate 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 Fig. 7. The major measured parameters and estimated system accuracies for this investigation are listed below:

Parameter	Instrumentation	System Accuracy
Fuel flow	Hydraulic wheatstone bridge flowmeter	±0.5%
Induction air flow	Turbine-type flowmeter	±0.6%
Induction air pressure	Absolute transducer	±0.5%
Cooling air flow	Orifice ΔP transducer	±1.5%
Cooling air pressure	Absolute transducer	±0.5%
Injection air flow	Orifice ΔP transducer	±1.5%
Injection air pressure	Absolute transducer	±0.5%
Dew point	Temp. controlled mirrored photoelectric sensor	±0.7° F
Engine torque	Shaft mounted rotary transformer type	±0.5%
Dyno torque	Load cell	±0.5%
Speed	Magnetic pickup	±0.25%
Exhaust gas temp.	Chromel-Alumel thermocouple	±0.5%
Cylinder head temp.	Iron-Constantan thermocouple	±0.5%

All instrumentation was connected to the CADDE (Central Automatic Digital Data Encoder) central data acquisition system and the data processed on a 360/67 time-sharing computer.

TEST PROCEDURE

The baseline engine testing procedure was conducted essentially as specified by the Environmental Protection Agency in the Federal

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Register, Vol. 38, No. 136, Part II, dated Tuesday, July 17, 1973. However, the EPA five-mode LTO cycle was expanded into a seven-mode cycle by separating the idle/taxi mode and further defining the power/speed conditions as shown below:

Mode	Mode description	Power level, %	Speed, rpm	Time in mode, min
1	Idle out	---	600	1.0
2	Taxi out	4	1200	11.0
3	Takeoff	100	2800	0.3
4	Climb	80	2520	5.0
5	Approach	40	2436	6.0
6	Taxi in	4	1200	3.0
7	Idle in	---	600	1.0

Prior to the start of the LTO cycle tests the engine was warmed up at 2000 rpm for approximately 10 minutes or until all parts were temperature stabilized and all cylinder head temperatures were at least 300° F.

At the start of the cycle the engine speed was reduced to 600 rpm and the cooling air pressure set at 0.25" H_2O. After a short temperature stabilization interval the gas analyzer was turned on, all meter needles stabilized, and the data for the idle-out mode taken. The engine speed was then increased to 1200 rpm and a torque of 40 foot pounds was applied by the dynamometer again, after stabilization, the data for the taxi-out mode was taken. Cooling air pressure was then increased to 6" H_2O and the takeoff, climb, and approach modes were taken in sequence with appropriate torque loads applied. The speed was then reduced to 1200 rpm, torque set at 40 foot pounds, cooling air pressure reduced to 0.25" H_2O, temperature stabilized, and taxi-in mode data taken. The idle-in mode followed in a manner similar to the idle-out mode. Throughout the test program, and if any changes occurred on the engine, baseline data was repeated before proceeding with the next phase of testing.

The test procedure for air injection into the exhaust system involved operating the engine at each of the five modes, at each mode the speed and torque were set, the injection air was turned on to represent a percentage of the combustion air for that particular mode, and data was taken. The engine fuel-air ratio was then reduced and data again taken. After leanout conditions were complete, injection air flow was increased, and the leanout process repeated. Each mode covered approximately five fuel-air ratios and five injected air mixtures. All tests were carried out using a induction and cooling air temperature of 59° F and a relative humidity of 60%. The injection dry air temperature was approximately 80° F.

DATA REDUCTION

The LeRC emission data reduction procedures are as specified by the EPA in the Federal Register (1). Shown in Fig. 8 is the flow diagram outlining the data reduction process. Some of the intermediate steps used in the raw emission data reduction which are not explicitly defined in the Federal Register are summarized below and presented in the appendix.

Five exhaust products are measured by the emissions analyzer. The HC and NO_x are measure on a "wet" basis. The other three, CO, CO_2, and O_2 are measured on a dry basis and as a result their volumetric percentages must be corrected for the water removed. The water correction factor (K_W) used for this conversion is defined as

$$K_W = 1 - (H_2O)$$

where H_2O 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. The calculations are included in the appendix.

The Federal Register (1) states that the total engine exhaust volume flow rate is to be used in the computation of the pollutant emission rate. The appendix contains the procedure used in obtaining the exhaust volume flow rate. Primarily, it is based on the total intake mass flow rate, air injection 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 is then calculated per Federal Register (1).

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RESULTS AND DISCUSSION

EXHAUST GAS ANALYSIS - The effectiveness of exhaust manifold air injection in oxidizing hydrocarbons and carbon monoxide is governed by the following basic factors:

1. Composition of the reacting mixture
2. Temperature of the mixture
3. Pressure of the mixture
4. Time available for the reaction

The composition of the reacting mixture is effected by the engine fuel-air ratio and injection air flow rate. The fuel-air ratio effects the amount and type of combustibles present in the exhaust mixture, whereas the injection air flow rate generally determines the amount of oxygen available for reaction. The products of combustion that are under consideration for further oxidation in the exhaust manifold are the unburned hydrocarbons (HC) and carbon monoxide (CO). The following exothermic reactions involve the reduction of hydrocarbons and a corresponding decrease in the carbon monoxide of the exhaust gas.

$$C_xH_y + O_2 \rightarrow CO + CO_2 + H_2O$$

$$2CO + O_2 \rightarrow 2CO_2$$

The injection air flow rate determines the extent to which these reactions occur. The temperature and pressure of the exhaust gas mixture along with the residence time, or time available for reactions to take place are also involved in the extent to which complete combustion is accomplished (7).

FULL RICH LTO CYCLE - The fuel rich LTO cycle runs were made in accordance with the test procedure described previously. Figure 9 shows that prior to injecting any air into the exhaust system the amount of carbon monoxide and hydrocarbons far exceeded the standards as set forth by the EPA. The carbon monoxide content represented 224% of the standard while the hydrocarbon quantity was 172%. This exhaust gas contained oxides of nitrogen in an amount equal to 14.9% of the standard. The extent to which each mode is involved in the production of emissions is shown in Table 1. These data show that the climb mode followed by the approach mode were the largest contributors of CO and NO_x to the EPA cycle emissions, whereas the taxi mode was the largest contributor of HC emissions.

LEANOUT MODE EMISSIONS - Leanout runs were made in which the fuel-air ratio was varied from the full-rich condition. Each of the five modes were used. Emissions were taken and calculated on a pounds per mode basis. Figures 10 to 24 present this data where the pollutant in pounds per mode is plotted against the fuel-air ratio. These tests were made to establish reference data in which no injection air was used so that a correlation could be made as to the effects of air injection on emissions produced on a mode basis. These figures show that in all modes both carbon monoxide and hydrocarbons decreased as the oxides of nitrogen increased while the fuel-air ratio was decreased.

EFFECTS OF AIR INJECTION ON FULL RICH MODE EMISSIONS - In Fig. 25 the percent conversion of carbon monoxide for each of the five modes is plotted as a function of the injected air, expressed as a percentage of induction air. Each of the five modes were run using the full-rich fuel-air ratio. The idle mode shows an increase in carbon monoxide of 5% as air was injected at the rate of 7.5 lb/hr, or 15% of an idle induction air value of 50 lb/hr. As injection air is further increased the carbon monoxide is decreased so that when 25 lb/hr or 50% of the induction air for idle is reached then there is a 25% reduction of CO in the exhaust gas. There is also an increase of carbon monoxide as air is injected in the taxi mode, however, at 7% or 9.5 lb/hr this trend is reversed and as further air is added the CO decreases. This initial increase in the CO content of the exhaust gas indicates that when air is injected in small amounts the burning of the hydrocarbons to carbon monoxide occurs faster than the oxidation of CO to CO_2. In the higher power modes the conversion of carbon monoxide takes place when air is initially added and continues until the injected air reaches approximately 30% of the induction air for each mode. At this point there is a 75% reduction of CO.

The reduction of hydrocarbon content of the exhaust gas takes place at a faster rate than the carbon monoxide conversion. The fuel-air ratios for each mode are the full-rich values. Figure 26 shows that there is a slight increase in hydrocarbons at idle and taxi as air is initially injected into the exhaust system. As soon as the amount of injection air exceeds 24% of the induction air both idle and taxi exhaust gas hydrocarbon content is reduced. When the amount of injected air reaches 50% of the induction air for idle and taxi there is a hydrocarbon reduction of 24% and 28%, respectively. For the takeoff, climb, and approach modes it can be seen that when the injected air reaches approximately 20% of the induction air there is a 90% reduction in the hydrocarbon content of the exhaust gas.

EFFECTS OF AIR INJECTION ON LEANOUT MODE EMISSIONS - A series of tests were made in which the fuel-air ratio was varied for each mode. Air was injected into the exhaust system for each leanout condition and then increased based on a percentage of the full-rich induction air required for each mode.

At various fuel-air ratios the amount of carbon monoxide initially increased in the idle mode. Figure 27 shows that a pattern is established whereby the carbon monoxide conversion begins as the injected air reaches between 10% and 20% of the modal induction air. The conversion rate is more rapid when the amount of injected air is between 20% and 60% converting approximately 25% of the carbon monoxide. The rate of conversion then slows as further air is added.

The hydrocarbon content of the exhaust gas decreases as the amount of injection air increases. Figure 28 indicates that a richer idle mode engine mixture has a slightly higher conversion rate then the leaner conditions. In the idle power mode the richer the burnable mixture available in the exhaust gas the higher the conversion rate. It can be seen that the elimination of between 20% and 30% of the hydrocarbons can be accomplished when the injected air exceeds 60% of the modal induction air.

In the taxi mode Fig. 29 shows that the amount of carbon monoxide in the exhaust gas is reduced as the amount of injected air is increased. However when the injected air reaches 55% of the induction air then the carbon monoxide starts to increase. It can be noted that the maximum conversion of CO involves the higher fuel-air ratios. When more than 55% of induction air is added to the exhaust gas the temperature of the gas is lowered to the point that carbon monoxide will not readily convert to carbon dioxide and an increase in carbon monoxide is noted. Therefore, for the taxi mode, there appears to be an optimum quantity of injection air which results in the maximum conversion of CO. The optimum value appears to be insensitive to the fuel-air ratio.

The hydrocarbon content of the exhaust gas increases slightly as injected air is added until the additional air represents 30% of the induction air. Further burning of the hydrocarbons then occurs. Under the full-rich condition 30% of the hydrocarbons are converted when the injection air reaches 90% of the modal induction air. This is shown in Fig. 30. As the engine is leaned out less conversion takes place as the injection air is increased. At a fuel-air ratio of 0.073 it can be seen than only 5% of the original hydrocarbon content is converted.

The takeoff mode represents the use of an aircraft engine at 100% power. Because of this power load the maximum rate of fuel consumption is encountered. The cylinder head temperature and the exhaust gas temperature are at a higher level than when in any other mode. The injection of air into the hot exhaust gas causes the carbon monoxide to convert readily into carbon dioxide. It can be seen from Fig. 31 that the conversion rate for the leaner engine operating condition is slightly higher than for the full-rich operating mode.

A more complete combustion of the fuel is accomplished by injecting air into the hot exhaust pipe containing some of the unburned hydrocarbons. Figure 32 shows that a relatively small amount of injection air reduces the hydrocarbons in the exhaust gas at a rapid rate. The amount of HC converted is a function of the fuel-air ratio. When the injected air is approximately 7% of the takeoff induction air at least 75% of the hydrocarbons have been eliminated. Conversion of the hydrocarbons continues as further air is injected so that when the amount of injected air represents 12% of the induction air then more than 90% of the hydrocarbons are converted or burned.

In the climb mode Fig. 33 shows that for any given amount of injection air the leaner mixture has a higher conversion rate of carbon monoxide.

Figure 34 shows that the conversion of hydrocarbons in the climb mode requires less injected air to facilitate a higher conversion rate than that of carbon monoxide.

The approach mode represents a 40% power condition. When the engine is operated with a full-rich mixture the conversion of carbon monoxide begins slowly as injected air is initiated, becomes more rapid as the amount of injected air reaches 20%, and again slows as further air injection exceeds 35%. Figure 35 shows that when the engine mixture is leaned out the conversion rate of carbon monoxide is much higher for any given quantity of injection air.

Figure 36 shows the reduction of hydrocarbons in the exhaust gas as air is injected into it. The rate of hydrocarbon conversion is higher for lower fuel-air ratios. Less injected air is required for a 90% conversion of hydrocarbons when the engine is running under a leaned out condition. However, regardless of fuel-air ratio, most of the hydrocarbons produced in the approach mode are readily reduced.

EFFECTS OF AIR INJECTION ON TURBOCHARGER-TURBINE INLET TEMPERATURE - As air is injected into an exhaust system and reacts to oxidize or burn the carbon monoxide and hydrocarbon content of the gas, heat is given off. This heat combines with the existing exhaust gas heat to produce a higher temperature gas that, in the case of turbocharged engines, enters the turbine of the turbocharger. The maximum recommended turbine inlet temperature for the Continental TSIO-360-C engine is 1650° F. Tests were run and data plotted for each of the modes of the LTO cycle. Various fuel air ratios were used as the engine was leaned out.

In the idle mode Fig. 37 shows that the rise in the turbine inlet temperature was negligible as the exhaust gas temperature remained at approximately 325° F as air was added. It was found that the turbine inlet temperature did not significantly change upon leaning the engine mixture.

The taxi data is shown on Fig. 38. For various fuel-air ratios the exhaust gas temperature ranged from 670° to 785° F. The turbine inlet temperature was slightly higher as the fuel-air ratio decreased. However, as with the idle mode, when the amount of injection air was increased the turbine inlet temperature remained relatively unchanged.

The takeoff turbine inlet temperature (TIT) as a function of injection air flow rate for four fuel-air ratios is shown in Fig. 39. For all of the tested fuel-air ratios the TIT rises initially, reaches a maximum, and then decreases as the injected air flow rate is increased. The peak TIT occurs for all of the fuel-air ratios at approximately a flow rate corresponding to 8% of the takeoff induction air flow rate. It can also be seen that for a fuel-air ratio of 0.077 the turbine inlet temperature limit of 1650° F is reached with only 2% air injection, whereas for a fuel-air ratio of 0.096, the maximum 1650° F turbine inlet temperature is reached at 6.8% of the induction air flow.

The same general trend of turbine inlet temperature is shown for the climb mode on Fig. 40. The turbine inlet temperature of 1650° F occurs for the fuel-air ratios of 0.077 and 0.089 at an injected air flow rate of 4% and 7.7%, respectively.

The effects of air injection on the approach mode turbine inlet temperatures for four fuel-air ratios is shown on Fig. 41. The curves show that initially as the injection air flow rate is increased the leaner fuel-air ratios result in higher turbine inlet temperatures. At approximately 10% injection air a crossover effect begins to occur. For leaner fuel-air ratios the maximum turbine inlet temperature occurs at lesser amount of injected air and the peak temperature magnitude is less. For example, for approximately 10% injected air the peak temperature of 1600° F occurs for a fuel-air ratio of 0.072. However, at approximately 50% injected air the peak temperature of 1875° F occurs for a fuel-air ratio of 0.094. The lower quantity of carbon monoxide and unburned hydrocarbons in the exhaust gas at the leaner fuel-air ratios account for the lower turbine inlet temperature.

CONSTRUCTED CYCLE EMISSIONS - In order to operate the engine within the emissions standards as set forth by the Environmental Protection Agency (EPA), using exhaust air injection, a typical air pump operating at a speed ratio of 1.71:1.00 can be used. This however would necessitate a change in the recommended maximum continuous turbine inlet temperature from 1650° to 1875° F. Under these conditions, a full-rich mixture for

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the landing-takeoff cycle would produce the following:

HC = 95.0% of EPA Standards
NO_x = 15.4% of EPA Standards
CO = 98.0% of EPA Standards

By constructing landing-takeoff cycles on a theoretical basis considering that the maximum turbine inlet temperature is to remain at 1650° F and, through fuel management, varying the fuel-air ratio on a mode basis Table 2 and Fig. 42 shows that emissions could be reduced. As the engine mixture is leaned out the oxides of nitrogen increases until it becomes the limiting factor exceeding 100% of the EPA standard.

A typical air pump which could be used to supply injection air to the exhaust system is the Saginaw 19.0 CID pump. The performance characteristics of this pump is shown on Fig. 43. The power consumption of this pump at takeoff is shown to be approximately 1.75 horsepower.

CONCLUDING REMARKS

The foregoing experimental results have shown that air injection can be effective in the reduction of the hydrocarbon and carbon monoxide emissions from turbocharged aircraft engines. At the lower power modes air injection was more effective in reducing both hydrocarbons and carbon monoxide at the richer fuel-air ratios. At the higher power modes air injection was more effective at the leaner fuel-air ratios.

The use of a simple air injection system confined to air flows achievable from an engine driven pump and air flows resulting in turbine inlet temperature below 1650° F gave hydrocarbon and carbon monoxide cycle emissions expressed as percent of EPA standard as 89% and 82%, respectively.

The EPA standards could be met within present turbine inlet temperature limits using commercially available air pumps provided the fuel-air ratios were leaned in the taxi, climb, and approach modes. The use of such air pumps would not use an unreasonable amount of engine power.

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 (4). Presented are only those equations and calculations which are not explicitly defined in the Federal Register.

SYMBOLS

A air flow, lb/hr

Ar argon

a moles of air

C_aH_b molecular formula of the fuel

c mass fraction of carbon in the fuel

D density of exhaust products, lb/ft^3

E exhaust molecular weight, lb/(lb-mole)

F fuel flow, lb/hr

f moles of fuel

h mass fraction of hydrogen in fuel

M molecular weight of air, 28.96 lb/(lb-mole)

m_n mole fraction of the compound n

P equals $(CO) + (CO_2)/[(CO) + (CO_2) + (HC)]$

Q equals $(O_2)/(CO_2)$

R equals $(CO)/(CO_2)$

V exhaust volume flow rate, ft^3/hr

W water flow rate, lb/hr

ρ density of air at 68° F and 760 mm hg pressure, 0.075 lb/ft^3

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:

$$fC_eH_b + a(O_2 + 3.72744\ N_2 + 0.04451\ A_r)$$
$$+ wH_2O \rightarrow m_1H_2O + m_2CO_2 + m_3CO + m_4NO$$
$$+ m_5O_2 + m_6HC + m_7H_2 + m_8N_2 + m_9Ar$$

An oxygen balance results in Eq. (1).

$$m_1 = 2a + w - 2m_2 - m_3 - m_4 - 2m_5 \qquad (1)$$

A carbon balance results in Eq. (2).

$$f = \frac{m_2 + m_3 + m_6}{e} \qquad (2)$$

The fuel-air mass ratio may be defined as

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

The water - dry air mass ratio may be defined as

$$\frac{W}{A} = \frac{w(18.016)}{a(138.2689)} \qquad (4)$$

Substituting Eqs. (2) to (4) into Eq. (1) and rearranging

$$m_1 = \left(2.0 + 7.67478\ \frac{W}{A}\right) \times \left[\frac{(m_2 + m_3 + m_6)\left(12.01 + 1.008\ \frac{b}{e}\right)}{138.2689\ \frac{F}{A}}\right] - 2m_2 - m_3 - m_4 - 2m_5 \qquad (5)$$

For clarity Eq. (5) may be written using chemical symbols to represent the mole fraction for each constituent

$$(H_2O) = \left(2.0 + 7.67478\ \frac{W}{A}\right) \times \left[\frac{(CO_2) + (CO) + (HC)\ \left(12.01 + 1.008\ \frac{b}{e}\right)}{138.2648\ \frac{F}{A}}\right] - 2(CO_2) - (CO) - (NO) - 2(O_2) \qquad (6)$$

The above Eq. (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

$$K_W = 1.0 - (H_2O) \qquad (7)$$

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

$$\frac{H_2O}{1 - (H_2O)} = \left(2.0 + 7.67478\ \frac{W}{A}\right) \times \left\{\frac{\left[(CO_2)_d + \frac{(HC)}{1 - (H_2O)}\right]\left[\left(12.01 + 1.008\ \frac{b}{e}\right)\right]}{138.2468\ \frac{F}{A}}\right\} - 2(CO_2)_d - (CO)_d - \frac{NO}{1 - (H_2O)} - 2(O_2)_d \qquad (8)$$

The solution to Eq. (8) for H_2O is an iteration process since HC and NO are measured wet. The water correction factor is then calculated using Eq. (7).

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II. EXHAUST VO'UME 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 sh,ws the relation between the exhaust molecular weight and F/A ratio obtained from "compu:er program for calculation of complex chemical equilibrium composition" NASA SP-273 (3). The pollution production rate is then calculated as specified in the Federal Register (4).

III. 'UEL AIR RATIO BASED ON EXHAUST GAS COMPONENTS ,ND PROCEDURE OF SPINDT (5) - The F/A ratio can be expressed as:

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

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TABLE 1

Full rich LTD cycle - no air injection						
Mode	HC		NO_x		CO	
	lb/mode	% of total	lb/mode	% of total	lb/mode	% of total
Idle	0.086	11.60	0.000013	0.03	0.100	0.50
Taxi	0.490	66.40	0.0021	4.17	2.683	12.70
Takeoff	0.010	1.40	0.0016	3.20	0.900	4.20
Climb	0.074	10.00	0.0333	66.20	10.250	48.40
Approach	0.078	10.60	0.0133	26.40	7.250	34.20
Total	0.738	100.00	0.0503	100.00	21.183	100.00
% of EPA std.	172.0%		14.9%		224%	

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TABLE 2

Constructed LTD cycles emissions - leanout with air injection

Case I				Case II				Case III				Case IV			
Mode	F/A ratio	Injection air		Mode	F/A ratio	Injection air		Mode	F/A ratio	Injection air		Mode	F/A ratio	Injection ir	
		#/hr	%			#/hr	%			#/hr	%			#/hr	%
Idle	0.115	25	50.0	Idle	0.103	25	50.0	Idle	0.093	25	50.0	Idle	0.085	25	50.0
Taxi	0.097	67	50.0	Taxi	0.093	67	50.0	Taxi	0.085	67	50.0	Taxi	0.073	67	50.0
Takeoff	0.096	100	6.8	Takeoff	0.090	73	5.0	Takeoff	0.083	26	1.8	Takeoff	0.077	10	0.7
Climb	0.089	85	7.5	Climb	0.083	65	5.7	Climb	0.077	43	3.8	Climb	0.072	27	2.4
Approach	0.094	110	17.5	Approach	0.087	95	15.0	Approach	0.080	72	11.4	Approach	0.072	53	8.5

Case I % EPA std.			Case II % EPA std.			Case III % EPA std.			Case IV % EPA std.		
HC	NO_x	CO	HC	NO_x	CO	HC	NO_x	CO	HC	NO_x	CO
115%	15%	167%	109%	30%	140%	39%	64%	82%	41%	138%	39%

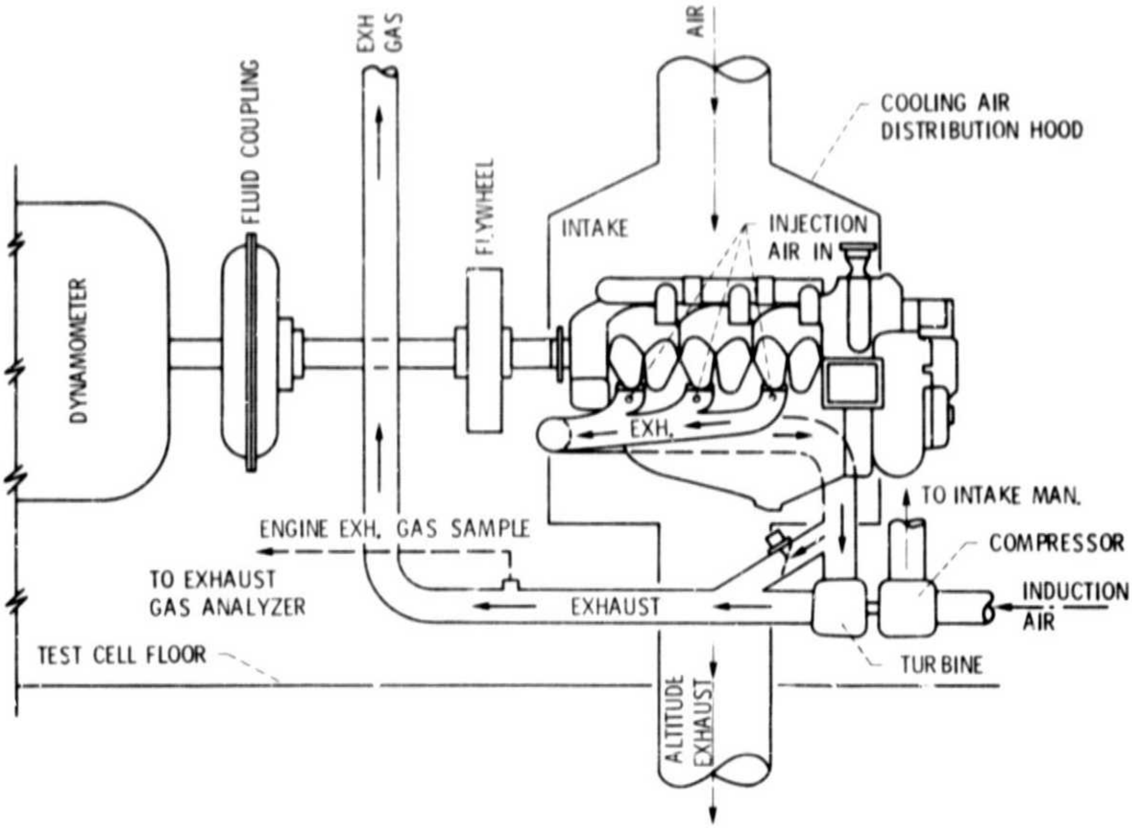

Figure 1. - Continental TSIO - 360 - C engine.

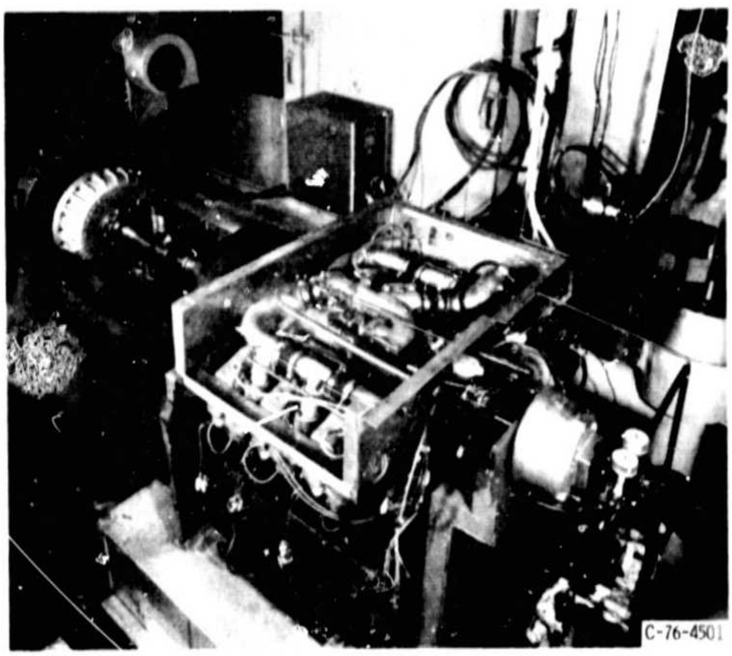

Figure 2. - Engine test stand.

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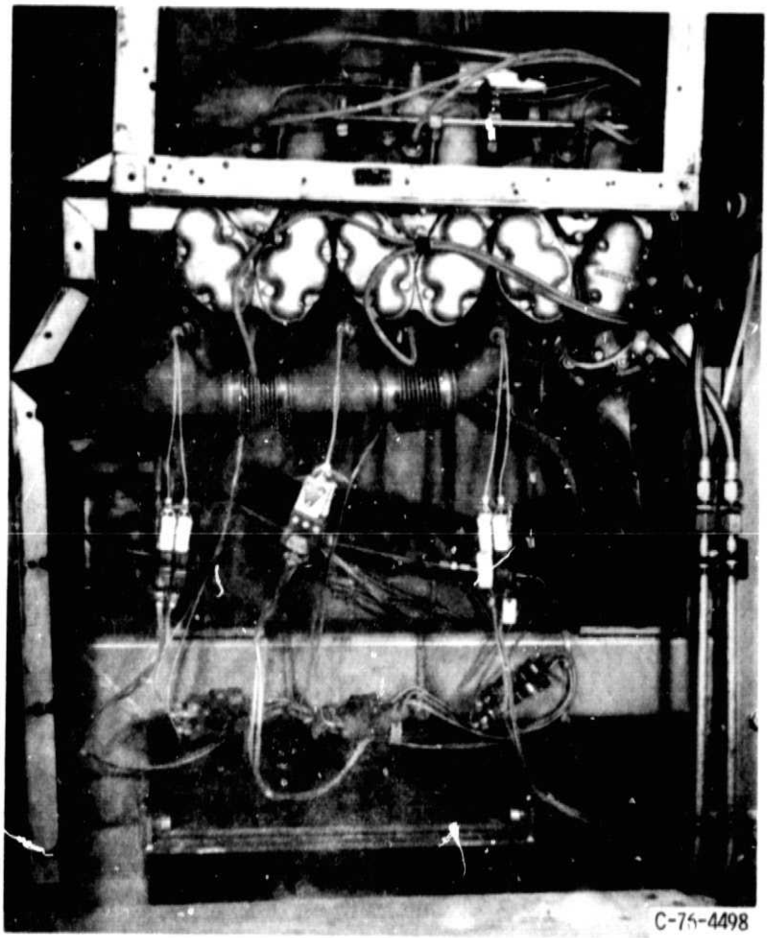

Figure 3. - Engine test stand.

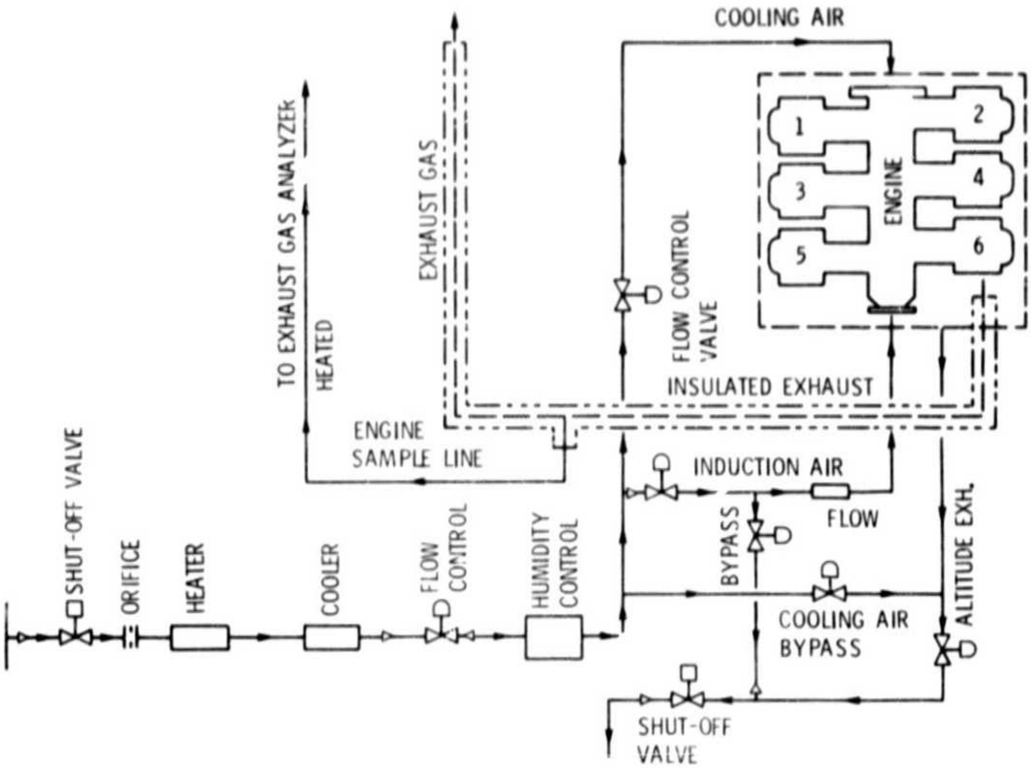

Figure 4. - Engine test stand facility systems.

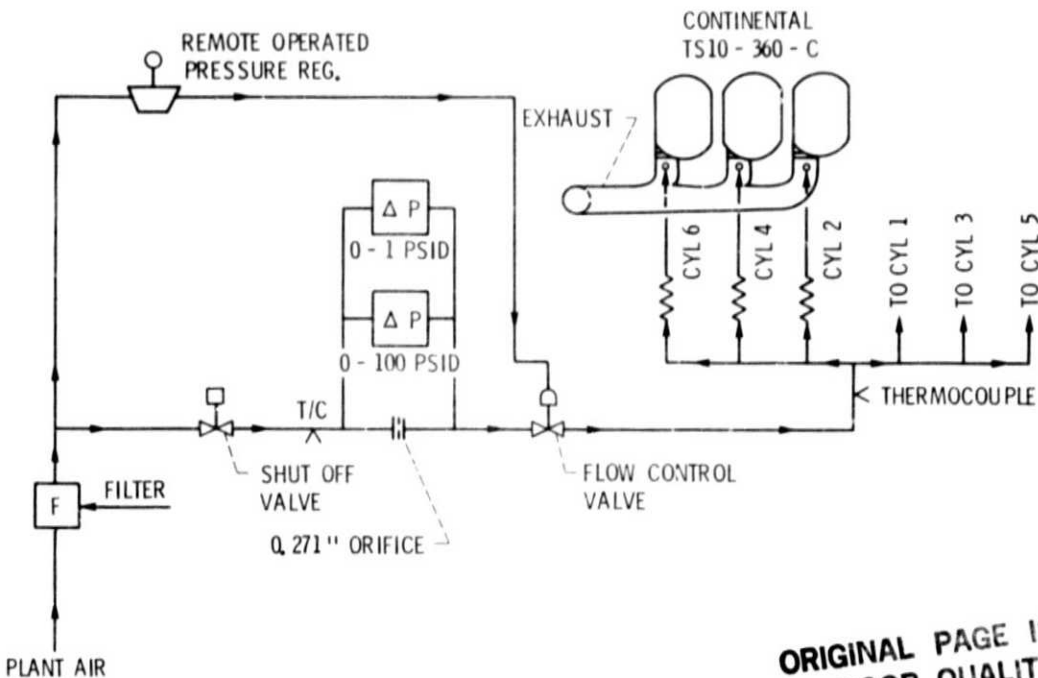

Figure 5. - Injection air system.

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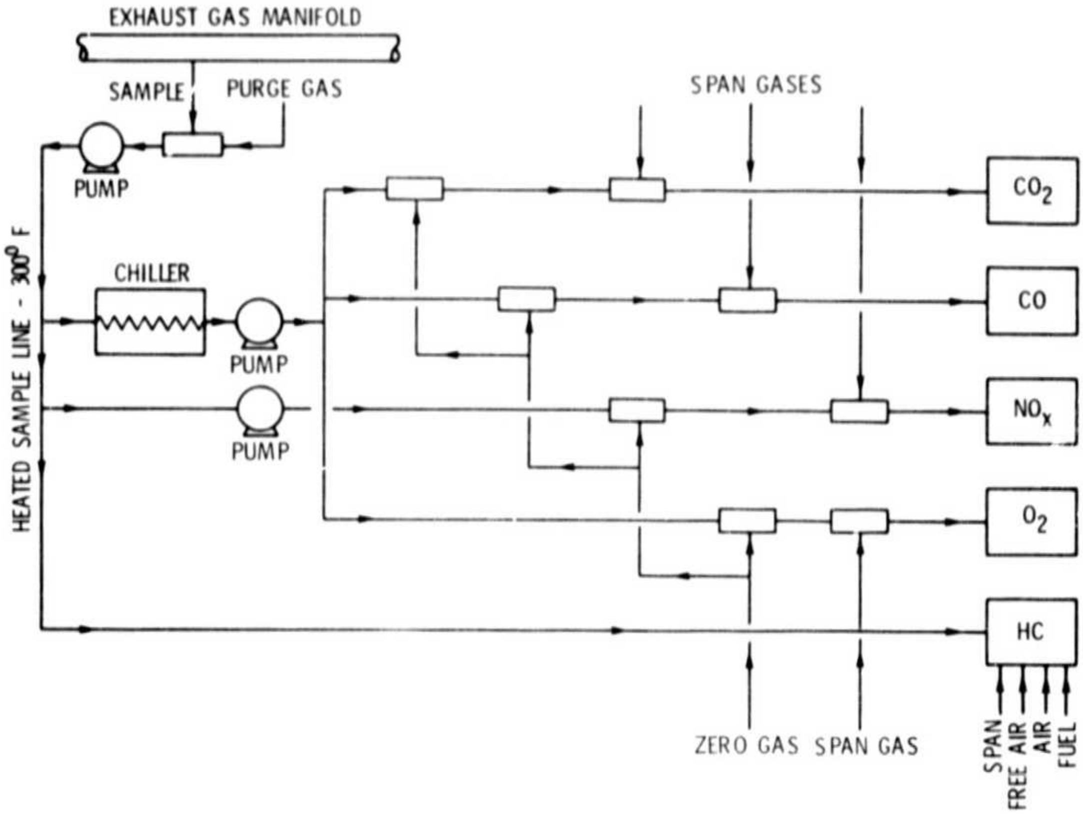

Figure 6. - Exhaust gas analyzer.

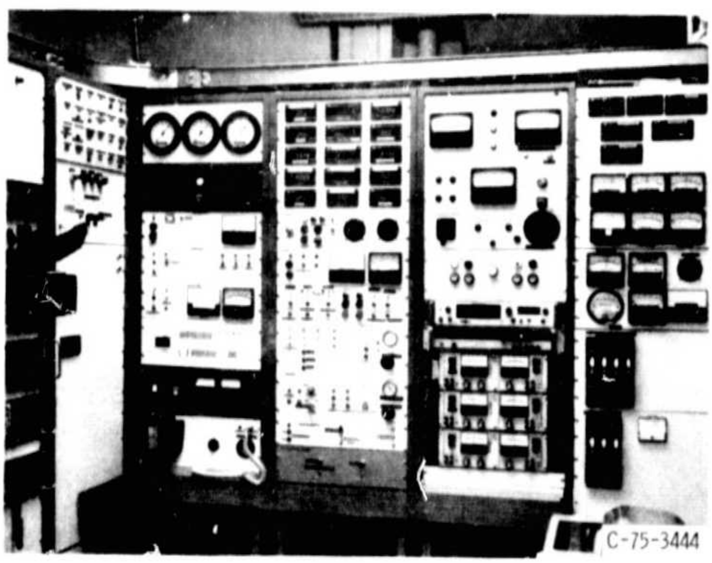

Figure 7. - Engine control panel.

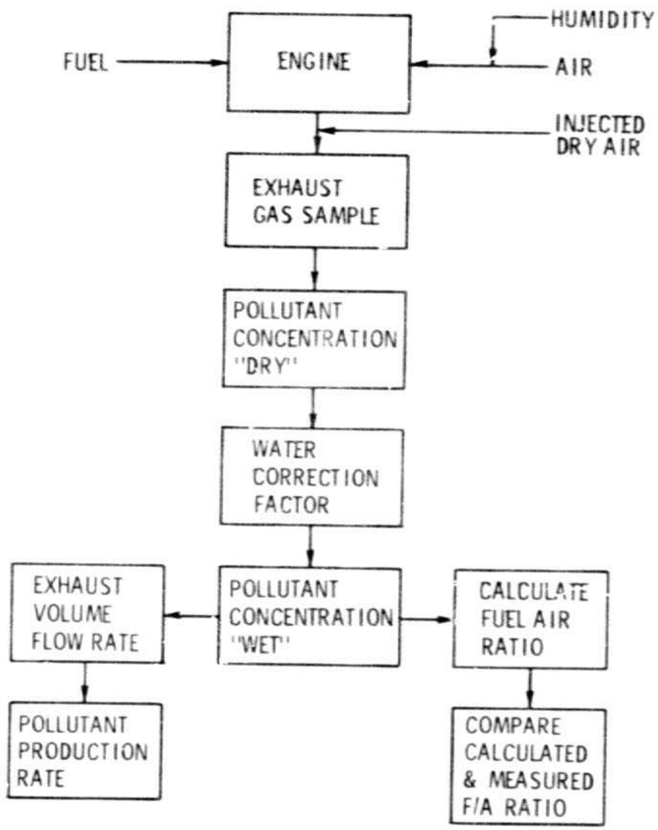

Figure 8. - Exhaust emission data reduction flow chart.

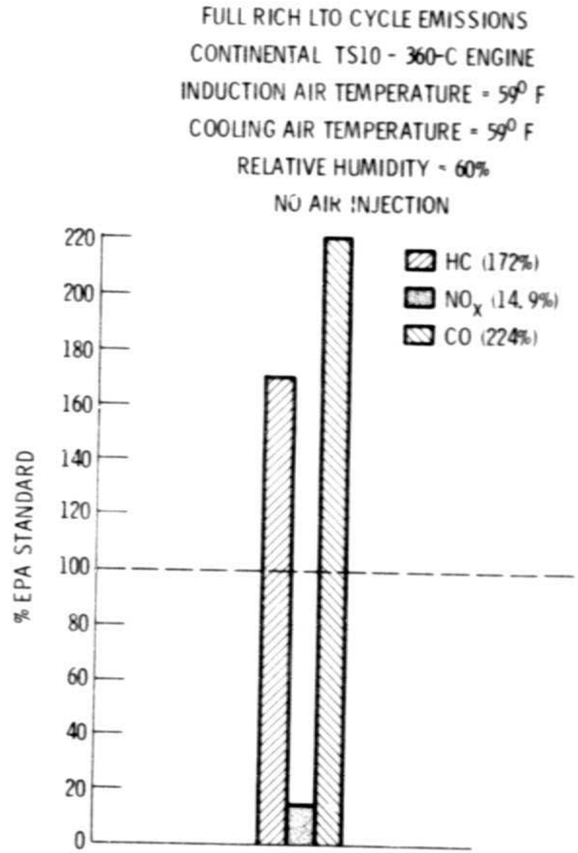

Figure 9.

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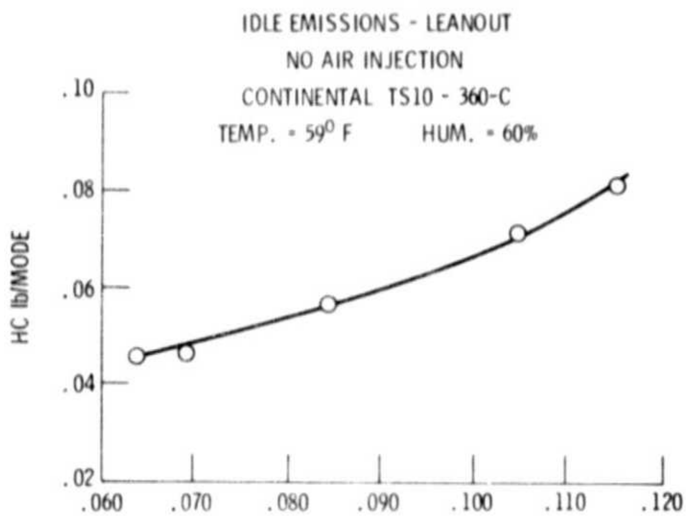

Figure 10. - Fuel-air ratio.

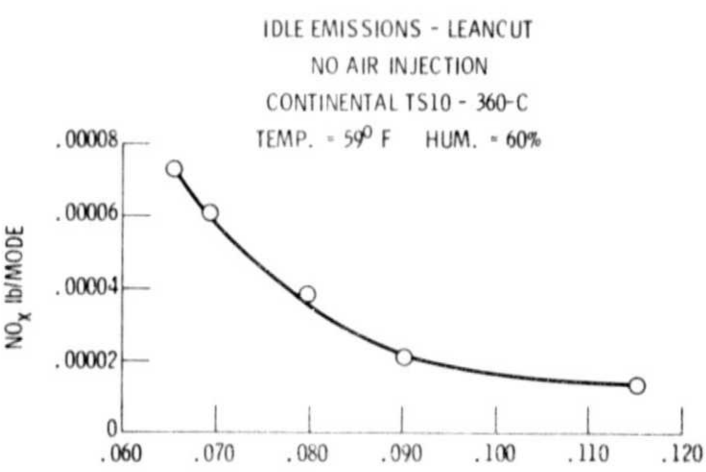

Figure 11. - Fuel-air ratio.

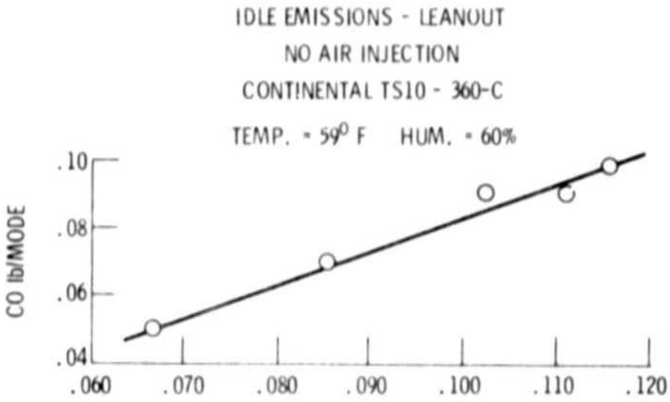

Figure 12. - Fuel-air ratio.

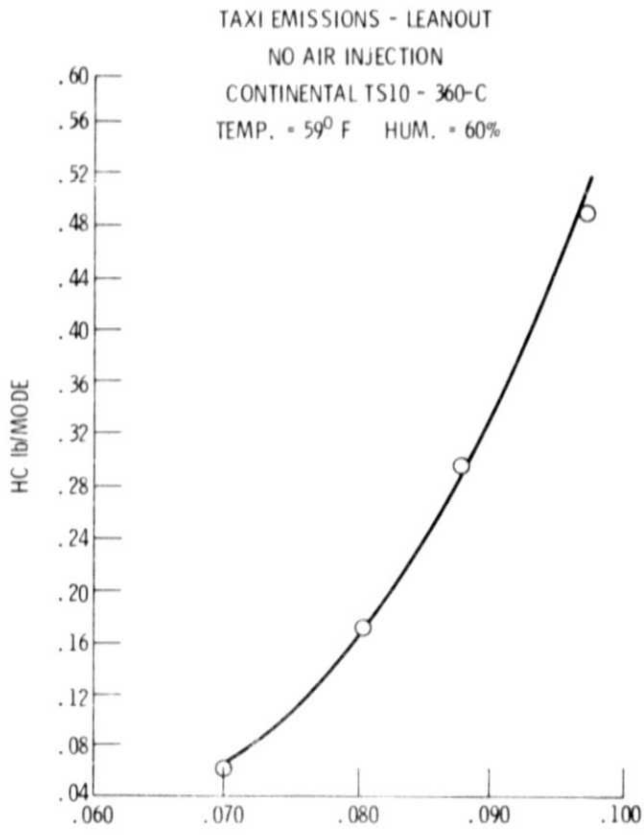

Figure 13. - Fuel-air ratio.

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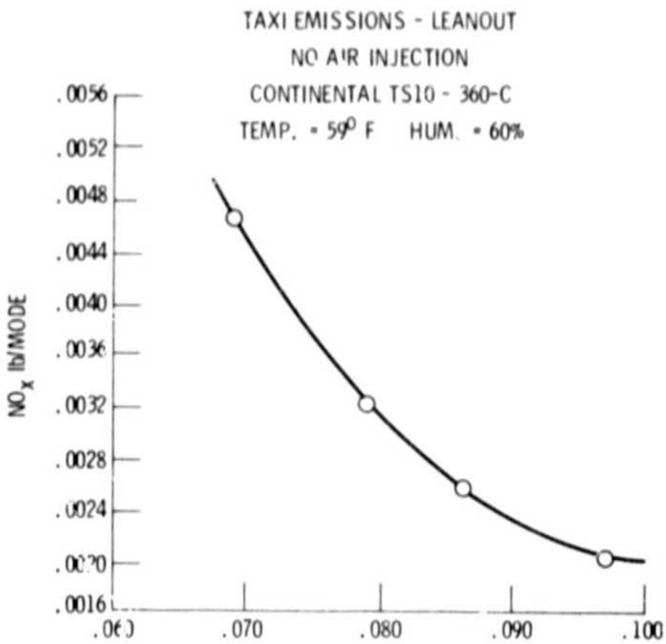

Figure 14. - Fuel-air ratio.

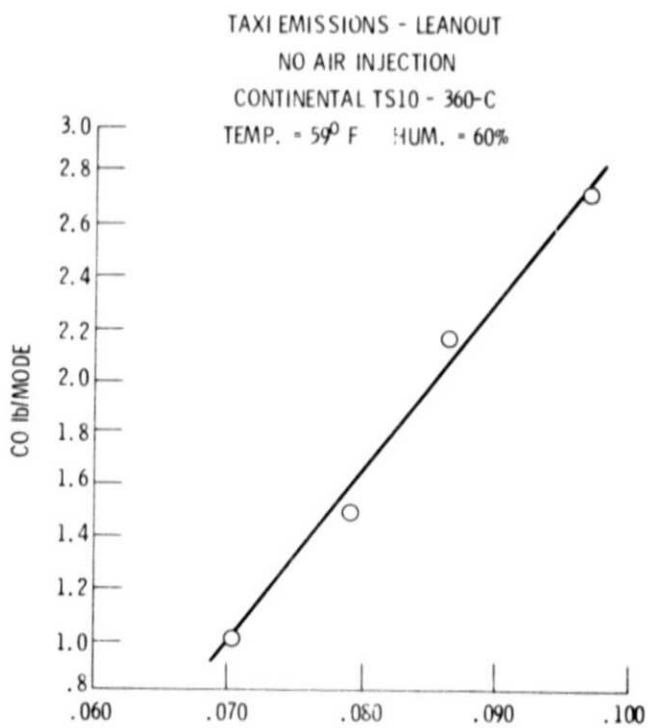

Figure 15. - Fuel-air ratio.

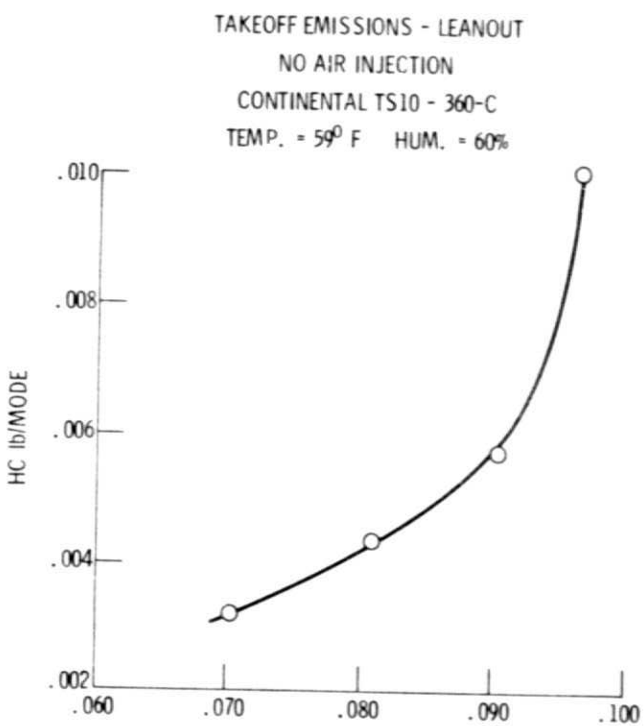

Figure 16. - Fuel-air ratio.

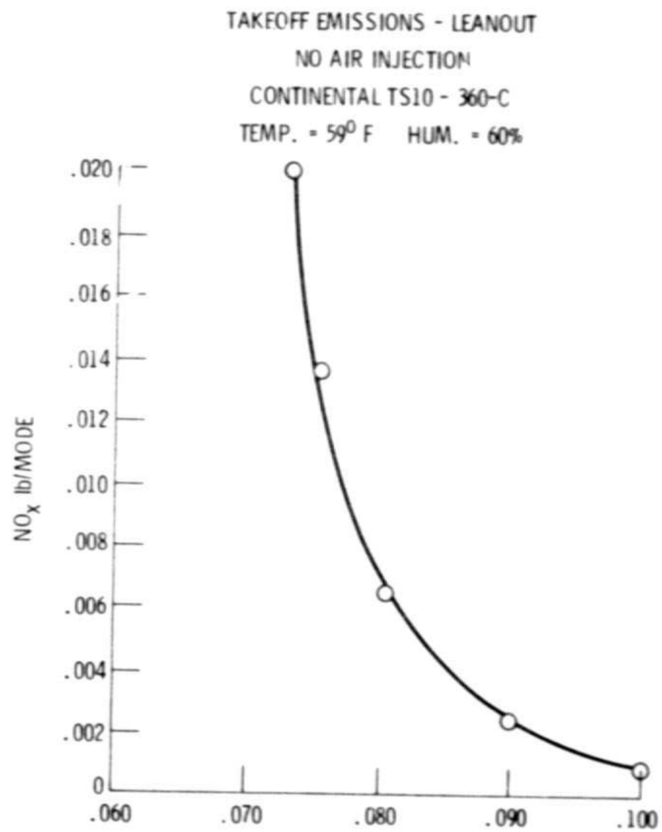

Figure 17. - Fuel-air ratio.

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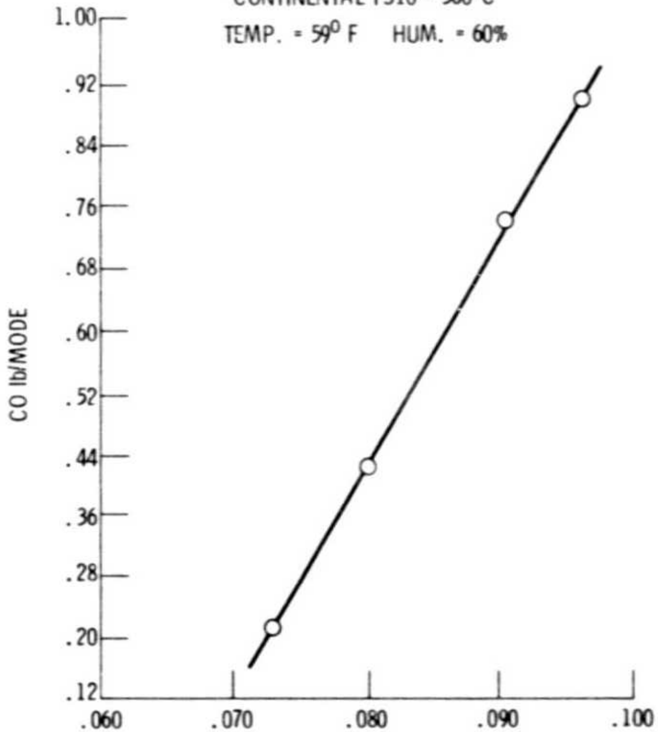

Figure 18. - Fuel-air ratio.

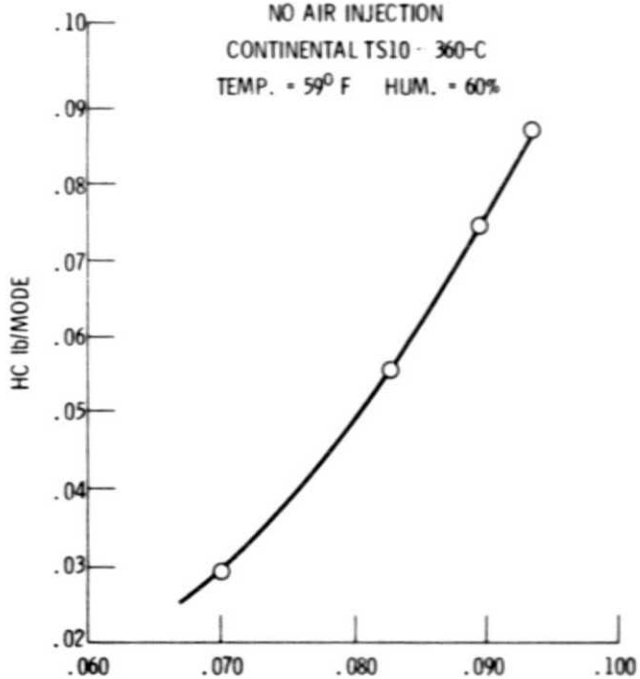

Figure 19. - Fuel-air ratio.

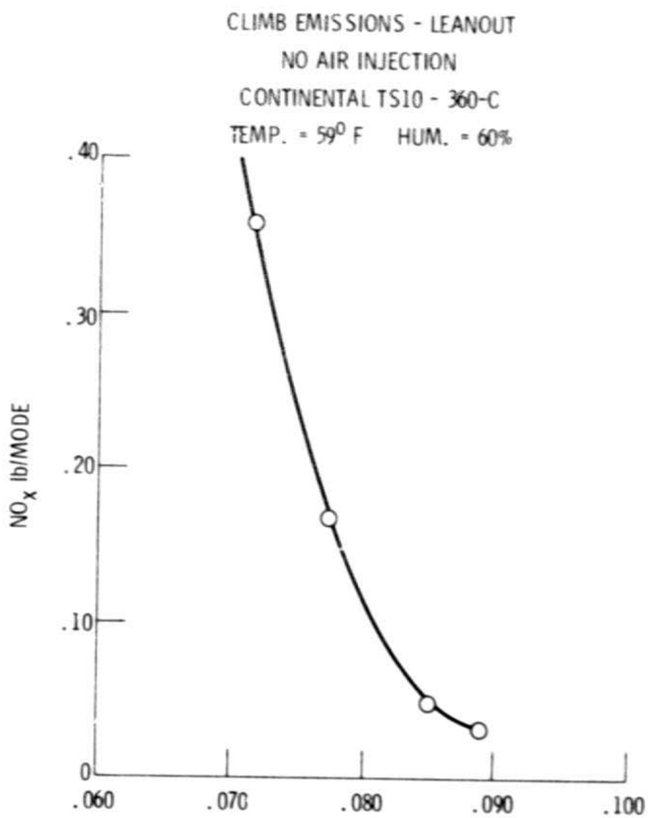

Figure 20. - Fuel-air ratio.

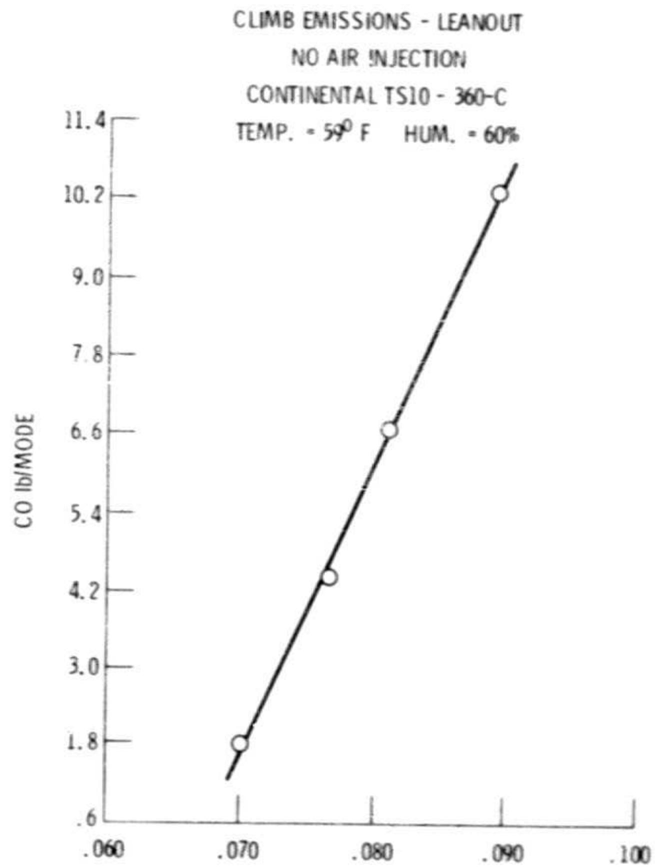

Figure 21. - Fuel-air ratio.

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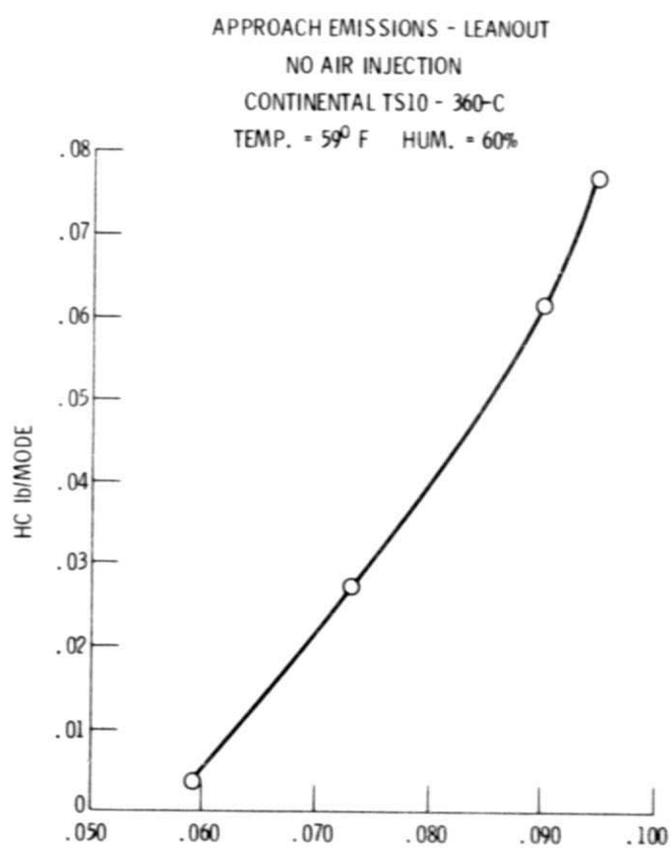

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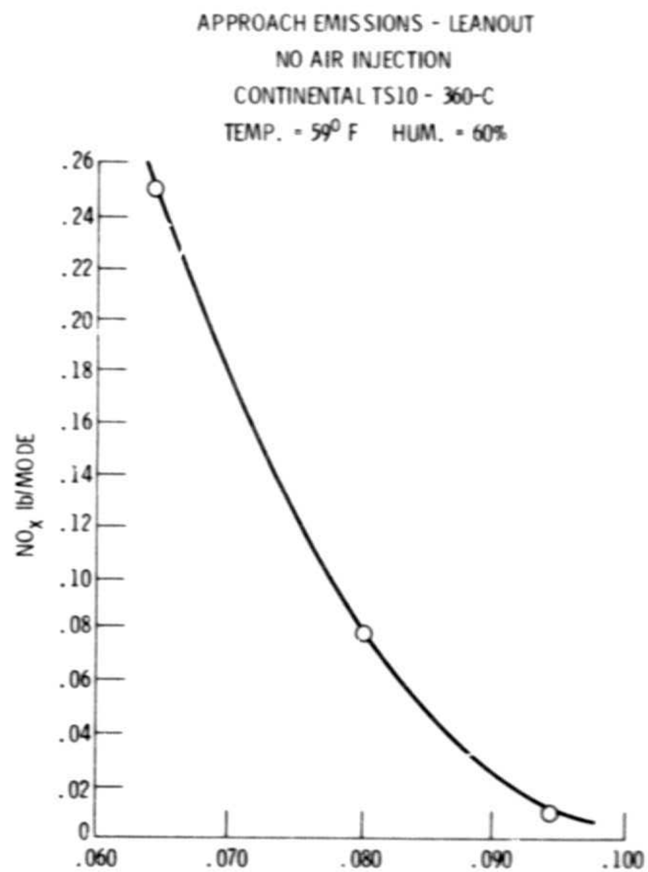

Figure 23. - Fuel-air ratio.

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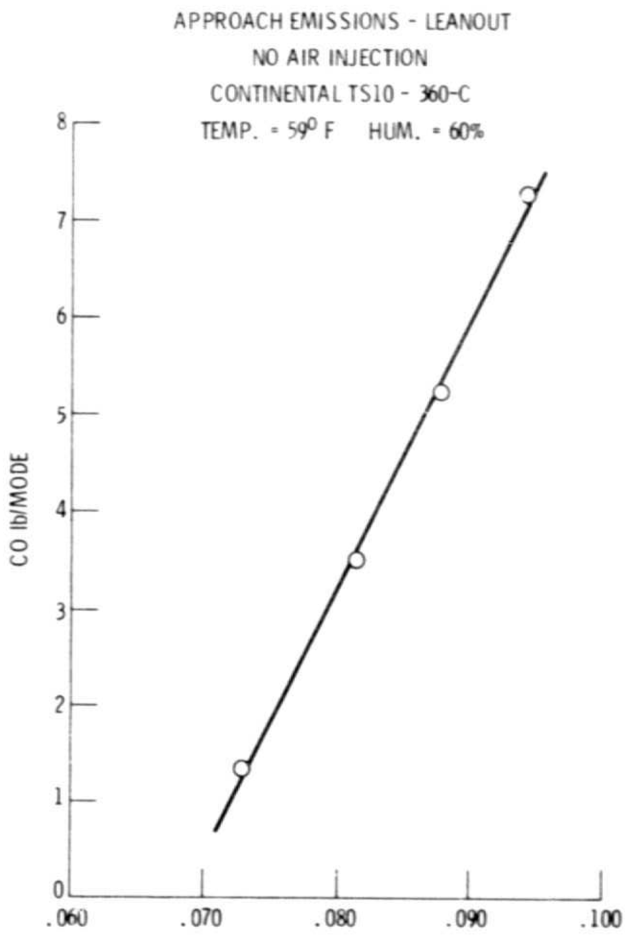

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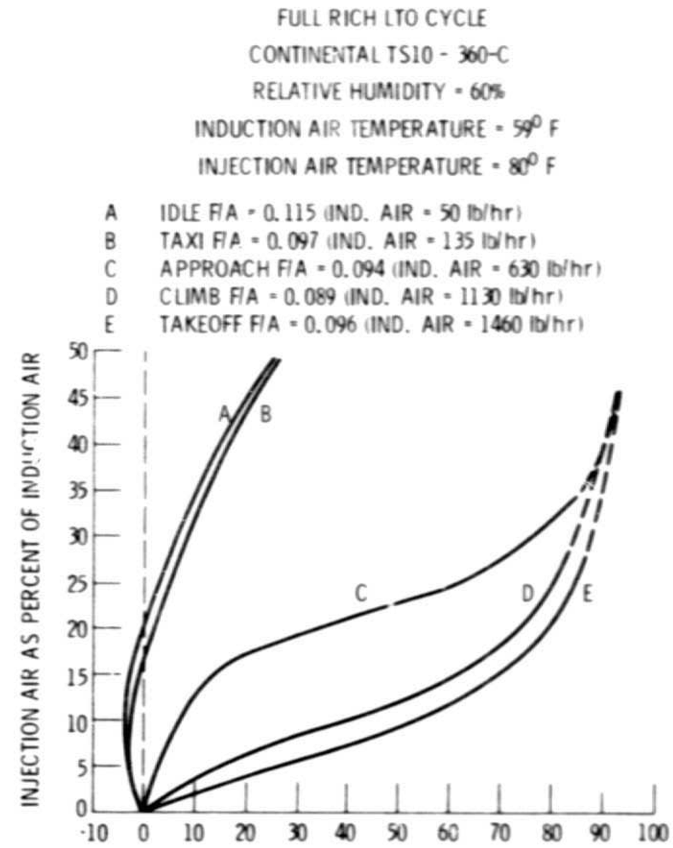

Figure 25. - Percent conversion - CO.

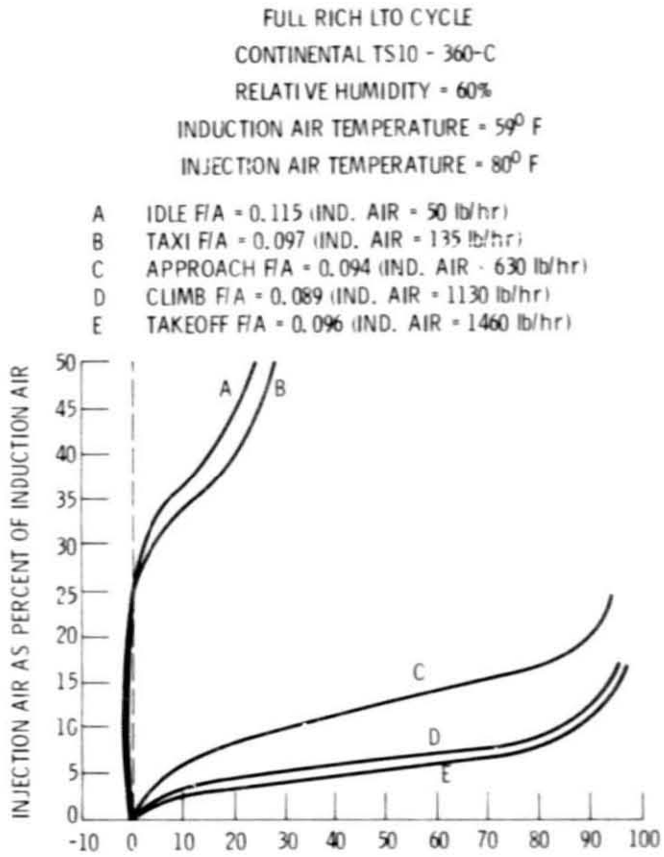

Figure 26. - Percent conversion - HC.

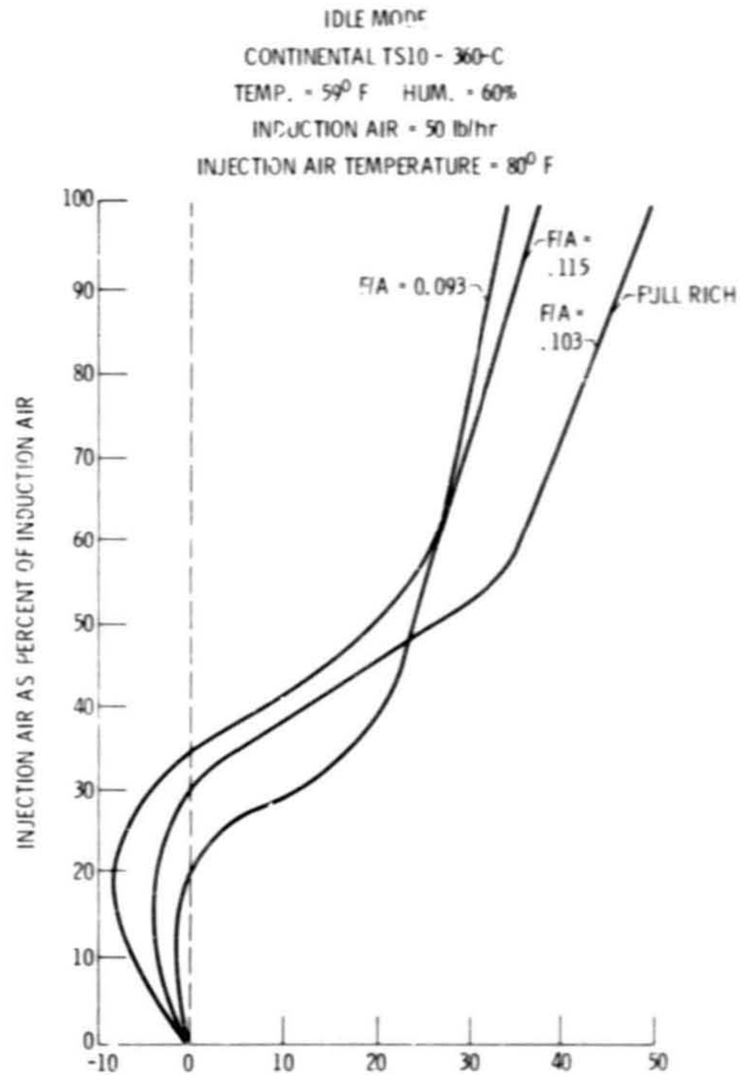

Figure 27. - Percent conversion - CO.

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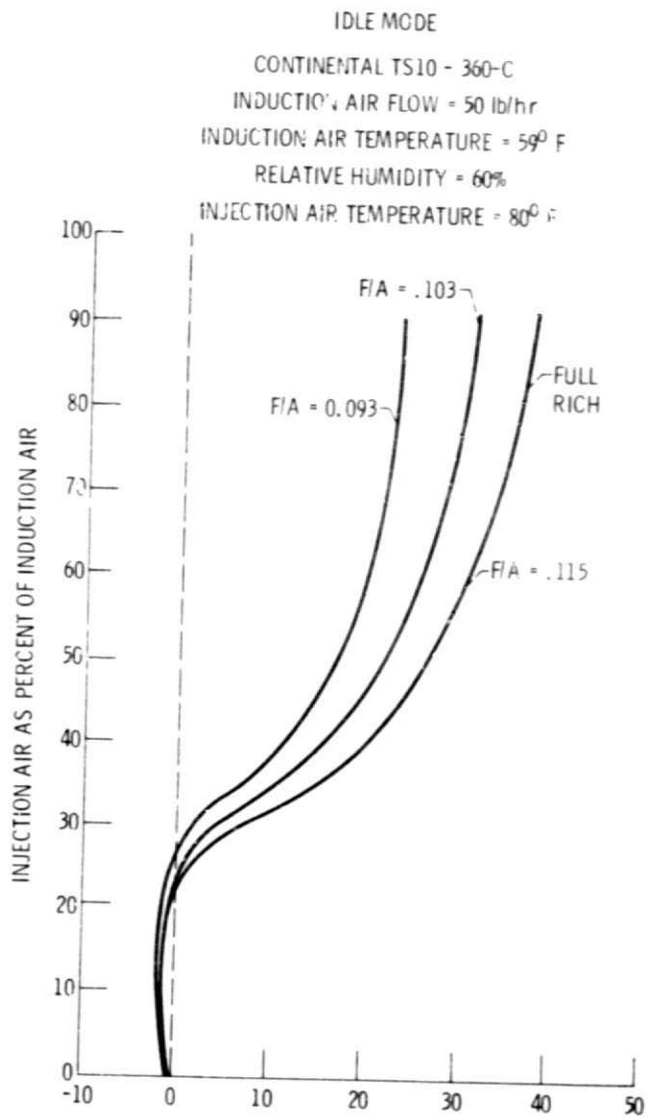

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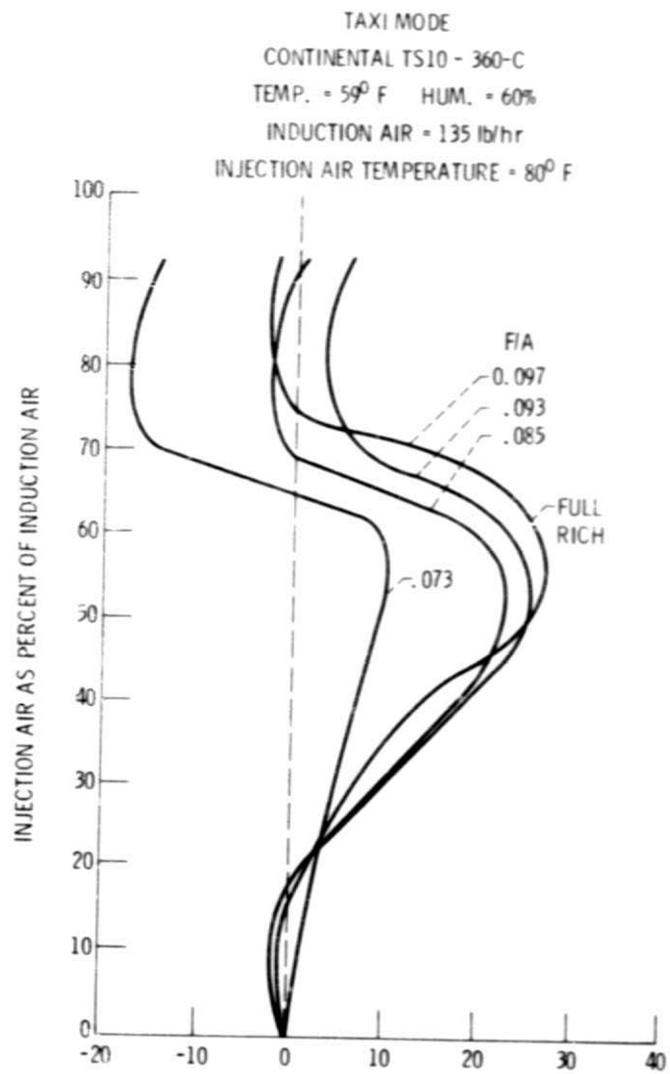

Figure 29. - Percent conversion - CO.

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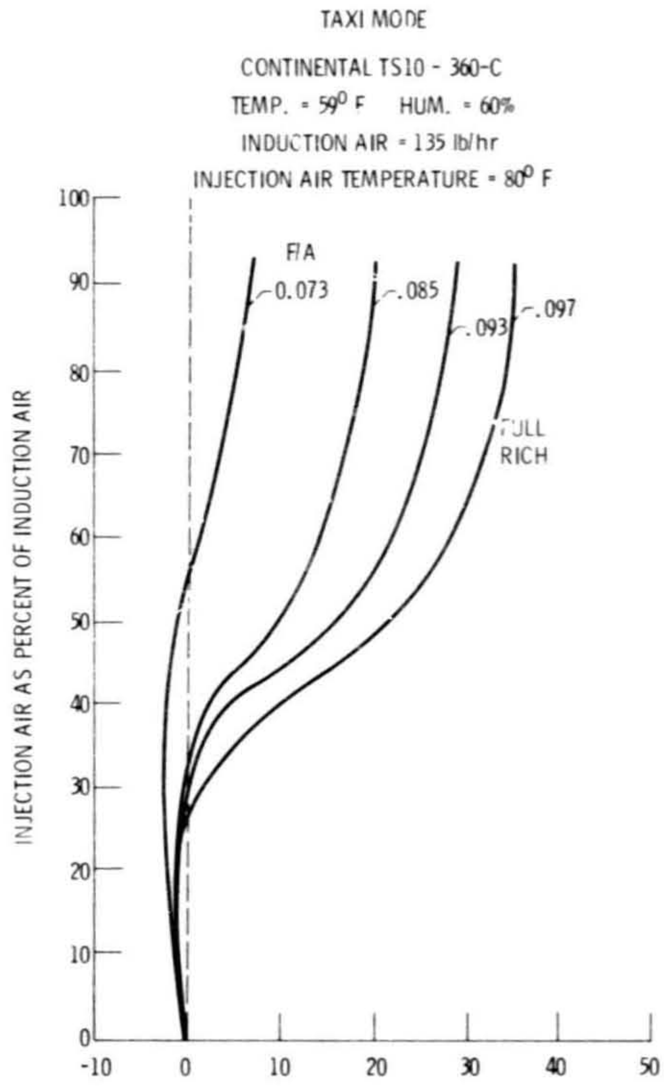

Figure 30. - Percent conversion - HC.

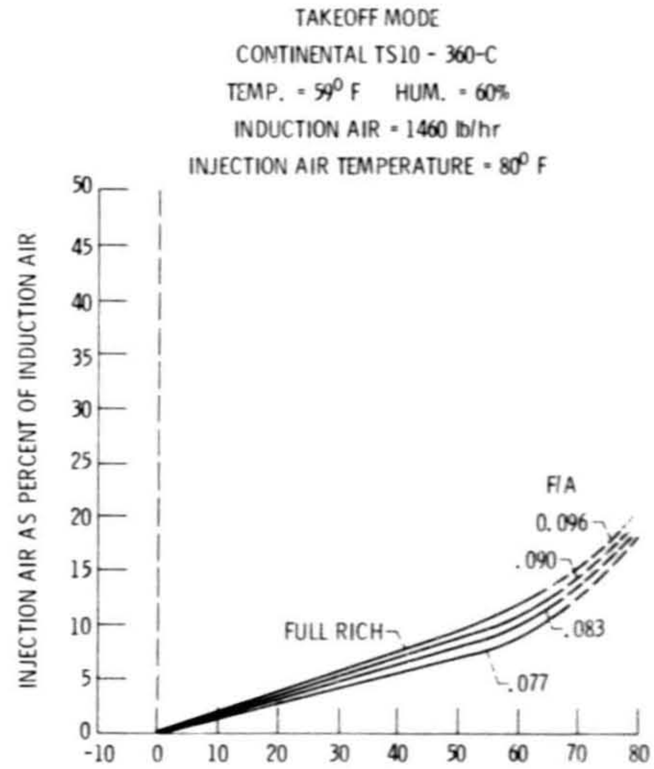

Figure 31. - Percent conversion - CO.

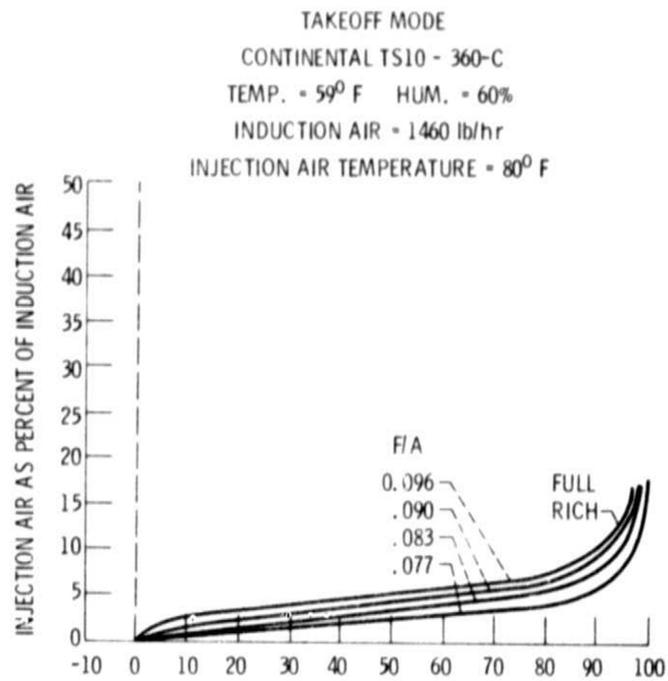

Figure 32. - Percent conversion - HC.

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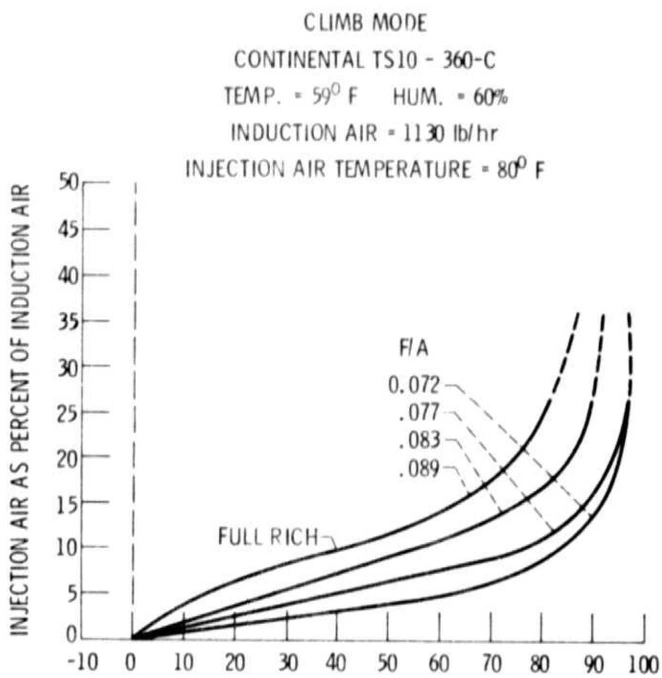

Figure 33. - Percent conversion - CO.

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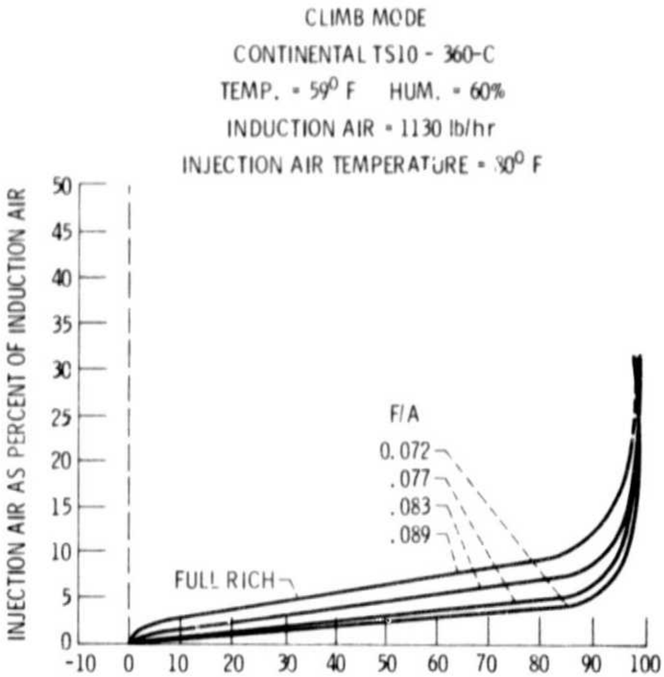

Figure 34. - Percent conversion - HC.

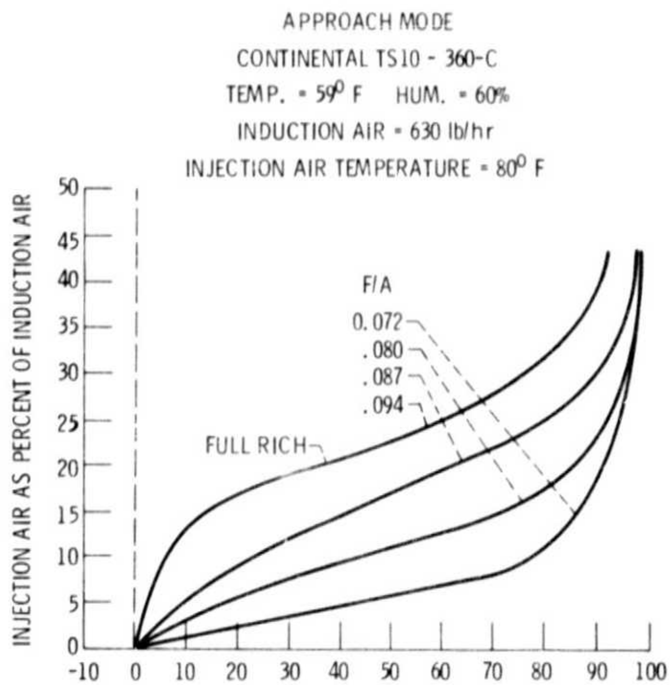

Figure 35. - Percent conversion - CO.

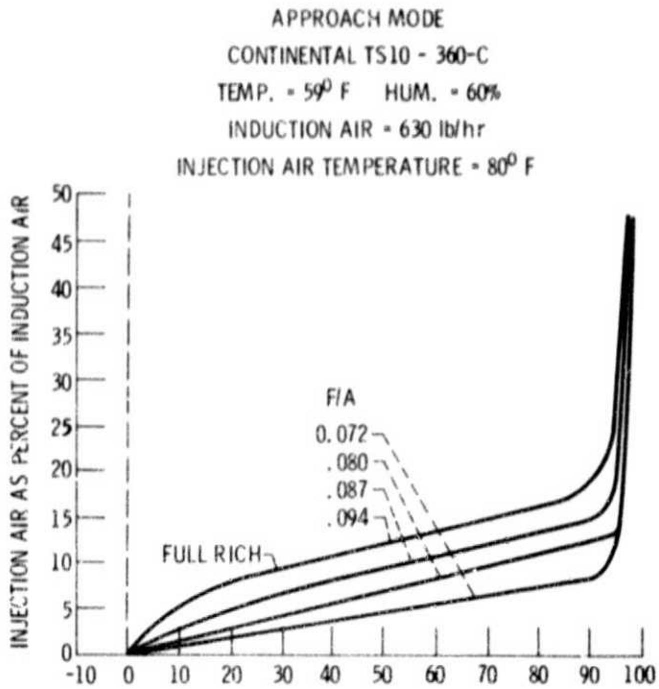

Figure 36. - Percent conversion - HC.

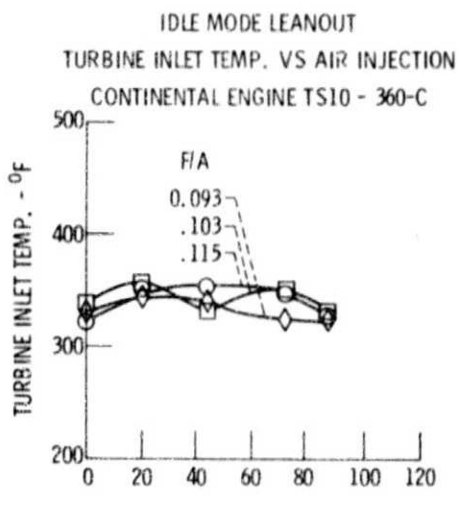

Figure 37. - Air injection - % of modal induction air.

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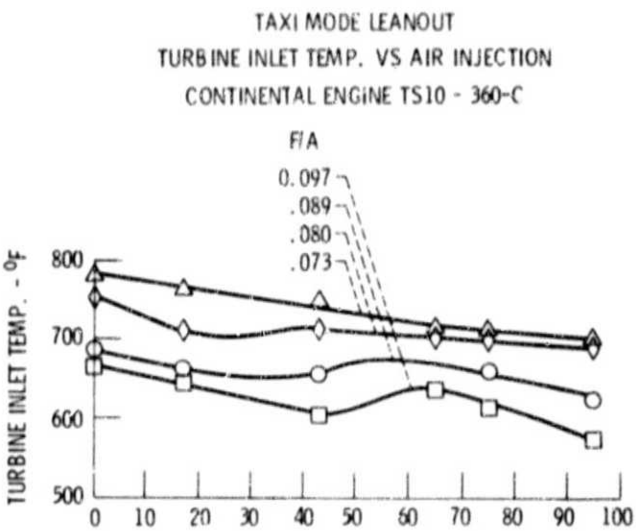

Figure 38. - Air injection - % of modal induction air.

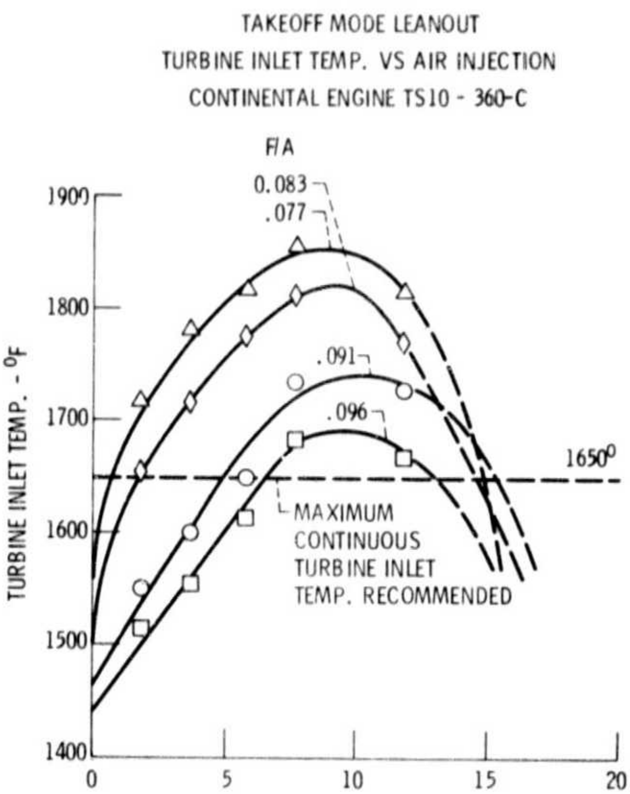

Figure 39. - Air injection - % of modal induction air.

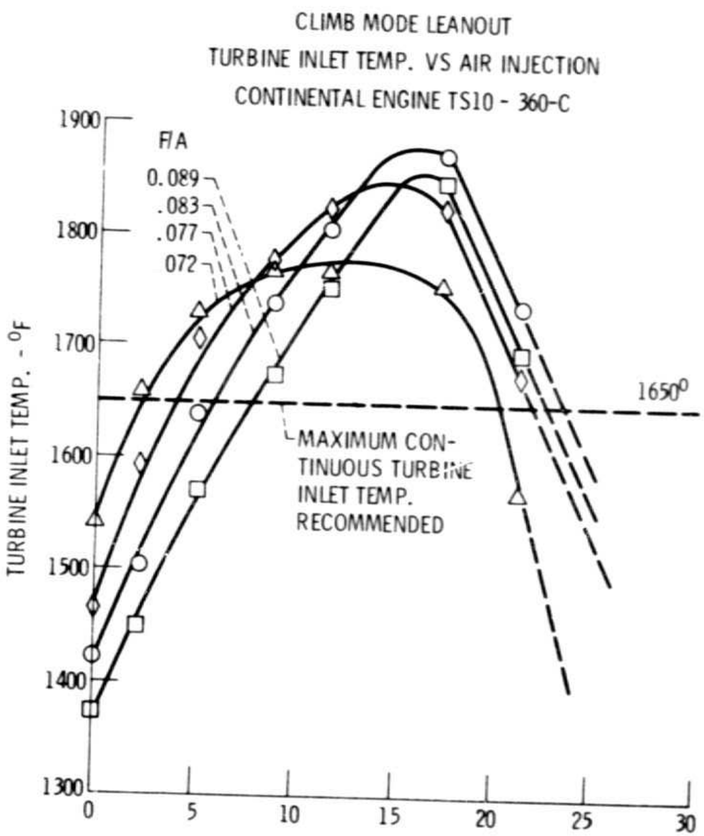

Figure 40. - Air injection - % of modal induction air.

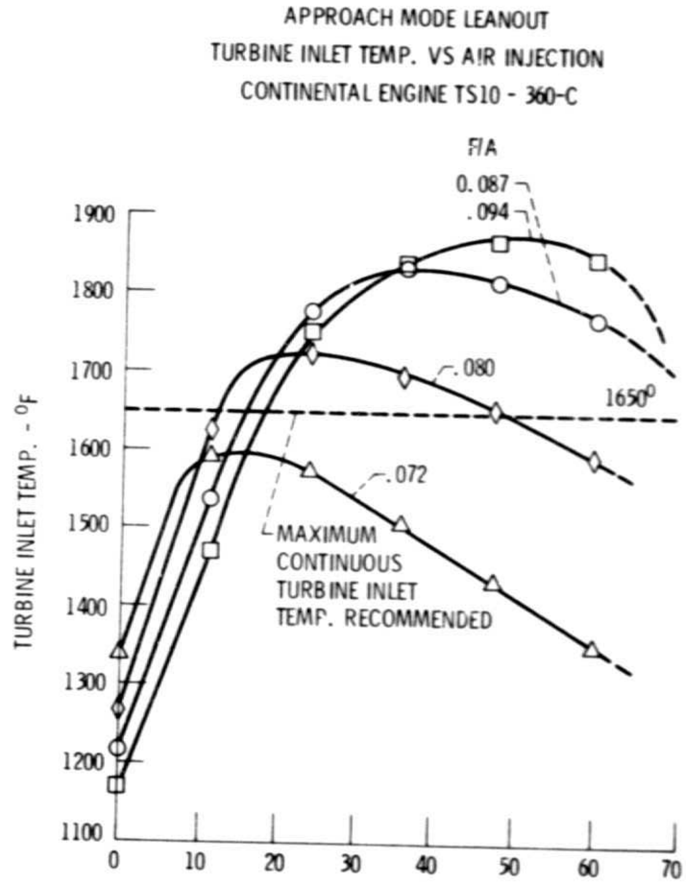

Figure 41. - Air injection - % of modal induction air.

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REDUCTION OF CONSTRUCTED LTO CYCLES EMISSIONS WITH AIR INJECTION

LEANOUT DATA - RECOMMENDED TURBINE INLET TEMP. = 1650° F

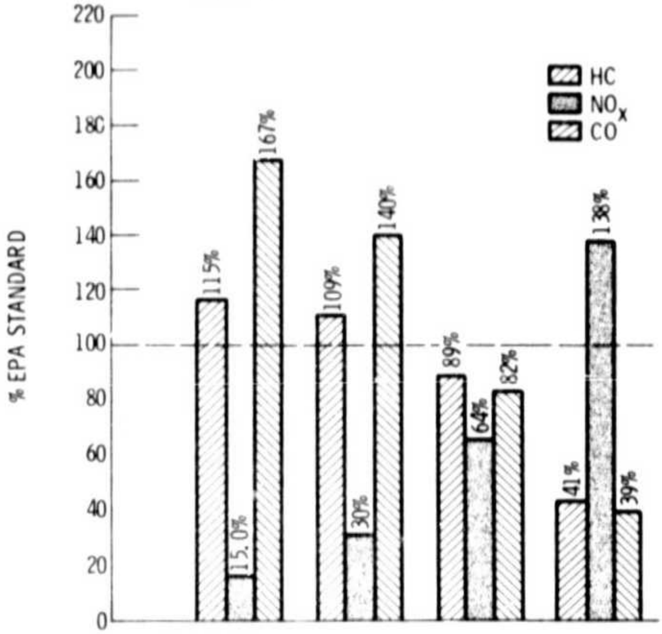
CONTINENTAL TSIO - 360-C ENGINE

INDUCTION AIR TEMP. = 59° F

COOLING AIR TEMP. = 59° F

RELATIVE HUMIDITY = 60%

INJECTION AIR TEMP. = 80° F



AIR INJECTION - lb/hr OR PERCENT MODAL INDUCTION AIR

	lb/hr	%	lb/hr	%	lb/hr	%	lb/hr	%
IDLE	25	50.0	25	50.0	25	50.0	25	50.0
TAXI	67	50.0	67	50.0	67	50.0	67	50.0
TAKEOFF	100	6.8	73	5.0	26	1.8	10	.7
CLIMB	85	7.5	65	5.7	43	3.8	27	2.4
APPROACH	110	17.5	95	15.0	72	11.4	53	8.5
	CASE I		CASE II		CASE III		CASE IV	

Figure 42.

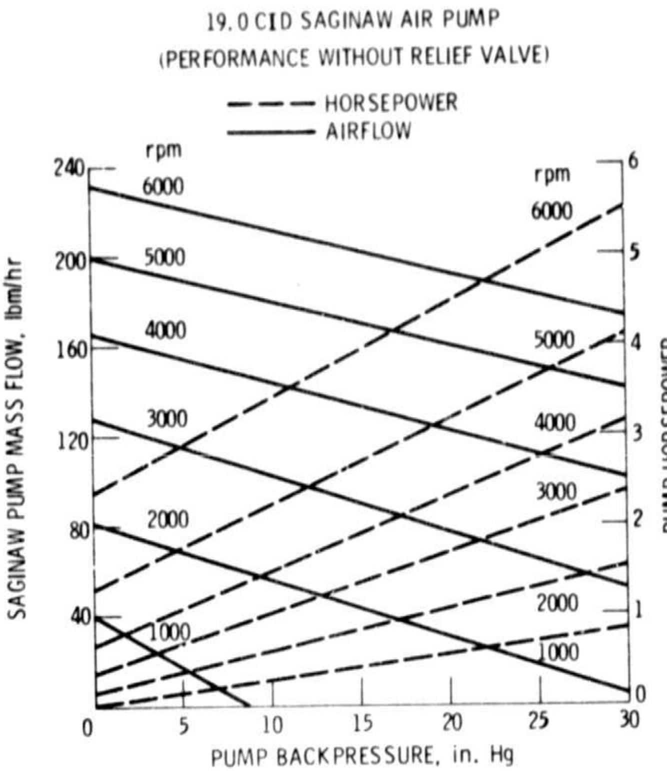


Figure 43.

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	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Donald V. Cosgrove and Erwin E. Kempke	E-9955
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15. Supplementary Notes

16. Abstract

A turbocharged fuel-injected aircraft engine was operated over a range of test conditions that included the EPA five-mode emissions cycle and fuel-air ratio variations for individual modes while injecting air into the exhaust gas. Air injection resulted in a decrease of hydrocarbons and carbon monoxide while exceeding the maximum recommended turbine inlet temperature of 1650° F at the full rich mixture of the engine. Leanout tests indicated that the EPA standards could be met through the combined use of fuel management and air injection.

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Emissions Turbocharged fuel-injected engine Air injection	Unclassified - unlimited STAR Category 45

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