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16. Abstract

A comprehensive mathematical analysis for evaluating the measured emissions from piston type general aviation aircraft engines is presented and discussed. The analysis is used to calculate the fuel-air ratio, molecular weight of the exhaust products, and water correction factor. Further, a sensitivity analysis is presented which shows the effects of emission measurement errors on calculated fuel-air ratio.

The University's test facility is briefly described and the associated emissions instrumentation is discussed in detail. The experimental results obtained in this facility on the AVCO-Lycoming LIO-320 engine are presented. This includes baseline and lean-out emissions data and the influence of sampling probe location in the exhaust pipe. The influence of leaks in the exhaust system or emissions console are investigated and evaluated in terms of the mathematical model.

Experimental data obtained from various facilities are compared and evaluated.

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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

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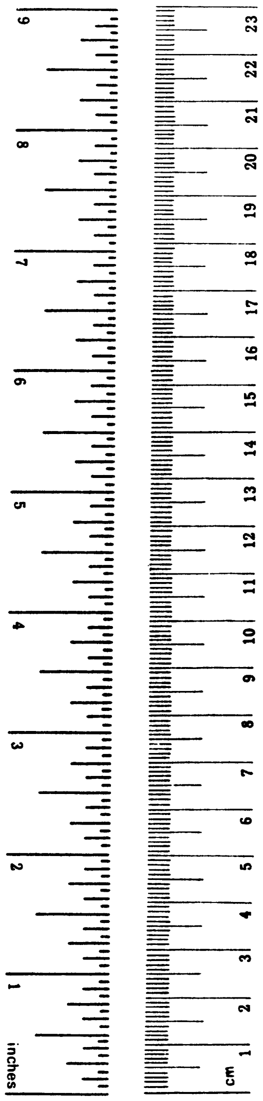
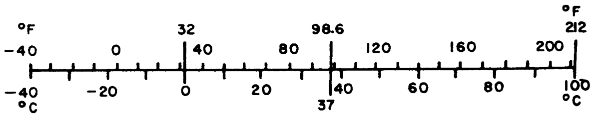
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



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

This investigation was conducted by personnel of the Aerospace Engineering and Mechanical Engineering Departments of The University of Michigan, Ann Arbor, Michigan under contract No. DOTFA74NA-1102. Professor J.A. Nicholls served as Project Director with Professor W. Mirsky as the Principal Investigator. The contract was administered by the National Aviation Facilities Experimental Center, Atlantic City, New Jersey.

ABSTRACT

comprehensive mathematical analysis for evaluating the measured emissions from piston type general aviation aircraft engines is presented and discussed. The analysis is used to calculate the fuel-air ratio, molecular weight of the exhaust products, and water correction factor. Further, a sensitivity analysis is presented which shows the effects of emission measurement errors on calculated fuel-air ratio.

The University's test facility is briefly described and the associated emissions instrumentation is discussed in detail. The experimental results obtained in this facility on the AVCO-Lycoming LIO-320 engine are presented. This includes baseline and lean-out emissions data and the influence of sampling probe location in the exhaust pipe. The influence of leaks in the exhaust system or emissions console are investigated and evaluated in terms of the mathematical model.

Experimental data obtained from various facilities are compared and evaluated.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Page

LIST OF TABLES

Table　　Page

LIST OF ABBREVIATIONS AND SYMBOLS

AA	Quantity of air in the combustion equation. Defined by Equation (2.4).
AIRO2	Moles dry air per mole oxygen in the dry combustion air.
ARA	Mole-percent argon in the dry combustion air.
ARAS	Standard value for mole-percent argon in the dry combustion air.
ARO2	Moles argon per mole oxygen in the combustion air.
C1	- (2 + 2 * CO2O2 + H2OO2)
C2	- CO2O2
C3	EHCC
C4	- 2 * H2OO2
C5	- HTCR
C6	EHCC * EHCR
C7	- PSAT/PTRP
C8	- 2 * N2O2
C9	- ARO2
C10	K(CO2W + CO2D + CO2DD)/(COW + COD + CODD)
C11	1 + CO2O2 + (H2OO2/2) + N2O2
COW,COD,CODD	Measured values of exhaust carbon monoxide concentration (wet, dry and dried).
CO2A	Mole-percent carbon dioxide in the dry combustion air.
CO2O2	Moles carbon dioxide per mole oxygen in the combustion air.
CO2W,CO2D, CO2DD	Measured values of exhaust carbon dioxide concentrations (wet, dry and dried).
dAO2	Moles dilution air per mole oxygen in the combustion air.

E(1.2),E(3.1)	Fuel-air ratio errors when using Methods 1.2, 3.1.
EHCC	Moles carbon per mole exhaust hydrocarbon.
EHCR	Exhaust hydrocarbon hydrogen-carbon ratio, mole basis.
EIE	Eltinge instrument error. See Section 2.3.1.
FACAL	Calculated fuel-air ratio, mass basis.
FAM	Measured fuel-air ratio, mass basis.
F/A	Fuel-air ratio.
FCHC	Fraction condensed, exhaust hydrocarbons, in the water trap.
FdA	Fraction dilution air, mixed with cold non-reacting exhaust sample
FF	Quantity of fuel in the combustion equation. Defined by equation (2.3).
H2OO2	Moles water vapor per mole oxygen in the combustion air.
HC	Hydrocarbon
HCCW, HCCD, HCCDD	Measured values of exhaust hydrocarbon concentration, carbon base (wet, dry or dried).
HTCR	Moles hydrogen per mole carbon in the fuel. Same as Z.
K	Water-gas reaction equilibrium constant.
KWD	Water correction factor for dry-to-wet measurements.
KWDD	Water correction factor for dried-to-wet measurements.
(M)	Used in describing a concentration. M = W when wet; M = D when dry; M = DD when dried.
m	Moles hydrogen per mole fuel.
MWAIR	Molecular weight of dry combustion air.
MWEXH	Molecular weight of the exhaust.
MWH2O	Molecular weight of water.

N	Used as a prefix to indicate number of moles of a substance (e.g. NCO2).
n	Moles carbon per mole fuel.
N2A	Mole-percent nitrogen in the dry combustion air.
N2AS	Standard value for mole-percent nitrogen in the dry combustion air.
N2O2	Moles nitrogen per mole oxygen in the combustion air.
NdAM	Moles dilution air in the measured sample.
NGD	Moles of gaseous dry products.
NGDD	Moles of gaseous dried products.
NGM	Moles of gaseous products in the measured sample.
NGT	Moles of gaseous wet products (total).
NOW,NOD, NODD	Measured values of exhaust nitrogen oxide concentrations (wet, dry and dried).
NOXW,NOXD, NOXDD	Measured values of NOX concentrations (wet, dry and dried).
NT	Total moles of products.
NY	Moles of any specie Y.
O2A	Mole-percent oxygen in the dry combustion air.
O2AS	Standard value for mole-percent oxygen in the dry combustion air.
O2W,O2D,O2DD	Measured values of exhaust oxygen concentrations (wet, dry and dried).
PHICAL	Calculated equivalence ratio.
PHIM	Measured equivalence ratio.
PSAT	Saturation pressure of water at the water trap temperature.
PTRP	Measured water trap pressure.
S_x	Eltinge mixture-distribution parameter.
SS	Specific sensitivity. Defined by equation 2.63.
W	Specific humidity of the combustion air.

X	Mole-fraction.
XD	Total mole fraction of dry products (wet basis). Also XD(W).
XDD	Total mole fraction of dried products (wet basis). Also XDD(W).
XGD	Total mole-fraction of dry gaseous products (wet basis). Also XGD(W). In the analyzer.
XGDD	Total mole-fraction of dried gaseous products (wet basis). Also XGDD(W). In the analyzer.
XGW	Total mole-fraction of wet gaseous products (wet basis). Also XGW(W). By definition XGW(W) = 1. In the analyzer.
XT	Total mole-fraction of products (wet basis). Also XT(W).
XY(D)	Mole-fraction of specie Y on a dry gaseous basis.
XY(DD)	Mole-fraction of specie Y on a dried gaseous basis.
XY(W)	Mole-fraction of specie Y on a wet gaseous basis.
XY(T)	Mole-fraction of specie Y on a total mole basis.
XYd(M)	Mole-fraction of specie Y in the air-diluted sample. (M) indicates wet, dry or dried measurement.
YO2	Moles specie Y per mole oxygen.
Z	Moles hydrogen per mole carbon in the fuel. Same as HTCR.
ΔE	Fuel-air ratio error difference. $\Delta E = E(3.1) - E(1.2)$.
Σ	Summation.
ϕ	Equivalence ratio. $\phi = (F/A)/(F/A)_{stoich}$
*	Multiplication sign.

1. INTRODUCTION

The Environmental Protection Agency (EPA) promulgated aircraft exhaust emission standards for piston engines in the Federal Register of July 17, 1973, Volume 38, Number 136, Part II (the EPA Standards). The Federal Aviation Administration (FAA), in assuming its role assigned by Public Law in implementing and enforcing the EPA standards, had to insure that any attempts to reduce the exhaust emissions from light aircraft piston engines did not result in lowered safety of operation.

In accordance with the above FAA contracted with two engine manufacturers, AVCO-Lycoming and Teledyne-Continental, to ascertain the baseline emissions levels actually being produced by a number of their engines. In addition lean-out emissions levels were to be determined. National Aviation Facilities Experimental Center (NAFEC), the experimental arm of FAA,was also to measure the emissions levels from the same engines as tested by the companies.

In addition to the above, FAA contracted with The University of Michigan to establish correct emission measurement techniques, to establish correct procedures for analyzing the measured emissions data, and to verify the type of instrumentation that would insure compliance with the EPA regulations. The University was also directed to establish baseline and lean-out data for the AVCO-Lycoming LIO-320 engine. This program went into effect on June 1, 1974. This report represents the final formal report on the project.

The major thrust of this report, then, is the comprehensive treatment given to the analysis of the measured emissions data. In this way conclusions can then be drawn with confidence as to the sensitivity of the predictions to simplifying assumptions, instrument errors, and measurement errors. Measurements made in the University facility are examined in this light.

2. DATA ANALYSIS AND EVALUATION

An expression for combustion air, which takes into account the variable composition due to ambient carbon dioxide and water vapor, is developed. This is followed by the development of five methods for calculating fuel-air ratio from measured exhaust gas constituents. The sensitivity of these methods to variations of input quantities is then examined and the methods are next applied to a representative sample of data from various sources to illustrate the applicability of these methods in determining data reliability. The calculations of exhaust molecular weights and water correction factors for exhaust measurements are also discussed.

2.1 DEVELOPMENT OF COMBUSTION EQUATION MODELS

2.1.1 The Simple Combustion Reaction Equation

The complete combustion of a hydrocarbon fuel C_nH_m with air in a stoichiometric mixture is represented by the combustion equation,

$$C_nH_m + \left(\frac{m}{4} + n\right) [O2 + 3.764\ N2] \rightarrow n\ CO2 + \frac{m}{2}\ H2O + 3.764 \left(\frac{m}{4} + n\right) N2$$

In a non-stoichiometric mixture, leading to incomplete combustion, we have,

$$\phi\ C_nH_m + \left(\frac{m}{4} + n\right) [O2 + 3.764\ N2] \rightarrow NCO2 + NCO + NCXHY + NO2 + NH2O + NH2 + NN2 + NNO + NNO2 \qquad (2.1)$$

where the prefix N before each exhaust product is used to indicate moles of each product. The products NO and NO2 are included because of their importance in air pollution.

It is desirable to convert the above expression from a mole basis to a mole-fraction basis by dividing through by some specified total number of moles, which could be any of the following quantities:

1.	NT	Total number of moles of exhaust products in the instrument analyzers, including both gaseous and solid products. The mole fraction would be on a total-mole basis and would be indicated by symbols such as XCO2(T).
2.	NGW	Total number of moles of wet gaseous exhaust products in the instrument analyzers. The mole fraction would be on a wet basis and would be indicated by XCO2(W). Since most of the development in this report will be on a wet basis, we shall drop the (W) for convenience and simply use XCO2. Mole fractions on any other basis shall be properly identified.
3.	NGDD	Total number of moles of dried gaseous exhaust products in the instrument analyzers, containing saturated water at the water trap temperature. Indicated by XCO2(DD).
4.	NGD	Total number of moles of dry gaseous exhaust products in the analyzers (all water removed). Indicated by XCO2(D).

The need for these distinctions arises because different instruments make measurements on different bases. For example, the instrument cart at The University of Michigan makes the following measurements:

CO2, O2	dried basis
CO	dry basis
HCC,NO,NOX	wet basis

Converting equation 2.1 to mole-fractions based on wet gaseous products, we have

$$\frac{\phi}{NGW} C_nH_m + \frac{1}{NGW}\left(\frac{m}{4} + n\right) [O2 + 3.764\ N2] \rightarrow XCO2 + XCO$$
$$+ XCXHY + XO2 + XH2O + XH2 + XN2 + XNO + XNO2 \qquad (2.2)$$

where the prefix X is used to indicate mole-fractions. Next let

$$\frac{\phi}{NGW} C_nH_m = \frac{\phi * n}{NGW} CH_{m/n} = FF * CHZ \qquad (2.3)$$

where the symbol * is used as the multiplication sign, Z is the molar hydrogen-to-carbon ratio (m/n) of the fuel, and

$$\frac{1}{NGW}\left(\frac{m}{4} + n\right) = AA \qquad (2.4)$$

Note that both AA and FF are defined on a wet gaseous basis. The simple form of the combustion reaction then becomes,

$$FF * CHZ + AA\ [O2 + 3.764\ N2] \rightarrow XCO2 + XCO + XCXHY + XO2 + XH2O + XH2 + XN2 + XNO + XNO2 \qquad (2.5)$$

HTCR shall also be used for the molar hydrogen-to-carbon ratio of the fuel.

2.1.2 Combustion Air

The treatment of combustion air as consisting of 3.764 moles of N2 per mole of O2 lumps all of the inert gases with the nitrogen. In this report nitrogen shall be treated as a pure gas and the only inert gases to be considered will be argon and carbon dioxide. Other inerts in atmospheric air such as neon and helium will be neglected because of their very low concentrations.

A search of the literature shows lack of agreement on the exact composition of air, two examples being given in table 2.1. These differences are negligibly small for our purposes, and the values from reference 1 shall be used. The suffix AS in the symbols in table 2.1 is used to indicate the <u>s</u>tandard value for <u>a</u>tmospheric air.

TABLE 2.1. COMPOSITION OF DRY AIR
MAJOR CONSTITUENTS: MOLE PERCENT

Constituent	Symbol	Ref. 1	Ref. 2
N2	N2AS	78.09	78.084
O2	O2AS	20.95	20.946
AR	ARAS	0.93	0.934
CO2	CO2A	0.03	0.033

The amount of CO2 in the atmosphere will vary from location-to-location, being somewhat higher in urban areas (reference 3). At locations where engines are being tested, the CO2 levels may be even higher. However, since calculated fuel-air ratios are insensitive to ambient CO2 (see table 2.3 for CO2A specific sensitivity values), a background value in the range 0.03 to 0.05 mole percent can be used when ambient measurements are not made.

The treatment of air involving the more accurate composition and possible variation in CO2 levels will lead to more accurate atom-balances when calculating fuel-air ratios and a better value for the calculated molecular weight of air.

2.1.3 Computational Procedure for Ambient Air

2.1.3.1 Air Molecular Weight

Let

N2AS = percent N2 in the standard dry intake air
O2AS = percent O2 in the standard dry intake air
ARAS = percent AR in the standard dry intake air
CO2A = percent CO2 in the existing dry intake air

Then define,

$$\text{N2O2} = \frac{\text{moles N2}}{\text{mole O2}} = \frac{\text{N2AS}}{\text{O2AS}} \qquad (2.6)$$

$$\text{ARO2} = \frac{\text{moles AR}}{\text{mole O2}} = \frac{\text{ARAS}}{\text{O2AS}} \qquad (2.7)$$

$$\text{CO2O2} = \frac{\text{moles CO2}}{\text{mole O2}} = \frac{\text{CO2A}}{\text{O2A}} \qquad (2.8)$$

For any ambient CO2 level, the following relations must hold for dry air (the actual value will be slightly less than 100% in the first relation because of the neglect of other minor constituents of air).

$$\text{N2A} + \text{O2A} + \text{ARA} + \text{CO2A} = 100 \qquad (2.9)$$

The symbols represent the mole percent of each constituent in the dry ambient air, allowing for variable CO2 concentration. For the fixed constituents,

$$\frac{N2A}{N2AS} = \frac{O2A}{O2AS} = \frac{ARA}{ARAS}. \tag{2.10}$$

Then

$$O2A = \frac{O2AS}{N2AS} * N2A \tag{2.11}$$

and

$$ARA = \frac{ARAS}{N2AS} * N2A. \tag{2.12}$$

Substituting in equation 2.9,

$$N2A + \frac{O2AS}{N2AS} * N2A + \frac{ARAS}{N2AS} * N2A = 100 - CO2A \tag{2.13}$$

we get

$$N2A = \frac{100 - CO2A}{1 + \frac{O2AS}{N2AS} + \frac{ARAS}{N2AS}}. \tag{2.14}$$

Using the following atomic weights based on carbon-12 (reference 2),

ATOM	ATOMIC WEIGHT
AR	39.948
C	12.01115
H	1.00797
N	14.0067
O	15.9994

the molecular weights for the various exhaust gas constituents become,

MOLECULE	MOLECULAR WEIGHT
CO2	44.00995
N2	28.0134
O2	31.9988
H2O	18.01534

The molecular weight of dry combustion air is then given by:

$$\begin{aligned} MWAIR = {} & 0.319988 * O2A + 0.280134 * N2A \\ & + 0.39948 * ARA + 0.4400995 * CO2A \end{aligned} \tag{2.15}$$

2.1.3.2 Inclusion of Atmospheric Moisture

From the definition of specific humidity (W) we have

$$W = \frac{\text{lbm atmospheric moisture}}{\text{lbm dry air}} = \frac{(\text{moles H2O})(\text{MWH2O})}{(\text{moles dry air})(\text{MWAIR})} \tag{2.16}$$

Multiplying by AIRO2, which is defined as,

$$\text{AIRO2} = \frac{\text{moles dry air}}{\text{mole atmospheric O2}} \tag{2.17}$$

we have

$$\text{W} * \text{AIRO2} = \frac{(\text{moles H2O})(\text{MWH2O})}{(\text{moles dry air})(\text{MWAIR})} \cdot \frac{(\text{moles dry air})}{(\text{mole O2})}$$

$$= \frac{\text{moles H2O}}{\text{mole O2}} \quad \frac{\text{MWH2O}}{\text{MWAIR}} \tag{2.18}$$

Solving for (moles H2O/mole O2) = H2OO2, we get

$$\text{H2OO2} = \frac{\text{moles H2O}}{\text{mole O2}} = \text{W} * \text{AIRO2} * \frac{\text{MWAIR}}{\text{MWH2O}} \tag{2.19}$$

where

$$\text{AIRO2} = 1 + \text{N2O2} + \text{ARO2} + \text{CO2O2} \tag{2.20}$$

2.1.3.3 Detailed Expression for Combustion Air

From the above analysis, the detailed expression for the number of moles of wet combustion air per mole of O2 becomes:

$$1 * \text{O2} + \text{N2O2} * \text{N2} + \text{ARO2} * \text{AR} + \text{CO2O2} * \text{CO2} + \text{W} * \text{AIRO2} * \frac{\text{MWAIR}}{\text{MWH2O}} * \text{H2O}$$

2.1.4 The Expanded Combustion Equation

By expanding the combustion equation to include the more accurate composition of air, we more accurately model the combustion process. Furthermore, in addition to introducing argon into the products, we shall also allow for the possibility of atomic carbon in the products. A further complication is introduced by considering the exhaust products in the three different states, "wet", "dried" and "dry". The expanded combustion equation is then written as,

FF [CHZ] + AA [1 * O2 + N2O2 * N2 + ARO2 * AR + CO2O2 * CO2
+ H2OO2 * H2O] →

Wet Products	Dried Products	Dry Products	
XCO2	XCO2	XCO2	
XCO	XCO	XCO	
XHC	XHC	XHC	
XO2	XO2	XO2	
XH2O	XH2ODD	---	
XH2	XH2	XH2	
XN2	XN2	XN2	
XNO	XNO	XNO	
XNO2	XNO2	XNO2	
XAR	XAR	XAR	
XC	XC	XC	
ΣX = XT	ΣX = XDD	ΣX = XD	(2.21)

where the sums of mole fractions (ΣX) include carbon. When carbon is in the solid state, we have for the sum of mole-fractions of gaseous products

XGW = total mole-fraction of wet gaseous products
XGDD = mole-fraction of dried gaseous products
XGD = mole-fraction of dry gaseous products

2.1.5 Methods for Computing Fuel-Air Ratio

Five methods for computing fuel-air ratio will be considered. These will be divided into:

Group 1. Those methods based on the use of the water-gas reaction equilibrium constant K.

Group 2. The method based on the sum of the gaseous-product mole-fractions XGW.

Group 3. The methods which combine the use of K and XGW.

To illustrate the computational procedure, we shall start with the simple case and progress to the more complex conditions.

2.1.5.1 Development of Method 1.1

Consider the combustion reaction in the simple form,

$$\text{FF [CHZ]} + \text{AA [1} * \text{O2} + 3.764\ \text{N2]} \rightarrow \text{XCO2} + \text{XCO} + \text{XHC} + \text{XO2} + \text{XH2O} + \text{XH2} + \text{XN2}. \qquad (2.22)$$

In this case, the simplified air composition is used and we neglect NO, NO2, AR and C in the exhaust. We assume that measurements are made of CO2, CO, HC on a mole carbon basis (HCC), and O2 which give or can be coverted to XCO2, XCO, XHCC and XO2 (i.e. a wet basis).

The calculated fuel-air ratio, FACAL, can then be determined from

$$\text{FACAL} = \frac{\text{FF} * [12.011 + 1.008 * \text{Z}]}{\text{AA} * [31.999 + 3.764 * 28.013]}. \qquad (2.23)$$

The unknown quantities are FF and AA, so we proceed to determine these from the known measurements. We have the following governing equations:

(1) C-Balance $\text{FF} = \text{XCO2} + \text{XCO} + \text{XHCC}$

(2) O-Balance $\text{AA} * 2 = \text{XCO} + \text{XH2O} + 2 * (\text{XCO2} + \text{XO2})$

(3) H-Balance $\text{FF} * \text{Z} = \text{XHCC} * \text{EHCR} + 2 * (\text{XH2O} + \text{XH2})$

In addition to the unknown quantities FF and AA, these equations introduce the unknown quantities XH2O and XH2. Since we now have four unknowns (FF, AA, XH2O and XH2) and only three equations in these unknowns, it becomes necessary to find one additional equation.

At this point we introduce the equilibrium constant for the water-gas reaction,

$$\text{CO2} + \text{H2} \rightleftarrows \text{CO} + \text{H2O}. \qquad (2.24)$$

The equilibrium constant is given by

$$\text{K} = \frac{[\text{XCO}]\,[\text{XH2O}]}{[\text{XCO2}]\,[\text{XH2}]}. \qquad (2.25)$$

Even though the equilibrium constant varies considerably with temperature, as shown in figure 2.1, the reaction tends to freeze out at a relatively constant temperature during the expansion stroke. This permits the use of a fixed value for K and values of 3.5 (reference 4) and 3.8 (reference 5) appear in the literature. We shall use K = 3.5. Table 2.3 shows how changes in K will affect the calculated fuel-air ratio.

It should be recognized that some variation in freeze-out temperature will occur so that equilibrium conditions may not be reached, necessitating some changes in the value of K to get good agreement between calculated and measured fuel-air ratios.

At this point we have a system of four equations in the four unknowns, so that the equations may be solved for these four unknowns.

To accomplish this, and to establish the procedure for the more complex system of equations to come, we set up the equations in matrix form for solution. The matrix is derived from the system of four equations, each equation being written in terms of the four unknown and a constant for the right-hand-side of the equation, i.e. having the general form,

$$C_{i1} * AA + C_{i2} * FF + C_{i3} * XH2O + C_{i4} * XH2 = Const \qquad (2.26)$$

where i is the equation number. The system of four equations becomes:

O-Balance $$2 * AA + 0.0 * FF - 1 * XH2O + 0.0 * XH2 = XCO + 2 * (XCO2 + XO2) \qquad (2.27)$$

C-Balance $$0.0 * AA + 1 * FF + 0.0 * XH2O + 0.0 * XH2 = XCO2 + XCO + XHCC \qquad (2.28)$$

H-Balance $$0.0 * AA + Z * FF - 2 * XH2O - 2 * XH2 = XHCC * EHCR \qquad (2.29)$$

K-Equation $$0.0 * AA + 0.0 * FF + 1 * XH2O - (K * XCO2/XCO) * XH2 = 0.0. \qquad (2.30)$$

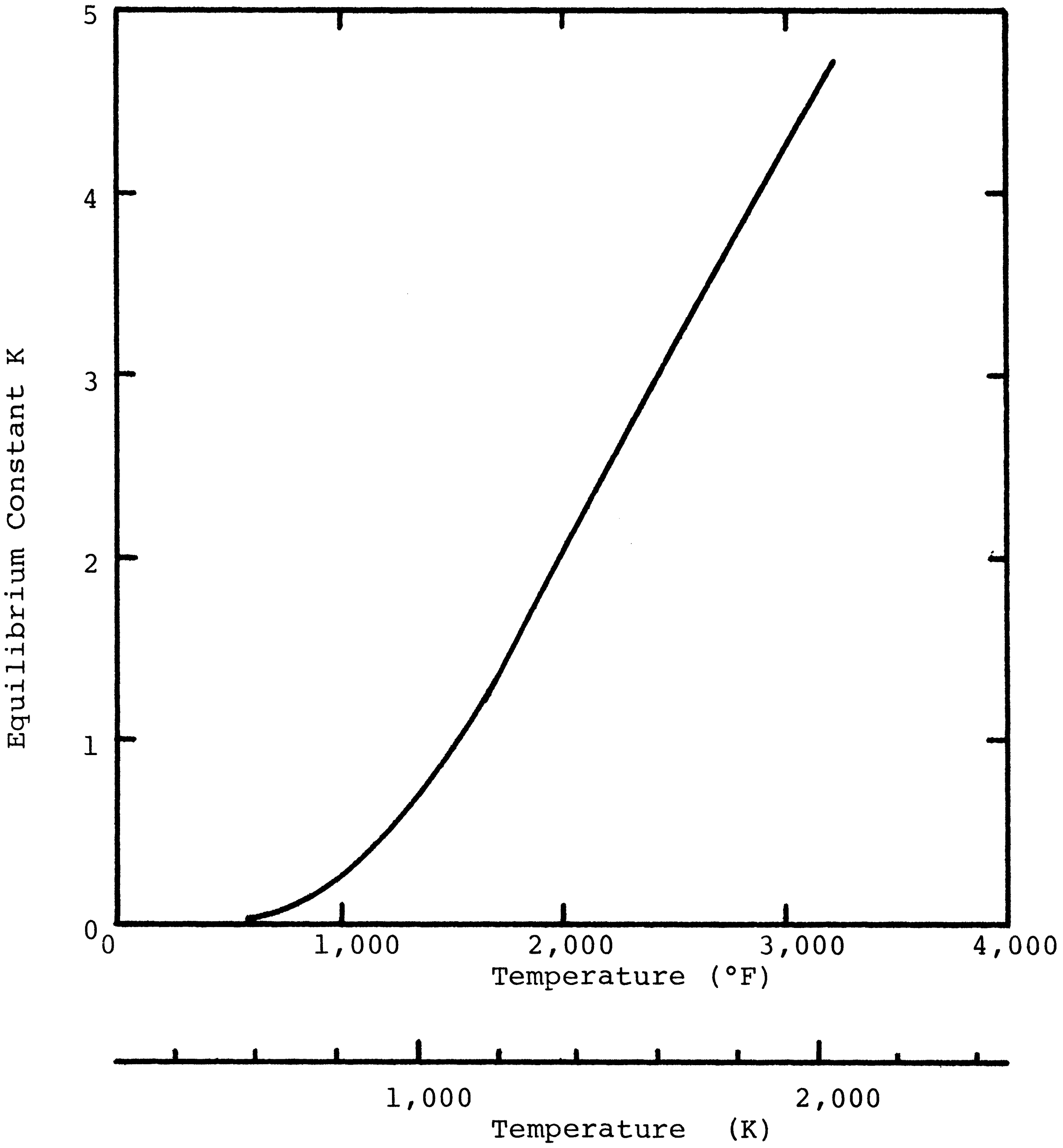


Figure 2.1. Variation of the Water-Gas Equilibrium Constant with Temperature.

In matrix form this becomes:

$$\begin{array}{lccccl} & \underline{\text{AA}} & \underline{\text{FF}} & \underline{\text{XH2O}} & \underline{\text{XH2}} & \underline{\text{Const}} \\ \text{O-Balance} & 2 & 0.0 & -1 & 0.0 & \text{XCO} + 2 * (\text{XCO2} + \text{XO2}) \\ \text{C-Balance} & 0.0 & 1 & 0.0 & 0.0 & \text{XCO2} + \text{XCO} + \text{XHCC} \\ \text{H-Balance} & 0.0 & \text{Z} & -2 & -2 & \text{XHCC} * \text{EHCR} \\ \text{K-Equation} & 0.0 & 0.0 & 1 & -\frac{\text{K} * \text{XCO2}}{\text{XCO}} & 0.0. \end{array} \qquad (2.31)$$

Solutions for AA, FF, XH2O and XH2 can then be obtained for given measured quantities of XCO, XCO2, XO2 and XHCC. A value for EHCR (exhaust hydrocrabon hydrogen-to-carbon ratio) is assumed and is usually taken to be 1.85, as recommended in the Federal Register. The values of AA and FF are used in computing fuel-air ratio using equation 2.23. In addition the water correction factor KWD, which is used to correct dry-to-wet exhaust gas measurements, is obtained from

$$\text{KWD} = 1 - \text{XH2O}. \qquad (2.32)$$

The above method, although developed in a different manner, essentially corresponds to the solution presented by Spindt (reference 4). A comparison of his results, with results obtained by the method developed in this section, shows excellent agreement.

2.1.5.2 Development of Method 1.2

The method developed in the previous section will now be expanded to include the following features:

1. Detailed expression for the combustion air.
2. Addition of products NO, NO2 and AR, but not atomic carbon.
3. Use of concentrations based on wet, dried or dry measurements.

The combustion reaction is as given by equation 2.21, with the exclusion of atomic carbon. For this case, the number of unknown quantities grows to fifteen. These are:

1. XGD
2. XGDD
3. AA
4. FF
5. XCO2
6. XCO
7. XHC
8. XO2
9. XNO
10. XNO2
11. XH2O
12. XH2ODD
13. XN2
14. XAR
15. XH2

The required fifteen equations which govern these unknowns are:

1. Equation defining XGD

$$\mathrm{XGD} + \mathrm{XH2O} = \mathrm{XGW} \tag{2.33}$$

2. Equation defining XGDD

$$\mathrm{XGD} + \mathrm{XH2ODD} = \mathrm{XGDD} \tag{2.34}$$

3. Oxygen balance

$$\begin{aligned} \mathrm{AA}\ [2 + 2 * \mathrm{CO2O2} + \mathrm{H2OO2}] &= 2 * \mathrm{XCO2} + \mathrm{XCO} \\ &+ 2 * \mathrm{XO2} + \mathrm{XH2O} + \mathrm{XNO} + 2 * \mathrm{XNO2} \end{aligned} \tag{2.35}$$

4. Carbon balance

$$\mathrm{FF} + \mathrm{CO2O2} * \mathrm{AA} = \mathrm{XCO2} + \mathrm{XCO} + \mathrm{EHCC} * \mathrm{XHC} \tag{2.36}$$

5. CO2 measurement (measured value on left)

$$\mathrm{CO2W} = \mathrm{XCO2} \quad \text{(if wet measurement)} \tag{2.37a}$$

or

$$\mathrm{CO2DD} = \mathrm{XCO2/XGDD} \quad \text{(if dried measurement)} \tag{2.37b}$$

or

$$\mathrm{CO2D} = \mathrm{XCO2/XGD} \quad \text{(if dry measurement)} \tag{2.37c}$$

6. CO measurement (measured value on left)

$$\mathrm{COW} = \mathrm{XCO} \quad \text{(if wet measurement)} \tag{2.38a}$$

or

$$\mathrm{CODD} = \mathrm{XCO/XGDD} \quad \text{(if dried measurement)} \tag{2.38b}$$

or

$$\mathrm{COD} = \mathrm{XCO/XGD} \quad \text{(if dry measurement)} \tag{2.38c}$$

7. HCC measurement (measured value on left)

$$\mathrm{HCCW} = \mathrm{XHC} * \mathrm{EHCC} \quad \text{(if wet measurement)} \tag{2.39a}$$

or

$$\mathrm{HCCDD} = \mathrm{XHC} * \mathrm{EHCC/XGDD} \quad \text{(if dried measurement)} \tag{2.39b}$$

or

$$\mathrm{HCCD} = \mathrm{XHC} * \mathrm{EHCC/XGD} \quad \text{(if dry measurement)} \tag{2.39c}$$

8. O2 measurement (measured value on left)

$$\mathrm{O2W} = \mathrm{XO2} \quad \text{(if wet measurement)} \tag{2.40a}$$

or

$$\mathrm{O2DD} = \mathrm{XO2/XGDD} \quad \text{(if dried measurement)} \tag{2.40b}$$

or

$$\mathrm{O2D} = \mathrm{XO2/XGD} \quad \text{(if dry measurement)} \tag{2.40c}$$

9. NO measurement (measured value on left)

$$\mathrm{NOW} = \mathrm{XNO} \qquad \text{(if wet measurement)} \tag{2.41a}$$

or

$$\mathrm{NODD} = \mathrm{XNO/XGDD} \qquad \text{(if dried measurement)} \tag{2.41b}$$

or

$$\mathrm{NOD} = \mathrm{XNO/XGD} \qquad \text{(if dry measurement)} \tag{2.41c}$$

10. NOX measurement (measured values on left)

$$(\mathrm{NOXW} - \mathrm{NOW}) = \mathrm{XNO2} \qquad \text{(if wet measurement)} \tag{2.42a}$$

or

$$(\mathrm{NOXDD} - \mathrm{NODD}) = \mathrm{XNO2/XGDD} \qquad \text{(if dried measurement)} \tag{2.42b}$$

or

$$(\mathrm{NOXD} - \mathrm{NOD}) = \mathrm{XNO2/XGD} \qquad \text{(if dry measurement)} \tag{2.42c}$$

11. Hydrogen balance

$$\mathrm{HTCR} * \mathrm{FF} + 2 * \mathrm{H2O2} * \mathrm{AA} = \mathrm{EHCR} * \mathrm{EHCC} * \mathrm{XHC} + 2 * \mathrm{XH2O} + 2 * \mathrm{XH2} \tag{2.43}$$

12. Condition in water trap

$$\mathrm{XH2ODD/XGDD} = \mathrm{PSAT/PTRP} \tag{2.44}$$

13. Nitrogen balance

$$2 * \mathrm{N2O2} * \mathrm{AA} = 2 * \mathrm{XN2} + \mathrm{XNO} + \mathrm{XNO2} \tag{2.45}$$

14. Argon balance

$$\mathrm{ARO2} * \mathrm{AA} = \mathrm{XAR} \tag{2.46}$$

15. Water-gas equilibrium

$$K = (\mathrm{XCO} * \mathrm{XH2O})/(\mathrm{XCO2} * \mathrm{XH2}) \tag{2.47}$$

This system of equations is shown in matrix form in figure 2.2. Symbols are defined in the List of Abbreviations and Symbols. Since we have fifteen equations involving the fifteen unknowns, a solution of the matrix will give values for the fifteen unknowns for the given input values of

(a) Measured CO2, CO, HCC, O2, NO and NOX.

(b) Fuel HTCR and exhaust hydrocarbon EHCC and EHCR.

(c) Water trap conditions PSAT and PTRP (saturation pressure and total pressure of sample in the water trap).

(d) Computed air properties N2O2, ARO2, CO2O2 and H2OO2.

(e) Water gas equilibrium constant K.

	XGD	XGDD	AA	FF	XCO2	XCO	XHC	XO2	XNO	XNO2	XH2O	XH2ODD	XN2	XAR	XH2	CONST
XGD	1										1					XGW
XGDD	1	-1										1				0
O-Bal			C1*		2	1		2	1	2	1					0
C-Bal			C2	-1	1	1	C3									0
CO2	-CO2D	-CO2DD			1											CO2W
CO	-COD	-CODD				1										COW
HCC	-HCD	-HCDD					1									HCW
O2	-O2D	-O2DD						1								O2W
NO	-NOD	-NODD							1							NOW
NO2	-NOXD +NOD	-NOXDD +NODD								1						NOXW -NOW
H-Bal			C4	C5			C6				2				2	0
Trap		C7										1				0
N-Bal			C8						1	1			2			0
AR-Bal			C9											1		0
Water-Gas											-1				C10	0

*See List of Abbreviations and Symbols.

Figure 2.2. Matrix for the Governing Equations of Method 1.2.

It should be pointed out that Method 1.2 will reduce to Method 1.1 by proper selection of some of the input quantities. This is accomplished when

N2O2 = 3.764   H2OO2 = 0
ARAS = 0   NO = 0
CO2A = 0   NOX = 0

Since Method 1.2 is more general than Method 1.1, it is used as one of the four methods in The University of Michigan data reduction program FAA (see appendix A). The other three methods, Methods 2.1, 3.1, and 3.2, are developed in the following sections.

2.1.5.3 Development of Method 2.1

In Methods 1.1 and 1.2 we introduced the equation for the water-gas equilibrium constant to come up with an additional equation governing the unknowns. This was done so that the number of equations equaled the number of unknowns. We can also use other reasonable constraints. The one selected for study in what we call Method 2.1 is that the sum of the mole-fractions of the gaseous wet products is equal to XGW, i.e.

$$\Sigma XY(W) = XGW \qquad (2.48)$$

The value of XGW is generally taken to be 1, but can be less because of omitted unknown minor gaseous products.

This appeared to be a more reasonable constraint than the water-gas equilibrium equation, because of the possible variation of the equilibrium constant K due to changes in freeze-out temperature. In addition, all of the major stable gaseous species are accounted for in the products, making it reasonable to assume that the summation of the gaseous mole fractions should be very nearly equal to 1.

We again have 15 equations for the same 15 unknowns shown in Section 2.1.5.2, and the corresponding matrix is similar to that shown in figure 2.2. The only change occurs when equation 2.47 for the water-gas equilibrium constant is replaced by the summation

$$XCO2 + XCO + XHC + XO2 + XNO + XNO2 + XH2O + XN2 + XAR + XH2 = XGW = 1. \qquad (2.49)$$

2.1.5.4 Development of Method 3.1

This method was developed after finding that Method 2.1 often led to negative values of XH2. It was felt that this occurred because of the neglect of carbon in the products. By including carbon as an additional unknown, an additional equation also had to be introduced to make the number of governing equations equal to the number of unknowns. Therefore, the equation for the water-gas equilibrium constant was re-introduced to the system of equations in Method 2.1.

We further assume that by the time the exhaust measurements are made, the carbon would be in solid form and would be filtered from the sample stream. Thus, the equations involving mole fractions of gaseous products are not affected by the presence of solid carbon and only the carbon balance equation is affected.

The addition of solid carbon, XC, and the introduction of the water gas equilibrium constant equation gives us a system of 16 unknowns and 16 equations. The resulting matrix is similar to that shown in figure 2.2, with the addition of equation 2.49.

2.1.5.5 Development of Method 3.2

This method is a modification and expansion of the method presented by Stivender (reference 5). Its value lies in the fact that it does not require an oxygen measurement of the exhaust products. An examination of Stivender's paper shows that the method falls into the category of Group 3, in that both the water-gas-equilibrium-constant and sum-of-mole-fraction equations are used. Being the second method in Group 3, it is identified as Method 3.2.

Development of this method starts with the combustion reaction equation as given by equation 2.21 and the system of sixteen unknowns and governing equations of Method 3.1. The development then proceeds as follows:

1. Equation 2.48 is solved for XO2 and the result is substituted into the other governing equations, eliminating two equations [equation 2.48 and equation 2.40] and one unknown (XO2). Two of the resulting equations of interest are the O-N-balance equations.

   From the O-balance we get,

$$AA(2 + 2 * CO2O2 + H2OO2) = 2 * (XGW - XHC - XH2 - XAR) - XCO - XH2O - (2 * XN2 + XNO) \qquad (2.50)$$

   while the N-balance equation remains unchanged,

$$AA(2 * N2O2) = (2 * XN2 + XNO) + XNO2 \qquad (2.51)$$

2. Equation 2.51 is solved for (2 * XN2 + XNO), the result is substituted in equation 2.50 and the equation is divided by 2 to give,

$$AA(1 + CO2O2 + \frac{H2OO2}{2} + N2O2) = (XGW - XHC - XH2 - XAR) + \frac{1}{2}(XNO2 - XCO - XH2O) \qquad (2.52)$$

   This step eliminates the unknowns XN2 and XNO as well as equation 2.45 or 2.51 and 2.41.

Thus, this procedure has eliminated four equations [2.48, 2.40, 2.45, and 2.41] but only three unknowns (XO2, XN2 and XNO). An additional unknown has to be eliminated and we select the mole fraction of carbon, XC, thereby ending up with a system of twelve equations in twelve unknowns. The corresponding matrix is shown in figure 2.3.

2.1.5.6 Matrix Solutions

The matrices thus formed in Methods 1.1, 1.2, 2.1, 3.1, and 3.2 represent systems of linear equations in the unknown quantities. Standard methods are available for the solution of such a system of equations. The method selected for our programs is called Crout's Method and the subroutines are included with our programs - FAA and FARAT (for <u>f</u>uel-<u>a</u>ir <u>rat</u>io), and are listed

	XGD	XGDD	AA	FF	XCO2	XCO	XHC	XNO2	XH2O	XH2O DD	XAR	XH2	CONST
XGD	1								1				XGW
XGDD	-1	1								-1			0
O-Bal			C11*			0.5	1	-0.5	0.5		1	1	1
C-Bal			-C2	1	-1	-1	-C3						0
XCO2	-CO2D	-CO2DD			1								CO2W
XCO	-COD	-CODD				1							COW
XHC	-HCD	-HCDD					1						HCW
XNO2	-NOXD +NOD	-NOXDD +NODD						1					NOXW -NOW
H-Bal			-C4	-C5			-C6		-2			-2	0
Trap		C7								1			0
Ar-Bal			-C9								-1		0
Water-Gas									-1			C10	0

*See List of Abbreviations and Symbols.

Figure 2.3. Matrix for the Governing Equations of Method 3.2.

in the appendices. They are,

SUBROUTINE CRT4
SUBROUTINE CRT12
SUBROUTINE CRT15
SUBROUTINE CRT16

for solving the system of 4, 12, 15 and 16 equations, respectively.

2.1.5.7 Effect of Hydrocarbon Loss in the Water Trap

The question of possible loss of some of the exhaust sample hydrocarbons by condensation in the water trap and the resulting effect on calculated fuel-air ratio is considered next. It turns out that the required modification to the computer program FARAT is extremely simple. It involves only a redefinition of the sum-of-mole-fractions of dry gaseous products in the analyzers from

$$\mathrm{XGD} + \mathrm{XH2O} = \mathrm{XGW} \qquad (2.33)$$

to

$$\mathrm{XGD} + \mathrm{XH2O} + \mathrm{FCHC} * \mathrm{XHC} = \mathrm{XGW} \qquad (2.53)$$

where

FCHC = fraction condensed hydrocarbons
= 0 for zero condensation
= 1 for total condensation of exhaust hydrocarbons.

That is, the total mole-fraction of dry gaseous products in the instrument analyzers consists of what is left of the gaseous exhaust sample after all of the water and a portion of the hydrocarbons have been removed from the exhaust sample. The effects of FCHC on FACAL are presented in table 2.3 in terms of specific sensitivities.

2.1.5.8 Effect of Dilution Air (Mixing without Reaction)

The possibility of dilution of the cooled exhaust sample with air without further reaction, such as might result from an air leak in the instrumentation package, was examined. This was accomplished by means of a modification to the computer program FARAT. Measured concentrations are modified to simulate the effect of air dilution, and the resulting diluted concentrations are used to compute fuel-air ratio. In this manner, the effect of varying degrees of dilution on computed fuel-air ratio can be determined.

The development begins with a definition of fraction dilution air (FdA),

FdA = moles wet dilution air/moles gaseous wet products in the undiluted sample

or

$$FdA = NdAW/NGW \tag{2.54}$$

Next, recalling that the composition of air per mole of oxygen is given by,

1 mole oxygen per mole oxygen
N2O2 moles nitrogen per mole oxygen
ARO2 moles argon per mole oxygen
CO2O2 moles carbon dioxide per mole oxygen
H2OO2 moles water vapor per mole oxygen

we get for the moles dilution air per mole oxygen, in dilution air,

$$\begin{aligned} dAO2 &= 1 + N2O2 + ARO2 + CO2O2 + H2OO2 \\ &= AIRO2 + H2OO2 \end{aligned} \tag{2.55}$$

It is assumed that the dilution air has the same composition as the combustion air, so that the value of AIRO2 used in this section is the same as used in section 2.1.3.2 for the combustion air.

In the diluted sample the concentration of any specie Y will be given by

$$\frac{NY + NdAW * (YO2/dAO2)}{NGM + NdAM} = XYd(M) \tag{2.56}$$

where M is used to indicate the "measurement" condition, i.e. either wet, dry or dried. The various terms are defined by,

NY	moles of specie Y in the undiluted sample
NdAW * (YO2/dAO2)	moles of specie Y in the dilution air
NGM	moles of gas in the undiluted sample
NdAM	moles of dilution air in the diluted sample
XYd(M)	mole-fraction of specie Y in the diluted sample.

Dividing numerator and denominator by NGW gives,

$$\frac{XY(W) + FdA * (YO2/dAO2)}{XGM(W) + (NdAM/NGW)} = XYd(M) \qquad (2.57)$$

For dry or dried measurements, the wet mole fraction XY(W) must be replaced by its equivalent in terms of the dry or dried measurement. To accomplish this we use

$$\frac{NY}{NGW} = \frac{NY}{NGD} * \frac{NGD}{NGW}$$

to get

$$XY(W) = XY(D) * XGD(W) \qquad (2.58)$$

for dry measurements, and in a similar manner we get

$$XY(W) = XY(DD) * XGDD(W) \qquad (2.59)$$

for dried measurements. Substitution leads to the following set of equations for wet, dry and dried measurements. For wet measurements, we have

$$\frac{XY(W) + FdA * (YO2/dAO2)}{1 + FdA} = XYd(W) \qquad (2.60)$$

For dry measurements, from equations 2.57 and 2.58,

$$\frac{XY(D) * XGD(W) + FdA * (YO2/dAO2)}{XGD(W) + \frac{NdAD}{NGW}} = XYd(D)$$

But the number of moles of dry dilution air is given by

$$NdAD = FdA * NGW * (AIRO2/dAO2)$$

Therefore, for dry measurements,

$$\frac{XY(D) * XGD(W) + FdA * (YO2/dAO2)}{XGD(W) + FdA * (AIRO2/dAO2)} = XYd(D) \qquad (2.61)$$

Finally, for dried measurements, from equations 2.57 and 2.59,

$$\frac{XY(DD) * XGDD(W) + FdA * (YO2/dAO2)}{XGDD(W) + \frac{NdADD}{NGW}} = XYd(DD) \quad .$$

To simplify the computation without introducing a serious error, we can assume that the number of moles of dried dilution air is equal to the number of moles of dry dilution air, so that

$$\frac{NdADD}{NGW} = \frac{NdAD}{NGW} = FdA * (AIRO2/dAO2)$$

Therefore, for dried measurements,

$$\frac{XY(DD) * XGDD(W) + FdA * (YO2/dAO2)}{XGDD(W) + FdA * (AIRO2/dAO2)} = XYd(DD) \qquad (2.62)$$

To determine the effects of dilution air on calculated fuel-air ratio, the actual measurements, XY(W), XY(D) and XY(DD), of the undiluted sample are used to compute fuel-air ratio, XGD(W) and XGDD(W). With these values and assumed values of FdA and YO2, the diluted concentrations are computed using equations 2.60, 2.61 and 2.62. These are then used to calculate the fuel-air ratio as determined from the diluted concentrations. The results of this analysis are presented in table 2.3 in terms of specific sensitivities for the variable FdA (fraction dilution air).

2.1.5.9 Comments on Computational Methods

Each of the methods developed above possesses unique desirable properties to be considered when selecting one method over the other.

Method 1.1 is the easiest to use and gives results equal to those obtained by the conventional Spindt method (reference 4). In addition the mole fractions of H2 and H2O are computed and the latter can be used to compute the dry-to-wet water correction factor using equation 2.32. One drawback is that the method, as developed, requires that all concentration measurements be on a "wet" basis. However, modifications to permit the use of any combination of "wet" and "dry" measurements could easily be made.

Method 1.2 is based on a more accurate combustion model and was used as the principal means for calculating fuel-air ratio at Michigan. The main features of this method are:

1. Any combination of "wet", "dry" or "dried" measurements can be used. Conversions to the "wet" measurement are handled within the program.
2. Mole fractions of the principal stable exhaust species, except solid carbon, are computed. This information is used when computing exhaust molecular weight (see section 2.4).
3. The computed sum of exhaust mole-fractions (XTC) serves as an excellent internal check on data validity. A value of XTC which deviates by more than ±3% from a value of about 1.02 (a value that should be established by each test facility and should be based on the average value from a large number of test data) is a good indication of poor data.

This last feature has been used extensively at Michigan to quickly spot poor data and is the main reason for adopting this as the principal method at Michigan.

Method 2.1 has most of the features of Method 1.2 except that XTC is not computed and is thus not available as an internal check. This is considered to be a major deficiency of this method. However, the method is one of the more sensitive to errors in concentration measurements (see figures 2.4 to 2.7) and the use of XTC in place of the water-gas reaction equilibrium constant may be desirable in some cases.

Method 3.1 is similar to Method 2.1 in that XTC is assigned a fixed value and is thus not available as an internal check on data validity. The added feature of this method is that the mole-fraction of solid carbon is computed. Visual checks of carbon deposited on filter paper from sampling line filters shows good qualitative agreement with calculated concentrations of solid carbon.

The main feature of Method 3.2 is that it does not require an O2 concentration measurement. Neither XTC nor solid carbon concentrations are computed by this method.

2.2 SENSITIVITY ANALYSIS OF FUEL-AIR RATIO COMPUTATIONAL MODELS

The four principal models for calculating fuel-air ratio were subjected to a sensitivity analysis to determine how strongly small changes in the various input quantities affected the calculated fuel-air ratio. This was accomplished by selecting several runs covering a broad range of exhaust pollutant concentrations and then calculating fuel-air ratio while varying one of the input variables at a time. The effects of the following thirteen variables on all four models were determined and the results are given in figures 2.4 to 2.7 and in table 2.3.

		Variable Name
1.	Measured CO2 concentration	CO2DD
2.	Measured CO concentration	COD
3.	Measured O2 concentration	O2DD
4.	Measured HCC concentration	HCCW
5.	Measured NO concentration	NOW
6.	Combustion air nitrogen-oxygen ratio	N2O2
7.	Combustion air CO2 content	CO2A
8.	Combustion air water vapor content	W
9.	Fuel hydrogen-to-carbon ratio	HTCR
10.	Exhaust hydrocarbon carbon number	EHCC
11.	Exhaust hydrocarbon hydrogen-carbon ratio	EHCR
12.	Sum of wet gaseous exhaust mole-fractions	XGW
13.	Water gas reaction equilibrium constant	K

Results are reported in terms of what we shall call specific sensitivity (SS) for the particular variable. Specific sensitivity is defined by

$$SS = \frac{\text{Percent change in calculated fuel-air ratio}}{1\% \text{ increase in variable}} \qquad (2.63)$$

Specific sensitivity is strongly dependent upon the method used for computing fuel-air ratio, somewhat less dependent upon the magnitude of the variable being tested (e.g. the level of concentration of a pollutant) and to a lesser extent upon the magnitude of the other pollutant concentrations.

Figures 2.4 through 2.7 show plots of specific sensitivity versus concentration for the exhaust products CO2, CO, O2 and HCC. The fact that the specific sensitivity shows various combinations of being plus and minus for the various pollutants, as shown in table 2.2, introduces the possibility of determining which pollutant measurement contributes most strongly to the calculated fuel-air ratio error.

TABLE 2.2. POSITIVE AND NEGATIVE SIGNS OF SPECIFIC SENSITIVITY

Method	CO2	CO	O2	HCC
1.2	-	+	-	+
2.1	+	+	+	+
3.1	-	-	-	+
3.2	+	+	**	+

**The O2 measurement is not involved in Method 3.2.

As an example, one test run of the Lycoming 0-320 engine resulted in the following fuel-air ratio errors:

Method	Original Error Percent
1.2	3.030
2.1	24.733
3.1	-10.053
3.2	10.477

For the concentrations involved, the specific sensitivities are:

	CO2	CO	O2	HCC
Concentration (PPM)	67022	129820	4310	15688
Method				
1.2	-0.15	+0.24	-0.02	+0.094
2.1	+1.10	+1.77	+0.05	+0.150
3.1	-1.28	-0.95	-0.08	+0.054
3.2	+0.32	+0.78	0.00	+0.115

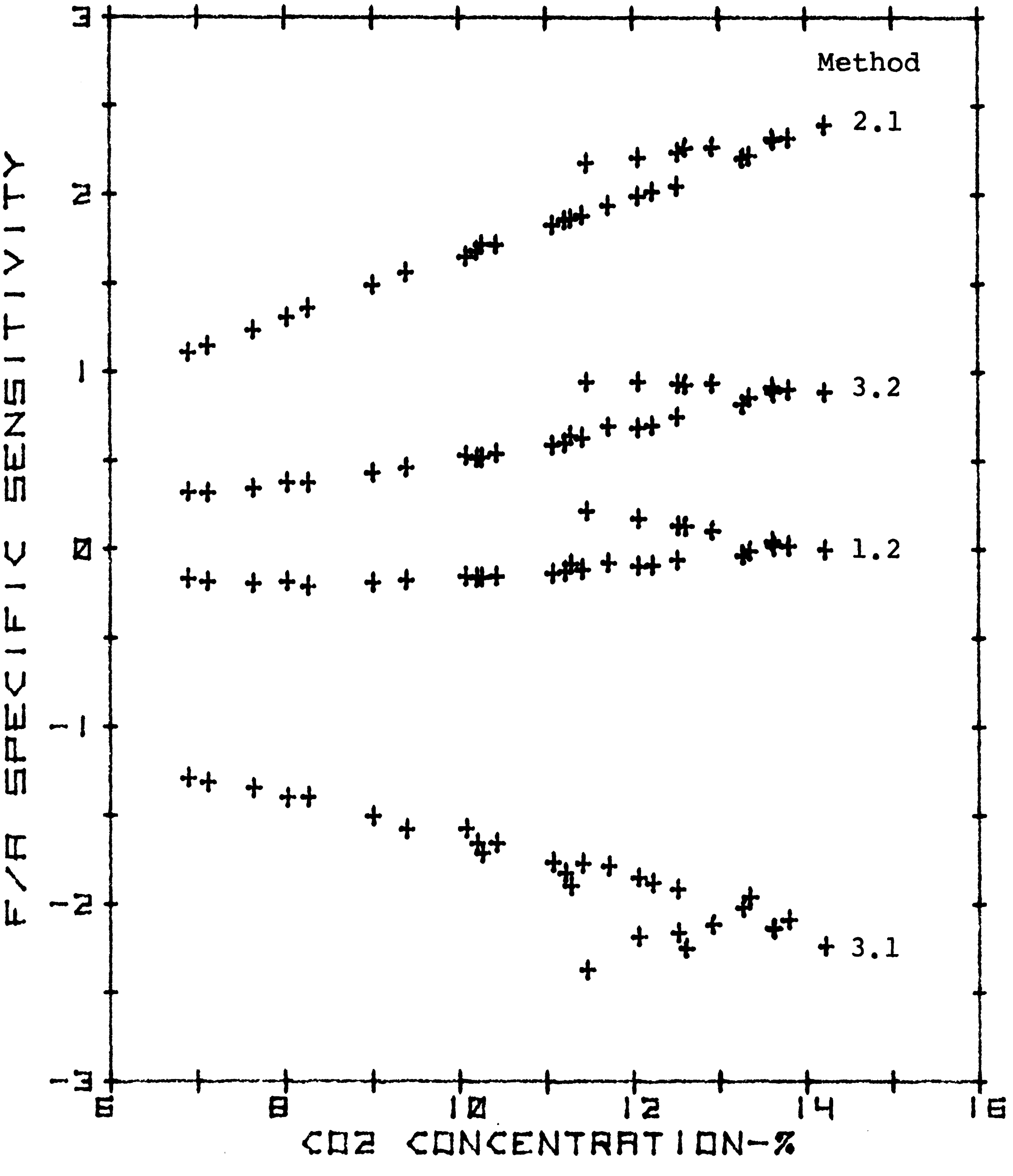


Figure 2.4. Specific Sensitivity vs CO2 Concentration

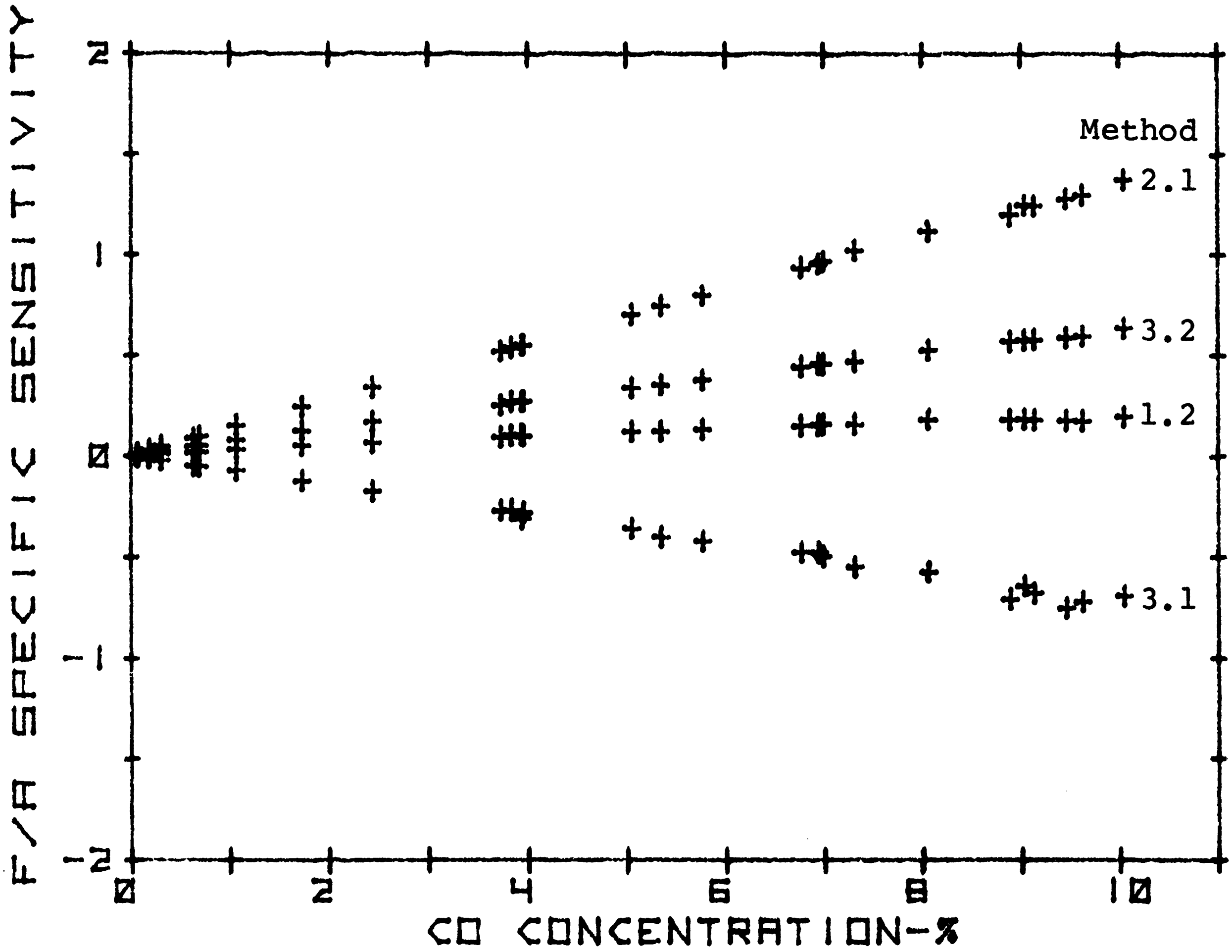


Figure 2.5. Specific Sensitivity vs CO Concentration

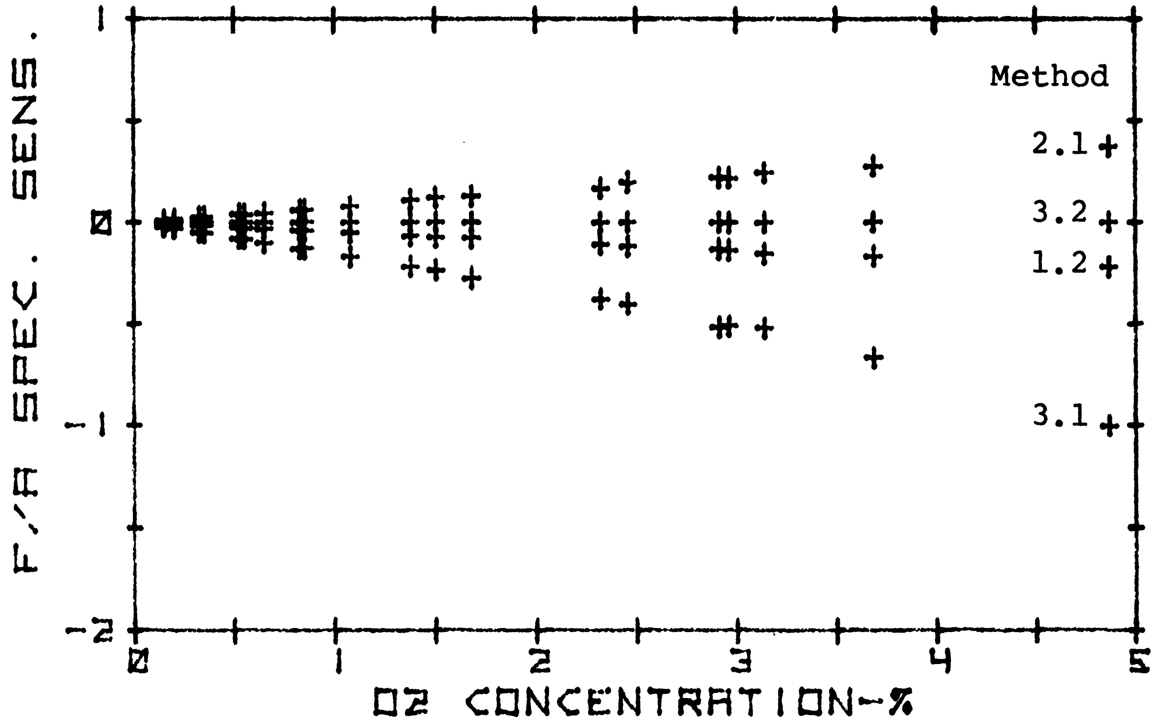


Figure 2.6. Specific Sensitivity vs O2 Concentration

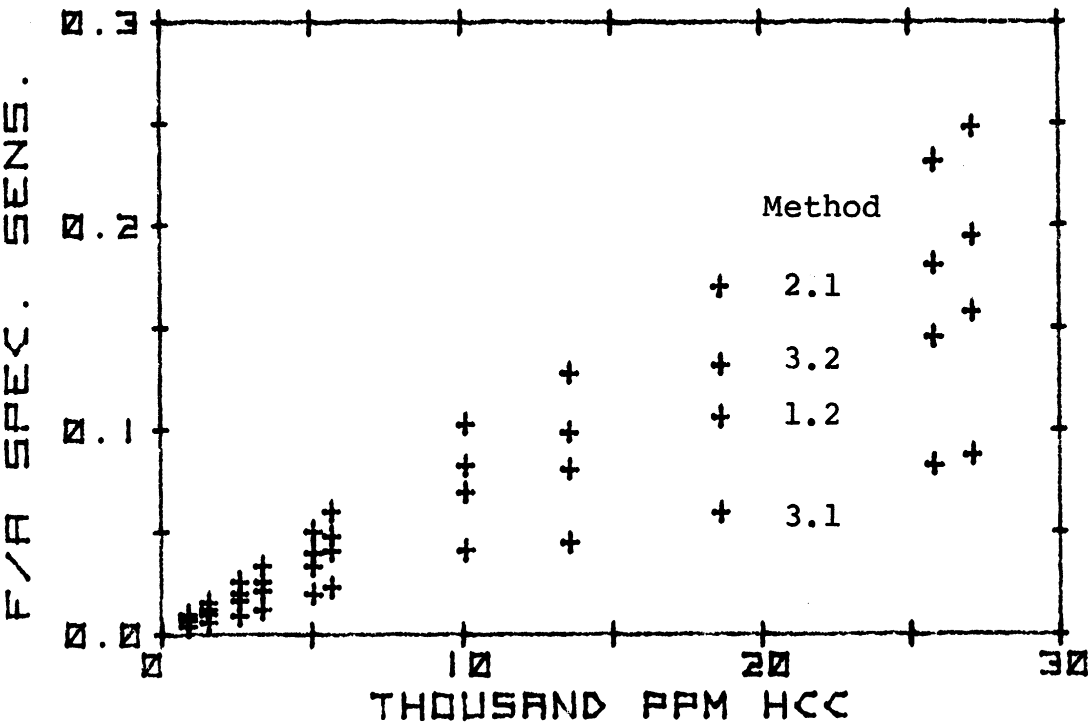


Figure 2.7. Specific Sensitivity vs HCC Concentration

The data is next examined for a possible change in one concentration measurement which would reduce fuel-air ratio errors from all four methods to essentially zero. The required changes in concentration is determined by dividing each fuel-air error by the corresponding specific error and taking the negative of these values.

$$\text{Percent Change} = -\frac{\text{fuel-air ratio error}}{\text{specific sensitivity}}$$

REQUIRED CONCENTRATION CHANGES (%)

Method	CO2	CO	O2	HCC
1.2	20.20	-12.63	151.5	-32.33
2.1	-22.48	-13.97	-494.66	-164.89
3.1	- 7.85	-10.58	-125.66	186.17
3.2	-32.74	-13.43	--	-91.10

Only the CO changes are reasonably consistent. Therefore, considering the fact that the CO specific sensitivity for Method 2.1 is much larger than the others and deserves a higher weighting factor, a CO concentration correction of about -12% is chosen. A computer check using a CO reduction of 11.8% did in fact reduce all errors to below 1% as shown.

ERROR AFTER AN 11.8% REDUCTION IN CO

Method	Percent
1.2	0.632
2.1	0.850
3.1	0.483
3.2	0.717

Shown in table 2.3 are the values for specific sensitivity for the remaining variables checked. As stated earlier, these will vary somewhat from one test case to another, but in general the magnitudes are accurate enough for comparative predictions.

Given in the table are the maximum values obtained from a large number of test runs.

TABLE 2.3. VALUES OF SPECIFIC SENSITIVITY

Variable	Specific Sensitivity Method 1.2	Method 2.1	Method 3.1	Method 3.2
NOW	0.0080	-0.0075	0.023	0.0016
N2O2	-0.78	1.3	-3.0	0.0027
CO2A	-0.0012	-0.0082	0.0064	-0.0037
W	0.012	0.0025	0.020	0.0075
HTCR	-0.20	0.69	-0.85	0.15
EHCC	0.0	-0.082	0.074	-0.032
EHCR	0.048	-0.076	0.16	0.0031
XGW	-0.16	-0.25	-0.088	1.2
K	-0.093	0.0	-0.16	-0.058

An examination of the specific sensitivity values for Method 1.2 shows that the method is most sensitive to changes in the N2O2 ratio (the ratio of atmospheric nitrogen to oxygen). If we consider the effect of going from a value of 3.7274 to a value of 3.76 (the value in common use), where the change in N2O2 is a +0.875 percent change, we find that the resulting contribution to the Method 1.2 fuel-air error is about -0.6%. Neglect of combustion air humidity, at a specific humidity level of about 0.008, would contribute approximately another -1.0% to the error. Together, these two contributions would amount to approximately -1.6%. The actual computed results are shown in table 2.4 where the original FACAL of 0.05145 was reduced to 0.05111 by assuming that N2O2 is 3.76 and was further reduced to 0.05079 by neglecting atmospheric moisture. Thus, the non-negligible effects on calculated fuel-air ratio of seemingly minor assumptions becomes obvious. In this example the effect was to reduce the calculated fuel-air ratio by -1.28%.

TABLE 2.4. EFFECTS OF CHANGES OF N2O2 AND W ON FACAL

```
   RUN:  5. 1                    CO2        CO         O2        HCC        NO        NOX
   DRY MEASUREMENTS               0.      17656.        0.         0.        0.         0.
   DRIED MEASUREMENTS          51214.         0.    109523.        0.        0.         0.
   WET MEASUREMENTS               0.         0.         0.     31808.      173.       223.
    HTCR      EHCC          EHCR       CO2A       PSAT       PTRP          W        N2O2
    2. 190     1. 000       1. 850     0. 030    0. 08866    19. 000    0. 0081    3. 7274
   XCO2     XCO     XHC     XO2     XH2O     XH2     XN2     XNO     XNO2     XAR     XC
0. 0474 0. 0163 0. 0318 0. 1014 0. 0788 0. 0077 0. 7091 0. 0002 0. 0001 0. 0084 0. 0000
   MTD     XTC       K    FCHC     FDA     PHI   MWEXH     KWD   FACAL       FAM   ERROR
   1. 2 1. 0013 3. 5000 0. 0000 0. 0000 0. 7742 27. 8375 0. 9211 0. 05145 0. 05251 -2. 011

   RUN:  5. 1                    CO2        CO         O2        HCC        NO        NOX
   DRY MEASUREMENTS               0.      17656.        0.         0.        0.         0.
   DRIED MEASUREMENTS          51214.         0.    109523.        0.        0.         0.
   WET MEASUREMENTS               0.         0.         0.     31808.      173.       223.
    HTCR      EHCC          EHCR       CO2A       PSAT       PTRP          W        N2O2
    2. 190     1. 000       1. 850     0. 030    0. 08866    19. 000    0. 0081    3. 7600
   XCO2     XCO     XHC     XO2     XH2O     XH2     XN2     XNO     XNO2     XAR     XC
0. 0474 0. 0163 0. 0318 0. 1014 0. 0789 0. 0077 0. 7152 0. 0002 0. 0001 0. 0085 0. 0000
   MTD     XTC       K    FCHC     FDA     PHI   MWEXH     KWD   FACAL       FAM   ERROR
   1. 2 1. 0075 3. 5000 0. 0000 0. 0000 0. 7743 27. 8384 0. 9211 0. 05111 0. 05251 -2. 659

   RUN:  5. 1                    CO2        CO         O2        HCC        NO        NOX
   DRY MEASUREMENTS               0.      17656.        0.         0.        0.         0.
   DRIED MEASUREMENTS          51214.         0.    109523.        0.        0.         0.
   WET MEASUREMENTS               0.         0.         0.     31808.      173.       223.
    HTCR      EHCC          EHCR       CO2A       PSAT       PTRP          W        N2O2
    2. 190     1. 000       1. 850     0. 030    0. 08866    19. 000    0. 0000    3. 7600
   XCO2     XCO     XHC     XO2     XH2O     XH2     XN2     XNO     XNO2     XAR     XC
0. 0479 0. 0164 0. 0318 0. 1025 0. 0688 0. 0067 0. 7250 0. 0002 0. 0001 0. 0086 0. 0000
   MTD     XTC       K    FCHC     FDA     PHI   MWEXH     KWD   FACAL       FAM   ERROR
   1. 2 1. 0081 3. 5000 0. 0000 0. 0000 0. 7694 27. 9789 0. 9312 0. 05079 0. 05251 -3. 270
```

2.3 EVALUATION OF DATA RELIABILITY

An important aspect of this study was the problem of determining the uncertainty associated with the reliability of the collected engine emission test data. It is implicit in the Federal Register that agreement between the measured and calculated values of fuel-air ratio would be taken as a measure of data reliability. However, as the study at The University of Michigan progressed and the study led to the development of four seemingly equally reliable methods for calculating fuel-air ratio, the question arose as to which of the four calculated fuel-air ratios was to be compared with the measured value.

Analysis of engine emission data demonstrated that quite frequently the four computational methods led to four appreciably different values of fuel-air ratio. At times the error from Method 1.2 (essentially an expanded Spindt method) would be acceptably very low while the other methods gave errors that were unacceptably very high. Values for an extreme case are shown. (See table 5.4, run 16, mode 4.)

Method	Fuel/Air Error Percent	XTC
1.2	0.570	0.73928
2.1	-51.906	---
3.1	56.095	---
3.2	-28.482	---

Since the Spindt method is quite commonly used to calculate fuel-air ratio, it is important to realize that cases can arise where the calculated Spindt error is not in itself a sufficient check of data reliability. (Note that XTC differs appreciably from 1.0.)

In the search for a more acceptable method for determining data reliability, the following factors were taken into consideration:

1. Since all four fuel-air calculation methods are based on sound chemical and mathematical principles, all errors should be essentially zero when the correct input

quantities are used. However, because of the different specific sensitivity values for the different methods (see section 2.2) all four errors would change at different rates as one of the input quantities is changed from its correct value. Therefore, it appeared that the difference between two errors quantities would be a measure of how far the input variables were from their correct values. This was tested by selecting the errors of Methods 1.2 and 3.1 for evaluation.

Method 1.2 was selected because of its common usage and low sensitivity to variable changes and Method 3.1 was selected because it constituted the most complete specification of the system. The error difference [E(3.1) - E(1.2)] is identified by ΔE in this report.

2. The sum of mole fractions (XTC) was also selected as a possible indicator of data reliability because it seemed reasonable to assume that the value should be close to unity since all major stable species are included in the analysis. Because the mole fractions normally referred to in this report are based on the sum of gaseous wet products, the total sum XTC should have a maximum value of unity when only gaseous products are included, i.e. not including solid carbon. It is this value of XTC which is calculated by Method 1.2 and which is used in the following test of data reliability.

Data from various sources were next examined by plotting ΔE versus XTC as shown in figure 2.8. The result shows that the data is well correlated by a straight line.

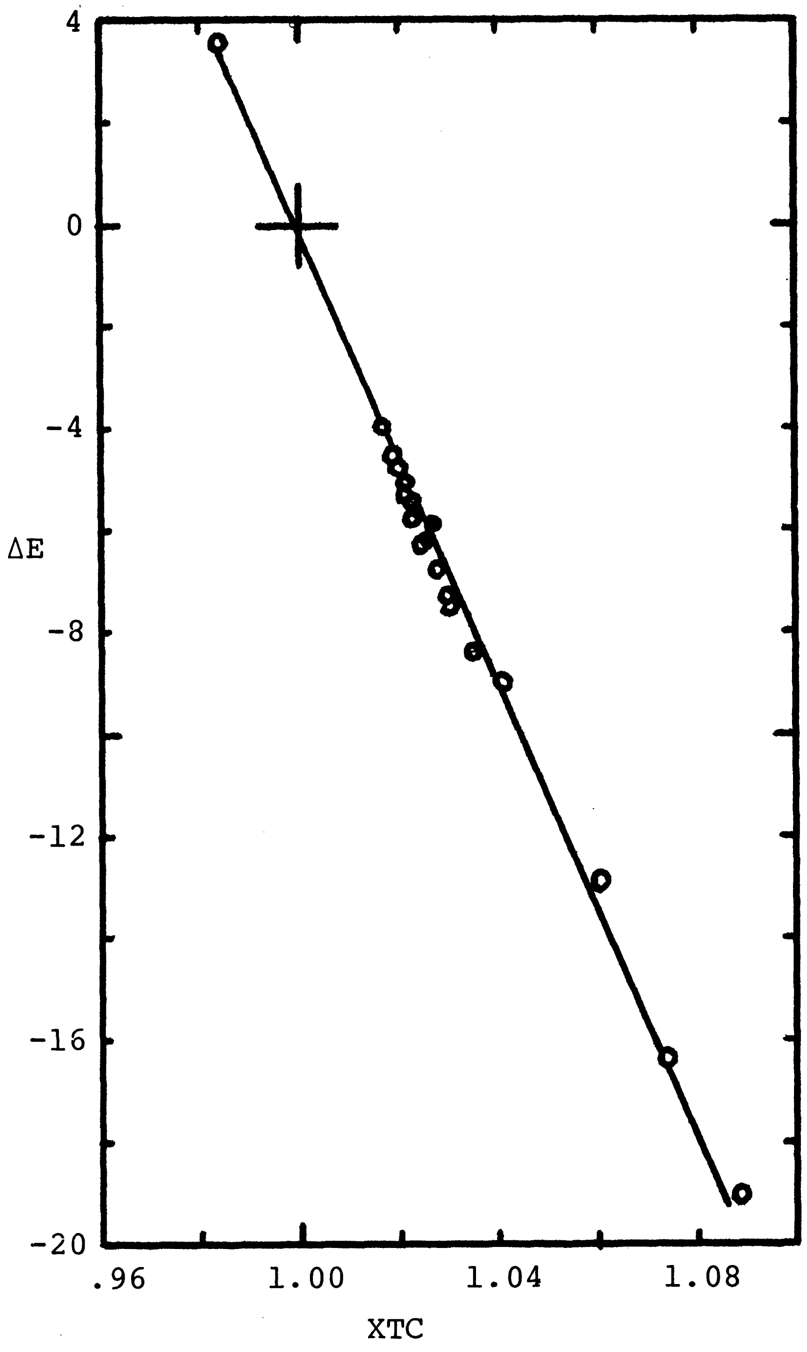


Figure 2.8. ΔE vs XTC: Lycoming Data.
(Reference 12) Runs 153-159, 448-454, 467-473 (all modes included).

Additional plots were made to determine whether any correlations existed between fuel-air errors from the other methods and XTC. Figure 2.9 for Method 1.2 (expanded Spindt Method) shows no correlation while figure 2.10 for Method 3.1 shows a reasonable correlation, although not as good as that in figure 2.8 for ΔE vs XTC.

Our conclusion is that either XTC or ΔE is a better indicator of data validity than either the Spindt or Method 3.1 fuel-air errors alone. Since XTC can be obtained from the application of only one method, Method 1.2, it is considered to be the more practical indicator of good data.

2.3.1 Comparison of Michigan and Eltinge Methods

A limited comparison of the Michigan method and the method reported by Eltinge(reference 7) was made. In the Eltinge method one enters one of several charts, see figure 2.11, with corrected (for UHC) values of percent CO2, O2 and CO. The lines representing these values form a triangle such that the centroid falls on a line representing the calculated fuel-air ratio and the height of the triangle gives an indication of "instrument error" in terms of percent CO. In this report EIE shall be used when referring to the Eltinge instrument error. In figure 2.11 the fuel-air ratio for the example is 0.0669 and the EIE is +0.45, which are in good agreement with Eltinge's results (reference 7).

The initial part of the comparison consisted of analyzing some of Eltinge's engine data using the Michigan method and comparing the Eltinge and Michigan results. These results are tabulated in table 2.5 while figure 2.12 shows both ΔE and XTC plotted against EIE.

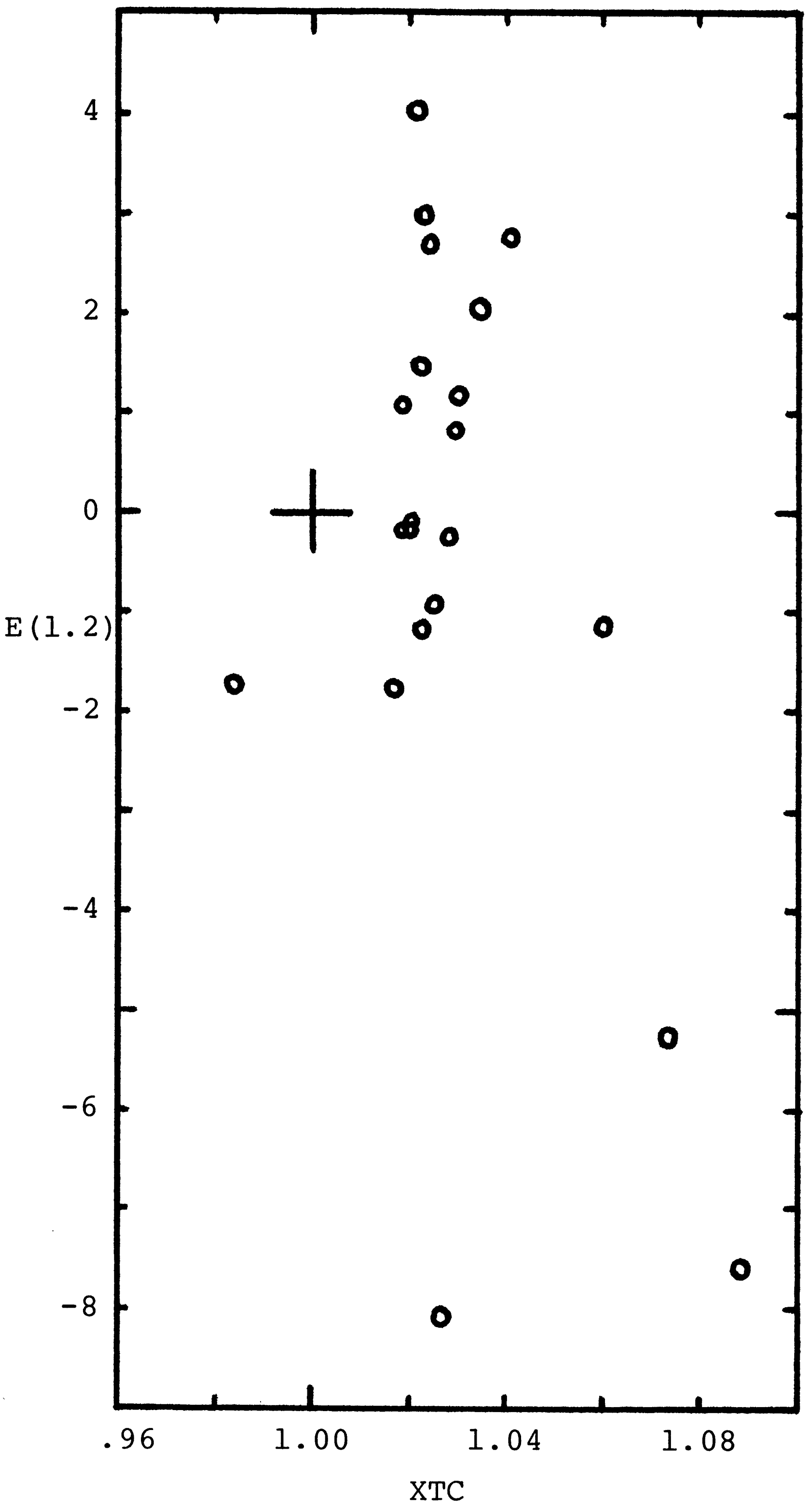


Figure 2.9. E(1.2) vs XTC: Lycoming Data (Reference 12) Runs 153-159, 448-454, 467-473 (all modes included).

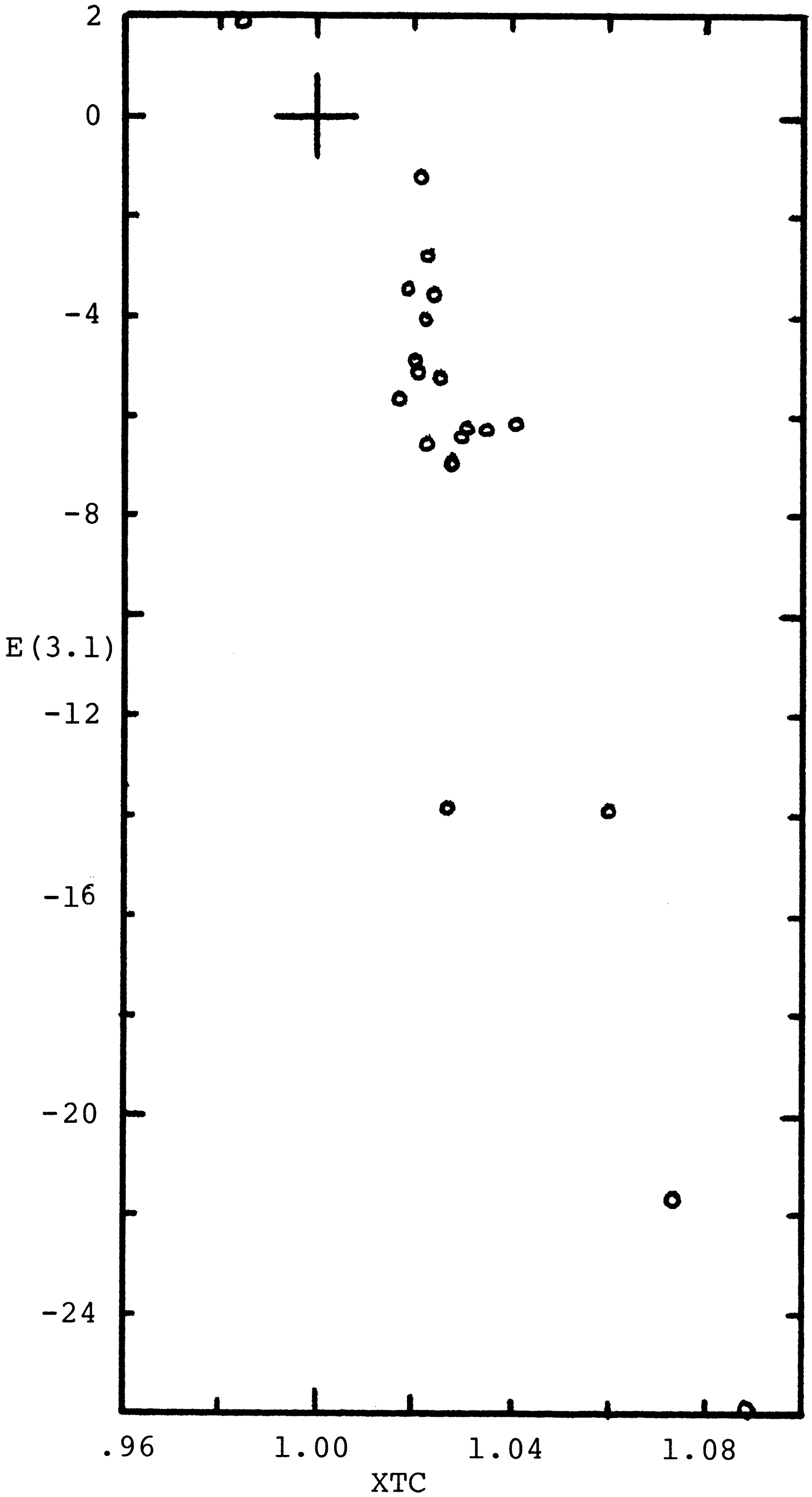


Figure 2.10. E(3.1) vs XTC: Lycoming Data

(Reference 12) Runs 153-159, 448-454, 467-473 (all modes included)

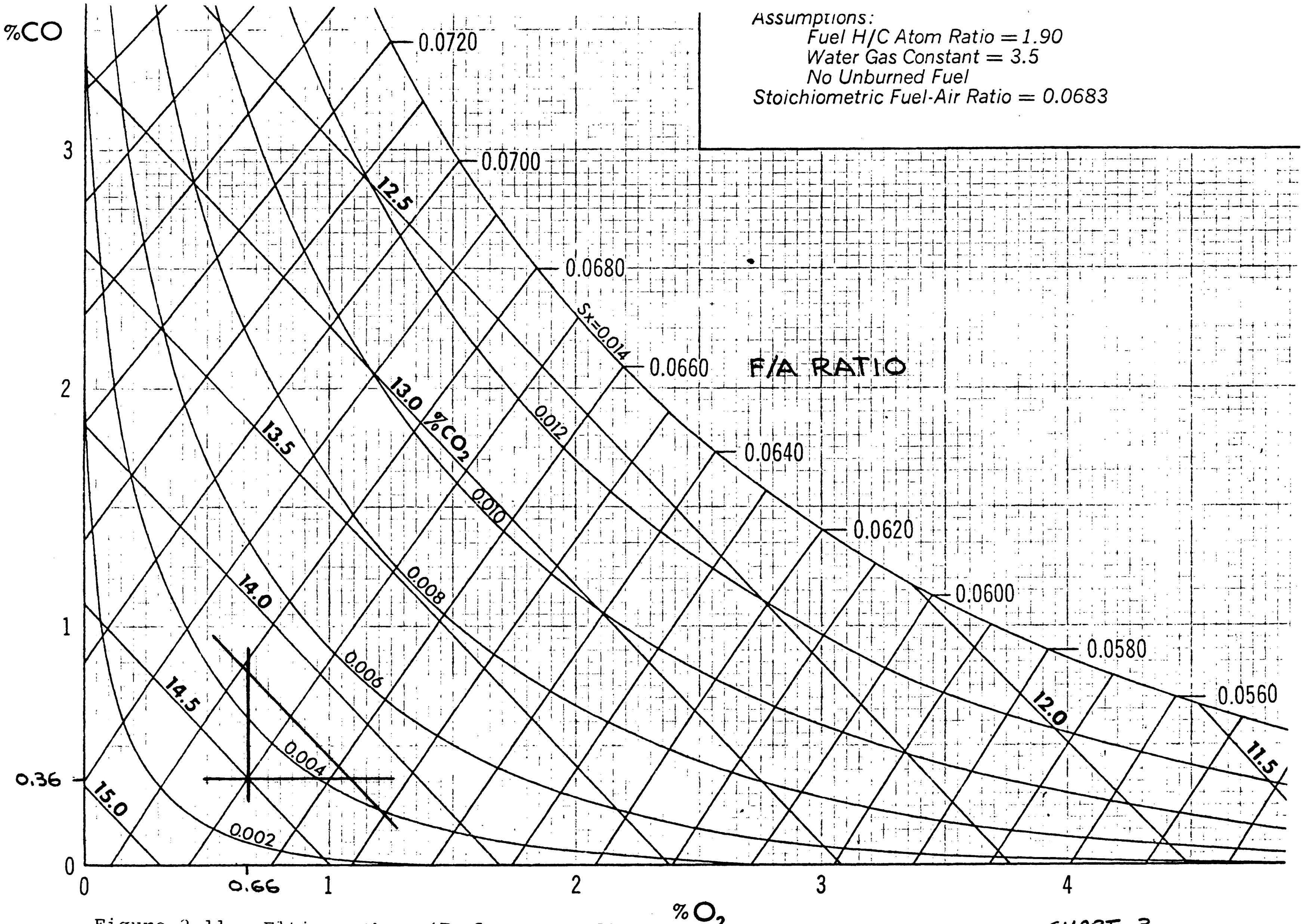


Figure 2.11- Eltinge Chart (Reference 7).

CHART 3

TABLE 2.5. COMPARISON OF MICHIGAN AND ELTINGE ANALYSES

Eltinge Run*	Eltinge		Michigan		
	EIE	Spindt Error	E(1.2)	ΔE	XTC
1	+0.4	1.671	1.667	4.394	.983
2	+0.4	0.600	0.567	5.384	.982
3	+0.3	1.356	1.214	5.030	.985
4	-0.2	0.887	0.858	-0.494	1.002
5	+0.6	1.751	1.639	8.437	.977
6	+0.1	0.156	0.009	1.640	.995
7	+0.1	1.727	1.625	2.395	.994
8	+0.4	-1.560	-1.672	5.777	.982
9	+0.3	1.605	1.510	3.561	.989
10	+0.5	2.087	2.128	7.243	.977
11	+0.3	2.100	1.906	4.653	.986
12	-0.1	1.902	1.973	0.517	.998
13	-0.1	1.170	1.169	-0.400	1.001

The data spread in figure 2.12 is due in part to the fact that Eltinge reports EIE only to the first decimal place.

Table 2.5 shows good agreement between Eltinge's Spindt error and the error E(1.2). Furthermore, an examination of figure 2.12 shows that both ΔE and XTC correlate well with EIE, so that any one of the three parameters EIE, ΔE or XTC could be used as an indicator of "instrument error."

Having related ΔE and XTC to EIE, the second part of the comparison was made in order to answer the following question. If we were to select an ideal run according to the Eltinge criteria, i.e. one having zero instrument error, and use the corresponding exhaust concentrations in the four Michigan methods, would there be differences in the calculated fuel-air ratio and what would be the magnitudes of the errors? Five points were selected from chart 5 of reference 7. These points were along the line of constant F/A equal to 0.066 and at CO2 concentrations of 14.0, 13.5, 13.0, 12.5 and 12.0 percent. Corresponding

---

*See table 1 in reference 7.

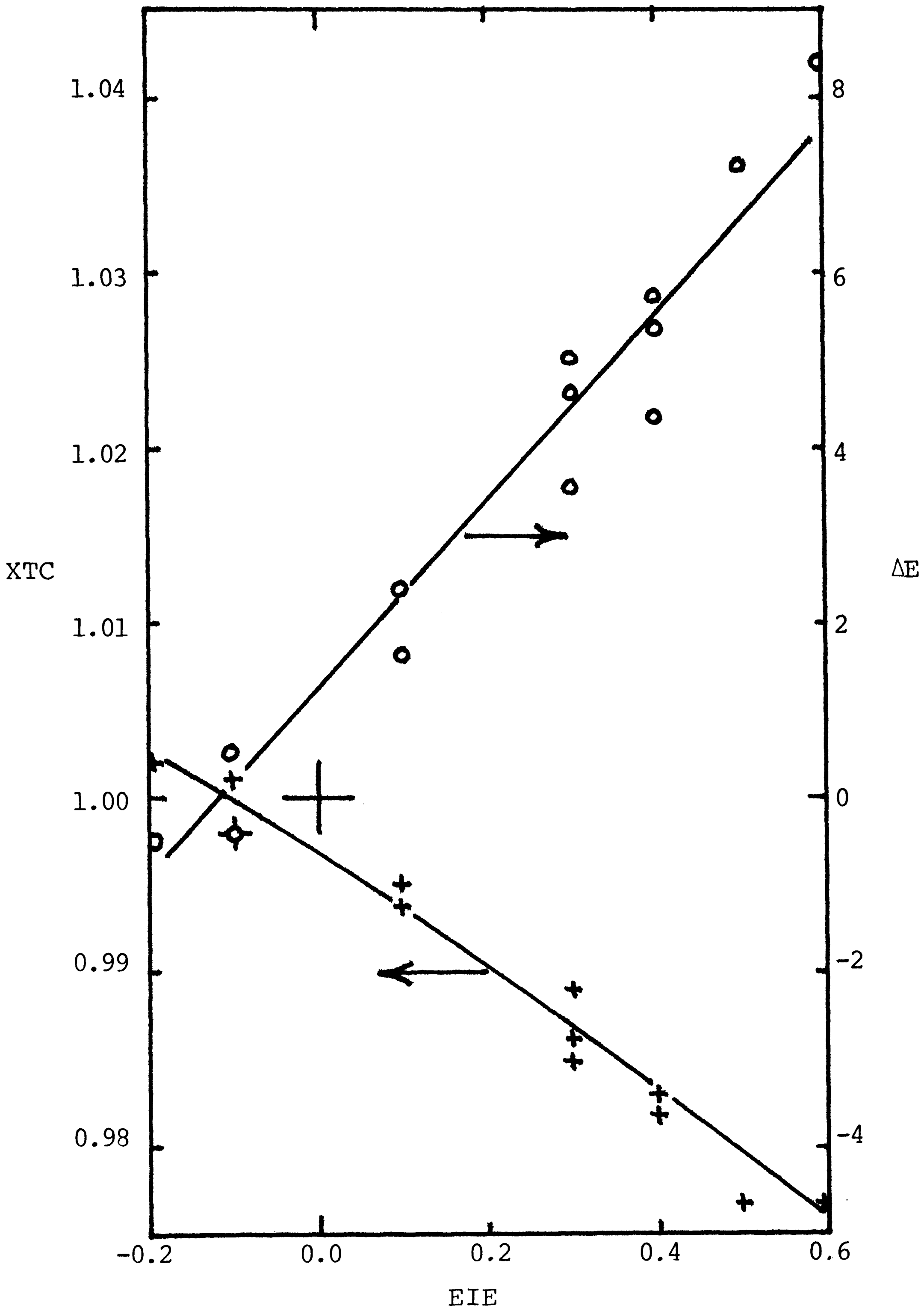


Figure 2.12. XTC and ΔE vs EIE:
Eltinge Data (Reference 7)

values of percent CO and O2 were selected from the chart and these values were used in computing fuel-air ratio using the four Michigan methods. The results, together with ΔE and XTC are shown in Table 2.6.

TABLE 2.6. CALCULATED FUEL/AIR ERRORS FOR ELTINGE ZERO-EIE DATA POINTS*

	F/A Percent Error				
Method	Point 1	Point 2	Point 3	Point 4	Point 5
1.2	0.143	-0.061	-0.234	-0.316	-0.426
2.1	-0.392	-0.534	-0.638	-0.670	-0.626
3.1	0.410	0.343	0.116	-0.006	-0.249
3.2	-0.119	-0.237	-0.384	-0.447	-0.500
ΔE	0.367	0.404	0.350	0.310	0.177
XTC	0.9985	0.9984	0.9986	0.9988	0.9993

*See chart 5 in reference 7.

The fact that all fuel-air errors are below one percent indicates excellent agreement between the Eltinge and Michigan methods over the region checked. On the basis of the above analysis, we come to the following conclusions:

1. There is excellent agreement between the Eltinge and Michigan methods for calculating fuel-air ratio and determining data validity.
2. When valid emission data is obtained, all four of the Michigan methods will give essentially the same calculated fuel-air ratio.
3. An indication of data validity is given by either XTC, ΔE or EIE. Ideal runs will result in the following values:

XTC ~ 1.00
ΔE ~ 0.0
EIE ~ 0.0

4. The Spindt error, in itself, is not a good indicator of data validity since some runs showing small Spindt errors can have excessively large fuel-air errors when calculated by the other Michigan methods. Under these conditions, values of XTC will be appreciably different from 1.0 (see section 2.3) and values of both ΔE and EIE will differ appreciably from 0.0.

2.4 CALCULATION OF EXHAUST MOLECULAR WEIGHT

One of the benefits of the Michigan computational procedure is the ability to compute exhaust molecular weight. This is made possible because the procedure determines the mole-fraction values of the ten major stable gaseous species in the exhaust. With these values, exhaust gas molecular weight is computed using the sum of products of mole fractions and molecular weights,

$$MWEXH = \sum_{i} X(i) * MW(i) \qquad (2.64)$$

Figure 2.13 shows calculated exhaust molecular weights, based on emission data from several sources, versus equivalence ratio. Also included is a curve based on equilibrium calculations by Teledyne-Continental Motors (reference 8) and a slightly modified curve used by AVCO-Lycoming (reference 9). It is evident that all values tend to agree within ± 1% at the high equivalence ratios. However, there is appreciable differences at the low equivalence ratios. Molecular weights calculated by the Michigan method using Eltinge's data, from automotive engine measurements, show excellent agreement with the curve based on the TCM equilibrium calculations. Results from lean-mixture runs at Michigan show much lower values. Lean runs from other sources were not examined.

The reason for the differences for lean mixtures becomes apparent when one examines the data in table 2.7. Eltinge's data, which was obtained for a 389 $in.^3$ V-8 engine, shows high values of CO2 concentration (11.25%) and low values of UHC and O2. This indicates relatively complete combustion. However, the Michigan data for the LIO-320 shows relatively low CO2 and high CO, UHC and O2. This results from poor combustion because of poor mixing during the idle operation. Therefore, this difference will affect the relative amounts of light and heavy molecular components in the exhaust, as also shown in table 2.7. The Michigan data shows a much lower mole-fraction of the heavy molecular specie CO2 and higher mole-fractions of the lighter species H2 and UHC. This will naturally result in a lower exhaust molecular weight.

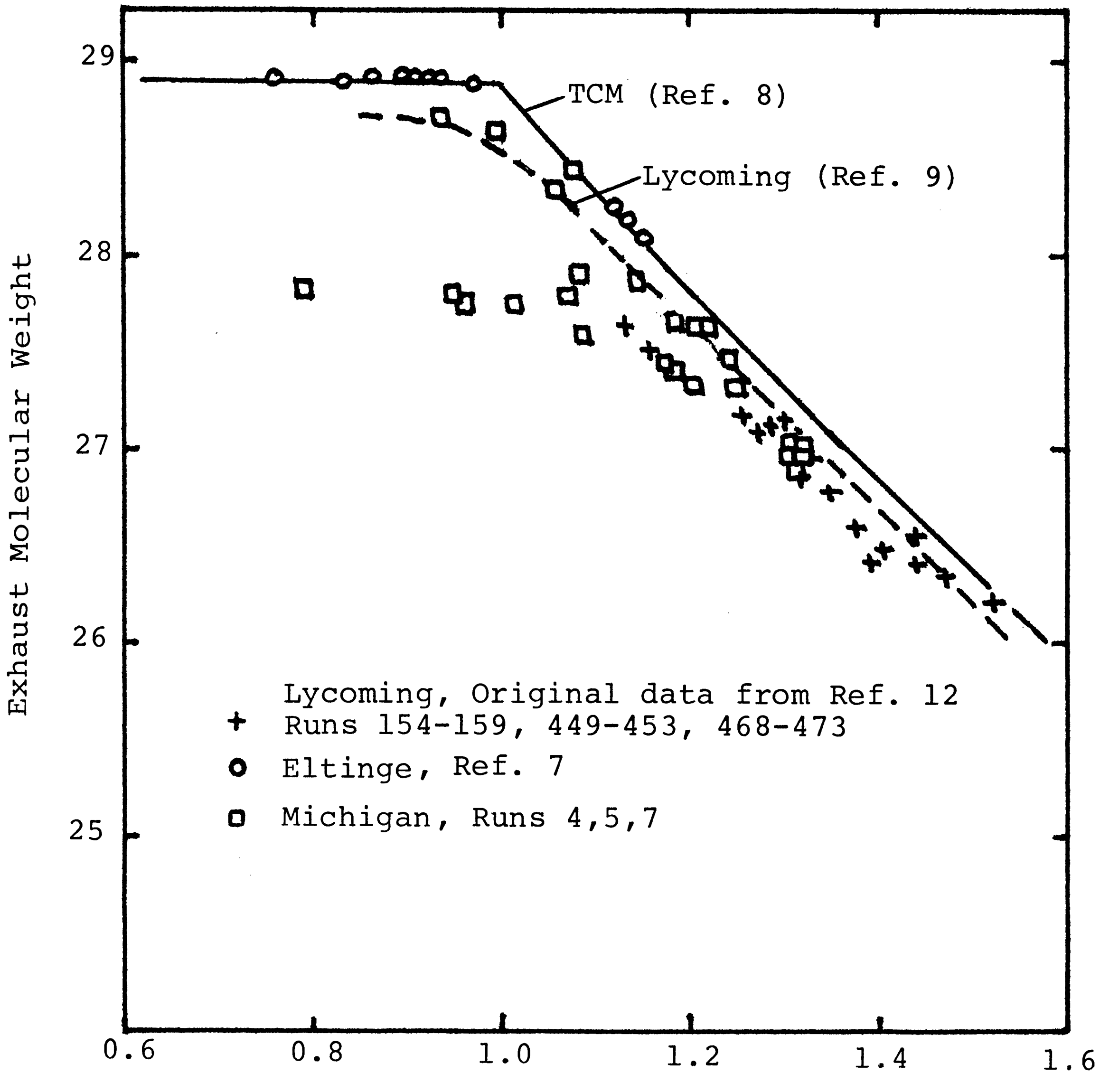


Figure 2.13. Calculated Exhaust Molecular Weight vs Equivalence Ratio

TABLE 2.7. CALCULATED EXHAUST PROPERTIES-LEAN MIXTURES

A. Eltinge Data

```
RUN:  7. 0                   CO2          CO          O2        HCC         NO        NOX
DRY MEASUREMENTS   112500.       1000.      53000.        0.         0.         0.
DRIED MEASUREMENTS      0.          0.         0.         0.         0.         0.
WET MEASUREMENTS        0.          0.         0.      1788.         0.         0.
  HTCR       EHCC       EHCR       CO2A       PSAT       PTRP          W       N2O2
 1. 900     1. 000     1. 850     0. 030    0. 08866    19. 000    0. 0000    3. 7274

  MTD     XTC        K    KWDD     KWD    PHIM   MWEXH PHICAL   FACAL      FAM  ERROR
 1. 2 0. 9964 3. 5000 0. 9073 0 9031 0. 7629 28. 9371 0. 7745 0. 05289 0. 05210  1 515
 XCO2    XCO     XHC     XO2    XH2O     XH2     XN2     XNO    XNO2     XAR     XC
0. 1016 0 0009 0. 0018 0. 0479 0. 0969 0. 0002 0. 7383 0. 0000 0. 0000 0. 0087 0. 0000
```

B. Michigan Data

```
RUN:  5. 1                   CO2          CO          O2        HCC         NO        NOX
DRY MEASUREMENTS        0.      17656.         0.         0.         0.         0.
DRIED MEASUREMENTS  51214.          0.    109523.         0.         0.         0.
WET MEASUREMENTS        0.          0.         0.     31808.       173.       223.
  HTCR       EHCC       EHCR       CO2A       PSAT       PTRP          W       N2O2
 2. 190     1 000      1. 850     0. 030    0. 08866    19. 000     0 0081     3 7274

  MTD     XTC        K    KWDD     KWD    PHIM   MWEXH PHICAL   FACAL      FAM  ERROR
 1. 2 1 0013 3. 5000 0. 9254 0. 9211 0. 7901 27. 8375 0. 7742 0. 05145 0 05251 -2. 011
 XCO2    XCO     XHC     XO2    XH2O     XH2     XN2     XNO    XNO2     XAR     XC
0. 0474 0. 0163 0 0318 0. 1014 0. 0788 0. 0077 0 7091 0. 0002 0. 0001 0. 0084 0. 0000
```

This leads to the conclusion that reasonably large differences in exhaust molecular weights can occur at low equivalence ratios, depending on the completeness of combustion. It appears that any value is possible in the range from about 27.75 to 28.95. Therefore, values based on equilibrium calculations are valid only when combustion is reasonably complete while a method such as the Michigan method, which is applicable under all conditions, should give better values of molecular weights over a broad range of combustion conditions.

These results therefore indicate that exhaust molecular weight can be used as an indicator of completeness of combustion. For any equivalence ratio, the exhaust molecular weight tends to approach the value given by the equilibrium calculation as the completeness of combustion improves. This is also brought out in our analysis of the data in chart 5, reference 7, where a direct correlation was found between Eltinge's mixture distribution parameter S_x and the calculated exhaust molecular weight. The results, for a fixed fuel-air ratio of 0.0660, show that as the mixture distribution improves (lower S_x), the molecular weight increases.

S_x	MWEXH
0.0116	28.356
0.0092	28.430
0.0067	28.503
0.0044	28.573
0.0022	28.643

2.5 CALCULATION OF WATER CORRECTION FACTORS FOR EXHAUST CONCENTRATION MEASUREMENTS

The computational procedures as set up in Section 2.1.5 of this report eliminate the need for water correction factors since the methods permit the use of either wet, dry or dried measurements. However, when desired for comparison purposes, water correction factors can be easily obtained from the computed values of XGD and XGDD since

$$KWD = XGD = 1 - XH2O \tag{2.65}$$

and

$$KWDD = XGDD = XGD + XH2ODD \tag{2.66}$$

The dry-to-wet correction factor is given by KWD and the dried-to-wet by KWDD. Some values are shown in table 2.7. Values for KWD are also shown in the various computer print-outs throughout this report.

3. UNIVERSITY OF MICHIGAN TEST FACILITY

The engine emissions test facility is located in a two room concrete structure within the Gas Dynamics Laboratories of the Department of Aerospace Engineering. The engine, dynamometer, and related instrumentation are located in a 22 ft x 13 ft test cell (figure 3.1) while the test operator, data acquisition system, and emission instrumentation are located in an adjacent 22 ft x 10 ft air conditioned control room (figure 3.2). Support equipment for the facility includes a 3000 psi high pressure air supply, water, electrical power (440, 220, and 110 volt circuits), and a Data General Nova computer.

Engines requiring dynafocal or bed mounts can be easily installed in the test stand. The present engine (Lycoming LIO-320-B1A), which required dynafocal mounting, was installed using a production aircraft engine mount with machined aluminum bushings in place of the standard rubber Lord bushings.

An eddy current — dry gap dynamometer with a 350 HP and 5000 RPM continuous operation capability is used as a solid state blending type system which allows the dynamometer to be operated in speed control, load control or a blend of these two modes. In the speed control mode the controller holds a desired RPM by varying the load in conjunction with engine power changes. In the load control mode the operator selects a given constant load level to apply to the engine regardless of speed. The blending option allows the selection of any combination of load and speed control.

The air flow distribution system, which includes the cooling air and engine induction air, is shown schematically in figures 3.3 - 3.5. The cooling air is supplied by a ceiling mounted centrifugal blower which has a capacity approaching 10,000 CFM at 10 in. H_2O. A damper system on the blower allows control of the blower pressure output over the range of 0 - 10 in. H_2O. The cooling air temperature can be controlled over a limited range by using two air intakes for the blower system, one intake drawing outside

Figure 3.1 Engine Test Stand

Figure 3.2 Engine Control Room

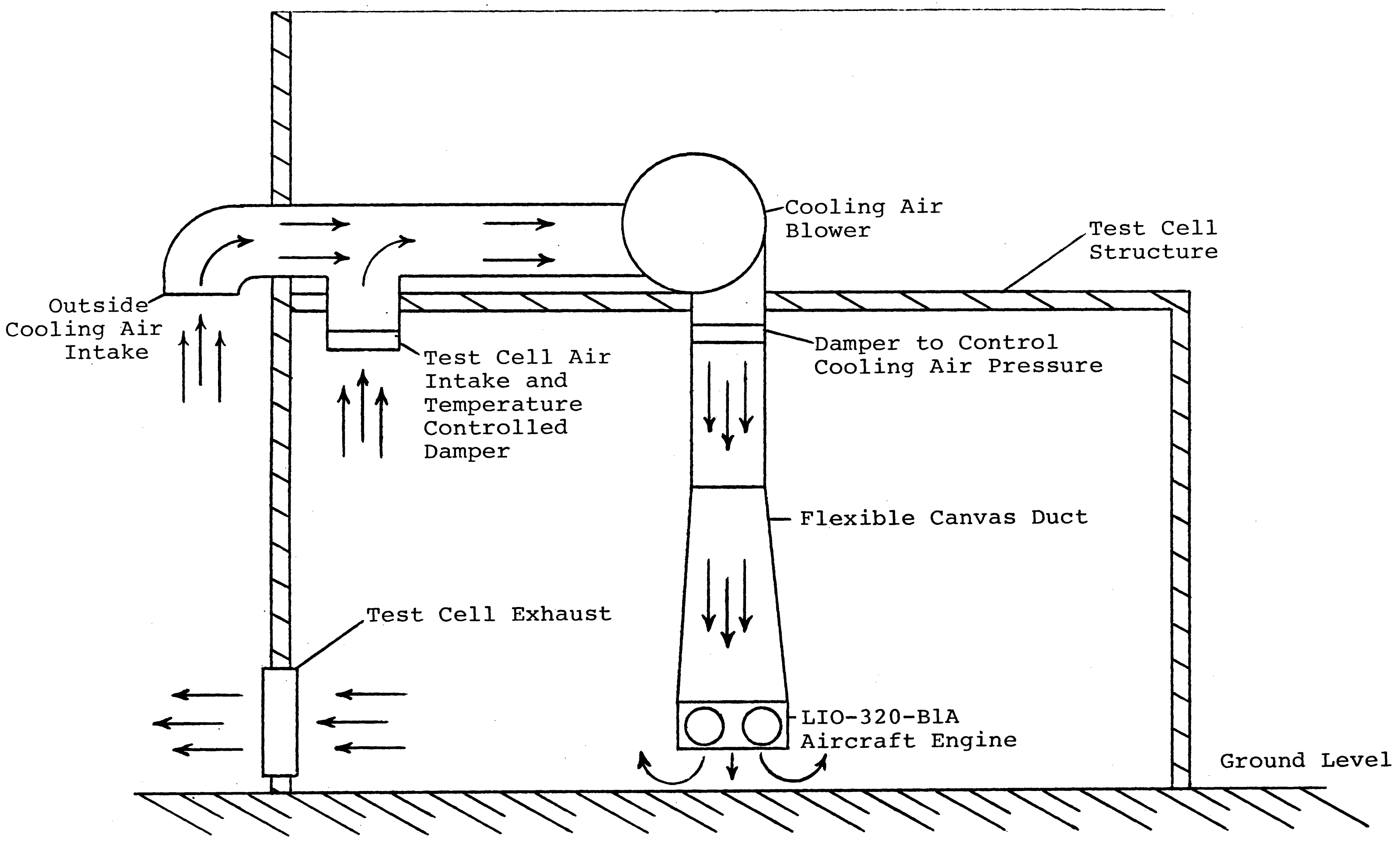


Figure 3.3. Cooling Air Flow Schematic

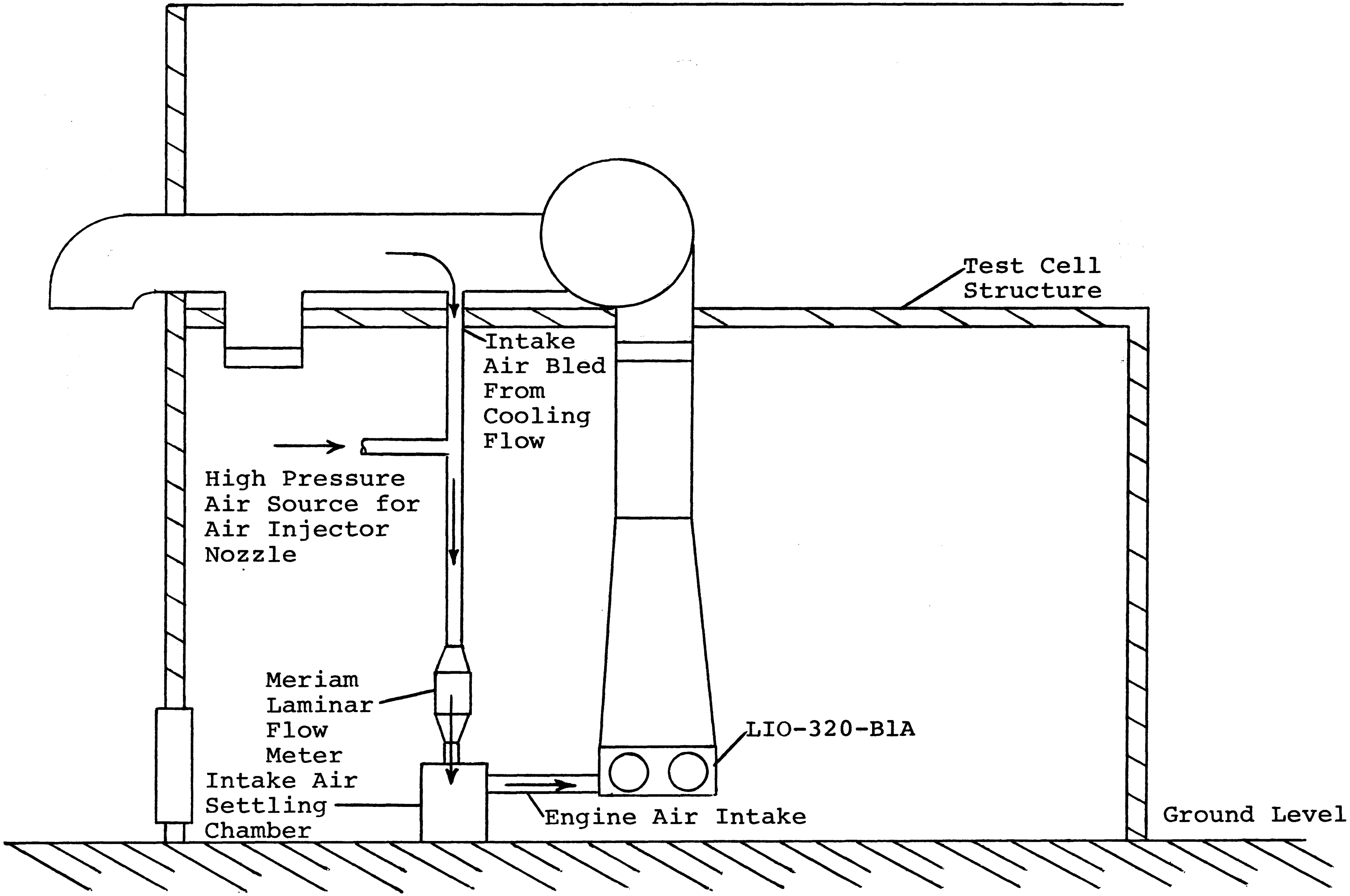


Figure 3.4. Intake Air Flow Schematic

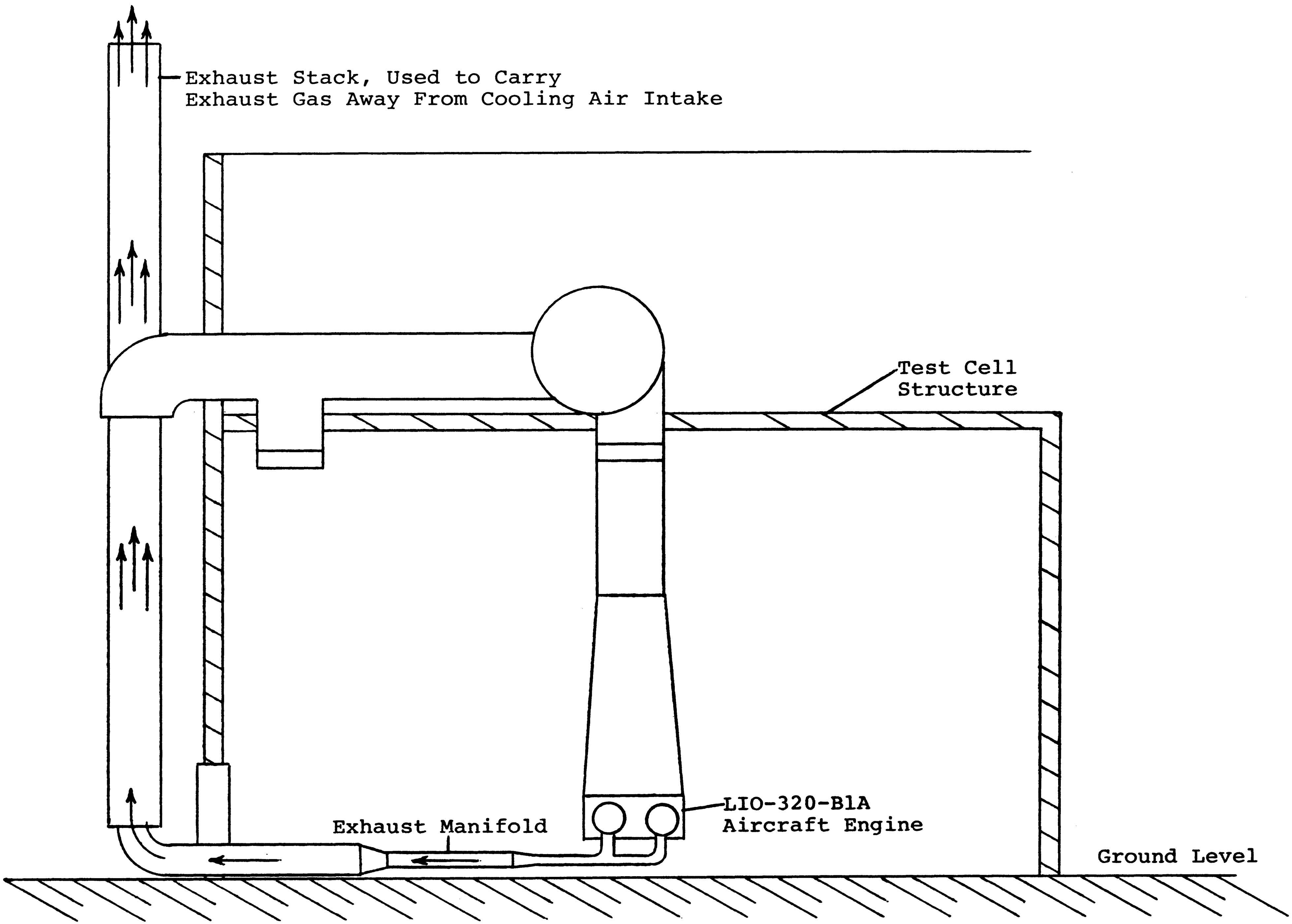


Figure 3.5. Exhaust Gas Flow Schematic

air and the other drawing air from inside the test cell. By varying the mixture of the test cell air and the outside air, it is possible to obtain a cooling air temperature in the range between the test cell temperature and the outside air temperature. To minimize any temperature differences between the induction air and cooling air, the induction air is obtained by bleeding air from the cooling air system.

Induction air flow rates are measured using a 2 in. Meriam laminar flow meter. Air flow rates are obtained by measuring the pressure drop across the meter and utilizing the previously obtained meter calibration curve. Calibration tests were periodically performed to check accuracy. A 2 in. flow meter was chosen to insure accuracy of the low air flow rates encountered in the idle and taxi modes. Due to the small size of this device, large pressure drops result from the high air flow rates encountered during the takeoff, climbout, and approach modes. These high pressure drops across the meter cause a low engine intake air pressure. In order to correct for this low pressure, a supersonic air injector was installed upstream of this device. By varying the flow through this injector, it is possible to set the induction air total pressure at the engine intake to the desired pressure level for all test conditions. This pressure is usually set to ambient pressure.

Fuel flow rates are measured using an electronic timer and a weight and balance system. As a check on this method, flow rotameters have been installed and are monitored during testing.

The following pressure and temperature measurements are also recorded during engine operations.

Pressure

1. Intake Air ΔP
2. Intake Air, Total
3. Intake Air, Static
4. Engine Manifold
5. Fuel
6. Cooling Air, Total
7. Engine Oil
8. Induction Air Injector, Upstream
9. Barometric

Temperature

1. Cylinder Head
2. Exhaust Gas
3. Cooling Air
4. Intake Air, Dry Bulb
5. Intake Air, Dew Point
6. Fuel Intake
7. Oil
8. Dynamometer Cooling Water
9. Ambient (Barometer)

A high speed data acquisition system is being integrated into the facility. This system consists of a high speed analog processor, an analog to digital converter, a small mini-computer, and a high speed paper tape punch. This system has the capability of obtaining two to three high speed (up to 20,000 samples/sec) data scans for a given steady state operating level and storing these points in memory. While in memory, the capability is available to perform some data scaling or reduction. This data can then be transferred to the paper tape punch for further data reduction using either the laboratories' "in-house" computer system or by using the University's time sharing computer system.

The emissions measuring system used in this facility is a modified Scott model 108-H and is described in Section 4 of this report. This system was designed to meet the specifications pertaining to sampling procedures, particularly with regard to response times, as given in the Federal Register (reference 6). A more detailed description and discussion of this equipment is given in section 4 of this report.

To provide the capability of rapidly changing from one probe position to another from which the exhaust sample is to be taken, an electrically heated system of stainless steel valves was assembled. This valving system allows convenient selection during a test of any one of four gas sample probes, located at different positions in the exhaust system. The valve system is controlled from the control room of the test facility, thereby allowing maximum safety and flexibility during the sampling procedure.

A variable position sampling probe, which allows an exhaust gas sample to be taken at any position within the engine exhaust tailpipe, is also available.

4. INSTRUMENTATION FOR EMISSION MEASUREMENTS

The objectives of this program are met only when reliable emission measurements are made. Therefore, a considerable portion of our effort was directed at the problems associated with the instrumentation, which included problems of design, construction and usage. Examples of problem areas are:

1. Reliable NOX-converter performance.
2. Water condensation at various points in the system.
3. Response times associated with sample flow rates and possible reactions in the sampling line.
4. Manufacturing quality control.
5. Reliability and frequency of repair.

Our conclusion is that some efforts should be made to improve the overall reliability of the instrumentation package and to standardize the instrument package and operating procedures.

4.1 EMISSION MEASUREMENT CONSOLE

A Scott Laboratories Emission Measurement Console, a modified Model No. 108-H, was used in this test program. The unit is pictured in figure 3.2 and houses the following five major analytical components.

1. Beckman Model 864 Infrared Analyzer for CO2.
2. Beckman Model 865 Infrared Analyzer for CO.
3. Beckman Model 741 Oxygen Analyzer.
4. Scott Model 125 Chemiluminescence Analyzer for NO/NOX.
5. Scott Model 415 Hydrocarbon Analyzer.

The sample gas, after entering the console, is split three ways. One portion passes directly to the total hydrocarbon analyzer resulting in a wet hydrocarbon measurement. The second portion passes to the NOX analyzer, where it can go directly to the analzer or can first pass through the NOX converter. This provides wet measurements of either NO or

NOX. The third portion passes through the water trap where most of the water vapor is condensed, resulting in a dried sample, and then the sample is further split. One portion passes in series through the CO2 and O2 analyzers to give dried measurements, the other portion passes through a drier and then to the CO analyzer, resulting in a dry measurement. The sample lines are either heated or insulated to minimize condensation, the temperatures being in the range from 300 to 390°F.

4.2. INSTRUMENTATION PROBLEMS

A large number of problems were encountered with the emissions measurement console, some of which were the result of poor quality control during assembly while others were because of inadequate design. Following is a list of major problems encountered and their solutions if found:

1. Fittings must be checked periodically for tightness to eliminate leakage. Fittings covered with insulation are difficult to check.
2. The reed valve in the external pump requires frequent checks for failure. Heat at the pump distorts the teflon seal such that the reed valve is stuck open and the pump's efficiency is drastically reduced. Also, air leakage may occur past the teflon seal diluting the sample.
3. After several months of operation the two internal pumps began an on-off cycle during operation due to overheating. This produced drastic changes in flows throughout the system requiring the operators to continually correct flows. This problem can be avoided by eliminating the internal pumps from the system and increasing the external pump capacity. This solution is desirable since it will decrease the possible problems of emission sample dilution due to air leakage since the system will be under positive pressure.

4. Valves were insufficient to hold pressure resulting in leakage when spanning and zeroing.
5. Excessive dirt accumulation led to valve failures. See item 9.
6. Water condensation in the flow lines occurred during initial emissions sampling. System corrections were required.
7. The emissions measurement system contained two pumps internal to the console and an external boost pump was added to increase the sample flow rates and thus meet the response times required by the Federal Register. The resulting increased flow through the system exceeded the capacity of the condensation coils in the trap causing condensation at various points in the measurement system. The condensation problem was partially alleviated by using two traps in series.
8. Bypass vents are required because the analyzer flow requirements are much smaller than the sample flow rates. This was especially true on our system since its sample flow rate was increased to reduce system response time. These bypass systems were not heated nor sized to the higher flow rates. Hence they served as condensation points in the system. Since all bypasses but one have a flow meter, condensed droplets passing through the meter would strike the floats and induce an oscillation in the measurement systems. When this would occur data taking had to be stopped and the system purged with dry nitrogen. After the system was dried out, data could again be taken. This condensation particularly affected the NO/NOX line. The problem has been effectively overcome by adding insulation to some lines and heating additional lines. The NO/NOX line temperature was increased to 390°F and the external sample line temperature was increased to 370°F.

9. The probe-purge system as originally designed bypassed the external filter. Valving did not allow for sufficient purge pressure to avoid drawing exhaust gases into the measurement console bypassing the filter. This resulted in dirt accumulation in some valves, during purging, leading to leakage. This system was redesigned using a 1500 psi valve and directing all flow through the filter.

4.2.1. CO INFRARED ANALYZER

We have found two main causes for failure of the CO measurement system. First, dirt accumulation in the check valves between the CO flow line and the CO2 flow line resulted in a leak between the two lines causing the CO analyzer to be very sensitive to the sample flow rate. This problem was corrected by cleaning the check valves. This problem could occur in field tests if the operating personnel are unaware of the problem.

The second problem was leakage between the high concentration sample cell and the low concentration sample cell resulting in a continuously increasing CO reading as sample gas (or span gas) leaks from the HI cell to the LO cell. The analyzer cannot be properly zeroed unless both cells are then purged with N2. This problem, due to a poorly cemented window between the two cells, occurred twice within nine months. A temporary fix consisting of a slow purge of the low concentration cell with N2 permits satisfactory operation.

CO2 interference with the CO analyzer was tested by passing a 13.11% CO2 span gas through the CO analyzer after initial calibration. A zero reading was obtained indicating no interference at this concentration level. Thereafter, the use of Ascarite for removal of CO2 as an interference gas was discontinued.

4.2.2. CO2 INFRARED ANALYZER

No problems have been encountered with the CO2 analyzer in our testing.

CO interference with the CO2 analyzer was tested by passing a span gas of 10.70% CO through the CO2 analyzer after initial calibration. This resulted in a reading of approximately 0.2 of a chart unit. This indicates that during emissions measurement CO interference would be within the noise level of the recorder trace. This error can be neglected since the span gas for calibration is accurate to within only ± 5.0%.

4.2.3. O2 ANALYZER

In terms of the instrumentation sensitivity, the O2 detector does not have the sensitivity required to make good measurements in the fuel rich environment of an aircraft engine. The O2 detector has the slowest response time of all the components, on the order of 2.5 seconds, somewhat higher than the 2 second response time required by the Federal Register.

4.2.4. TOTAL HYDROCARBON FLAME IONIZATION DETECTOR (FID)

The FID is very sensitive to sample pressure. A change in sample pressure of 2 or 3 inches of water out of 40 inches of water can result in a 10% to 15% change in the total hydrocarbon (HCC) reading when sampling or spanning. Careful regulation of this pressure is required.

Condensation was a problem encountered with the FID when sampling at engine high power modes. To alleviate this problem a bleed valve was installed immediately ahead of the FID to allow only necessary flow through the FID. Also a surge tank (6 ounce volume) was installed between the bleed valve and the FID to collect the small amount of condensed water. The valve and upper section of the surge tank were insulated.

At idle and taxi modes, chart readings consisted of a wide band of "hash" occupying up to 70% of the chart scale. The surge tank afforded better mixing of the low and high

THC concentration pulses allowing easier and more accurate determination of the average of the chart reading.

O2 interference with the HCC measurement was tested. The FID was calibrated on range 1K and a 99.6% O2 span gas was passed through the FID resulting in a HCC reading of approximately 75 ppm carbon. At a concentration of 5% O2 (roughly equivalent to the O2 level at idle and taxi) interference would result in an increase of the HCC measurement of only about 3 ppm carbon. This compares with measurements on the order of 25000 ppm carbon at idle. At higher power levels the O2 concentration falls to about 0.15%, so the effect is negligible.

4.2.5. NO/NOX CHEMILUMINESCENCE ANALYZER

The central problem encountered with the NO analyzer was condensation and the resultant oscillations as mentioned previously. Heating and insulating additional segments of the sample lines, increasing the line temperature to 390°F and increasing the external sample line temperature to 370°F has largely eliminated the condensation problem.

The flow lines in the interior of the NO analyzer were also insulated and heated, helping to decrease the effect of changes of viscosity between sampling hot exhaust gases and spanning with gas at room temperature. Pre-heating of the span gas should also improve performance, decreasing span drift, but as yet has not been tried.

Efforts at EPA, Ann Arbor, Michigan, have shown that for accurate measurement of NO/NOX in exhaust gases the sample flow supplied by the external pump should be, at a minimum, 60 scfh. Otherwise, reactions will significantly reduce the concentrations of NO/NOX. Also, EPA testing has shown that no effects on NO/NOX measurements result by passing the sample through a condenser which would alleviate the condensation problem. This needs to be looked into further at varying levels of NO/NOX.

Measurement of NOX has been generally unsuccessful. Only at high power modes is a NOX reading usually obtainable. At idle and taxi the NOX reading is usually lower than the separate NO reading indicating other reactions are taking place other than conversion of NOX to NO. Some tests reported in the literature indicate that NOX reacts with CO to eliminate NO2 in a sample. We have run tests mixing known amounts of CO with an NO/NO2 span gas to determine the extent of this effect. CO dilution of the NO/NO2 gas was increased for a series of experiments. The results show that very high concentrations of CO are required in order for an appreciable effect to occur. However, these experiments were conducted with cold gases and the possibility remains that hot sample gases would lead to a different conclusion. While this problem is worth further investigation, it is not critical to the problem at hand in that NOX levels are well below EPA standards and, further, our sensitivity analysis shows that NO has no significant effect on calculated fuel/air ratio.

4.3. COMMENTS

1. To obtain accurate measurements, constant control is required of the flow rates and engine temperatures. Constant monitoring is also required for the detection of partial failures which are not always obvious, e.g. small leaks in flow lines or analyzers.
2. When an open engine exhaust pipe is used, probe location is important, especially during the idle and taxi modes. If the probe is not far enough upstream of the open end of the exhaust, engine pulsations will draw ambient air into the region of the probe and dilute the sample.
3. An automated data acquisition system is highly desirable since the time consumed in manual reduction of the data on the recorder charts is great. It is also desirable to have on-line capabilities to obtain quick feedback of the computed fuel/air ratio in order to have quick evaluation of the test run.
4. Experience has demonstrated that the emission instrument console should be checked at frequent intervals for leaks and other malfunctions.

5. There is a need for a standardized design for the emissions measurement console and for greatly improved quality control in its manufacture.
6. A standardized test procedure should be developed specifying the operational steps for both the instrument console and the engine.
7. If the emission measurement package is viewed in its entirety, a number of shortcomings were found which would reflect not only on the accuracy of the data taken but also on whether or not data taken by other systems is indeed comparable. This included those data taken from emission systems made by the same manufacturer.

   It was found that the emission packages made by the same manufacturer varied as a function of when they were made. We found different types of NO and HC detectors used on supposedly identical systems. Different recorders were used. And, most importantly, if the sample lines flow rates vary between units, the time response and effect of condensation will be a strong variable.
8. It was found that when spanning the CO, FID, and NO/NOX analyzers, particularly after sampling hot exhaust gases, that the span reading would quickly respond towards the correct span reading until reaching about 90% of the span value, after which the reading gradually increases approaching the correct span reading. This could be cause for error in the chart readings. Heated span gas should be tested to determine the effect on readings.

5. UNIVERSITY OF MICHIGAN ENGINE EMISSION DATA

5.1 AVCO-LYCOMING LIO-320 BASELINE RUNS

Test results for two low error baseline runs (runs 4 and 7) and one high error baseline run (run 16) on the AVCO-Lycoming LIO-320 BlA engine are included in the form of bar charts, figures 5.1.A-5.3.C, and computer outputs, tables 5.2-5.4, at the end of this section. Test facilities for running the tests are shown in figures 3.1 and 3.2 in section 3 of this report.

The bar charts show the fraction of EPA standard contributed by each of the modes for each of the pollutants. At the extreme right are the total emissions relative to the EPA standard for the 7-mode cycle. The Federal Standards used are:

Hydrocarbons	0.00190	lb/rated power/cycle
Carbon Monoxide	0.042	lb/rated power/cycle
Oxides of Nitrogen	0.0015	lb/rated power/cycle

A separate chart is shown for each of the computational procedures, Methods 1.2, 2.1, and 3.1, and it is obvious that the three methods show good agreement for the low error runs but poor agreement for the high error run.

Table 5.1 shows the results of an error analysis of these runs. Shown are the fuel-air percent errors for Methods 3.1 and 1.2, the differences between these values (ΔE) and the sums of gaseous mole-fractions (XTC). An examination of E(1.2) values for the three baseline runs shows relatively small differences. Neglecting the idle runs, the values are in general below about 2.5%, implying that the Spindt error shows these runs to be of equal reliability. However, an examination of ΔE and XTC values shows that only runs 4 and 7 have acceptable values, but that run 16 does not. This is further evidence that the Spindt error in itself is not a good indicator of data reliability.

The bar chart results for runs 4 and 7 show that the levels of CO far exceed the Federal Standards, that HC is a borderline pollutant which may measure above or below the Standard and that NO_x is far below the Standard.

TABLE 5.1. ERROR ANALYSIS OF RUNS 4, 7 AND 16

Run	E(3.1)	E(1.2)	ΔE	XTC
4.1	17.332	7.204	10.128	0.969
4.2	2.707	-2.099	4.806	0.980
4.3	1.918	0.678	1.240	0.995
4.4	-1.128	-1.198	0.070	0.999
4.5	-2.572	-2.202	-0.370	1.002
4.6	1.671	-1.443	3.114	0.987
4.7	21.718	11.484	10.234	0.970
7.1	-11.579	1.884	-13.463	1.039
7.2	-5.565	-2.180	-3.385	1.013
7.3	3.746	1.537	2.209	0.990
7.4	-0.059	-0.295	0.236	0.999
7.5	-0.711	-1.249	0.538	0.998
7.6	-6.991	-1.354	-5.637	1.023
7.7	-8.582	0.107	-8.689	1.028
16.1	60.171	-14.658	74.829	0.763
16.2	48.539	0.043	48.496	0.784
16.3	56.581	2.815	53.766	0.752
16.4	56.095	0.570	55.525	0.739
16.5	51.188	-1.157	52.345	0.751
16.6	47.140	-5.785	52.925	0.770
16.7	52.759	-15.091	67.850	0.776

Attention is called to run 7.4 in the computer print-outs at the end of this section. Note that the four methods of computation give excellent agreement, not only for fuel-air ratio, but for all computed values as well. Because of such runs it is felt that all four methods of computation will give similar results if measurements of exhaust concentrations are accurate. However, it is possible that slight changes of the water gas equilibrium constant may be required for the different modes of operation to reflect possible differences in freeze-out temperatures of the exhaust products. This may be most important at idle and taxi modes. Because of the complex interaction of the many input variables, the problem of selecting the proper value of the equilibrium constant for the various operating modes cannot be solved without further study.

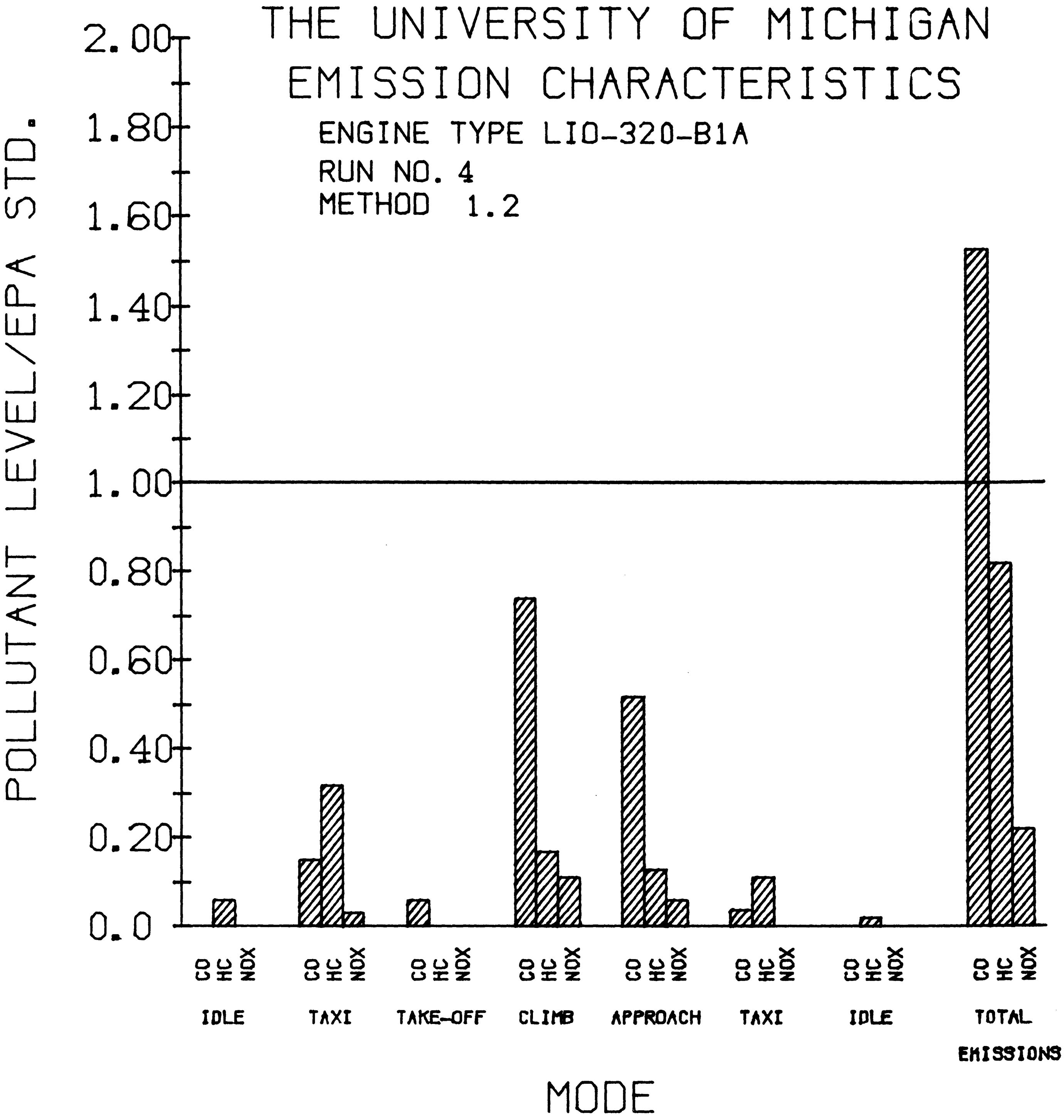


Figure 5.1.A. LIO-320 Baseline Results: Run 4, Method 1.2.

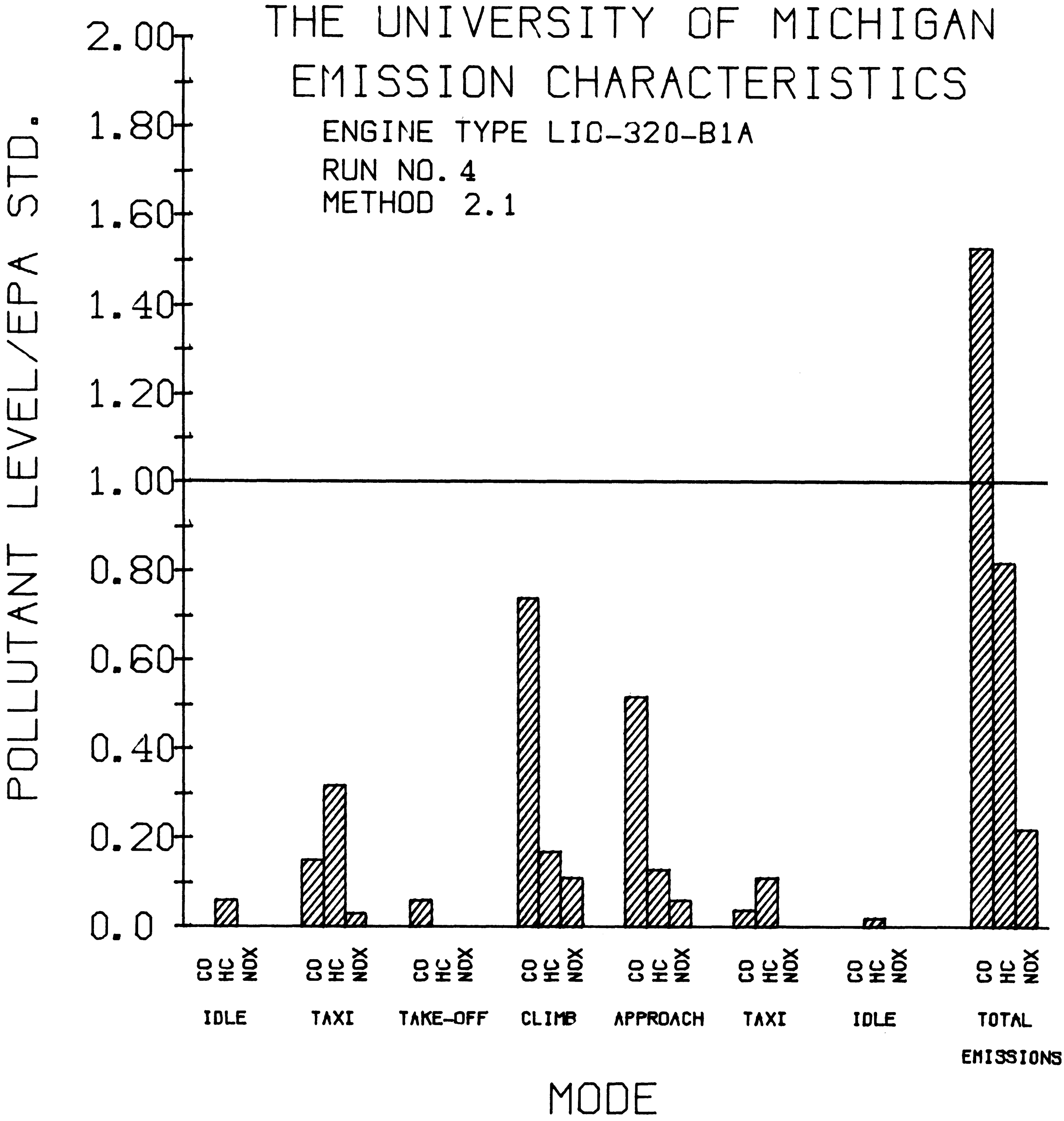


Figure 5.1.B. LIO-320 Baseline Results: Run 4, Method 2.1.

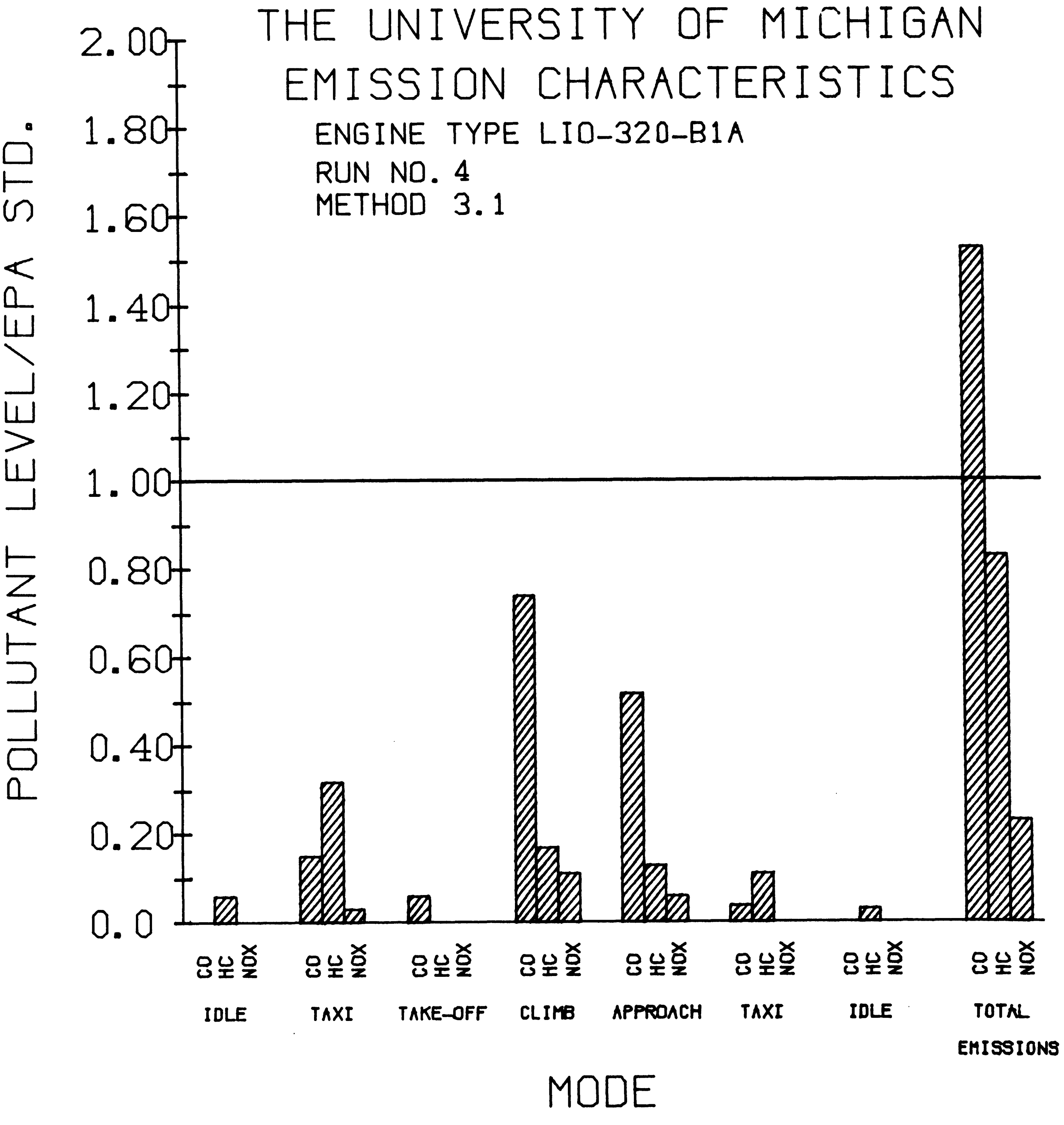


Figure 5.1.C. LIO-320 Baseline Results:
Run 4, Method 3.1.

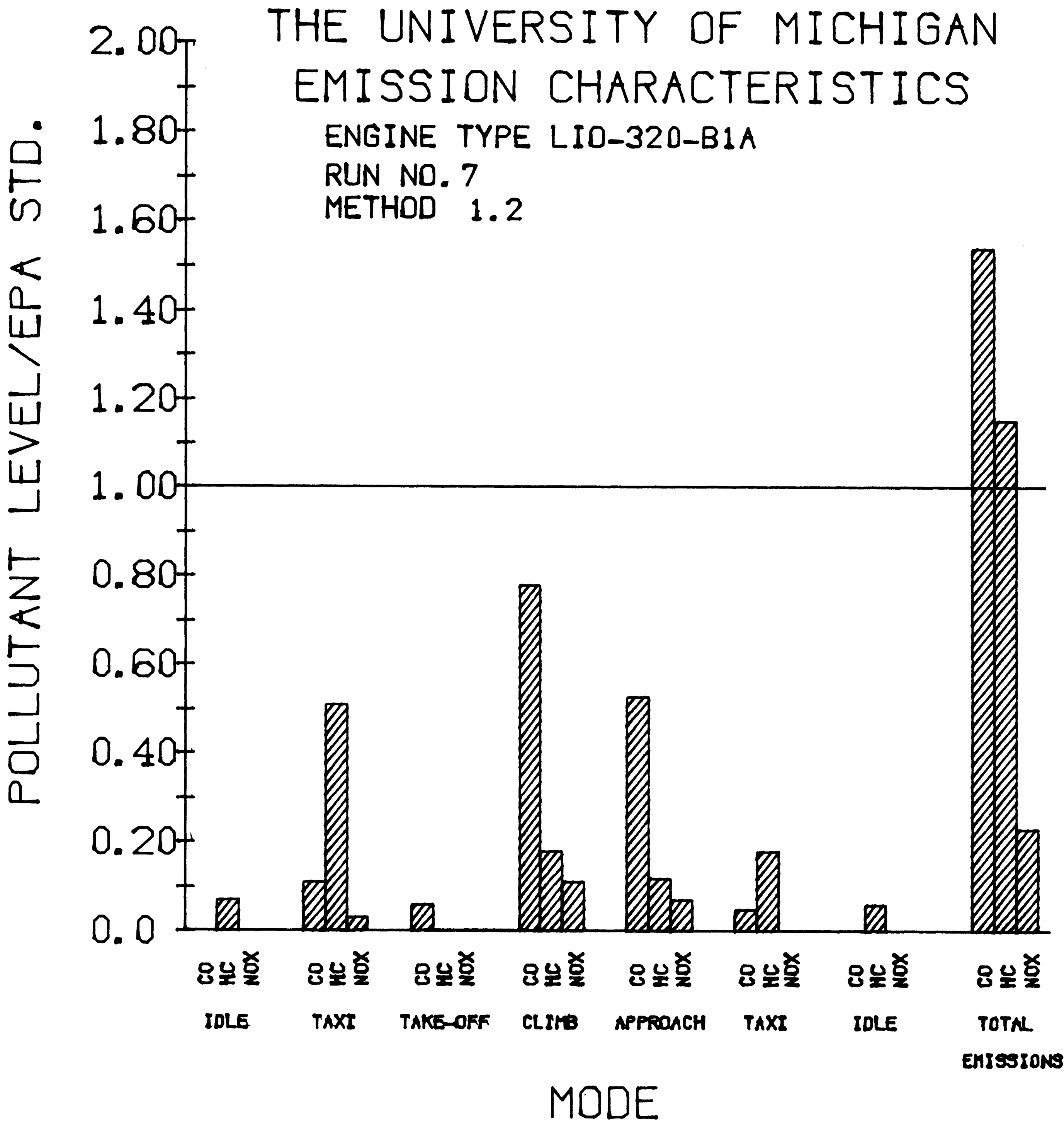


Figure 5.2.A. LIO-320 Baseline Results: Run 7, Method 1.2.

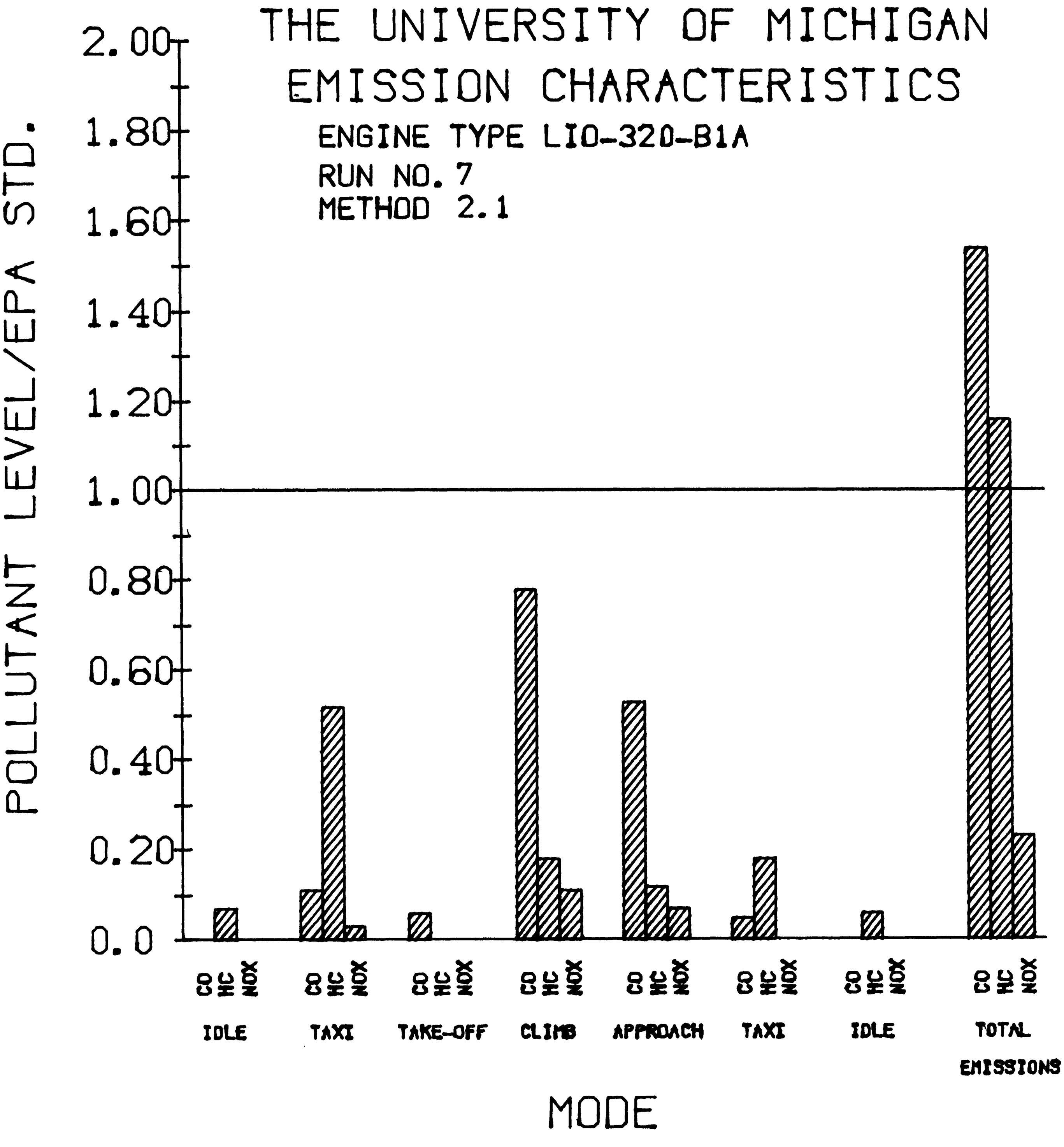


Figure 5.2.B. LIO-320 Baseline Results: Run 7, Method 2.1.

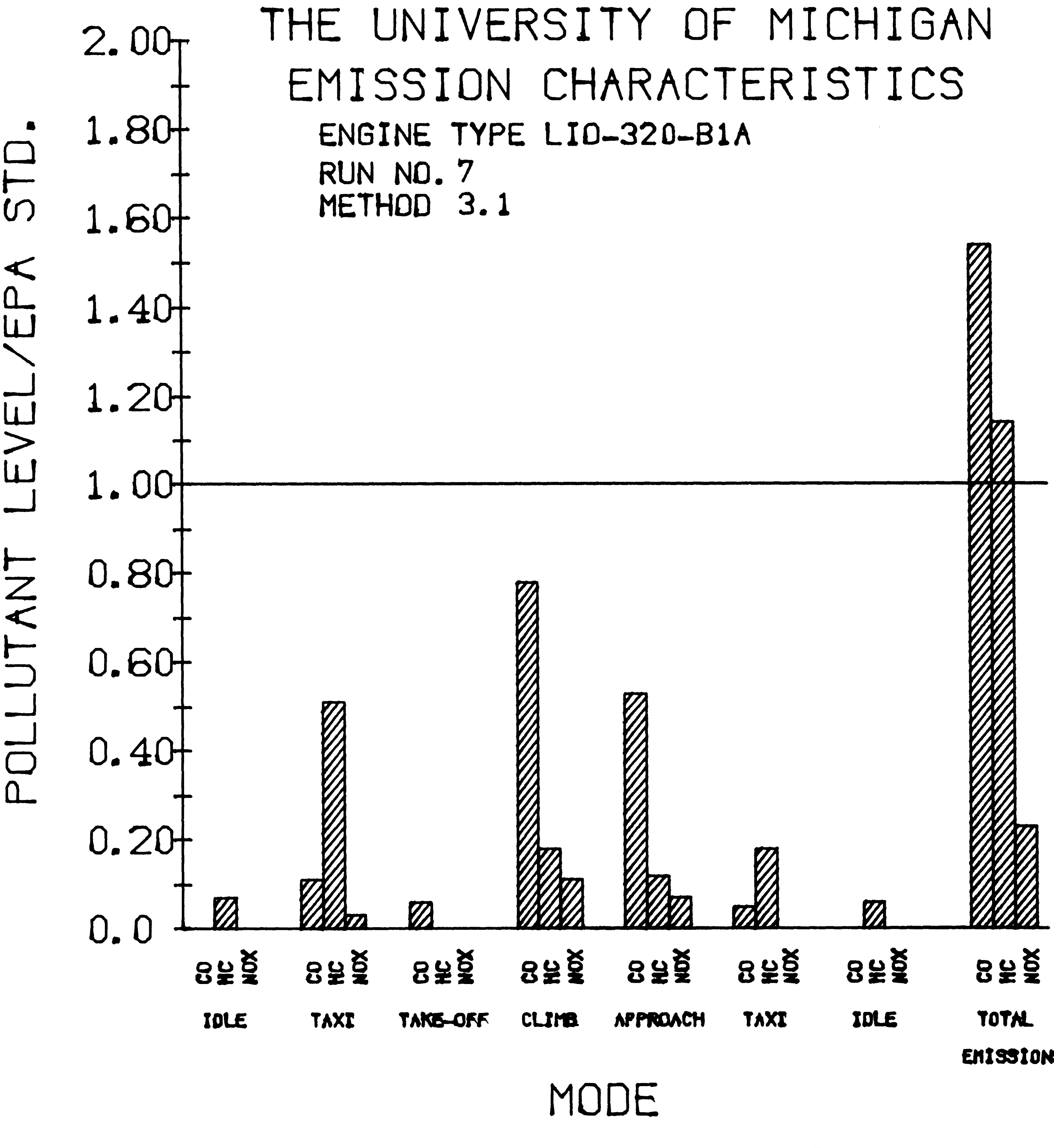


Figure 5.2.C. LIO-320 Baseline Results:
Run 7, Method 3.1.

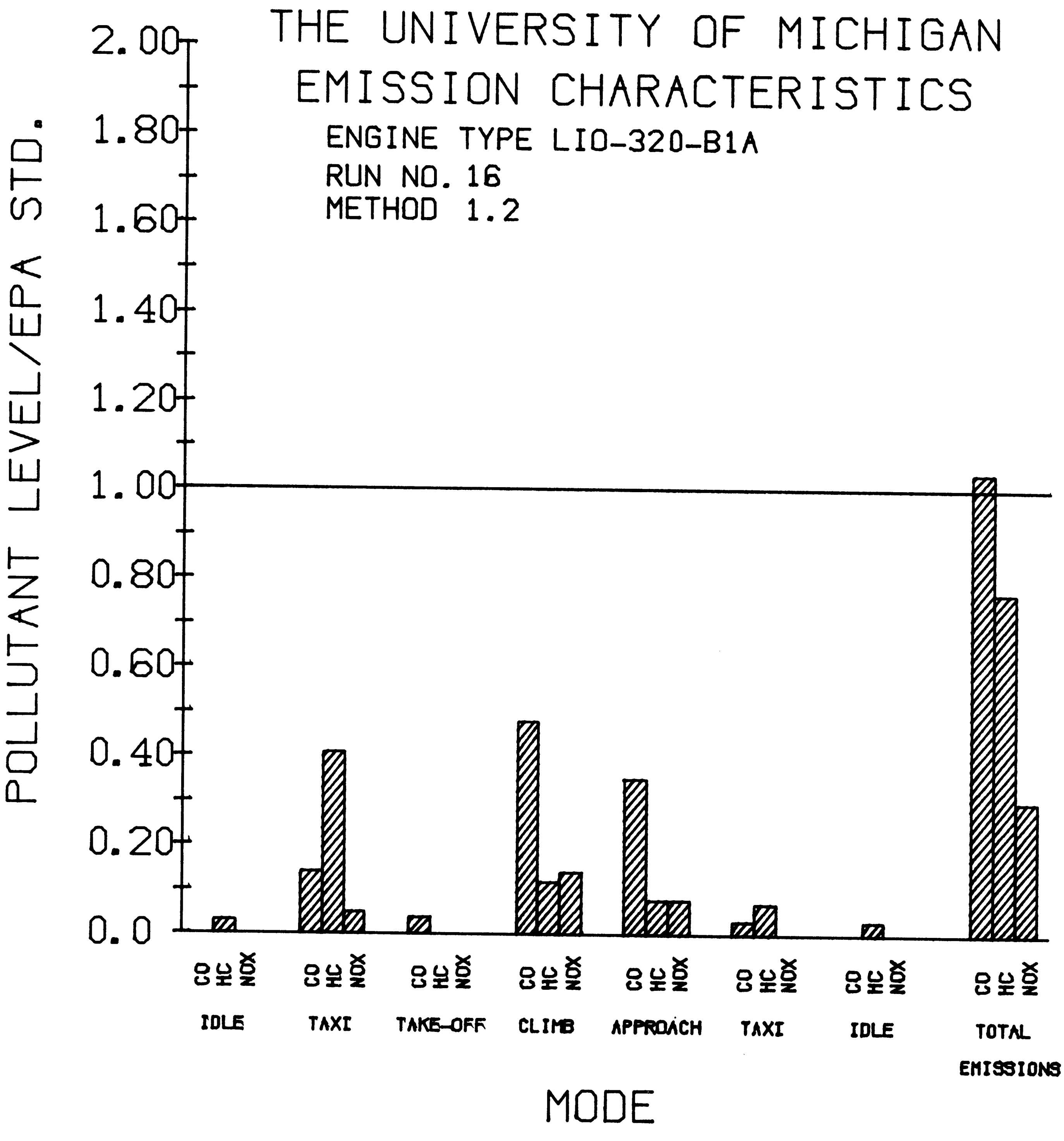


Figure 5.3.A. LIO-320 Baseline Results:
Run 16, Method 1.2.

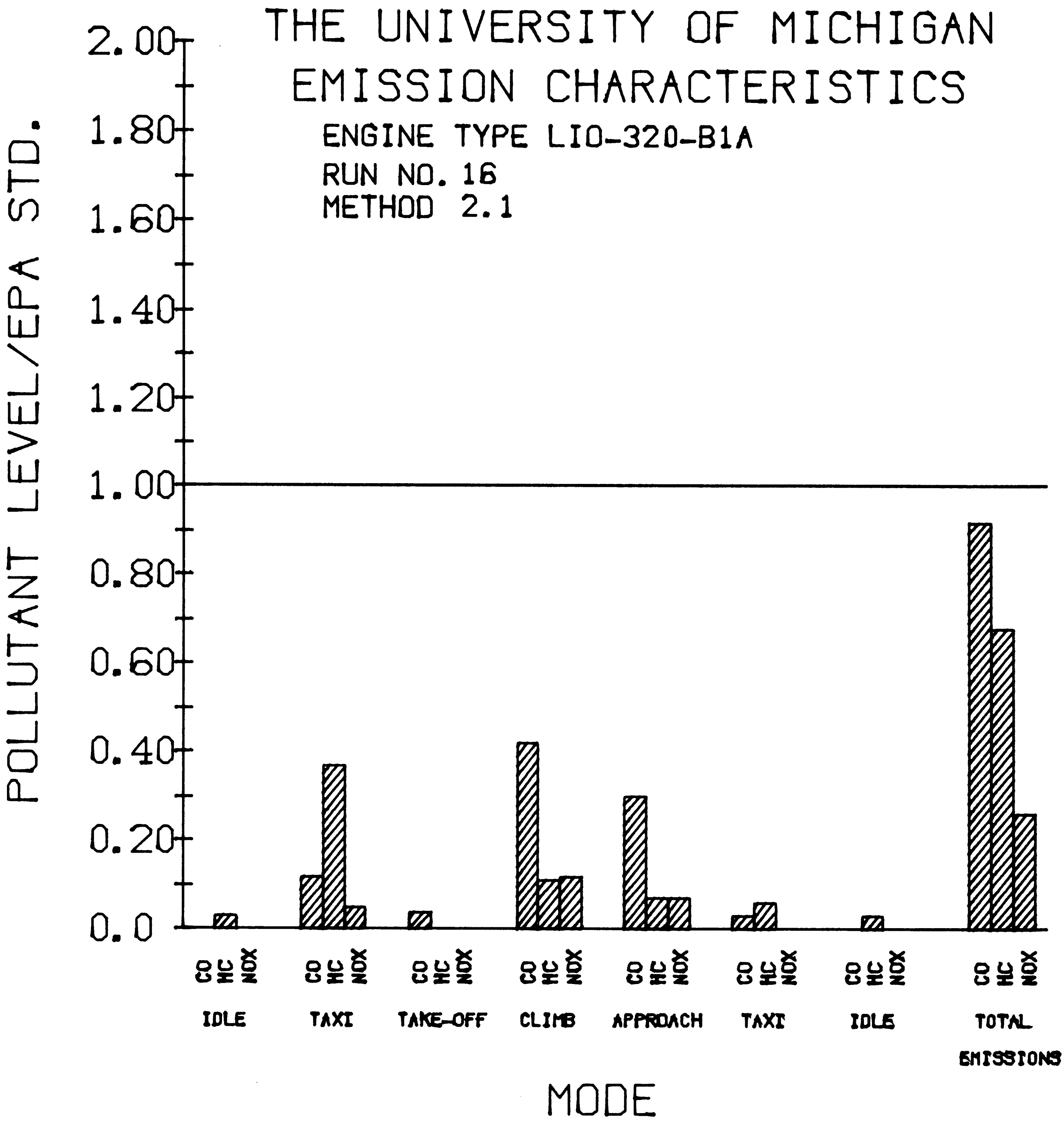


Figure 5.3.B LIO-320 Baseline Results: Run 16, Method 2.1.

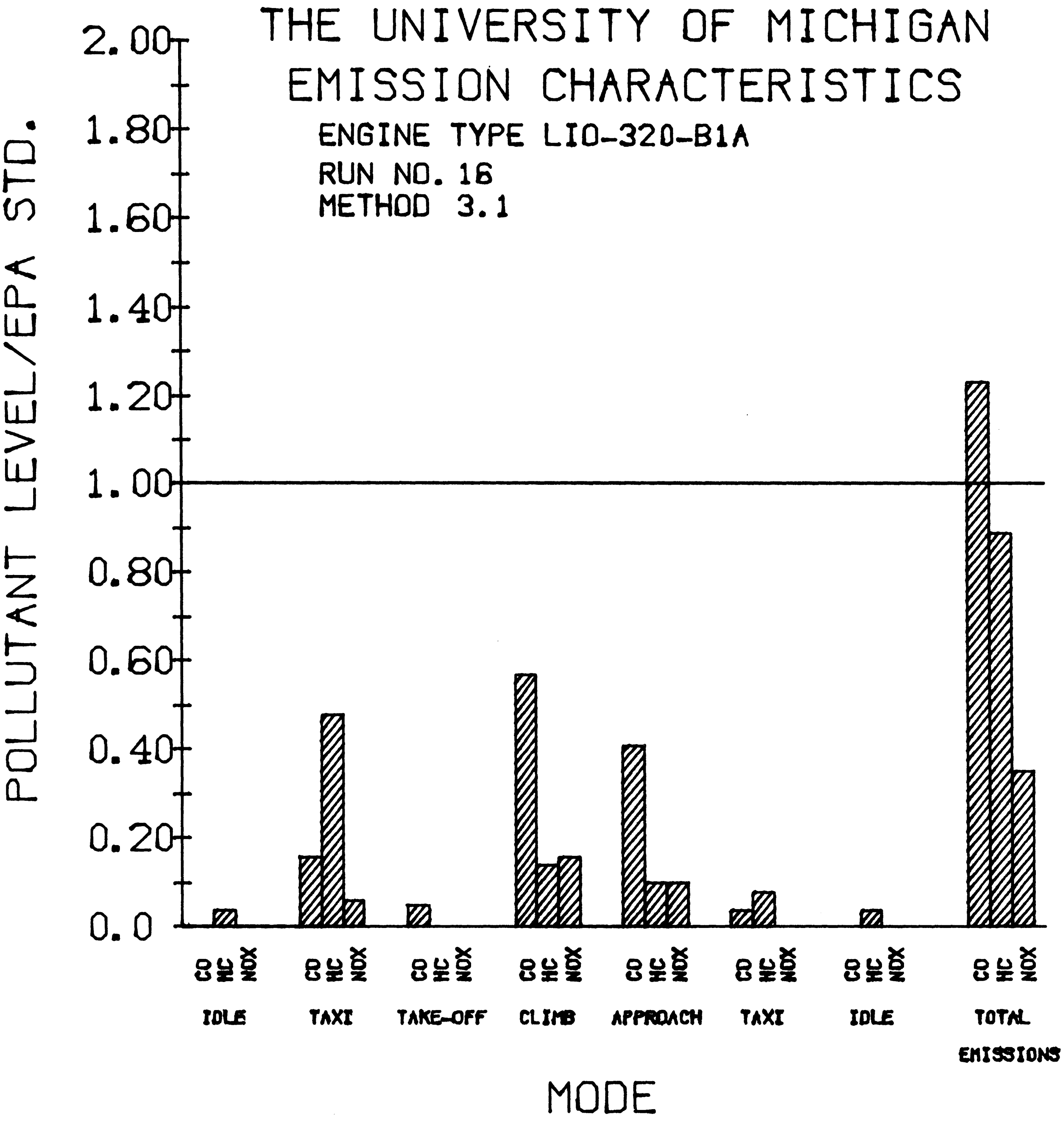


Figure 5.3.C. LIO-320 Baseline Results: Run 16, Method 3.1.

TABLE 5.2. COMPUTER PRINTOUT: RUN 4

```
 DATE:       8-11-75         ENGINE TYPE:    LIO-320-B1A    FUEL H/C RATIO = 2. 190
 LOCATION: UNIV OF MICH  SERIAL NUMBER: L-287-66A      IGNITION TIMING= 25DEG
 OPERATORS: PACE, PERRY, PONSONBY, LEO

RUN NO.   4
MODE:     1
COMMENTS: BASELINE DATA RUN4. 1
TEMP(DB)       = 96. 06F       FUEL RATE=    4. 2595#/HR      ENGINE RPM(NOM)= 700 RPM
TEMP(DP)       = 67. 00F       AIR RATE =   70. 0810#/HR      ENGINE RPM(ACT)= 744. RPM
TEMP(BAR)      = 85. 00F       F/A RATIO=    0. 0608#/#       BHP(OBS)        =  2. 0HP
BAR PRESS(OB)= 29. 11"HG      PHIM      =    0. 9144          BHP(CORR)       =  0. 0HP
BAR PRESS(CR)= 28. 96"HG                                      MAN VAC(OBS)    =17. 00"HG
SPEC HUMIDITY=0. 0146#/#                                      MAN PRESS(CORR)= 0. 00"HG
                         CO2         O2          UHCC        CO          NO          NOX
CONC(PPM)               68368.      69080.      27388.      27735.       192.        219.
                   KWD       XTC      MWEXH    EXH FLOW      FACAL        FAM   ERROR
METHOD 1. 2      0. 89356 0. 96902 27. 55150  1040. 114  0. 06515  0. 06078  7 204
MASS/MODE(LBM)          0. 13535    0. 09939    0. 01704    0. 03491    0. 00026    0. 00045
MASS/RATED HP(#/HP)     0. 00084    0. 00062    0. 00011    0. 00022    0. 00000    0. 00000
                   KWD       XTC      MWEXH    EXH FLOW      FACAL        FAM   ERROR
METHOD 2. 1      0. 86278 1. 00000 28. 07666  1020. 660  0. 06004  0. 06078 -1 214
MASS/MODE(LBM)          0. 13282    0. 09753    0. 01673    0. 03425    0. 00025    0. 00044
MASS/RATED HP(#/HP)     0. 00083    0. 00061    0. 00010    0. 00021    0. 00000    0. 00000
                   KWD       XTC      MWEXH    EXH FLOW      FACAL        FAM   ERROR
METHOD 3. 1      0. 87942 1. 01530 27. 13356  1056. 135  0. 07131  0. 06078 17. 332
MASS/MODE(LBM)          0. 13743    0. 10092    0 01731     0. 03544    0. 00026    0. 00046
MASS/RATED HP(#/HP)     0. 00085    0. 00063    0 00011     0. 00022    0. 00000    0 00000
                   KWD       XTC      MWEXH    EXH FLOW      FACAL        FAM   ERROR
METHOD 3. 2      0 89298 0. 24116 27. 50000  1042. 062  0. 06289  0. 06078  3. 473
MASS/MODE(LBM)          0. 13560    0. 09958    0. 01708    0. 03497    0. 00026    0. 00045
MASS/RATED HP(#/HP)     0. 00084    0. 00062    0. 00011    0. 00022    0. 00000    0. 00000

RUN NO.   4
MODE:     2
COMMENTS: BASELINE DATA RUN4. 2
TEMP(DB)       = 96. 27F       FUEL RATE=    7. 9051#/HR      ENGINE RPM(NOM)=1200 RPM
TEMP(DP)       = 66. 00F       AIR RATE =  101. 5497#/HR      ENGINE RPM(ACT)=1201. RPM
TEMP(BAR)      = 85 00F        F/A RATIO=    0. 0778#/#       BHP(OBS)        =  6. 2HP
BAR PRESS(OB)= 29 11"HG       PHIM      =    1. 1712          BHP(CORR)       =  0. 0HP
BAR PRESS(CR)= 28. 96"HG                                      MAN VAC(OBS)    =19. 00"HG
SPEC HUMIDITY=0 0141#/#                                       MAN PRESS(CORR)= 0. 00"HG
                         CO2         O2          UHCC        CO          NO          NOX
CONC(PPM)               92875.      21854.       9600.      48817.       214.        237
                   KWD       XTC      MWEXH    EXH FLOW      FACAL        FAM   ERROR
METHOD 1 2       0. 86498 0. 98035 27. 45172  1536. 971  0. 07621  0. 07784 -2. 099
MASS/MODE(LBM)          2. 98862    0. 51112    0. 09711    0. 99864    0. 00470    0. 00794
MASS/RATED HP(#/HP)     0. 01868    0. 00319    0. 00061    0. 00624    0. 00003    0 00005
                   KWD       XTC      MWEXH    EXH FLOW      FACAL        FAM   ERROR
METHOD 2. 1      0. 84542 1. 00000 27. 80904  1517. 223  0. 07191  0. 07784 -7. 619
MASS/MODE(LBM)          2. 95022    0. 50455    0. 09586    0. 98581    0. 00464    0. 00784
MASS/RATED HP(#/HP)     0. 01844    0. 00315    0. 00060    0. 00616    0. 00003    0. 00005
                   KWD       XTC      MWEXH    EXH FLOW      FACAL        FAM   ERROR
METHOD 3. 1      0. 85634 1. 01002 27. 17859  1552. 417  0. 07995  0. 07784  2. 707
MASS/MODE(LBM)          3. 01865    0. 51626    0. 09808    1. 00868    0. 00475    0. 00802
MASS/RATED HP(#/HP)     0. 01887    0. 00323    0. 00061    0. 00630    0. 00003    0 00005
                   KWD       XTC      MWEXH    EXH FLOW      FACAL        FAM   ERROR
METHOD 3. 2      0. 86466 0. 29629 27. 50000  1534. 273  0. 07450  0. 07784 -4. 296
MASS/MODE(LBM)          2. 98337    0. 51022    0. 09694    0. 99689    0. 00469    0 00793
MASS/RATED HP(#/HP)     0 01865     0. 00319    0. 00061    0. 00623    0. 00003    0 00005
```

TABLE 5.2. Continued

```
RUN NO.   4
MODE      3
COMMENTS: BASELINE DATA RUN4. 3
TEMP(DB)       = 89. 27F      FUEL RATE=  75. 1880#/HR      ENGINE RPM(NOM)=2700 RPM
TEMP(DP)       = 61. 00F      AIR RATE = 859. 1758#/HR      ENGINE RPM(ACT)=2695. RPM
TEMP(BAR)      = 86. 00F      F/A RATIO=   0. 0875#/#       BHP(OBS)        =138. 4HP
BAR PRESS(OB)= 29. 11"HG      PHIM      =   1. 3166         BHP(CORR)       =153. 4HP
BAR PRESS(CR)= 28. 96"HG                                    MAN VAC(OBS)    = 0. 70"HG
SPEC HUMIDITY=0. 0118#/#                                    MAN PRESS(CORR)=29. 00"HG
                          CO2         O2         UHCC        CO          NO          NOX
CONC(PPM)                87484.       1758.      1746.      85456.       201.         205.
                    KWD        XTC      MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 1. 2      0. 85993 0. 99461 26. 87442 13402. 240  0. 08810  0. 08751  0. 678
MASS/MODE(LBM)          0. 66949    0. 00978    0. 00420   0. 41574   0. 00105   0. 00164
MASS/RATED HP(#/HP)  0. 00418    0. 00006    0. 00003   0. 00260   0. 00000   0. 00001
                    KWD        XTC      MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 2. 1      0. 85449 1. 00000 26. 98341 13348. 100  0. 08661  0. 08751 -1. 031
MASS/MODE(LBM)          0. 66678    0. 00974    0. 00418   0. 41406   0. 00104   0. 00163
MASS/RATED HP(#/HP)  0. 00417    0. 00006    0. 00003   0. 00259   0. 00000   0. 00001
                    KWD        XTC      MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 3. 1      0. 85771 1. 00292 26. 79637 13441. 270  0. 08919  0. 08751  1. 918
MASS/MODE(LBM)          0. 67144    0. 00980    0. 00421   0. 41695   0. 00105   0. 00164
MASS/RATED HP(#/HP)  0. 00420    0. 00006    0. 00003   0. 00261   0. 00000   0. 00001
                    KWD        XTC      MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 3. 2      0. 85987 0. 33790 27. 50000 13097. 360  0. 08754  0. 08751  0. 038
MASS/MODE(LBM)          0. 65426    0. 00955    0. 00410   0. 40629   0. 00102   0 00160
MASS/RATED HP(#/HP)  0. 00409    0. 00006    0. 00003   0. 00254   0. 00000   0 00001

RUN NO.   4
MODE:     4
COMMENTS: BASELINE DATA RUN4. 4
TEMP(DB)       = 93. 06F      FUEL RATE=  57 4712#/HR      ENGINE RPM(NOM)=2430 RPM
TEMP(DP)       = 63. 00F      AIR RATE = 655. 3093#/HR      ENGINE RPM(ACT)=2449 RPM
TEMP(BAR)      = 85. 00F      F/A RATIO=   0. 0877#/#       BHP(OBS)        =104 2HP
BAR PRESS(OB)= 29. 12"HG      PHIM      =   1. 3194         BHP(CORR)       =  0. 0HP
BAR PRESS(CR)= 28. 97"HG                                    MAN VAC(OBS)    = 3 50"HG
SPEC HUMIDITY=0 0127#/#                                     MAN PRESS(CORR)= 0. 00"HG
                          CO2         O2         UHCC        CO          NO          NOX
CONC(PPM)                91052.       1758.      1742       81134.       245          253.
                    KWD        XTC      MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 1. 2      0 85711 0. 99969 26. 96886 10188. 110  0. 08665  0. 08770 -1. 198
MASS/MODE(LBM)          8. 82815    0. 12391    0. 05308   5. 00097   0. 01617   0. 02559
MASS/RATED HP(#/HP)  0. 05518    0. 00077    0. 00033   0. 03126   0. 00010   0. 00016
                    KWD        XTC      MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 2. 1      0. 85680 1. 00000 26. 97507 10185. 770  0. 08656  0. 08770 -1 294
MASS/MODE(LBM)          8. 82612    0. 12388    0. 05307   4. 99982   0. 01617   0 02558
MASS/RATED HP(#/HP)  0. 05516    0. 00077    0. 00033   0. 03125   0. 00010   0 00016
                    KWD        XTC      MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 3. 1      0. 85698 1. 00017 26. 96439 10189. 800  0. 08671  0. 08770 -1 128
MASS/MODE(LBM)          8. 82962    0. 12393    0. 05309   5. 00180   0. 01617   0. 02559
MASS/RATED HP(#/HP)  0. 05519    0. 00077    0. 00033   0. 03126   0 00010    0. 00016
                    KWD        XTC      MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 3. 2      0. 85711 0. 33685 27. 50000  9991. 336  0. 08661  0. 08770 -1. 233
MASS/MODE(LBM)          8. 65764    0. 12152    0. 05206   4. 90438   0. 01586   0. 02509
MASS/RATED HP(#/HP)  0. 05411    0. 00075    0. 00033   0. 03065   0. 00009   0. 00016
```

TABLE 5.2. Continued

```
RUN NO.   4
MODE:     5
COMMENTS: BASELINE DATA RUN4. 5
TEMP(DB)       = 98. 79F       FUEL RATE=   34. 8432#/HR      ENGINE RPM(NOM)=2350 RPM
TEMP(DP)       = 65. 00F       AIR RATE =  396. 3127#/HR      ENGINE RPM(ACT)=2358. RPM
TEMP(BAR)      = 88. 00F       F/A RATIO=    0. 0879#/#       BHP(OBS)        = 53. 0HP
BAR PRESS(OB)= 29. 12"HG       PHIM      =   1. 3227          BHP(CORR)       =  0. 0HP
BAR PRESS(CR)= 28. 96"HG                                      MAN VAC(OBS)    =11. 50"HG
SPEC HUMIDITY=0. 0136#/#                                      MAN PRESS(CORR)= 0. 00"HG
                         CO2        O2         UHCC       CO         NO          NOX
CONC(PPM)                92861.     1758.      1768.      78852.     207.        213.
                    KWD      XTC       MWEXH    EXH FLOW   FACAL      FAM   ERROR
METHOD 1. 2       0. 85528 1. 00164 27. 00743 6153. 914 0. 08598  0. 08791 -2 202
MASS/MODE(LBM)           6. 52609   0. 08981   0. 03905   3. 52292   0. 00992   0. 01561
MASS/RATED HP(#/HP)      0. 04079   0. 00056   0. 00024   0. 02202   0. 00006   0. 00009
                    KWD      XTC       MWEXH    EXH FLOW   FACAL      FAM   ERROR
METHOD 2. 1       0. 85696 1. 00000 26. 97456 6161. 414 0. 08643  0. 08791 -1. 692
MASS/MODE(LBM)           6. 53405   0. 08992   0. 03910   3. 52722   0. 00993   0. 01563
MASS/RATED HP(#/HP)      0. 04084   0. 00056   0. 00024   0. 02205   0. 00006   0. 00009
                    KWD      XTC       MWEXH    EXH FLOW   FACAL      FAM   ERROR
METHOD 3. 1       0. 85597 0. 99912 27. 03120 6148. 504 0. 08565  0. 08791 -2 572
MASS/MODE(LBM)           6. 52036   0. 08973   0. 03902   3. 51983   0. 00991   0. 01560
MASS/RATED HP(#/HP)      0. 04075   0. 00056   0. 00024   0. 02200   0. 00006   0 00009
                    KWD      XTC       MWEXH    EXH FLOW   FACAL      FAM   ERROR
METHOD 3. 2       0. 85531 0. 33670 27. 50000 6043. 687 0. 08614  0. 08791 -2. 014
MASS/MODE(LBM)           6. 40920   0. 08820   0. 03835   3 45982    0. 00974   0 01534
MASS/RATED HP(#/HP)      0. 04006   0. 00055   0. 00024   0. 02162   0. 00006   0. 00009

RUN NO.   4
MODE:     6
COMMENTS: BASELINE DATA RUN4. 6
TEMP(DB)       =100. 35F       FUEL RATE=    7. 7963#/HR      ENGINE RPM(NOM)=1200 RPM
TEMP(DP)       = 66. 00F       AIR RATE =   99. 5044#/HR      ENGINE RPM(ACT)=1222. RPM
TEMP(BAR)      = 88. 00F       F/A RATIO=    0. 0783#/#       BHP(OBS)        =  4. 3HP
BAR PRESS(OB)= 29. 12"HG       PHIM      =   1. 1788          BHP(CORR)       =  0. 0HP
BAR PRESS(CR)= 28. 96"HG                                      MAN VAC(OBS)    =19. 10"HG
SPEC HUMIDITY=0. 0141#/#                                      MAN PRESS(CORR)= 0. 00"HG
                         CO2        O2         UHCC       CO         NO          NOX
CONC(PPM)                92260.     23362.     12300.     49025.     204         229.
                    KWD      XTC       MWEXH    EXH FLOW   FACAL      FAM   ERROR
METHOD 1. 2       0. 86504 0. 98720 27. 40898 1509. 072 0. 07722  0. 07835 -1 443
MASS/MODE(LBM)           0. 79499   0. 14630   0. 03332   0. 26855   0 00120    0. 00206
MASS/RATED HP(#/HP)      0. 00497   0. 00091   0. 00021   0. 00168   0 00000    0. 00001
                    KWD      XTC       MWEXH    EXH FLOW   FACAL      FAM   ERROR
METHOD 2. 1       0. 85223 1. 00000 27. 64326 1496. 282 0. 07436  0. 07835 -5. 083
MASS/MODE(LBM)           0. 78825   0. 14506   0. 03304   0. 26628   0. 00119   0. 00204
MASS/RATED HP(#/HP)      0. 00493   0. 00090   0. 00021   0. 00166   0. 00000   0. 00001
                    KWD      XTC       MWEXH    EXH FLOW   FACAL      FAM   ERROR
METHOD 3. 1       0. 85940 1. 00654 27 23067  1518. 953 0. 07966  0. 07835  1. 671
MASS/MODE(LBM)           0. 80019   0. 14726   0. 03354   0. 27031   0. 00121   0 00207
MASS/RATED HP(#/HP)      0. 00500   0. 00092   0. 00021   0. 00169   0. 00000   0. 00001
                    KWD      XTC       MWEXH    EXH FLOW   FACAL      FAM   ERROR
METHOD 3. 2       0. 86482 0. 29866 27. 50000 1504. 077 0. 07608  0 07835 -2. 889
MASS/MODE(LBM)           0. 79236   0. 14582   0. 03321   0. 26766   0. 00120   0. 00205
MASS/RATED HP(#/HP)      0. 00495   0. 00091   0. 00021   0. 00167   0. 00000   0. 00001
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TABLE 5.2. Continued

```
RUN NO.   4
MODE:     7
COMMENTS: BASELINE DATA RUN4. 7
TEMP(DB)     = 98. 40F     FUEL RATE=   3. 9002#/HR    ENGINE RPM(NOM)= 680 RPM
TEMP(DP)     = 66. 00F     AIR RATE =  68. 6606#/HR    ENGINE RPM(ACT)= 639. RPM
TEMP(BAR)    = 88. 00F     F/A RATIO=   0. 0568#/#     BHP(OBS)        =  1. 9HP
BAR PRESS(OB)= 29. 12"HG   PHIM     =   0. 8546        BHP(CORR)       =  0. 0HP
BAR PRESS(CR)= 28. 96"HG                               MAN VAC(OBS)   =16. 80"HG
SPEC HUMIDITY=0. 0141#/#                               MAN PRESS(CORR)= 0. 00"HG
                       CO2       O2        UHCC      CO        NO         NOX
CONC(PPM)             80621.    53003.    12700.    30954.      258.       300.
                  KWD     XTC     MWEXH   EXH FLOW    FACAL       FAM  ERROR
METHOD 1. 2   0. 88312 0. 97038 27. 75290  1007. 845  0. 06332  0. 05680 11. 484
MASS/MODE(LBM)       0. 15465  0. 07389   0. 00765   0. 03775   0. 00034   0 00060
MASS/RATED HP(#/HP)  0. 00096  0. 00046   0. 00005   0. 00024   0. 00000   0. 00000
MASS/HP/CYC(#/HP/C)  0. 12561  0. 00658   0. 00157   0. 06424   0. 00021   0. 00034
                  KWD     XTC     MWEXH   EXH FLOW    FACAL       FAM  ERROR
METHOD 2. 1   0. 85348 1. 00000 28. 26257   989. 670  0. 05826  0. 05680  2. 566
MASS/MODE(LBM)       0. 15186  0. 07256   0. 00752   0. 03707   0. 00033   0. 00059
MASS/RATED HP(#/HP)  0. 00094  0. 00045   0. 00005   0. 00023   0. 00000   0. 00000
MASS/HP/CYC(#/HP/C)  0. 12531  0. 00652   0. 00156   0. 06415   0. 00021   0. 00034
                  KWD     XTC     MWEXH   EXH FLOW    FACAL       FAM  ERROR
METHOD 3. 1   0. 86963 1. 01474 27. 34329  1022. 943  0. 06914  0. 05680 21 718
MASS/MODE(LBM)       0. 15697  0. 07500   0. 00777   0. 03831   0. 00034   0. 00061
MASS/RATED HP(#/HP)  0. 00098  0. 00047   0. 00005   0. 00024   0. 00000   0. 00000
MASS/HP/CYC(#/HP/C)  0. 12584  0. 00664   0. 00158   0. 06432   0. 00021   0. 00034
                  KWD     XTC     MWEXH   EXH FLOW    FACAL       FAM  ERROR
METHOD 3. 2   0. 88259 0. 25013 27. 50000  1017. 114  0. 06123  0. 05680  7. 797
MASS/MODE(LBM)       0. 15607  0. 07457   0. 00772   0. 03809   0. 00034   0 00061
MASS/RATED HP(#/HP)  0. 00097  0. 00047   0 00005   0. 00024   0. 00000   0. 00000
MASS/HP/CYC(#/HP/C)  0. 12368  0. 00655   0. 00156   0. 06317   0 00021   0. 00033
```

TABLE 5.3. COMPUTER PRINTOUT: RUN 7

```
DATE:       8-14-75        ENGINE TYPE:   LIO-320-BIA    FUEL H/C RATIO = 2. 190
LOCATION:  UNIV OF MICH   SERIAL NUMBER:  L-287-66A      IGNITION TIMING= 25DEG
OPERATORS: PACE, PONSONBY, LEO, CARLOS

RUN NO.   7
MODE:     1
COMMENTS: 4TH BASELINE RUN
TEMP(DB)       =102. 08F        FUEL RATE=    3. 7585#/HR       ENGINE RPM(NOM)= 650 RPM
TEMP(DP)       = 54. 00F        AIR RATE =   64. 5482#/HR       ENGINE RPM(ACT)= 650. RPM
TEMP(BAR)      = 82. 00F        F/A RATIO=    0. 0582#/#        BHP(OBS)        =   0. 4HP
BAR PRESS(OB)= 29. 32"HG        PHIM      =   0. 8760           BHP(CORR)       =   0. 0HP
BAR PRESS(CR)= 29. 18"HG                                        MAN VAC(OBS)    =17. 50"HG
SPEC HUMIDITY=0. 0090#/#                                        MAN PRESS(CORR)= 0. 00"HG
                          CO2         O2         UHCC        CO          NO          NOX
CONC(PPM)                66000.      98219.      40787.     13423.       120.        120.
                   KWD        XTC      MWEXH    EXH FLOW     FACAL        FAM   ERROR
METHOD 1. 2      0. 90611 1. 03925 27. 78641   947. 613  0. 05932  0. 05823  1. 884
MASS/MODE(LBM)           0. 11904    0. 12875    0. 02313    0. 01539    0. 00015    0. 00022
MASS/RATED HP(#/HP)      0. 00074    0. 00080    0. 00014    0. 00009    0. 00000    0. 00000
                   KWD        XTC      MWEXH    EXH FLOW     FACAL        FAM   ERROR
METHOD 2. 1      0. 94739 1. 00000 27. 09962   971. 628  0. 06544  0. 05823 12. 393
MASS/MODE(LBM)           0. 12206    0. 13201    0. 02371    0. 01578    0. 00015    0. 00023
MASS/RATED HP(#/HP)      0. 00076    0. 00082    0. 00015    0. 00009    0 00000    0. 00000
                   KWD        XTC      MWEXH    EXH FLOW     FACAL        FAM   ERROR
METHOD 3. 1      0. 92503 0. 98058 28. 33650   929. 217  0. 05149  0. 05823-11. 579
MASS/MODE(LBM)           0. 11673    0. 12625    0. 02268    0. 01509    0. 00014    0. 00022
MASS/RATED HP(#/HP)      0. 00073    0. 00078    0. 00014    0. 00009    0. 00000    0. 00000
                   KWD        XTC      MWEXH    EXH FLOW     FACAL        FAM   ERROR
METHOD 3. 2      0. 90659 0. 22023 27. 50000   957. 482  0. 06192  0. 05823  6. 339
MASS/MODE(LBM)           0. 12028    0. 13009    0. 02337    0. 01555    0. 00015    0. 00023
MASS/RATED HP(#/HP)      0. 00075    0. 00081    0. 00015    0. 00009    0. 00000    0. 00000

RUN NO.   7
MODE:     2
COMMENTS 4TH BASELINE RUN
TEMP(DB)       =101. 73F        FUEL RATE=    8. 1544#/HR       ENGINE RPM(NOM)=1200 RPM
TEMP(DP)       = 56. 00F        AIR RATE = 114. 4802#/HR       ENGINE RPM(ACT)=1200 RPM
TEMP(BAR)      = 81. 00F        F/A RATIO=    0. 0712#/#        BHP(OBS)        =   5 4HP
BAR PRESS(OB)= 29. 30"HG        PHIM      =   1. 0716           BHP(CORR)       =   0 0HP
BAR PRESS(CR)= 29. 16"HG                                        MAN VAC(OBS)    =18. 90"HG
SPEC HUMIDITY=0. 0097#/#                                        MAN PRESS(CORR)= 0. 00"HG
                          CO2         O2         UHCC        CO          NO          NOX
CONC(PPM)                98093.      35921.      13902.     32589.       152.        180.
                   KWD        XTC      MWEXH    EXH FLOW     FACAL        FAM   ERROR
METHOD 1. 2      0. 87097 1. 01283 27. 81004  1699. 855  0. 06967  0. 07123 -2. 180
MASS/MODE(LBM)           3 49107     0. 92915    0. 15553    0. 73733    0. 00368    0 00668
MASS/RATED HP(#/HP)      0. 02182    0. 00581    0. 00097    0. 00461    0. 00002    0. 00004
                   KWD        XTC      MWEXH    EXH FLOW     FACAL        FAM   ERROR
METHOD 2. 1      0. 88404 1. 00000 27. 57799  1714. 158  0. 07229  0. 07123  1 499
MASS/MODE(LBM)           3. 52044    0. 93697    0. 15684    0. 74353    0. 00372    0. 00674
MASS/RATED HP(#/HP)      0. 02200    0. 00586    0. 00098    0. 00465    0. 00002    0. 00004
                   KWD        XTC      MWEXH    EXH FLOW     FACAL        FAM   ERROR
METHOD 3. 1      0. 87681 0. 99352 27 99283   1688. 755  0. 06726  0. 07123 -5. 565
MASS/MODE(LBM)           3. 46828    0. 92308    0. 15452    0. 73251    0. 00366    0. 00664
MASS/RATED HP(#/HP)      0. 02168    0. 00577    0. 00096    0. 00458    0. 00002    0. 00004
                   KWD        XTC      MWEXH    EXH FLOW     FACAL        FAM   ERROR
METHOD 3. 2      0 87112 0 27754 27. 50000  1719. 020  0. 07068  0. 07123 -0. 769
MASS/MODE(LBM)           3. 53043    0. 93962    0 15728     0. 74564    0. 00373    0 00676
MASS/RATED HP(#/HP)      0 02207     0. 00587    0. 00098    0. 00466    0. 00002    0 00004
```

TABLE 5.3. Continued

```
RUN NO.  7
MODE:    3
COMMENTS: 4TH BASELINE RUN
TEMP(DB)     = 92. 75F      FUEL RATE=  76. 0456#/HR     ENGINE RPM(NOM)=2700 RPM
TEMP(DP)     = 52. 00F      AIR RATE = 875. 0493#/HR     ENGINE RPM(ACT)=2700. RPM
TEMP(BAR)    = 82. 00F      F/A RATIO=   0. 0869#/#      BHP(OBS)       =140. 4HP
BAR PRESS(OB)= 29. 30"HG    PHIM      =   1. 3074        BHP(CORR)      =154. 3HP
BAR PRESS(CR)= 29. 16"HG                                 MAN VAC(OBS)    = 0. 60"HG
SPEC HUMIDITY=0. 0084#/#                                 MAN PRESS(CORR)=29. 10"HG
                       CO2        O2        UHCC      CO         NO        NOX
CONC(PPM)             86102.     1758.      1635.     86374.      216.      211.
                  KWD     XTC    MWEXH  EXH FLOW     FACAL      FAM  ERROR
METHOD 1. 2   0. 86403 0. 99042 26. 90207 13628. 200  0. 08824  0. 08690  1. 537
MASS/MODE(LBM)       0. 67002   0. 00994   0. 00400   0. 42730   0. 00115   0. 00171
MASS/RATED HP(#/HP)  0. 00419   0. 00006   0. 00002   0. 00267   0. 00000   0. 00001
                  KWD     XTC    MWEXH  EXH FLOW     FACAL      FAM  ERROR
METHOD 2. 1   0. 85449 1. 00000 27. 09535 13530. 990  0. 08561  0. 08690 -1. 485
MASS/MODE(LBM)       0. 66524   0. 00987   0. 00397   0. 42425   0. 00114   0. 00170
MASS/RATED HP(#/HP)  0. 00416   0. 00006   0. 00002   0. 00265   0. 00000   0. 00001
                  KWD     XTC    MWEXH  EXH FLOW     FACAL      FAM  ERROR
METHOD 3. 1   0. 86014 1 00517 26. 76370 13698. 660  0. 09016  0 08690  3. 746
MASS/MODE(LBM)       0. 67349   0. 00999   0. 00402   0. 42950   0. 00115   0. 00172
MASS/RATED HP(#/HP)  0. 00421   0. 00006   0. 00003   0. 00268   0. 00000   0. 00001
                  KWD     XTC    MWEXH  EXH FLOW     FACAL      FAM  ERROR
METHOD 3. 2   0. 86395 0. 33392 27. 50000 13331. 890  0. 08724  0. 08690  0. 395
MASS/MODE(LBM)       0. 65546   0. 00972   0. 00391   0. 41800   0. 00112   0. 00168
MASS/RATED HP(#/HP)  0. 00410   0. 00006   0. 00002   0. 00261   0. 00000   0. 00001

RUN NO.  7
MODE:    4
COMMENTS. 4TH BASELINE RUN
TEMP(DB)     = 94. 75F      FUEL RATE=  58. 9970#/HR     ENGINE RPM(NOM)=2440 RPM
TEMP(DP)     = 52. 00F      AIR RATE = 679. 1985#/HR     ENGINE RPM(ACT)=2440. RPM
TEMP(BAR)    = 82. 00F      F/A RATIO=   0. 0868#/#      BHP(OBS)       =108. 5HP
BAR PRESS(OB)= 29. 30"HG    PHIM      =   1. 3068        BHP(CORR)      =  0. 0HP
BAR PRESS(CR)= 29. 16"HG                                 MAN VAC(OBS)    = 3. 30"HG
SPEC HUMIDITY=0. 0084#/#                                 MAN PRESS(CORR)= 0. 00"HG
                       CO2        O2        UHCC      CO         NO        NOX
CONC(PPM)             90052.     2010.      1752.     81991.      251.      250.
                  KWD     XTC    MWEXH  EXH FLOW     FACAL      FAM  ERROR
METHOD 1. 2   0. 86169 0. 99896 27. 01823 10532. 100  0. 08660  0. 08686 -0. 295
MASS/MODE(LBM)       9 02598   0. 14639   0. 05520   5. 22438   0. 01716   0. 02615
MASS/RATED HP(#/HP)  0. 05641   0. 00091   0. 00035   0. 03265   0. 00011   0. 00016
                  KWD     XTC    MWEXH  EXH FLOW     FACAL      FAM  ERROR
METHOD 2. 1   0. 86065 1. 00000 27. 03915 10523. 950  0. 08632  0. 08686 -0. 621
MASS/MODE(LBM)       9. 01899   0. 14628   0. 05516   5. 22034   0. 01715   0. 02613
MASS/RATED HP(#/HP)  0. 05637   0. 00091   0. 00034   0. 03263   0 00011    0. 00016
                  KWD     XTC    MWEXH  EXH FLOW     FACAL      FAM  ERROR
METHOD 3. 1   0. 86127 1. 00056 27. 00317 10537. 970  0. 08681  0. 08686 -0. 059
MASS/MODE(LBM)       9. 03101   0. 14647   0. 05523   5. 22730   0. 01717   0. 02617
MASS/RATED HP(#/HP)  0. 05644   0. 00091   0. 00035   0. 03267   0. 00011   0. 00016
                  KWD     XTC    MWEXH  EXH FLOW     FACAL      FAM  ERROR
METHOD 3. 2   0. 86169 0. 33258 27. 50000 10347. 590  0. 08650  0. 08686 -0 416
MASS/MODE(LBM)       8. 86786   0. 14383   0. 05424   5. 13286   0. 01686   0. 02569
MASS/RATED HP(#/HP)  0 05542    0. 00089   0. 00034   0. 03208   0. 00011   0. 00016
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TABLE 5.3. Continued

```
RUN NO.   7
MODE:     5
COMMENTS: 4TH BASELINE RUN
TEMP(DB)      =101. 08F      FUEL RATE=   35. 1288#/HR      ENGINE RPM(NOM)=2350 RPM
TEMP(DP)      = 54 OOF       AIR RATE = 404. 5498#/HR      ENGINE RPM(ACT)=2350. RPM
TEMP(BAR)     = 84. OOF      F/A RATIO=    0. 0868#/#       BHP(OBS)        = 55. 6HP
BAR PRESS(OB)= 29 30"HG      PHIM      =    1. 3064         BHP(CORR)       =  0. OHP
BAR PRESS(CR)= 29. 15"HG                                    MAN VAC(OBS)    =11. 50"HG
SPEC HUMIDITY=0. 0090#/#                                    MAN PRESS(CORR)= 0. 00"HG
                         CO2         O2         UHCC        CO          NO         NOX
CONC(PPM)              92065.       1758.       1674.      78783.        252.        248.
                   KWD       XTC       MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 1. 2     0. 86035 0. 99762 27. 07744   6259. 336  0. 08575  0. 08683 -1. 249
MASS/MODE(LBM)           6. 58094    0. 09135    0. 03761    3. 58011    0. 01228    0. 01848
MASS/RATED HP(#/HP)     0. 04113    0. 00057    0. 00024    0. 02238    0. 00007    0. 00012
                   KWD       XTC       MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 2. 1     0. 85796 1. 00000 27. 12497   6248. 367  0. 08511  0. 08683 -1. 986
MASS/MODE(LBM)           6. 56941    0. 09119    0. 03754    3. 57383    0. 01226    0 01845
MASS/RATED HP(#/HP)     0. 04106    0. 00057    0. 00023    0. 02234    0. 00007    0 00012
                   KWD       XTC       MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 3. 1     0. 85936 1. 00127 27. 04303   6267. 301  0. 08621  0. 08683 -0. 711
MASS/MODE(LBM)           6. 58932    0. 09146    0. 03766    3. 58466    0. 01229    0 01850
MASS/RATED HP(#/HP)     0. 04118    0. 00057    0. 00024    0. 02240    0. 00007    0. 00012
                   KWD       XTC       MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 3. 2     0. 86032 0. 33079 27. 50000   6163 156   0. 08551  0. 08683 -1. 524
MASS/MODE(LBM)           6. 47982    0. 08994    0. 03703    3. 52510    0. 01209    0. 01820
MASS/RATED HP(#/HP)     0. 04050    0. 00056    0. 00023    0 02203     0. 00007    0. 00011

RUN NO.   7
MODE:     6
COMMENTS: 4TH BASELINE RUN
TEMP(DB)      =107. 22F      FUEL RATE=    8. 7566#/HR      ENGINE RPM(NOM)=1200 RPM
TEMP(DP)      = 53. OOF      AIR RATE = 109. 4959#/HR      ENGINE RPM(ACT)=1200. RPM
TEMP(BAR)     = 83. OOF      F/A RATIO=    0. 0799#/#       BHP(OBS)        =  5. 4HP
BAR PRESS(OB)= 29 30"HG      PHIM      =    1. 2031         BHP(CORR)       =  0. OHP
BAR PRESS(CR)= 29. 16"HG                                    MAN VAC(OBS)    =19 30"HG
SPEC HUMIDITY=0. 0087#/#                                    MAN PRESS(CORR)= 0. 00"HG
                         CO2         O2         UHCC        CO          NO         NOX
CONC(PPM)              88252.      30897.      18375.      54301.        135.        139.
                   KWD       XTC       MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 1. 2     0. 87100 1. 02314 27. 33202   1667. 781  0. 07888  0. 07997 -1. 354
MASS/MODE(LBM)           0. 84043    0. 21385    0. 05501    0. 32874    0. 00087    0 00138
MASS/RATED HP(#/HP)     0. 00525    0. 00134    0. 00034    0. 00205    0. 00001    0. 00000
                   KWD       XTC       MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 2. 1     0. 89465 1. 00000 26. 88763   1695. 345  0. 08442  0. 07997  5. 572
MASS/MODE(LBM)           0 85432     0. 21738    0. 05592    0. 33417    0. 00088    0. 00140
MASS/RATED HP(#/HP)     0. 00534    0. 00136    0. 00035    0. 00209    0. 00001    0. 00000
                   KWD       XTC       MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 3. 1     0. 88112 0. 98790 27. 66672   1647. 605  0. 07438  0. 07997 -6. 991
MASS/MODE(LBM)           0. 83026    0. 21126    0. 05434    0. 32476    0. 00086    0. 00136
MASS/RATED HP(#/HP)     0. 00519    0. 00132    0. 00034    0. 00203    0 00001     0. 00000
                   KWD       XTC       MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 3. 2     0. 87124 0. 30238 27. 50000   1657. 593  0. 08099  0. 07997  1. 279
MASS/MODE(LBM)           0. 83529    0. 21254    0. 05467    0. 32673    0. 00086    0. 00137
MASS/RATED HP(#/HP)     0. 00522    0. 00133    0. 00034    0 00204     0. 00001    0 00000
```

TABLE 5.3. Continued

```
RUN NO.  7
MODE:    7
COMMENTS:4TH BASELINE RUN
TEMP(DB)     =105. 49F     FUEL RATE=   4. 1557#/HR    ENGINE RPM(NOM)= 650 RPM
TEMP(DP)     = 54. 00F     AIR RATE =  65. 0877#/HR    ENGINE RPM(ACT)= 650. RPM
TEMP(BAR)    = 83. 00F     F/A RATIO=   0. 0638#/#     BHP(OBS)       =  1. 7HP
BAR PRESS(OB)= 29. 30"HG   PHIM     =   0. 9606        BHP(CORR)      =  0. 0HP
BAR PRESS(CR)= 29. 16"HG                               MAN VAC(OBS)   =17. 00"HG
SPEC HUMIDITY=0. 0090#/#                               MAN PRESS(CORR)= 0. 00"HG
                       CO2       O2        UHCC      CO        NO        NOX
CONC(PPM)             77579.    75862.    33092.    19262.        93.       105.
                  KWD     XTC    MWEXH  EXH FLOW    FACAL      FAM  ERROR
METHOD 1. 2   0. 89368 1. 02850 27. 78122  960. 788 0. 06391 0. 06384 0. 107
MASS/MODE(LBM)       0. 14187  0. 10083  0. 01902  0. 02239  0. 00012  0. 00020
MASS/RATED HP(#/HP)  0. 00088  0. 00063  0. 00012  0. 00014  0. 00000  0. 00000
MASS/HP/CYC(#/HP/C)  0. 13043  0. 01013  0. 00218  0. 06459  0. 00022  0. 00034
                  KWD     XTC    MWEXH  EXH FLOW    FACAL      FAM  ERROR
METHOD 2. 1   0. 92318 1. 00000 27. 27859  978. 491 0. 06887 0. 06384 7. 877
MASS/MODE(LBM)       0. 14448  0. 10269  0. 01937  0. 02281  0. 00012  0. 00020
MASS/RATED HP(#/HP)  0. 00090  0. 00064  0. 00012  0. 00014  0. 00000  0. 00000
MASS/HP/CYC(#/HP/C)  0. 13059  0. 01023  0. 00220  0. 06459  0. 00022  0. 00034
                  KWD     XTC    MWEXH  EXH FLOW    FACAL      FAM  ERROR
METHOD 3. 1   0. 90711 0. 98583 28. 18137  947. 145 0. 05837 0. 06384 -8. 582
MASS/MODE(LBM)       0. 13985  0. 09939  0. 01875  0. 02208  0. 00011  0. 00020
MASS/RATED HP(#/HP)  0. 00087  0. 00062  0. 00012  0. 00014  0. 00000  0. 00000
MASS/HP/CYC(#/HP/C)  0. 13031  0. 01005  0. 00217  0. 06459  0. 00022  0. 00034
                  KWD     XTC    MWEXH  EXH FLOW    FACAL      FAM  ERROR
METHOD 3. 2   0. 89402 0. 24180 27. 50000  970. 613 0. 06595 0. 06384 3. 299
MASS/MODE(LBM)       0. 14332  0. 10186  0. 01922  0. 02262  0. 00012  0. 00020
MASS/RATED HP(#/HP)  0. 00089  0. 00063  0. 00012  0. 00014  0. 00000  0. 00000
MASS/HP/CYC(#/HP/C)  0. 12895  0. 01017  0. 00219  0. 06366  0. 00022  0. 00034
```

TABLE 5.4. COMPUTER PRINTOUT: RUN 16

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 DATE:      10/2/75         ENGINE TYPE:    LIO-320-B1A   FUEL H/C RATIO = 2. 190
 LOCATION: UNIV OF MICH  SERIAL NUMBER: L-287-66A      IGNITION TIMING= 25DEG
 OPERATORS: PACE, PONSONBY, GRIFFIN

RUN NO. 016
MODE.    1
COMMENTS: BASELINE DATA RUN#16
TEMP(DB)       = 81. 40F       FUEL RATE=    3. 3925#/HR      ENGINE RPM(NOM)= 640 RPM
TEMP(DP)       = 29. 00F       AIR RATE =   56. 9457#/HR      ENGINE RPM(ACT)= 633. RPM
TEMP(BAR)      = 75. 00F       F/A RATIO=    0. 0596#/#       BHP(OBS)        =  0. 5HP
BAR PRESS(OB)= 29. 53"HG      PHIM      =    0. 8963          BHP(CORR)       =  0. 0HP
BAR PRESS(CR)= 29. 41"HG                                      MAN VAC(OBS)    =17. 00"HG
SPEC HUMIDITY=0. 0033#/#                                      MAN PRESS(CORR)= 0. 00"HG
                        CO2         O2          UHCC       CO          NO          NOX
CONC(PPM)               44726.     72373.      19556.     12661.       118.        151.
                    KWD       XTC      MWEXH   EXH FLOW     FACAL       FAM  ERROR
METHOD 1. 2     0. 93159 0. 76304 28. 20909   824. 525  0. 05084  0. 05957-14. 658
MASS/MODE(LBM)          0. 07019    0. 08254    0. 00964    0. 01263    0. 00013    0. 00025
MASS/RATED HP(#/HP)     0. 00044    0. 00052    0. 00006    0. 00007    0. 00000    0. 00000
                    KWD       XTC      MWEXH   EXH FLOW     FACAL       FAM  ERROR
METHOD 2. 1     0. 73639 1. 00000 31. 40211   740. 686  0. 02882  0. 05957-51. 626
MASS/MODE(LBM)          0. 06305    0. 07415    0. 00866    0. 01135    0. 00011    0. 00022
MASS/RATED HP(#/HP)     0. 00039    0. 00046    0. 00005    0. 00007    0. 00000    0. 00000
                    KWD       XTC      MWEXH   EXH FLOW     FACAL       FAM  ERROR
METHOD 3. 1     0. 83071 1. 10457 25. 45438   913. 756  0. 09542  0. 05957 60. 171
MASS/MODE(LBM)          0. 07778    0. 09148    0. 01069    0. 01400    0. 00014    0. 00027
MASS/RATED HP(#/HP)     0. 00049    0. 00057    0. 00006    0. 00008    0. 00000    0. 00000
                    KWD       XTC      MWEXH   EXH FLOW     FACAL       FAM  ERROR
METHOD 3. 2     0. 93055 0. 14801 27. 50000   845. 785  0. 03803  0. 05957-36. 158
MASS/MODE(LBM)          0. 07200    0. 08467    0. 00989    0. 01296    0. 00013    0. 00025
MASS/RATED HP(#/HP)     0. 00045    0. 00053    0. 00006    0. 00008    0. 00000    0. 00000

RUN NO. 016
MODE:    2
COMMENTS: 1
TEMP(DB)       = 69. 47F       FUEL RATE=    8. 9153#/HR      ENGINE RPM(NOM)=1201 RPM
TEMP(DP)       = 28. 00F       AIR RATE = 113. 8139#/HR      ENGINE RPM(ACT)=1201 RPM
TEMP(BAR)      = 74. 00F       F/A RATIO=    0. 0783#/#       BHP(OBS)        =  8. 7HP
BAR PRESS(OB)= 29. 53"HG      PHIM      =    1. 1785          BHP(CORR)       =  0 0HP
BAR PRESS(CR)= 29. 41"HG                                      MAN VAC(OBS)    =18. 80"HG
SPEC HUMIDITY=0. 0032#/#                                      MAN PRESS(CORR)= 0. 00"HG
                        CO2         O2          UHCC       CO          NO          NOX
CONC(PPM)               69065.     16506.      11111.     41059.       320.        326
                    KWD       XTC      MWEXH   EXH FLOW     FACAL       FAM  ERROR
METHOD 1. 2     0. 89862 0. 78428 27. 56613  1716. 218  0. 07836  0. 07833  0. 043
MASS/MODE(LBM)          2. 48164    0. 43106    0. 12551    0. 93790    0. 00783    0. 01221
MASS/RATED HP(#/HP)     0. 01551    0. 00269    0. 00078    0 00586     0. 00005    0. 00007
                    KWD       XTC      MWEXH   EXH FLOW     FACAL       FAM  ERROR
METHOD 2. 1     0 72254 1. 00000 30. 82196  1534. 928  0. 04377  0. 07833-44. 125
MASS/MODE(LBM)          2. 21949    0. 38552    0. 11225    0. 83883    0. 00700    0. 01092
MASS/RATED HP(#/HP)     0. 01387    0. 00241    0. 00070    0. 00524    0. 00004    0. 00006
                    KWD       XTC      MWEXH   EXH FLOW     FACAL       FAM  ERROR
METHOD 3. 1     0. 81257 1. 10074 25. 02763  1890. 291  0. 11635  0. 07833 48. 539
MASS/MODE(LBM)          2. 73335    0 47478     0. 13824    1. 03303    0. 00862    0. 01345
MASS/RATED HP(#/HP)     0. 01708    0. 00297    0. 00086    0. 00645    0. 00005    0. 00008
                    KWD       XTC      MWEXH   EXH FLOW     FACAL       FAM  ERROR
METHOD 3. 2     0. 89782 0 23312 27. 50000  1720. 346  0. 05969  0. 07833-23. 797
MASS/MODE(LBM)          2. 48761    0. 43209    0. 12581    0. 94016    0. 00785    0. 01224
MASS/RATED HP(#/HP)     0. 01555    0. 00270    0. 00078    0. 00588    0. 00005    0. 00007
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TABLE 5.4. Continued

```
RUN NO. 016
MODE:     3
COMMENTS: 1
TEMP(DB)       = 64. 38F       FUEL RATE=  77. 2798#/HR       ENGINE RPM(NOM)=2688 RPM
TEMP(DP)       = 32. 00F       AIR RATE = 932. 1025#/HR       ENGINE RPM(ACT)=2689. RPM
TEMP(BAR)      = 74. 00F       F/A RATIO=   0. 0829#/#        BHP(OBS)        =151. 5HP
BAR PRESS(OB)= 29. 52"HG       PHIM      =   1. 2473          BHP(CORR)       =156. 2HP
BAR PRESS(CR)= 29. 40"HG                                      MAN VAC(OBS)    = 0. 70"HG
SPEC HUMIDITY=0. 0038#/#                                      MAN PRESS(CORR)=29. 09"HG
                          CO2          O2         UHCC       CO         NO          NOX
CONC(PPM)               67432.        635.        1047.     56747.       238.        231.
                     KWD       XTC      MWEXH  EXH FLOW     FACAL       FAM  ERROR
METHOD 1. 2     0. 89779 0. 75240 27. 19536 14307. 420  0. 08524  0. 08290  2. 815
MASS/MODE(LBM)          0. 55089   0. 00377   0. 00269   0. 29472   0. 00133   0. 00197
MASS/RATED HP(#/HP)  0. 00344   0. 00002   0. 00002   0. 00184   0. 00000   0. 00001
                     KWD       XTC      MWEXH  EXH FLOW     FACAL       FAM  ERROR
METHOD 2. 1     0. 69915 1. 00000 31. 04938 12531. 500  0. 04205  0. 08290-49. 285
MASS/MODE(LBM)          0. 48251   0. 00330   0. 00236   0. 25814   0. 00116   0. 00172
MASS/RATED HP(#/HP)  0. 00302   0. 00002   0. 00001   0. 00161   0. 00000   0. 00001
                     KWD       XTC      MWEXH  EXH FLOW     FACAL       FAM  ERROR
METHOD 3. 1     0. 80301 1. 11823 24. 31953 15999. 300  0. 12982  0. 08290 56. 581
MASS/MODE(LBM)          0. 61603   0. 00422   0. 00301   0. 32957   0. 00148   0. 00220
MASS/RATED HP(#/HP)  0. 00385   0. 00003   0. 00002   0. 00206   0. 00000   0. 00001
                     KWD       XTC      MWEXH  EXH FLOW     FACAL       FAM  ERROR
METHOD 3. 2     0. 89676 0. 24859 27. 50000 14148. 930  0. 06169  0. 08290-25. 598
MASS/MODE(LBM)          0. 54479   0. 00373   0. 00266   0. 29145   0. 00131   0. 00194
MASS/RATED HP(#/HP)  0. 00340   0. 00002   0. 00002   0. 00182   0. 00000   0. 00001

RUN NO. 016
MODE:     4
COMMENTS: 1
TEMP(DB)       = 65. 90F       FUEL RATE=  56. 4972#/HR       ENGINE RPM(NOM)=2434 RPM
TEMP(DP)       = 30. 00F       AIR RATE = 683. 9753#/HR       ENGINE RPM(ACT)=2434. RPM
TEMP(BAR)      = 74. 00F       F/A RATIO=   0. 0826#/#        BHP(OBS)        =111. 0HP
BAR PRESS(OB)= 29. 52"HG       PHIM      =   1. 2427          BHP(CORR)       =  0. 0HP
BAR PRESS(CR)= 29. 40"HG                                      MAN VAC(OBS)    = 3 60"HG
SPEC HUMIDITY=0. 0035#/#                                      MAN PRESS(CORR)= 0. 00"HG
                          CO2          O2         UHCC       CO         NO          NOX
CONC(PPM)               68709.        1270.       1182.     50737.       326.        320.
                     KWD       XTC      MWEXH  EXH FLOW     FACAL       FAM  ERROR
METHOD 1. 2     0. 89923 0. 73928 27. 34589 10438. 000  0. 08307  0. 08260  0. 570
MASS/MODE(LBM)          6. 82518   0 09166   0. 03691   3. 20402   0. 02207   0. 03311
MASS/RATED HP(#/HP)  0. 04266   0. 00057   0. 00023   0. 02003   0. 00014   0. 00021
                     KWD       XTC      MWEXH  EXH FLOW     FACAL       FAM  ERROR
METHOD 2. 1     0. 69241 1. 00000 31. 29414  9121. 082  0. 03973  0. 08260-51 906
MASS/MODE(LBM)          5. 96408   0. 08010   0. 03225   2. 79978   0. 01929   0. 02894
MASS/RATED HP(#/HP)  0. 03728   0. 00050   0. 00020   0. 01750   0. 00012   0. 00018
                     KWD       XTC      MWEXH  EXH FLOW     FACAL       FAM  ERROR
METHOD 3. 1     0. 79867 1. 12233 24. 36182 11716. 550  0. 12894  0. 08260 56. 095
MASS/MODE(LBM)          7. 66120   0. 10290   0. 04143   3. 59648   0. 02478   0. 03717
MASS/RATED HP(#/HP)  0. 04788   0. 00064   0. 00026   0. 02248   0. 00015   0. 00023
                     KWD       XTC      MWEXH  EXH FLOW     FACAL       FAM  ERROR
METHOD 3. 2     0. 89821 0. 23986 27 50000 10379. 510  0. 05907  0. 08260-28. 482
MASS/MODE(LBM)          6. 78693   0. 09115   0. 03670   3. 18606   0. 02195   0. 03293
MASS/RATED HP(#/HP)  0. 04242   0. 00057   0. 00023   0. 01991   0. 00014   0. 00021
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TABLE 5.4. Continued

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RUN NO. 016
MODE:     5
COMMENTS: 1
TEMP(DB)      = 69. 07F      FUEL RATE=  34. 6021#/HR     ENGINE RPM(NOM)=2353 RPM
TEMP(DP)      = 32. 00F      AIR RATE = 413. 1118#/HR     ENGINE RPM(ACT)=2354. RPM
TEMP(BAR)     = 74. 00F      F/A RATIO=   0. 0837#/#      BHP(OBS)       = 58. 5HP
BAR PRESS(OB)= 29. 52"HG     PHIM     =   1. 2601         BHP(CORR)      =  0. 0HP
BAR PRESS(CR)= 29. 40"HG                                  MAN VAC(OBS)   =11. 50"HG
SPEC HUMIDITY=0. 0038#/#                                  MAN PRESS(CORR)= 0. 00"HG
                        CO2        O2        UHCC       CO          NO          NOX
CONC(PPM)              70433.     1270.      1155.     50870.       279.        276.
                    KWD       XTC      MWEXH   EXH FLOW    FACAL        FAM  ERROR
METHOD 1. 2      0. 89723 0. 75093 27. 36317  6307. 168  0. 08279  0. 08376 -1. 157
MASS/MODE(LBM)          5. 07313    0. 06646    0. 02615   2. 32934   0. 01367   0. 02072
MASS/RATED HP(#/HP)  0. 03171    0. 00042    0. 00016   0. 01456   0. 00008   0. 00013
                    KWD       XTC      MWEXH   EXH FLOW    FACAL        FAM  ERROR
METHOD 2. 1      0. 69783 1. 00000 31. 16397  5537 941  0. 04087  0. 08376-51. 210
MASS/MODE(LBM)          4. 45441    0. 05836    0. 02296   2. 04525   0. 01200   0. 01819
MASS/RATED HP(#/HP)  0. 02784    0. 00036    0. 00014   0. 01278   0. 00007   0. 00011
                    KWD       XTC      MWEXH   EXH FLOW    FACAL        FAM  ERROR
METHOD 3. 1      0. 80060 1. 11724 24. 48836  7047. 602  0. 12663  0. 08376 51 188
MASS/MODE(LBM)          5. 66869    0. 07427    0. 02922   2. 60280   0. 01527   0. 02315
MASS/RATED HP(#/HP)  0. 03543    0. 00046    0. 00018   0. 01627   0. 00009   0. 00014
                    KWD       XTC      MWEXH   EXH FLOW    FACAL        FAM  ERROR
METHOD 3. 2      0. 89616 0. 24327 27. 50000  6275. 789  0. 05992  0. 08376-28. 467
MASS/MODE(LBM)          5. 04789    0. 06613    0. 02602   2. 31775   0. 01360   0. 02061
MASS/RATED HP(#/HP)  0. 03155    0. 00041    0. 00016   0. 01449   0. 00008   0 00013

RUN NO. 016
MODE      6
COMMENTS: 1
TEMP(DB)      = 69. 73F      FUEL RATE=   8. 4986#/HR     ENGINE RPM(NOM)=1194 RPM
TEMP(DP)      = 26. 00F      AIR RATE = 110. 4127#/HR     ENGINE RPM(ACT)=1202. RPM
TEMP(BAR)     = 74. 00F      F/A RATIO=   0. 0769#/#      BHP(OBS)       =  7. 9HP
BAR PRESS(OB)= 29. 52"HG     PHIM     =   1. 1580         BHP(CORR)      =  0. 0HP
BAR PRESS(CR)= 29. 40"HG                                  MAN VAC(OBS)   =18. 80"HG
SPEC HUMIDITY=0. 0029#/#                                  MAN PRESS(CORR)= 0 00"HG
                        CO2        O2        UHCC       CO          NO          NOX
CONC(PPM)              67856.    21585.      7500.     35862.       271.        276.
                    KWD       XTC      MWEXH   EXH FLOW    FACAL        FAM  ERROR
METHOD 1. 2      0. 90406 0. 77050 27. 73962  1652 429  0. 07251  0. 07697 -5. 785
MASS/MODE(LBM)          0. 64025    0. 14802    0. 02225   0. 21511   0 00174    0 00271
MASS/RATED HP(#/HP)  0 00400    0. 00092    0. 00014   0. 00134   0 00001    0 00002
                    KWD       XTC      MWEXH   EXH FLOW    FACAL        FAM  ERROR
METHOD 2 1       0 71739 1. 00000 31 12189  1472. 846  0 03895  0. 07697-49 392
MASS/MODE(LBM)          0. 57067    0. 13193    0. 01983   0. 19174   0. 00155   0 00242
MASS/RATED HP(#/HP)  0. 00357    0. 00082    0. 00012   0. 00120   0 00001    0 00002
                    KWD       XTC      MWEXH   EXH FLOW    FACAL        FAM  ERROR
METHOD 3 1       0 81176 1. 10596 25. 04637  1830. 116  0. 11325  0. 07697 47. 140
MASS/MODE(LBM)          0. 70909    0 16394    0. 02464   0. 23825   0. 00193   0. 00301
MASS/RATED HP(#/HP)  0. 00443    0 00102    0. 00015   0. 00149   0. 00001   0 00002
                    KWD       XTC      MWEXH   EXH FLOW    FACAL        FAM  ERROR
METHOD 3. 2      0 90328 0. 21786 27. 50000  1666. 828  0. 05432  0. 07697-29. 424
MASS/MODE(LBM)          0. 64583    0 14931    0. 02244   0. 21699   0. 00176   0. 00274
MASS/RATED HP(#/HP)  0 00404    0. 00092    0. 00014   0. 00136   0. 00001   0 00002
```

TABLE 5.4. Continued

```
RUN NO. 016
MODE:     7
COMMENTS: 1
TEMP(DB)     = 70. 13F      FUEL RATE=   3. 4463#/HR     ENGINE RPM(NOM)= 662 RPM
TEMP(DP)     = 34. 00F      AIR RATE =  55. 9467#/HR     ENGINE RPM(ACT)= 663. RPM
TEMP(BAR)    = 74. 00F      F/A RATIO=   0. 0616#/#      BHP(OBS)        =  0. 7HP
BAR PRESS(OB)= 29. 52"HG    PHIM     =   0. 9267         BHP(CORR)       =  0. 0HP
BAR PRESS(CR)= 29. 40"HG                                 MAN VAC(OBS)    =17. 50"HG
SPEC HUMIDITY=0. 0042#/#                                 MAN PRESS(CORR)= 0. 00"HG
                       CO2       O2        UHCC      CO        NO        NOX
CONC(PPM)             48153.    69833.    19405.    13124.      138.      138.
                  KWD     XTC      MWEXH  EXH FLOW    FACAL      FAM  ERROR
METHOD 1. 2   0. 92714 0. 77648 28. 19276   812. 079 0. 05230 0. 06160-15. 091
MASS/MODE(LBM)       0. 07442  0. 07844  0. 00942  0. 01290  0. 00015  0. 00022
MASS/RATED HP(#/HP)  0. 00047  0. 00049  0. 00006  0. 00008  0. 00000  0. 00000
MASS/HP/CYC(#/HP/C)  0. 09822  0. 00564  0. 00145  0. 04379  0. 00029  0. 00044
                  KWD     XTC      MWEXH  EXH FLOW    FACAL      FAM  ERROR
METHOD 2. 1   0. 74120 1. 00000 31. 23962   732. 875 0. 03046 0. 06160-50. 549
MASS/MODE(LBM)       0. 06716  0. 07079  0. 00850  0. 01164  0. 00013  0. 00020
MASS/RATED HP(#/HP)  0. 00042  0. 00044  0. 00005  0. 00007  0. 00000  0. 00000
MASS/HP/CYC(#/HP/C)  0. 08638  0. 00503  0. 00129  0. 03848  0. 00026  0. 00039
                  KWD     XTC      MWEXH  EXH FLOW    FACAL      FAM  ERROR
METHOD 3. 1   0. 83146 1. 09909 25. 57610   895. 162 0. 09409 0. 06160 52. 759
MASS/MODE(LBM)       0. 08204  0. 08647  0. 01039  0. 01422  0. 00016  0. 00025
MASS/RATED HP(#/HP)  0. 00051  0. 00054  0. 00006  0. 00008  0. 00000  0. 00000
MASS/HP/CYC(#/HP/C)  0. 10968  0. 00624  0. 00161  0. 04893  0 00033  0. 00050
                  KWD     XTC      MWEXH  EXH FLOW    FACAL      FAM  ERROR
METHOD 3. 2   0. 92591 0. 15601 27. 50000   832. 536 0. 03984 0 06160-35. 325
MASS/MODE(LBM)       0. 07630  0. 08042  0. 00966  0. 01322  0. 00015  0. 00023
MASS/RATED HP(#/HP)  0. 00048  0. 00050  0. 00006  0. 00008  0. 00000  0. 00000
MASS/HP/CYC(#/HP/C)  0 09788  0. 00567  0. 00146  0. 04362  0. 00029  0. 00044
```

5.2 AVCO-LYCOMING LIO-320 LEAN-OUT RUNS

The purpose of this test was to observe the effect of fuel-air ratio on emission levels. The standard test setup was used for this series of measurements except for the addition of a knock sensor to detect the onset of detonation.

The test procedure consisted of operating the engine at the five modes of the seven mode test cycle. The fuel-air ratio was varied within each mode. The first data point taken for each mode was with the mixture set full-rich. This data point was used to establish the baseline emission levels and to establish the cooling air requirements necessary to hold the cylinder heads at the maximum continuous operating temperature. This cooling air flow rate was held constant throughout the leaning process. Other values held constant throughout leaning were engine RPM and engine power output.

There were three criteria used to judge the lean limit for this engine. They were engine cylinder head temperature exceeding the maximum continuous operating temperature, the onset of detonation (either audible or by means of the knock sensor), and severe power and RPM drops. During testing, large power and RPM drops were encountered before the knock or cylinder head temperature limits were exceeded.

The results from these tests are plotted in figures 5.4 to 5.8, which are taken from reference 10. CO and CO2 concentrations are shown to be dependent on fuel-air ratio only and independent of operating mode. This is also true for O2 concentrations at mixture ratios leaner than stoichiometric. However, NOX levels are strongly dependent upon both operating mode and mixture ratio, the peak levels for all modes occurring at about a fuel-air ratio of 0.065. The strong dependence of NOX concentration on mixture ratio is clearly illustrated.

"Computer print-outs from these tests are given in tables 5.5-5.8."

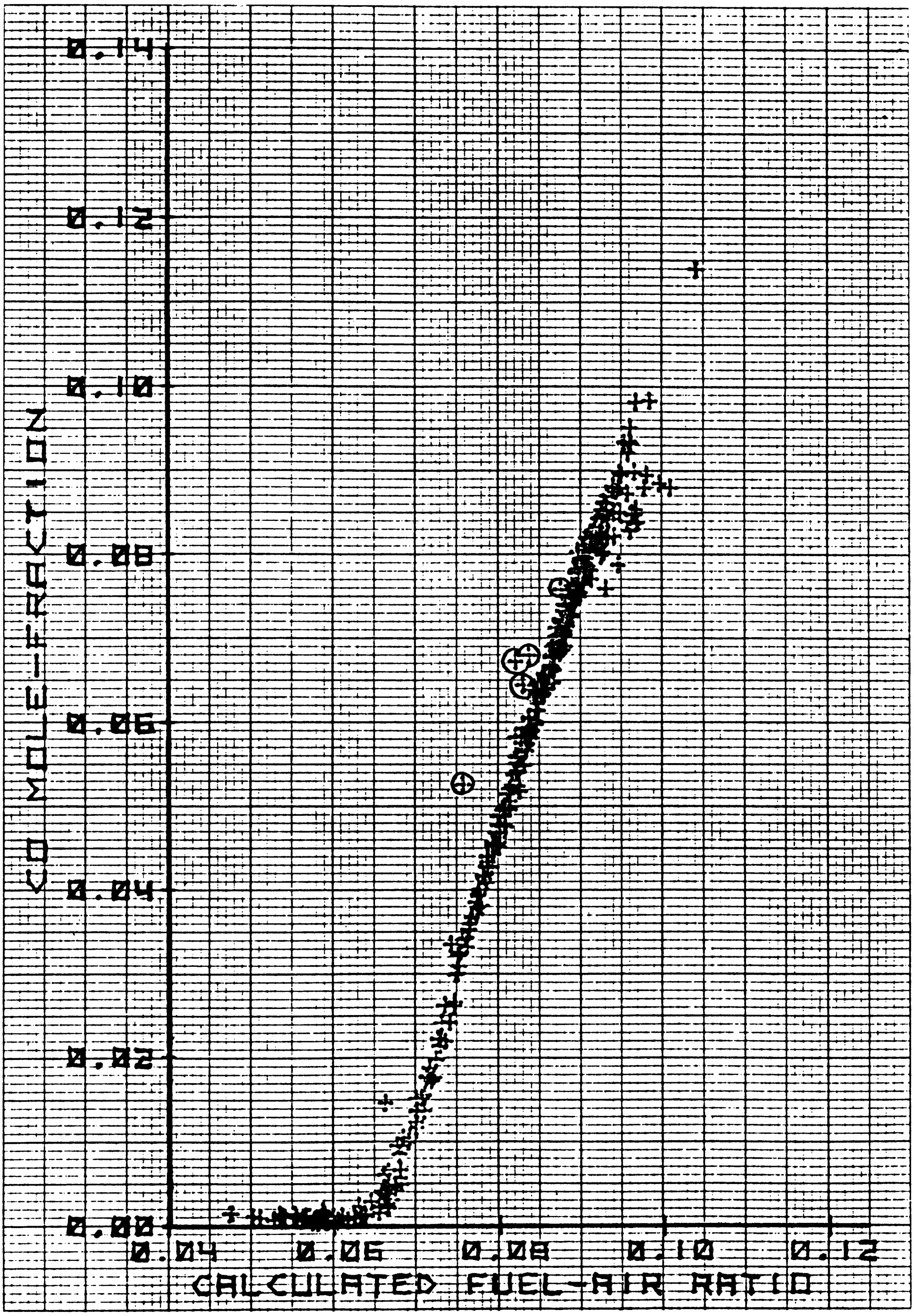

Figure 5.4. LIO-320 Lean-Out Results for CO (Reference 10)

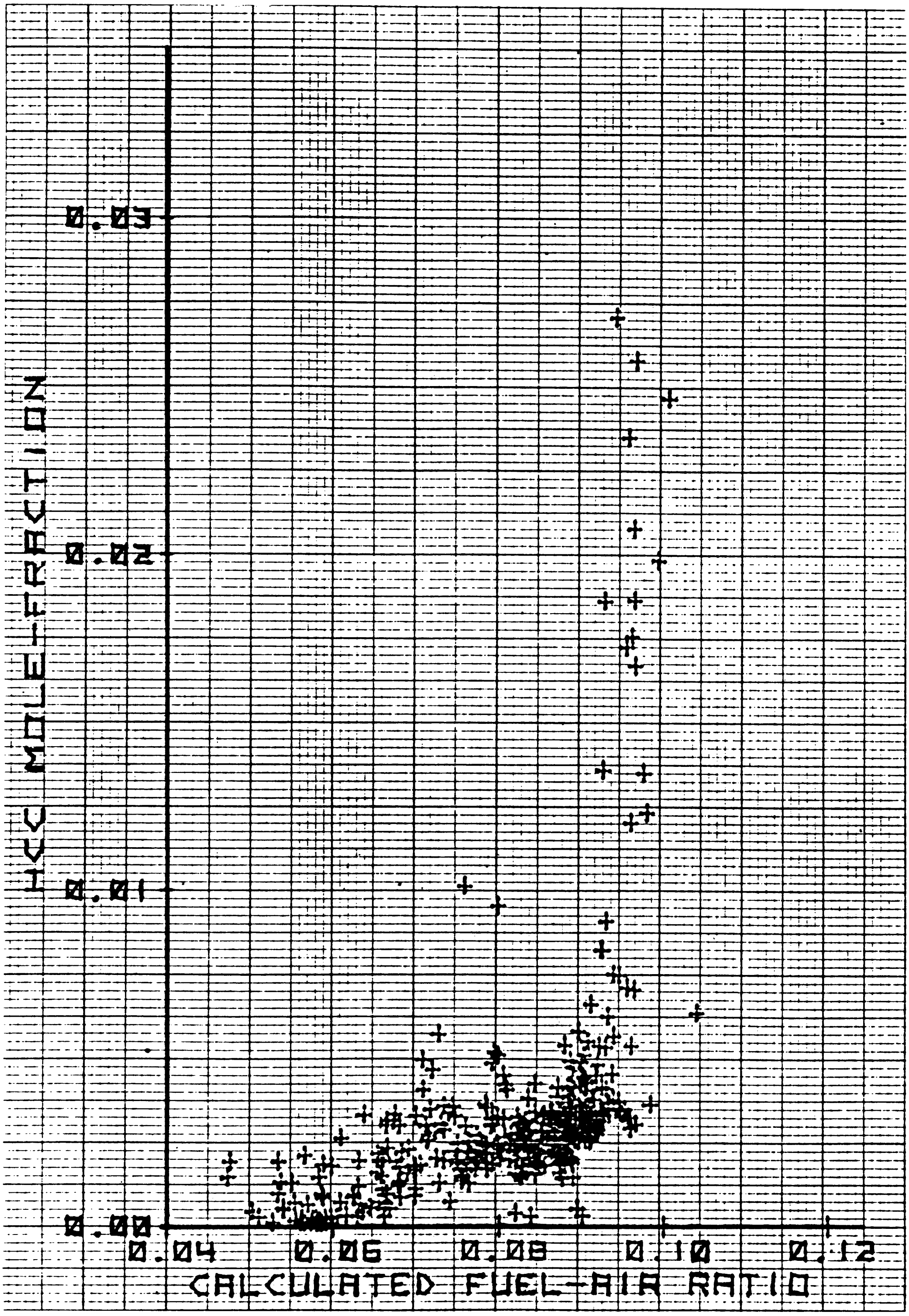

Figure 5.5. LIO-320 Lean-Out Results for UHCC (Reference 10)

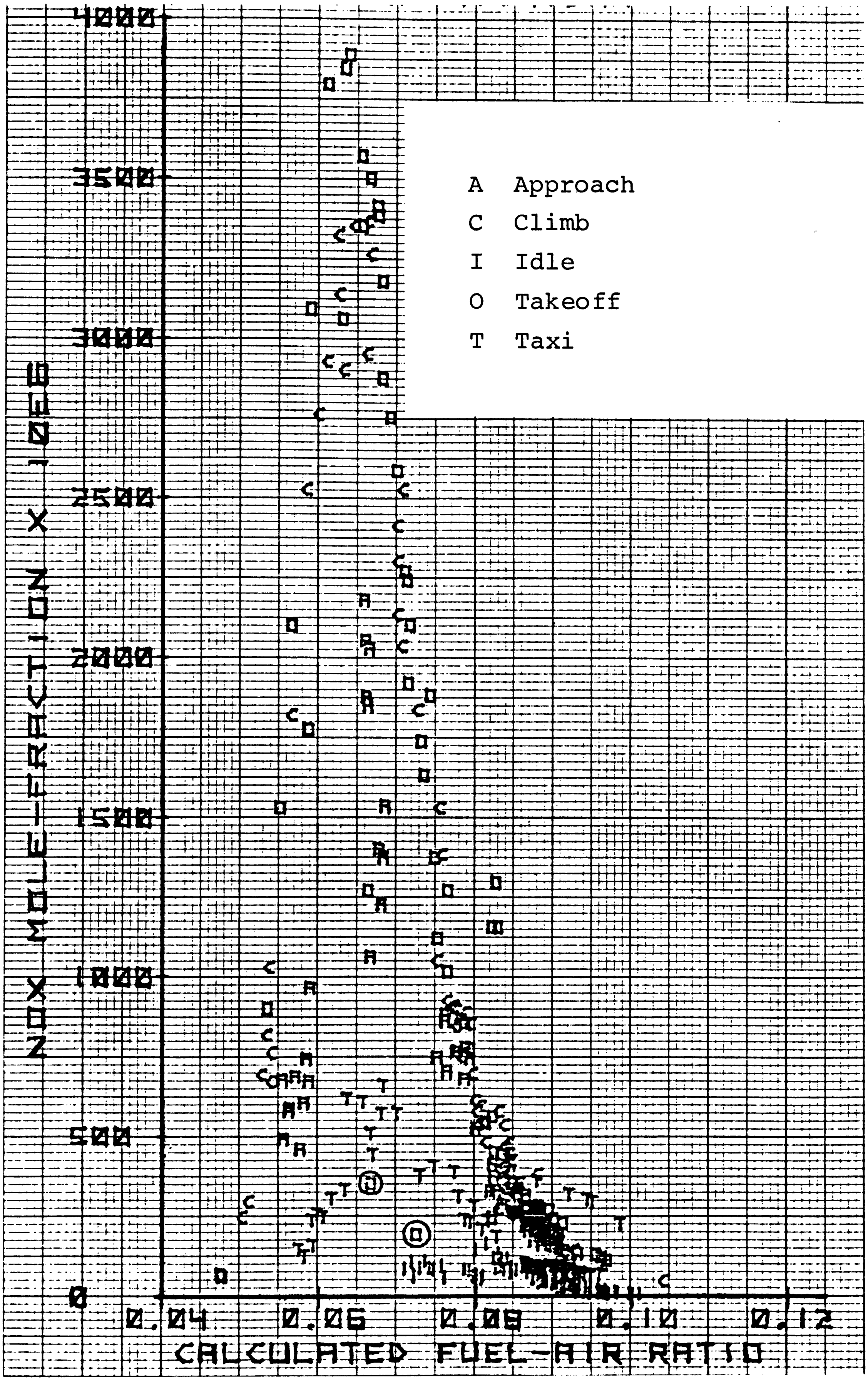

Figure 5.6. LIO-320 Lean-Out Results for NOX (Reference 10)

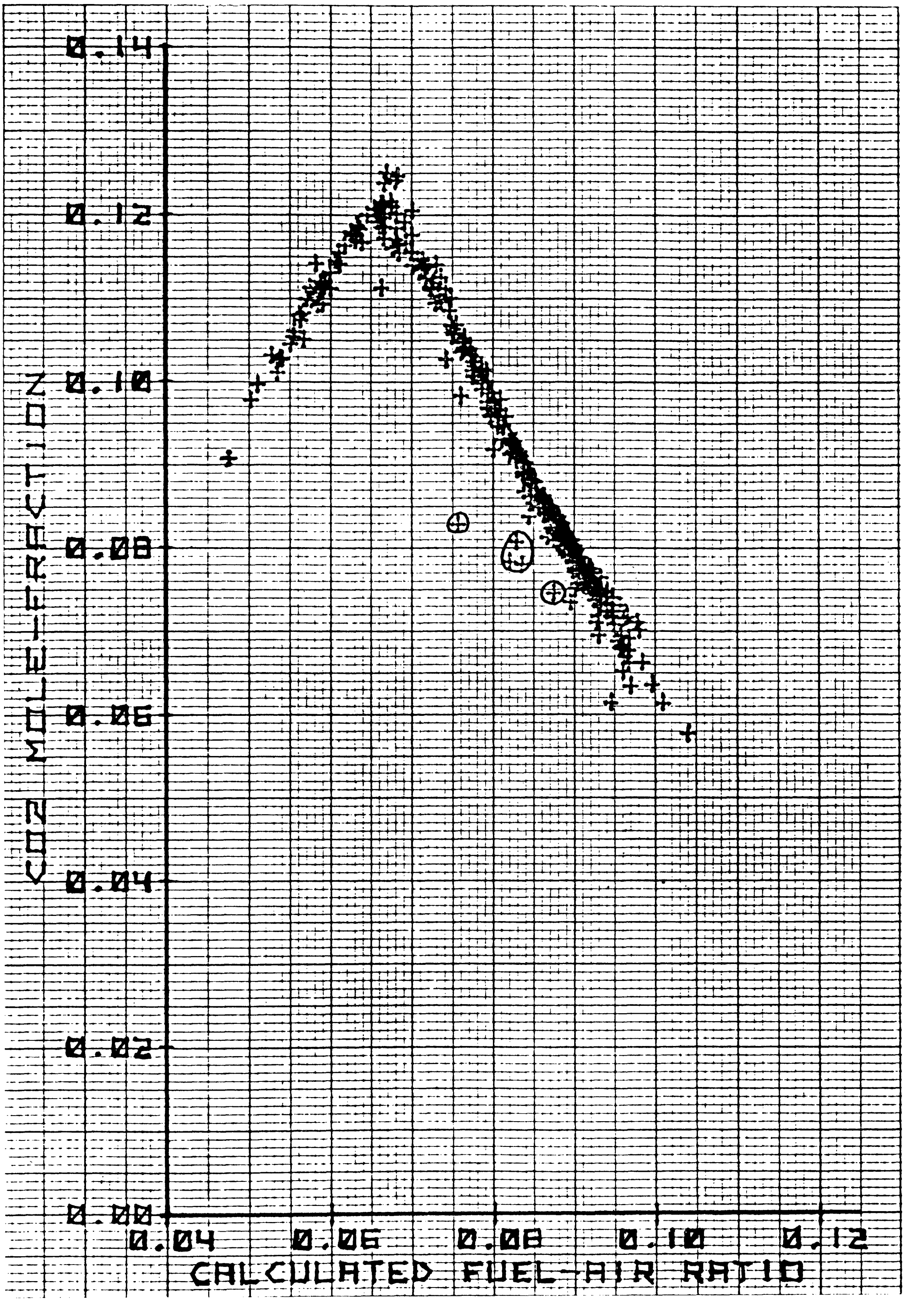

Figure 5.7. LIO-320 Lean-Out Results for CO2 (Reference 10)

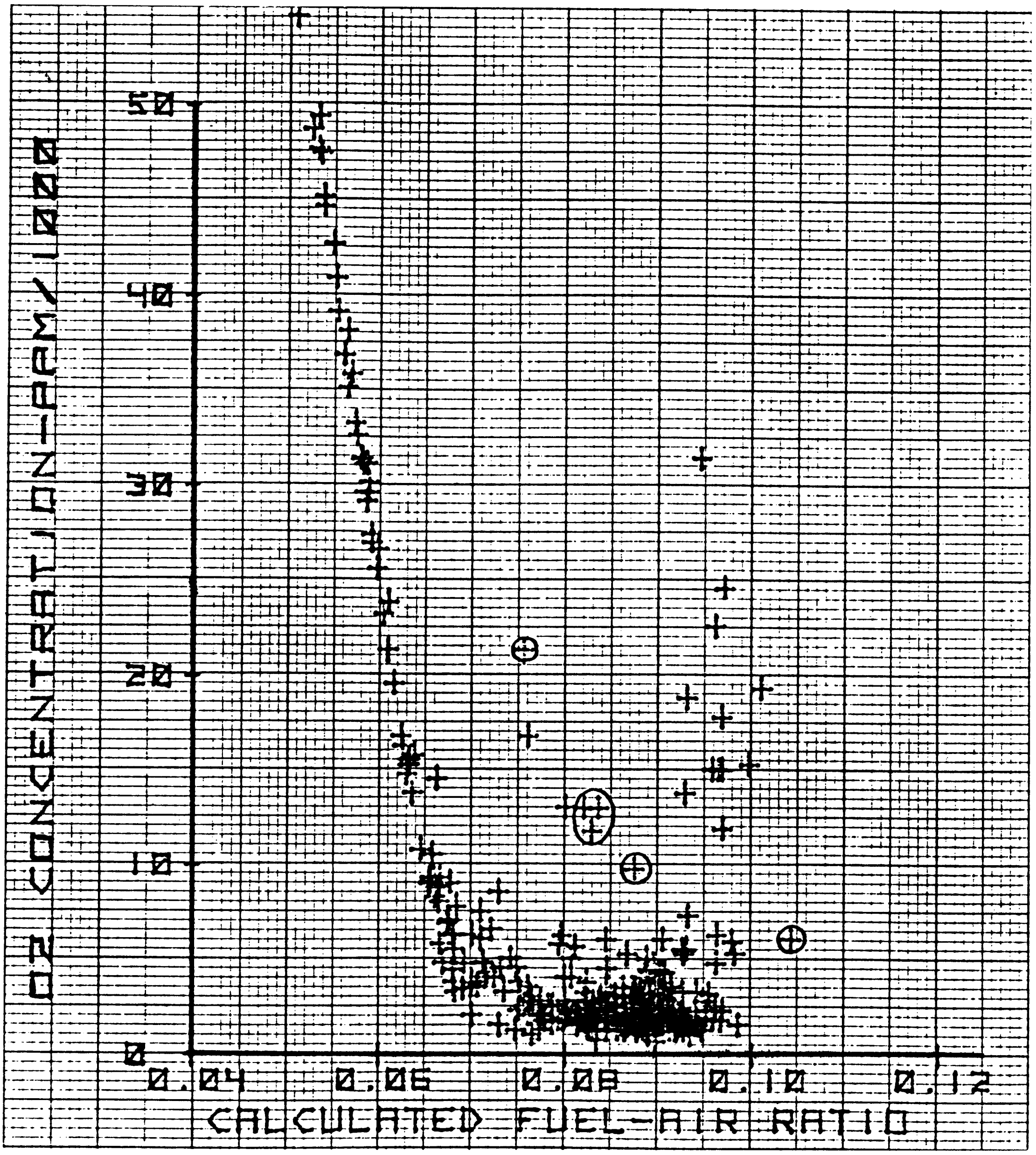

Figure 5.8. LIO-320 Lean-Out Results for O2 (Reference 10)

TABLE 5.5. COMPUTER PRINTOUT: LEAN-OUT RESULTS, MODE 2.

```
 DATE:        12/11/75       ENGINE TYPE:    LIO-320-B1A    FUEL H/C RATIO = 2. 180
 LOCATION: UNIV OF MICH  SERIAL NUMBER  L-287-66A      IGNITION TIMING= 25DEG
 OPERATORS: PACE, GRIFFIN, DRAXLER

RUN NO. 24
MODE:      #2
COMMENTS: LEAN OUT TESTS-TAXI MODE
TEMP(DB)        = 95. 93F        FUEL RATE=    8. 9847#/HR       ENGINE RPM(NOM)=1207 RPM
TEMP(DP)        = 36. 00F        AIR RATE = 112. 0691#/HR       ENGINE RPM(ACT)=1206. RPM
TEMP(BAR)       = 76. 00F        F/A RATIO=    0. 0801#/#        BHP(OBS)          =  8. 0HP
BAR PRESS(OB)= 29. 34"HG     PHIM       =    1. 2051           BHP(CORR)         =  0. 0HP
BAR PRESS(CR)= 29. 21"HG                                        MAN VAC(OBS)     =18. 20"HG
SPEC HUMIDITY=0. 0045#/#                                        MAN PRESS(CORR)= 0. 00"HG
                           CO2         O2          UHCC        CO          NO          NOX
CONC(PPM)                102873..    16986.       6000.      55262.        387         387.
                    KWD        XTC      MWEXH    EXH FLOW     FACAL       FAM   ERROR
METHOD 1. 2     0. 86407 1. 04070 27. 63261   1688. 718  0. 07625  0. 08017 -4. 882
MASS/MODE(LBM)           3. 63719    0. 43650    0. 06668    1. 24210    0. 00933    0. 01428
MASS/RATED HP(#/HP)  0. 02273    0. 00273    0. 00042    0. 00776    0. 00006    0. 00008
                    KWD        XTC      MWEXH    EXH FLOW     FACAL       FAM   ERROR
METHOD 2. 1     0. 90621 1. 00000 26. 83102   1739. 169  0. 08637  0. 08017  7. 731
MASS/MODE(LBM)           3. 74585    0. 44954    0. 06868    1. 27921    0. 00961    0. 01470
MASS/RATED HP(#/HP)  0. 02341    0. 00281    0. 00043    0. 00799    0. 00006    0. 00009
                    KWD        XTC      MWEXH    EXH FLOW     FACAL       FAM   ERROR
METHOD 3. 1     0. 88191 0. 97848 28. 24356   1652. 189  0. 06847  0. 08017-14. 595
MASS/MODE(LBM)           3. 55851    0. 42705    0. 06524    1. 21523    0. 00913    0. 01397
MASS/RATED HP(#/HP)  0. 02224    0. 00267    0. 00041    0. 00759    0. 00006    0. 00008
                    KWD        XTC      MWEXH    EXH FLOW     FACAL       FAM   ERROR
METHOD 3. 2     0. 86428 0. 30780 27. 50000   1696. 862  0. 07979  0. 08017 -0. 473
MASS/MODE(LBM)           3. 65473    0. 43860    0. 06700    1. 24809    0. 00937    0. 01435
MASS/RATED HP(#/HP)  0. 02284    0. 00274    0. 00042    0. 00780    0. 00006    0. 00009

RUN NO. 24
MODE:      2
COMMENTS: TAXI MODE-. 5 IN.  LEANED
TEMP(DB)        = 96. 62F        FUEL RATE=    8. 8679#/HR       ENGINE RPM(NOM)=1204 RPM
TEMP(DP)        = 36. 00F        AIR RATE = 108. 7265#/HR       ENGINE RPM(ACT)=1197. RPM
TEMP(BAR)       = 76. 00F        F/A RATIO=    0. 0815#/#        BHP(OBS)          =  8. 0HP
BAR PRESS(OB)= 29. 34"HG     PHIM       =    1. 2259           BHP(CORR)         =  0. 0HP
BAR PRESS(CR)= 29. 21"HG                                        MAN VAC(OBS)     =18. 30"HG
SPEC HUMIDITY=0. 0045#/#                                        MAN PRESS(CORR)= 0. 00"HG
                           CO2         O2          UHCC        CO          NO          NOX
CONC(PPM)                101772.     16357.       5700.      54562.       412.        412.
                    KWD        XTC      MWEXH    EXH FLOW     FACAL       FAM   ERROR
METHOD 1. 2     0. 86542 1. 02855 27. 63574   1640. 272  0. 07626  0. 08156 -6. 499
MASS/MODE(LBM)           3. 49505    0. 40827    0. 06154    1. 19121    0. 00965    0. 01476
MASS/RATED HP(#/HP)  0. 02184    0. 00255    0. 00038    0. 00744    0. 00006    0. 00009
                    KWD        XTC      MWEXH    EXH FLOW     FACAL       FAM   ERROR
METHOD 2. 1     0. 89461 1. 00000 27. 08130   1673. 854  0. 08317  0 08156  1. 980
MASS/MODE(LBM)           3. 56661    0. 41663    0. 06279    1. 21560    0. 00984    0. 01506
MASS/RATED HP(#/HP)  0. 02229    0. 00260    0. 00039    0. 00759    0 00006    0. 00009
                    KWD        XTC      MWEXH    EXH FLOW     FACAL       FAM   ERROR
METHOD 3. 1     0. 87788 0. 98499 28. 05896   1615. 532  0. 07082  0. 08156-13. 166
MASS/MODE(LBM)           3. 44234    0. 40211    0. 06061    1. 17324    0. 00950    0. 01454
MASS/RATED HP(#/HP)  0. 02151    0. 00251    0. 00038    0. 00733    0. 00006    0. 00009
                    KWD        XTC      MWEXH    EXH FLOW     FACAL       FAM   ERROR
METHOD 3. 2     0. 86557 0. 30464 27. 50000   1648. 369  0. 07873  0. 08156 -3. 464
MASS/MODE(LBM)           3. 51230    0. 41029    0. 06184    1. 19709    0. 00969    0. 01483
MASS/RATED HP(#/HP)  0. 02195    0. 00256    0. 00039    0. 00748    0 00006    0. 00009
```

TABLE 5.5. Continued

```
RUN NO. 24
MODE:      #2
COMMENTS: TAXI MODE-1 IN.  LEANED
TEMP(DB)        = 97. 40F        FUEL RATE=    8. 5837#/HR       ENGINE RPM(NOM)=1195 RPM
TEMP(DP)        = 36. 00F        AIR RATE  = 105 8810#/HR       ENGINE RPM(ACT)=1188. RPM
TEMP(BAR)       = 76. 00F        F/A RATIO=    0. 0810#/#        BHP(OBS)         =  7. 9HP
BAR PRESS(OB)= 29. 34"HG         PHIM      =    1. 2186          BHP(CORR)        =  0. 0HP
BAR PRESS(CR)= 29. 21"HG                                         MAN VAC(OBS)     =18. 40"HG
SPEC HUMIDITY=0. 0045#/#                                         MAN PRESS(CORR)= 0. 00"HG
                              CO2          O2         UHCC       CO          NO          NOX
CONC(PPM)                  102873.      18245.       6300.     54911.       375.        375.
                     KWD       XTC     MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 1 2       0. 86416 1. 04490 27. 63931   1596. 412  0. 07591  0. 08106 -6. 360
MASS/MODE(LBM)           3. 43838   0. 44320    0. 06619   1. 16677   0. 00853   0. 01306
MASS/RATED HP(#/HP)    0. 02149   0. 00277    0. 00041   0. 00729   0. 00005   0. 00008
                     KWD       XTC     MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 2. 1      0. 91088 1. 00000 26. 75163   1649. 384  0. 08710  0. 08106  7. 443
MASS/MODE(LBM)           3. 55247   0. 45791    0. 06839   1. 20548   0. 00882   0 01349
MASS/RATED HP(#/HP)    0. 02220   0. 00286    0. 00043   0. 00753   0. 00006   0. 00008
                     KWD       XTC     MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 3. 1      0. 88390 0. 97621 28. 31651   1558. 233  0. 06729  0. 08106-16. 987
MASS/MODE(LBM)           3. 35615   0. 43260    0. 06461   1 13886   0. 00833   0. 01275
MASS/RATED HP(#/HP)    0. 02098   0. 00270    0. 00040   0. 00711   0. 00005   0. 00008
                     KWD       XTC     MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 3. 2      0. 86439 0. 30756 27. 50000   1604. 499  0. 07979  0. 08106 -1 571
MASS/MODE(LBM)           3. 45580   0. 44545    0. 06653   1. 17268   0. 00858   0. 01313
MASS/RATED HP(#/HP)    0. 02160   0. 00278    0. 00042   0. 00732   0. 00005   0. 00008

RUN NO. 24
MODE:      #2
COMMENTS: TAXI MODE-1. 5 IN.  LEANED
TEMP(DB)        = 98. 05F        FUEL RATE=    8. 4364#/HR       ENGINE RPM(NOM)=1207 RPM
TEMP(DP)        = 36. 00F        AIR RATE  = 107. 0497#/HR      ENGINE RPM(ACT)=1188. RPM
TEMP(BAR)       = 76. 00F        F/A RATIO=    0. 0788#/#        BHP(OBS)         =  8. 2HP
BAR PRESS(OB)= 29. 34"HG         PHIM      =    1. 1846          BHP(CORR)        =  0. 0HP
BAR PRESS(CR)= 29. 21"HG                                         MAN VAC(OBS)     =18. 50"HG
SPEC HUMIDITY=0. 0045#/#                                         MAN PRESS(CORR)= 0. 00"HG
                              CO2          O2         UHCC       CO          NO          NOX
CONC(PPM)                  102322.      20132.       6750.     53868.       375.        387.
                     KWD       XTC     MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 1. 2      0. 86502 1. 04606 27. 65285   1609. 869  0. 07532  0. 07880 -4. 416
MASS/MODE(LBM)           3. 44878   0. 49317    0. 07152   1. 15426   0. 00861   0. 01361
MASS/RATED HP(#/HP)    0. 02155   0. 00308    0. 00045   0. 00721   0. 00005   0. 00008
                     KWD       XTC     MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 2. 1      0. 91302 1. 00000 26. 74348   1664. 610  0. 08671  0. 07880 10. 027
MASS/MODE(LBM)           3. 56605   0. 50994    0. 07395   1. 19351   0. 00890   0. 01407
MASS/RATED HP(#/HP)    0. 02229   0. 00319    0. 00046   0. 00745   0. 00006   0. 00008
                     KWD       XTC     MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 3 1       0. 88531 0 97561 28. 34837   1570 371   0. 06647  0. 07880-15. 651
MASS/MODE(LBM)           3. 36417   0. 48107    0. 06976   1. 12594   0. 00840   0. 01328
MASS/RATED HP(#/HP)    0. 02103   0 00301     0 00044   0. 00703   0 00005    0. 00008
                     KWD       XTC     MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 3. 2      0. 86526 0. 30551 27 50000   1618. 817  0. 07927  0. 07880  0. 594
MASS/MODE(LBM)           3. 46795   0. 49591    0. 07191   1. 16067   0 00865    0. 01369
MASS/RATED HP(#/HP)    0..02167   0 00310     0. 00045   0. 00725   0 00005    0. 00008
```

TABLE 5.5. Continued

```
RUN NO. 24
MODE:       2
COMMENTS: TAXI MODE-2 IN. LEANED
TEMP(DB)      = 98. 48F       FUEL RATE=    7. 8575#/HR      ENGINE RPM(NOM)=1203 RPM
TEMP(DP)      = 36. 00F       AIR RATE = 108. 6463#/HR      ENGINE RPM(ACT)=1171. RPM
TEMP(BAR)     = 76. 00F       F/A RATIO=    0. 0723#/#       BHP(OBS)        =  7. 7HP
BAR PRESS(OB)= 29. 34"HG      PHIM      =   1. 0871          BHP(CORR)       =  0. 0HP
BAR PRESS(CR)= 29. 21"HG                                     MAN VAC(OBS)    =18. 30"HG
SPEC HUMIDITY=0. 0045#/#                                     MAN PRESS(CORR)= 0. 00"HG
                         CO2         O2          UHCC        CO          NO          NOX
CONC(PPM)              102873.     33973.        8250.      38085.       412.        450.
                      KWD       XTC     MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 1. 2       0. 87134 1. 04769 27. 92587  1608. 177  0. 06837  0. 07232 -5. 455
MASS/MODE(LBM)          3. 46372    0. 83136    0. 08732    0. 81520    0. 00946    0. 01579
MASS/RATED HP(#/HP)     0. 02165    0. 00520    0. 00055    0. 00509    0. 00006    0. 00009
MASS/HP/CYC(#/HP/C)     0. 10927    0. 01633    0. 00221    0. 03481    0. 00028    0. 00045
                      KWD       XTC     MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 2. 1       0. 92138 1. 00000 27. 01570  1662. 357  0. 07881  0. 07232  8. 983
MASS/MODE(LBM)          3. 58041    0. 85936    0. 09026    0. 84266    0. 00978    0. 01632
MASS/RATED HP(#/HP)     0. 02238    0. 00537    0. 00056    0. 00527    0. 00006    0. 00010
MASS/HP/CYC(#/HP/C)     0. 11257    0. 01683    0. 00228    0. 03585    0. 00029    0. 00046
                      KWD       XTC     MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 3. 1       0. 89300 0. 97519 28. 64545  1567. 779  0. 05924  0. 07232-18. 088
MASS/MODE(LBM)          3. 37671    0. 81047    0. 08512    0. 79472    0. 00922    0. 01539
MASS/RATED HP(#/HP)     0. 02110    0. 00507    0. 00053    0. 00497    0. 00006    0. 00009
MASS/HP/CYC(#/HP/C)     0. 10686    0. 01596    0. 00216    0. 03405    0. 00028    0. 00044
                      KWD       XTC     MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 3. 2       0. 87160 0. 28186 27. 50000  1633. 082  0. 07202  0. 07232 -0. 408
MASS/MODE(LBM)          3. 51736    0. 84423    0. 08867    0. 82782    0. 00960    0. 01603
MASS/RATED HP(#/HP)     0. 02198    0. 00528    0. 00055    0. 00517    0. 00006    0. 00010
MASS/HP/CYC(#/HP/C)     0. 11005    0. 01647    0. 00222    0. 03504    0. 00029    0. 00045
```

TABLE 5.6. COMPUTER PRINTOUT: LEAN-OUT RESULTS, MODE 3.

```
 DATE:        12/22/75         ENGINE TYPE:    LIO-320-B1A   FUEL H/C RATIO = 2. 180
 LOCATION: UNIV OF MICH  SERIAL NUMBER: L-287-66A      IGNITION TIMING= 25DEG
 OPERATORS: PACE, GRIFFIN, PONSONBY

RUN NO. 28
MODE:      3
COMMENTS: LEAN OUT, TAKEOFF, FULL RICH
TEMP(DB)       = 89. 84F        FUEL RATE=   75. 8533#/HR        ENGINE RPM(NOM)=2700 RPM
TEMP(DP)       = 15. 00F        AIR RATE = 868. 2720#/HR        ENGINE RPM(ACT)=2702. RPM
TEMP(BAR)      = 76. 00F        F/A RATIO=    0. 0873#/#         BHP(OBS)         =140. 7HP
BAR PRESS(OB)= 29. 31"HG      PHIM      =    1. 3131             BHP(CORR)        =156. 2HP
BAR PRESS(CR)= 29. 18"HG                                        MAN VAC(OBS)    = 1. 20"HG
SPEC HUMIDITY=0. 0015#/#                                        MAN PRESS(CORR)=29. 22"HG
                          CO2          O2         UHCC        CO          NO          NOX
CONC(PPM)               93400.       1507.       1169.      88666.        255.        255.
                    KWD       XTC      MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 1. 2     0. 86331 1. 04202 27. 10544 13426. 840  0. 08675  0. 08736 -0. 690
MASS/MODE(LBM)           0. 71607    0. 00839    0. 00282    0. 43215    0. 00133    0. 00204
MASS/RATED HP(#/HP)  0. 00448    0. 00005    0. 00002    0. 00270    0. 00000    0. 00001
                    KWD       XTC      MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 2. 1     0. 90663 1. 00000 26. 21115 13884. 940  0. 09929  0. 08736 13. 663
MASS/MODE(LBM)           0. 74050    0. 00868    0. 00291    0. 44690    0. 00138    0. 00211
MASS/RATED HP(#/HP)  0. 00463    0. 00005    0. 00002    0. 00279    0. 00000    0. 00001
                    KWD       XTC      MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 3. 1     0. 88056 0. 97680 27. 74921 13115. 340  0. 07835  0. 08736-10 307
MASS/MODE(LBM)           0. 69946    0. 00820    0. 00275    0 42213    0. 00130    0. 00199
MASS/RATED HP(#/HP)  0. 00437    0. 00005    0. 00002    0. 00264    0. 00000    0 00001
                    KWD       XTC      MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 3 2      0. 86337 0. 34037 27. 50000 13234 190   0. 09103  0. 08736  4 201
MASS/MODE(LBM)           0. 70580    0. 00827    0. 00278    0 42595    0. 00131    0 00201
MASS/RATED HP(#/HP)  0. 00441    0. 00005    0. 00002    0. 00266    0 00000    0. 00001

RUN NO. 28
MODE:      3
COMMENTS: TAKEOFF, . 75 IN.  LEAN
TEMP(DB)       = 90. 71F        FUEL RATE=   65. 6455#/HR        ENGINE RPM(NOM)=2700 RPM
TEMP(DP)       = 15. 00F        AIR RATE = 860. 6604#/HR        ENGINE RPM(ACT)=2695. RPM
TEMP(BAR)      = 76. 00F        F/A RATIO=    0. 0762#/#         BHP(OBS)         =140. 7HP
BAR PRESS(OB)= 29. 31"HG      PHIM      =    1 1465              BHP(CORR)        =155. 7HP
BAR PRESS(CR)= 29. 18"HG                                        MAN VAC(OBS)    = 1. 30"HG
SPEC HUMIDITY=0. 0015#/#                                        MAN PRESS(CORR)=28. 99"HG
                          CO2          O2         UHCC        CO          NO          NOX
CONC(PPM)               119976.      1884.        874.      49810.       705.        705
                    KWD       XTC      MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 1 2      0. 85606 1 05295 27 88744 12804. 020  0. 07637  0 07627  0   33
MASS/MODE(LBM)           0. 87716    0. 01001    0. 00201    0. 23151    0. 00351    0 00537
MASS/RATED HP(#/HP)  0. 00548    0. 00006    0 00001    0. 00145    0. 00002    0 00003
MASS/HP/CYC(#/HP/C)  0. 00995    0 00012    0. 00003    0. 00415    0. 00003    0. 00005
                    KWD       XTC      MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 2. 1     0 91085 1 00000 26. 84024 13303. 580  0. 09002  0. 07627 18. 030
MASS/MODE(LBM)           0. 91138    0. 01040    0. 00209   .0. 24054    0. 00365    0. 00558
MASS/RATED HP(#/HP)  0. 00570    0. 00006    0. 00001    0. 00150    0. 00002    0. 00003
MASS/HP/CYC(#/HP/C)  0. 01032    0. 00012    0 00003    0. 00430    0 00003    0 00005
                    KWD       XTC      MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 3. 1     0 87941 0. 97212 28. 69218 12444 890  0. 06668  0. 07627-12. 572
MASS/MODE(LBM)           0. 85255    0. 00973    0. 00195    0. 22501    0 00341    0 00522
MASS/RATED HP(#/HP)  0. 00533    0. 00006    0. 00001    0. 00141    0. 00002    0. 00003
MASS/HP/CYC(#/HP/C)  0 00970    0. 00011    0. 00003    0. 00404    0 00003    0. 00005
                    KWD       XTC      MWEXH   EXH FLOW     FACAL        FAM   ERROR
METHOD 3 2      0. 85614 0. 31590 27 50000 12984. 410  0. 08093  0. 07627  6 115
MASS/MODE(LBM)           0 88951    0. 01015    0. 00204    0. 23477    0. 00356    0. 00544
MASS/RATED HP(#/HP)  0. 00556    0. 00006    0. 00001    0. 00147    0. 00002    0. 00003
MASS/HP/CYC(#/HP/C)  0. 00997    0 00012    0. 00003    0. 00413    0. 00003    0. 00005
```

TABLE 5.7. COMPUTER PRINTOUT: LEAN-OUT RESULTS, MODE 4.

```
 DATE:       12/19/75       ENGINE TYPE     LIO-320-B1A    FUEL H/C RATIO = 2. 180
 LOCATION: UNIV OF MICH  SERIAL NUMBER: L-287-66A      IGNITION TIMING= 25DEG
 OPERATORS: PACE, PONSONBY, GRIFFIN

RUN NO. 27
MODE:     4
COMMENTS: LEAN OUT, CLIMBOUT, FULL RICH
TEMP(DB)        = 82. 80F       FUEL RATE=  56. 0224#/HR       ENGINE RPM(NOM)=2419 RPM
TEMP(DP)        = 23. 00F       AIR RATE = 672. 9324#/HR       ENGINE RPM(ACT)=2451. RPM
TEMP(BAR)       = 72. 00F       F/A RATIO=    0. 0832#/#       BHP(OBS)          =110. 8HP
BAR PRESS(OB)= 29. 32"HG        PHIM     =    1. 2513          BHP(CORR)         =   0. 0HP
BAR PRESS(CR)= 29. 21"HG                                       MAN VAC(OBS)      = 3. 50"HG
SPEC HUMIDITY=0. 0025#/#                                       MAN PRESS(CORR)= 0. 00"HG
                            CO2         O2         UHCC         CO         NO        NOX
CONC(PPM)                  97445.      3140.       1121.       76223.      386.       386
                     KWD       XTC     MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 1. 2      0. 86325 1. 02568 27. 31596 10286. 900  0. 08324  0. 08325 -0. 004
MASS/MODE(LBM)          9. 53961    0. 22341    0. 03451    4. 74380    0. 02574    0. 03937
MASS/RATED HP(#/HP)  0. 05962    0 00140     0. 00022    0. 02965    0. 00016    0. 00025
                     KWD       XTC     MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 2. 1      0. 88931 1 00000 26 79305 10487. 670  0. 09025  0. 08325  8. 407
MASS/MODE(LBM)          9. 72579    0. 22777    0. 03518    4. 83639    0. 02624    0. 04014
MASS/RATED HP(#/HP)  0. 06079    0. 00142    0. 00022    0. 03023    0. 00016    0. 00025
                     KWD       XTC     MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 3 1       0. 87398 0. 98615 27. 70000 10144. 280  0. 07825  0. 08325 -6. 000
MASS/MODE(LBM)          9 40735     0. 22032    0. 03403    4 67803     0. 02538    0. 03882
MASS/RATED HP(#/HP)  0. 05880    0. 00138    0. 00021    0. 02924    0. 00016    0 00024
                     KWD       XTC     MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 3. 2      0. 86332 0. 32672 27. 50000 10218. 060  0. 08571  0. 08325  2. 965
MASS/MODE(LBM)          9. 47577    0 22192     0. 03428    4. 71206    0. 02557    0 03910
MASS/RATED HP(#/HP)  0. 05922    0. 00139    0. 00021    0. 02945    0. 00016    0. 00024

RUN NO. 27
MODE:     4
COMMENTS: LEAN OUT, CLIMBOUT, 1 IN.  LEAN
TEMP(DB)        = 87. 83F       FUEL RATE=  46. 8018#/HR       ENGINE RPM(NOM)=2423 RPM
TEMP(DP)        = 23. 00F       AIR RATE = 663. 4822#/HR       ENGINE RPM(ACT)=2378 RPM
TEMP(BAR)       = 72. 00F       F/A RATIO=    0 0705#/#        BHP(OBS)          =106. 2HP
BAR PRESS(OB)= 29. 32"HG        PHIM     =    1 0603           BHP(CORR)         =   0. 0HP
BAR PRESS(CR)= 29. 21"HG                                       MAN VAC(OBS)      = 3 30"HG
SPEC HUMIDITY=0 0025#/#                                        MAN PRESS(CORR)= 0 00"HG
                            CO2         O2         UHCC         CO         NO        NOX
CONC(PPM)                 132928.      3768.        728.       19990.     1565.      1565
                     KWD       XTC     MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 1. 2      0 85878 1 02230 28. 37965  9647. 734  0. 06946  0 07054 -1 519
MASS/MODE(LBM)         12. 20466    0. 25144    0. 02101    1. 16680    0. 09791    0. 14976
MASS/RATED HP(#/HP)  0. 07627    0 00157     0. 00013    0. 00729    0. 00061    0 00093
                     KWD       XTC     MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 2 1       0 88114 1. 00000 27. 98036  9785. 414  0. 07423  0 07054  5. 238
MASS/MODE(LBM)         12. 37883    0. 25503    0 02131     1. 18345    0. 09931    0 15190
MASS/RATED HP(#/HP)  0. 07736    0. 00159    0. 00013    0. 00739    0. 00062    0. 00094
                     KWD       XTC     MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 3. 1      0 86891 0. 98881 28 70715  9537 672   0. 06559  0. 07054 -7. 009
MASS/MODE(LBM)         12 06543     0. 24857    0. 02077    1. 15349    0. 09679    0. 14806
MASS/RATED HP(#/HP)  0. 07540    0 00155     0 00013     0. 00720    0. 00060    0. 00092
                     KWD       XTC     MWEXH   EXH FLOW     FACAL       FAM   ERROR
METHOD 3. 2      0 85885 0 28830 27 50000  9956 344   0. 07116  0. 07054  0 892
MASS/MODE(LBM)         12 59506     0. 25948    0. 02168    1. 20412    0. 10105    0. 15455
MASS/RATED HP(#/HP)  0. 07871    0. 00162    0 00014     0. 00752    0. 00063    0 00096
```

TABLE 5.7. Continued

```
RUN NO. 27
MODE:     4
COMMENTS:LEAN OUT,CLMBOUT,1. 25 IM.  LEAN
TEMP(DB)      = 89. 49F       FUEL RATE=  45. 4890#/HR      ENGINE RPM(NOM)=2428 RPM
TEMP(DP)      = 23. 00F       AIR RATE = 688. 7046#/HR      ENGINE RPM(ACT)=2354. RPM
TEMP(BAR)     = 72. 00F       F/A RATIO=   0. 0660#/#       BHP(OBS)        =105. 1HP
BAR PRESS(OB)= 29. 32"HG      PHIM     =   0. 9928          BHP(CORR)       =  0. 0HP
BAR PRESS(CR)= 29. 21"HG                                    MAN VAC(OBS)    = 2. 50"HG
SPEC HUMIDITY=0. 0025#/#                                    MAN PRESS(CORR)= 0. 00"HG
                          CO2        O2        UHCC       CO         NO        NOX
CONC(PPM)               136877     13816.       331.      4752.      2307.     2351
                     KWD      XTC     MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 1. 2      0. 86382 1. 02799 28. 65352  9877. 184  0. 06320  0. 06605 -4. 301
MASS/MODE(LBM)         12. 86614   0. 94387   0. 00976   0. 28396   0. 14772   0. 23028
MASS/RATED HP(#/HP)  0. 08041   0. 00590   0 00006    0. 00177   0. 00092   0. 00144
MASS/HP/CYC(#/HP/C)  0. 21631   0. 00886   0 00041    0. 03872   0. 00170   0. 00262
                     KWD      XTC     MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 2. 1      0 89220 1. 00000 28. 16641 10048. 000  0. 06862  0. 06605  3 901
MASS/MODE(LBM)         13. 08864   0. 96019   0. 00993   0. 28887   0. 15028   0. 23426
MASS/RATED HP(#/HP)  0. 08180   0. 00600   0. 00006   0. 00181   0. 00093   0 00146
MASS/HP/CYC(#/HP/C)  0 21996    0. 00901   0. 00042   0. 03943   0. 00172   0. 00266
                     KWD      XTC     MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 3. 1      0. 87687 0. 98613 29. 06889  9736. 043  0. 05834  0. 06605-11 675
MASS/MODE(LBM)         12. 68229   0. 93038   0. 00962   0. 27991   0. 14561   0 22699
MASS/RATED HP(#/HP)  0. 07926   0. 00581   0. 00006   0. 00175   0. 00091   0. 00142
MASS/HP/CYC(#/HP/C)  0. 21347   0. 00874   0. 00040   0. 03820   0. 00167   0. 00259
                     KWD      XTC     MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 3 2       0. 86391 0. 26934 27. 50000 10291. 490  0. 06512  0. 06605 -1 404
MASS/MODE(LBM)         13. 40582   0. 98346   0. 01018   0. 29587   0. 15392   0 23994
MASS/RATED HP(#/HP)  0. 08378   0 00615    0. 00006   0. 00185   0. 00096   0. 00150
MASS/HP/CYC(#/HP/C)  0. 22173   0. 00915   0 00041    0. 03883   0. 00175   0 00271
```

TABLE 5.8. COMPUTER PRINTOUT: LEAN-OUT RESULTS, MODE 5.

```
 DATE        12/17/75        ENGINE TYPE:     LIO-320-B1A    FUEL H/C RATIO = 2. 180
 LOCATION: UNIV OF MICH  SERIAL NUMBER. L-287-66A        IGNITION TIMING= 25DEG
 OPERATORS: PACE, PONSONBY, GRIFFIN, DRAXLER

RUN NO 26
MODE:      5
COMMENTS: LEAN OUT RUN, APPROACH MODE, FULL RICH
TEMP(DB)        = 82. 27F       FUEL RATE=   34 4827#/HR      ENGINE RPM(NOM)=2350 RPM
TEMP(DP)        = 13. 00F       AIR RATE = 417. 0754#/HR      ENGINE RPM(ACT)=2349. RPM
TEMP(BAR)       = 74. 00F       F/A RATIO=    0. 0826#/#      BHP(OBS)         = 58 7HP
BAR PRESS(OB)= 29. 28"HG       PHIM      =    1. 2427         BHP(CORR)        =  0. 0HP
BAR PRESS(CR)= 29. 16"HG                                      MAN VAC(OBS)    =11. 10"HG
SPEC HUMIDITY=0. 0012#/#                                      MAN PRESS(CORR)= 0. 00"HG
                          CO2          O2           UHCC        CO          NO         NOX
CONC(PPM)               102873.       2768.          828.      71083        425.       425.
                    KWD       XTC      MWEXH   EXH FLOW      FACAL        FAM   ERROR
METHOD 1 2      0. 86179 1. 03683 27. 46640   6337. 418   0. 08152   0. 08267 -1. 397
MASS/MODE(LBM)           7. 44525    0. 14561    0. 01884    3. 27051    0. 02098    0. 03208
MASS/RATED HP(#/HP)   0. 04653    0. 00091    0. 00012    0. 02044    0 00013    0. 00020
                    KWD       XTC      MWEXH   EXH FLOW      FACAL        FAM   ERROR
METHOD 2 1      0. 89941 1. 00000 26. 71649   6515. 305   0. 09152   0. 08267 10. 703
MASS/MODE(LBM)           7. 65424    0. 14969    0. 01937    3. 36231    0. 02157    0. 03299
MASS/RATED HP(#/HP)   0. 04784    0. 00093    0. 00012    0. 02101    0. 00013    0. 00021
                    KWD       XTC      MWEXH   EXH FLOW      FACAL        FAM   ERROR
METHOD 3 1      0. 87737 0. 98020 28. 02197   6211. 770   0. 07447   0. 08267 -9. 925
MASS/MODE(LBM)           7. 29764    0 14272    0. 01846    3. 20567    0. 02056    0. 03145
MASS/RATED HP(#/HP)   0. 04561    0. 00089    0. 00012    0. 02004    0. 00013    0. 00020
                    KWD       XTC      MWEXH   EXH FLOW      FACAL        FAM   ERROR
METHOD 3. 2     0. 86183 0. 32472 27. 50000   6329. 676   0. 08497   0. 08267  2. 776
MASS/MODE(LBM)           7. 43616    0 14543    0. 01881    3. 26651    0 02095    0 03205
MASS/RATED HP(#/HP)   0. 04648    0. 00090    0. 00012    0. 02042    0. 00013    0 00020

RUN NO. 26
MODE:      5
COMMENTS: LEAN OUT RUN, APPROACH, 1 IN. LEAN
TEMP(DB)        = 87 74F        FUEL RATE=   29. 6296#/HR      ENGINE RPM(NOM)=2350 RPM
TEMP(DP)        = 13. 00F       AIR RATE = 414. 9094#/HR      ENGINE RPM(ACT)=2370. RPM
TEMP(BAR)       = 74. 00F       F/A RATIO=    0. 0714#/#      BHP(OBS)         = 59. 2HP
BAR PRESS(OB)= 29. 28"HG       PHIM      =    1. 0734         BHP(CORR)        =  0. 0HP
BAR PRESS(CR)= 29. 16"HG                                      MAN VAC(OBS)    =10. 90"HG
SPEC HUMIDITY=0. 0012#/#                                      MAN PRESS(CORR)= 0 00"HG
                          CO2          O2           UHCC        CO          NO         NOX
CONC(PPM)               132928        3775.          730.      16253.       1042       1071
                    KWD       XTC      MWEXH   EXH FLOW      FACAL        FAM   ERROR
METHOD 1 2      0. 86235 1 00651 28. 45932   6021. 238   0. 06881   0. 07141 -3 634
MASS/MODE(LBM)           9 14044    0. 18865    0. 01578    0 71048    0 04883    0 07673
MASS/RATED HP(#/HP)   0. 05713    0. 00118    0 00009    0. 00444    0. 00031    0 00048
                    KWD       XTC      MWEXH   EXH FLOW      FACAL        FAM   ERROR
METHOD 2. 1     0. 86876 1. 00000 28 34541   6045. 434   0. 07014   0. 07141  1 770
MASS/MODE(LBM)           9. 17717    0. 18941    0 01584    0. 71334    0 04902    0. 07704
MASS/RATED HP(#/HP)   0. 05737    0. 00118    0. 00009    0. 00446    0. 00031    0. 00048
                    KWD       XTC      MWEXH   EXH FLOW      FACAL        FAM   ERROR
METHOD 3. 1     0 86529 0. 99677 28. 55357   6001. 363   0. 06770   0. 07141 -5. 198
MASS/MODE(LBM)           9. 11027    0. 18803    0 01573    0. 70814    0. 04867    0. 07648
MASS RATED HP(#/HP)   0. 05694    0. 00118    0. 00009    0. 00443    0 00030    0 00048
                    KWD       XTC      MWEXH   EXH FLOW      FACAL        FAM   ERROR
METHOD 3. 2     0. 86235 0. 28093 27. 50000   6231. 285   0. 06930   0. 07141 -2. 949
MASS/MODE(LBM)           9. 45930    0. 19523    0 01633    0. 73527    0 05053    0. 07941
MAS- RATED HP(#/HP)   0 05912    0. 00122    0. 00010    0. 00460    0. 00032    0. 00050
```

TABLE 5.8. Continued

```
RUN NO. 26
MODE:    5
COMMENTS:LEAN OUT,APPROACH,1. 25 IN.  LEAN
TEMP(DB)       = 88. 27F      FUEL RATE=  28. 1955#/HR     ENGINE RPM(NOM)=2355 RPM
TEMP(DP)       = 13. 00F      AIR RATE = 451. 8899#/HR     ENGINE RPM(ACT)=2352. RPM
TEMP(BAR)      = 74. 00F      F/A RATIO=    0. 0624#/#     BHP(OBS)        = 59. 1HP
BAR PRESS(OB)= 29. 28"HG      PHIM      =   0. 9379        BHP(CORR)       =  0. 0HP
BAR PRESS(CR)= 29. 16"HG                                   MAN VAC(OBS)    = 9. 60"HG
SPEC HUMIDITY=0. 0012#/#                                   MAN PRESS(CORR)= 0. 00"HG
                         CO2        O2        UHCC       CO         NO         NOX
CONC(PPM)              134208.    20132.        13.      2291.      1220.      1220.
                   KWD      XTC      MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 1. 2    0. 86914 1. 02540 28. 72362  6442. 875  0. 06094  0. 06239 -2. 335
MASS/MODE(LBM)        9. 87467   1. 07658   0. 00030   0. 10714   0. 06117   0. 09356
MASS/RATED HP(#/HP)   0. 06172   0. 00672   0. 00000   0. 00067   0. 00038   0. 00058
MASS/HP/CYC(#/HP/C)   0. 16538   0. 00881   0. 00022   0. 02555   0. 00081   0. 00126
                   KWD      XTC      MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 2. 1    0. 89494 1. 00000 28. 28355  6543. 121  0. 06564  0. 06239  5. 205
MASS/MODE(LBM)       10. 02832   1. 09333   0. 00031   0. 10881   0. 06212   0. 09501
MASS/RATED HP(#/HP)   0. 06267   0. 00683   0. 00000   0. 00068   0. 00039   0. 00059
MASS/HP/CYC(#/HP/C)   0. 16787   0. 00895   0. 00022   0. 02615   0. 00082   0. 00128
                   KWD      XTC      MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 3 1     0. 88103 0. 98744 29 10121   6359. 277  0. 05648  0. 06239 -9. 476
MASS/MODE(LBM)        9. 74655   1. 06261   0. 00030   0. 10575   0. 06038   0. 09234
MASS/RATED HP(#/HP)   0. 06092   0. 00664   0. 00000   0. 00066   0. 00038   0. 00058
MASS/HP/CYC(#/HP/C)   0. 16347   0. 00870   0. 00022   0. 02512   0. 00081   0. 00125
                   KWD      XTC      MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 3. 2    0 86917 0. 25933 27. 50000   6729. 555  0. 06260  0. 06239  0. 333
MASS/MODE(LBM)       10. 31405   1. 12449   0. 00032   0. 11191   0. 06389   0. 09772
MASS/RATED HP(#/HP)   0. 06446   0. 00702   0. 00000   0. 00069   0. 00040   0. 00061
MASS/HP/CYC(#/HP/C)   0. 17006   0 00915    0. 00022   0. 02571   0. 00084   0. 00131
```

Unburned hydrocarbon levels are low and almost independent of fuel-air ratio at lean mixtures but increase rapidly with fuel enrichment beyond stoichiometric. The primary reason for the latter is, of course, the lack of sufficient oxygen for combustion. However, at quite high fuel-air ratio, there is poor mixing of the unburned hydrocarbons with the available oxygen and, in general, quite poor combustion. Figure 5.8 shows this effect through the high oxygen levels.

Some data points in these figures were found to be in error and are shown circled.

5.3 EFFECT OF PROBE LOCATION ON AIR-DILUTION OF EXHAUST SAMPLE

Experience in automotive emission measurement practice has shown that air dilution of the exhaust gases can extend some distance upstream from the open end of the tail pipe. Therefore, when using short, open-ended exhaust pipes during engine emission testing, care must be taken to select a probe location that will avoid sample dilution. Tests were run to determine the extent of dilution at various probe locations at the different operating modes. This was accomplished with a sliding probe which was inserted into the end of the exhaust pipe and centered in the pipe with fin guides. Any axial position could be selected by sliding the probe to the desired location.

A test was first made to compare the results from both the variable and standard fixed probes at the fixed probe position. No significant differences in results were found. Tests were then run at five probe locations, equally spaced from 2 to 32 inches from the open end of the exhaust pipe, and at each of the seven operating modes. The results are plotted in figures 5.9 and 5.10 showing both O2 concentration and calculated fuel-air ratio as a function of probe position.

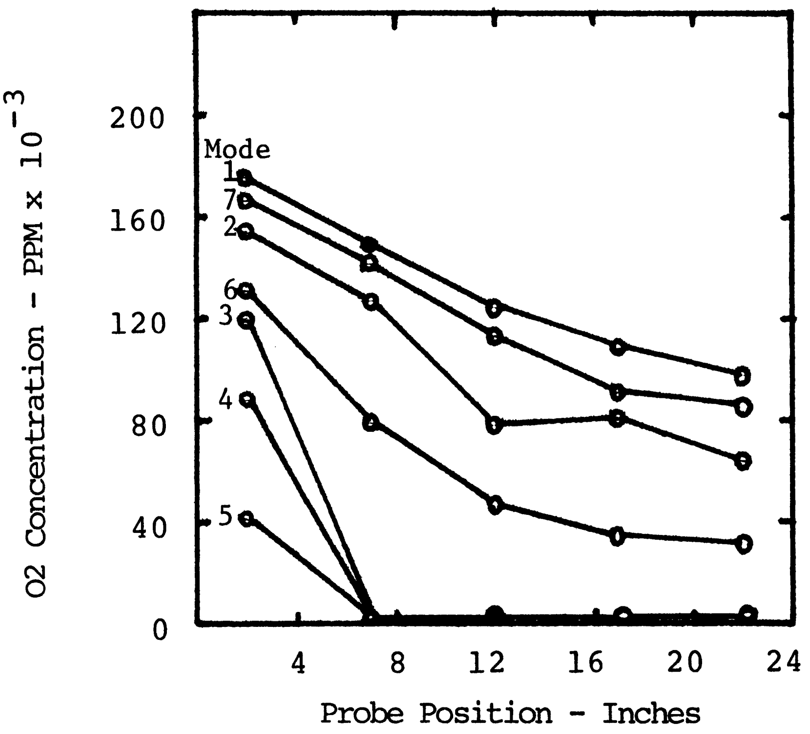

Figure 5.9. Effect of Probe Location on O2 Concentration

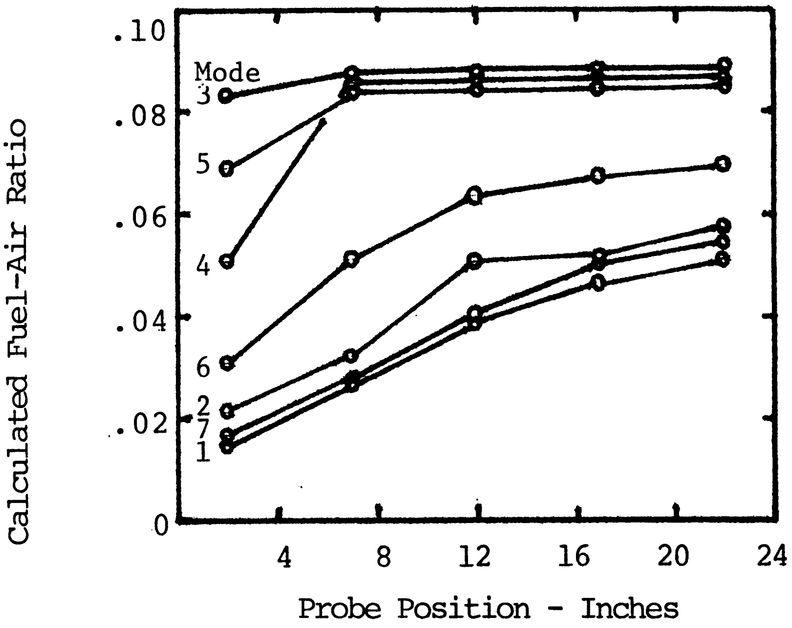

Figure 5.10. Effect of Probe Location on Calculated Fuel-Air Ratio

These results indicate that dilution is not a problem for the high power modes for probes located seven or more inches from the open end of the exhaust pipe. However, when operating at idle and taxi modes, dilution effects are detectable at distances up to and possibly beyond 22 in. The reliability of the data is indicated by the fact that the 35 data points show low values of the error parameters ΔE and XTC, as indicated below.

Number of Points	ΔE Range (Percent)	XTC Range
31	-4.0 to 6.7	0.980 to 1.016
4	-7.7 to 13.0	0.967 to 1.030

The usefulness of the error parameters as indicators of data reliability should be pointed out, since the attempted use of the Spindt error would be completely useless in this test. Values of Spindt errors for the above runs ranged from -75 to 2.9%, the negative values resulting from the leaning of the mixture due to air dilution.

5.4 CHECK FOR AIR LEAKS

Two tests were run to check the gas analysis and exhaust systems for possible air leaks. This was done when the data analysis indicated consistently low values of calculated fuel-air ratio from all four computational methods.

5.4.1 Leak Check of Gas Analysis System

Both the gas sampling inlet system and lines to the O2 analyzer were checked for possible air leaks. This was accomplished by first determining the normal pressure at the sampling probe during engine testing. Since this pressure is below atmospheric, any leaks in the line would cause air dilution of the sample rather than leak exhaust gas to the atmosphere. Then the line normally connected to the probe was connected to a bottle of nitrogen gas, which was then used as the sample gas while operatin the instrumentation in the normal engine-test modes. A measurement for O2 was then recorded.

If air leaks into the system were present, some level of oxygen would be measured. A leak-tight system would be free of oxygen and a zero reading would be recorded. (Possible oxygen impurities in the nitrogen gas could give rise to very small oxygen readings.) Our tests showed practically zero values of oxygen, indicating a leak-tight system.

5.4.2 Leak Check of Engine Exhaust System

Air leaks into the exhaust system are possible because of the existence of transient negative pressures in the exhaust pipe (reference 11), especially at idle and taxi modes. Since the data analysis indicated air leakage (large negative fuel-air errors) and because the instrument check in section 5.4.1 proved negative, tests were run to check the exhaust system for leaks.

Two reference runs, one at idle and one at taxi, were made to determine the extent of exhaust gas dilution as indicated by the negative fuel/air errors. The exhaust system was then sealed at the flanges and slip joints using a high temperature exhuast system sealer. When the sealant had dried, the runs were repeated and the fuel-air errors checked (run A). Since the results showed a large decrease in errors, a complete baseline was then run (run B). The results are given in table 5.9.

TABLE 5.9. ERROR ANALYSIS OF EXHAUST SYSTEM LEAK TESTS

Pre-Seal

Mode	E(3.1)	E(1.2)	ΔE
1	-56.55	-41.78	-14.77
2	-27.28	-10.93	-16.35

Post Seal

	Run A			Run B		
Mode	E(3.1)	E(1.2)	ΔE	E(3.1)	E(1.2)	ΔE
1	-12.10	-6.64	-5.46	-21.44	-10.05	-11.39
2	-16.20	-4.86	-11.34	-15.98	-3.08	-12.90
3	-	-	-	-3.19	1.43	-4.62
4	-	-	-	-3.60	0.04	-3.64
5	-	-	-	-7.09	-1.71	-5.38
6	-	-	-	-15.91	-5.79	-10.12
7	-	-	-	-26.41	-30.72	4.31

The decrease in negative values of both E(1.2) and E(3.1) from the pre-seal to post-seal tests indicate a substantial reduction, but possibly not elimination, of air leakage into the exhaust system. The substantial increase in E(1.2) for Mode 7 was due to a sealant failure at one of the joints.

6. INTER-FACILITY DATA ANALYSIS

An analysis and correlation study of inter-facility data on the Lycoming 320 engine was run. These efforts show promise that an effective method for determining data validity has been developed.

It is obvious that before any correlations of data from the various facilities are made, the validity of the data should be established. Otherwise, wrong conclusions can be reached. For this reason, a considerable effort was undertaken at Michigan to develop a method to evaluate data validity, based on the use of fuel-air error E(1.2), ΔE and XTC. In the following section, plots of ΔE vs XTC are shown and their significance is discussed.

6.1 DATA ANALYSIS CHARTS - ΔE vs XTC

Preliminary data on the Lycoming 320 engine from Lycoming and Michigan and one set of 13 runs on an automotive V-8 engine from Eltinge (reference 7) are plotted to show ΔE vs XTC in figures 6.1-6.3. These charts show that the data from various sources and for different engines give straight line plots with negative slopes.

These results suggest that the best data should lie at the intersection of the $\Delta E = 0$ and $XTC = 1$ axes, and that the extent of departure from this point gives an indication of the errors involved. The method suggests that imposed limits on ΔE or XTC would provide one of the criteria for good data, together with a limit on E(1.2).

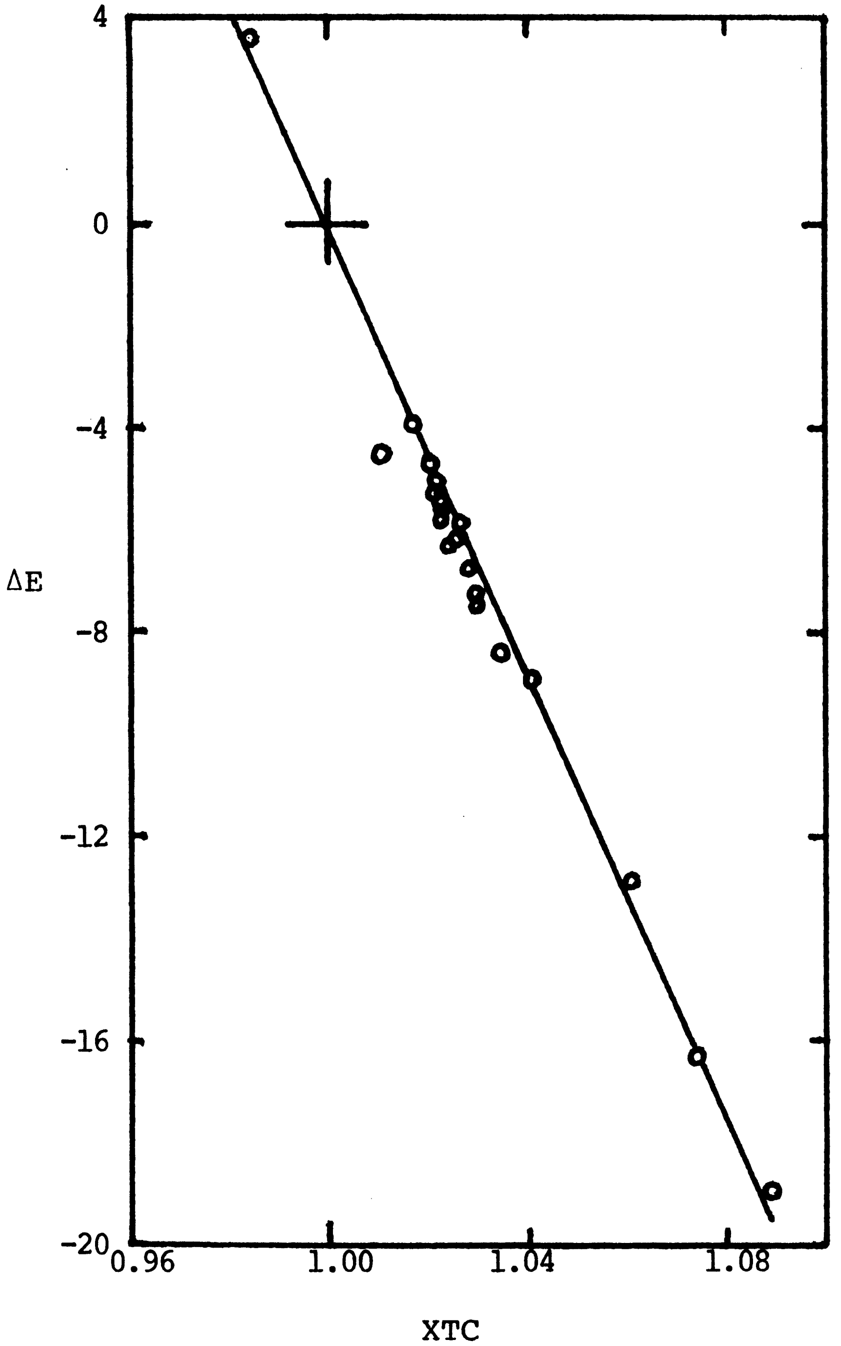

Figure 6.1. ΔE vs XTC: Lycoming Data (Reference 12)

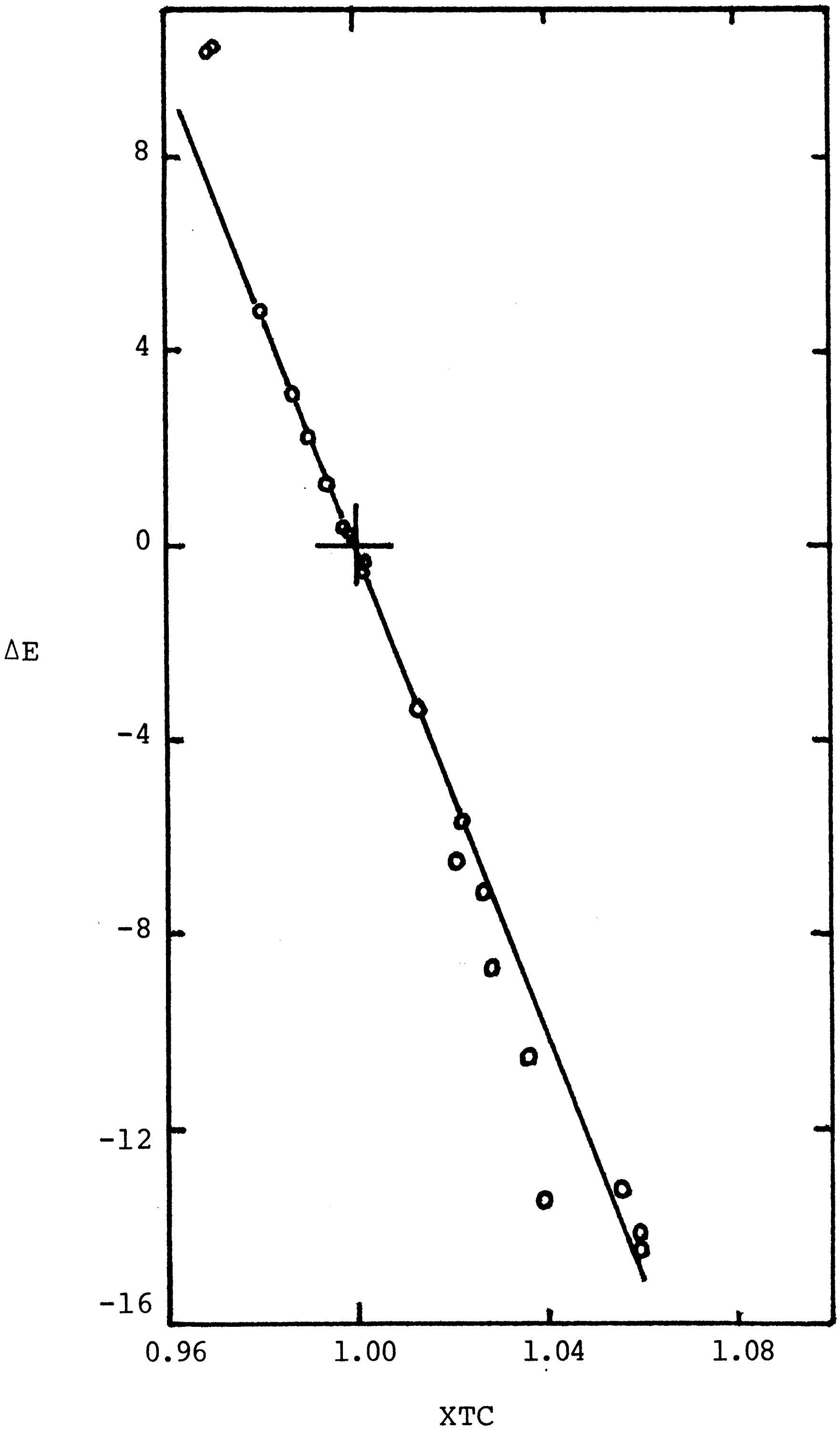

Figure 6.2. ΔE vs XTC: Michigan Data Runs 4, 5, 7 - All Modes (Reference 12)

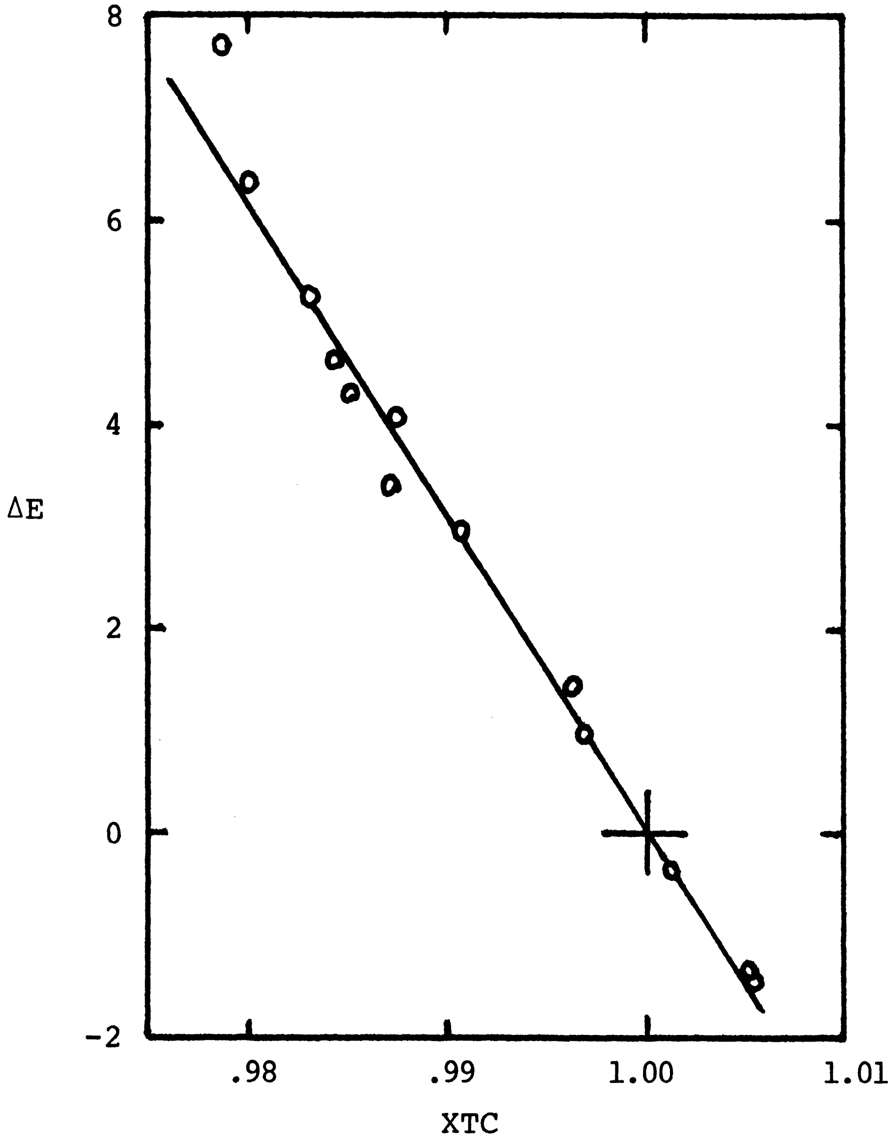

Figure 6.3. ΔE vs XTC: Eltinge Data (Reference 7)

6.2 DATA ANALYSIS CHARTS - E(1.2) vs XTC

The use of either ΔE or XTC as an indicator of data reliability appears to be optional since close correlations were found to exist as shown in section 6.1. However, ΔE requires the use of two computational methods, Method 3.1 and Method 1.2, while XTC is computed using Method 1.2. Therefore, if one selects E(1.2) and XTC as indicators of data reliability, only one computational method need be used. The use of either indicator by itself was shown in section 2.3 to be insufficient.

An examination of plots of E(1.2) vs XTC in figures 6.4 to 6.8 shows that data can be expected to fall in a band of ± 5% for XTC and a somewhat larger band for E(1.2). Data for these plots were taken from Michigan Runs 4 and 7, given at the end of Section 5, and Run 5, given at the end of this section, together with AVCO-Lycoming data from reference 12.

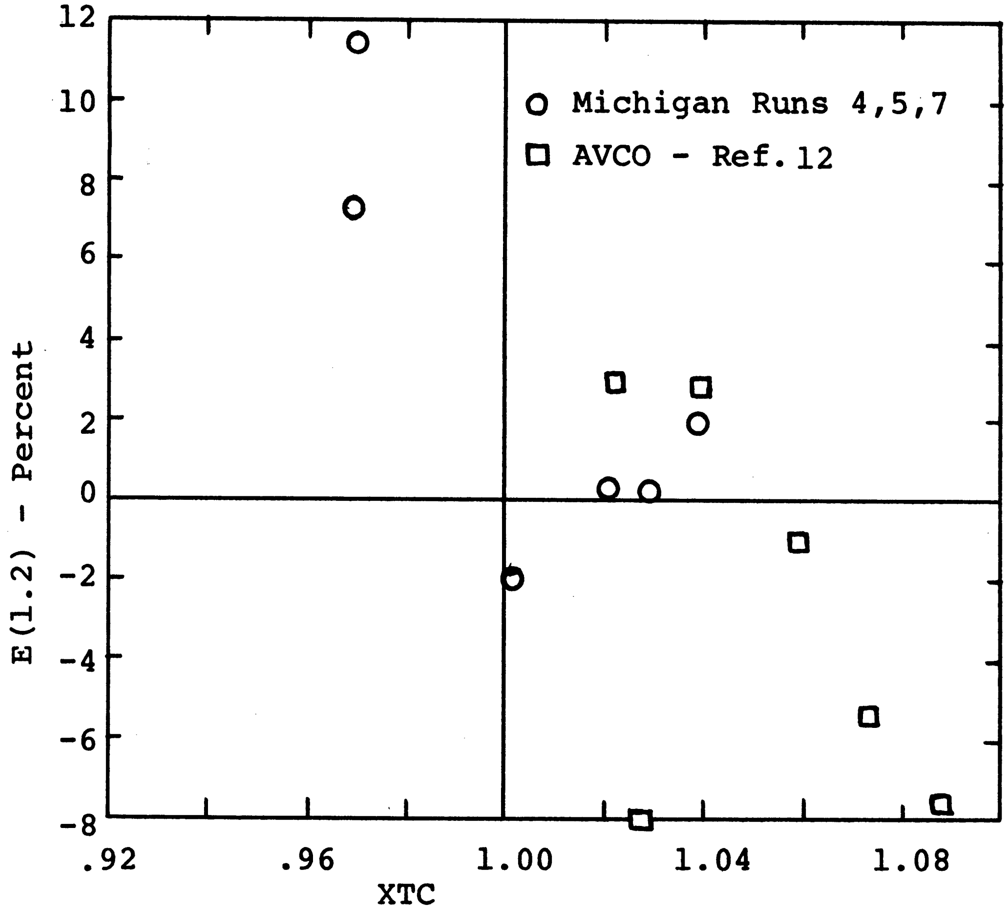

Figure 6.4. E(1.2) vs XTC: Idle Mode

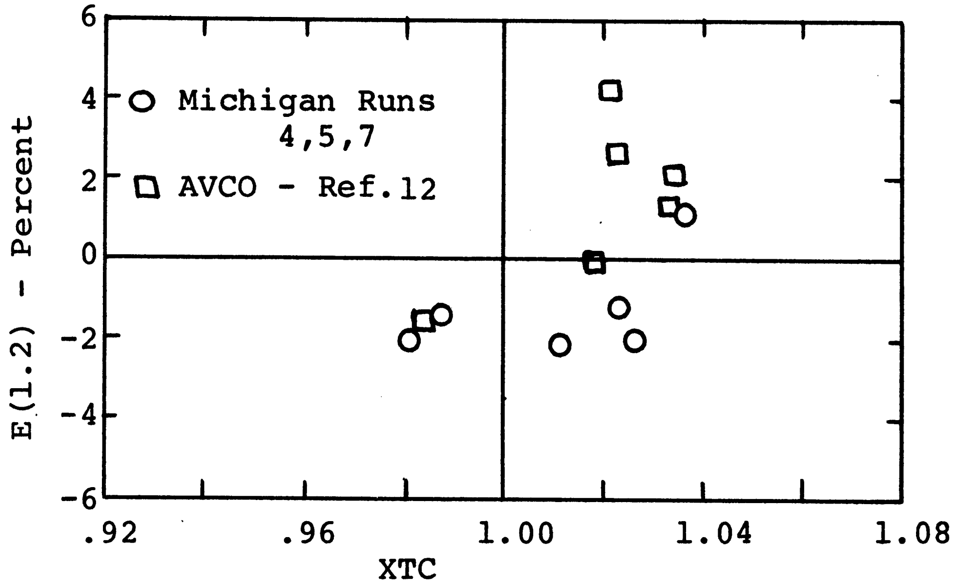

Figure 6.5. E(1.2) vs XTC: Taxi Mode

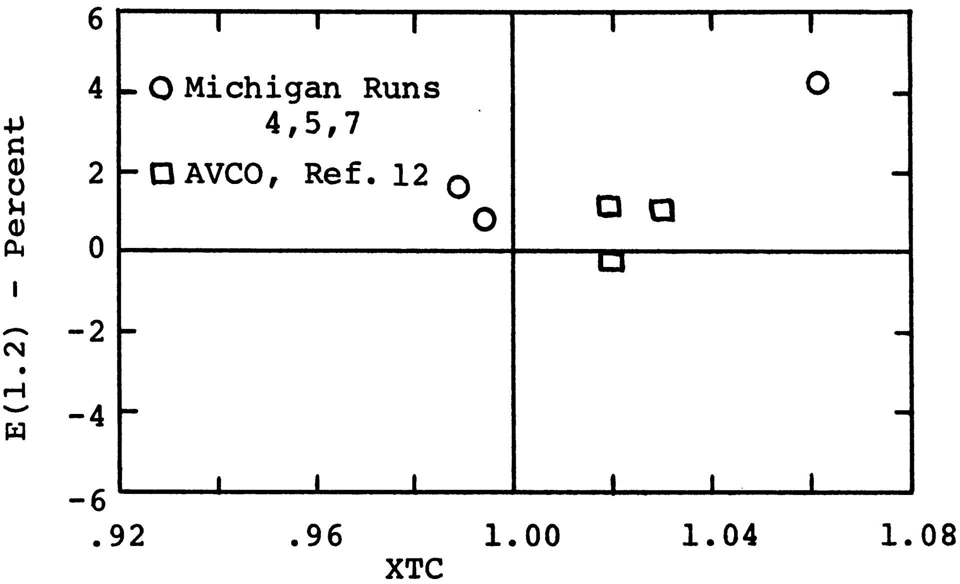

Figure 6.6. E(1.2) vs XTC: Takeoff Mode

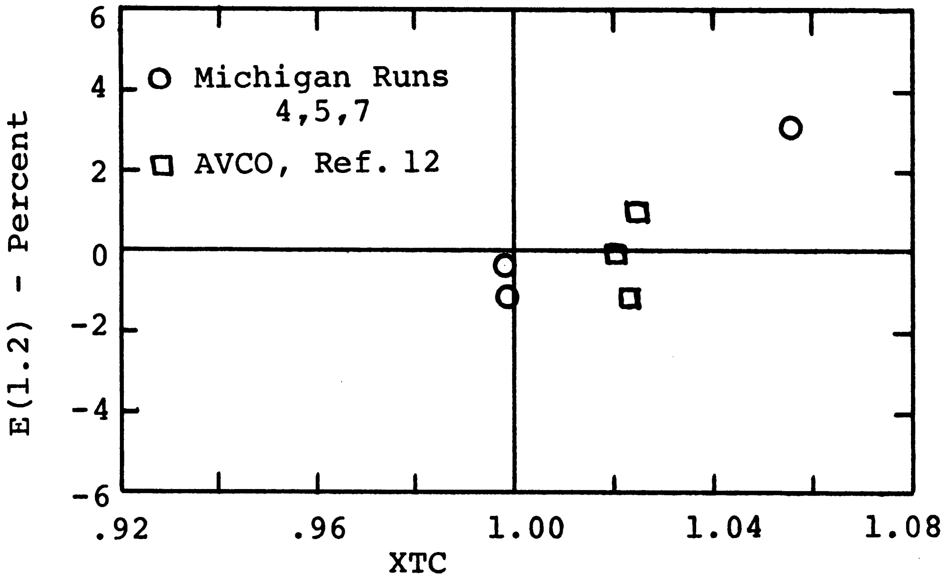

Figure 6.7. E(1.2) vs XTC: Climbout Mode

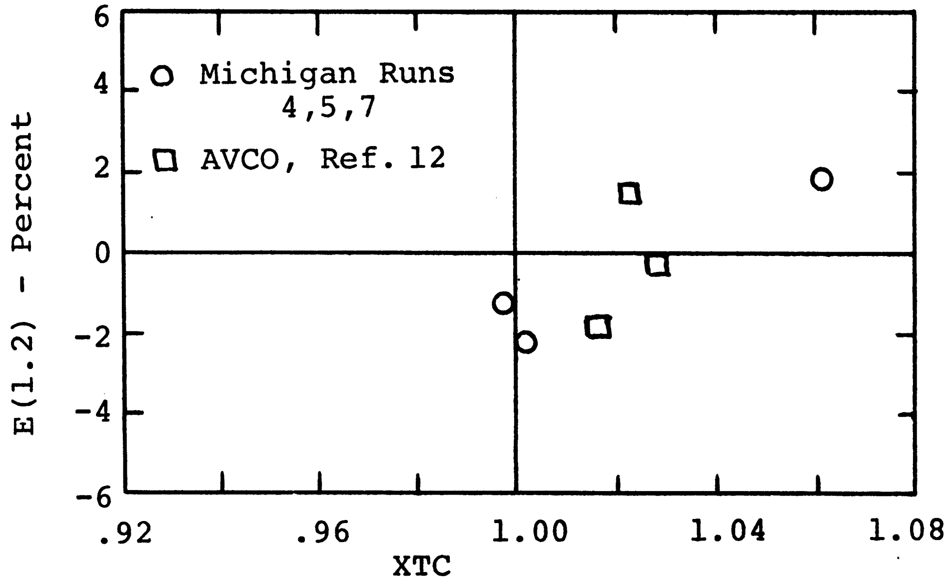

Figure 6.8 E(1.2) vs XTC: Approach Mode

TABLE 6.1 COMPUTER PRINTOUT: RUN 5

```
 DATE:       8-12-75        ENGINE TYPE:    LIO-320-BIA    FUEL H/C RATIO = 2. 190
 LOCATION: UNIV OF MICH  SERIAL NUMBER: L-287-66A      IGNITION TIMING= 25DEG
 OPERATORS: PERRY, PACE, PONSONBY, LEO

(UN NO.   5
MODE:     1
COMMENTS: BASELINE DATA RUN5. 1
TEMP(DB)       = 94. 71F        FUEL RATE=    3. 3681#/HR        ENGINE RPM(NOM)= 720 RPM
TEMP(DP)       = 51. 00F        AIR RATE =   64. 1414#/HR        ENGINE RPM(ACT)= 712. RPM
TEMP(BAR)      = 81. 00F        F/A RATIO=    0. 0525#/#         BHP(OBS)        =   0. 2HP
BAR PRESS(OB)= 29. 24"HG                                         BHP(CORR)       =   0. 0HP
BAR PRESS(CR)= 29. 10"HG                                         MAN VAC(OBS)    =17. 50"HG
SPEC HUMIDITY=0 0081#/#                                          MAN PRESS(CORR)= 0 00"HG
                             CO2         O2          UHCC        CO          NO          NOX
CONC(PPM)                   51214.      109523.     31808.      17656.       173.        223.
                      KWD        XTC       MWEXH    EXH FLOW    FACAL       FAM  ERROR
METHOD 1. 2      0. 92108 1. 00125 27 83681    934. 859  0. 05146   0. 05251 -1 995
MASS/MODE(LBM)           0. 09112    0. 14164    0. 01779    0. 01997    0. 00021    0. 00041
MASS/RATED HP(#/HP)  0. 00057    0. 00088    0. 00011    0. 00012    0 00000     0 00000
                      KWD        XTC       MWEXH    EXH FLOW    FACAL       FAM  ERROR
METHOD 2. 1      0. 92237 1. 00000 27. 81548   935. 576  0. 05162   0 05251 -1. 690
MASS/MODE(LBM)           0. 09119    0. 14175    0. 01781    0. 01999    0. 00021    0. 00041
MASS/RATED HP(#/HP)  0. 00057    0. 00088    0. 00011    0. 00012    0. 00000    0. 00000
                      KWD        XTC       MWEXH    EXH FLOW    FACAL       FAM  ERROR
METHOD 3. 1      0. 92166 0. 99938 27. 85442   934. 268  0 05120   0. 05251 -2. 495
MASS/MODE(LBM)           0. 09106    0. 14155    0. 01778    0 01996     0 00021     0. 00041
MASS/RATED HP(#/HP)  0. 00057    0. 00088    0. 00011    0 00012     0. 00000    0. 00000
                      KWD        XTC       MWEXH    EXH FLOW    FACAL       FAM  ERROR
METHOD 3. 2      0. 92109 0. 19063 27. 50000   946. 308  0 05153   0. 05251 -1 861
MASS/MODE(LBM)           0. 09224    0. 14337    0. 01801    0. 02022    0. 00021    0. 00042
 ASS/RATED HP(#/HP)  0. 00058    0. 00089    0. 00011    0. 00013    0 00000     0. 00000

RUN NO.   5
MODE:     2
COMMENTS: BASELINE DATA RUN5. 2
TEMP(DB)       = 96. 53F        FUEL RATE=    7. 0805#/HR        ENGINE RPM(NOM)=1200 RPM
TEMP(DP)       = 52. 00F        AIR RATE = 104. 9433#/HR        ENGINE RPM(ACT)=1189. RPM
TEMP(BAR)      = 81. 00F        F/A RATIO=    0. 0674#/#         BHP(OBS)        =   5. 8HP
BAR PRESS(OB)= 29. 23"HG                                         BHP(CORR)       =   0. 0HP
BAR PRESS(CR)= 29. 09"HG                                         MAN VAC(OBS)    =18. 80"HG
SPEC HUMIDITY=0 0084#/#                                          MAN PRESS(CORR)= 0. 00"HG
                             CO2         O2          UHCC        CO          NO          NOX
CONC(PPM)                   93691.      42201.      12006.      39227.       226.        267.
                      KWD        XTC       MWEXH    EXH FLOW    FACAL       FAM  ERROR
METHOD 1. 2      0. 87335 1. 03655 27. 75891  1555. 637  0. 06821   0 06747  1. 106
MASS/MODE(LBM)           3 05150     0 99898     0. 12293    0. 81222    0 00501     0. 00907
MASS/RATED HP(#/HP)  0. 01907    0. 00624    0. 00076    0. 00508    0. 00003    0. 00006
                      KWD        XTC       MWEXH    EXH FLOW    FACAL       FAM  ERROR
METHOD 2. 1      0. 91167 1. 00000 27. 06935  1595. 266  0. 07595   0 06747 12 574
MASS/MODE(LBM)           3. 12924    1 02442     0. 12606    0. 83291    0 00514     0. 00930
MASS/RATED HP(#/HP)  0. 01956    0. 00640    0. 00078    0. 00521    0 00003     0. 00006
                      KWD        XTC       MWEXH    EXH FLOW    FACAL       FAM  ERROR
METHOD 3. 1      0. 88997 0. 98110 28. 30031  1525. 877  0. 06109   0 06747 -9 454
MASS/MODE(LBM)           2. 99312    0. 97987    0. 12057    0. 79669    0. 00492    0. 00890
MASS/RATED HP(#/HP)  0. 01871    0 00612     0. 00075    0. 00498    0 00003     0. 00006
                      KWD        XTC       MWEXH    EXH FLOW    FACAL       FAM  ERROR
METHOD 3. 2      0. 87372 0. 27819 27 50000   1570. 284  0. 07102   0. 06747  5. 271
MASS/MODE(LBM)           3. 08023    1 00838     0. 12408    0. 81987    0 00506     0. 00916
MASS/RATED HP(#/HP)  0. 01925    0 00630     0. 00077    0. 00512    0 00003     0. 00006
```

TABLE 6.1. Continued

```
RUN NO.   5
MODE:     3
COMMENTS: BASELINE DATA RUN5. 3
TEMP(DB)       = 89. 18F       FUEL RATE=  75. 7576#/HR       ENGINE RPM(NOM)=2700 RPM
TEMP(DP)       = 58. 00F       AIR RATE = 864. 6914#/HR       ENGINE RPM(ACT)=2694. RPM
TEMP(BAR)      = 82. 00F       F/A RATIO=   0. 0876#/#        BHP(OBS)       =139. 8HP
BAR PRESS(OB)= 29. 23"HG                                      BHP(CORR)      =153. 7HP
BAR PRESS(CR)= 29. 09"HG                                      MAN VAC(OBS)   = 0. 70"HG
SPEC HUMIDITY=0. 0105#/#                                      MAN PRESS(CORR)=29. 00"HG
                         CO2        O2        UHCC       CO         NO         NOX
CONC(PPM)              88079.      1256.      1607.    102717.      213.        185
                    KWD      XTC      MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 1. 2     0. 85456 1. 06022 26. 66957 13593. 140  0. 09128  0. 08761  4. 196
MASS/MODE(LBM)          0. 68364   0. 00708   0. 00392   0. 50684   0. 00113   0. 00150
MASS/RATED HP(#/HP)  0. 00427   0. 00004   0. 00002   0. 00317   0. 00000   0. 00000
                    KWD      XTC      MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 2. 1     0. 91968 1. 00000 25. 31911 14318. 160  0. 11171  0. 08761 27. 501
MASS/MODE(LBM)          0. 72010   0. 00746   0. 00413   0. 53387   0. 00119   0. 00158
MASS/RATED HP(#/HP)  0. 00450   0. 00005   0. 00003   0. 00334   0. 00000   0. 00001
                    KWD      XTC      MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 3. 1     0. 87924 0. 96585 27. 61258 13128. 910  0. 07858  0. 08761-10. 304
MASS/MODE(LBM)          0. 66029   0. 00684   0. 00379   0. 48953   0. 00109   0. 00145
MASS/RATED HP(#/HP)  0. 00413   0. 00004   0. 00002   0. 00306   0. 00000   0. 00000
                    KWD      XTC      MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 3. 2     0. 85519 0. 36584 27. 50000 13182. 660  0. 09791  0. 08761 11. 754
MASS/MODE(LBM)          0. 66300   0. 00687   0. 00380   0. 49153   0. 00109   0 00145
MASS/RATED HP(#/HP)  0. 00414   0. 00004   0. 00002   0. 00307   0. 00000   0 00000

RUN NO    5
MODE      4
COMMENTS. BASELINE DATA RUN5. 4
TEMP(DB)       = 92. 75F       FUEL RATE=  57. 8592#/HR       ENGINE RPM(NOM)=2450 RPM
TEMP(DP)       = 58. 00F       AIR RATE = 669. 1042#/HR       ENGINE RPM(ACT)=2430. RPM
TEMP(BAR)      = 82. 00F       F/A RATIO=   0. 0864#/#        BHP(OBS)       =107. 3HP
BAR PRESS(OB)= 29. 24"HG                                      BHP(CORR)      =   0 0HP
BAR PRESS(CR)= 29 10"HG                                       MAN VAC(OBS)   = 3 50"HG
SPEC HUMIDITY=0 0105#/#                                       MAN PRESS(CORR)= 0 00"HG
                         CO2        O2        UHCC       CO         NO         NOX
CONC(PPM)               91453      1758.      1676.     95383.      269        244
                    KWD      XTC      MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 1. 2     0. 85357 1 05545 26. 81676 10449 770  0. 08908  0 08647  3. 025
MASS/MODE(LBM)          9 09468    0. 12709   0. 05239   6. 03019   0. 01823   0. 02531
MASS/RATED HP(#/HP)  0 05684    0. 00079   0. 00033   0. 03769   0. 00011   0. 00016
                    KWD      XTC      MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 2. 1     0. 91309 1 00000 25 60011 10946. 390  0 10704  0. 08647 23. 788
MASS/MODE(LBM)          9 52691    0 13313    0. 05488   6. 31678   0. 01910   0. 02651
MASS/RATED HP(#/HP)  0. 05954   0 00083    0. 00034   0 03948    0. 00012   0. 00017
                    KWD      XTC      MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 3 1      0. 87661 0. 96896 27. 67520 10125. 630  0. 07763  0 08647-10. 222
MASS/MODE(LBM)          8 81258    0. 12315   0. 05076   5. 84315   0. 01767   0. 02453
MASS/RATED HP(#/HP)  0. 05508   0 00077    0. 00032   0. 03652   0. 00011   0 00015
                    KWD      XTC      MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 3. 2     0 85418 0. 35864 27 50000 10190. 140  0 09498  0 08647  9. 849
MASS/MODE(LBM)          8. 86872   0. 12393   0. 05109   5 88037   0. 01778   0. 02468
MASS/RATED HP(#/HP)  0. 05543   0. 00077   0. 00032   0 03675   0 00011   0. 00015
```

TABLE 6.1. Continued

```
RUN NO.   5
MODE:     5
COMMENTS: BASELINE DATA RUN5. 5
TEMP(DB)       = 97. 83F       FUEL RATE=   34. 3840#/HR      ENGINE RPM(NOM)=2360 RPM
TEMP(DP)       = 60. 00F       AIR RATE = 393. 1924#/HR      ENGINE RPM(ACT)=2363. RPM
TEMP(BAR)      = 82. 00F       F/A RATIO=    0. 0874#/#      BHP(OBS)        = 53. 6HP
BAR PRESS(OB)= 29. 23"HG                                     BHP(CORR)       =  0. 0HP
BAR PRESS(CR)= 29. 09"HG                                     MAN VAC(OBS)    =11. 70"HG
SPEC HUMIDITY=0. 0113#/#                                     MAN PRESS(CORR)= 0. 00"HG
                         CO2          O2         UHCC        CO          NO         NOX
CONC(PPM)             • 92056.       1758.       1600.      95696.        232.        217.
                  KWD        XTC     MWEXH   EXH FLOW     FACAL        FAM  ERROR
METHOD 1. 2     0. 85213 1. 05975 26. 80812  6148. 195  0. 08905  0. 08744  1. 841
MASS/MODE(LBM)           6. 46348   0. 08973   0. 03532   4. 27147   0. 01110   0. 01590
MASS/RATED HP(#/HP)  0. 04040   0. 00056   0. 00022   0. 02670   0. 00006   0. 00009
                  KWD        XTC     MWEXH   EXH FLOW     FACAL        FAM  ERROR
METHOD 2. 1     0. 91670 1. 00000 25. 49028  6466. 055  0. 10864  0. 08744 24 230
MASS/MODE(LBM)           6. 79764   0. 09437   0. 03714   4. 49230   0. 01167   0. 01672
MASS/RATED HP(#/HP)  0. 04249   0. 00059   0. 00023   0. 02808   0. 00007   0. 00010
                  KWD        XTC     MWEXH   EXH FLOW     FACAL        FAM  ERROR
METHOD 3. 1     0. 87703 0. 96648 27. 73703  5942. 293  0. 07668  0. 08744-12. 307
MASS/MODE(LBM)           6. 24702   0. 08672   0. 03413   4. 12842   0. 01073   0. 01536
MASS/RATED HP(#/HP)  0. 03904   0. 00054   0. 00021   0. 02580   0. 00006   0. 00009
                  KWD        XTC     MWEXH   EXH FLOW     FACAL        FAM  ERROR
METHOD 3. 2     0. 85282 0. 36071 27. 50000  5993. 512  0. 09542  0. 08744  9 119
MASS/MODE(LBM)           6. 30086   0. 08747   0. 03443   4. 16400   0. 01082   0. 01550
MASS/RATED HP(#/HP)  0. 03938   0. 00055   0. 00022   0. 02603   0. 00006   0 00009

RUN NO    5
MODE:     6
COMMENTS: BASELINE DATA RUN5. 6
TEMP(DB)       =102. 29F       FUEL RATE=    7. 2604#/HR      ENGINE RPM(NOM)=1220 RPM
TEMP(DP)       = 64. 00F       AIR RATE = 100. 4240#/HR      ENGINE RPM(ACT)=1203. RPM
TEMP(BAR)      = 82. 00F       F/A RATIO=    0. 0723#/#      BHP(OBS)        =  2. 4HP
BAR PRESS(OB)= 29. 23"HG                                     BHP(CORR)       =  0. 0HP
BAR PRESS(CR)= 29. 09"HG                                     MAN VAC(OBS)    =19 70"HG
SPEC HUMIDITY=0. 0131#/#                                     MAN PRESS(CORR)= 0. 00"HG
                         CO2          O2         UHCC        CO          NO         NOX
CONC(PPM)               89063.      47728.      21791.      34916.        107         127.
                  KWD        XTC     MWEXH   EXH FLOW     FACAL        FAM  ERROR
METHOD 1. 2     0. 87295 1. 02668 27. 59329  1504. 354  0. 07079  0 07229 -2. 085
MASS/MODE(LBM)           0. 76504   0. 29797   0. 05884   0. 19067   0. 00062   0. 00114
MASS/RATED HP(#/HP)  0. 00478   0. 00186   0. 00037   0. 00119   0. 00000   0. 00000
                  KWD        XTC     MWEXH   EXH FLOW     FACAL        FAM  ERROR
METHOD 2. 1     0. 90069 1. 00000 27. 10353  1531. 537  0. 07635  0 07229  5. 608
MASS/MODE(LBM)           0. 77886   0. 30335   0. 05991   0. 19412   0. 00063   0. 00116
MASS/RATED HP(#/HP)  0. 00487   0. 00190   0. 00037   0. 00121   0 00000   0. 00000
                  KWD        XTC     MWEXH   EXH FLOW     FACAL        FAM  ERROR
METHOD 3. 1     0. 88520 0. 98640 27. 97520  1483. 816  0. 06561  0. 07229 -9 241
MASS/MODE(LBM)           0. 75459   0. 29390   0. 05804   0. 18807   0. 00062   0. 00112
MASS/RATED HP(#/HP)  0. 00472   0. 00184   0. 00036   0. 00118   0. 00000   0 00000
                  KWD        XTC     MWEXH   EXH FLOW     FACAL        FAM  ERROR
METHOD 3. 2     0. 87338 0. 27941 27. 50000  1509. 457  0. 07293  0. 07229  0. 885
MASS/MODE(LBM)           0. 76763   0. 29898   0. 05904   0. 19132   0. 00062   0. 00114
MASS/RATED HP(#/HP)  0. 00480   0. 00187   0. 00037   0. 00120   0. 00000   0. 00000
```

TABLE 6.1. Continued

```
RUN NO.   5
MODE:     7
COMMENTS: BASELINE DATA RUN5. 7
TEMP(DB)      =101. 60F       FUEL RATE=    4. 9859#/HR      ENGINE RPM(NOM)= 700 RPM
TEMP(DP)      = 66. 00F       AIR RATE =   78. 9251#/HR      ENGINE RPM(ACT)= 712. RPM
TEMP(BAR)     = 82. 00F       F/A RATIO=    0. 0631#/#       BHP(OBS)        =  3. 3HP
BAR PRESS(OB)= 29. 23"HG                                     BHP(CORR)       =  0. 0HP
BAR PRESS(CR)= 29. 09"HG                                     MAN VAC(OBS)    =16. 00"HG
SPEC HUMIDITY=0. 0140#/#                                     MAN PRESS(CORR)= 0. 00"HG
                          CO2        O2        UHCC       CO         NO         NOX
CONC(PPM)                83260.     66568.     24878.     21292.      156.       194
                    KWD      XTC      MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 1. 2     0. 88268 1. 02108 27. 78891  1163. 986  0. 06330  0. 06317  0. 202
MASS/MODE(LBM)         0. 18446    0. 10719   0. 01733   0. 02999   0. 00024   0. 00045
MASS/RATED HP(#/HP)    0. 00115    0. 00067   0. 00011   0. 00019   0. 00000   0. 00000
MASS/HP/CYC(#/HP/C)    0. 12709    0. 01106   0. 00193   0. 07413   0. 00023   0. 00034
                    KWD      XTC      MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 2. 1     0. 90468 1. 00000 27. 41754  1179. 752  0. 06703  0. 06317  6. 118
MASS/MODE(LBM)         0. 18696    0. 10864   0. 01756   0. 03039   0. 00024   0. 00045
MASS/RATED HP(#/HP)    0. 00117    0. 00067   0. 00011   0. 00019   0. 00000   0. 00000
MASS/HP/CYC(#/HP/C)    0. 13269    0. 01133   0. 00198   0. 07762   0. 00024   0. 00035
                    KWD      XTC      MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 3. 1     0. 89267 0. 98948 28. 08633  1151. 659  0. 05918  0. 06317 -6. 312
MASS/MODE(LBM)         0. 18250    0. 10605   0. 01714   0. 02967   0. 00023   0. 00044
MASS/RATED HP(#/HP)    0. 00114    0. 00066   0. 00011   0. 00019   0. 00000   0. 00000
MASS/HP/CYC(#/HP/C)    0. 12338    0. 01086   0. 00189   0. 07184   0. 00022   0. 00033
                    KWD      XTC      MWEXH   EXH FLOW    FACAL       FAM   ERROR
METHOD 3. 2     0. 88307 0. 25133 27. 50000  1176. 214  0. 06479  0. 06317  2. 570
MASS/MODE(LBM)         0. 18640    0. 10831   0. 01751   0. 03030   0. 00024   0. 00045
MASS/RATED HP(#/HP)    0. 00116    0. 00067   0. 00011   0. 00019   0. 00000   0. 00000
MASS/HP/CYC(#/HP/C)    0. 12474    0. 01111   0. 00192   0. 07248   0. 00022   0. 00033
```

7. SUMMARY

Four methods have been developed for computing fuel-air ratios from exhaust gas analyses. These methods are based on atom balances, partial sums of mole-fractions, defined wet, dry and dried measurements and the water-gas reaction equilibrium constant equation. For an ideal case, all methods give the same calculated fuel-air ratio. However, when measurement errors occur, each method gives a different result. This occurs because of differences in specific errors among the different methods.

In addition to providing a check on fuel-air and concentration errors, the Michigan method calculates exhaust molecular weight from the calculated mole-fractions of ten gaseous exhaust products. Calculated results indicate that poor fuel-air mixtures, and the resulting poor combustion, lead to low exhaust molecular weights. As the mixture and combustion improve, the molecular weights increase and approach the values obtained from equilibrium calculations. The Michigan method also eliminates the need for dry-to-wet water correction factors, since the method can use wet, dry or dried concentration measurements directly.

The rationale behind selecting a particular procedure for determining data validity is developed in this report. It leads to the conclusion that no single variable can be used alone to determine data validity. E(1.2) is a good measure of fuel-air ratio error, but a low error can come about because of compensating errors in concentration measurements. On the other hand, XTC is a good measure of the accuracy of concentration measurements. When coupled together, they indicate those runs which have low fuel-air errors together with low concentration measurement errors. Use of Method 1.2, together with E(1.2) and XTC as indicators of data validity, is suggested.

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Appendix A

Computer Program FAA

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C      THE UNIVERSITY OF MICHIGAN
C      FAA.FR   (5-19-76 VERSION)

C      FAA ENGINE EMISSIONS DATA REDUCTION PROGRAM
C      USE WITH SUBROUTINES CRT12 CRT15,CRT16

       REAL K1,K2,K3,NO,NOX,NOSP,NOXSP,NOSPR,NOXSPR,NOR,NOXR,NOMPC,
      1NOXMPC,MUINA,MWEXH,NOMFR,NOXMFR,NOMPM,
      2NOXMPM,NOMMP,NOXMMP,NO2SP,KWD,KWDD,N2O2,N2A,MWAIR,MET
       INTEGER RPMN,CO2RNG,CORNG,HCRNG,WOT,DIA,DIAM
       DIMENSION A2(15,16),A3(16,17),A4(12,13) B(16,17),X(16),IDATE(4),
      1IOPERS(24),IENGT(6),IENGSN(6),IRUN(3)
       DIMENSION INFO(34),DATAF(10),YP(24,4),HCMPC(4),NOXMPC(4),
      1COMPC(4),CO2MPC(4),O2MPC(4),NOMPC(4)
       COMMON/INIT/B,X
       COMMON/INIT2/A2
       COMMON/INIT3/A3
       COMMON/INIT4/A4
       COMMON/STOR1/C1,C2,C3,C4,C5,C6,C7,C11,C12,C13,C15,C16,C17,C27U,
      1C28U,C29U,C18,C19,C20,C21,C22,C23,C24,C25,C26,C27,C28,C29,C30 C31,
      2C32,C33,C34,C35,C36,C37,C38,C40,C41 C42,C43,C44,C45,C68,C69,C70
      3C71,C72,C73,C74,C75,C76,C77,C78,C79,C77U,C78U,C79U,C80,C81,C82
      4C83,C84,C85,C86,C87,C88,C89,C90,C91,C93,C94,C95
       COMMON/STOR2/CO2RNG,CO2SP,CO2SPR,CO2R,CO2,CO2SPC,CO2RK,CO2MFR
      1CO2MPM,CO2MMP,CO2MPC,CORNG,COSP,COSPR,COR,CO,
      2COSPC,CORK,COMFR,COMPM,COMMP,COMPC,O2SP,O2SPR,O2R,
      3O2,O2MFR,O2MPM,O2MMP,O2MPC,HCRNG,HCSP,HCCSP,HCSPR,
      4HCR,HCC,HCSPC,HCRK,HCMFR,HCMPM,HCMMP,HCMPC,NOSP,NOSPR,
      5NOR,NO,NOMFR,NOMPM,NOMMP,NOMPC,NOXSP,NOXSPR,NOXR,
      6NOX,NOXMFR,NOXMPM,NOXMMP,NOXMPC,NO2SP
       COMMON/STOR3/KWD,KWDD,AA,FF,XCO2,XCO,XHC,XO2,XNO,XNO2,XH2O XN2
      1XAR,XH2,XC
       COMMON/STOR4/YP
       DATA A2/2*1.0,14*0.0,-1.0,31*0.0,-1.0,13*0.0,2.0,2*1.0,
      112*0.0,2*1.0,0.0,1.0,15*0.0,1.0,10*0.0,2.0,4*0.0,1.0,9*0.0
      21.0,5*0.0,1.0,3*0.0,1.0,4*0.0,2.0,6*0.0,1.0,2*0.0,1.0,2*0.0
      31.0,6*0.0,1.0,7*0.0,2.0,5*0.0,1.0,9*0.0,1.0,15*0.0,2.0,
      415*0.0,1.0,11*0.0,2.0,4*0.0,1.0,14*0.0/
       DATA A3/2*1.0,15*0.0,-1.0,45*0.0,-1.0,2*0.0,2.0,0.0,1.0,5*0.0,1.0
      14*0.0,1.0,2*0.0,1.0,2*0.0,1.0,4*0.0,1.0,4*0.0,1.0,6*0.0,1.0,3*0.0
      21.0,7*0.0,2.0,4*0.0,1.0,2*0.0,1.0,7*0.0,1.0,5*0.0,1.0,0.0,
      30.0,1.0,5*0.0,2.0,6*0.0,2*1.0,0.0,1.0,3*0.0,1.0,0.0,1.0,1.0,
      46*0.0,1.0,3*0.0,-1.0,2*0.0,1.0,9*0.0,1.0,14*0.0,1.0,0.0,2.0
      513*0.0,1.0,2*0.0,1.0,5*0.0,2.0,6*0.0,1.0,20*0.0,2*1.0,15*0.0
       DATA A4/1.0,-1.0,11*0.0,1.0,25*0.0,1.0,11*0.0,-1.0,1.0,
      19*0.0,0.5,1.0,0.0,1.0,8*0.0,1.0,3*0.0,1.0,7*0.0,
      2-0.5,4*0.0,1.0,4*0.0,1.0,0.0,0.5,5*0.0,-2.0,
      32*0.0,-1.0,0.0,-1.0,7*0.0,1.0,4*0.0,1.0,7*0.0,
      4-1.0,3*0.0,1.0,5*0.0,-2.0,5*0.0,1.0,9*0.0/
    79 FORMAT(" DATAFILE NAME                ",Z)
    80 FORMAT(S19)
    81 FORMAT(I1)
    82 FORMAT(I2)
    83 FORMAT(3A2)
    84 FORMAT(I4)
    85 FORMAT(I5)
    86 FORMAT(G8.5)
    90 FORMAT(4A2)
    91 FORMAT(6A2)
    92 FORMAT(34A2)
    93 FORMAT(34A2)
    99 FORMAT(1H ,"COMMENTS: ",34A2)
   100 FORMAT(1H ,//"  DATE ",5X,4A2,T27,"ENGINE TYPE: ",3X,6A2,T56,"FUEL H/C
      1 RATIO =",F6.3)
   101 FORMAT(1H ," LOCATION: UNIV OF MICH",T27,"SERIAL NUMBER: ",1X,6A2,T56,"IGN
      1ITION TIMING= ",I2,"DEG")
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102 FORMAT(1H ," OPERATORS: ", 24A2)
103 FORMAT(1HO, "RUN NO. ", 3A2/" MODE: ", I5)
104 FORMAT(1H ,"TEMP(DB)       =",F6. 2,"F",T29,"FUEL RATE=",F9. 4,"#/HR",T57,"EN
   1GINE RPM(NOM)=", I4," RPM")
105 FORMAT(1H ,"TEMP(DP)       =",F6. 2,"F",T29,"AIR RATE =",F9. 4,"#/HR",T57,"EN
   1GINE RPM(ACT)=",F5. 0,"RPM")
106 FORMAT(1H ,"TEMP(BAR)      =",F6. 2,"F",T29,"F/A RATIO=",F9. 4,"#/#",T57,"BHP
   1(OBS)         =",F5. 1,"HP")
107 FORMAT(1H ,"BAR PRESS(OB)=",F6. 2,'"HG',T29,"PHIM       =",F9. 4,T57,"BHP
   1(CORR)        =",F5. 1,"HP")
108 FORMAT(1H ,"BAR PRESS(CR)=",F6. 2,'"HG',T57,"MAN VAC(OBS)    =",F5. 2, "HG')
109 FORMAT(1H ,"SPEC HUMIDITY=",F6. 4,"#/#",T57,"MAN PRESS(CORR)=",F5. 2,'"HG')
110 FORMAT(1H ,T25,"CO2",T35,"O2",T45,"UHCC",T55,"CO",T65,"NO",T75,"NOX')
111 FORMAT(1H ,"CONC(PPM)",T23,F7. 0,T33,F7. 0,T43,F7. 0,T53,F7. 0,T63,F7. 0,T73,
   1F7. 0)
115 FORMAT(1H ,"MASS/MODE(LBM)",T22,F8. 5,T32,F8. 5,T42,F8. 5,T52,F8. 5,T62,F8. 5,
   1T72,F8. 5)
116 FORMAT(1H ,"MASS/RATED HP(#/HP)",T23,F7. 5,T33,F7. 5,T43,F7. 5,T53,F7. 5,T63,
   1F7. 5,T73,F7. 5)
117 FORMAT(1H ,T20,"KWD",T28,"XTC",T35,"MWEXH",T42,"EXH FLOW",T54,
   1"FACAL",T65,"FAM",T70,"ERROR")
118 FORMAT(1H ,"METHOD",F4. 1,3X,2F8. 5,F9. 5,F10. 3,2F9. 5,F7. 3)
119 FORMAT(1H ,"MASS/HP/CYC(#/HP/C)",T23,F7. 5,T33,F7. 5,T43,F7. 5,T53,F7. 5,T63,
   1F7. 5,T73,F7. 5)
120 FORMAT(1H1,/)
122 FORMAT(1H ," (2F5. 2)"/"  24")
123 FORMAT(1H ,(2F5. 2))
    FITT(K1,K2,K3,VAR)=K1*VAR+K2*VAR*VAR+K3*VAR**3
    C1=1. 81792E-4
    C2=1. 75E-10
    C3=3. 5116E-11
    C4=4. 71177E1
    C5=-2. 00984
    C6=3. 28746E-1
    C7=. 01934
    C11=-1. 26635E-2
    C12=5. 36797E-3
    C13=4. 91015E-8
    C15=-3. 0205E-3
    C16=5. 66919E-6
    C17=-4. 59596E-10
    C18=6. 70727E-2
    C19=4. 07332E-4
    C20=4. 35863E-6
    C21=3. 09387E-2
    C22=1. 88357E-4
    C23=5. 76719E-8
    C24=1. 80806E-2
    C25=6. 37274E-5
    C26=8. 39907E-9
    C27=6. 08450E-2
    C28=3. 28671E-4
    C29=3. 96270E-6
    C27U=4. 92230E-1
    C28U=-1. 00439E-2
    C29U=6. 62162E-5
    C30=2. 60958E-2
    C31=7. 83471E-5
    C32=1. 86948E-7
    C33=6. 10711
    C34=1. 44451E-2
    C35=2. 44838E-4
    C36=1. 62481
    C37=5. 33428E-3
    C38=-1. 58241E-5
    C40=164. 581
```

```
  C41=.245
  C42=992.E-7
  C43=3.89549E2
  C44=1.27588
  C45=-6.23371E-3
  C68=1.38694E1
  C69= 8.38889E-1
  C70=2.37654E-2
  C71=3.07229E1
  C72=-3.4629
  C73=2.59663E-1
  C74=5.44677E1
  C75=-8.05437
  C76=1.01355
  C77=1.62951E1
  C78=-1.35417
  C79=5.90278E-2
  C77U=1.32639E1
  C78U=-5.55556E-1
  C79U=7.71605E-3
  C80=3.78735E1
  C81=-2.71806
  C82=2.62956E-1
  C83=1.66345E-1
  C84=-9.70595E-5
  C85=3.07143E-8
  C86=6.07292E-1
  C87=-8.75E-4
  C88=1.69271E-6
  C89=2.59127E6
  C90=-2.59517E4
  C91=3.48605E2
  C93=2.52202E-3
  C94=-1.41714E-8
  C95=1.55315E-13

  GENERAL INPUT DATA

  WRITE(10,79)
  READ(11,80)DATAF(1)
  CALL OPEN(13,DATAF(1),2,IER)
  IF (IER.NE.1) GO TO 38
  ACCEPT "OUTPUT?LPT=1,PTP=2,BOTH=3",IOUT
  READ(13,90)(IDATE(I),I=1,4)
  READ(13,92)(IOPERS(I),I=1,24)
  READ(13,91)(IENGT(I),I=1,6)
  READ(13,91)(IENGSN(I),I=1,6)
  READ(13,86)HPR,HTCR,EHCR,EHCC
  READ(13,82)IGNT
  READ(13,81)DIAM
  GO TO (2,3,2), IOUT
2 WRITE(12,100)IDATE,IENGT,HTCR
  WRITE(12,101)IENGSN,IGNT
  WRITE(12,102)IOPERS
3 READ(13,81)MMAX
  DO 4 I=1,4
  HCMPC(I)=0.0
  NOXMPC(I)=0.0
  COMPC(I)=0.0
  CO2MPC(I)=0.0
  O2MPC(I)=0.0
  NOMPC(I)=0.0
4 CONTINUE
  DO 5 I=1,24
  DO 5 J=1,4
5 YP(I,J)=0.0
```

```
      IPAGE=0
      DO 37 MODE=1,MMAX

      IF(IOUT.EQ.2) GO TO 6
      IPAGE=IPAGE+1
      IF(IPAGE.LT.3) GO TO 6
      WRITE(12,120)
      IPAGE=1

C     INPUT DATA PER RUN

    6 READ(13,93)(INFO(I),I=1,34)
      READ(13,83)(IRUN(I),I=1,3)
      READ(13,81)M
      READ(13,81)WOT
      READ(13,84)RPMN
      READ(13,81)CO2RNG,CORNG
      READ(13,85)HCRNG
      READ(13,86)TIM,PBAR,TBAR,TWB,TDP,REV,TIME,DYNL,PMANV,
     1TINAV,DPINA,PINAS,WFUEL,CO2SP,COSP,O2SP,HCSP,NOSP,
     2NO2SP,CO2SPR,COSPR,O2SPR,HCSPR,NOSPR,CO2R,COR,
     3O2R,HCR,NOR,NOXR,DPINJ

C     START OF COMPUTATION

      TBARC=(TBAR-32.)*5./9.
      TINA=FITT(C4,C5,C6,TINAV)+32.
      TDB=TINA
      PBARK=PBAR*(1.+1.84E-5*(TBARC-16.667))/(1.+FITT(C1,C2,C3,TBARC))
      PBARE=PBARK+7.33623E-2*DPINJ
      PSAT=C11+C12*TDP+C13*TDP**3.73
      W=.622*PSAT/(PBARK-PSAT)
      PVAP=W*PBARK/(W+.62197)
      RPM=REV/(6.*TIME)

C     CORRECTED BRAKE HORSEPOWER

      HPB=DYNL*RPM/3000.
      HPBK=0.0
      PMANK=0.0
      IF (WOT.EQ.1) GO TO 10
      CFVAP=PBARK/(PBARK-PVAP)
      PMANK=29.53-.555*SIN((RPM-2000.)/8.333)+.038*SIN((RPM-2000.)/3.889)
      CFMP=PMANK/(PBARK-PMANV)
      CFTEMP=((TINA+460.)/520.)**.8
      CFTOT=CFVAP*CFMP*CFTEMP
      HPF=FITT(C15,C16,C17,RPM)
      HPBK=(HPB+HPF)*CFTOT-HPF
   10 MUINA=C40+C41*TINA+C42*TINA*TINA
      DIA=DIAM/2
      GO TO (11,12,13), DIA
   11 FVINA=FITT(C89,C90,C91,DPINA)*(PBARK+.0733623*PINAS-PVAP)/
     1((460.+TINA)*MUINA)
   12 GO TO 14
   13 FVINA=2.5177E7*DPINA*(PBARK-.0733623*PINAS-PVAP)/((460.+TINA)*MUINA)
   14 FMINA=.07486*FVINA
      FMFUEL=WFUEL*60./TIME
      BSFC=FMFUEL/HPB
      FAM=FMFUEL/FMINA

C     CORRECTED CONCENTRATION

      HCCSP=HCSP*3.
      HCRNG=HCRNG/15000+1
      GO TO (17,18), HCRNG
   17 HCC=HCCSP*HCR/HCSPR
```

```
      GO TO 19
   18 HCSPC=FITT(C93,C94,C95,HCCSP)
      HCRK=HCR*HCSPC/HCSPR
      HCC=FITT(C43,C44,C45,HCRK)
   19 NO=NOSP*NOR/NOSPR
      O2=(O2SP*O2R/O2SPR)*1E4
      NOXSP=NOSP+NO2SP
      NOXSPR=NOXSP*NOSPR/NOSP
      NOX=NOXSP*NOXR/NOXSPR
      GO TO (20,24,25,26), CORNG
   20 IF (COSP.GE.9.0) GO TO 21
      COSPC=FITT(C77,C78,C79,COSP)
      GO TO 22
   21 COSPC=FITT(C77U,C78U,C79U,COSP)
   22 CORK=COR*COSPC/COSPR
      IF (CORK.GE.80.0) GO TO 23
      CO=FITT(C27,C28,C29,CORK)*1E4
      GO TO 27
   23 CO=FITT(C27U,C28U,C29U,CORK)*1E4
      GO TO 27
   24 COSPC=FITT(C80,C81,C82,COSP)
      CORK=COR*COSPC/COSPR
      CO=FITT(C30,C31,C32,CORK)*1E4
      GO TO 27
   25 COSPC=FITT(C83,C84,C85,COSP)
      CORK=COR*COSPC/COSPR
      CO=FITT(C33,C34,C35,CORK)
      GO TO 27
   26 COSPC=FITT(C86,C87,C88,COSP)
      CORK=COR*COSPC/COSPR
      CO=FITT(C36,C37,C38,CORK)
   27 CONTINUE
      GO TO (28,29,30),CO2RNG
   28 CO2SPC=FITT(C68,C69,C70,CO2SP)
      CO2RK=CO2R*CO2SPC/CO2SPR
      CO2=FITT(C18,C19,C20,CO2RK)*1E4
      GO TO 31
   29 CO2SPC=FITT(C71,C72,C73,CO2SP)
      CO2RK=CO2R*CO2SPC/CO2SPR
      CO2=FITT(C21,C22,C23,CO2RK)*1E4
      GO TO 31
   30 CO2SPC=FITT(C74,C75,C76,CO2SP)
      CO2RK=CO2R*CO2SPC/CO2SPR
      CO2=FITT(C24,C25,C26,CO2RK)*1E4
   31 CONTINUE
      GO TO 44

C     EMISSION FLOW RATES (LBM/HR)

   40 HCMFR=FVEXH*.0359*HCC/1E6
      NOXMFR=FVEXH*.119*NOX/1E6
      COMFR=FVEXH*.0726*CO/1E6
      CO2MFR=FVEXH*.1142*CO2/1E6
      O2MFR=FVEXH*.083*O2/1E6
      NOMFR=FVEXH*.0778*NO/1E6

C     EMISSION MASS PER MODE (LBM)

      HCMPM=HCMFR*TIM/60.
      NOXMPM=NOXMFR*TIM/60
      COMPM=COMFR*TIM/60
      CO2MPM=CO2MFR*TIM/60
      O2MPM=O2MFR*TIM/60
      NOMPM=NOMFR*TIM/60.

C     MASS PER MODE PER RATED HORSEPOWER
```

```
      HCMMP=HCMPM/HPR
      NOXMMP=NOXMPM/HPR
      COMMP=COMPM/HPR
      CO2MMP=CO2MPM/HPR
      O2MMP=O2MPM/HPR
      NOMMP=NOMPM/HPR

      YP(3*MODE-2, METH)=COMMP/0. 042
      YP(3*MODE-1, METH)=HCMMP/0. 0019
      YP(3*MODE, METH)=NOXMMP/0. 0015

C     MASS PER RATED HORSEPOWER PER CYCLE

      HCMPC(METH)=HCMPC(METH)+HCMMP
      NOXMPC(METH)=NOXMPC(METH)+NOXMMP
      COMPC(METH)=COMPC(METH)+COMMP
      CO2MPC(METH)=CO2MPC(METH)+CO2MMP
      O2MPC(METH)=O2MPC(METH)+O2MMP
      NOMPC(METH)=NOMPC(METH)+NOMMP

      IF(MODE. LT. MMAX) GO TO 41
      YP(22, METH)=COMPC(METH)/0. 042
      YP(23, METH)=HCMPC(METH)/0 0019.
      YP(24, METH)=NOXMPC(METH)/0. 0015

   41 GO TO (65, 32, 32, 32), METH

      COMPUTED AIR-FUEL RATIO
      METHOD 1. 2(EXP K); METHOD 2. 1(EXF XGW); METHOD 3. 1(K & XGW);
      METHOD 3. 2(K, XGW & NO O2)

   44 N2O2=78. 09/20. 95
      ARO2=. 93/20. 95
      CO2O2=. 03/20. 95
      AIRO2=1. 0+N2O2+ARO2+CO2O2
      N2A=(100. -CO2A)/(1. 0+20. 95/78. 09+. 93/78 09)
      O2A=20. 95*N2A/78. 09
      ARA=. 93*N2A/78. 09
      MWAIR=. 39948*ARA+. 4400995*CO2A+ ?80134*N2A+. 319988*O2A
      H2OO2=W*AIRO2*MWAIR/18. 01534
      WTR=. 08866/19

      A2(3, 3)=-(2. 0+2 0*CO2O2+H2OO2)
      A2(4, 3)=-CO2O2
      A2(4, 7)=EHCC
      A2(5, 2)=-CO2/1E6
      A2(6, 1)=-CO/1E6
      A2(7, 16)=HCC/(1E6*EHCC)
      A2(8, 2)=-O2/1E6
      A2(9, 16)=NO/1E6
      A2(10, 16)=(NOX-NO)/1E6
      A2(11, 3)=-2. 0*H2OO2
      A2(11, 4)=-HTCR
      A2(11, 7)=EHCC*EHCR
      A2(12, 2)=-WTR
      A2(13, 3)=-2 0*N2O2
      A2(14, 3)=-ARO2

      MET=1 2
      METH=1
      A2(15, 5)=0. 0
      A2(15, 6)=0. 0
      A2(15, 7)=0 0
      A2(15, 8)=0 0
      A2(15, 9)=0 0
```

```
   A2(15,10)=0.0
   A2(15,11)=-1.0
   A2(15,13)=0.0
   A2(15,14)=0.0
   A2(15,15)=3.5*CO2/CO
   A2(15,16)=0.0
   GO TO 48

46 MET=2.1
   METH=2
   A2(15,5)=1.0
   A2(15,6)=1.0
   A2(15,7)=1.0
   A2(15,8)=1.0
   A2(15,9)=1.0
   A2(15,10)=1.0
   A2(15,11)=1.0
   A2(15,13)=1.0
   A2(15,14)=1.0
   A2(15,15)=1.0
   A2(15,16)=1.0

48 CALL CRT15

   KWD=X(1)
   KWDD=X(2)
   AA=X(3)
   FF=X(4)
   XCO2=X(5)
   XCO=X(6)
   XHC=X(7)
   XO2=X(8)
   XNO=X(9)
   XNO2=X(10)
   XH2O=X(11)
   XN2=X(13)
   XAR=X(14)
   XH2=X(15)
   XC=0.0
   GO TO 60

50 MET=3.1
   METH=3
   A3(3,3)=-(2.0+2.0*CO2O2+H2OO2)
   A3(4,3)=-2.0*H2OO2
   A3(4,4)=-HTCR
   A3(4,7)=EHCC*EHCR
   A3(5,2)=-CO2/1E6
   A3(6,1)=-CO/1E6
   A3(7,17)=HCC/(1E6*EHCC)
   A3(8,2)=-O2/1E6
   A3(9,17)=NO/1E6
   A3(10,17)=(NOX-NO)/1E6
   A3(11,17)=1.0
   A3(12,2)=-WTR
   A3(13,3)=-2.0*N2O2
   A3(14,3)=-ARO2
   A3(15,15)=3.5*CO2/CO
   A3(16,3)=-CO2O2
   A3(16,7)=EHCC

   CALL CRT16

   KWD=X(1)
   KWDD=X(2)
   AA=X(3)
```

```
      FF=X(4)
      XCO2=X(5)
      XCO=X(6)
      XHC=X(7)
      XO2=X(8)
      XNO=X(9)
      XNO2=X(10)
      XH2O=X(11)
      XN2=X(13)
      XAR=X(14)
      XH2=X(15)
      XC=X(16)
      GO TO 60

   55 MET=3.2
      METH=4
      A4(1,13)=1.0
      A4(3,3)=1.0+CO2O2+H2OO2/2.0+N2O2
      A4(4,3)=CO2O2
      A4(4,7)=-EHCC
      A4(5,2)=-CO2/1E6
      A4(6,1)=-CO/1E6
      A4(7,13)=HCC/(1E6*EHCC)
      A4(8,13)=(NOX-NO)/1E6
      A4(9,3)=2.0*H2OO2
      A4(9,4)=HTCR
      A4(9,7)=-EHCC*EHCR
      A4(10,2)=-WTR
      A4(11,3)=ARO2
      A4(12,12)=3.5*CO2/CO

      CALL CRT12

      KWD=X(1)
      KWDD=X(2)
      AA=X(3)
      FF=X(4)
      XCO2=X(5)
      XCO=X(6)
      XHC=X(7)
      XO2=0.0
      XNO=0.0
      XNO2=X(8)
      XH2O=X(9)
      XN2=0.0
      XAR=X(11)
      XH2=X(12)
      XC=0.0

   60 XTC=XCO2+XCO+XHC+XO2+XNO+XNO2+XH2O+XN2+XAR+XH2+XC
      FACAL=FF*(12.01115+1.00797*HTCR)/(AIRO2*MWAIR*AA)
      ERROR=(FACAL-FAM)*100./FAM
      PHIM=FAM*(HTCR/4.+1.)*AIRO2*MWAIR/(12.01115+1.00797*HTCR)
      IF(METH.NE.4) GO TO 61
      MWEXH=27.5
      GO TO 62
   61 MWEXH=(44.00995*XCO2+28.01055*XCO+(12.01115*EHCC+1.00797*EHCC*EHCR)
     1*XHC+31.9988*XO2+18.01534*XH2O+2.01594*XH2+28.0134*XN2+
     230.0061*XNO+46.0055*XNO2+39.948*XAR+12.01115*XC)/XTC
   62 FVEXH=385.479*(FMINA+FMFUEL)/MWEXH
      GO TO 40

   65 GO TO (67,68,67), IOUT
   67 WRITE(12,103)IRUN,M
      WRITE(12,99)INFO
      WRITE(12,104)TDB,FMFUEL,RPMN
```

```
      WRITE(12, 105)TDP, FMINA, RPM
      WRITE(12, 106)TBAR, FAM, HPB
      WRITE(12, 107)PBAR, PHIM, HPBK
      WRITE(12, 108)PBARK, PMANV
      WRITE(12, 109)W, PMANK
      WRITE(12, 110)
      WRITE(12, 111)CO2, O2, HCC, CO, NO, NOX
   32 IF(IOUT. EQ. 2) GO TO 68
      WRITE(12, 117)
      WRITE(12, 118)MET, KWD, XTC, MWEXH, FVEXH, FACAL, FAM, ERROR
      WRITE(12, 115)CO2MPM, O2MPM, HCMPM, COMPM, NOMPM, NOXMPM
      WRITE(12, 116)CO2MMP, O2MMP, HCMMP, COMMP, NOMMP, NOXMMP
   68 IF (MODE. LT. MMAX) GO TO 36
      IF(IOUT. EQ. 1) GO TO 70
      WRITE(14, 122)
      DO 69 I=1, 24
      XP=0. 25+0. 25*(I-1)+0. 5*((I-1)/3)+0. 25*((I-1)/21)
   69 WRITE(14, 123)XP, YP(I, METH)
      IF(IOUT. EQ. 2) GO TO 36
   70 WRITE(12, 119)CO2MPC(METH), O2MPC(METH), HCMPC(METH), COMPC(METH),
     1NOMPC(METH), NOXMPC(METH)
   36 CONTINUE
      GO TO (46, 50, 55, 37), METH
   37 CONTINUE
      READ(13, 81)MORE
      IF(MORE. EQ. 0) GO TO 39
      GO TO 3
   38 TYPE "FILE NOT OPENED"
   39 CONTINUE
      CALL RESET
      STOP
      END
```

Appendix B

Computer Program FARAT

```
           C      THE UNIVERSITY OF MICHIGAN
C      FARAT. FR    (5/20/76 VERSION)

C      FUEL-AIR RATIO CALCULATION
C      USE WITH CRT4, CRT12, CRT15, CRT16

       REAL N2O2, N2A, N2AS, MWAIR, MWEXH, NO, NOW, NOD, NODD, NOX, NOXW, NOXD, NOXDD
       REAL KWDD, KWD, MET, INCR, K, KR
       INTEGER GT, FMAT, VAR, DISP1, DISP2, DISP3, DISP4, DISPS, FLAG
       DIMENSION A1(4,5), A2(15, 16), A3(16, 17), A4(12, 13), B(16, 17), X(16)
       COMMON/INIT/B, X
       COMMON/INIT1/A1
       COMMON/INIT2/A2
       COMMON/INIT3/A3
       COMMON/INIT4/A4
       COMMON/STOR/JCO2W, JCO2D, JCO2DD, JCOW, JCOD, JCODD, JO2W, JO2D, JO2DD,
      1JHCCW, JHCCD, JHCCDD, JNOW, JNOD, JNODD, JNOXW, JNOXD, JNOXDD
  100 FORMAT(1H , T7, "HTCR", T17, "EHCC", T27, "EHCR", T37, "CO2A", T47,
      1"PSAT", T57, "PTRP", T70, "W", T77, "N2O2")
  110 FORMAT(1H , T6, F5. 3, T16, F5. 3, T25, F6. 3, T36, F5. 3, T44, F7. 5, T55, F6. 3,
      1T65, F6. 4, T74, F7. 4)
  120 FORMAT(1H , //T5, "RUN: ", F5. 1, T27, "CO2", T38, "CO", T48, "O2", T57,
      1"HCC", T68, "NO", T77, "NOX")
  130 FORMAT(1H , T5, "DRY MEASUREMENTS", T24, F7. 0, T34, F7. 0, T44, F7. 0,
      1T54, F7. 0, T64, F7. 0, T74, F7. 0)
  131 FORMAT(1H , T5, "DRIED MEASUREMENTS", T24, F7. 0, T34, F7. 0, T44, F7. 0,
      1T54, F7. 0, T64, F7. 0, T74, F7. 0)
  132 FORMAT(1H , T5, "WET MEASUREMENTS", T24, F7. 0, T34, F7. 0, T44, F7. 0,
      1T54, F7. 0, T64, F7. 0, T74, F7. 0)
  135 FORMAT(1H , /, T5, "ONLY WET MEASUREMENTS ALLOWED  USE METHOD 2")
  140 FORMAT(1H , T5, "XCO2", T13, "XCO", T20, "XHC", T27, "XO2", T33, "XH2O",
      1T41, "XH2", T48, "XN2", T55, "XNO", T61, "XNO2", T69, "XAR", T77, "XC")
  150 FORMAT(1H , 11F7. 4)
  160 FORMAT(1H , T6, "MTD", T13, "XTC", T22, "K", T26, "KWDD", T34, "KWD", T40,
      1"PHIM", T47, "MWEXH", T53, "PHICAL", T62, "FACAL", T72, "FAM", T77, "ERROR")
  163 FORMAT(1H , T4, "N2O2", T10, "CO2A", T20, "W", T22, "HTCR", T27, "EHCC",
      1T33, "EHCR", T40, "XGW", T47, "K", T50, "MTD", T56, "KWD",
      2T62, "FACAL", T72, "FAM", T77, "ERROR")
  164 FORMAT(1H , 2F6. 3, F7. 4, F6. 3, F4. 1, 2F6. 3, F5. 2, F5. 1, F6. 3, 2F8. 5, F7. 3)
  165 FORMAT(1H , T6, "CO2", T14, "CO", T21, "O2", T26, "HCC", T32, "NO",
      1T36, "NOX", T40, "FCHC", T46, "FDA", T50, "MTD", T56, "XTC", T62, "FACAL",
      2T72, "FAM", T77, "ERROR")
  166 FORMAT(1H , F8. 0, 2F7. 0, F6. 0, 2F5. 0, F4. 2, F5. 2, F4. 1, F6. 3, 2F8. 5, F7. 3)
  170 FORMAT(1H , F7. 1, 5F7. 4, F8. 4, F7. 4, 2F8. 5, F7. 3)
  180 FORMAT(1H1)
  181 FORMAT(1H )

        J=0
        Z=0. 0
        ACCEPT "HTCR    ", HTCR,
       1"RUN      ", RUN, "CO2      ", CO2I, "CO        ", COI, "O2        ", O2I,
       2"HCC      ", HCCI, "NO        ", NOI, "NOX      ", NOXI,
       3"MEASURED FUEL/AIR   ", FAM,
       4"METHOD 1. 1(1), 1. 2(2), 2. 1(3), 3. 1(4), 3. 2(5)   ", METHR,
       5"IMETH, METHMX    ", IMETH, METHMX,
       6"DISP1, DISP2, DISP3, DISP4   ", DISP1, DISP2, DISP3, DISP4
        METHMX=METHMX+1
        METH=METHR
        DISPS=DISP1+DISP2+DISP3+DISP4

    28 EHCC=1. 0
        EHCR=1. 85
        CO2A=0. 03
        W=0. 01
        PSAT=0. 08866
        PTRP=19. 0
```

```
      XGW=1.0
      K=3.5
      FCHC=0.0
      FDA=0.0
      N2AS=78.09
      O2AS=20.95
      ARAS=0.93
      NNEG=0
      NPOS=1
      INCR=0.0
      VAR=18

      JCO2W=0
      JCO2D=0
      JCO2DD=1
      JCOW=0
      JCOD=1
      JCODD=0
      JO2W=0
      JO2D=0
      JO2DD=1
      JHCCW=1
      JHCCD=0
      JHCCDD=0
      JNOW=1
      JNOD=0
      JNODD=0
      JNOXW=1
      JNOXD=0
      JNOXDD=0

   29 CO2W=CO2I*JCO2W
      CO2D=CO2I*JCO2D
      CO2DD=CO2I*JCO2DD
      COW=COI*JCOW
      COD=COI*JCOD
      CODD=COI*JCODD
      O2W=O2I*JO2W
      O2D=O2I*JO2D
      O2DD=O2I*JO2DD
      HCCW=HCCI*JHCCW
      HCCD=HCCI*JHCCD
      HCCDD=HCCI*JHCCDD
      NOW=NOI*JNOW
      NOD=NOI*JNOD
      NODD=NOI*JNODD
      NOXW=NOXI*JNOXW
      NOXD=NOXI*JNOXD
      NOXDD=NOXI*JNOXDD

    0 ACCEPT "GT  ",GT
      GO TO (1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24
     125,26,27,28),GT
    1 ACCEPT "HTCR,EHCC,EHCR  ",HTCR,EHCC,EHCR
      GO TO 0
    2 ACCEPT "CO2A,W  ",CO2A,W
      GO TO 0
    3 ACCEPT "JCO2W,JCO2D,JCO2DD,JCOW,JCOD,JCODD  ",JCO2W,JCO2D,JCO2DD,
     1JCOW,JCOD,JCODD
      GO TO 29
    4 ACCEPT "JO2W,JO2D,JO2DD,JHCCW,JHCCD,JHCCDD  ",JO2W,JO2D,JO2DD,
     1JHCCW,JHCCD,JHCCDD
      GO TO 29
    5 ACCEPT "JNOW,JNOD,JNODD,JNOXW,JNOXD,JNOXDD  ",JNOW,JNOD,JNODD,
     1JNOXW,JNOXD,JNOXDD
      GO TO 29
```

```
   6 ACCEPT "RUN   ",RUN
     GO TO 0
   7 ACCEPT "CO2   ",CO2I
     GO TO 29
   8 ACCEPT "CO   ",COI
     GO TO 29
   9 ACCEPT "O2   ",O2I
     GO TO 29
  10 ACCEPT "HCC   ",HCCI
     GO TO 29
  11 ACCEPT "NO   ",NOI
     GO TO 29
  12 ACCEPT "NOX   ",NOXI
     GO TO 29
  13 ACCEPT "MEASURED FUEL/AIR   ",FAM
     GO TO 0
  14 ACCEPT "XGW,K   ",XGW,K
     GO TO 0
  15 ACCEPT "FCHC,FDA   ",FCHC,FDA
     GO TO 0
  16 ACCEPT "PSAT,PTRP   ",PSAT,PTRP
     GO TO 0
  17 ACCEPT "N2AS,O2AS,ARAS   ",N2AS,O2AS,ARAS
     GO TO 0
  18 ACCEPT "METHOD: 1.1(1),1.2(2),2.1(3),3.1(4),3.2(5)   ",METHR
     METH=METHR
     GO TO 0
  19 ACCEPT"IMETH,METHMX   ",IMETH,METHMX
     METHMX=METHMX+1
     GO TO 0
  20 ACCEPT "DISP1,DISP2,DISP3,DISP4   ",DISP1,DISP2,DISP3,DISP4
     DISPS=DISP1+DISP2+DISP3+DISP4
     GO TO 0
  21 J=0
     GO TO 0
  22 WRITE(12,181)
     GO TO 0
  23 WRITE(12,180)
     GO TO 0
  25 ACCEPT "NNEG,NPOS,INCR   ",NNEG,NPOS,INCR
     NNEG=-NNEG
     GO TO 0
  26 ACCEPT "VAR=HTCR(1),EHCC(2),EHCR(3),CO2A(4),W(5),PSAT(6),PTRP(7),
    1CO2(8),CO(9),O2(10),HCC(11),NO(12),NOX(13),XGW(14),K(15),FCHC(16),
    2FDA(17),NONE(18)   ",VAR
     GO TO 0

  27 DO 90 NN=NNEG,NPOS
     FLAG=0
     GO TO (1010,1020,1030,1040,1050,1060,1070,1080,1090,1100,1110,1120,
    11130,1140,1150,1160,1170,1300),VAR

1010 IF (NN.GT.NNEG) GO TO 1011
     HTCRR=HTCR
1011 IF (NN.EQ.NPOS) GO TO 1012
     HTCR=HTCRR*(1.0+INCR*NN)
     GO TO 1300
1012 HTCR=HTCRR
     GO TO 90

1020 IF (NN.GT.NNEG) GO TO 1021
     EHCCR=EHCC
1021 IF (NN.EQ.NPOS) GO TO 1022
     EHCC=EHCCR*(1.0+INCR*NN)
     GO TO 1300
1022 EHCC=EHCCR
```

```
      GO TO 90

 1030 IF (NN.GT.NNEG) GO TO 1031
      EHCRR=EHCR
 1031 IF (NN.EQ.NPOS) GO TO 1032
      EHCR=EHCRR*(1.0+INCR*NN)
      GO TO 1300
 1032 EHCR=EHCRR
      GO TO 90

 1040 IF (NN.GT.NNEG) GO TO 1041
      CO2AR=CO2A
 1041 IF (NN.EQ.NPOS) GO TO 1042
      CO2A=CO2AR*(1.0+INCR*NN)
      GO TO 1300
 1042 CO2A=CO2AR
      GO TO 90

 1050 IF (NN.GT.NNEG) GO TO 1051
      WR=W
 1051 IF (NN.EQ.NPOS) GO TO 1052
      W=WR*(1.0+INCR*NN)
      GO TO 1300
 1052 W=WR
      GO TO 90

 1060 IF (NN.GT.NNEG) GO TO 1061
      PSATR=PSAT
 1061 IF (NN.EQ.NPOS) GO TO 1062
      PSAT=PSATR*(1.0+INCR*NN)
      GO TO 1300
 1062 PSAT=PSATR
      GO TO 90

 1070 IF (NN.GT.NNEG) GO TO 1071
      PTRPR=PTRP
 1071 IF (NN.EQ.NPOS) GO TO 1072
      PTRP=PTRPR*(1.0+INCR*NN)
      GO TO 1300
 1072 PTRP=PTRPR
      GO TO 90

 1080 IF (NN.EQ.NPOS) GO TO 1081
      CO2W=CO2I*(1.0+INCR*NN)*JCO2W
      CO2D=CO2I*(1.0+INCR*NN)*JCO2D
      CO2DD=CO2I*(1.0+INCR*NN)*JCO2DD
      GO TO 1300
 1081 CO2W=CO2I*JCO2W
      CO2D=CO2I*JCO2D
      CO2DD=CO2I*JCO2DD
      GO TO 90

 1090 IF (NN.EQ.NPOS) GO TO 1091
      COW=COI*(1.0+INCR*NN)*JCOW
      COD=COI*(1.0+INCR*NN)*JCOD
      CODD=COI*(1.0+INCR*NN)*JCODD
      GO TO 1300
 1091 COW=COI*JCOW
      COD=COI*JCOD
      CODD=COI*JCODD
      GO TO 90

 1100 IF (NN.EQ.NPOS) GO TO 1101
      O2W=O2I*(1.0+INCR*NN)*JO2W
      O2D=O2I*(1.0+INCR*NN)*JO2D
      O2DD=O2I*(1.0+INCR*NN)*JO2DD
```

```
      GO TO 1300
 1101 O2W=O2I*JO2W
      O2D=O2I*JO2D
      O2DD=O2I*JO2DD
      GO TO 90

 1110 IF (NN.EQ.NPOS) GO TO 1111
      HCCW=HCCI*(1.0+INCR*NN)*JHCCW
      HCCD=HCCI*(1.0+INCR*NN)*JHCCD
      HCCDD=HCCI*(1.0+INCR*NN)*JHCCDD
      GO TO 1300
 1111 HCCW=HCCI*JHCCW
      HCCD=HCCI*JHCCD
      HCCDD=HCCI*JHCCDD
      GO TO 90

 1120 IF (NN.EQ.NPOS) GO TO 1121
      NOW=NOI*(1.0+INCR*NN)*JNOW
      NOD=NOI*(1.0+INCR*NN)*JNOD
      NODD=NOI*(1.0+INCR*NN)*JNODD
      GO TO 1300
 1121 NOW=NOI*JNOW
      NOD=NOI*JNOD
      NODD=NOI*JNODD
      GO TO 90

 1130 IF (NN.EQ.NPOS) GO TO 1131
      NOXW=NOXI*(1.0+INCR*NN)*JNOXW
      NOXD=NOXI*(1.0+INCR*NN)*JNOXD
      NOXDD=NOXI*(1.0+INCR*NN)*JNOXDD
      GO TO 1300
 1131 NOXW=NOXI*JNOXW
      NOXD=NOXI*JNOXD
      NOXDD=NOXI*JNOXDD
      GO TO 90

 1140 IF (NN.GT.NNEG) GO TO 1141
      XGWR=XGW
 1141 IF (NN.EQ.NPOS) GO TO 1142
      XGW=XGWR*(1.0+INCR*NN)
      GO TO 1300
 1142 XGW=XGWR
      GO TO 90

 1150 IF (NN.GT.NNEG) GO TO 1151
      KR=K
 1151 IF (NN.EQ.NPOS) GO TO 1152
      K=KR*(1.0+INCR*NN)
      GO TO 1300
 1152 K=KR

 1160 IF (NN.GT.NNEG) GO TO 1161
      FCHCR=FCHC
 1161 IF (NN.EQ.NPOS) GO TO 1162
      FCHC=FCHCR*(1.0+INCR*NN)
      GO TO 1300
 1162 FCHC=FCHCR
      GO TO 90

 1170 IF (NN.GT.NNEG) GO TO 1171
      FDAR=FDA
 1171 IF (NN.EQ.NPOS) GO TO 1172
      FDA=FDAR*(1.0+INCR*NN)
      GO TO 1300
 1172 FDA=FDAR
      CO2W=CO2I*JCO2W
```

```
      CO2D=CO2I*JCO2D
      CO2DD=CO2I*JCO2DD
      COW=COI*JCOW
      COD=COI*JCOD
      CODD=COI*JCODD
      O2W=O2I*JO2W
      O2D=O2I*JO2D
      O2DD=O2I*JO2DD
      HCCW=HCCI*JHCCW
      HCCD=HCCI*JHCCD
      HCCDD=HCCI*JHCCDD
      NOW=NOI*JNOW
      NOD=NOI*JNOD
      NODD=NOI*JNODD
      NOXW=NOXI*JNOXW
      NOXD=NOXI*JNOXD
      NOXDD=NOXI*JNOXDD
      GO TO 90

 1300 CONTINUE

      IF (NN.EQ.NPOS) GO TO 90
      CO2=CO2W+CO2D+CO2DD
      CO=COW+COD+CODD
      O2=O2W+O2D+O2DD
      HCC=HCCW+HCCD+HCCDD
      NO=NOW+NOD+NODD
      NOX=NOXW+NOXD+NOXDD

      GO TO (30,40,40,40,40), METH

C     METHOD 1.1  (SIMPLE K,WET MEASUREMENTS ONLY) **********

   30 MET=1.1
      IF (CO2W.LT.1.) GO TO 32
      IF (COW.LT.1.) GO TO 32
      GO TO 34
   32 WRITE (12,135)
      GO TO 0
   34 CONTINUE
      N2O2=79.01/20.99
      ARO2=0.0
      CO2O2=0.0
      AIRO2=4.764
      N2A=79.01
      O2A=20.99
      ARA=0.0
      MWAIR=28.97
      H2OO2=0.0

      DATA A1/2.0,4*0.0,1.0,2*0.0,-1.0,0.0,-2.0,1.0,2*0.0,-2.0,5*0.0/

      A1(1,5)=(COW+2.*(CO2W+O2W))/1E6
      A1(2,5)=(CO2W+COW+HCCW)/1E6
      A1(3,2)=HTCR
      A1(3,5)=EHCR*HCCW/1E6
      A1(4,4)=-K*CO2W/COW

      CALL CRT4
      KWD=1.0-X(3)
      AA=X(1)
      FF=X(2)
      XCO2=CO2W/1E6
      XCO=COW/1E6
      XHC=HCCW/(EHCC*1E6)
      XO2=O2W/1E6
```

```
      XH2O=X(3)
      XH2=X(4)
      XN2=N2O2*X(1)
      XNO=0.0
      XNO2=0.0
      XAR=0.0
      XC=0.0
      GO TO 75

C     METHOD 1.2 (EXP K); METHOD 2.1 (EXP XGW); METHOD 3.1 (K & XGW)  *******
C     METHOD 3.2 (K,XGW & NOT O2)  ****************
   40 N2O2=N2AS/O2AS
      ARO2=ARAS/O2AS
      CO2O2=CO2A/O2AS
      AIRO2=1.+N2O2+ARO2+CO2O2
      N2A=(100.-CO2A)/(1.+O2AS/N2AS+ARAS/N2AS)
      O2A=O2AS*N2A/N2AS
      ARA=ARAS*N2A/N2AS
      MWAIR=.39948*ARA+.4400995*CO2A+.280134*N2A+.319988*O2A
      H2OO2=W*AIRO2*MWAIR/18.01534
      WTR=PSAT/PTRP

      GO TO (30,50,50,60,70), METH

      DATA A2/1.0,1.0,14*0.0,-1.0,31*0.0,-1.0,13*0.0,2.0,2*1.0,
     112*0.0,2*1.0,0.0,1.0,15*0.0,1.0,10*0.0,2.0,4*0.0,1.0,9*0.0,1.0,
     25*0.0 1.0,3*0.0,1.0,4*0.0,2.0,6*0.0,1.0,2*0.0,1.0,2*0.0,1.0,
     30.0,1 0,7*0.0,2.0,5*0.0,1.0,9*0.0,1.0,15*0.0,2.0,
     415*0.0,1.0,11*0.0,2.0,4*0.0,1.0,14*0.0/

   50 A2(1,7)=FCHC
      A2(3,3)=-(2.0+2.0*CO2O2+H2OO2)
      A2(4,3)=-CO2O2
      A2(4,7)=EHCC
      A2(5,1)=-CO2D/1E6
      A2(5 2)=-CO2DD/1E6
      A2(5,16)=CO2W/1E6
      A2(6,1)=-COD/1E6
      A2(6,2)=-CODD/1E6
      A2(6,16)=COW/1E6
      A2(7,1)=-HCCD/(1E6*EHCC)
      A2(7,2)=-HCCDD/(1E6*EHCC)
      A2(7,16)=HCCW/(1E6*EHCC)
      A2(8,1)=-O2D/1E6
      A2(8,2)=-O2DD/1E6
      A2(8,16)=O2W/1E6
      A2(9,1)=-NOD/1E6
      A2(9,2)=-NODD/1E6
      A2(9 16)=NOW/1E6
      A2(10,1)=-(NOXD-NOD)/1E6
      A2(10 2)=-(NOXDD-NODD)/1E6
      A2(10,16)=(NOXW-NOW)/1E6
      A2(11,3)=-2.0*H2OO2
      A2(11,4)=-HTCR
      A2(11,7)=EHCR*EHCC
      A2(12,2)=-WTR
      A2(13,3)=-2.0*N2O2
      A2(14,3)=-ARO2

      GO TO (30,51,52), METH

C     METHOD 1 2 (EXPANDED K) **********

   51 MET=1 2
      A2(15,5)=0.0
      A2(15,6)=0.0
```

```
      A2(15,7)=0. 0
      A2(15,8)=0. 0
      A2(15,9)=0. 0
      A2(15,10)=0. 0
      A2(15,11)=-1. 0
      A2(15,13)=0. 0
      A2(15,14)=0. 0
      A2(15,15)=K*CO2/CO
      A2(15,16)=0. 0
      GO TO 55

C     METHOD 2. 1 (EXPANDED XGW) **********

   52 MET=2. 1
      A2(15,5)=1. 0
      A2(15,6)=1. 0
      A2(15,7)=1. 0
      A2(15,8)=1 0
      A2(15,9)=1. 0
      A2(15,10)=1. 0
      A2(15,11)=1. 0
      A2(15,13)=1. 0
      A2(15,14)=1. 0
      A2(15,15)=1. 0
      A2(15,16)=XGW
      GO TO 55

   55 CALL CRT15
      KWD=X(1)
      KWDD=X(2)
      AA=X(3)
      FF=X(4)
      XCO2=X(5)
      XCO=X(6)
      XHC=X(7)
      XO2=X(8)
      XNO=X(9)
      XNO2=X(10)
      XH2O=X(11)
      XN2=X(13)
      XAR=X(14)
      XH2=X(15)
      XC=0. 0
      GO TO 75

C     METHOD 3. 1 (K & XGW)  ****************

      DATA A3/2*1. 0,15*0. 0,-1. 0,45*0. 0,-1. 0,2*0 0,2. 0,0. 0,1. 0,5*0 0,1. 0,
     14*0. 0,1. 0 2*0. 0,1 0,2*0. 0,1. 0,4*0. 0,1 0,4*0 0,1. 0,6*0. 0,1. 0,3*0. 0,
     21 0,7*0. 0,2 0,4*0. 0,1. 0,2*0. 0,1. 0,7*0. 0,1. 0,5*0. 0,1. 0,0. 0,1 0,
     30. 0,1. 0,5*0. 0,2. 0,6*0. 0,2*1. 0,0. 0,1. 0,3*0. 0. 1. 0,0. 0,1. 0,2. 0,
     46*0 0,1. 0,3*0. 0,-1. 0,2*0. 0,1. 0,9*0. 0,1. 0,14*0 0,1. 0,0. 0,2. 0,
     513*0 0,1. 0,2*0 0,1 0,5*0. 0,2. 0,6*0. 0,1. 0,20*0. 0,2*1. 0,15*0. 0/

   60 MET=3. 1
      A3(1,7)=FCHC
      A3(3,3)=-(2. 0+2. 0*CO2O2+H2OO2)
      A3(4,3)=-2. 0*H2OO2
      A3(4,4)=-HTCR
      A3(4,7)=EHCR*EHCC
      A3(5,1)=-CO2D/1E6
      A3(5,2)=-CO2DD/1E6
      A3(5,17)=CO2W/1E6
      A3(6,1)=-COD/1E6
      A3(6,2)=-CODD/1E6
      A3(6,17)=COW/1E6
```

```
      A3(7,1)=-HCCD/(1E6*EHCC)
      A3(7,2)=-HCCDD/(1E6*EHCC)
      A3(7,17)=HCCW/(1E6*EHCC)
      A3(8,1)=-O2D/1E6
      A3(8,2)=-O2DD/1E6
      A3(8,17)=O2W/1E6
      A3(9,1)=-NOD/1E6
      A3(9,2)=-NODD/1E6
      A3(9,17)=NOW/1E6
      A3(10,1)=-(NOXD-NOD)/1E6
      A3(10,2)=-(NOXDD-NODD)/1E6
      A3(10,17)=(NOXW-NOW)/1E6
      A3(11,17)=XGW
      A3(12,2)=-WTR
      A3(13,3)=-2.0*N2O2
      A3(14,3)=-ARO2
      A3(15,15)=K*CO2/CO
      A3(16,3)=-CO2O2
      A3(16,7)=EHCC

      CALL CRT16

      KWD=X(1)
      KWDD=X(2)
      AA=X(3)
      FF=X(4)
      XCO2=X(5)
      XCO=X(6)
      XHC=X(7)
      XO2=X(8)
      XNO=X(9)
      XNO2=X(10)
      XH2O=X(11)
      XN2=X(13)
      XAR=X(14)
      XH2=X(15)
      XC=X(16)
      GO TO 75

C     METHOD 3 2 (K,XGW,BUT O2 NOT REQ'D)   ***************

      DATA A4/1 0,-1.0,11*0.0,1.0,25*0.0,1.0,11*0.0,-1.0,1.0,
     19*0 0,0.5,-1.0,0.0,1 0,8*0 0,1.0,3*0.0,1.0,7*0.0,
     2-0.5,4*0.0,1.0,4*0.0,1.0,0.0,0.5,5*0.0,-2.0,
     32*0 0,-1 0,0 0,-1.0,7*0.0,1.0,4*0.0,1 0,7*0.0,
     4-1 0,3*0.0,1.0,5*0.0,-2 0,5*0.0,1.0,9*0.0/

   70 MET=3.2
      A4(1,7)=FCHC
      A4(1,13)=XGW
      A4(3,3)=1 0+CO2O2+H2OO2/2 0+N2O2
      A4(4,3)=CO2O2
      A4(4,7)=-EHCC
      A4(5,1)=-CO2D/1E6
      A4(5,2)=-CO2DD/1E6
      A4(5,13)=CO2W/1E6
      A4(6,1)=-COD/1E6
      A4(6,2)=-CODD/1E6
      A4(6,13)=COW/1E6
      A4(7,1)=-HCCD/(1E6*EHCC)
      A4(7,2)=-HCCDD/(1E6*EHCC)
      A4(7,13)=HCCW/(1E6*EHCC)
      A4(8,1)=-(NOXD-NOD)/1E6
      A4(8,2)=-(NOXDD-NODD)/1E6
      A4(8,13)=(NOXW-NOW)/1E6
      A4(9,3)=2.0*H2OO2
```

```
      A4(9,4)=HTCR
      A4(9,7)=-EHCR*EHCC
      A4(10,2)=-WTR
      A4(11,3)=ARO2
      A4(12,12)=K*CO2/CO

      CALL CRT12

      KWD=X(1)
      KWDD=X(2)
      AA=X(3)
      FF=X(4)
      XCO2=X(5)
      XCO=X(6)
      XHC=X(7)
      XO2=0.0
      XNO=0.0
      XNO2=X(8)
      XH2O=X(9)
      XN2=0.0
      XAR=X(11)
      XH2=X(12)
      XC=0.0

   75 IF (FLAG.EQ.1) GO TO 80
      IF (FDA.EQ.0) GO TO 80
      FLAG=1
      DAO2=AIRO2+H2OO2
      V1=FDA/DAO2
      V2=AIRO2*V1

      CO2W=((CO2I+V1*CO2O2)*JCO2W)/(1.0+FDA)
      CO2D=((CO2I*KWD+V1*CO2O2)*JCO2D)/(KWD+V2)
      CO2DD=((CO2I*KWDD+V1*CO2O2)*JCO2DD)/(KWDD+V2)

      COW=(COI*JCOW)/(1.0+FDA)
      COD=(COI*KWD*JCOD)/(KWD+V2)
      CODD=(COI*KWDD*JCODD)/(KWDD+V2)

      O2W=((O2I+V1)*JO2W)/(1.0+FDA)
      O2D=((O2I*KWD+V1)*JO2D)/(KWD+V2)
      O2DD=((O2I*KWDD+V1)*JO2DD)/(KWDD+V2)

      HCCW=(HCCI*JHCCW/EHCC)/(1.0+FDA)
      HCCD=(HCCI*KWD*JHCCD/EHCC)/(KWD+V2)
      HCCDD=(HCCI*KWDD*JHCCDD/EHCC)/(KWDD+V2)

      NOW=(NOI*JNOW)/(1.0+FDA)
      NOD=(NOI*KWD*JNOD)/(KWD+V2)
      NODD=(NOI*KWDD*JNODD)/(KWDD+V2)

      NOXW=(NOXI*JNOXW)/(1.0+FDA)
      NOXD=(NOXI*KWD*JNOXD)/(KWD+V2)
      NOXDD=(NOXI*KWDD*JNOXDD)/(KWDD+V2)

      GO TO 1300

   80 XTC=XCO2+XCO+XHC+XO2+XNO+XNO2+XH2O+XN2+XAR+XH2+XC
      FACAL=FF*(12.01115+1.00797*HTCR)/(AIRO2*MWAIR*AA)
      ERROR=(FACAL-FAM)*100./FAM
      PHIM=FAM*(HTCR/4.+1.)*AIRO2*MWAIR/(12.01115+1.00797*HTCR)
      PHICAL=PHIM*FACAL/FAM
      MWEXH=(44.00995*XCO2+28.01055*XCO+(12.01115+1.00797*EHCR)*EHCC
     1*XHC+31.9988*XO2+18.01534*XH2O+2.01594*XH2+28.0134*XN2+
     230.0061*XNO+46.0055*XNO2+39.948*XAR+12.01115*XC)/XTC
```

```
      IF (J. GT. 0) GO TO 81
      WRITE(12, 120)RUN
      WRITE(12, 130)CO2D, COD, O2D, HCCD, NOD, NOXD
      WRITE(12, 131)CO2DD, CODD, O2DD, HCCDD, NODD, NOXDD
      WRITE(12, 132)CO2W, COW, O2W, HCCW, NOW, NOXW
      WRITE(12, 100)
      WRITE(12, 110)HTCR, EHCC, EHCR, CO2A, PSAT, PTRP, W, N2O2
      WRITE(12, 181)

   81 J=J+1
      IF (DISP1. EQ. 0) GO TO 83
      IF (DISPS. GT. 1) GO TO 811
      IF (J. GT. 1) GO TO 82
  811 WRITE(12, 165)
   82 WRITE(12, 166)CO2, CO, O2, HCC, NO, NOX, FCHC, FDA, MET, XTC, FACAL, FAM, ERROR

   83 IF (DISP2. EQ. 0) GO TO 85
      IF (DISPS. GT. 1) GO TO 831
      IF (J. GT. 1) GO TO 84
  831 WRITE(12, 160)
   84 GO TO (841, 841, 842, 841, 841), METH
  841 WRITE(12, 170)MET, XTC, K, KWDD, KWD, PHIM, MWEXH, PHICAL, FACAL, FAM, ERROR
      GO TO 85
  842 WRITE(12, 170)MET, XTC, Z, KWDD, KWD, PHIM, MWEXH, PHICAL, FACAL, FAM, ERROR

   85 IF (DISP3. EQ. 0) GO TO 87
      IF (DISPS. GT 1) GO TO 851
      IF (J. GT. 1) GO TO 86
  851 WRITE(12, 140)
   86 WRITE(12, 150)XCO2, XCO, XHC, XO2, XH2O, XH2, XN2, XNO, XNO2, XAR, XC

   87 IF (DISP4. EQ. 0) GO TO 89
      IF (DISPS GT 1) GO TO 871
      IF (J. GT. 1) GO TO 88
  871 WRITE(12, 163)
   88 WRITE(12, 164)N2O2, CO2A, W, HTCR, EHCC, EHCR, XGW, K, MET, KWD, FACAL,
     1FAM, ERROR

   89 IF (DISPS. EQ. 1) GO TO 891
      WRITE(12, 181)
  891 IF (IMETH. EQ. 0) GO TO 0
      METH=METH+IMETH
      IF (METH LT METHMX) GO TO 27
      METH=METHR
      GO TO 0

   90 CONTINUE

   24 CONTINUE
      STOP
      END
```

Appendix C

Computer Subroutine CRT4

```
      SUBROUTINE CRT4
      INTEGER C
      DIMENSION A1(4,5),B(16,17),X(16)
      COMMON/INIT/B,X
      COMMON/INIT1/A1
      DO 1 I=1,16
      DO 1 J=1,17
      B(I,J)=0
  1   CONTINUE
      DO 2 I=1,16
      X(I)=0
  2   CONTINUE
      DO 3 I=1,4
      B(I,1)=A1(I,1)
  3   CONTINUE
      DO 4 J=2,5
      B(1,J)=A1(1,J)/A1(1,1)
  4   CONTINUE
      DO 8 C=2,4
      J=C
      DO 6 I=J,4
      SUM=0
      J1=J-1
      DO 5 K=1,J1
      SUM=SUM+B(I,K)*B(K,J)
  5   CONTINUE
      B(I,J)=A1(I,J)-SUM
  6   CONTINUE
      I=J
      I1=I+1
      DO 8 J=I1,5
      SUM=0
      J1=J-1
      DO 7 K=1,J1
      SUM=SUM+B(I,K)*B(K,J)
  7   CONTINUE
      B(I,J)=(A1(I,J)-SUM)/B(I,I)
  8   CONTINUE
      X(4)=B(4,5)
      DO 10 L=2,4
      I=4+1-L
      SUM=0
      I1=I+1
      DO 9 K=I1,4
      SUM=SUM+B(I,K)*X(K)
  9   CONTINUE
      X(I)=B(I,5)--SUM
 10   CONTINUE
      RETURN
      END
```

Appendix D

Computer Subroutine CRT12

```
      SUBROUTINE CRT12
      INTEGER C
      DIMENSION A4(12, 13), B(16, 17), X(16)
      COMMON/INIT/B, X
      COMMON/INIT4/A4
      DO 1 I=1, 16
      DO 1 J=1, 17
      B(I, J)=0
 1    CONTINUE
      DO 2 I=1, 16
      X(I)=0
 2    CONTINUE
      DO 3 I=1, 12
      B(I, 1)=A4(I, 1)
 3    CONTINUE
      DO 4 J=2, 13
      B(1, J)=A4(1, J)/A4(1, 1)
 4    CONTINUE
      DO 8 C=2, 12
      J=C
      DO 6 I=J, 12
      SUM=0
      J1=J-1
      DO 5 K=1, J1
      SUM=SUM+B(I, K)*B(K, J)
 5    CONTINUE
      B(I, J)=A4(I, J)-SUM
 6    CONTINUE
      I=J
      I1=I+1
      DO 8 J=I1, 13
      SUM=0
      J1=J-1
      DO 7 K=1, J1
      SUM=SUM+B(I, K)*B(K, J)
 7    CONTINUE
      B(I, J)=(A4(I, J)-SUM)/B(I, I)
 8    CONTINUE
      X(12)=B(12, 13)
      DO 10 L=2, 12
      I=12+1-L
      SUM=0
      I1=I+1
      DO 9 K=I1, 12
      SUM=SUM+B(I, K)*X(K)
 9    CONTINUE
      X(I)=B(I, 13)-SUM
 10   CONTINUE
      RETURN
      END
```

Appendix E

Computer Subroutine CRT15

```
      SUBROUTINE CRT15
      INTEGER C
      DIMENSION A2(15, 16), B(16, 17), X(16)
      COMMON/INIT/B, X
      COMMON/INIT2/A2
      DO 1 I=1, 16
      DO 1 J=1, 17
      B(I, J)=0
    1 CONTINUE
      DO 2 I=1, 16
      X(I)=0
    2 CONTINUE
      DO 3 I=1, 15
      B(I, 1)=A2(I, 1)
    3 CONTINUE
      DO 4 J=2, 16
      B(1, J)=A2(1, J)/A2(1, 1)
    4 CONTINUE
      DO 8 C=2, 15
      J=C
      DO 6 I=J, 15
      SUM=0
      J1=J-1
      DO 5 K=1, J1
      SUM=SUM+B(I, K)*B(K, J)
    5 CONTINUE
      B(I, J)=A2(I, J)-SUM
    6 CONTINUE
      I=J
      I1=I+1
      DO 8 J=I1, 16
      SUM=0
      J1=J-1
      DO 7 K=1, J1
      SUM=SUM+B(I, K)*B(K, J)
    7 CONTINUE
      B(I, J)=(A2(I, J)-SUM)/B(I, I)
    8 CONTINUE
      X(15)=B(15, 16)
      DO 10 L=2, 15
      I=15+1-L
      SUM=0
      I1=I+1
      DO 9 K=I1, 15
      SUM=SUM+B(I, K)*X(K)
    9 CONTINUE
      X(I)=B(I, 16)-SUM
   10 CONTINUE
      RETURN
      END
```

Appendix F

Computer Subroutine CRT16

```
      SUBROUTINE CRT16
      INTEGER C
      DIMENSION A3(16,17),B(16,17),X(16)
      COMMON/INIT/B,X
      COMMON/INIT3/A3
      DO 1 I=1,16
      DO 1 J=1,17
      B(I,J)=0
    1 CONTINUE
      DO 2 I=1,16
      X(I)=0
      CONTINUE
      DO 3 I=1,16
      B(I,1)=A3(I,1)
    3 CONTINUE
      DO 4 J=2,17
      B(1,J)=A3(1,J)/A3(1,1)
    4 CONTINUE
      DO 8 C=2,16
      J=C
      DO 6 I=J,16
      SUM=0
      J1=J-1
      DO 5 K=1,J1
      SUM=SUM+B(I,K)*B(K,J)
    5 CONTINUE
      B(I,J)=A3(I,J)-SUM
    6 CONTINUE
      I=J
      I1=I+1
      DO 8 J=I1,17
      SUM=0
      J1=J-1
      DO 7 K=1,J1
      SUM=SUM+B(I,K)*B(K,J)
    7 CONTINUE
      B(I,J)=(A3(I,J)-SUM)/B(I,I)
    8 CONTINUE
      X(16)=B(16,17)
      DO 10 L=2,16
      I=16+1-L
      SUM=0
      I1=I+1
      DO 9 K=I1,16
      SUM=SUM+B(I,K)*X(K)
    9 CONTINUE
      X(I)=B(I,17)-SUM
   10 CONTINUE
      RETURN
      END
```