APPENDIX A

REVIEW OF MEASUREMENT AND TESTING PROBLEMS*

Avco Lycoming
Williamsport, Pennsylvania

PROBLEMS EXPERIENCED

I. Instrumentation - Good instrumentation is required to obtain reliable and repeatable baseline data. Problems have been encountered in developing such a total system.

A. Accurate airflow measurement at all modes is essential. Leanout curve trends have substantial dependence on this quantity.

B. Precise fuel flow measurement is required to maintain good fuel/air ratio agreements. The small flows typical of the idle/taxi modes demand extreme accuracy.

C. The instrumentation used for pollutant measurement has proven to be susceptible to frequent malfunctions and has required certain modifications.

1. Changes to console pumps, filters, and gas sample path have been made in an attempt to comply with the 2 second response time.
2. Modifications to the NO/NO_x analyzer have been recommended to eliminate possible water condensation in the reaction chamber.
3. The instrument pump in the FID was replaced with a larger unit to improve response time.
4. An oxygen analyzer has been added to the sample analysis instrumentation to permit computation of the carbon balance. There is no requirement or specification for this instrument by the EPA, Part 87.
5. Frequent instrument and component failures, some requiring lengthy trouble shooting and repair periods have been encountered throughout the test program. A partial list of the failures follows:

---
*Material distributed but not presented at the Symposium.

Instrument	Problem
HC FID	Pressure regulator failed
HC FID	Pressure gage failed
HC FID	Thermistor failed
HC FID	Heater failed
HC FID	Meter readout miswired
NO/NO_x chem.	Thermistor switch failed, resulting in heater failure
NO/NO_x chem.	Photomultiplier tube cracked
NO/NO_x chem.	Meter readout failed
CO	Detector failed
Heated sample line	Thermistor failed

6. During low power operation (idle/taxi) there is considerable fluctuation in indicated pollutant concentrations, as recorded by the plotter. No determination has yet been made as to whether this variation is inherent in the instrumentation or reflects pulses in the exhaust sample. At present Avco Lycoming approximates the mean of the recorded plotter output as the measured pollutant concentration. Of course, each signal could be electrically dampened or averaged; however, some determination must be made to evaluate the true average and isolate the cause of the fluctuations.

II. Span Gases - Span gas quality has a significant effect on emissions test results.

A. The rejection rate of incoming span gases based on a ±2 percent tolerance is approximately 15 percent.

B. Until sufficient test experience was accumulated, it was often difficult to identify span gas discrepancies and divorce them completely from instrumentation problems.

C. The Scott Reference Service is performed only four times a year. Such variables as span gas replacement and instrumentation changes must be considered. In addition, this service publishes an average value from the reported results of the participants. No allowance is made for an abnormal pattern in results for a given test period. The Scott Service provides an indication of major span gas discrepancies and should be used in that manner.

D. NAFEC has established its own cross reference service. Sample periods have been increased to one a month; however, this service has been limited to only four sample periods. In addition, the baseline engine test program was completed prior to receipt of the first sample. It will be extremely difficult to use these results to improve correlation of past testing.

III. Engine Condition - It has been shown that the mechanical condition of the test engine can affect the test results substantially.

A. Prolonged low power operation in the idle/taxi modes without interceding extensive higher power operation is not considered to be normal of in-service engine operating conditions.

1. Such extended operation at idle/taxi results in fouled spark plugs and glazed cylinder barrels.

2. If the barrel glazing condition is severe, oil will move past the rings into the combustion chamber, resulting in oil fouled plugs or plugged fuel nozzles.

3. An engine in this condition may exhibit high oil consumption, moderate to extreme roughness or a loss of ignition in one or more cylinders.

B. The engine condition should be closely monitored for any possible mechanical malfunctions throughout all modes of operation.

C. Emissions data taken on an engine experiencing mechanical difficulties cannot be used to predict baseline characteristics.

1. Emissions data reflecting extremely poor combustion characteristics for the idle/taxi modes is not representative of actual in-service engine operation.

2. Constant effort should be made to ensure that the test engine is maintained in satisfactory condition.

IV. Test Procedure - Test procedures have been shown to have considerable effect on emissions test results.

A. The required test procedures as specified by the EPA, Part 87, are incomplete and do not promote the adoption of one unified test procedure by all test facilities. Additional description on the following should be provided:

1. An acceptable method of performing the precycle warmup should be noted.

2. Specific description of the required exhaust collection system should be made. There is no system representative of all aircraft models in the general aviation fleet.

3. The sample transport and response time should be changed to a time representative of the test system and state-of-the-art instrumentation.

4. An instrument specification for the oxygen analyzer should be included if it is to be an optional piece of equipment.

5. If the cycle is to be run consecutively with no intervening operating points, the allowable length of time for operation at the initial idle/taxi modes should be specified to prevent possible deterioration in engine condition.

6. The specified cyclic power settings are at best unrepresentative of typical in-service engine operation. The percent power for the climb mode should be specified, not 75 to 100 percent.

7. There is no specification regarding standard inlet conditions at the entrance to the injector or carburetor or for cooling air supplied to the engine.

8. Some minimum requirement should be noted for the exhaust gas temperature of the sample at the probe inlet to prevent loss of hydrocarbon sample.

B. If the EPA is unable or unwilling to make these specifications, industry and other facilities involved with this testing should formulate and approve a well-defined procedure.

C. Avco Lycoming has experienced problems with air leakages in both the induction and exhaust systems.

1. Since the induction air system is pressurized above ambient pressure, leakages between the air flow measuring system and engine result in the observed air flow readings being higher than the quantity of flow being used by the engine.

2. Cracks forming in the exhaust system usually permit air leakage into the exhaust sample. The resultant pollutant concentrations show signs of dilution or higher than normal oxygen values.

3. Avco Lycoming has found that the data affected by these system discrepancies can be minimized by careful attention to quantities and trends of the fuel/air ratio agreement (utilizing the Spindt Method for carbon balance). However, this requires that all data be reduced daily and reviewed completely.

D. The total emissions data system is fairly complex and Avco Lycoming has experienced substantial "down" time for system maintenance and repair.

V. Calculation Procedure - The required calculation procedure, as specified by the EPA, Part 87, for reducing raw emissions data leaves several intermediate steps to "good engineering practice."

A. It is possible that some differences in reported emissions values between test facilities can be attributed to differences in calculation procedures. A well-defined procedure for determining the following variables should be specified by the EPA:

1. Some method for determining the correction factor for ambient and combustion formed water vapor should be specified.

2. The calculation procedure for the exhaust molecular weight should be defined.

3. Acceptable methods to perform the required carbon balance should be specified. The 5 percent agreement, as specified, is considered excessively intolerant when dealing with the low air and fuel flows of the idle/taxi modes.

B. Again, if the EPA cannot or will not make well-defined requirements in these areas, industry together with other facilities involved with the actual testing should specify acceptable procedures.

C. Correction factors for the effect that nonstandard conditions have on cyclic emissions totals should be developed between facilities and approved.

1. Avco Lycoming has developed in-house correction factors for the effect of temperature and variations in power output on emissions when reduced to a pound/mode basis.

2. However, correction factors for the effect that humidity or temperature variations have on pollutant formation (ppm or percent by volume) are needed.

RECOMMENDATIONS

I. Engine Test Procedures

A. The engine must be maintained in good condition for the entire test program to ensure that representative data is obtained.

1. A performance calibration should be made to ensure that the engine is within production limits and typical of that particular model. The calibration should consist of the following types of runs: full throttle performance, mixture dis-

tribution at rated speed, variable manifold pressure at rated speed, fuel metering response with varying propeller load, oil consumption. Additional testing may be included, if necessary.

2. Daily inspections of the engine and sampling system should be made to inspect for possible discrepancies. The inspection procedure currently used by Avco Lycoming is described in attachment I.

3. During operation, frequent magneto checks should be made to ensure that the ignition system is functioning properly.

4. Cylinder head temperatures should be monitored closely for signs of engine problems. For idle and taxi modes, a comparatively low head temperature could be indicative of ignition or fuel nozzle problems. Comparing cylinder head temperature trends for the takeoff, climb, and approach mode leanout runs can also be used in the same manner.

5. The engine must be constantly monitored for abnormally rough or uneven operation, particularly in the idle/taxi modes. Prolonged running at low power conditions causes deterioration in engine condition such as fouled spark plugs and glazed cylinder barrels which are not representative of an engine in good condition.

    a. A possible indicator of glazed cylinder barrels is higher than normal engine oil consumption.

    b. Frequent magneto checks will show a high rpm drop between magnetos or highly uneven cylinder head temperatures when on single ignition as indicative of possible fouled spark plugs.

    c. Corrective actions are prolonged periods of operation at high power conditions. Badly fouled spark plugs may require removal and cleaning.

    d. A period (10-20 min) of continuous operation at takeoff power should precede a baseline run to improve spark plug and cylinder barrel conditions. Avco Lycoming has found that this procedure tends to minimize data scatter in the idle/taxi modes for the baseline cycle.

    e. Once the baseline cycle has been initiated, the modes must be run in sequence with no "clearing" between modes.

f. The only time a brief period (2-5 sec) of engine clearing is permitted between consecutive idle or taxi runs is during a leanout test when engine deterioration is suspected due to prolonged low power operation. The engine should be briefly cleared after each run.

B. Two types of tests are currently employed to determine the emissions characteristics of an engine model:

1. The baseline cycle consists of a seven-mode test program run consecutively with stabilized engine conditions at each mode. The following are the engine speeds and power settings for each mode :

Mode	Engine speed	Power, percent
Idle	600	--
Taxi	1200	--
Takeoff	Rated	Full throttle
Climb	90% rated	80
Approach	87% rated	40
Taxi	1200	--
Idle	600	--

2. The leanout run shows the effects of mixture variations on emissions output and vital engine parameters for each mode. The results of the leanout run when plotted on a pounds/mode or percent pollutant concentration versus fuel/air ratio basis can be used to identify emissions trends, formulate possible temperature or humidity correction factors or construct improved or optimum baseline cycles based on leaner fuel schedules.

II. Emissions Instrumentation

A. It is required by the EPA, in Part 87, that the following exhaust emissions concentrations be measured:

CO	(Carbon monoxide)
CO_2	(Carbon dioxide)
NO/NO_x	(Oxides of nitrogen)
HC	(Hydrocarbons)

In addition to the above quantities, measurement of the O_2 concentration in the exhaust sample is necessary to complete the carbon balance calculation procedure (Spindt Method) currently in use.

1. Avco Lycoming has experienced several instrumentation difficulties since the initiation of testing.

   a. The instrumentation employed is basically sensitive laboratory test equipment. Usage for extended periods of time results in the need for frequent adjustment or in equipment malfunctions.

   b. Careful daily monitoring of instrument response characteristics provides aid in determining the onset of instrumentation difficulties.

2. Avco Lycoming essentially follows the procedures outlined in the EPA, in Part 87; however, revisions are necessary to update and improve the required test procedures.

   a. Revisions for improving and updating instrument calibration procedures and specifications are necessary.

   b. It has been stated by the EPA that changes will be made to the 2 second sample response time. Such a revision is necessary and should also include a well defined procedure for determining this response time.

B. The exhaust collector and sample probe should be designed and fabricated in accordance with the requirements by the EPA in Part 87.

1. The exhaust system should be made of a suitable material and designed to permit no exhaust gas dilution but minimize engine power loss. Carefully fitted slip joints are permitted but may require additional sealing to guard against dilution.

2. The sample probe is fabricated from 1/4 inch diameter stainless steel tube with 5 inlet holes approximately 1/16 inch diameter located evenly across the tailpipe. The sample probe inlet holes are positioned into the exhaust flow, although testing has shown no difference in measured concentrations for other rotated positions.

3. The sample probe should be located far enough downstream to allow for good mixing in the tailpipe. However, the EPA in Part 87 specifies that the sample path to and through the Hydrocarbon Analyzer must be maintained at 302° F (150° C) to prevent the loss of heavy hydrocarbons in the sample line. Therefore, the minimum allowable EGT at the inlet of the sample path is 302° F. Avco Lycoming has noted that failure to maintain sufficient exhaust gas temperature at the sample probe inlet results in similar losses. In addition, low EGT's are often indicative of exhaust sample dilution.

III. Span Gases

A. Maintaining a set of good quality working span gases is important in obtaining accurate and repeatable emissions data.

1. Comparative services such as the Scott Reference Service and the NAFEC Cross Reference Service can be used as indicators of possible span gas discrepancies.

a. Due to the 3 month period between samples with the Scott Service other factors such as changes in instruments and depletion and replacement of span gases must be considered.

b. The Scott Service uses the average of the reported values as a basis for comparison. This average could be influenced in a specified test period by an abnormal reporting pattern from the participants. It is invalid to use this average as the absolute value of the sample gas in an attempt to revise span gas values.

c. A review of the Scott Service results between facilities shows no definite relative trends. It is difficult to justify the use of either service to formulate correlation correction factors either for past or present testing.

2. Avco Lycoming has established an in-house quality control procedure for testing working span gas accuracy. A set of master grade span gases have been purchased to be used as comparative standards. Periodically, all in-house working span gases will be checked against two or more of the master standards. At present, details as to frequency of testing, acceptable tolerances, etc., are being formulated.

IV. Computational Procedure

A. The basic computational procedure employed by Avco Lycoming is as specified by the EPA in Part 87, Federal Register. Figure A-1 shows a flow diagram summarizing the data reduction process. Shown in attachment II is a complete detailed description of the procedure currently used.

1. The EPA, in Part 87, does not require that the inlet air pressure, temperature, or humidity be controlled to a specified range. Differences in mass of induction air flow between varying ambient conditions can be substantial. As the air flow quantity is involved directly in the calculation for pollutant pound/mode, some effort should be made to

correct for varying ambient conditions. At present, Avco Lycoming is investigating possible correction factors which will improve data agreement.

2. In addition to affecting air flow mass, temperature and humidity differences can affect pollutant concentration output. Avco Lycoming has made limited effort at defining correction factors for these effects. Other facilities such as NASA Lewis, which have the ability to fully control ambient test conditions, should provide better controlled data trends for a complete analysis.

B. Although the basic calculation procedure for reduction of raw emissions data is specified by the EPA in Part 87, some of the intermediate steps are not defined adequately.

1. The method for determining exhaust molecular weight should be specified.

2. The procedure for calculating water correction factors for both combustion formed water and ambient water vapor should be outlined.

3. A method for performing the required carbon balance should be included.

V. Data Analysis Criteria

A. In emissions testing, the review and analysis of data trends and quality becomes a complex procedure because of the large number of values recorded as input parameters.

1. Some method of carbon balance must be used to identify possible data discrepancies. At present the Spindt Method is used by all facilities involved in the piston aircraft emissions program.

a. The Spindt Method provides a comparative computational procedure for fuel/air ratio based on measured emissions concentrations.

b. The fuel/air ratio agreement is obtained by comparing the measured and calculated fuel/air ratios. The EPA, in Part 87, requires that this agreement be within ±5 percent for all modes. Although this requirement is realistic for the higher power and taxi modes, compliance for the idle mode is difficult where low air and fuel flow values as well as small changes in engine speed necessitates extremely precise measurements.

2. Avco Lycoming has found that emissions data with considerable scatter in fuel/air ratio agreements usually produces the same scatter when plotted on a pound/mode versus fuel/air ratio basis. In addition, the best data correlations between facilities, or even in-house testing, are obtained when the fuel/air ratio agreements are well within the tolerance.

3. Experience has shown that the fuel/air ratio agreement between measured and calculated fuel/air ratios is possibly the most valuable indicator in recognizing and locating discrepancies in the emissions system. Recognizing these trends or variations in trends in the fuel/air ratio agreement is most important.

ATTACHMENT I

EXPERIMENTAL BULLETIN NO. 129
Cl. 11
April 22, 1975

CHECK LIST TO PERFORM BEFORE BEGINNING EMISSIONS TESTING - (Daily)

1. Sample System:

   Please remove heated sample line from probe. Remove covering from teflon section of line and inspect for any heat damage. If teflon has become discolored, replace section. Check all fittings for tightness. Cap off end of sample line and turn on console pump to leak check.

   Remove stainless steel probe and inspect for cracks. Check exhaust system from exhaust ports to probe location for cracks. Reconnect all parts of line and reinstall probe.

2. Induction Air:

   Please inspect induction air hose for leaks. Check clamp at airbox for tightness.

3. Magneto Timing Device (if installed):

   Please check connecting arm for tightness. Inspect around magneto base for oil leakage or gasket slippage. Tighten slightly if necessary. Check position indicator cable connector for tightness.

4. Torquemeter:

   Please check for oil leakage around any portion of the torquemeter, adapter plates or propeller. Inspect restraining wires to torquemeter to make sure they are in good condition.

R. Moffett

DATA REDUCTION TECHNIQUES EMPLOYED BY AVCO LYCOMING

The following data reduction techniques are currently employed by Avco Lycoming:

1. Water Correction Factors - to account for the water vapor condensed from the analyzed exhaust samples

2. Exhaust Molecular Weight - to convert the volumetric percentages read from the exhaust analyzers to a gravimetric percentage

3. Exhaust Volume Technique - to calculate the total mass exhausted from the engine based on the mass percentage of the individual pollutants and the total gas flow through the engine

4. Carbon Balance - to verify that those pollutants detected by the exhaust gas analyzers are indicative of the fuel-air mixture supplied to the engine

WATER VAPOR CORRECTION

Water vapor in the exhaust sample originates from two sources: (1) combustion formed water vapor, (2) water vapor contained in ambient induction air. Avco Lycoming has developed independent correction factors for each source.

Correction Factor for Combustion Formed Water Vapor

Considering a general equation for the combustion process at equilibrium in the form

$$a_o C_c H_h + a_1[O_2 + 3.76\ N_2] \rightarrow a_2 CO_2 + a_3 CO + a_4 H_2 O + a_5 H_{1.85} C + a_6 H_2 \qquad (1)$$

where

$$\sum_{2}^{n} a = 1$$

a carbon balance yields

$$a_o = \frac{a_2 + a_3 + a_5}{c} \tag{2}$$

and a hydrogen balance yields

$$a_o = \frac{2a_4 + 1.85a_5 + 2a_6}{h} \tag{3}$$

Combining (2) and (3) and solving for a_4 gives

$$\frac{a_2 + a_3 + a_5}{c} = \frac{2a_4 + 1.85a_5 + 2a_6}{h}; \qquad \frac{h}{c} = \alpha$$

$$\alpha(a_2 + a_3 + a_5) = 2a_4 + 1.85a_5 + 2a_6$$

At this point the relationship $0.51\ a_3 = a_6$ or $0.51\ CO = H_2$:

reference: "Relation of Exhaust Gas Composition to A/F Ratio," B. A. D'Alleva and W. G. Lovell, SAE Journal (Trans.), Vol. 38, No. 3

Therefore

$$a_4 = \frac{\alpha}{2}\ a_2 + a_3\left(\frac{\alpha}{2} - 0.51\right) + a_5\left(\frac{\alpha}{2} - \frac{1.85}{2}\right) \tag{4}$$

At this point because equation (4) is still in terms of mol fractions we can substitute the chemical terms for a_2, a_3 . . . to simplify the equation. Of course, the CO and CO_2 quantities are measured dry and represent such in the equation, so they must be converted to wet concentration $(1 - H_2O)$.

$$H_2O = \frac{\alpha}{2}\ (1 - H_2O)CO_2 + CO(1 - H_2O)\left(\frac{\alpha}{2} - 0.51\right) + \frac{HC}{10^4}\left(\frac{\alpha}{2} - \frac{1.85}{2}\right)$$

$$= (1 - H_2O)\left[\frac{\alpha}{2}\ CO_2 + \left(\frac{\alpha}{2} - 0.51\right)CO\right] + \frac{HC}{10^4}\left(\frac{\alpha}{2} - \frac{1.85}{2}\right)$$

$$= \left[\frac{\alpha}{2}\ CO_2 + \left(\frac{\alpha}{2} - 0.51\right)CO\right] - H_2O\left[\frac{\alpha}{2}\ CO_2 + \left(\frac{\alpha}{2} - 0.51\right)CO\right]$$

$$+ \frac{HC}{10^4}\left(\frac{\alpha}{2} - \frac{1.85}{2}\right) \tag{5}$$

$$H_2O = \frac{\left[\frac{\alpha}{2} CO_2 + \left(\frac{\alpha}{2} - 0.51\right)CO\right] + \frac{HC}{10^4}\left(\frac{\alpha}{2} - \frac{1.85}{2}\right)}{\left[1 + \frac{\alpha}{2} CO_2 + \left(\frac{\alpha}{2} - 0.51\right)CO\right]} \tag{6}$$

By definition

$$C_w = 1 - H_2O$$

Finally,

$$1 - \frac{\left[\frac{\alpha}{2} CO_2 + \left(\frac{\alpha}{2} - 0.51\right)CO\right] + \frac{(\alpha - 1.85)HC}{2\times10^4}}{\left[1 + \frac{\alpha}{2} CO_2 + \left(\frac{\alpha}{2} - 0.51\right)CO\right]} \tag{7}$$

equals the water correction factor C_w for that contribution arising from the combustion process.

Correction Factor Ambient Water Vapor Development

Previously it was assumed that the fuel was represented by a specific fuel molecule. However, this approach, while allowing calculation of the water contained in the air, fixed the definition too rigidly. With little or no difference in the final result a more general approach was adopted that is based on the assumption that the water contained in the intake mixture does not enter into any combustion reaction and simply passes directly through the engine. Expressing this in a word equation

$$(\text{Water in exhaust - lb/hr}) = (\text{Air flow into engine - lb/hr})(\%\ \text{humidity}) \tag{1}$$

Dividing each side of the equation by the total flow through the engine, air plus fuel, yields the percentage of water in the exhaust due to humidity.

In a final form the humidity correction becomes

$$\text{Fraction water} = \frac{(\text{Air flow})(\%\ \text{humidity})}{(\text{Air flow} + \text{Fuel flow})} = \frac{M_{air}\left(0.622\ \frac{\text{Vapor press.}}{\text{Patm - Vapor press.}}\right)}{(M_{air} + M_{fuel})} \tag{2}$$

or

$$\text{Water correction factor}]_{\text{Humidity}} = 1 - \text{Fraction water} \quad (3)$$

The total water correction factor, therefore becomes a multiplicative combination of the two individual contributions.

The exhaust molecular weight computation is based on "Procedure and Charts for Estimating Exhaust Gas Quantities and Compositions" - GMR 372, B. A. D'Alleva, May 15, 1960. Figure A-2 shows the variation of exhaust molecular weight with fuel/air ratio, as determined by this method.

Exhaust Volume Calculation Procedure

The method specified by the EPA for treating the emissions measurements is specified in the Federal Register, Part 87.99, Vol. 38, 7-17-73. As stated in this section, par. 3, "The engine exhaust volume shall be calculated in accordance with good engineering practice from actual air and fuel flow measurements . . ."

The exhaust volume can be equated as

$$V_e = \frac{W_a + W_f}{D}$$

where

W_a airflow, lb/hr

W_f fuel flow, lb/hr

D density of exhaust

The exhaust density can be expressed as

$$D = \frac{0.075\ E_m}{28.96}$$

where

0.075 density of air

28.96 molecular weight of air

E_m exhaust molecular weight

At this point it is necessary to provide the exhaust molecular weight. Figure A-2 shows the relationship between exhaust molecular weight and A/F ratio as derived according to "Procedure and Charts for

Estimating the Exhaust Gas Quantities and Compositions," GMR 372, by B. A. D'Alleva.

Substituting the value for E_m and working according to the calculation procedure in the Federal Register, the mass emission rate of any exhaust component is

$$\text{Pollutant} = \frac{(P)}{100} V_e P_p$$

where

(P) the pollutant concentration in percent

P_p the pollutant density at standard conditions and is specified in the Federal Register

This yields the emission rate in pounds/hr. To convert to lb/mode it is necessary to multiply by one of the corresponding mode times:

Idle	0.0167 hr
Taxi	.1833 hr
Takeoff	.005 hr
Climb	.083 hr
Approach	.100 hr
Taxi	.05 hr
Idle	.0167 hr

Summing the emissions for each mode for the three pollutants and dividing by the rated horsepower of the engine gives the desired end result in pollutant lb/hp-hr, which corresponds to the limits set by the EPA.

Carbon Balance

The intent of the carbon balance technique is to verify that those concentrations indicated by the exhaust analysis equipment are representative of the actual pollutant levels present. This is accomplished by calculating an operating fuel/air ratio ingested into the engine on the basis of the measured exhaust gas components. A measured fuel/air ratio obtained from actual air and fuel flows serves as the standard for comparison.

To predict the fuel/air ratio from the concentrations of the exhaust gas components the procedure of Spindt (SAE Paper 650507) was chosen. This method assumes that a fraction (F_b) of the fuel supplied to the engine is involved in a combustion process that proceeds to completion and the remaining fuel (F_u) passes through the engine essentially unchanged. That is to say, for the total mixture introduced into the engine,

$$F_u + F_b = 1$$

or

$$\frac{(HC)}{(CO) + (CO_2) + (HC)} + \frac{(CO) + (CO_2)}{(CO) + (CO_2) + (HC)} = 1$$

where the measured exhaust concentration of each specie is indicated by the parentheses.

In terms of CO, CO_2, O_2, and HC, the air/fuel ratio is expressed by

$$A/F = F_b\left[11.492\ F_c\left(\frac{1 + R/2 + Q}{1 + R}\right) + \left(\frac{120\ F_n}{3.5 + R}\right)\right]$$

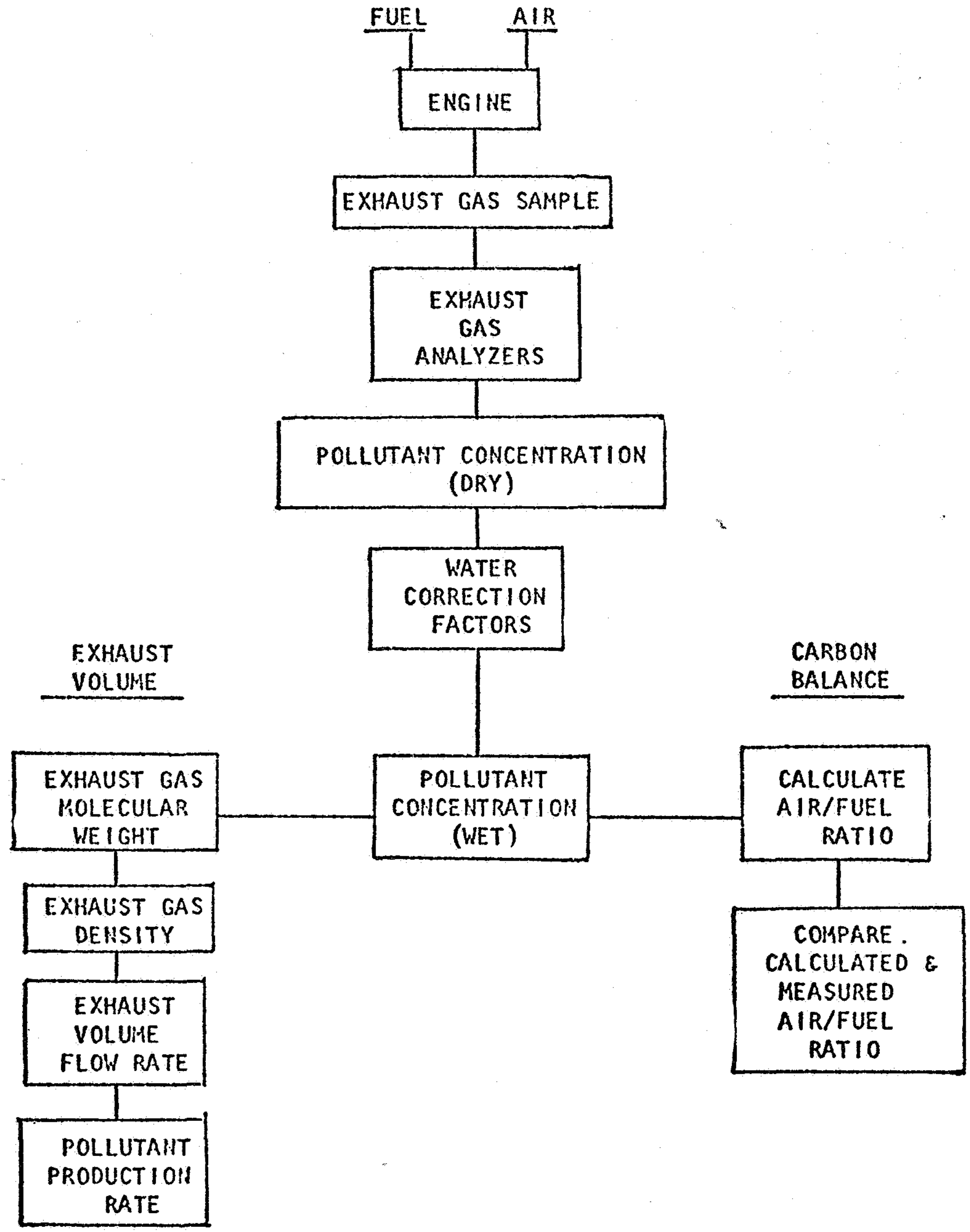
where

F_c fraction of carbon in fuel

F_n fraction of hydrogen in fuel

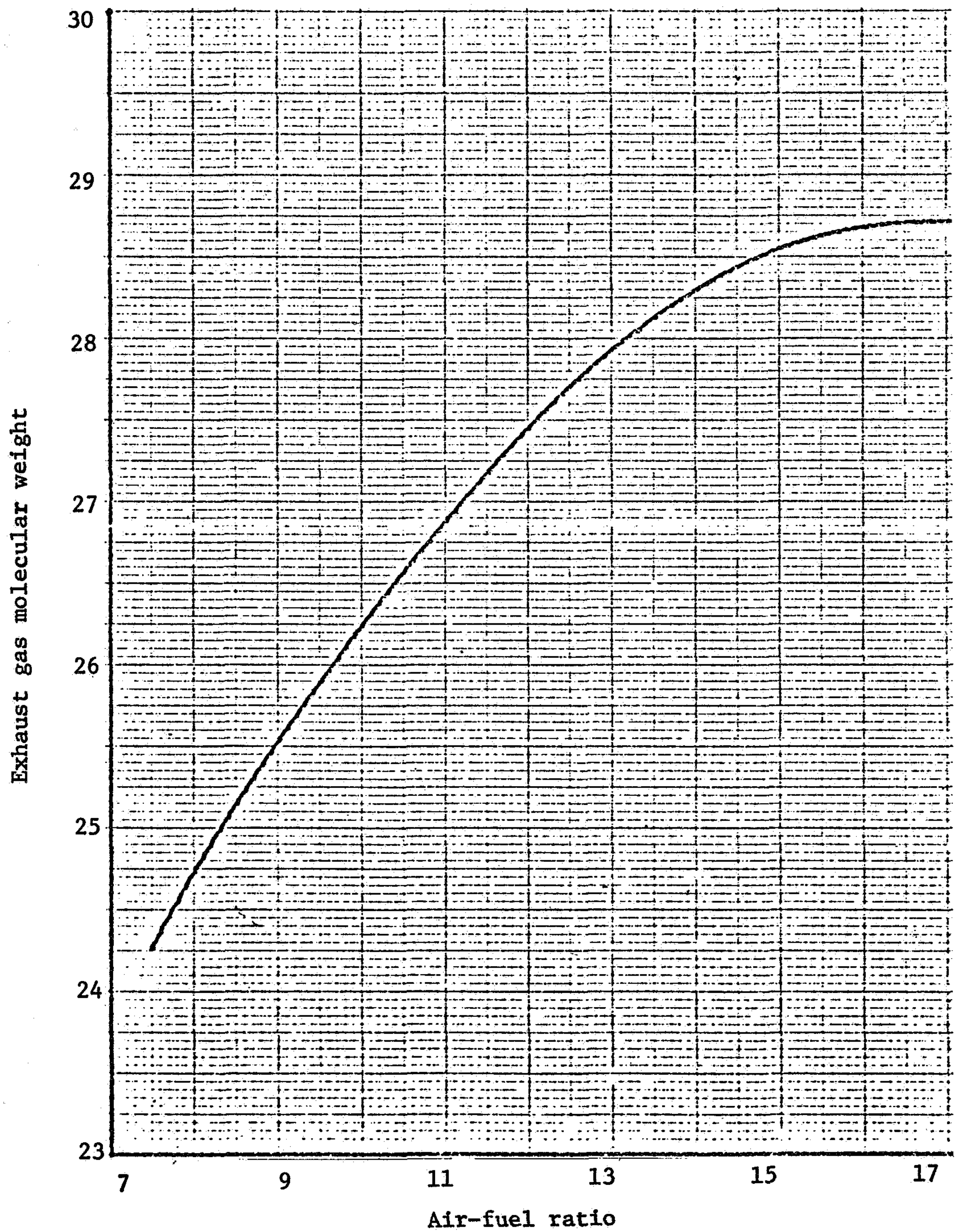
R $(CO)/(CO_2)$

Q $(O_2)/(CO_2)$



AVCO-LYCOMING
EXHAUST EMISSION DATA
REDUCTION SCHEMATIC

Figure A-1



AVCO-LYCOMING

EXHAUST MOLECULAR WEIGHT VERSUS AIR/FUEL RATIO

FROM GMR 372

Figure A-2