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EXHAUST EMISSIONS CHARACTERISTICS FOR A GENERAL AVIATION LIGHT AIRCRAFT TELEDYNE CONTINENTAL MOTORS TSIO-360-C PISTON ENGINE

Eric E. Becker

MAY 1979

FINAL REPORT

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16. Abstract

The Teledyne Continental Motors TSIO-360-C engine (S/N 300244) was tested at the National Aviation Facilities Experimental Center (NAFEC) to develop an exhaust emissions data base. This data base consists of current production baseline emissions characteristics, lean-out emissions data, effects of leaning-out the fuel schedule on cylinder head temperatures, and data showing ambient effects on exhaust emissions and cylinder head temperatures. The engine operating with its current full-rich production fuel schedule could not meet the proposed Environmental Protection Agency (EPA) standard for carbon monoxide (CO) and unburned hydrocarbons(HC) under sea level standard-day conditions. The engine did, however, meet the proposed EPA standard for oxides of nitrogen (NO_x) under the same sea level conditions. The results of engine testing under different ambient conditions (essentially sea level standard day to sea level hot day) are also presented, and these results show a trend toward higher levels of emissions output for CO and HC while producing slightly lower levels of NO_x.

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METRIC CONVERSION FACTORS

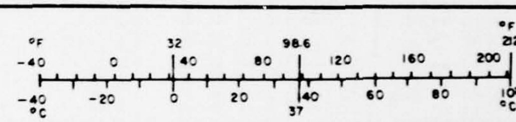
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The author would like to record his appreciation to the following individuals for contributions they made during the conduct of the Federal Aviation Administrations light-aircraft piston engine emissions program:

Mr. S. Imbrogno--For his technical supervision, direction, and description of the emissions measuring system, the incorporation of important modifications and improvements to the system, and the development and operational usefulness of the Emissions Data Direct Digital Readout System which was available for monitoring the test data for the first time during the testing of the TCM TSIO-360-C and subsequent engines.

Mr. R. Salmon--For his technical expertise and experience in the design and development of the basic engine induction airflow and fuel flow systems utilized throughout the piston engine emissions test program. An additional word of appreciation is recorded for Mr. Salmon's help and encouragement in the analysis and evaluation of test data.

Messers S. Rutherford and W. Cavage--For their dedicated work in preparing each test engine for testing and for their loyal and faithful dedication to the program with regard to conducting the testing functions and modifying test equipment and instrumentation. The program benefitted greatly from numerous suggestions that these men made.

Mr. E. Klueg--For the dedicated leadership he provided to the program as its program manager.

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PURPOSE.

General aviation piston engine exhaust emission tests were conducted at the National Aviation Facility Experimental Center (NAFEC) for the following reasons:

1. Determine and establish total exhaust emissions characteristics for a representative group of current production general aviation piston engines.

2. Determine the effects of leaning-out of the fuel metering system on exhaust emissions.

3. Verify the acceptability of test procedures, testing techniques, instrumentation, etc.

4. Determine reductions in operating limits and safety margins resulting from fuel system adjustments/modifications evaluated for improved piston engine exhaust emissions characteristics.

BACKGROUND.

Beginning in 1967, Congress enacted a series of laws which added environmental considerations to the civil aviation safety, control, and promotional functions of the Federal Aviation Administration (FAA). This legislation was in response to the growing public concern over environmental degradation. Thus, the FAA was committed to the development, evaluation, and execution of programs designed to identify and minimize the undesirable environmental effects attributable to aviation.

In accordance with the Clean Air Act Amendments of 1970, the Environmental Protection Agency (EPA) established emission standards and outlined test procedures when it used EPA rule part 87 in January 1973. The Secretary of Transportation and, therefore, the FAA was charged with the responsibility for issuing regulations to implement this rule and enforcing these standards.

Implementation of this rule was contingent on the FAA's finding that safety was not impaired by whatever means was employed to achieve the standards. For this reason the FAA undertook a program, subsequent to the issuance of the EPA emission standards in July 1973, to determine the feasibility of implementation, verify test procedures, and validate test results.

There was concern that the actions suggested in order to comply with the EPA emission standards, such as operating engines at leaner mixture settings during landing and takeoff cycles, might compromise safety and/or significantly reduce engine operating margins. Therefore, the FAA contracted with Avco Lycoming and Teledyne Continental Motors to select engines that they considered typical of their production, test these engines as normally produced to establish a baseline emissions data base, and then alter (by lean-out adjustments) the fuel schedule and ignition timing to demonstrate methods by which the proposed EPA limits could be reached.

In the event that hazardous operating conditions were indicated by the manufacturer's tests, independent verification of data would be necessary. Therefore, it was decided that duplication of the manufacturer's tests be undertaken at NAFEC to provide the needed verification. This report presents the NAFEC test results for the Teledyne Continental Motors (TCM) TSIO-360-C piston engine (S/N300244). It should be noted that since the time of these tests, the EPA has rescinded the promulgated piston engine standards (reference 1). This work is reported upon herein in the same light as it would have been if the requirements were still in effect.

DISCUSSION

DESCRIPTION OF TELEDYNE CONTINENTAL MOTORS TSIO-360-C ENGINE.

The TSIO-360-C engine tested at NAFEC is a turbo supercharged fuel injected, horizontally opposed engine with a nominal 360 cubic inch displacement (cid), rated at 225 brake horsepower (bhp) for a nominal brake specific fuel consumption (bsfc) of 0.60. This engine is designed to operate on 100/130 octane aviation gasoline (appendix A--Fuel Sample Analysis of NAFEC Test Fuel). The vital statistics for this engine are provided in table 1.

TABLE 1. TCM TSIO-360-C ENGINE

No. of Cylinders	6
Cylinder Arrangement	HO
Max. Engine Takeoff Power (HP, RPM)	225,2800
Bore and Stroke (in.)	4.44 x 3.87
Displacement (cu. in.)	360
Weight, Dry (lbs)--Basic Engine	300
Propeller Drive	Direct
Fuel Grade--Octane Rating	100/130
Compression Ratio	7.5:1
Max. Cylinder Head Temperature Limit (°F)	460

DESCRIPTION OF TEST SET-UP AND BASIC FACILITIES.

For the NAFEC sea level static tests, the engines were installed in the propeller test stand shown in figures 1 and 2. This test stand was located in the NAFEC General Aviation Piston Engine Test Facility. The test facility provided the following capabilities for testing light aircraft piston engines:

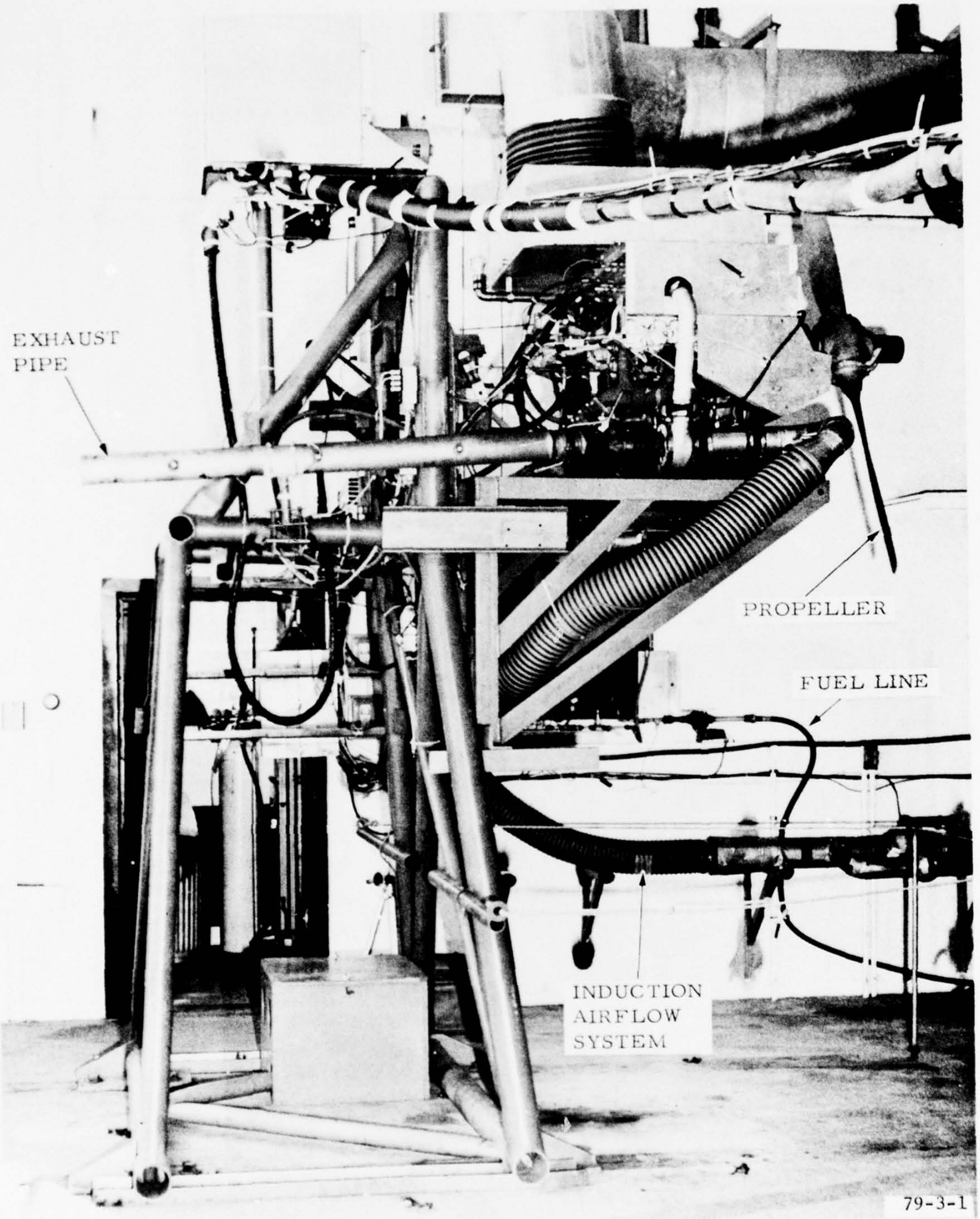


FIGURE 1. SEA LEVEL PROPELLER TEST STAND--TCM-TSIO-360-C ENGINE INSTALLATION--EMISSIONS TESTING--SIDE VIEW

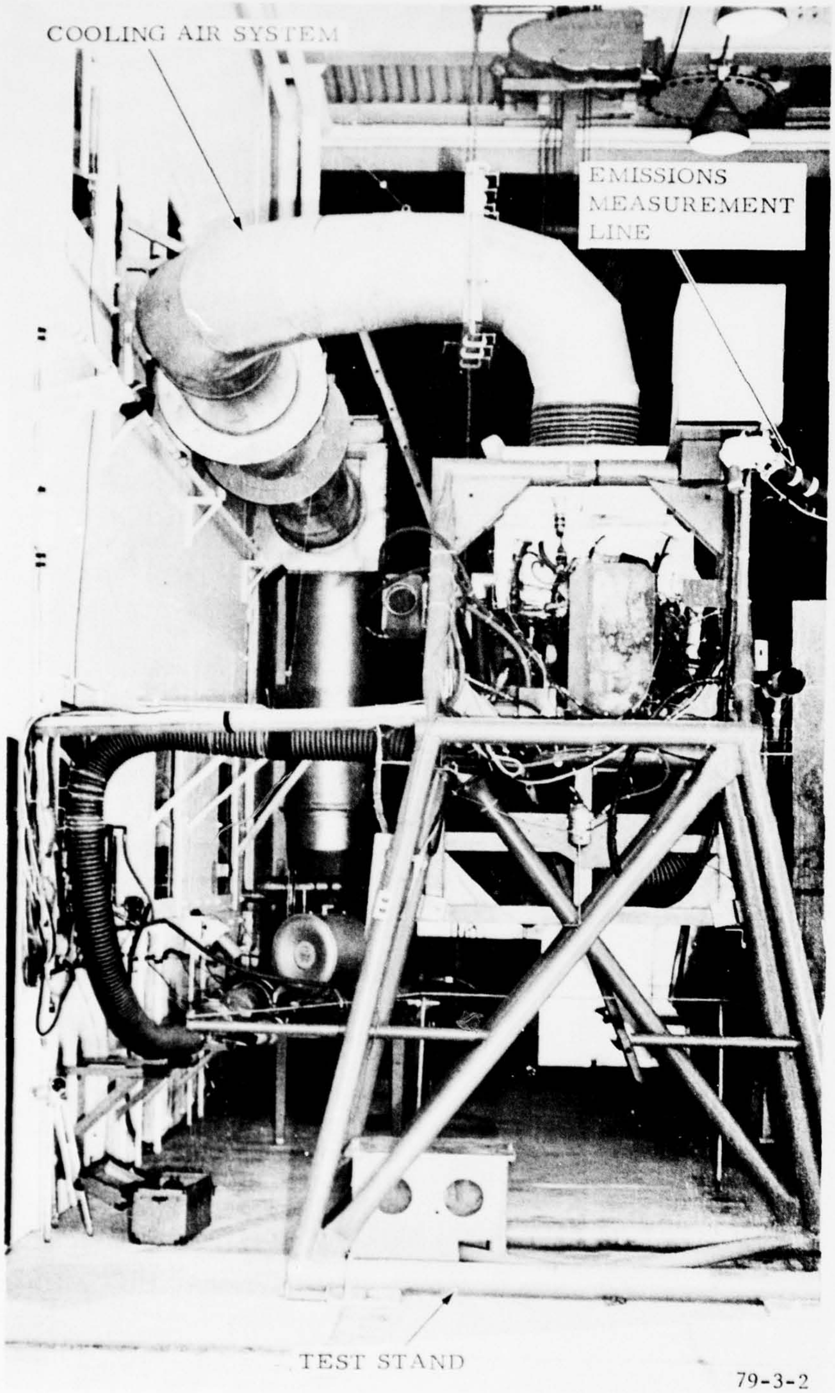


FIGURE 2. SEA LEVEL PROPELLER TEST STAND--TCM TSIO-360-C ENGINE INSTALLATION--EMISSIONS TESTING--REAR VIEW LOOKING FORWARD

(1) Two basic air sources--dry bottled and ambient air
(2) Ambient temperatures (20 to 140 degrees Fahrenheit (°F))
(3) Nominal sea level pressures (29.50 to 30.50 inches of mercury absolute (inHgA)
(4) Humidity (specific humidity--0 to 0.020 lb of water (H_2O) vapor/lb dry air)
(5) Fuel (100/130 octane aviation gasoline--a dedicated 5,000-gallon tank)

DESCRIPTION OF AIR INDUCTION SYSTEM AND AIRFLOW COMPUTATIONS.

The airflow system (induction system) utilized at NAFEC for testing light-aircraft piston engines is illustrated in figure 3. This system incorporated a redundant airflow-measuring system for accuracy and reliability. In the high-flow measuring section NAFEC utilized a 3.792-inch orifice and an Autronics air meter (model 100-750S). The capability of this high-flow system ranged from 500 to 3,000 pounds per hour with an estimated tolerance in flow accuracy of ±2 percent. The low-flow measuring section utilized a small 1.375-inch orifice and an Autronics air meter (model 100-100S). The capability of this system ranged from 50 to 500 pounds per hour with an estimated tolerance in flow accuracy of ±3 percent. The size of the basic air duct was 8.0 inches (inside diameter) for the high-flow system and 2.0 inches (inside diameter) for the low-flow system.

The TSIO-360-C engine incorporates a bleed air system which removes bleed air from the discharge side of the turbo-supercharger. This bleed air is used for aircraft cabin heating. As a result of this bleed air feature, it is necessary to calculate net airflow (the airflow that the engine actually uses) based on the following basic equation.

$$Wa\ (net) = Wa\ (total) - Wa\ (bleed)$$

The total airflow was computed from the orifice differential pressure and induction air density using the following equation:

$$Wa\ (total) = (1891)\ (C_f)\ (d_o)^2 \left[(.03609)\ \Delta P_\rho\right]^{1/2} \quad \text{(Reference 2)}$$

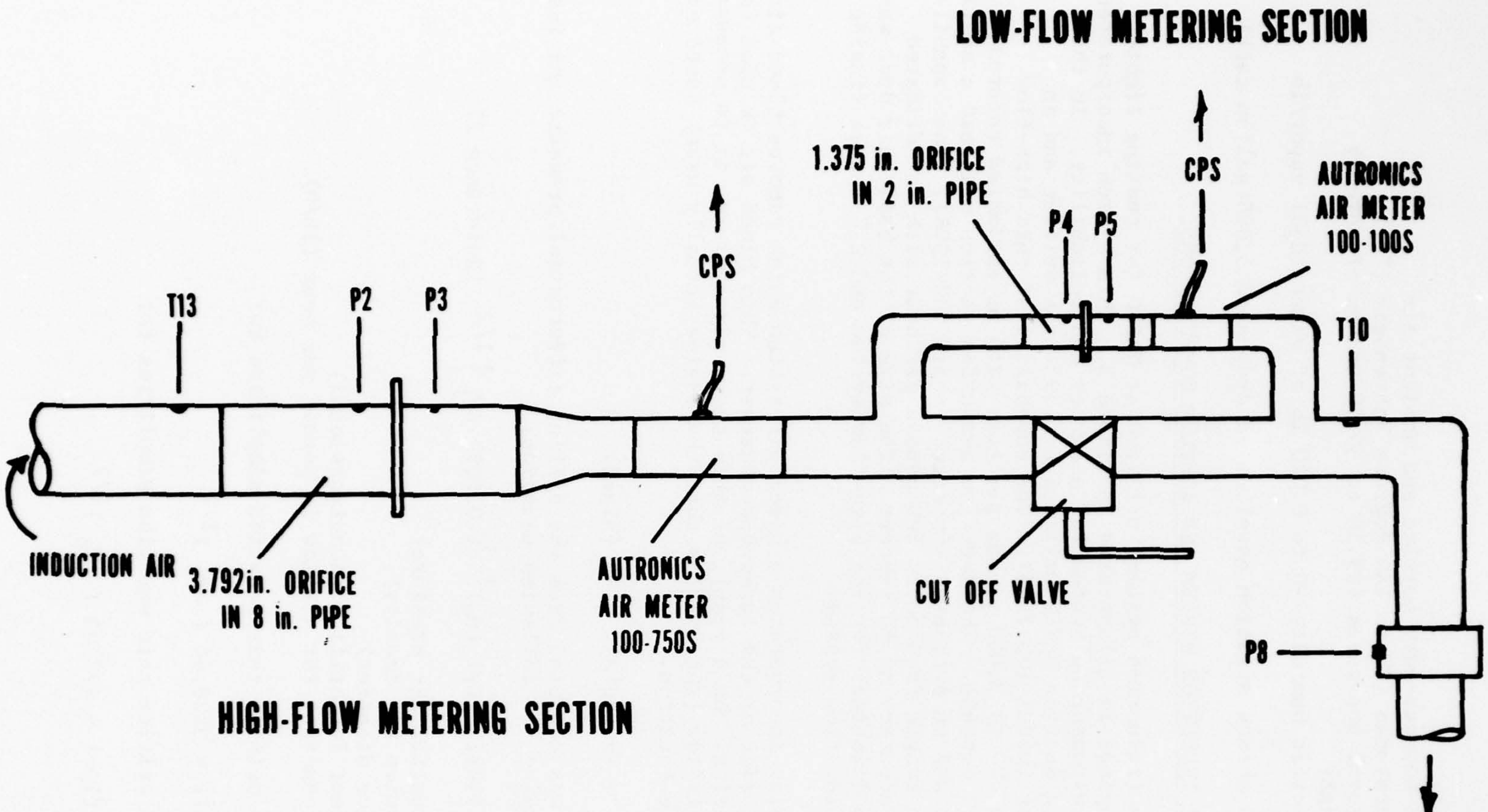
ΔP = inH_2O (differential air pressure)
ρ = lb/ft^3 (induction air density)
d_o = inches (orifice diameter)
C_f = flow coefficient for orifice (nondimensional)
1891 = conversion constant for airflow in pounds per hour (lb/h).

For the 3.792-inch orifice this equation simplifies to:

$$Wa\ (total) = 3228.44\ (\Delta P_\rho)^{1/2}$$

For the 1.375-inch orifice this equation simplifies to:

$$Wa\ (low\ flow) = 472.03\ (\Delta P_\rho)^{1/2}$$



NOTE: (1) VALVE IS OPEN FOR TAKE-OFF, CLIMB AND APPROACH POWER
(2) VALVE IS CLOSED FOR TAXI AND IDLE POWER

FIGURE 3. NAFEC AIR INDUCTION (AIRFLOW MEASUREMENT) SYSTEM FOR LIGHT-AIRCRAFT PISTON ENGINE EMISSION TESTS

The bleed airflow was determined in the following manner during the NAFEC tests: (1) a 1.0 inch-orifice was installed in a 2.0-inch flow duct which was connected to bleed air discharge duct, and (2) the bleed airflow was computed using the following orifice equation:

$$Wa\ (bleed) = 215.54\ (\ \Delta P_{\rho}\ )^{1/2}$$

The net airflow was determined as follows:

$$Wa\ (net) = Wa\ (total) - Wa\ (bleed)$$

$$Wa\ (net) = 3228.44\ (\ \Delta P_{\rho}\ )^{1/2} - 215.54\ (\ \Delta P_{\rho}\ )^{1/2}$$

DESCRIPTION OF FUEL FLOW SYSTEM.

The fuel flow system utilizied during the NAFEC light-aircraft piston engine emission tests incorporated rotameters, turboflow meters, and a burette. The high-flow section incorporated a rotameter in series with a high-flow turbometer, while the low-flow section incorporated a low-flow turbometer in series with a burette. The high-flow system was capable of measuring fuel flows from 50 lb/h up to 300 lb/h with an estimated tolerance of ± 1.0 percent. The low-flow system was capable of flow measurements ranging from 0-50 lb/h with an estimated tolerance of ± 2.0 percent. Figure 4 illustrates the NAFEC fuel flow system in schematic form.

DESCRIPTION OF COOLING AIR SYSTEM.

The NAFEC piston engine test facility also incorporated a system which provided cooling air (see figure 1) to the engine cylinders. The engine mounted in the test stand was enclosed in a simulated nacelle, and cooling air was provided to this enclosure from an external source. The cooling air temperature was maintained within $\pm 10°$ F of the induction air supply temperature for any specified set of test conditions. This not only minimized variations in temperature but also minimized variations in the specific weight of air for all test conditions. All of the basic cooling air tests conducted with the TSIO-360-C engine (takeoff, climb, and approach modes (see appendix C)) were conducted with differential cooling air pressures of 3.5 inH_2O. During taxi mode tests, the cooling air differential pressure was approximately equal to 0 in H_2O. A range of differential cooling air pressures from 1.5 to 7.0 inH_2O (see table C-14) was also evaluated to determine the effects of variable cooling air conditions on maximum cylinder head temperatures.

DESCRIPTION OF TEST PROCEDURES AND EPA STANDARDS.

The data presented in this report were measured while conducting tests in accordance with specific landing and takeoff cycles (LTO) and by modal lean-out tests. The basic EPA LTO cycle is defined in table 2.

The FAA/NAFEC contract and in-house test programs utilized an LTO cycle which was a modification of the table 2 test cycle. Table 3 defines this modified LTO cycle which was used to evaluate the total full-rich emission characteristics of light-aircraft piston engines.

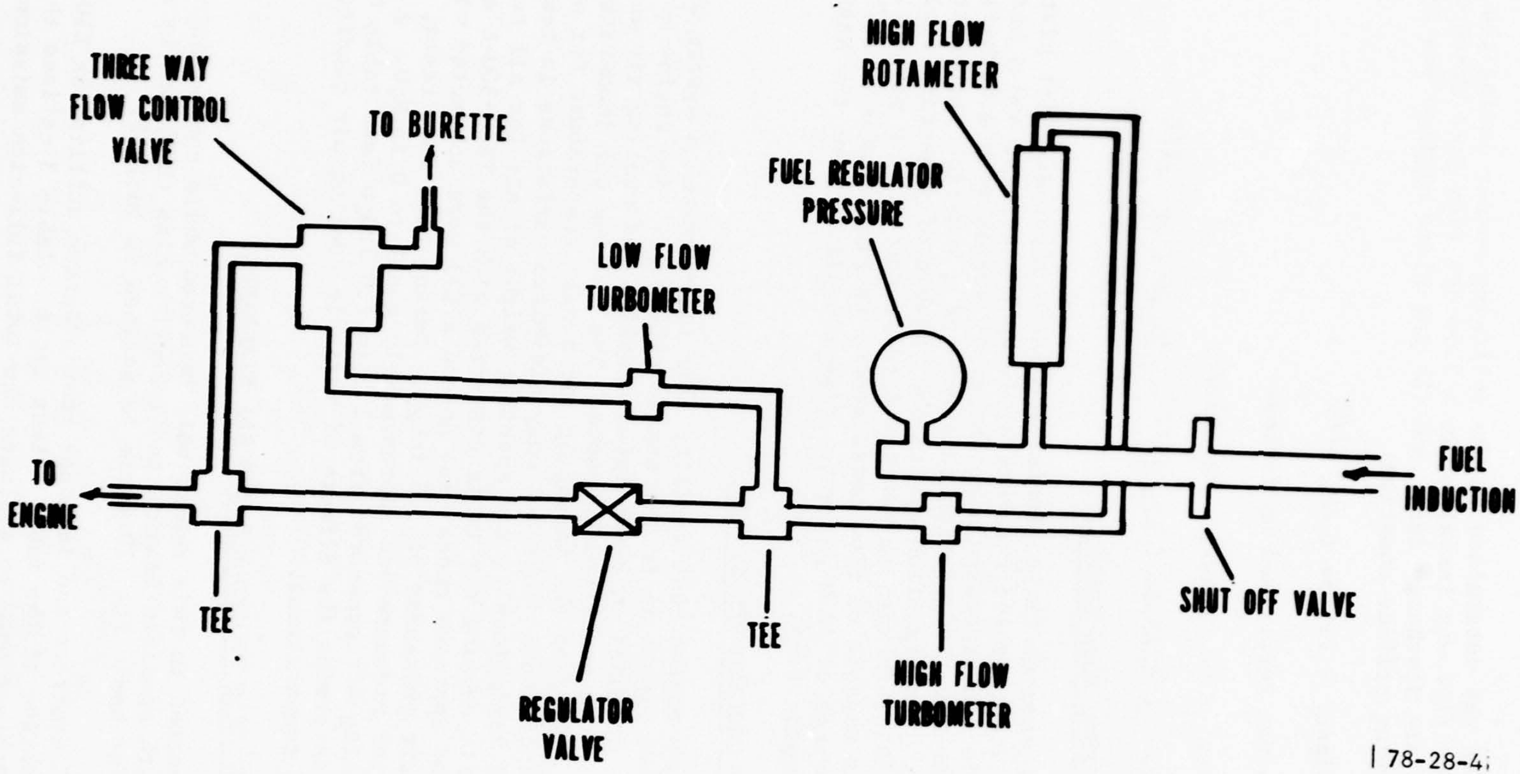


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FIGURE 4. NAFEC FUEL FLOW SYSTEM FOR LIGHT-AIRCRAFT PISTON ENGINE EMISSION TESTS

TABLE 2. EPA FIVE-MODE LTO CYCLE

Mode No.	Mode Name	Time-In-Mode (Min.)	Power (%)	Engine Speed (%)
1	Taxi/idle (out)	12.0	*	*
2	Takeoff	0.3	100	100
3	Climb	5.0	75-100	*
4	Approach	6.0	40	*
5	Taxi/idle (in)	4.0	*	*

*Manufacturer's Recommendation

TABLE 3. FAA/NAFEC SEVEN-MODE LTO CYCLE

Mode No.	Mode Name	Time-In-Mode (Min.)	Power (%)	Engine Speed (%)
1	Idle (out)	1.0	*	*
2	Taxi (out)	11.0	*	*
3	Takeoff	0.3	100	100
4	Climb	5.0	80	*
5	Approach	6.0	40	*
6	Taxi (in)	3.0	*	*
7	Idle (in)	1.0	*	*

*Manufacturer's Recommendation

An additional assessment of the test data clearly indicates that further evaluations of the general aviation piston exhaust emission must be analyzed with the climb mode emissions at 100-percent and 75-percent power setting (tables 4 and 5). This would then provide the basis for a complete evaluation of test data and permit a total assesment of the proposed EPA standard based on LTO cyclic tolerances.

TABLE 4. MAXIMUM FIVE-MODE LTO CYCLE

Mode No.	Mode Name	Time-In-Mode (Min.)	Power (%)	Engine Speed (%)
1	Taxi (out)	12.0	*	*
2	Takeoff	0.3	100	100
3	Climb	5.0	100	100
4	Approach	6.0	40	*
5	Taxi (in)	4.0	*	*

*Manufacturer's Recommended

TABLE 5. MINIMUM FIVE-MODE LTO CYCLE

Mode No.	Mode Name	Time-In-Mode (Min)	Power (%)	Engine Speed (%)
1	Taxi (out)	12.0	*	*
2	Takeoff	0.3	100	100
3	Climb	5.0	75	*
4	Approach	6.0	40	*
5	Taxi (in)	4.0	*	*

*Manufacturer's Recommended

The EPA Standards (reference 1) that were evaluated during this program were:

Carbon Monixide (CO)--0.042 lb/cycle/rated BHP
Unburned Hydrocarbon (HC)--0.0019 lb/cycle/rated BHP
Oxides of Nitrogen (NO_x)--0.0015 lb/cycle/rated BHP

DESCRIPTION OF EMISSIONS MEASUREMENT SYSTEM.

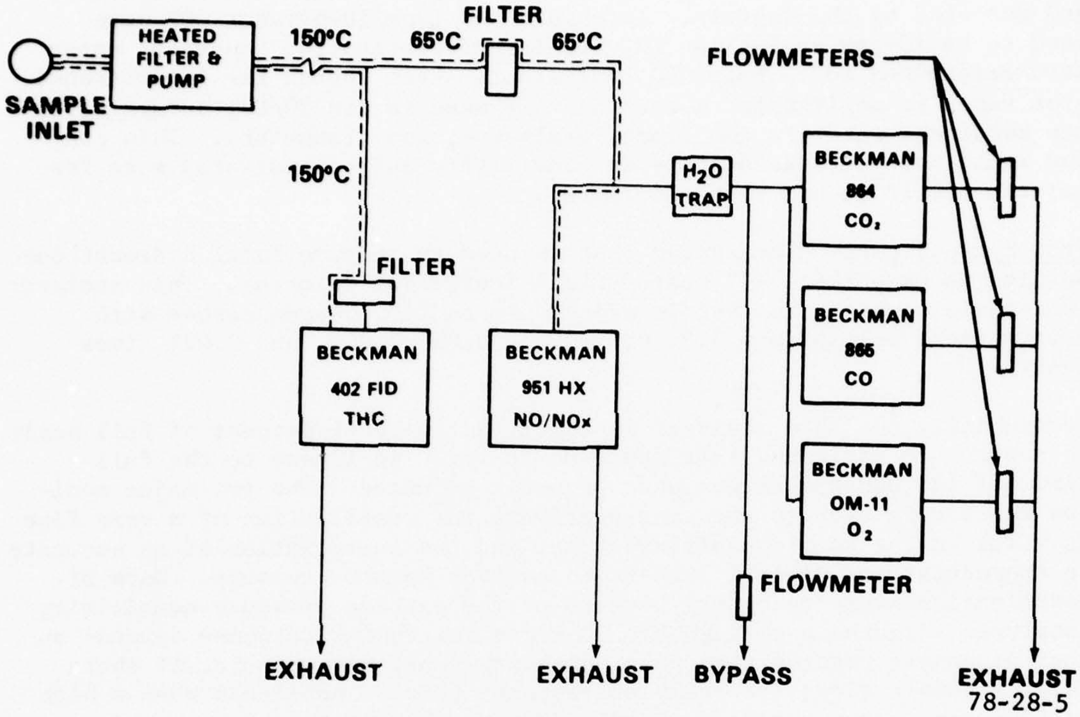
EMISSION ANALYZERS. The instrumentation used to monitor the exhaust emissions from general aviation piston engines was basically the same as that recommended by EPA, but with a number of modifications and additions to enhance the reliability and accuracy of the system. A schematic of the emissions measurement system is shown in figure 5.

EMISSION INSTRUMENTATION ACCURACY/MODIFICATION. The basic analysis instrumentation utilized for this system is explained in the following paragraphs.

Carbon Dioxide. The carbon dioxide (CO_2) subsystem is constructed around a Beckman model 864-23-2-4 nondispersive infrared analyzer (NDIR). This analyzer has a specified repeatability of ± 1 percent of full scale for each operating range. The calibration ranges on this particular unit are: Range 1, 0 to 20 percent; Range 3, 0 to 5 percent. Stated accuracy for each range is, therefore, ± 0.2 and ± 0.05 percent, respectively.

Carbon Monoxide. The subsystem used to measure carbon monoxide (CO) is constructed around a Beckman model 865-X-4-4-4 NIDR. This analyzer has a specified repeatability of ± 1 percent of full scale for ranges 1 and 2 and ± 2 percent of full scale for range 3.

Range 1 has been calibrated for 0 to 20 percent by volume, range 2 for 0 to 1,000 parts per million (ppm) and range 3 for 0 to 100 ppm. The wide-range capability of this analyzer is made possible by using stacked sample cells which in effect give this analyzer six usable ranges when completely calibrated.



- CARBON DIOXIDE – CO_2
  - NONDISPERSIVE INFRARED (NDIR)
  - RANGE 0-20%
  - REPEATABILITY ± 0.2% CO_2
- CARBON MONOXIDE – CO
  - NDIR
  - RANGE 0-20%
  - REPEATABILITY ± 0.2% CO
- TOTAL HYDROCARBONS – THC
  - FLAME IONIZATION DETECTOR (FID)
  - RANGE 0-150,000 ppm_C
  - MINIMUM SENSITIVITY 1.5 ppm_C
  - LINEAR TO 150,000 ppm_C
- **OXIDES OF NITROGEN – NO_X**
  - CHEMILUMINESCENT (CL)
  - RANGE 0-10,000 ppm
  - MINIMUM SENSITIVITY 0.1 ppm
- **OXYGEN – O_2**
  - POLARAGRAPHIC
  - RANGE 0-100%
  - REPEATABILITY 0.1% O_2
  - RESPONSE 200 ms

78-28-6

FIGURE 5. SCHEMATIC OF EMISSIONS MEASUREMENT SYSTEM AND ITS MEASUREMENT CHARACTERISTICS

Effects of interfering gases, such as CO_2 and water vapor, were determined and reported by the factory. Interferences from 10-percent CO_2 were determined to be 12-ppm equivalent CO, and interferences from 4-percent water vapor were determined to be 6-ppm CO equivalent. Even though the interference from water vapor is negligible, a condenser is used in the CO/CO_2 subsystem to eliminate condensed water in the lines, analyzers, and flowmeters. This condensation would have decreased analyzer sensitivity and necessitated more frequent maintenance if it had been eliminated.

Total Hydrocarbons. The system that is used to measure total hydrocarbons is a modified Beckman model 402 heated flame ionization detector. This analyzer has a full-scale sensitivity that is adjustable to 150,000-ppm carbon with intermediate range multipliers 0.5, 0.1, 0.05, 0.01, 0.005, and 0.001 times full scale.

Repeatability for this analyzer is specified to be ±1 percent of full scale for each range. In addition, this modified analyzer is linear to the full-scale limit of 150,000-ppm carbon when properly adjusted. The two major modifications which were made to this analyzer were the installation of a very fine metering value in the sample capillary tube, and the installation of an accurate pressure transducer and digital readout to monitor sample pressure. Both of these modifications were necessary because of the extreme pressure sensitivity of the analyzer (figures 6 through 8). Correct instrument response depends on the amount of sample passing through a capillary tube; as a result, if there is too high a sample flow, the analyzer response becomes nonlinear when a high concentration gas is encountered. Sample flow may be controlled by varying the pressure on this capillary or increasing the length of the capillary. On this analyzer, linearity to 50,000-ppm carbon was obtained by reducing the sample pressure to 1.5 pounds per square inch gauge (psig). However, the need for linearity to 120,000-ppm carbon was anticipated. Further reduction of the sample pressure increased the noise level of the analyzer to an unacceptable level. In order to reduce the flow through the capillary without using a lower pressure, either the length or the resistance of the capillary had to be increased. The standard modification for this analyzer in order to limit flow is the installation of an additional length of capillary tubing. This procedure requires trial-and-error determination of proper capillary length and is a permanent modification that limits sensitivity at low hydrocarbon levels. By installing a metering valve in the capillary, flow could be selectively set at either low flow for linearity at high concentrations or high flow for greater sensitivity at low concentrations. Installation time was reduced by eliminating the cut-and-try procedure for determining capillary length.

The addition of a sensitive pressure transducer and digital readout to monitor sample pressure was needed since the pressure regulator and gauge supplied with the analyzer would not maintain the pressure setting accurately at low pressures. Using the digital pressure readout, the sample pressure could be monitored and easily maintained to within 0.05 inH_2O.

Oxides of Nitrogen. Oxides of nitrogen (NO_x) are measured by a modified Beckman model 951H atmospheric pressure, heated, chemiluminescent analyzer (CL). This analyzer has a full-scale range of 10,000 ppm with six intermediate ranges. Nominal minimum sensitivity is 0.1 ppm on the 10-ppm full-scale range.

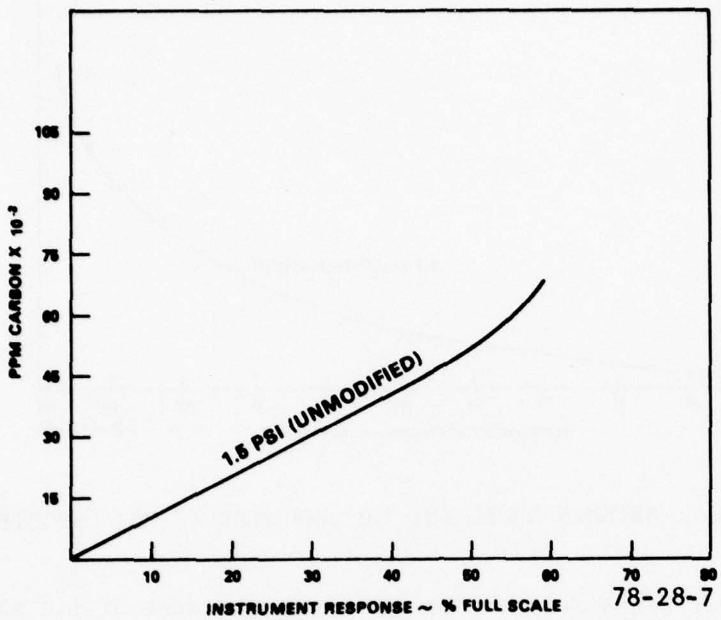


FIGURE 6. BECKMAN MODEL 402 THC ANALYZER (1.5 PSI UNMODIFIED)

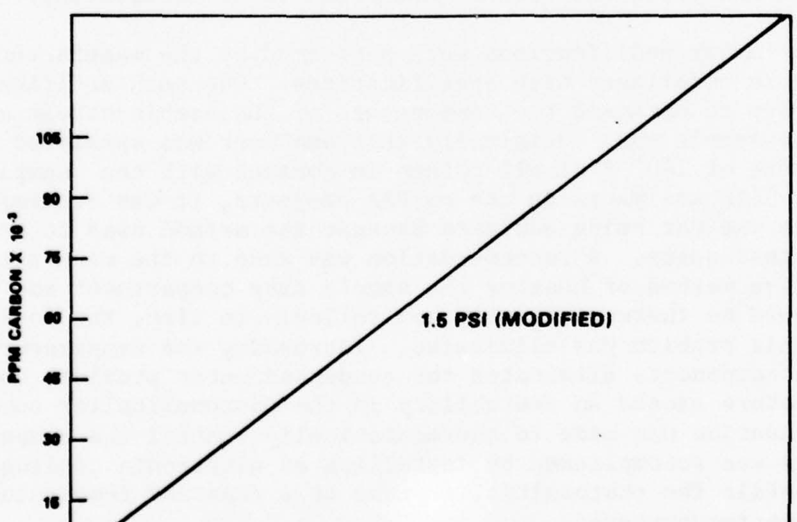


FIGURE 7. BECKMAN MODEL 402 THC ANALYZER (1.5 PSI MODIFIED)

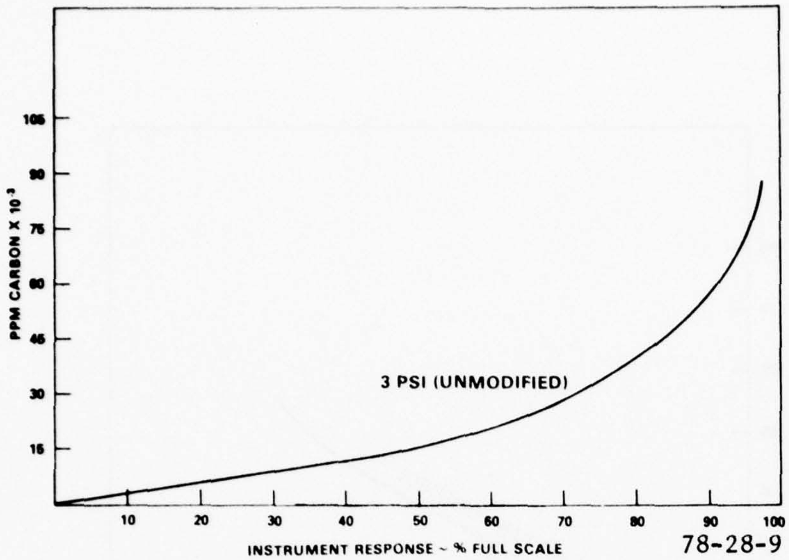


FIGURE 8. BECKMAN MODEL 402 THC ANALYZER (3 PSI UNMODIFIED)

The atmospheric pressure analyzer was chosen because of its simplicity, ease of maintenance, and compactness. Anticipated water vapor problems in the atmospheric pressure unit were to be handled by the heating of the internal sample train. Interference from CO_2 quenching, common in the atmospheric pressure type CL analyzer, was checked and found to be nonexistent.

A series of major modifications were performed by the manufacturer on this analyzer to insure compliance with specifications. One such modification was installed in order to maintain the temperature of the sample stream above the dew point of the sample gas. Originally this analyzer was specified to maintain a temperature of 140° F at all points in contact with the sample. After a survey of the 951H analyzers in use on FAA projects, it was determined that this temperature was not being achieved because the method used to heat the components was inadequate. A recommendation was made to the manufacturer to install a positive method of heating the sample tube compartment and reaction chamber that would be thermostatically controlled. In time, the modification was made, and this problem was eliminated. Increasing the temperature of the internal sample components eliminated the condensed water problem; however, the elevated temperature caused an instability in the photomulitplier tube output. Another recommendation was made to thermostatically control the temperature of this tube. This was accomplished by installing an electronic cooling jacket designed to maintain the photomultiplier tube at a constant temperature below the internal case temperature.

A further modification required was the addition of a flow control valve to adjust and balance the flow rate through the NO and NO_x legs. This valve replaced a restrictor clamp that was used by the manufacturer to set the NO to NO_x flow balance. The problem that was encountered with this clamp was that it was not a positive method of adjusting the restriction on the capillary. The clamp compression was affected by the flexible material on which the clamp was mounted and the variable flexibility of the Teflon® capillary as it was heated. This caused the restriction on the capillary to change with time and caused permanent deformation of the capillary allowing only an adjustment that would increase the restriction.

Oxygen Measurement. Oxygen (O_2) was measured by a Beckman model OM-11 oxygen analyzer. This analyzer uses a polagraphic-type sensor unit to measure oxygen concentration. An advanced sensor and amplification system combine to give an extremely fast response and high accuracy. Specified response for 90 percent of final reading is less than 200 milliseconds (ms) with an accuracy of less than $\pm$0.1-percent O_2. The range of this unit is a fixed 0 to 100 percent O_2 concentration.

EMISSIONS INSTRUMENTATION MODIFICATION STATUS DURING THE TESTING OF THE TSIO-360-C ENGINE. The tests conducted with the TCM TSIO-360-C engine utilized emissions and exhaust constituent measuring instruments/analyzers which incorporated the latest specified modifications described in this report.

DESCRIPTION OF SAMPLE HANDLING SYSTEM.

Exhaust samples are transported to the analysis instrumentation under pressure through a 35-foot-long, 3/8-inch O.D., heated, stainless steel sample line. The gas is first filtered and then pumped through this line by a heated Metal Bellows model MB-158 high temperature stainless steel sample pump. The pump, filter, and line are maintained at a temperature of 300° $\pm$4° F to prevent condensation of water vapor and hydrocarbons. At the instrument console, the sample is split to feed the hydrocarbon, oxides of nitrogen, and $CO/CO_2/O_2$ subsystems which require different temperature conditioning. The sample gas to the total hydrocarbon subsystem is maintained at 300° F while the temperature of remaining sample gas to the NO_x and $CO/CO_2/O_2$ system is allowed to drop to 150° F. Gas routed to the oxides of nitrogen subsystem is then maintained at 150° F, while the gas to the $CO/CO_2/O_2$ subsystem is passed through a 32° F condenser to remove any water vapor present in the sample. Flow rates to each analyzer are controlled by a fine-metering valve and are maintained at predetermined values to minimize sample transport and system response time. Flow is monitored at the exhaust of each analyzer by three 15-centimeter (cm) rotameters. Two bypasses are incorporated into the system to keep sample transport time through the lines and condenser to a minimum without causing adverse pressure effects in the analyzers.

DESCRIPTION OF FILTRATION SYSTEM.

Particulates are removed from the sample at three locations in the system, thereby minimizing downtime due to contaminated sample lines and analyzers (figure 5). Upstream of the main sample pump is a heated clamshell-type stainless steel filter body fitted with a Whatman GF/C glass fiber paper filter element capable of retaining particles in the 0.1-micron range. A similar filter is located in the total hydrocarbon analyzer upstream of the sample capillary. A Mine Safety Appliances (MSA) type H ultra filter capable of retaining 0.3-micron particles is located at the inlet to the oxides of nitrogen and $CO/CO_2/O_2$ subsystems.

COMPUTATION PROCEDURES.

The calculations required to convert exhaust emission measurements into mass emissions are the subject of this section.

Exhaust emission tests were designed to measure CO_2, CO, unburned hydrocarbons (HC), NO_x, and exhaust excess O_2 concentrations in percent or ppm by volume. Mass emissions were determined through calculations utilizing the data obtained during the simulation of the aircraft LTO cycle and from modal lean-out data.

COMBUSTION EQUATION. The basic combustion equation can be expressed very simply:

Fuel + Air = Exhaust Constituents

An initial examination of the problem requires the following simplifying assumptions:

1. The fuel consists solely of compounds of carbon and hydrogen.

2. The air is a mixture of oxygen and inert nitrogen in the volumetric ratio of 3.764 parts apparent nitrogen to 1.0 part oxygen (see appendix B for additional details).

3. If a stoichiometric combustion process exists, the fuel and air are supplied in chemically correct proportions.

4. The fuel (which consists usually of a complex mixture of hydrocarbons) can be represented by a single hydrocarbon having the same carbon-hydrogen ratio and molecular weight as the fuel; usually C_8H_{17} as an average fuel.

Applying the above assumptions for stoichiometric conditions, a useful general reaction equation for hydrocarbon fuel is:

$$M_fC_8H_{17} + M_a\left[O_2 + 3.764N_2 + M_wH_2O\right] \rightarrow M_1CO_2 + M_3H_2O + M_5N_2 \quad (1)$$

(References 3 and 4)

Where
M_f = Moles of Fuel
M_a = Moles of Air or Oxygen
M_1 = Moles of Carbon Dioxide (CO_2)
M_3 = Moles of Condensed Water (H_2O)
M_5 = Moles of Nitrogen (N_2) - Exhaust
$3.764M_a$ = Moles of Nitrogen (N_2) - In Air
M_aM_w = Moles of Humidity (H_2O) - In Air

The above equation is applicable to dry air when M_w is equal to zero.

From equation (1), and assuming dry air with one mole of fuel (M_f=1.0), the stoichiometric fuel-air ratio may be expressed as:

$$(F/A)_s = \frac{\text{Wt. Fuel}}{\text{Wt. Air Required}} = \frac{12.011\ (8) + 1.008\ (17)}{12.25\ (32.000) + 3.764(28.161)} \qquad (2)$$

$$(F/A)_s = \frac{113.224}{12.25(137.998)} = 0.067$$

The mass carbon-hydrogen ratio of the fuel may be expressed as follows:

$$C/H = \frac{12.001(8)}{1.008(17)} = \frac{96.088}{17.136} = 5.607 \qquad (3)$$

The atomic hydrogen-carbon ratio is:

$$17/8 = 2.125 \qquad (4)$$

The stoichiometric fuel-air ratio may be expressed as a function of the mass carbon-hydrogen ratio of the fuel. The derivation of this equation is presented in reference 3.

$$(F/A)_s = \frac{C/H + 1}{11.5(C/H+3)} \qquad (5)$$

$(F/A)_s$ = 0.067 for a mass carbon-hydrogen ratio of 5.607

With rich (excess fuel) mixtures, which are typical for general aviation piston engines, some of the chemical energy will not be liberated because there is not enough air to permit complete oxidation of the fuel. Combustion under such conditions is an involved process. By making certain simplifying assumptions based on test results, the effect of rich mixtures may be calculated with reasonable accuracy.

For rich (excess fuel) mixtures, equation (1) will now be rewritten to express the effects of incomplete combustion:

$$M_fC_8H_{17} + M_a(O_2 + 3.764N_2 + M_wH_2O) \longrightarrow M_1CO_2 + M_2CO + M_3H_2O + M_4H_2 +$$

$$M_5N_2 + M_6NO + M_7CH_4 + M_8O_2 + M_9C \qquad (6)$$

Since only a limited number of the exhaust constituents were measured during the testing of general aviation piston engines, the above equation can only be solved by applying certain expeditious assumptions and emperical data.

An important requirement was the accurate measurement of air and fuel flows. These parameters provide the data for determining engine mass flow (W_m), and with the aid of figure 9 (developed from reference 5), it is a simple compatation to calculate the total moles (M_{tp}) of exhaust products being expelled by general aviation piston engines.

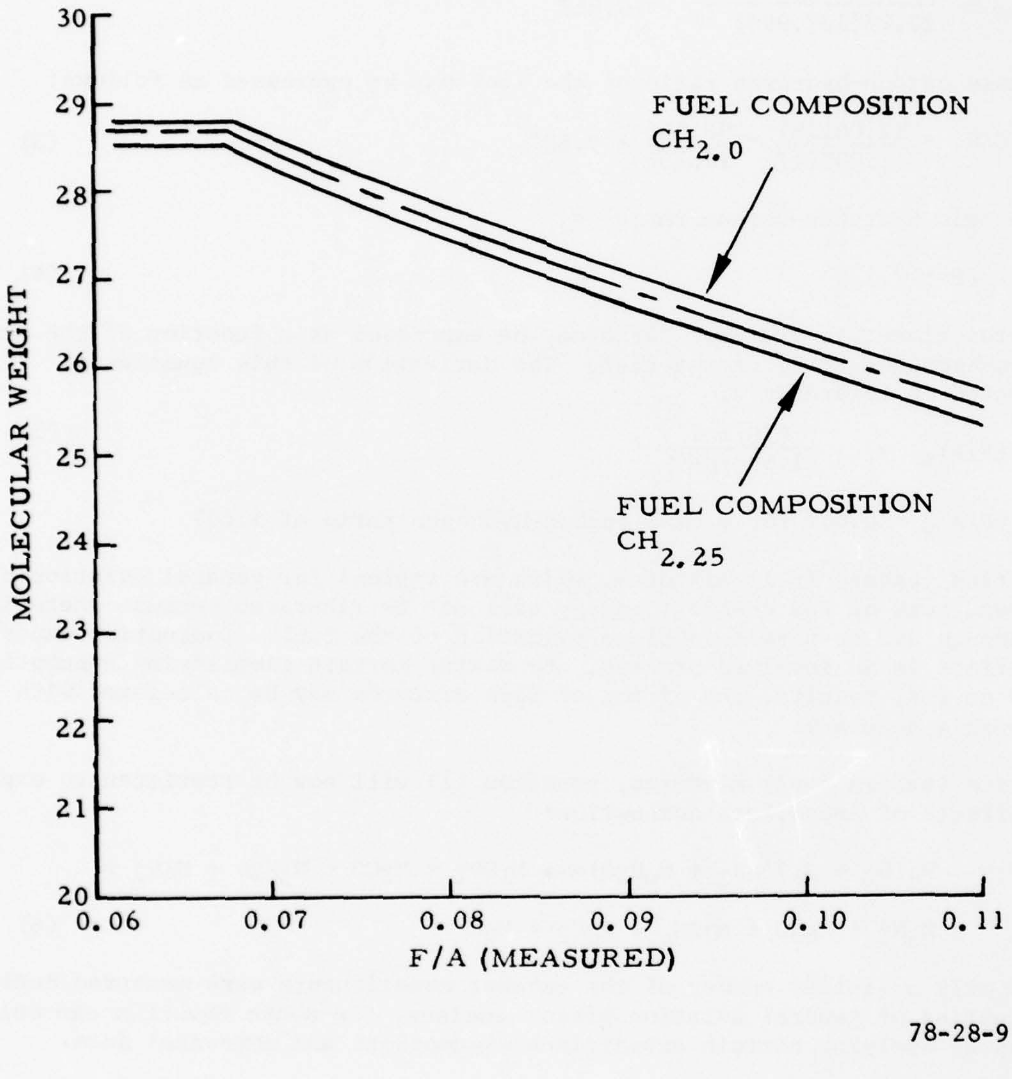


FIGURE 9. EXHAUST GAS MOLECULAR WEIGHTS

$$(M_{tp}) = W_m \text{ (engine mass flow) } \div \text{ (exh. mol. wt)} \quad (9)$$

Since the unburned hydrocarbons (HC) and oxides of nitrogen (NO_x) are measured wet, it becomes a very simple matter to compute the moles of HC and NO_x that are produced by light-aircraft piston engines.

$$M_7 \text{ (Moles of HC)} = (\text{ppm} \div 10^6)) \times M_{tp} \quad (8)$$

$$M_6 \text{ (Moles of } NO_x) = (\text{ppm} \div 10^6) \times M_{tp} \quad (9)$$

If the dry products (M_{dp}) of combustion are separated from the total exhaust products (M_{tp}), it is possible to develop a partial solution for five of the products specified in equation 6.

This can be accomplished as follows:

The summation of the mole fractions $(MF)_d$ for dry products is

$$m_1 + m_2 + m_4 + m_5 + m_8 = 1.0000 \quad (10)$$

$m_1 = MF(CO_2) = \%CO_2$ (measured dry), expressed as a fraction

$m_2 = MF(CO) = \%CO$ (measured dry), expressed as a fraction

$m_4 = MF(H_2) = K_4\ (\%CO)$ (see figure 10, also references 4, 5, and 6), expressed as a fraction

$m_8 = MF(O_2) = \%O_2$ (measured dry), expressed as a fraction

$m_5 = 1.0000 - (m_1 + m_2 + m_4 + m_8) = \%N_2$ (dry), expressed as a fraction (11)

Utilizing the nitrogen balance equation, it is now possible to determine the moles of nitrogen that are being exhausted from the engine.

$$M_5 = 3.764M_a - (M_6 \div 2);\ M_6 = \text{moles (NO)} \quad (12)$$

The moles of exhaust dry products (M_{dp}) may now be determined by dividing equation 12 by equation 11.

$$M_{dp} = M_5 \div M_5 \quad (13)$$

Using all the information available from equations (7), (8), (9), (10), (11), (12), and (13), it is now possible to determine the molar quantities for seven exhaust products specified in equation 6.

$$\text{Moles } (CO_2) = M_1 = m_1 \times M_{dp} \quad (14)$$

$$\text{Moles } (CO) = M_2 = m_2 \times M_{dp} \quad (15)$$

$$\text{Moles } (H_2) = M_4 = m_4 \times M_{dp} \quad (16)$$

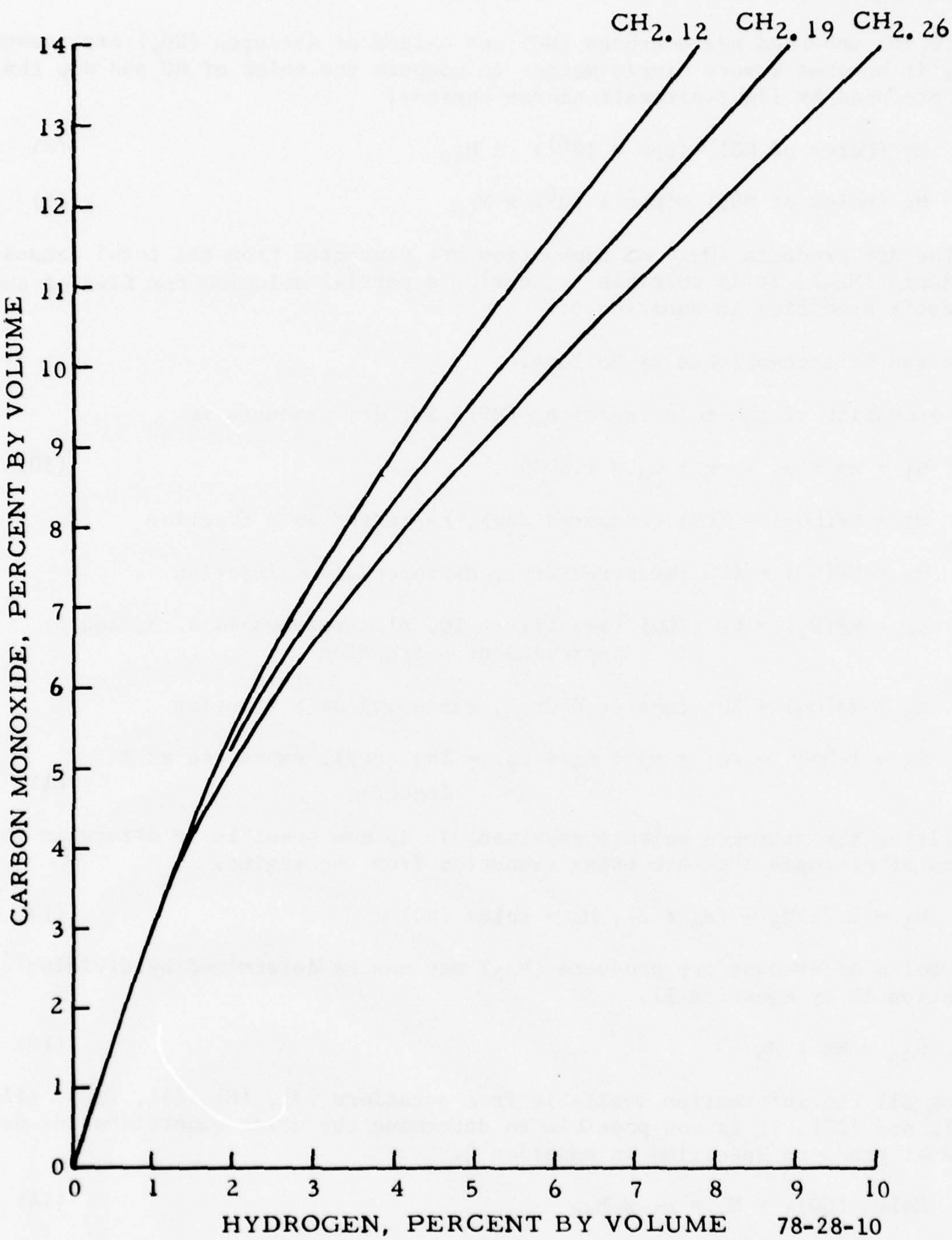


FIGURE 10. RELATION OF CARBON MONOXIDE AND HYDROGEN

$$\text{Moles } (CO_2) = M_5 = m_5 \times M_{dp} \qquad (17)$$

$$\text{Moles } (O_2) = M_8 = m_8 \times M_{dp} \qquad (18)$$

$$\text{Moles } (CH_4) = M_7 = (\text{ppm} \div 10^6) \times M_{tp} \qquad (19)$$

$$\text{Moles } (NO) = M_6 = (\text{ppm} \div 10^6) \times M_{tp} \qquad (20)$$

To determine M_3 (moles of condensed H_2O), it is now appropriate to apply the oxygen balance equation.

$$M_3 = M_a\ (2 + M_w) - (2M_1 + M_2 + M_6 + 2M_8) = \text{Moles } (H_2O) \qquad (21)$$

The remaining constituent specified in equation 6 may now be determined from the carbon balance equation 22.

$$M_9 = 8M_f - (M_1 + M_2 + M_7) \qquad (22)$$

A check for the total number of exhaust moles (M_{tp}), calculated from equation 9, may be determined from equation 23.

$$M_{tp} = M_1 + M_2 + M_3 + M_4 + M_5 + M_6 + M_7 + M_8 + M_9 \qquad (23)$$

$$\dot{m}_1 + \dot{m}_2 + \dot{m}_3 + \dot{m}_4 + \dot{m}_5 + \dot{m}_6 + \dot{m}_7 + \dot{m}_8 + \dot{m}_9 = 1.0000 \qquad (24)$$

$$\dot{m}_1 = MF(CO_2) = M_1 \div M_{tp}$$

$$\dot{m}_2 = MF(CO) = M_2 \div M_{tp}$$

$$\dot{m}_3 = MF(H_2O) = M_3 \div M_{tp}$$

$$\dot{m}_4 = MH(H_2) = M_4 \div M_{tp}$$

$$\dot{m}_5 = MF(N_2) = M_5 \div M_{tp}$$

$$\dot{m}_6 = MH(NO) = M_6 \div M_{tp}$$

$$\dot{m}_7 = MF(CH_4) = M_7 \div M_{tp}$$

$$\dot{m}_8 = MF(O_2) = M_8 \div M_{tp}$$

$$\dot{m}_9 = MF(C) = M_9 \div M_{tp}$$

The exhaust constituent mass flow rates may be computed in the following manner using each exhaust constituents molar constant with the appropriate molecular weight.

$$M_1 \times 44.011 = CO_2 \text{ in lb/h} \qquad (25)$$

$$M_2 \times 28.011 = CO \text{ in lb/h} \qquad (26)$$

$$M_3 \times 18.016 = H_2O \text{ in lb/h} \quad (27)$$

$$M_4 \times 2.016 = H_2 \text{ in lb/h} \quad (28)$$

$$M_5 \times 28.161 = N_2 \text{ in lb/h} \quad (29)$$

$$M_6 \times 30.008 = NO \text{ in lb/h} \quad (30)$$

$$M_7 \times 16.043 = CH_4 \text{ in lb/h} \quad (31)$$

$$M_8 \times 32.000 = O_2 \text{ in lb/h} \quad (32)$$

$$M_9 \times 12.011 = C \text{ in lb/h} \quad (33)$$

The exhaust fuel flow (W_{fe}), based on exhaust constituents, can now be calculated on a constituent-by-constituent basis as follows:

$$(M_1 + M_2 + M_9) \times 12.011 = \text{lb/h} \quad (34)$$

$$M_7 \times 16.043 = \text{lb/h} \quad (35)$$

$$(M_3 - M_a M_w) + M_4 \times 2.016 = \text{lb/h} \quad (36)$$

$$W_{fe} = (34) + (35) + (36) = \text{lb/h} \quad (37)$$

In a similar manner the exhaust airflow (W_{ae}) can also be calculated on a constituent-by-constituent basis:

$$M_1 \times 32.000 = \text{lb/h} \quad (38)$$

$$M_2 \times 16.000 = \text{lb/h} \quad (39)$$

$$(M_3 \times 16.000) + (M_a M_w \times 18.016) = \text{lb/h} \quad (40)$$

$$M_5 \times 28.161 = \text{lb/h} \quad (41)$$

$$M_6 \times 30.008 = \text{lb/h} \quad (42)$$

$$M_8 \times 32.000 = \text{lb/h} \quad (43)$$

$$W_{ae} = \Sigma\, (38) \rightarrow (43) = \text{lb/h} \quad (44)$$

Using equations (37) and (44) it is now possible to determine a calculated fuel-air ratio on the basis of total exhaust constituents.

$$(F/A)_{calculated} = (37) \div (44) \quad (45)$$

RESULTS

GENERAL COMMENTS.

General aviation pistion engine emission tests were conducted to provide the following categories of data:

1. Full-rich (or production fuel schedule) baseline data for each power mode specified in the LTO test cycle.

2. Lean-out data for each power mode specified in the LTO test cycle.

3. Data for the above categories at different spark settings.

4. Data for each power mode specified in the LTO test cycle utilizing different quantities of cooling air.

RESULTS OF BASELINE TESTS (LANDING-TAKEOFF CYCLE EFFECTS).

Based on an analysis of the factors affecting piston engine emissions, it can be shown that the mode conditions having the greatest influence on the gross pollutant levels produced by the combustion process are taxi, approach, and climb when using the LTO cycle defined in tables 3, 4, and 5. The five-mode LTO cycle shows that approximately 99 percent of the total cycle time (27.3-min) is attributed to these three modal conditions. Furthermore, the taxi modes (both out and in) account for slightly less than 59 percent of the total cycle time. The remainder of the time is almost equally apportioned to the approach and climb modes (22 and 18 percent, respectively).

As a result of these time apportionments, it was decided that an investigation and evaluation of the data should be undertaken to determine which mode(s) has the greatest influence on improving general aviation piston engine emissions. The subsequent sections of this report will show the exhaust emissions characteristics for a TCM TSIO-360-C engine (S/N300244) and what improvements are technically feasible within the limits of safe aircraft/engine operational requirements based on sea level propeller test stand evaluations conducted at NAFEC.

The first set of data to be presented and evaluated are the five-mode baseline runs conducted to establish the current production full-rich exhaust emissions characteristics of the TSIO-360-C engine. These are summarized in tabular form in appendix C (see tables C-1 through C-14) and includes data that were obtained for a range of sea level ambient conditions, specified as follows:

Induction air temperature (T_i)	= 50° F to 110° F
Cooling air temperature (T_c)	= $T_i \pm 10°$ F
Induction air pressure (P_i)	= 29.20 to 30.50 inHgA
Induction air density (ρ)	= 0.0690 to 0.0795 lb/ft^3

Figure 11 presents five-mode baseline data in bargraph form (for different sea level ambient conditions). It also compares the total emissions characteristics of the TSIO-360-C engine (current production configuration) with the proposed EPA standards as a function of percent of standard. The data that were utilized to develop figure 11 is tabulated in appendix C and plotted in various forms for analysis and evaluation in figures C-1 through C-14.

RESULTS OF LEAN-OUT TESTS.

In the subsequent sections of this report, it will be shown what improvements can be achieved as a result of making lean-out adjustments to the fuel metering device: (1) taxi mode only, (2) taxi and approach modes combined, and (3) leaning-out the climb mode to "best power" in combination with taxi and approach mode leaning.

EFFECTS OF LEANING-OUT ON CO EMISSIONS. The test data obtained as a result of NAFEC testing the TCM TSIO-360-C have been evaluated on the basis of leaning-out the taxi, approach, and climb modes while continuing the operation of the test engine at the production rich and lean limits in the takeoff mode. The results of leaning-out under this procedure are shown in bargraph form in figure 12.

When the taxi modes (out and in) were leaned-out from the production rich or lean limits to a fuel-air ratio of 0.075, but not lower than stoichiometric (F/A = 0.067) (see figure 12), CO emissions are reduced approximately 3.0 percent. However, adjustments to the taxi mode fuel schedule alone are not sufficient to bring the total five-mode LTO cycle CO emission level below the proposed federal standard.

Simultaneously, leaning-out both the taxi and approach modes to fuel-air ratios between 0.067 to 0.075 will result in additional improvements in CO emissions. In the case of operating the engine at production rich limits for takeoff and climb while operating taxi and approach at F/A = 0.075, the total five-mode LTO cycle CO emission level will be reduced approximately 14.0 percent as shown in figure 12.

Additional improvements in the total five-mode LTO cycle for CO emissions can be achieved, as shown in figure 12, if the engine is adjusted to operate at "best power" fuel-air ratios in the climb mode while operating the approach and taxi modes at F/A = 0.075 or lower (not lower than fuel-air ratio (F/A) = 0.067). The CO emission level will be reduced approximately 30 percent.

The preceding evaluation of CO emissions characteristics was based on the LTO cycle defined by table 5. However, the EPA five-mode LTO cycle defined by table 2 implies that the climb mode power levels range from 75 to 100 percent. The exhaust emissions produced will be drastically affected. Examination of the measured data produced at NAFEC shows that there is a significant difference in each engine's total LTO cycle emissions output when climbing at 100 percent power compared to climbing at 75-or 80-percent power. This data evaluation also shows that where as a CO limit of 0.042 pounds per cycle per rated brake horsepower may be approximately achievable as described

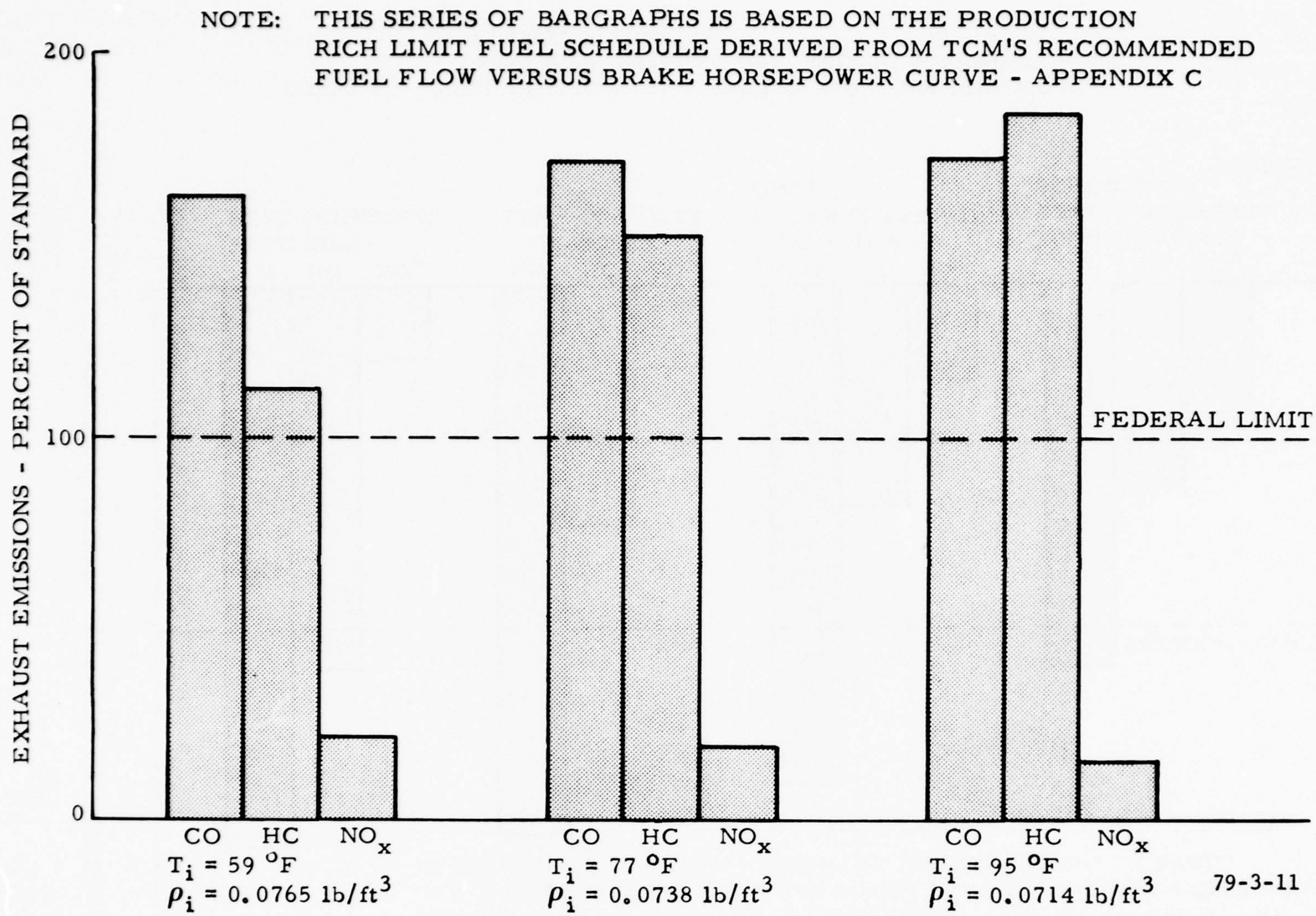


FIGURE 11. AVERAGE TOTAL EMISSIONS CHARACTERISITCS FOR A TCM TSIO-360-C ENGINE OPERATING UNDER VARING SEA LEVEL INDUCTION AIR TEMPERATURES AND DENSITIES

NOTES:

1. THIS FIGURE IS BASED ON THE TABLE 5 LTO CYCLE WITH THE CLIMB MODE AT APPROXIMATELY 80 PERCENT POWER.
2. THE MINIMUM F/A RATIO SETTING FOR THIS FIGURE IS 0.075 FOR THE TAXI AND APPROACH MODES; T.O. WAS SET AT THE LOWEST F/A RATIO THAT IS COMPATIBLE WITH THE MAXIMUM CHT LIMIT OF 460 °F; THE CLIMB MODE WAS SET FOR BEST POWER F/A RATIO. THESE CONDITIONS PRODUCED THE BARGRAPH WITH THE LOWEST OVERALL LEVEL.

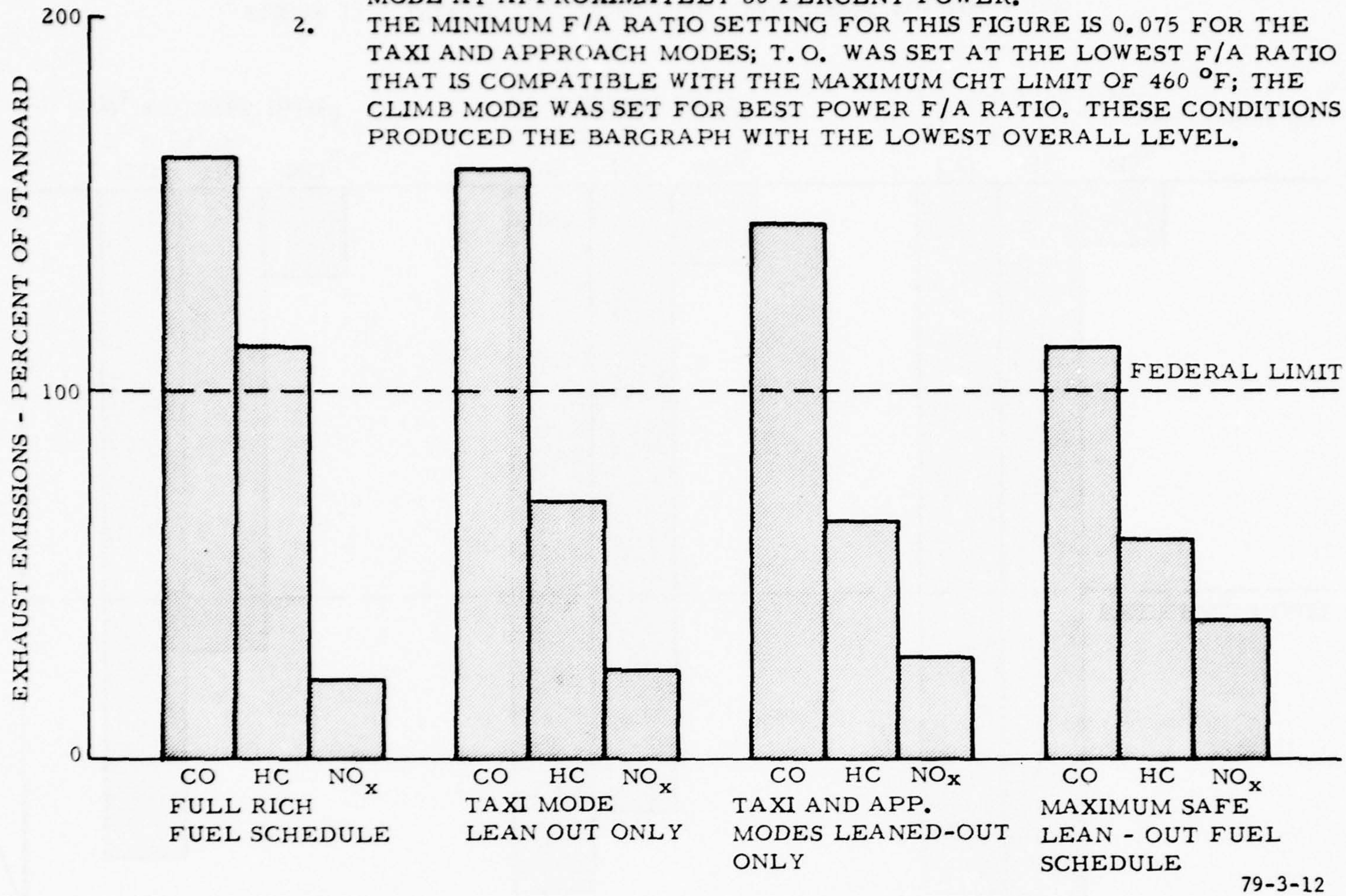


FIGURE 12. TOTAL EMISSIONS CHARATERISTICS FOR A TCM TSIO-360-C ENGINE WITH DIFFERENT FUEL SCHEDULE ADJUSTMENTS--SEA LEVEL STANDARD DAY

previously by using the LTO cycle defined by table 5; it is not achievable using an LTO cycle defined by table 4. When one considers the following safety considerations: (1) sea level, hot-day takeoff requirements with an aircraft at heavy gross weight and (2) altitude takeoff requirements with an aircraft at heavy gross weight, it would appear that the EPA 0.042 limit for CO is not realistic and cannot be complied with unless engine operational and safety limits are totally ignored.

Table 6 provides a summary of the NAFEC data which indicates what levels of improvement in CO emissions can be achieved by applying simple fuel management techniques (leaning-out by mixture control manipulations), albeit with drastically reduced margins between actual measured maximum cylinder head temperature (CHT) and the maximum CHT limit.

Example: Consider the engine installed in a sea level (SL.) propeller stand and operating with cooling air at a ΔP = 3.5 in H_2O and the following critical test conditions:

1. Ambient conditions (pressure, temperature, and density)--SL. standard day
2. Fuel schedule--production rich setting
3. Power setting--100%
4. Measured max. CHT--450° F
5. Max. CHT limit--460° F
6. Margin--(5) minus (4)-- 10° F

If we now adjust this engine fuel schedule setting to best power or max. CHT limit (all other parameters constant based on above conditions), we now find the following changes take place:

1. CO emissions are improved approx. 65% (nominal)
2. Measured max. CHT increases 3.4% (from 450° F to 460° F)
3. Max. CHT limit--460° F
4. Margin--(3) minus (2) = 0° F
5. Reduction in margin (max.CHT)--(10 ÷ 10) x 100 = 100.0%

Now, if we apply the above results to a SL. hot-day condition, we arrive at the following results:

Production Rich Limit Schedule (100% power)

1. Ambient conditions--SL. hot day (95° F)
2. Fuel schedule--production rich setting
3. Power setting--100% (nominal)
4. Measured max. CHT--460° F
5. Max. CHT limit--460° F
6. Margin--(5) minus (4) = 0° F

TABLE 6. SUMMARY OF EXHAUST EMISSIONS (C)) REDUCTION POSSIBILITIES FOR A TCM TSIO-360-C ENGINE--SEA LEVEL STANDARD DAY (EXCEPT AS NOTED)--COOLING AIR ΔP=3.5 inH_2O

	Modes	Parameter	F/A	CO lb/Mode	Max. CHT-°F	F/A	CO lb/Mode	Max. CHT-°F	Max. CHT-°F	Max. Limit CHT-°F
1	Taxi		0.0805	2.000		0.0750	1.653	-	-	-
2	Takeoff (100%)		0.0970	0.750	460	0.0970	0.750	460	460	460
3	Climb (100%)		0.0970	12.500	460	0.0970	12.500	460	460	460
4	Approach		0.0820	4.700	335	0.0750	3.400	345	370	460
5	lb/Cycle			19.950			18.303			
6	lb/Cycle/Rated BHP			0.0887			0.0813			
7	Federal Limit			0.0420			0.0420			
8	Diff. = (6) - (7)			0.0467			0.0393			
9	((8) ÷ (7)) x 100			111.2			93.6			
10	% of STD =(9) + 100			211.2			193.6			
					This Column For S.L. Standard Day			This Column For S.L. Standard Dav	This Column For S.L. Hot Day	
11	Taxi		0.0805	2.000		0.0750	1.653			
12	Takeoff (100%)		0.0970	0.750	460	0.0970	0.750	460	460	460
13	Climb (75%)		0.0850	7.917	415	0.0790	5.000	430	430	460
14	Approach		0.0820	4.700	335	0.0750	3.400	345	370	460
15	lb/Cycle			15.367			10.803			
16	lb/Cycle/Rated BHP			0.0683			0.0480			
17	Federal Limit			0.0420			0.0420			
18	Diff. = (16) - (17)			0.0263			0.0060			
19	((18) ÷ (17)) x 100			62.6			14.3			
20	% of STD = (19) + 100			162.6			114.3			

*This engine has **NO** takeoff power capability when this mode is leaned-out. For Hot Day operation this engine requires full rich fuel schedule settings. These limitations are also based on a cooling air ΔP=3.5 inH_2O

EFFECTS OF LEANING-OUT ON HC EMISSIONS. The test data show that the TCM engine can be leaned-out sufficiently in the taxi mode to bring the unburned hydrocarbon emissions below the federal standard (figure 12). Additional leaning-out in the approach and climb modes provides added improvements, but is not required to produce HC emission levels below the federal standard.

EFFECTS OF LEANING-OUT ON NO_x EMISSIONS. Oxides of nitrogen emissions are not improved as a result of applying lean-out adjustments to the fuel metering devices. In fact, the NO_x levels are at their lowest when the engine is operating full rich as shown in figure 11. Test results have shown that if all the test modes (takeoff, climb, approach, and taxi) were leaned-out excessively (F/A=0.067), the NO_x emission level would exceed the federal standard.

The negative effect on NO_x emissions is one of the reasons why it was decided to evaluate and study the effects of adjusting/manipulating selected mode conditions rather than adopt the philosophy of adjusting all modes.

EFFECTS ON ALLOWABLE MAXIMUM CYLINDER HEAD TEMPERATURE. One of the major problems that occurs as an effect of leaning-out general aviation piston engines in order to improve emissions is the increase or rise in maximum cylinder head temperatures.

Most general aviation aircraft are designed to operate with cooling air pressure differentials of 4.0 inH_2O or less. The tests conducted with the TCM engine utilized 3.5 inH_2O as the basic cooling flow condition.

Additional tests were conducted using variations in cooling air flow to evaluate these effects on different lean-out schedules. Some of the tests were also conducted under different ambient conditions so that changes in ambient conditions could also be evaluated.

Data shown in tables C-1 through C-14 and plotted in figures 13 through 15 show the results of these tests.

In summary it can be concluded that any attempts to lean-out current production-type horizontally opposed general aviation piston engines in the takeoff mode to F/A ratios lower than production lean limits will produce CHT's that are higher than the manufacturer's specified limit.

Any attempt to lean-out the climb mode to F/A ratios below best power will result in higher than normal CHT's. This could become particularly acute under hot-day takeoff and climb conditions at sea level or altitude.

RESULTS OF TESTS WITH VARYING SPARK SETTINGS.

This engine was not evaluated with different spark settings. The basic production setting is 20° BTC. Tests conducted with other light-aircraft piston engines demonstrated that very little practical benefit could be derived by adjusting the basic production spark setting.

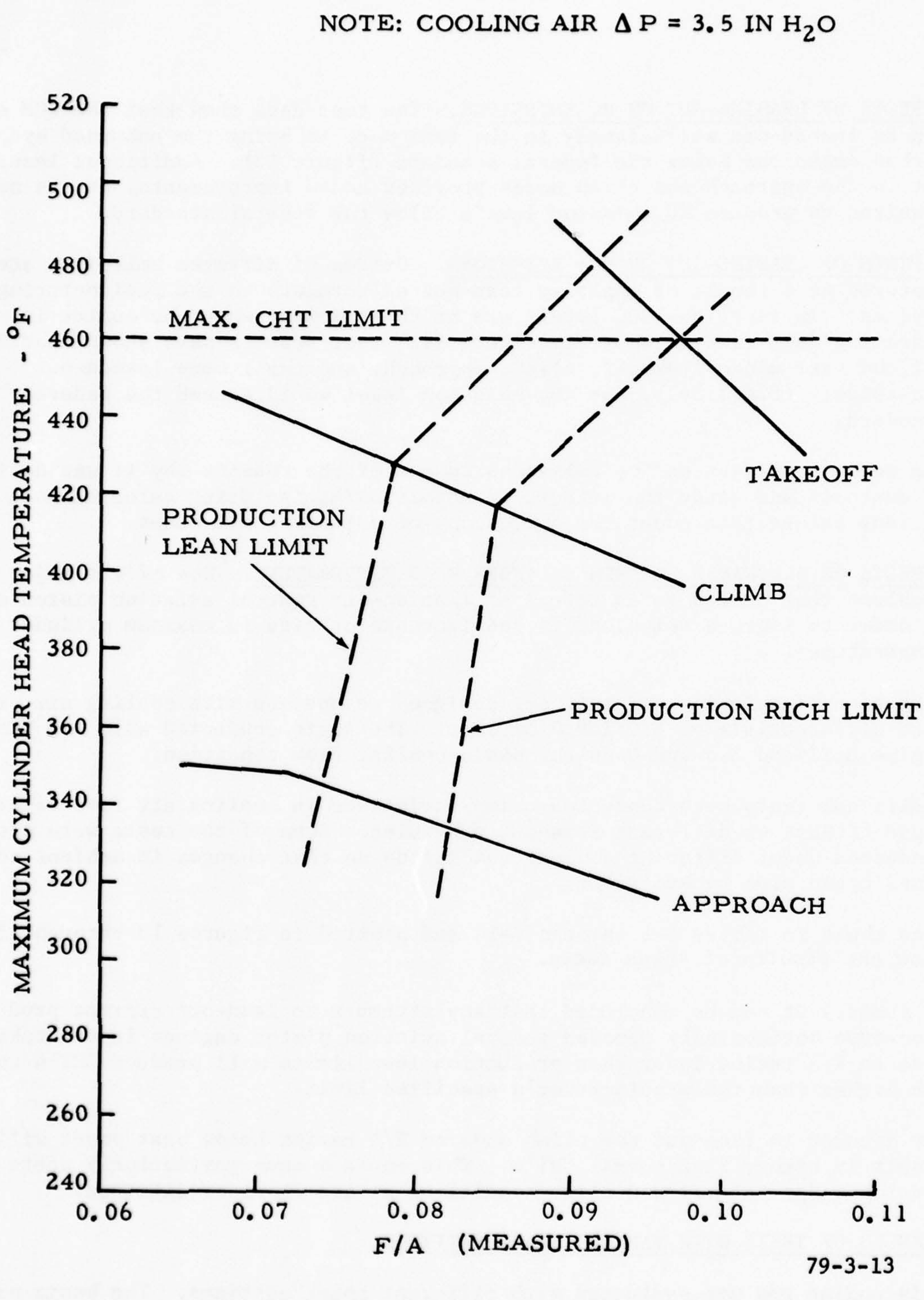


FIGURE 13. SEA LEVEL STANDARD DAY MAXIMUM CYLINDER HEAD TEMPERATURES FOR DIFFERENT POWER MODE CONDITIONS AND VARYING FUEL-AIR RATIOS--TCM TSIO-360-C

NOTE: COOLING AIR $\Delta P = 3.5$ IN H_2O

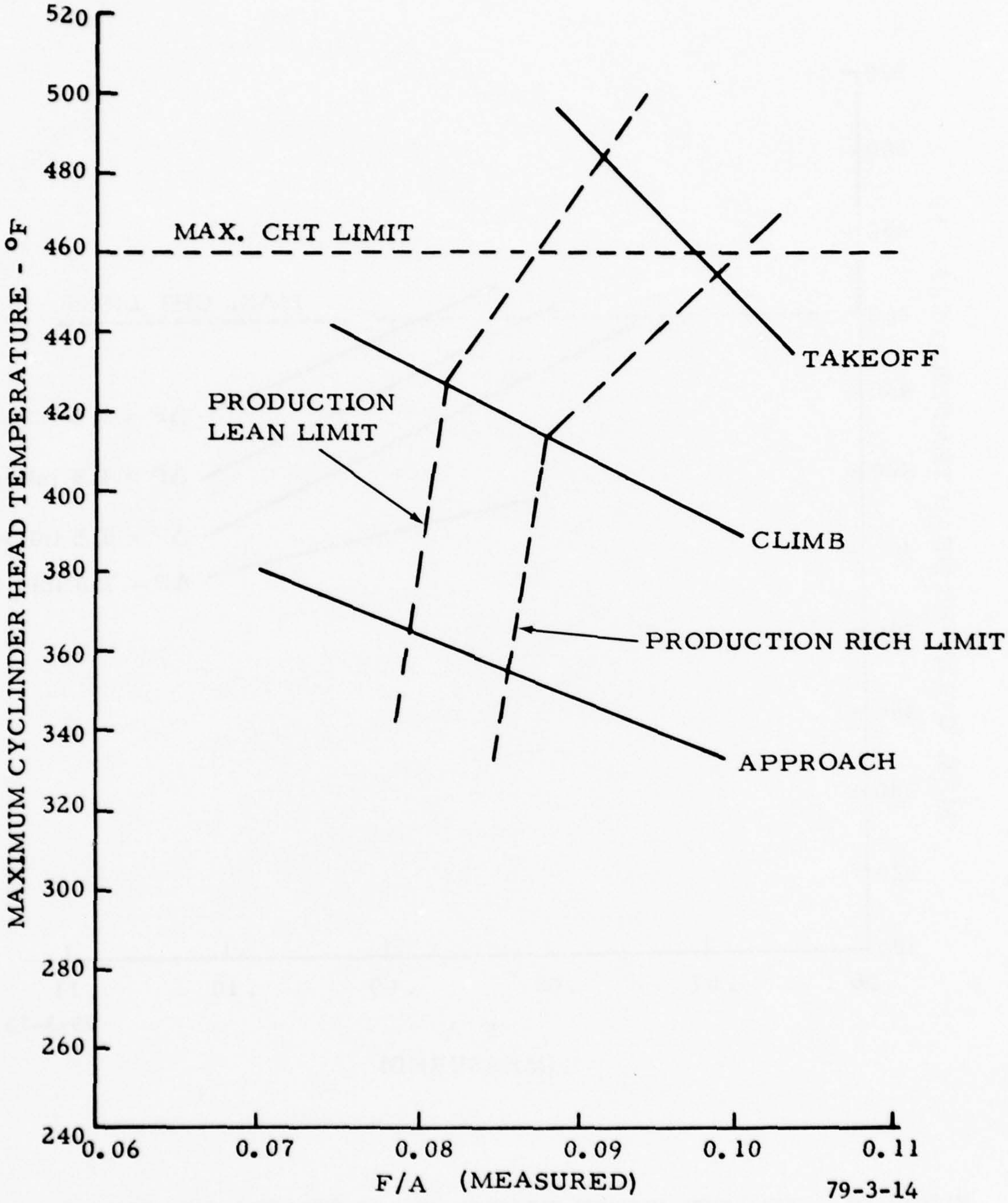


FIGURE 14. SEA LEVEL HOT DAY (T_i = 95° F) MAXIMUM CYLINDER HEAD TEMPERATURE FOR DIFFERENT POWER MODE CONDITIONS AND VARYING FUEL-AIR RATIOS--TCM TSIO-360-C ENGINE

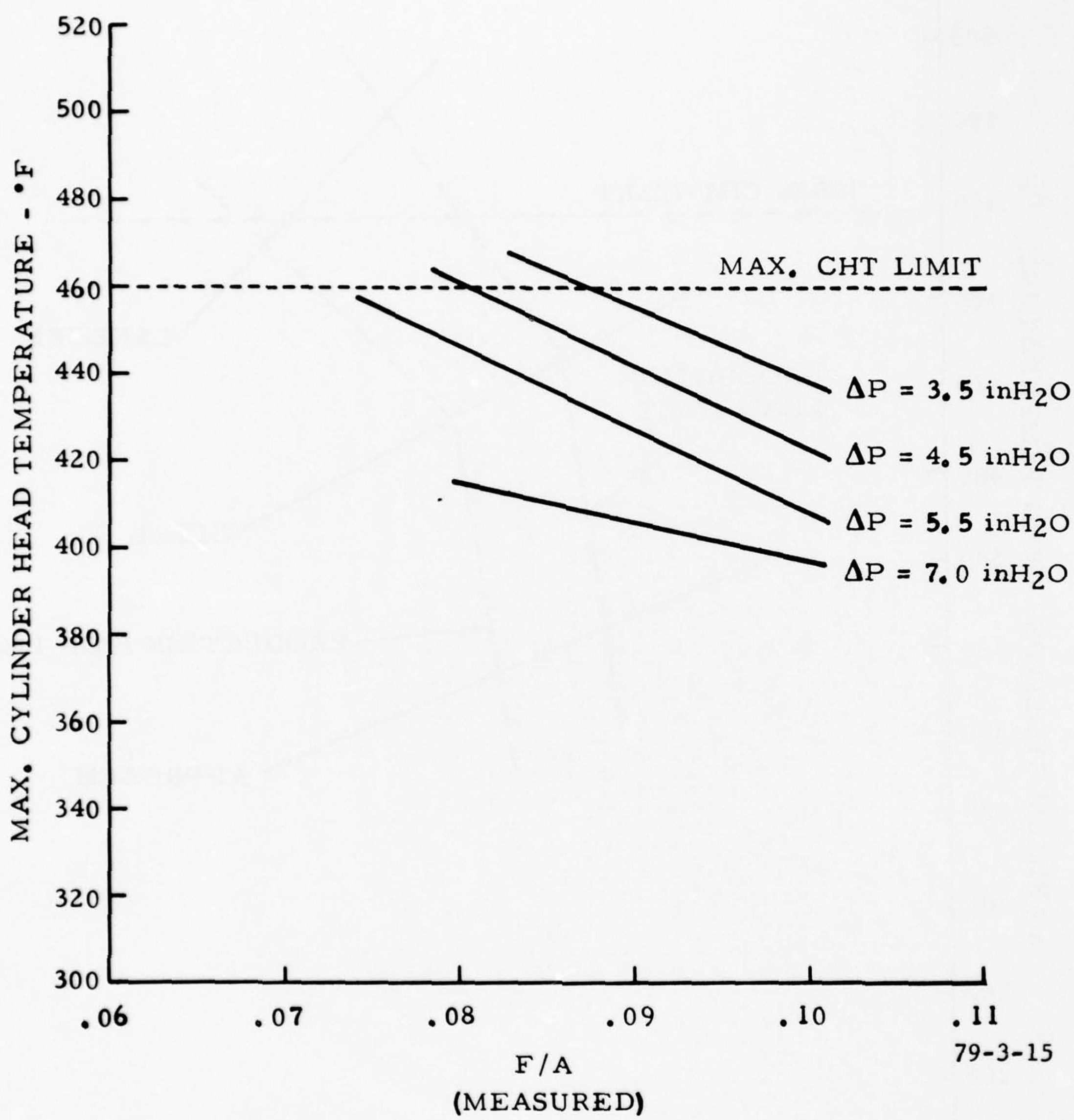


FIGURE 15. SEA LEVEL MAXIMUM CYLINDER HEAD TEMPERATURE VARIATIONS FOR DIFFERENT COOLING AIR DIFFERENTIAL PRESSURE CONDITIONS AND VARYING FUEL-AIR RATIOS--TCM TSIO-360-C ENGINE--TAKEOFF MODE (SEA LEVEL STANDARD DAY)

SUMMARY OF RESULTS

EXHAUST EMISSIONS.

1. The TSIO-360-C engine does not meet the proposed EPA carbon monoxide and unburned hydrocarbon standards for 1979/80 under sea level standard day conditions.

2. The TSIO-360-C engine meets the EPA oxides of nitrogen standard for 1979/80.

3. The engine fuel metering device could be adjusted on the test stand to reduce the current CO exhaust emission level, but not to levels required by EPA standards when operating under the most severe LTO cycle requirements.

4. The engine could be adjusted on the test stand to reduce the unburned hydrocarbon exhaust emission level below the proposed EPA standard.

MAXIMUM CYLINDER HEAD TEMPERATURES.

1. Adjusting the fuel metering device in the takeoff mode to the constant best power operation results in an increase in maximum CHT, which will exceed the engine specification limit if cooling air ΔP is limited to 3.5 inH_2O or less.

2. Adjusting the fuel metering device in the climb mode to constant best power operation will result in an increase in maximum CHT. This change will necessitate an increase in cooling air flow to provide adequate temperature margins for hot-day operations. An increase in cooling air differential pressure of approximately 1.0 inH_2O may be required for critical aircraft installations.

3. No critical maximum CHT's result from leaning-out the approach and taxi modes. However, taxi mode maximum CHT's were measured in excess of 400° F while operating under warm temperature ambient conditions or during lean-out tests with no measurable cooling air ΔP, a condition considered similar to actual operation.

CRITICAL LANDING AND TAKEOFF CYCLE.

1. The most critical LTO cycle with respect to emission control is the cycle defined in this report as maximum five-mode LTO cycle (table 4). Engine operation in accordance with the maximum five-mode LTO cycle in a sea level propeller test stand could not be adjusted to meet the proposed EPA emission standards for 1979/80 without exceeding engine maximum CHT limits.

2. Engine operation in a sea level propeller test stand, in accordance with the minimum five-mode LTO cycle (table 5), could be adjusted to approximately the proposed EPA emission standards for 1979/80 without exceeding engine maximum CHT limits while operating with a cooling air ΔP = 3.5 inH_2O.

3. This engine, operating in a sea level propeller test stand, could be adjusted to meet the proposed EPA emission standards for 1979/80 while testing for the minimum five-mode cycle (table 5), if cooling air $\Delta P = 5.5$ inH_2O is used for nacelle cooling.

4. Test data evaluated on the basis of a literal interpretation of the EPA LTO cycle defined in reference 1 indicate that the emission standards should be defined with a maximum and minimum tolerance or should be redefined on the basis of a maximum (not to exceed) limit for sea level hot-day operating conditions.

CONCLUSIONS

The following conclusions are based on the testing accomplished with the TCM TSIO-360-C engine.

1. The single use of simple fuel management adjustments (altering of fuel schedule) do not allow safe reduction of exhaust emissions of the test engine, the TCM TSIO-360-C. In conjunction with other data, references 11 and 12, this appears to be a valid general conclusion for typical light-aircraft piston engines.

2. The test data indicate that fuel management adjustments must be combined with engine/nacelle cooling modifications before safe, low-emission aircraft/engine combination can be achieved.

3. The EPA CO limit of 0.042 lb/cycle/rated BHP was not acheivable when hot-day takeoff and climb requirements combined with aircraft heavy gross weight and the need to pay close attention to CHT limitations.

4. An assessment of the maximum five-mode LTO cycle (table 4) test data indicate that the following standard changes should be made to the proposed EPA emission standards:

Proposed EPA Standard for 1979/1980 (lb/cycle/rated BPH)	Recommended Change for Standard 1979/1980 (lb/cycle/rated BHP)
CO Standard 0.042	0.075
HC Standard 0.0019	0.0025
NO_x Standard 0.0015	0.0015

5. To avoid CHT problems in the takeoff mode (100-percent power), it is advisable not to adjust the fuel metering device. Engine operation in this mode should continue to be accomplished within current production rich/lean limits.

REFERENCES

1. Control of Air Pollution from Aircraft Engines, Environmental Protection Agency, Federal Register, Volume 38, No. 136, Part II, July 17, 1973.

2. Flow of Fluids Through Valves, Fittings, and Pipe, Crane Industrial Products Group, Technical Paper No. 410, 1957.

3. Liston, J., Power Plants for Aircraft, McGraw-Hill Book Company, Inc., New York, 1953.

4. Obert, E. F., Internal Combustion Engines and Air Pollution, Intext Educational Publishers, New York, 1973.

5. D'Alleva, B. A., Procedure and Charts for Estimating Exhaust Gas Quantities and Compositions, General Motors Corp., Research Laboratories, GMR-372, May 15, 1960.

6. Graf, Gleeson, and Paul, Interpretation of Exhaust Gas Analyses, Engineering Experiment Station, Oregon State Agricultural College, Bulletin Series No. 4, 1934.

7. Guide to Aviation Products, Humble Oil and Refining Company, 1969.

8. NAPTC Fuel Sample Analysis -- 100/130 Octane Aviation Gasoline, 1976.

9. G.E. Aircraft Propulsion Data Book, General Electric, 1957.

10. Aeronautical Vest-Pocket Handbook, Pratt and Whitney Aircraft, 1957.

11. Becker, E. E., Exhaust Emissions Characteristics for a General Aviation Light-Aircraft AVCO Lycoming IO-360-BIBD Piston Engine, DOT/FAA/NAFEC, Report No. FAA-RD-78-129, 1978.

12. Becker, E. E., Exhaust Emissions Characteristics for a General Aviation Light-Aircraft AVCO Lycoming IO-360 A1B6D Piston Engine, DOT/FAA/NAFEC, Report No. FAA-RD-78-142, 1978.

13. Stukas, L. J., Aircraft Piston Engines, DOT/FAA/NAFEC, Report No. FAA-RD-78-79, March 1979.

APPENDIX A

FUEL SAMPLE ANALYSIS

COMBUSTIBLE ELEMENTS IN FUELS (AVIATION FUEL).

1. Carbon and hydrogen are the predominant combustible elements in fuels (aviation type), with small amounts of sulphur as the only other fuel element.

2. Liquid fuels are mixtures of complex hydrocarbons.

3. For combustion calculations, gasoline or fuel oil can be assumed to have the average molecular formula C_8H_{17}.

Note: The Exxon® data presented in table A-1 may be found in reference 7.

TABLE A-1. TYPICAL SPECIFICATIONS FOR AVIATION FUELS

Item	D910-76 Grade 100/130	Exxon Aviation Gas 100/130	D910-70 Grade 115/145	Exxon Aviation Gas 115/145
Freezing Point, °F	-72 Max.	Below -76	-76 Max.	Below -76
Reid Vapor Press., PSI	7.0 Max.	6.8	7.0 Max.	6.8
Sulfur, % by Weight	0.05 Max.	0.02	0.05 Max.	0.02
Lower Heating Value, BTU/lb	18,720 Min.		18,800 Min.	
Heat of Comb. (NET). BTU/lb		18,960		19,050
Distillation, %Evaporated				
At 167° F (Max.)	10	22	10	21
At 167° F (Min.)	40		40	
At 221° F (Max.)	50	76	50	62
At 275° F (Max.)	90	97	90	96
Distillation End Point	338° F Max.		338° F Max.	
Final Boiling Point °F		319		322
Tel Content, ML/U.S. Gal.	4.0 Max.	3.9	4.6 Max.	4.5
Color	Green	Green	Purple	Purple

4. NAFEC used 100/130 (octane rated) aviation gasoline for the piston engine emission tests. The following analysis of a typical fuel sample (table A-2) made at the U.S. Naval Air Propulsion Test Center (NAPTC), Trenton, N.J. (reference 8).

TABLE A-2. ANALYSIS OF NAFEC FUEL SAMPLE, 100/130 FUEL

Item	NAFEC Sample 100/130	Grade 100/130(MIL-G-5572E) Spec Limits Min.	Max.
Freezing Point, °F	Below -76° F		-76
Reid Vapor Press., PSI	6.12	5.5	7.0
Sulfur % By Weight	0.024		0.05
Lower Heating Value BTU/lb		18,700	
Heat of Comb. (NET) BTU/lb	18,900		

Distillation, % Evaporated	NAFEC Sample 100/130	Distillation % Evaporation		
At 158° F	10			
At 167° F (Min.)		167° F	10	
At 167° F (Max.)			40	167° F
At 210° F	40			
At 220° F	50			
At 221° F		221° F	50	
At 242° F	90			
At 275° F		275° F	90	
Distillation End Point	313° F			338° F
Specific Gravity @60° F	0.7071	Report		Report
API Gravity @60° F	68.6	No Limit		
Tel Content, ML/U.S. Gal.	1.84			4.60

Computation for the fuel hydrogen-carbon ratio is based on the fuel net heating value, h_f, equal to 18,900 BTU/lb and figure A-1.

$C/H = 5.6$

$C = 12.011$

$C_8 = 8 \times 12.011 = 96.088$

$H_y = (96.088) \div 5.6 = 17.159$

$H = 1.008$

$Y = (17.159) \div 1.008 = 17.022$ Use $Y = 17$

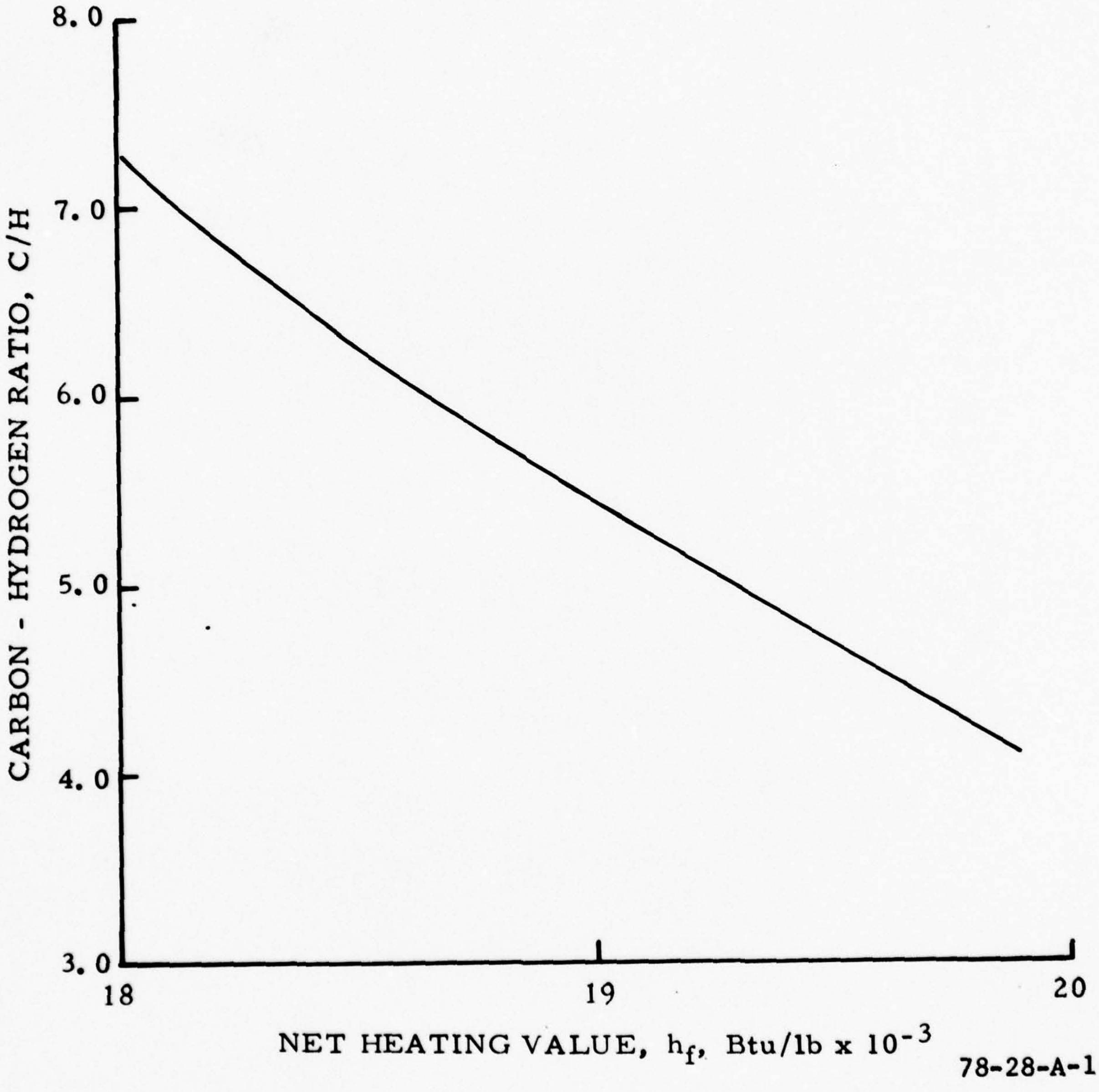


FIGURE A-1. NET HEATING VALUE FOR AVIATION GASOLINE AND CARBON-HYDROGEN RATIO CORRELATION

APPENDIX B

COMPOSITION OF AIR (GENERAL PROPERTIES)

1. Dry air is a mixture of gases that has a representative volumetric analysis in percentages as follows:

Oxygen (O_2)--20.99%
Nitrogen (N_2)--78.03%
Argon (A)--0.94% (Also includes traces of the rare gases neon, helium, and krypton)
Carbon Dioxide (CO_2)--0.03%
Hydrogen (H_2)--0.01%

2. For most calculations it is sufficiently accurate to consider dry air as consisting of:

O_2 = 21.0%
N_2 = 79.0% (including all other inert gases)

3. The moisture or humidity in atmospheric air varies over wide limits, depending on meteorological conditions; its presence in most cases simply implies an additional amount of essentially inert material.

Note: Information given in items 1, 2, and 3 is recommended for computation purposes (reference 3, 4, 9, and 10).

TABLE B-1. MASS ANALYSIS OF PURE DRY AIR

Gas	Volumetric Analysis %	Mole Fraction	Molecular Weight	Relative Weight
O_2	20.99	0.2099	32.00	6.717
N_2	78.03	0.7803	28.016	21.861
A	0.94	0.0094	39.944	0.376
CO_2	0.03	0.0003	44.003	0.013
Inert Gases	0.01	0.0001	48.0	0.002
	100.00	1.000		28.969 = M for air

4. The molecular weight of the apparent nitrogen can be similarly determined by dividing the total mass of the inert gases by the total number of moles of these components:

$$M_{\substack{\text{Apparent}\\\text{Nitrogen}}} = \frac{2225}{79.01} = 28.161$$

5. This appendix advocates the term nitrogen as referring to the entire group of inert gases in the atmosphere, and therefore the molecular weight of 28.161 will be the correct value (rather than the value 28.016 for pure nitrogen).

6. In combustion processes the active constituent is oxygen (O_2), and the apparent nitrogen can be considered to be inert. Then for every mole of oxygen supplied, 3.764 moles of apparent nitrogen accompany or dilute the oxygen in the reaction:

$$\frac{79.01}{20.99} = 3.764 \ \frac{\text{Moles Apparent Nitrogen}}{\text{Mole Oxygen}}$$

7. The information given in items 4, 5, and 6 is recommended for computational purposes in reference 4. Therefore, one mole of air (dry), which is composed of one mole of oxygen (O_2) and 3.764 moles of nitrogen (N_2), has a total weight of 137.998 pounds.

$$(O_2 + 3.764\ N_2) = 137.998$$

This gives the molecular weight of air = 28.97.

APPENDIX C

NAFEC TEST DATA AND WORKING PLOTS FOR ANALYSIS AND EVALUATION
TCM TSIO-360-C ENGINE

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

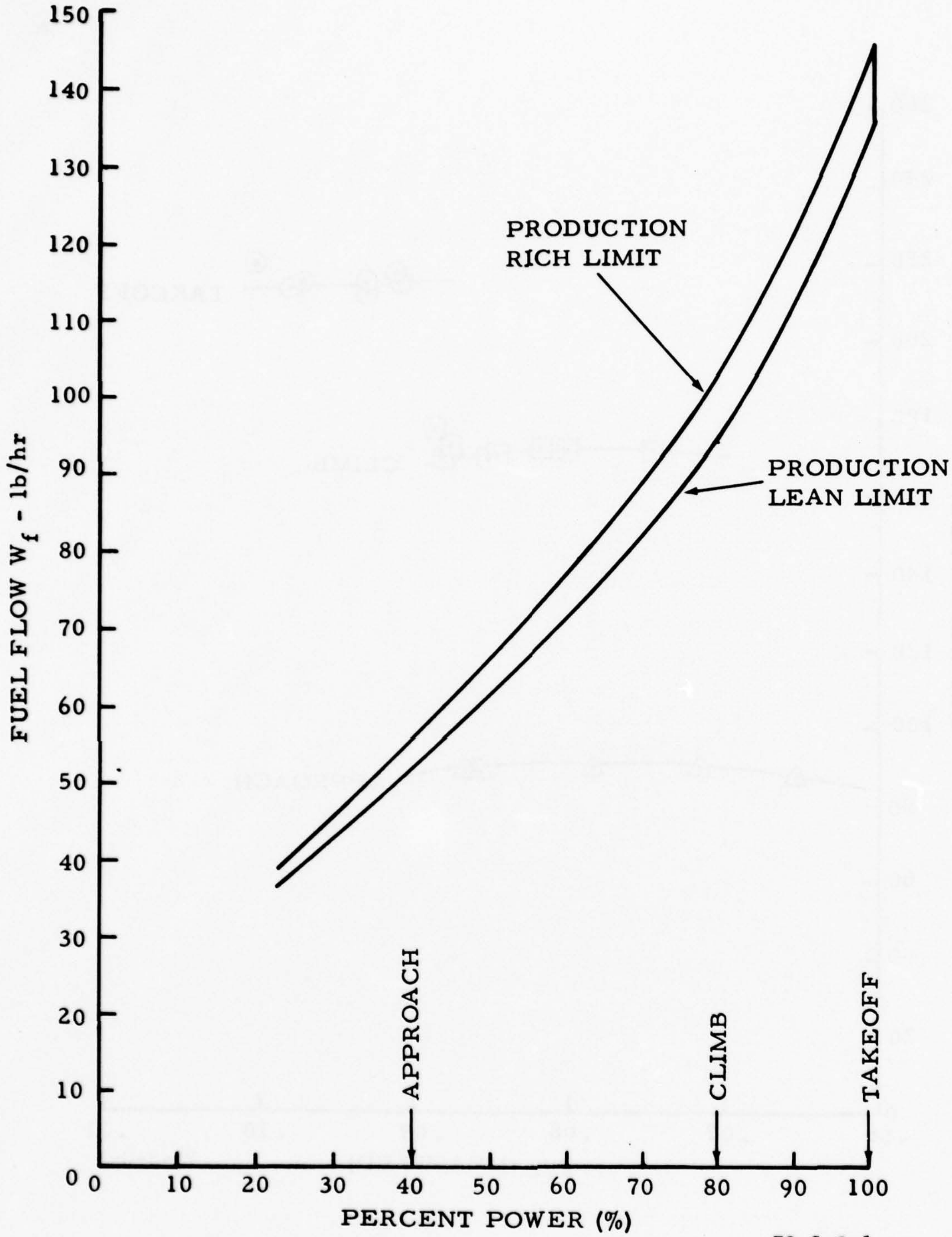


FIGURE C-1. RECOMMENDED FUEL FLOW VERSUS POWER FOR A TCM TSIO-360-C ENGINE (DERIVED FROM REFERENCE 13)

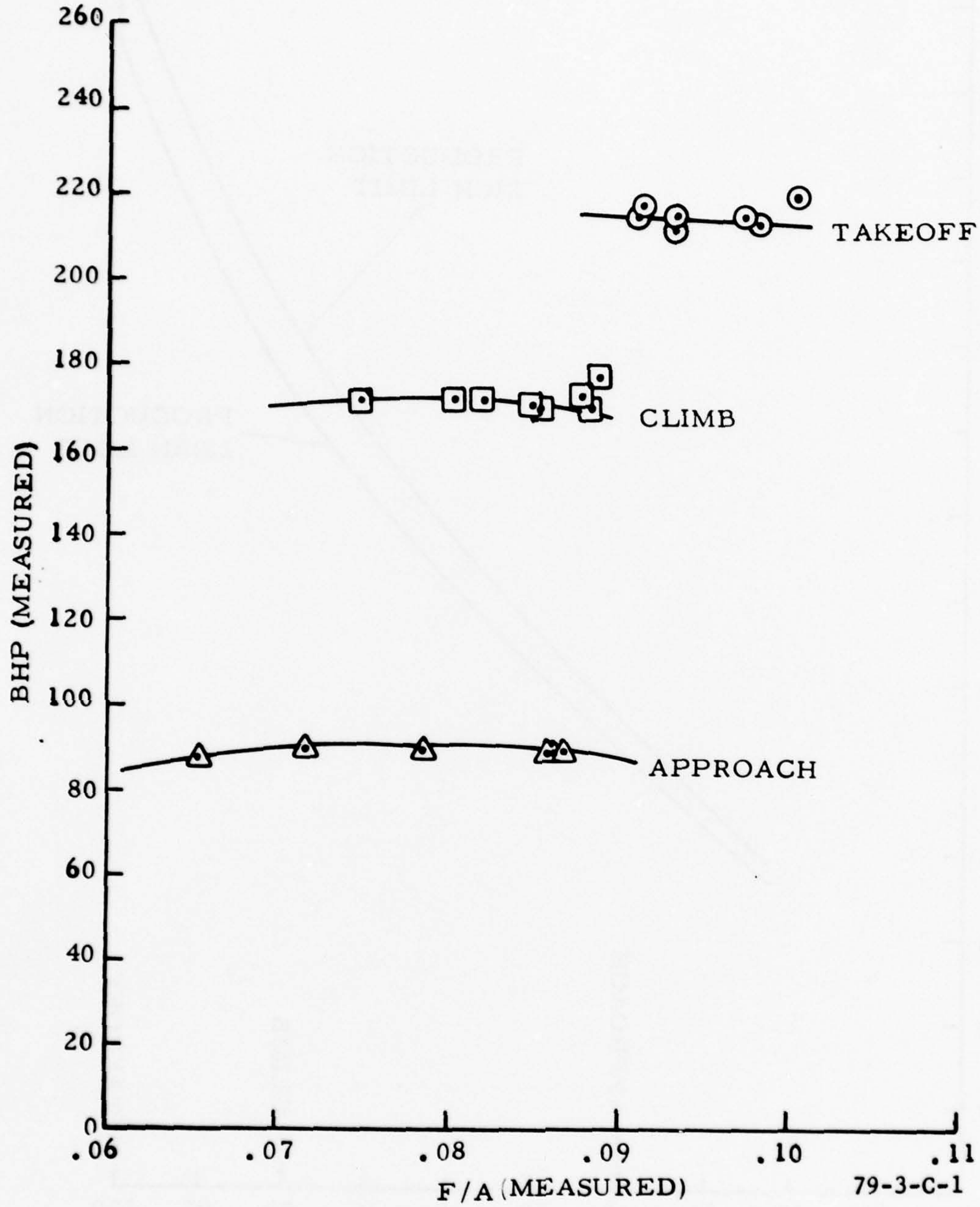


FIGURE C-2. MEASURED PERFORMANCE--TCM TSIO-360-C ENGINE--TAKEOFF, CLIMB, AND APPROACH MODES--NOMINAL SEA LEVEL AIR DENSITY 0.0760 lb/ft^3

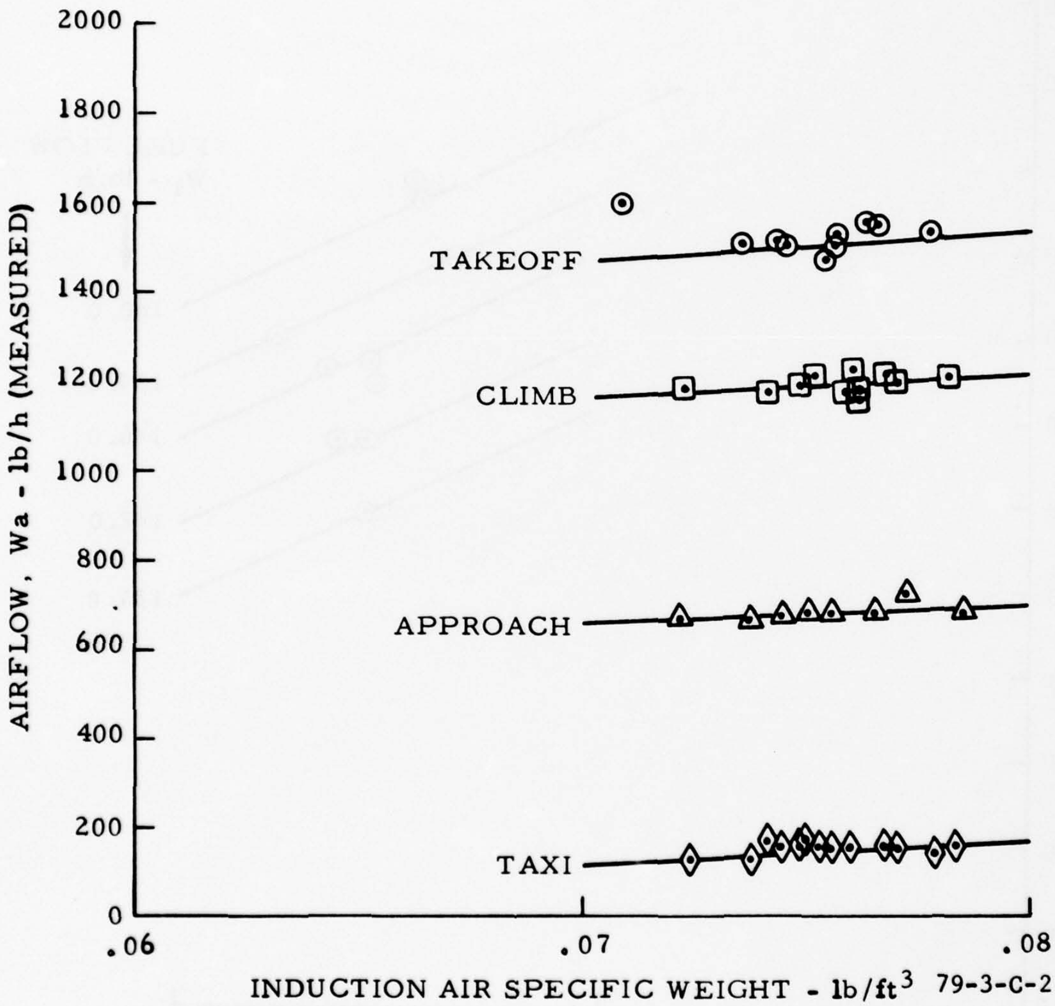


FIGURE C-3. AIRFLOW AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR A TCM TSIO-360-C ENGINE--NOMINAL SEA LEVEL TEST DATA

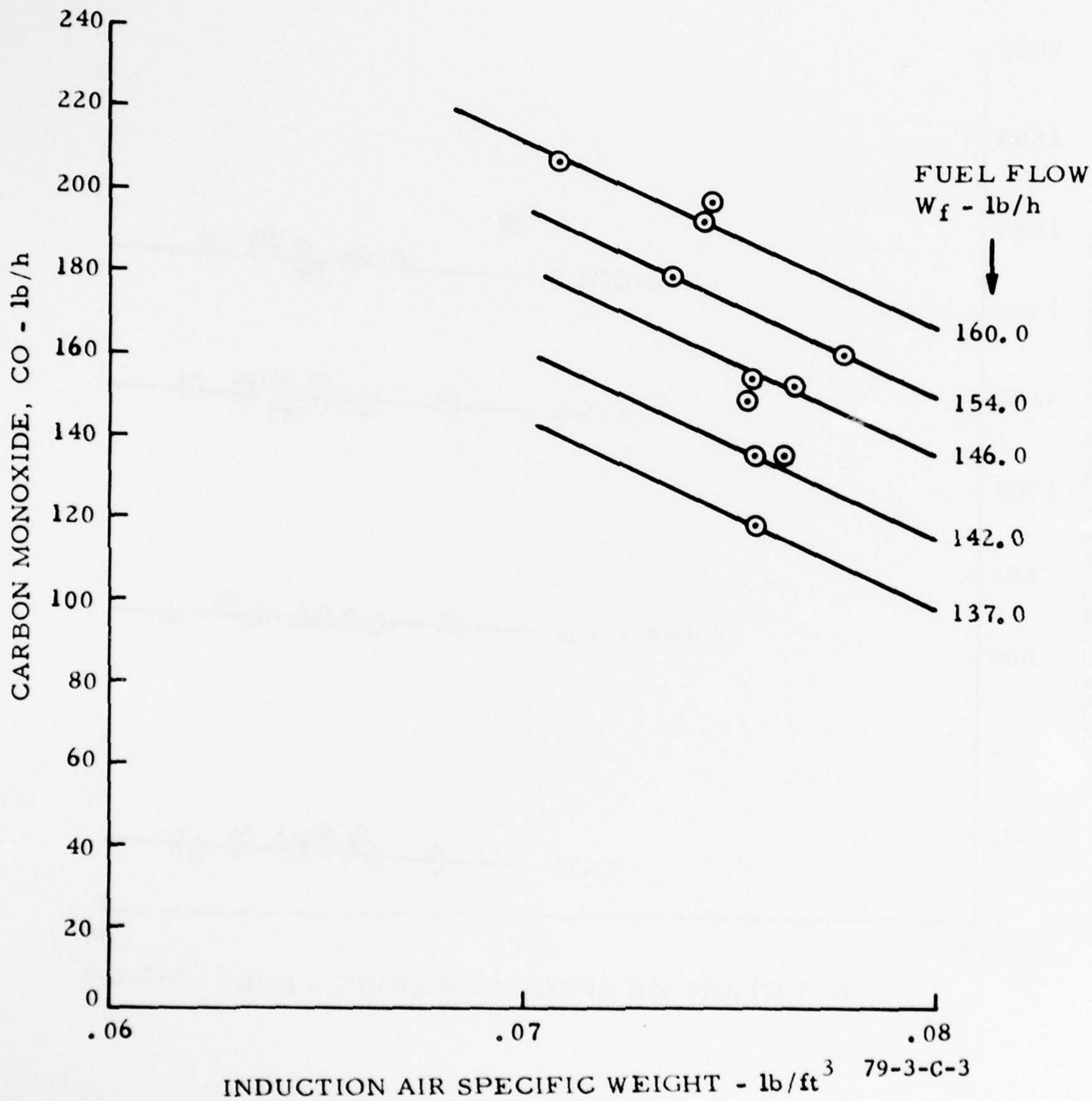


FIGURE C-4. EXHAUST CARBON MONOXIDE AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL TAKEOFF CONSTANT FUEL FLOW SCHEDULES--TCM TSIO-360-C ENGINE

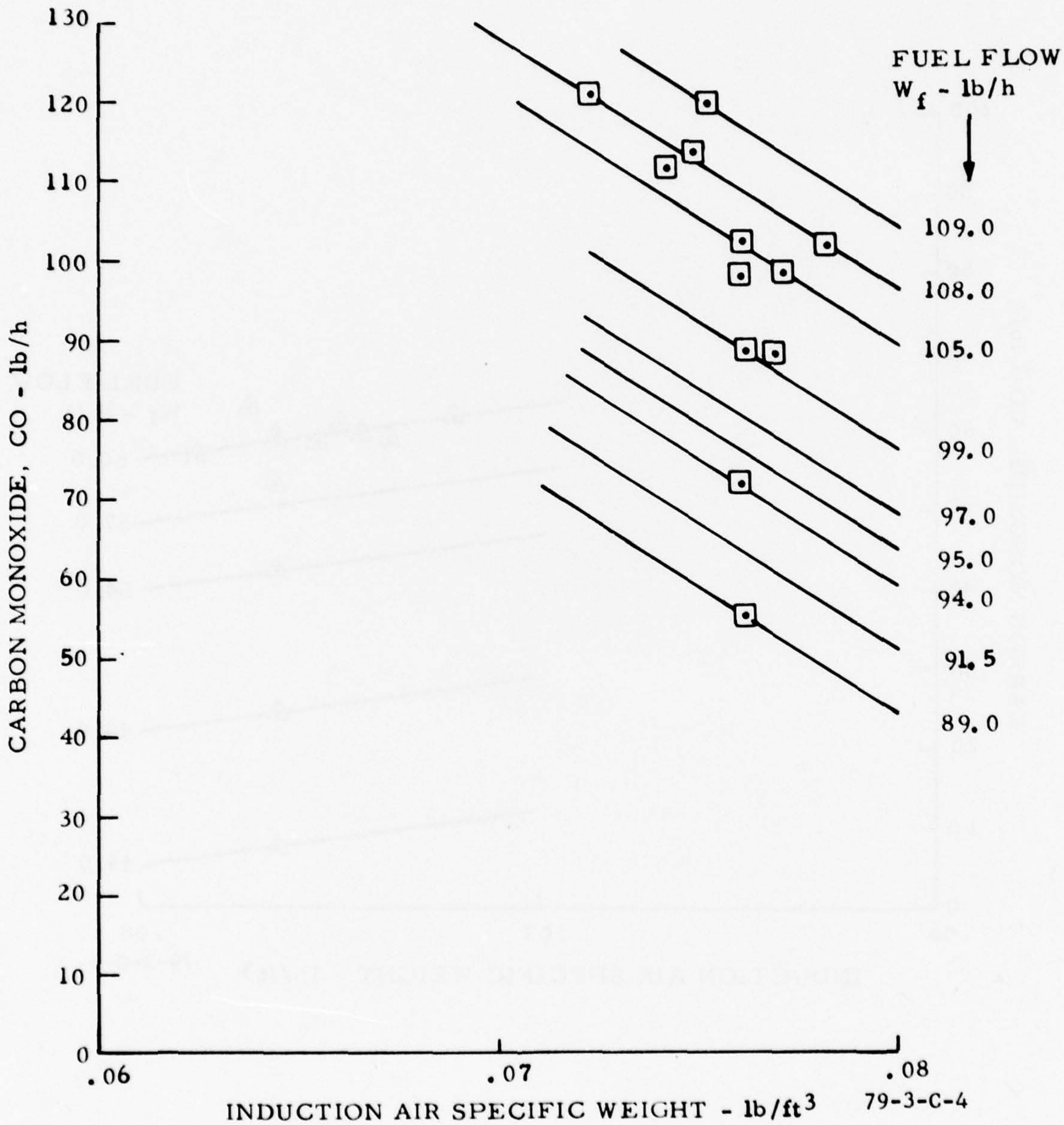


FIGURE C-5. EXHAUST CARBON MONOXIDE AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL CLIMB MODE CONSTANT FUEL FLOW SCHEDULES--TCM TSIO-360-C ENGINE

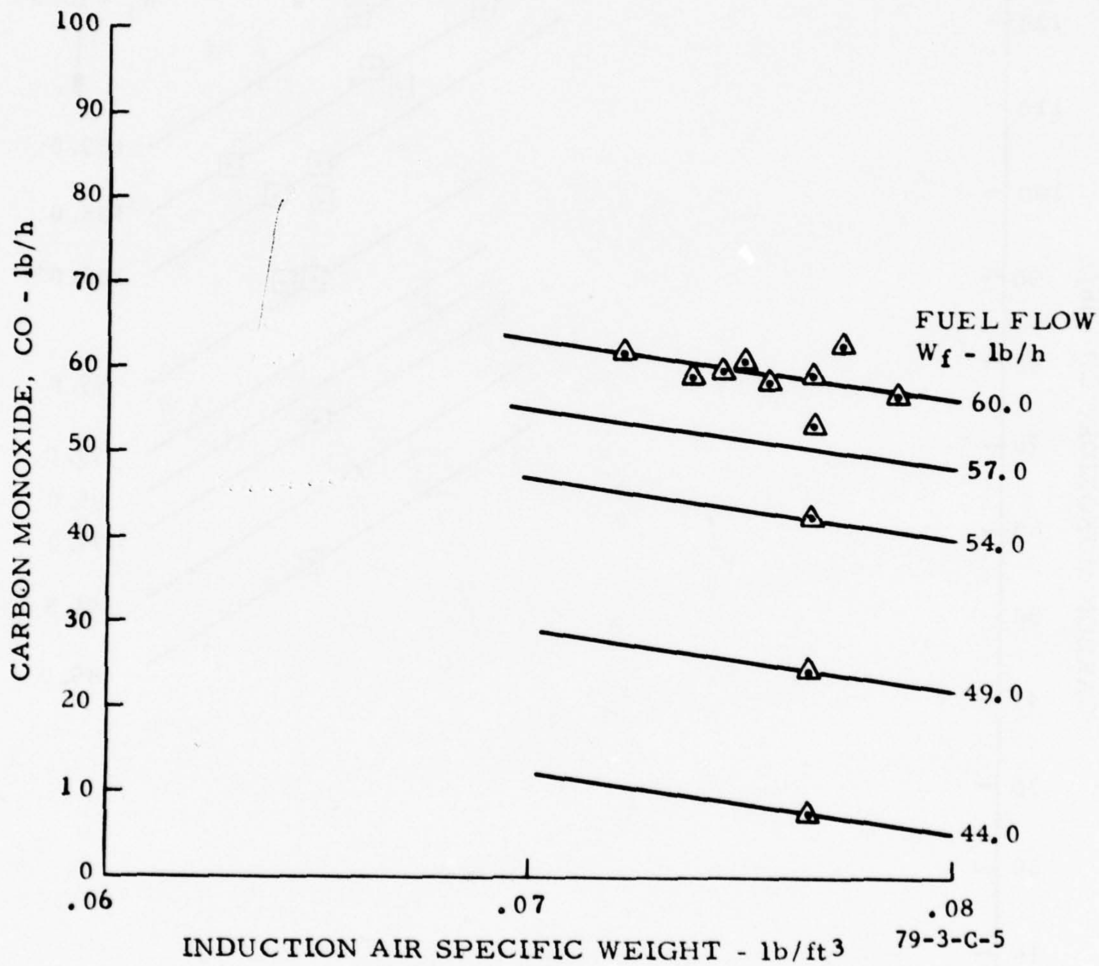


FIGURE C-6. EXHAUST CARBON MONOXIDE AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL APPROACH MODE CONSTANT FUEL FLOW SCHEDULES--TCM TSIO-360-C ENGINE

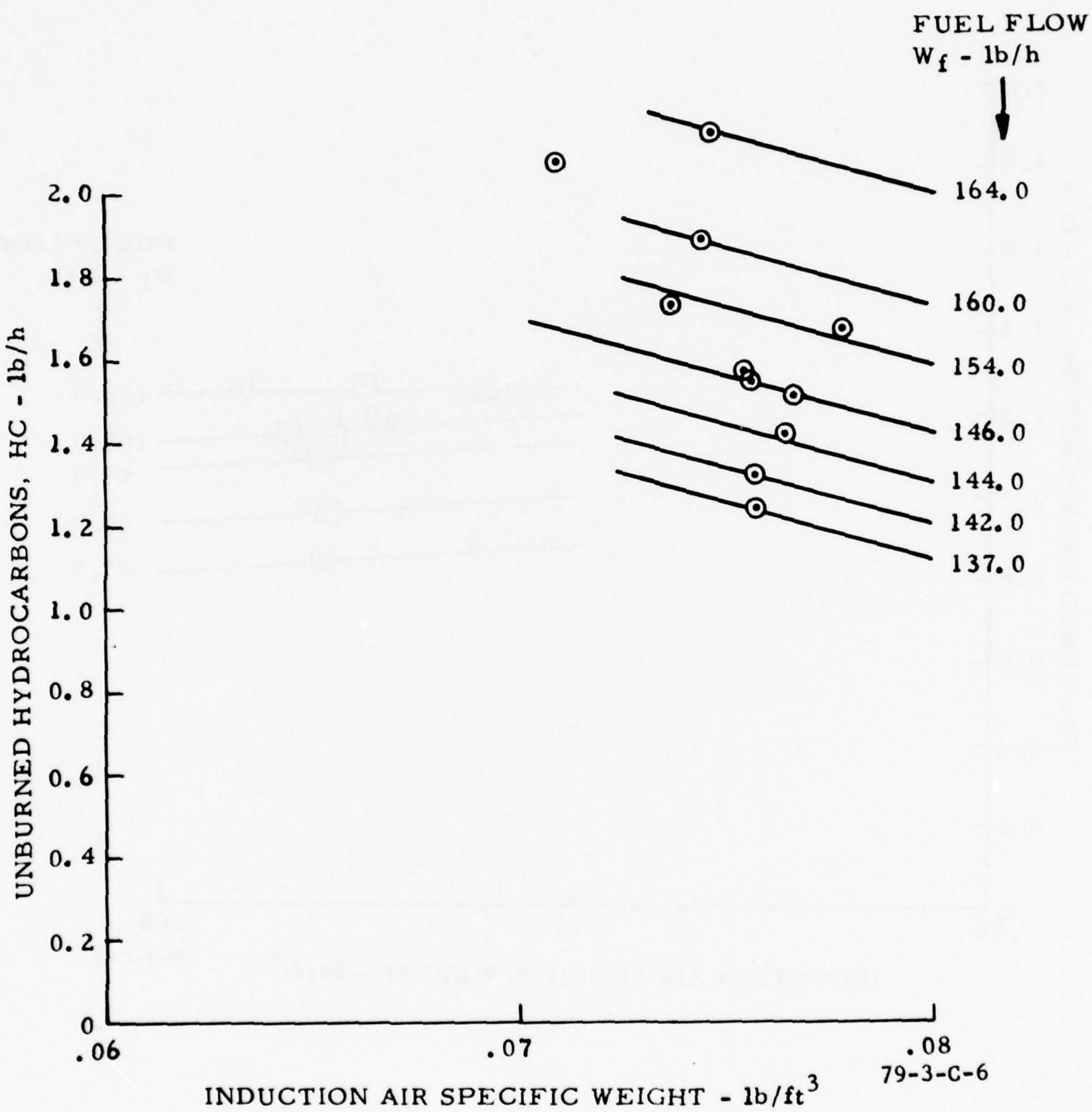


FIGURE C-7. UNBURNED EXHAUST HYDROCARBONS AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL TAKEOFF CONSTANT FUEL FLOW SCHEDULES—TCM TSIO-360-C ENGINE

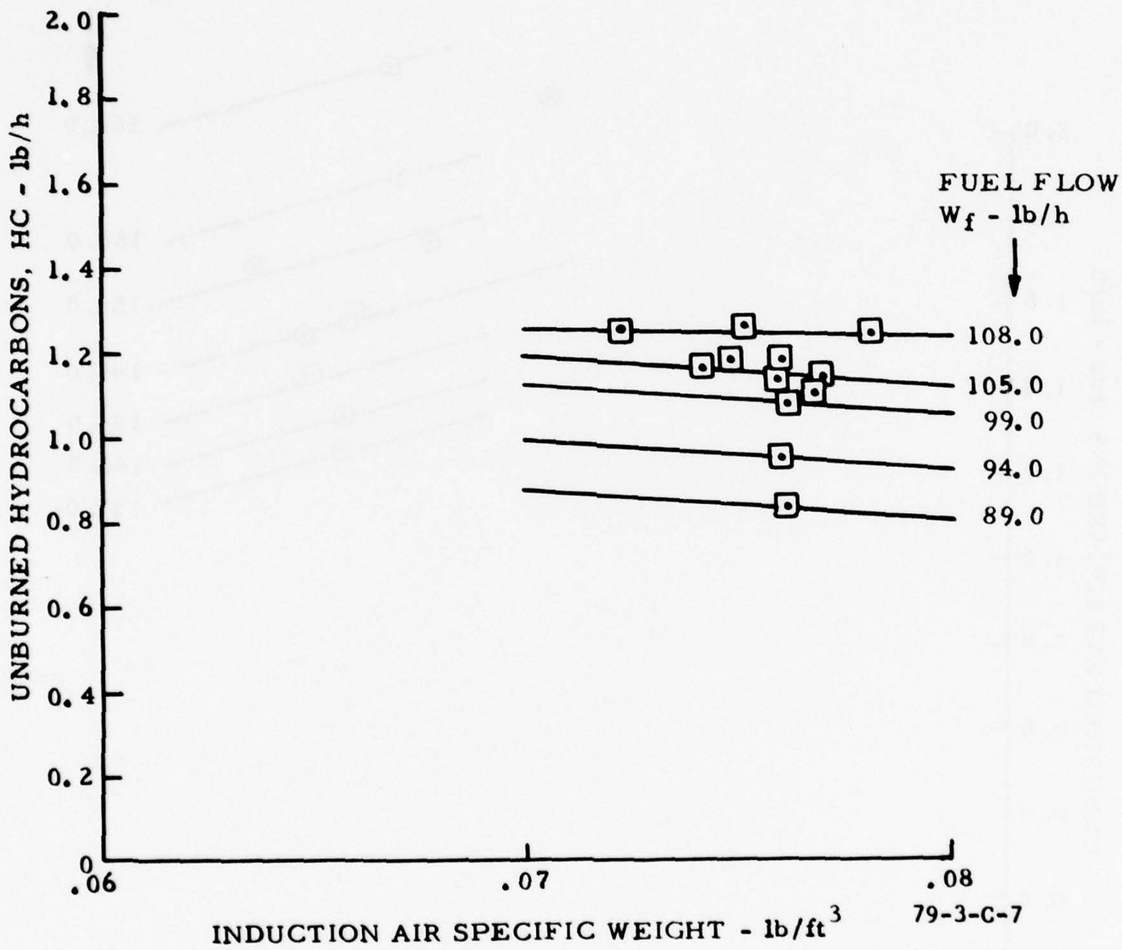
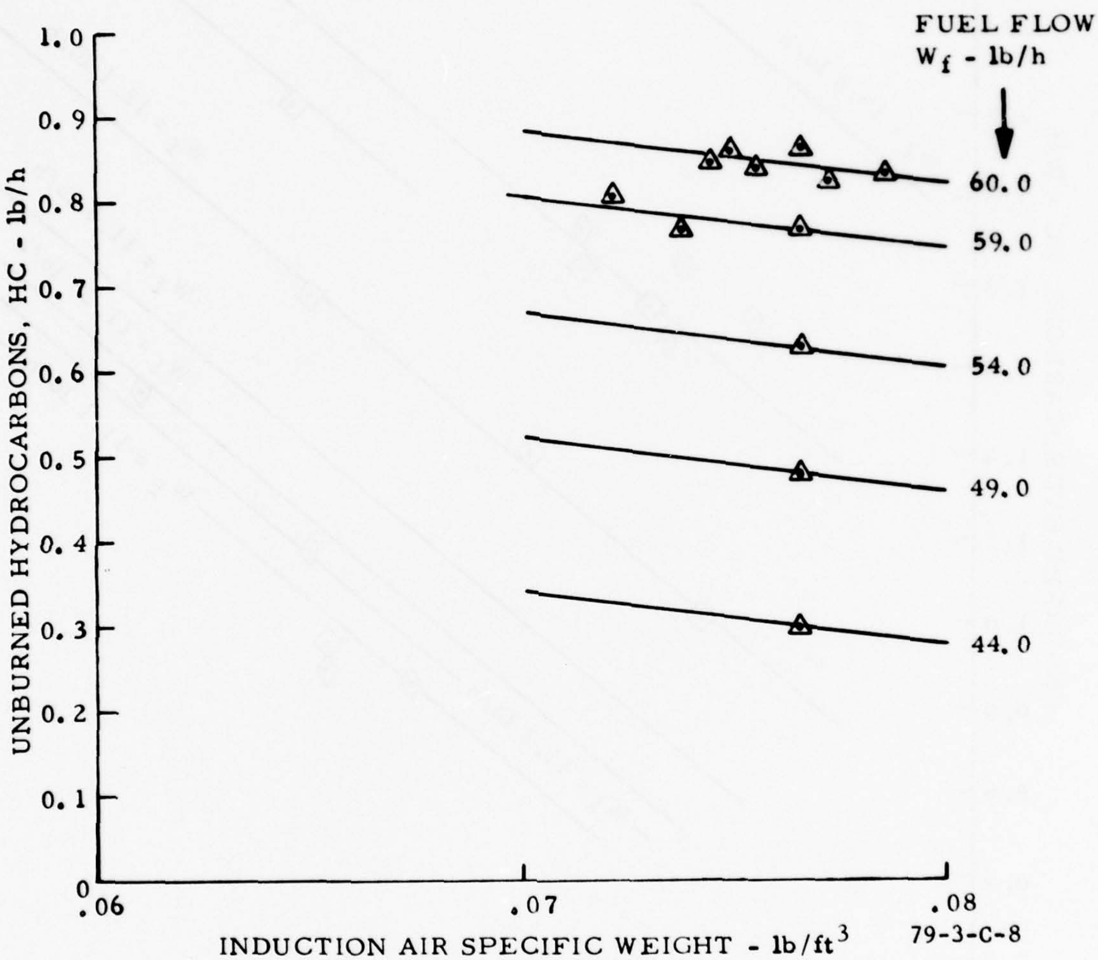


FIGURE C-8. UNBURNED EXHAUST HYDROCARBONS AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL CLIMB MODE CONSTANT FUEL FLOW SCHEDULES--TCM TSIO-360-C ENGINE



FIUGRE C-9. UNBURNED EXHAUST HYDROCARBONS AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL APPROACH MODE CONSTANT FUEL FLOW SCHEDULES--TCM TSIO-360-C ENGINE

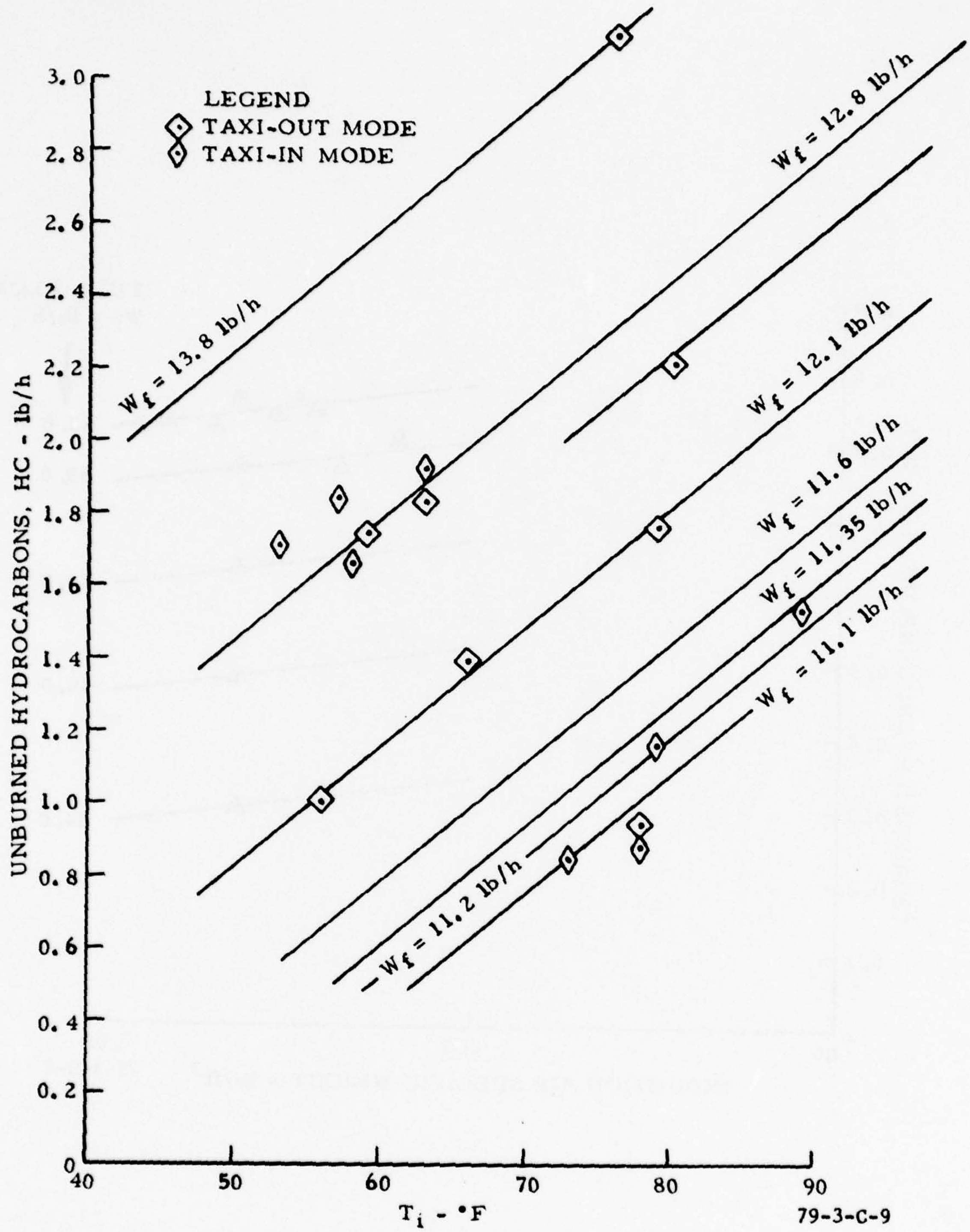


FIGURE C-10. UNBURNED EXHAUST HYDROCARBONS AS A FUNCTION OF INDUCTION AIR TEMPERATURE (T_i) FOR SEVERAL TAXI MODE CONSTANT FUEL FLOW SCHEDULES--TCM TSIO-360-C ENGINE

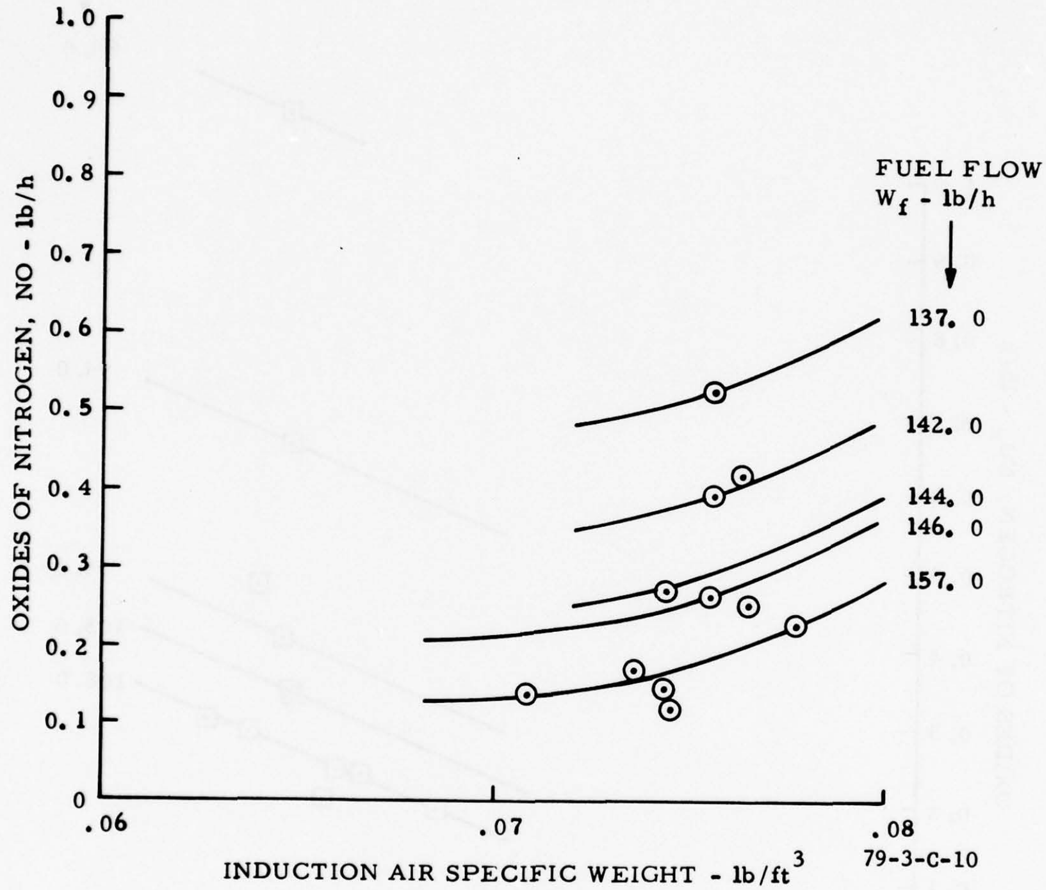


FIGURE C-11. UNBURNED EXHAUST HYDROCARBONS AS A FUNCTION OF INDUCTION AIR TEMPERATURE (T_i) FOR SEVERAL TAKEOFF CONSTANT FUEL FLOW SCHEDULES--TCM TSIO-360-C ENGINE

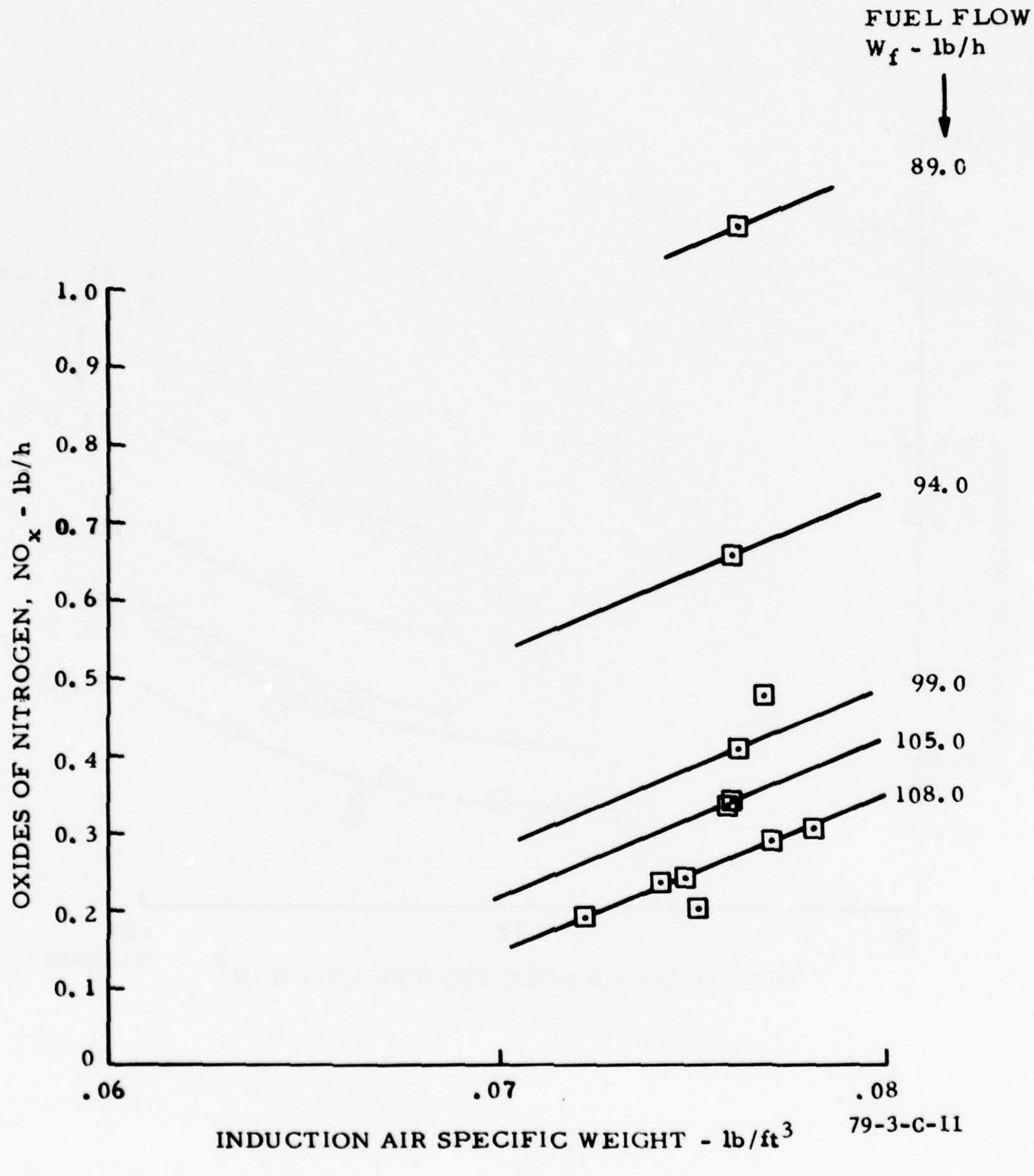


FIGURE C-12. OXIDES OF NITROGEN (NO_x) AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL CLIMB MODE CONSTANT FUEL FLOW SCHEDULES--TCM TSIO-360-C ENGINE

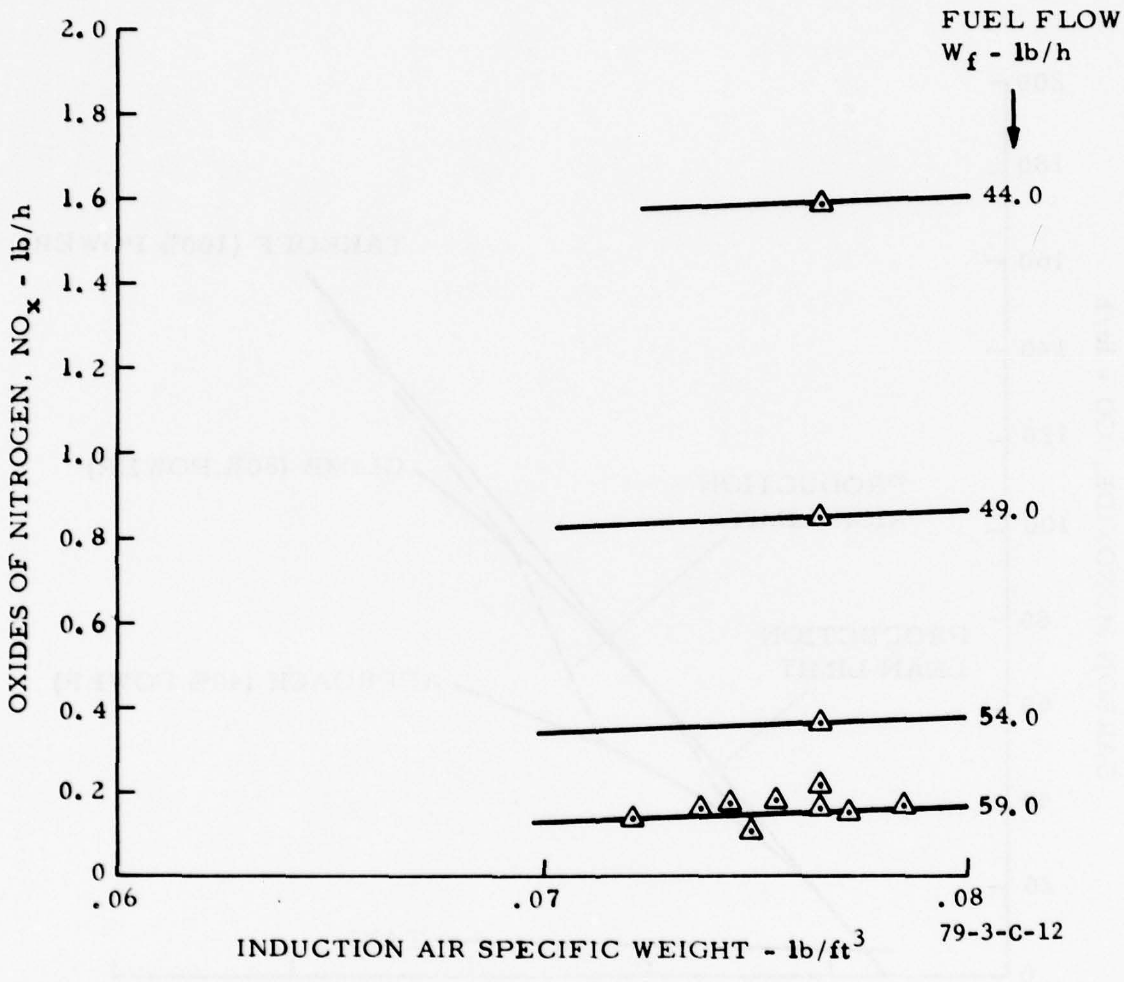


FIGURE C-13. OXIDES OF NITROGEN (NO_x) AS A FUNCTION OF INDUCTION AIR SPECIFIC WEIGHT FOR SEVERAL APPROACH MODE CONSTANT FUEL FLOW SCHEDULES--TCM TSIO-360-C ENGINE

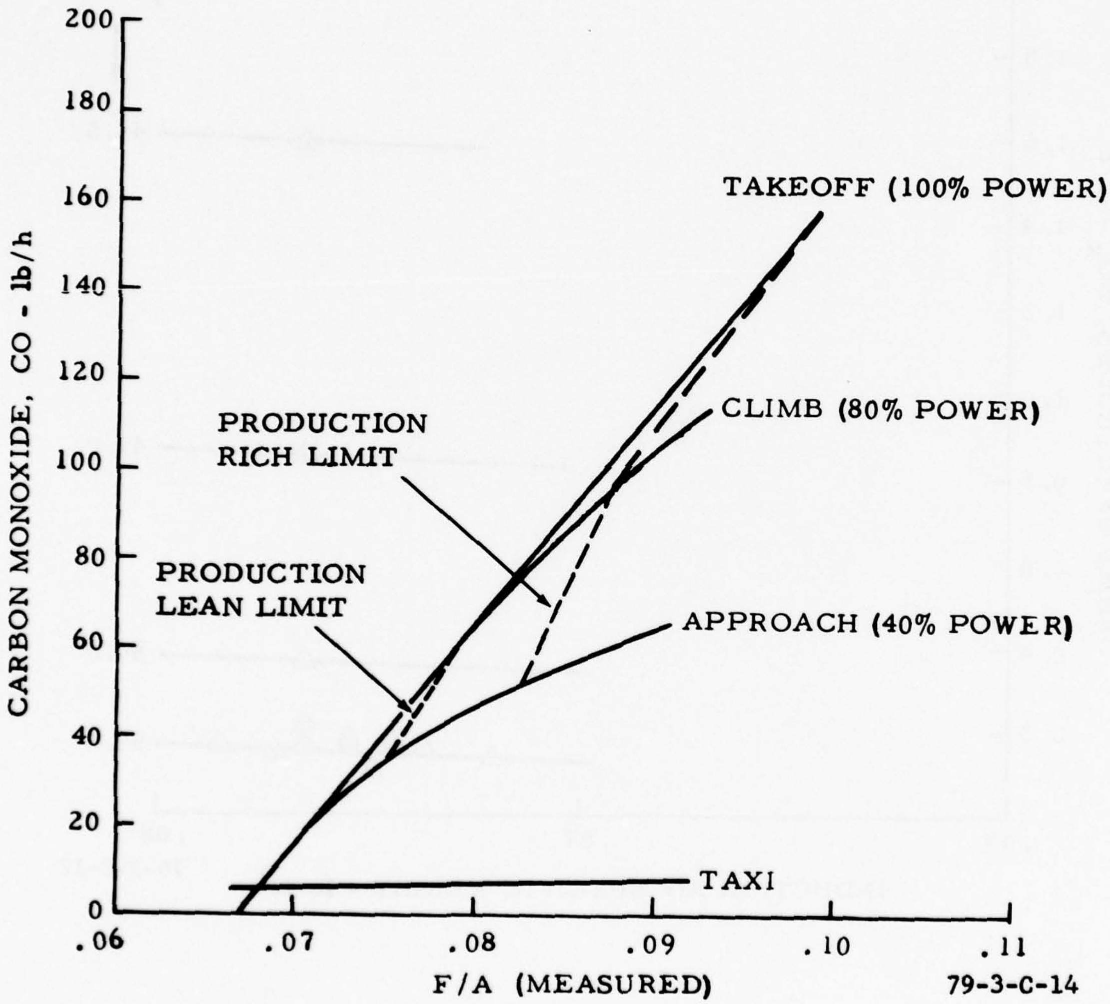


FIGURE C-14. SEA LEVEL STANDARD DAY EMISSION CHARACTERISTICS FOR A TCM TSIO-360-C ENGINE--CARBON MONOXIDE

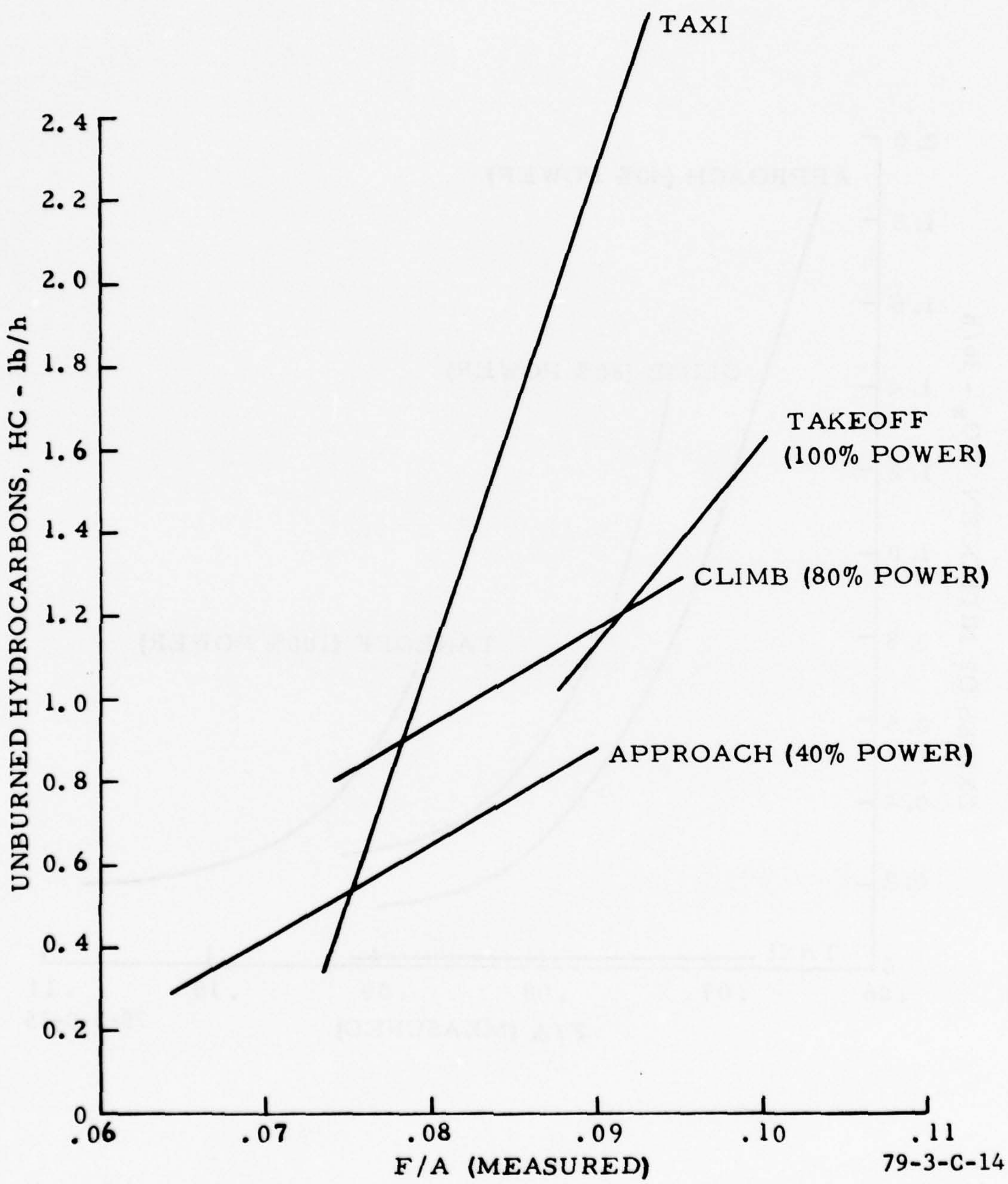


FIGURE C-15. SEA LEVEL STANDARD DAY EMISSIONS CHARACTERISTICS FOR A TCM TSIO-360-C ENGINE--UNBURNED HYDROCARBONS

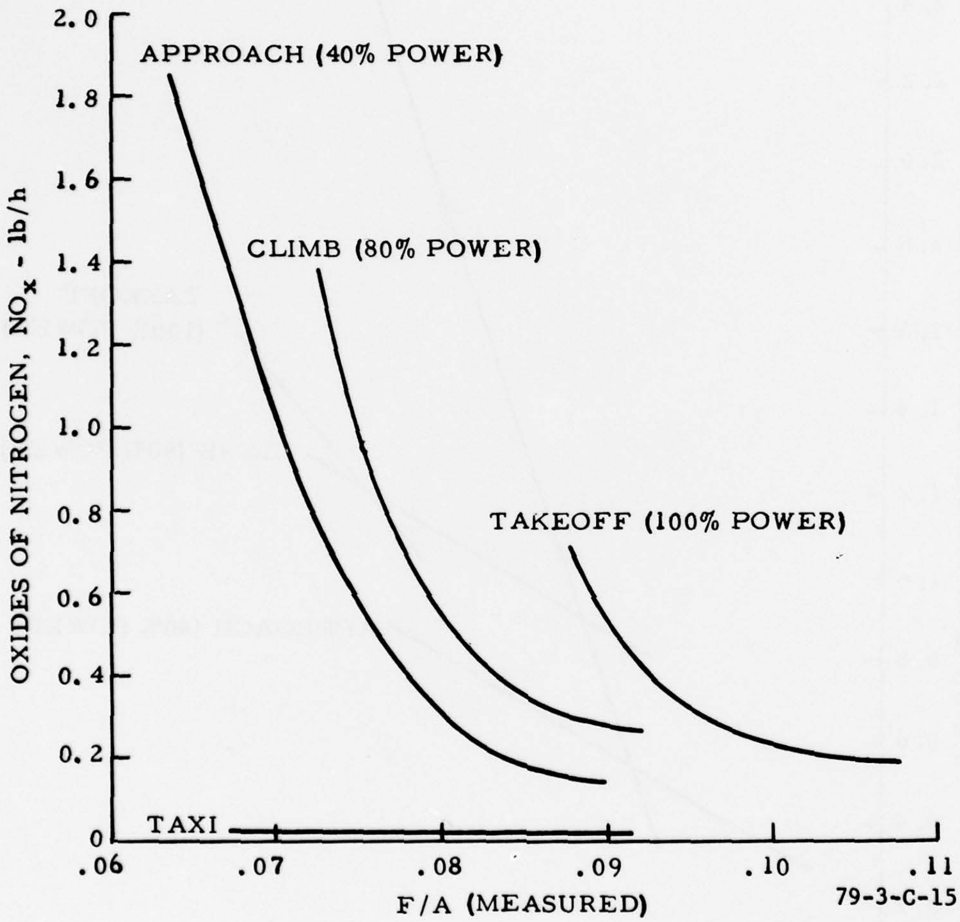


FIGURE C-16. SEA LEVEL STANDARD DAY EMISSIONS CHARACTERISTICS FOR A TCM TSIO-360-C ENGINE--OXIDES OF NITROGEN

TABLE C-1. TCM TSIO-360-C ENGINE NAFEC TEST DATA--BASELINE 1
RUN NUMBERS 2-6

	Run No.	2	3	4	5	6
Parameter	**Mode**	**Taxi Out**	**Takeoff**	**Climb**	**Approach**	**Taxi In**
1. Act. Baro. - inHgA		30.14	30.14	30.14	30.14	30.14
2. Spec. Hum. - lb/lb		0.0055	0.0055	0.0055	0.0055	0.0055
3. Induct. Air Temp.-°F		56	53	53	53	53
4. Cooling Air Temp.-°F		55	54	54	54	52
5. Induct. Air Press.-inHgA		30.29	30.08	30.24	30.38	30.29
6. Engine Speed - RPM		1200	2800	2520	2436	1200
7. Manifold Air Press.-inHgA		16.1	37.0	33.0	21.5	16.1
8. Induct. Air Density-lb/ft^3		0.0778	0.0777	0.0781	0.0785	0.0783
9. Fuel Flow, W_f-lb/h		12.35	154.0	108.0	62.0	12.95
10. Airflow, W_a-lb/h		142.10	1532.7	1216.7	683.7	159.20
11. F/A (Measured) = (9) / (10)		0.0869	0.1004	0.0888	0.0907	0.0813
12. Max. Cht - °F		360	448	410	335	374
13. Avg. Cht - °F		321	413	398	325	334
14. Min. Cht - °F		255	399	387	314	269
15. EGT - °F		950	1438	1419	1267	921
16. Torque, lb-ft		37	412	368	198	34
17. Obs. Bhp		8.5	219.6	176.6	91.8	7.8
18. % CO_2 (Dry)		10.78	7.90	8.93	8.98	10.47
19. % CO (Dry)		5.32	10.43	8.66	8.61	5.19
20. % O_2 (Dry)		0.60	0.19	0.28	0.21	1.23
21. HC-ppm (Wet)		10,912	1617	1573	1871	16,965
22. NO_x-ppm (Wet)		80	116	208	198	86
23. CO_2-lb/h		22.54	189.0	165.5	93.4	24.57
24. CO-lb/h		7.08	158.8	102.1	57.0	7.75
25. O_2-lb/h		0.91	3.30	3.77	1.59	2.10
26. HC-lb/h		1.00	1.67	1.24	0.834	1.71
27. NO_x-lb/h		0.014	0.224	0.306	0.165	0.016
28. CO-lb/Mode		1.4157	0.7940	8.5107	5.7009	0.5167
29. HC-lb/Mode		0.1994	0.0084	0.1032	0.0834	0.1142
30. NO_x-lb/Mode		0.0028	0.0011	0.0255	0.0165	0.0011

TABLE C-2. TCM TSIO-360-C ENGINE NAFEC TEST DATA--BASELINE 2—
RUN NOS. 30 THROUGH 34

Parameter	Mode	Taxi Out	Takeoff	Climb	Approach	Taxi In
	Run No.	30	31	32	33	34
1. Act. Baro. - inHgA		29.91	29.91	29.91	29.91	29.91
2. Spec. Hum. - lb/lb		0.0030	0.0030	0.0030	0.0030	0.0030
3. Induct. Air Temp.-°F		59	57	57	57	58
4. Cooling Air Temp.-°F		56	56	56	56	55
5. Induct. Air Press.-inHgA		30.09	29.84	30.02	30.13	30.09
6. Engine Speed - RPM		1200	2800	2520	2436	1200
7. Manifold Air Press.-inHgA		16.2	36.9	33.0	21.5	16.0
8. Induct. Air Density-lb/ft^3		0.0768	0.0765	0.0770	0.0772	0.0770
9. Fuel Flow, W_f-lb/h		13.80	145.0	105.0	62 0	13.95
10. Airflow, W_a-lb/h		157.90	1554.5	1195.8	726.3	153.00
11. F/A (Measured) = (9) / (10)		0.0874	0.0933	0.0878	0.0854	0.0912
12. Max. Cht - °F		394	439	411	343	380
13. Avg. Cht - °F		352	421	402	332	347
14. Min. Cht - °F		267	408	391	322	301
15. EGT - °F		879	1462	1424	1263	898
16. Torque, lb-ft		34	403	359	196	35
17. Obs. Bhp		7.8	214.9	172.3	90.9	8.0
18. % CO_2 (Dry)		9.44	7.74	8.50	8.29	9.72
19. % CO (Dry)		4.98	9.91	8.54	8.93	5.59
20. % O_2 (Dry)		2.24	0.17	0.21	0.16	1.05
21. HC-ppm (Wet)		17060	1473	1483	1774	16570
22. NO_x-ppm (Wet)		149	131	202	176	65
23. CO_2-lb/h		21.93	185.6	153.9	91.5	21.81
24. CO-lb/h		7.36	151.2	98.4	62.8	7.98
25. O_2-lb/h		3.78	2.96	2.76	1.28	1.71
26. HC-lb/h		1.74	1.51	1.14	0.824	1.66
27. NO_x-lb/h		0.0282	0.251	0.291	0.153	0.0120
28. CO-lb/Mode		1.4725	0.7562	8.1993	6.2752	0.5323
29. HC-lb/Mode		0.3470	0.00753	0.0953	0.0824	0.1104
30. NO_x-lb/Mode		0.00564	0.00125	0.0243	0.0153	0.00080

TABLE C-3. TCM TSIO-360-C ENGINE NAFEC TEST DATA—BASELINE 3—
RUN NUMBERS 64-68 S.L. HOT AIR

	Run No.	64	65	66	67	68
Parameter	Mode	Taxi Out	Takeoff	Climb	Approach	Taxi In
1. Act. Baro. - inHgA		30.08	30.08	30.08	30.08	30.08
2. Spec. Hum. - lb/lb		0.0115	0.0115	0.0115	0.0115	0.0115
3. Induct. Air Temp.-°F		79	103	97	93	89
4. Cooling Air Temp.-°F		87	105	97	91	84
5. Induct. Air Press.-inHgA		29.99	30.08	30.33	30.08	29.99
6. Engine Speed - RPM		1200	2800	2520	2436	1200
7. Manifold Air Press.-inHgA		16.5	36.9	33.0	21.5	15.8
8. Induct. Air Density-lb/ft^3		0.0737	0.0708	0.0722	0.0721	0.0724
9. Fuel Flow, W_f-lb/h		11.80	160.0	108.0	59.0	11.45
10. Airflow, W_a-lb/h		128.10	1598.4	1180.4	666 2	127.00
11. F/A (Measured) = (9) / (10)		0.0921	0.1001	0.0915	0.0886	0.0902
12. Max. Cht - °F		419	430	409	354	414
13. Avg. Cht - °F		371	414	400	342	382
14. Min. Cht - °F		293	406	389	330	330
15. EGT - °F		894	1378	1370	1250	905
16. Torque, lb-ft		35	376	332	180	34
17. Obs. Bhp		8.0	200.5	159.3	83.5	7.8
18. % CO_2 (Dry)		9.16	6.68	7.96	8.49	9.60
19. % CO (Dry)		5.03	12.42	10.28	9.38	5.83
20. % O_2 (Dry)		4.31	0.48	0.45	0.47	2.72
21. HC-ppm (Wet)		21,025	1934	1620	1870	18,545
22. NO_x-ppm (Wet)		123	68	133	172	76
23. CO_2-lb/h		17.52	174.0	147.3	87.8	18.34
24. CO-lb/h		6.12	205 9	121.0	61.7	7.09
25. O_2-lb/h		5.99	9.09	6.05	3.53	3.78
26. HC-lb/h		1.76	2.08	1.25	0.809	1.53
27. NO_x-lb/h		0.0192	0.137	0.192	0.139	0.0117
28. CO-lb/Mode		1.2244	1.0295	10.0875	6.1721	0.4725
29. HC-lb/Mode		0.3528	0.01041	0.1041	0.0809	0.1022
30. NO_x-lb/Mode		0.00384	0.00069	0.0160	0.0139	0.000780

TABLE C-4. TCM TSIO-360-C ENGINE NAFEC TEST DATA—BASELINE 4—
RUN NOS. 77 THROUGH 81

	Run No.	77	78	79	80	81
Parameter	**Mode**	**Taxi Out**	**Takeoff**	**Climb**	**Approach**	**Taxi In**
1. Act. Baro. - inHgA		29.99	29.99	29.99	29.99	29.99
2. Spec. Hum. - lb/lb		0.0110	0.0110	0.0110	0.0110	0.0110
3. Induct. Air Temp.-°F		78	79	78	79	79
4. Cooling Air Temp.-°F		78	80	79	81	79
5. Induct. Air Press.-inHgA		30.15	29.91	30.09	29.99	30 16
6. Engine Speed - RPM		1200	2800	2520	2436	1200
7. Manifold Air Press.-inHgA		16.5	36.9	33.0	21.5	15.8
8. Induct. Air Density-lb/ft^3		0.0743	0.07355	0.0741	0.0737	0.0742
9. Fuel Flow, W_f-lb/h		10.60	155.0	105.0	58.5	10.95
10. Airflow, W_a-lb/h		159.00	1507.4	1173.6	665.2	153.20
11. F/A (Measured) = (9) / (10)		0.0667	0.1028	0.0895	0.0879	0.0715
12. Max. Cht - °F		399	434	414	350	428
13. Avg. Cht - °F		367	418	404	338	389
14. Min. Cht - °F		321	407	394	324	320
15. EGT - °F		1020	1420	1394	1267	960
16. Torque, lb-ft		32	388	339	185	35
17. Obs. Bhp		7.3	206.9	162.7	85.8	8.0
18. % CO_2 (Dry)		11.38	7.16	8.32	8.66	10.71
19. % CO (Dry)		3.67	11.57	9.63	9.01	5.04
20. % O_2 (Dry)		1.67	0.42	0.45	0.46	1.37
21. HC-ppm (Wet)		9925	1688	1523	1783	12,470
22. NO_x-ppm (Wet)		103	88	166	198	96
23. CO_2-lb/h		26.22	172.9	151 3	88.9	24.09
24. CO-lb/h		5.38	177.9	111.5	58.9	7.21
25. O_2-lb/h		2.80	7.38	5.95	3.43	2.24
26. HC-lb/h		0.942	1.73	1.16	0.77	1.16
27. NO_x-lb/h		0.0183	0.169	0.236	0.16	0.0168
28. CO-lb/Mode		1.0763	0.8893	9.2905	5.8852	0.4809
29. HC-lb/Mode		0.1884	0.00866	0.0967	0.0768	0.0774
30. NO_x-lb/Mode		0.00366	0.000845	0.0197	0.0159	0.0011

TABLE C-5. TCM TSIO-360-C ENGINE NAFEC TEST DATA—BASELINE 5--
RUN NOS. 949-953

	Parameter	Run No. / Mode	949 Taxi Out	950 Takeoff	951 Climb	952 Approach	953 Taxi In
1.	Act. Baro. - inHgA		30.14	30.14	30.14	30.14	30.14
2.	Spec. Hum. - lb/lb		0.0075	0.0075	0.0075	0.0075	0.0075
3.	Induct. Air Temp.-°F		76	76	76	77	78
4.	Cooling Air Temp.-°F		76	78	78	79	78
5.	Induct. Air Press.-inHgA		30.29	30.07	30.24	30.14	30.31
6.	Engine Speed - RPM		1200	2800	2520	2436	1200
7.	Manifold Air Press.-inHgA		17.6	36 9	33.0	21.5	15.9
8.	Induct. Air Density-lb/ft^3		0.0749	0.0743	0.0748	0.0744	0.0747
9.	Fuel Flow, W_f-lb/h		12.30	160.0	107.0	60.0	11.10
10.	Airflow, W_a-lb/h		171.60	1508.4	1184.9	675.5	154.50
11.	F/A (Measured) = (9) / (10)		0.0717	0.1061	0.0903	0.0888	0.0718
12.	Max. Cht - °F		449	422	409	350	429
13.	Avg. Cht - °F		398	407	399	341	389
14.	Min. Cht - °F		324	395	388	331	317
15.	EGT - °F		928	1400	1393	1278	960
16.	Torque, lb-ft		35	390	345	194	36
17.	Obs. Bhp		8.0	207.9	165.5	90.0	8.2
18.	% CO_2 (Dry)		7.58	6.77	8.25	8.69	10.83
19.	% CO (Dry)		4.30	12.26	9.72	9.00	5.15
20.	% O_2 (Dry)		4.00	0.55	0.47	0.44	1.20
21.	HC-ppm (Wet)		29,898	1827	1540	1946	9308
22.	NO_x-ppm (Wet)		169	75	169	212	105
23.	CO_2-lb/h		19.26	165.8	151.7	90.4	24.69
24.	CO-lb/h		6.95	191.1	113.8	59.6	7.47
25.	O_2-lb/h		11.08	9.79	6.28	3.33	1.99
26.	HC-lb/h		3.12	1.89	1.18	0.851	0.875
27.	NO_x-lb/h		0.0330	0.145	0.243	0.173	0.0186
28.	CO-lb/Mode		1.3905	0.9553	9.4792	5.9616	0.4983
29.	HC-lb/Mode		0.6234	0.00945	0.0987	0.0851	0.0583
30.	NO_x-lb/Mode		0.00660	0.00072	0.0203	0.0173	0.00124

TABLE C-6. TCM TSIO-360-C ENGINE NAFEC TEST DATA--BASELINE 6--
RUN NOS. 71-75

	Run No.	71	72	73	74	75
	Parameter / **Mode**	**Taxi Out**	**Takeoff**	**Climb**	**Approach**	**Taxi In**
1.	Act. Baro. - inHgA	30.05	30.05	30.05	30.05	30.05
2.	Spec. Hum. - lb/lb	0.0110	0.0110	0.0110	0.0110	0.0110
3.	Induct. Air Temp.-°F	80	73	72	72	73
4.	Cooling Air Temp.-°F	77	78	77	78	76
5.	Induct. Air Press.-inHgA	30.20	29.98	30.14	30.05	30.21
6.	Engine Speed - RPM	1200	2800	2520	2436	1200
7.	Manifold Air Press.-inHgA	16.5	36.9	33.0	21.4	15.6
8.	Induct. Air Density-lb/ft^3	0.0741	0.0745	0.0751	0.0749	0.0751
9.	Fuel Flow, W_f-lb/h	12.3	164.0	109.0	59.5	11.45
10.	Airflow, W_a-lb/h	165.5	1503.3	1208.7	676.0	158.9
11.	F/A (Measured) = (9) / (10)	0.0743	0.1091	0.0902	0.0880	0.0721
12.	Max. Cht - °F	419	425	399	340	396
13.	Avg. Cht - °F	382	397	388	329	366
14.	Min. Cht - °F	318	376	374	317	318
15.	EGT - °F	907	1386	1389	1261	980
16.	Torque, lb-ft	33	387	338	187	36
17.	Obs. Bhp	7.5	206.3	162.2	86.7	8.2
18.	% CO_2 (Dry)	9.57	6.55	8.11	8.60	11.23
19.	% CO (Dry)	5.24	12.55	10.00	9.17	4.57
20.	% O_2 (Dry)	3.47	0.41	0.39	0.46	1.07
21.	HC-ppm (Wet)	21,755	2044	1603	1986	8720
22.	NO_x-ppm (Wet)	118	60	137	130	84
23.	CO_2-lb/h	23.63	160.7	152.8	89.6	26.04
24.	CO-lb/h	8.24	196.0	119.9	60.8	6.74
25.	O_2-lb/h	6.23	7.315	5.34	3.48	1.80
26.	HC-lb/h	2.21	2.15	1.26	0.867	0.843
27.	NO_x-lb/h	0.0225	0.118	0.202	0.106	0.0153
28.	CO-lb/Mode	1.6472	0.9800	9.9948	6.0779	0.4496
29.	HC-lb/Mode	0.4421	0.0108	0.1051	0.0867	0.0562
30.	NO_x-lb/Mode	0.0045	0.0006	0.0168	0.0106	0.00102

TABLE C-7. TCM TSIO-360-C ENGINE NAFEC TEST DATA--BASELINE 7--
RUN NOS. 902-906

	Run No.	902	903	904	905	906
Parameter	Mode	Taxi Out	Takeoff	Climb	Approach	Taxi In
1. Act. Baro. - inHgA		29.78	29.78	29.78	29.78	29.78
2. Spec. Hum. - lb/lb		0.0060	0.0060	0.0060	0.0060	0.0060
3. Induct. Air Temp.-°F		66	63	62	63	63
4. Cooling Air Temp.-°F		59	59	60	60	58
5. Induct. Air Press.-inHgA		29.96	29.74	29.88	29.78	29.96
6. Engine Speed - RPM		1200	2800	2520	2436	1200
7. Manifold Air Press.-inHgA		16.4	37.0	33.1	21.5	16.2
8. Induct. Air Density-lb/ft^3		0.0755	0.0754	0.0759	0.0755	0.0759
9. Fuel Flow, W_f-lb/h		12.2	144.0	105.0	59.0	11.95
10. Airflow, W_a-lb/h		156.9	1479.1	1181.7	685.7	152.3
11. F/A (Measured) = (9) / (10)		0.0782	0.0974	0.0889	0.0860	0.0785
12. Max. Cht - °F		419	461	415	334	386
13. Avg. Cht - °F		372	432	405	325	348
14. Min. Cht - °F		301	419	391	315	299
15. EGT - °F		926	1455	1418	1256	897
16. Torque, lb-ft		35	402	354	192	34
17. Obs. Bhp		8	214.3	169.9	89.1	8
18. % CO_2 (Dry)		10.41	8.04	8.94	8.79	10.11
19. % CO (Dry)		5.39	10.04	8.54	8.74	5.18
20. % O_2 (Dry)		1.46	0.47	0.31	0.31	1.89
21. HC-ppm (Wet)		14,198	1591	1474	1915	20,203
22. NO_x-ppm (Wet)		86	147	235	219	79
23. CO_2-lb/h		24.2	186.4	161.6	92.4	22.8
24. CO-lb/h		7.97	148.2	98.2	58.5	7.42
25. O_2-lb/h		2.47	7.92	4.07	2.37	3.09
26. HC-lb/h		1.39	1.57	1.13	0.842	1.92
27. NO_x-lb/h		0.0156	0.272	0.336	0.180	0.0141
28. CO-lb/Mode		1.5949	0.7409	8.1859	5.8487	0.4948
29. HC-lb/Mode		0.2774	0.00786	0.0940	0.0842	0.1279
30. NO_x-lb/Mode		0.00312	0.00136	0.0280	0.0180	0.000940

TABLE C-8. TCM TSIO-360-C ENGINE NAFEC TEST DATA--BASELINE 8--
RUN NOS. 909-913

	Run No.	909	910	911	912	913
Parameter	Mode	Taxi Out	Takeoff	Climb	Approach	Taxi In
1. Act. Baro. - inHgA		29.85	29.85	29.85	29.85	29.85
2. Spec. Hum. - lb/lb		0.0050	0.0050	0.0050	0.0050	0.0050
3. Induct. Air Temp.-°F		63	57.5	57	57	57
4. Cooling Air Temp.-°F		55	53	53	52	52
5. Induct. Air Press.-inHgA		30.03	29.78	29.95	29.85	30.03
6. Engine Speed - RPM		1200	2800	2520	2436	1200
7. Manifold Air Press.-inHgA		16.6	37.0	33.0	21.5	16.1
8. Induct. Air Density-lb/ft^3		0.0761	0.0763	0.0768	0.0765	0.0770
9. Fuel Flow, W_f-lb/h		11.85	142.0	100.0	59.0	12.70
10. Airflow, W_a-lb/h		149.3	1553.9	1219.6	681.8	156.2
11. F/A (Measured) = (9) / (10)		0.0794	0.0914	0.0820	0.0865	0.0813
12. Max. Cht - °F		426	453	408	330	410
13. Avg. Cht - °F		378	436	399	322	364
14. Min. Cht - °F		289	425	386	313	288
15. EGT - °F		909	1487	1437	1268	914
16. Torque, lb-ft		33	408	358	193	36
17. Obs. Bhp		7.5	217.5	172	89.5	8
18. % CO_2 (Dry)		10.10	8.75	9.40	9.07	9.93
19. % CO (Dry)		4.93	8.85	7.56	8.09	5.48
20. % O_2 (Dry)		1.66	0.14	0.15	0.15	1.24
21. HC-ppm (Wet)		19,641	1400	1432	1756	18,691
22. NO_x-ppm (Wet)		94	225	330	266	85
23. CO_2-lb/h		22.1	208.6	172.4	93.7	22.8
24. CO-lb/h		6.88	134.3	88.3	53.2	8.02
25. O_2-lb/h		2.65	2.43	2.00	1.13	2.07
26. HC-lb/h		1.83	1.42	1.10	0.769	1.84
27. NO_x-lb/h		0.0165	0.427	0.476	0.218	0.0156
28. CO-lb/Mode		1.3754	0.6713	7.3558	5.3210	0.5349
29. HC-lb/Mode		0.3669	0.00711	0.0919	0.0769	0.1226
30. NO_x-lb/Mode		0.00330	0.00214	0.0396	0.0218	0.00104
						-2.54

TABLE C-9. TCM TSIO-360-C ENGINE NAFEC TEST DATA--BASELINE 9--
RUN NOS. 97-101

Parameter	Mode / Run No.	Taxi Out 97	Takeoff 98	Climb 99	Approach 100	Taxi In 101
1.	Act. Baro. - inHgA	30.21	30.21	30.21	30.21	30.22
2.	Spec. Hum. - lb/lb	0.0035	0.0035	0.0035	0.0035	0.0035
3.	Induct. Air Temp.-°F	58	57	56	56	56
4.	Cooling Air Temp.-°F	54	54	54	55	54
5.	Induct. Air Press.-inHgA	30.39	30.28	30.31	30.21	30.41
6.	Engine Speed - RPM	1200	2800	2520	2436	1200
7.	Manifold Air Press.-inHgA	15.5	36.8	33.0	21.5	15.6
8.	Induct. Air Density-lb/ft^3	0.0778	0.0776	0.0778	0.0776	0.0781
9.	Fuel Flow, W_f-lb/h	11.50	162.0	112.0	61.0	11.85
10.	Airflow, W_a-lb/h	161.1	1563.0	1270.0	741.0	152.7
11.	F/A (Measured) = (9) / (10)	0.0714	0.1036	0.0882	0.0823	0.0776
12.	Max. Cht - °F	410	437	393	332	386
13.	Avg. Cht - °F	372	404	386	323	360
14.	Min. Cht - °F	306	389	376	312	307
15.	EGT - °F	993	1418	1408	1282	978
16.	Torque, lb-ft	44	370	342	220	47
17.	Obs. Bhp	10	197	164	102	11
18.	% CO2 (Dry)	11.64	7.37	8.68	9.28	12.03
19.	% CO (Dry)	3.87	11.44	9.32	8.44	3.84
20.	% O_2 (Dry)	0.67	0.13	0.18	0.19	1.59
21.	HC-ppm (Wet)	55.72	1704	1535	1837	4470
22.	NO_x-ppm (Wet)	168	78	162	212	106
23.	CO_2-lb/h	27.2	183.0	169.7	104.8	26.7
24.	CO-lb/h	5.8	180.8	116.0	60.7	5.4
25.	O_2-lb/h	1.14	2.35	2.56	1.56	1.0
26.	HC-lb/h	0.55	1.84	1.53	0.86	0.42
27.	NO_x-lb/h	0.031	0.155	0.302	0.186	0.02
28.	CO-lb/Mode	1.151	0.904	9.667	6.070	0.360
29.	HC-lb/Mode	0.110	0.009	0.128	0.086	0.028
30.	NO_x-lb/Mode	0.0061	0.0008	0.0251	0.0186	0.001

TABLE C-10. TCM TSIO-360-C ENGINE NAFEC TEST DATA--BASELINE 10--
RUN NOS. 102-106

Parameter	Run No. / Mode	102 Taxi Out	103 Takeoff	104 Climb	105 Approach	106 Taxi In
1. Act. Baro. - inHgA		30.22	30.22	30.22	30.22	30.23
2. Spec. Hum. - lb/lb		0.0035	0.0035	0.0035	0.0035	0.0035
3. Induct. Air Temp.-°F		57	55	55	55	56
4. Cooling Air Temp.-°F		53	55	55	54	53
5. Induct. Air Press.-inHgA		30.41	30.15	30.37	30.22	30.43
6. Engine Speed - RPM		1200	2800	2520	2436	1200
7. Manifold Air Press.-inHgA		15.6	36.9	33.0	21.5	15.5
8. Induct. Air Density-lb/ft^3		0.0780	0.0776	0.0782	0.0778	0.0782
9. Fuel Flow, W_f-lb/h		12.50	162.0	114.0	62.5	12.20
10. Airflow, W_a-lb/h		152.8	1584.6	1216.9	706.9	148.4
11. F/A (Measured) = (9) / (10)		0.0815	0.1022	0.0937	0.0884	0.0822
12. Max. Cht - °F		419	441	398	329	388
13. Avg. Cht - °F		371	421	389	322	358
14. Min. Cht - °F		307	404	376	309	300
15. EGT - °F		945	1412	1390	1270	935
16. Torque, lb-ft		42	365	353	249	52
17. Obs. Bhp		10	194.6	169.4	115.5	12
18. % CO_2 (Dry)		10.05	7.19	8.18	8.62	10.08
19. % CO (Dry)		4.29	11.45	9.76	8.88	4.15
20. % O_2 (Dry)		2.77	0.32	0.44	0.54	2.82
21. HC-ppm (Wet)		78962	1714	1656	1865	7826
22. NO_x-ppm (Wet)		93	83	132	176	84
23. CO_2-lb/h		21.15	181.0	154.5	93.5	21.94
24. CO-lb/h		5.75	183.5	117.3	61.3	5.75
25. O_2-lb/h		4.24	5.86	6.04	4.26	4.46
26. HC-lb/h		0.76	1.84	1.33	0.85	0.73
27. NO_x-lb/h		0.017	0.167	0.198	0.151	0.015
28. CO-lb/Mode		1.150	0.918	9.775	6.130	0.383
29. HC-lb/Mode		0.152	0.0092	0.111	0.085	0.049
30. NO_x-lb/Mode		0.0034	0.0008	0.0165	0.0151	0.0010

TABLE C-11. TCM TSIO-360-C ENGINE NAFEC TEST DATA--TAKEOFF MODE--RUN NOS. 8-11

	Run No.	8	9	10
Parameter	**Mode**	**Takeoff**	**Takeoff**	**Takeoff**
1. Act. Baro. - inHgA		29.78	29.78	29.78
2. Spec. Hum. - lb/lb		0.0050	0.0050	0.0050
3. Induct. Air Temp.-°F		62	61	61
4. Cooling Air Temp.-°F		60	60	60
5. Induct. Air Press.-inHgA		29.72	29.71	29.72
6. Engine Speed - RPM		2800	2800	2800
7. Manifold Air Press.-inHgA		37.0	37.0	37.0
8. Induct. Air Density-lb/ft^3		0.0755	0.0756	0.0756
9. Fuel Flow, W_f-lb/h		147.0	142.0	137.0
10. Airflow, W_a-lb/h		1496.2	1524.4	1503.4
11. F/A (Measured) = (9) / (10)		0.0982	0.0932	0.0911
12. Max. Cht - °F		455	474	485
13. Avg. Cht - °F		429	450	459
14. Min. Cht - °F		418	440	442
15. EGT - °F		1451	1490	1515
16. Torque, lb-ft		399	397	402
17. Obs. Bhp		212.7	211.7	214.3
18. % CO_2 (Dry)		7.84	8.62	9.19
19. % CO (Dry)		10 26	8.99	8.07
20. % O_2 (Dry)		0.24	0.43	0.32
21. HC-ppm (Wet)		1546	1312	1260
22. NO_x-ppm (Wet)		140	210	286
23. CO_2-lb/h		184.1	202.6	210.1
24. CO-lb/h		153.3	134.5	117.4
25. O_2-lb/h		4.10	7.35	5.32
26. HC-lb/h		1.55	1.32	1.24
27. NO_x-lb/h		0.263	0.392	0.525
28. CO-lb/Mode		0.7666	0.6724	0.5872
29. HC-lb/Mode		0.00775	0.00658	0.00618
30. NO_x-lb/Mode		0.00131	0.00196	0.00262

TABLE C-12. TCM TSIO-360-C ENGINE NAFEC TEST DATA--CLIMB MODE--RUN NOS. 12-15

	Run No.	12	13	14	15
Parameter	**Mode**	**Climb**	**Climb**	**Climb**	**Climb**
1. Act. Baro. - inHgA		29.78	29.78	29.78	29.80
2. Spec. Hum. - lb/lb		0.0050	0.0050	0.0050	0.0050
3. Induct. Air Temp.-°F		61	61	61	61
4. Cooling Air Temp.-°F		60	60	59	60
5. Induct. Air Press.-inHgA		29.87	29.90	29.89	29.90
6. Engine Speed - RPM		2520	2520	2520	2520
7. Manifold Air Press.-inHgA		33.0	32.9	33.0	32.9
8. Induct. Air Density-lb/ft^3		0.0760	0.0761	0.0760	0.0761
9. Fuel Flow, W_f-lb/h		104.0	99.0	94.0	89.0
10. Airflow, W_a-lb/h		1224.9	1160.7	1170.3	1187.9
11. F/A (Measured) = (9) / (10)		0.0849	0.0853	0.0803	0.0749
12. Max. Cht - °F		415	417	425	434
13. Avg. Cht - °F		404	406	413	422
14. Min. Cht - °F		389	392	400	409
15. EGT - °F		1423	1424	1459	1499
16. Torque, lb-ft		355	353	358	356
17. Obs. Bhp		170.3	169.4	171.8	170.8
18. % CO_2 (Dry)		8.85	9.29	10.16	10.72
19. % CO (Dry)		8.59	7.92	6.50	5.03
20. % O_2 (Dry)		0.24	0.26	0.20	0.20
21. HC-ppm (Wet)		1509	1441	1293	1135
22. NO_x-ppm (Wet)		233	294	479	787
23. CO_2-lb/h		165.7	163.5	176.8	185.3
24. CO-lb/h		102.4	88.7	72.0	55.3
25. O_2-lb/h		3.27	3.33	2.53	2.51
26. HC-lb/h		1.18	1.07	0.950	0.830
27. NO_x-lb/h		0.341	0.408	0.658	1.08
28. CO-lb/Mode		8.5314	8.5314	6.0000	4.6109
29. HC-lb/Mode		0.0983	0.0891	0.0792	0.0591
30. NO_x-lb/Mode		0.0284	0.0340	0.0549	0.0897

TABLE C-13. TCM TSIO-360-C ENGINE NAFEC TEST DATA--APPROACH MODE--RUN NOS. 16-19

	Run No.	16	17	18	19
Parameter	**Mode**	**Approach**	**Approach**	**Approach**	**Approach**
1. Act. Baro. - inHgA		29.80	29.80	29.80	29.80
2. Spec. Hum. - lb/lb		0.0050	0.0050	0.0050	0.0050
3. Induct. Air Temp.-°F		61	61	61	61
4. Cooling Air Temp.-°F		59	60	59	59
5. Induct. Air Press.-inHgA		30.08	30.07	30.07	30.08
6. Engine Speed - RPM		2425	2425	2425	2425
7. Manifold Air Press.-inHgA		21.5	21.5	21.5	21.6
8. Induct. Air Density-lb/ft^3		0.0765	0.0765	0.0765	0.0765
9. Fuel Flow, W_f-lb/h		59.0	54.0	49.0	44.0
10. Airflow, W_a-lb/h		680.0	687.3	683.3	674.3
11. F/A (Measured) = (9) / (10)		0.0868	0.0786	0.0717	0.0653
12. Max. Cht - °F		327	338	348	349
13. Avg. Cht - °F		319	330	341	342
14. Min. Cht - °F		309	321	333	334
15. EGT - °F		1252	1304	1362	1414
16. Torque, lb-ft		192	193	194	189
17. Obs. Bhp		88.7	89.1	89.6	87.3
18. % CO_2 (Dry)		8.88	10.03	11.72	13.26
19. % CO (Dry)		8.94	6.58	3.90	1.26
20. % O_2 (Dry)		0.20	0.21	0.24	0.51
21. HC-ppm (Wet)		1979	1468	1163	753
22. NO_x-ppm (Wet)		199	453	1094	2117
23. CO_2-lb/h		92.7	101.9	115.2	125.0
24. CO-lb/h		59.4	42.5	24.4	7.62
25. O_2-lb/h		1.52	1.55	1.72	3.52
26. HC-lb/h		0.866	0.629	0.482	0.302
27. NO_x-lb/h		0.163	0.363	0.849	1.589
28. CO-lb/Mode		5.9377	4.2539	2.4402	0.7621
29. HC-lb/Mode		0.0866	0.0629	0.0482	0.0302
30. NO_x-lb/Mode		0.0163	0.0363	0.0849	0.1589

TABLE C-14. SUMMARY CHART-CYLINDER HEAD COOLING TESTS FOR DIFFERENT COOLING AIR FLOW CONDITIONS (VARYING COOLING AIR ΔP FLOWING CONDITIONS)

	Run No.	155	156	157	158	159	160	161
Parameter	Mode	Takeoff	Takeoff	Takeoff	Takeoff	Takeoff	Takeoff	Takeoff
1. Act. Baro. - inHgA		30.20	30.20	30.20	30.20	30.20	30.20	30.20
2. Spec. Hum. - lb/lb		0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035
3. Induct. Air Temp.-°F		59	59	58	58	58	58	58
4. Cooling Air Temp.-°F		59	58	59	59	59	59	58
5. Induct. Air Press.-inHgA		30.11	30.13	30.12	30.14	30.12	30.12	30.13
6. Engine Speed - RPM		2800	2800	2800	2800	2800	2800	2800
7. Manifold Air Press.-inHgA		37.0	36.9	36.9	36.9	37.0	37.0	37.0
8. Induct. Air Density-lb/ft^3		0.0769	0.0769	0.0771	0.0771	0.0771	0.0771	0.0771
9. Fuel Flow, W_f-lb/h		162.0	162.5	163.0	163.0	155.0	154.0	152.0
10. Airflow, W_a-lb/h		1590.5	1558.8	1573.1	1529.4	1577.4	1580.8	1538.6
11. F/A (Measured) = (9) / (10)		0.1019	0.1042	0.1036	0.1066	0.0983	0.0974	0.0988
12. Max. Cht - °F		391	395	426	466	396	406	436
13. Avg. Cht - °F		—	—	—	—	—	—	—
14. Min. Cht - °F		342	358	390	424	360	373	406
15. EGT - °F		1434	1414	1420	1438	1451	1452	1460
16. Torque, lb-ft		405	407	410	403	426	424	426
17. Obs. Bhp		215.9	217.0	218.6	214.9	227.1	226.0	227.1
18. Cooling Air ΔP=inH_2O		7.0	5.5	3.5	1.5	7.0	5.5	3.5