

A DETAILED PERFORMANCE COMPARISON OF DISTILLATE
FUELS IN THE TEXACO STRATIFIED CHARGE ENGINE

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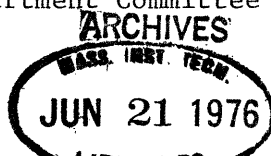
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Abstract

A stratified charge engine employing the Texaco Controlled Combustion System has been operated over a large range of load conditions on iso-octane, methanol, and a wide boiling point (100-600°F) residual fuel. Basic performance, emissions and combustion parameters were measured over a range of overall equivalence ratios from $\phi = 0.1 - 1.0$ at three engine speeds; 1500, 2000 and 2500 RPM. The basic performance and emissions data were found to vary little between iso-octane and residual fuels, and to compare very well with similar data collected on the same engine design at other research facilities. The engine operation on methanol was not entirely satisfactory due to an improper match between the specific fuel injection system used for these experiments and the design requirements imposed by the much lower heating value and higher stoichiometric fuel-air

mass ratio of methanol.

A direct, online data acquisition system, based on a Digital PDP 11/10 computer was developed to obtain accurate pressure-crankangle data for further combustion and thermodynamic studies. The acquisition program also computes a mean pressure - crankangle diagram and the statistics associated with cycle to cycle variation. The mean pressure - crankangle data is then integrated to compute indicated mean effective pressure. The opportunity to analyze pressure - crankangle data in this way substantially improves the accuracy and speed of data collection.

A simple thermodynamic model based on homogeneous charge engine combustion has been modified to compute the heat release and fuel fraction burnt from the pressure - crankangle data. The problems associated with calculation of these parameters in diesel or stratified charge engines are discussed. Recommendations are made for further development of the online data acquisition system and the thermodynamic model.

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I INTRODUCTION

A stratified charge engine is defined as a spark ignition, internal combustion engine with a non-uniform fuel air mixture in the combustion chamber. Stratified Charge engines have been recognized for good fuel economy potential, low emissions and the ability to burn a wide range of fuel types.^{(1)*} In this thesis, we analyse the performance of an engine based on the Texaco Controlled Combustion System (TCCS).

Several features specific to this design make the engine a strong candidate for small, low power applications. Load control can be achieved by changing the amount of fuel injected and inlet air throttling is unnecessary in most applications. As a result, the engine can be run at very lean overall equivalence ratios giving excellent fuel economy and low emissions. Fuel is injected late in the compression stroke just before the combustion process and is ignited with a spark discharge. The residence time at elevated temperatures is therefore shorter than the time for compression ignition and hence the engine does not display either octane or cetane requirements.

As illustrated schematically in Figure 1, the Texaco Controlled Combustion System uses an open combustion chamber with high air swirl, direct fuel injection and electronic ignition. Air swirl is generated by the inlet air flow, and amplified

*Numbers in parenthesis refer to the bibliography at the end of this paper.

during the compression stroke by constraining the vortex in the combustion chamber. The combustion chamber is essentially a cup with a cylindrical upper section and a toroidal bottom formed in the head of the piston. Fuel is injected with a Roosa Master Pencil Nozzle with a flat seat and a single hole orifice as shown in Figure 2. The positive ignition system uses a high energy multiple spark unit with controlled duration.⁽²⁾ The spark plug electrodes are carefully aligned to promote the formation of a stable flame front.

High pressure injection of fuel into the swirling air begins near the end of the compression stroke. Air swirl in the combustion chamber promotes mixing and controls the penetration and trajectory of the fuel spray in the cup. The combustible fuel-air mixture formed by turbulent mixing and air entrainment in the fuel jet is then ignited by the long duration spark discharge and burns downstream of the spark plug as shown in Figure 3.

Following B.C. Jain⁽³⁾ we divide the combustion process into three stages; a rapid combustion phase controlled by the injection rate and a slower "burn up" phase which is controlled by the rate on air entrainment and mixing of burning products and air downstream of the spark plug, and a heat transfer dominated phase which follows after mixing is complete. This sequence is illustrated on the diagram shown in Figure 4. During an isentropic compression or expansion of an ideal gas the value of PV^γ remains

constant. After a delay covering the jet transit time for the injector to the flame front, the value of PV^γ rises rapidly. This rapid combustion phase appears to be controlled by the injection rate. After the last fuel injected passes the spark plug, the rate of change of PV^γ is substantially slower and the rise is controlled by the rate of mixing of the plume of rich products with the surrounding air and residual gas. This phase ends when all mixing is complete or the exhaust valve opens. Any fall in the PV^γ curve prior to the exhaust valve opening can be attributed to heat losses.

This research project is a part of a larger program which includes work on a jet mixing model, a performance model and photographic studies with a rapid compression machine.⁽⁴⁾

The following areas of research are covered in this thesis;

- (1) The completion of the engine test setup and the development of all necessary instrumentation to record the variables of interest.
- (2) TCCS engine performance and emissions are presented for the three test fuels over a wide range of operating conditions. Differences in fuel characteristics are also presented.
- (3) The problems associated with heat release calculations in stratified charge and diesel engines

reviewed, with the further development of an existing thermodynamic model to predict heat release and mass fraction of fuel burnt outlined.

- (4) Log P vs Log V diagrams and plots summarizing the output of the thermodynamic model are presented for a matrix of comparable test data.
- (5) The development of computer programs to process raw data and accomplish online pressure data acquisition, along with listings of all computer programs are included as appendixes.

II TEST ENGINE AND INSTRUMENTATION

Single Cylinder Test Engine

The engine used in these experiments is located in the Sloan Automotive Laboratory at MIT, and is arranged as shown in Figure 5 . The single cylinder test engine is based on a CFR - 48 crankcase that has been modified to accept a cylinder sleeve assembly, head, piston, crankshaft and overhead cam and valve train assembly for the 3 7/8 inch bore by 3 7/8 inch stroke LIS - 183 TCCS geometry, as shown in Figure 6 . Engine specifications and dimensions are shown in Table 1. The engine is coupled to a dynamatic eddy current dynamometer equipped with a hydraulic scale, as shown in Figure 7 . The basic instrumentation is listed in Table 3 and whenever possible redundant measurements have been introduced to provide alternate data sources and to qualify experimental results.

The basic engine support facilities were constructed by Lazarewicz⁽⁵⁾ and follow standard practices as shown in Figures 8 through 11 . The engine cooling system is arranged to enable heat rejection measurements. A rotameter and throttling valve on the return line from the engine allows both flow regulation and measurement while holding system pressure above 5 psig, as shown in Figure 8 . Maximum water temperature at the engine cylinder outlet was held at $190 \pm 5^{\circ}\text{F}$. The lubrication

system shown in Figure 9 consists of two separate loops; a low pressure circulating loop for temperature control and a high pressure bearing feed and filter loop. The operating oil temperature and pressure were held at 165⁰F and 42 psig respectively. A pressure alarm incorporated in the filter system activates a siren and cuts off the fuel supply and ignition system when pressure falls below 20 psig. Inlet air flow is measured with an ASME square edge orifice with flange taps and water manometers as shown in Figure 10. Following recommendations made by Lazarewicz, the inlet and exhaust systems were rebuilt and the inlet settling tank and air heater were closely coupled to the engine with a short inlet pipe.

Injection and Ignition Systems:

Fuel system specifications appear in Table 3 and fuel flow is measured gravimetrically as shown in Figure 11. Transfer pump pressure is held at 25 psig. Fuel injector leakoff and the injector pump bleed are returned to the fuel reservoir mounted on a standard laboratory scale.

Ignition and injection timing, intensity and duration are monitored with a 565 Techtronix Oscilloscope. Ignition timing can be precisely set by a means of a vernier scale and adjustment arm. Injection timing is varied through the use of an American Bosch TMB - 12 Manual Timing mechanism. A pressure transducer

is mounted just ahead of the fuel injector in the high pressure supply line and the Needle Lift Indicator shown in Figure 12 has been developed to replace the standard fuel injector needle lift and cracking pressure adjustment assembly⁽⁵⁾. Both outputs are displayed on the oscilloscope cathode ray tube along with the cylinder pressure crankangle markers and BDC reference pulse as indicated in Figure 13. As presently designed, resolution of fuel injector timing is limited to 2 CA° by the time base necessary to include one entire revolution on the CRT display. The first peak in the pressure trace corresponds to the point of initial needle lift, however; as indicated by the needle lift trace, the injector does not open appreciably for about 2 CA° . Determination of injector cutoff and any secondary injection is only possible with the Needle Lift Indicator. Substantial signal processing problems occur with the linear displacement amplifier and a new design is recommended.

Emission Sampling System:

Engine emissions are measured using the Sloan Laboratory Exhaust Gas Analysis Cart (Table 3). The exhaust sample is removed from an engine exhaust tank consisting of several cylinder volumes and pulled through a heated teflon line and filter to the Gas Analysis Cart. Stainless steel pipe is used between the

engine and exhaust surge tank to reduce the potential for hydrocarbon reactions induced by "rust" and the elevated temperatures of the exhaust flow. An additional spun glass particle filter was installed in the sampling line when it was discovered that at high loads and equivalence ratios near $\phi = 1.0$, the gas analysis equipment was severely contaminated with carbon. This technique appears to have solved this immediate problem.

The development of a computer program to calculate basic engine performance and emissions from the recorded data is described in Appendix I with the complete program listing in Appendix III.

Pressure Volume Measurement:

Accurate combustion pressure and volume measurements are absolutely required for mathematical engine simulation, calculation of heat release rates, engine pumping losses and the compilation of statistics associated with cyclic variations and peak pressures. Acceptable pressure volume records can only be obtained when the entire monitoring system receives careful attention. First, high resolution signal recording equipment is required if the effort expended to obtain accurate pressure and volume measurements is to be worthwhile. Oscilloscopes were used in these experiments for qualitative analysis but they lack the accuracy required for quantitative resolution. The real time digital computer with analog to digital converters can provide the

resolution necessary; and for these experiments, an online digital data acquisition was developed for Sloan Laboratory PDP 11 Computer Facility. The analog to digital converter provides resolution to within 0.48 psi over a range of 0-1000 psia, well in excess of current engine pressure transducer performance as described in following paragraphs. The sampling intervals were 5 CA⁰. Appendix II provides details of the system hardware and the development of the software used for online computer sampling. Appendix III contains a listing of the pressure-crankangle data management program and the assembly language program that actually performs the data acquisition.

In these experiments the cylinder head geometry prevented the use of a large diaphragm, water cooled pressure transducer and a Kistler 609A piezoelectric pressure transducer was chosen. Considerable experimental art is required to obtain acceptable performance from available pressure measuring equipment, including this specific unit. For example, quartz piezoelectric transducers are high impedance devices and contamination of the electrical connectors can significantly degrade performance. All connections must be thoroughly cleaned with a freon base solvent and sealed with heat shrink tubing. Transducers are also subject to the thermal cycling that is fundamental to the combustion process in engines. In a chopped flame test by Jain and

Lazarewicz⁽⁵⁾, the 609A transducer showed an apparent 6 psi response when directly exposed to an acetylene flame at typical engine frequencies. This response was reduced with a coated diaphragm and a thin coating of silicone rubber was applied as recommended in the literature^(6, 7). The transducer was installed in a recessed adapter inserted through the water jacket of the cylinder head. The adapter cavity is designed to minimize attenuation and protect the transducer from engine temperature fluctuations. The engine coolant also serves to cool the transducer.

Careful preparation of the transducer is wasted if the cylinder volume is not known with similar accuracy. The cylinder volume is computed from engine dimensions and recorded crankangle data. Cylinder clearance volumes were determined by careful measurement of pertinent engine dimensions. The piston top dead center was located and the flywheel position pointer adjusted with a depth micrometer as recommended by Lancaster⁽⁷⁾. A crankshaft driven rotary pulse generator, supplying 720 pulses plus a marker every revolution was then aligned with the flywheel with an accuracy of approximately 1/4 degree. The alignment was tested by analyzing pressure crankangle diagrams and Log P - Log V plots of motoring runs as shown in Figures 14, 15 and 16. Lancaster provides a detailed explanation and interpretation of the plot orientations⁽⁷⁾.

A clamped disk balanced pressure indicator was also mounted through the engine water jacket to provide a technique for dynamic calibration for the cylinder pressure transducer. The balance pressure indicator is a pressure activated switch with a reference pressure applied to one side of a thin membrane disk and the cylinder pressure to the other. The balanced pressure indicator is connected to the oscilloscope display as shown in Figure 17. When the cylinder pressure rises above the reference pressure plus the disk contact pressure, the disk is deflected to ground the center electrode. The change in potential is converted by the cathode ray tube grid modulator to momentary changes in signal intensity on the oscilloscope display as shown in Figure 13. These pulses are then used to dynamically calibrate the signal from the piezoelectric transducer.

III BASIC PERFORMANCE AND EMISSIONS

The multifuel capability of the TCCS engine was investigated using methanol, iso-octane and a wide boiling point (100-600°F) fuel. Properties of these test fuels are summarized in Table 4. Performance and emissions data in Figures 18 through 39 represents engine operation over the range of fuel-air ratios and engine loads summarized in Table 5. The engine was naturally aspirated and exhausted to ambient pressure throughout the test series. All performance data was measured with injection timing set for maximum brake torque and ignition system timing set to commence 2 CA° prior to the start of injection. The injection duration exceeded the ignition duration of 20 CA° except at light load. The overall equivalence ratio was used as the abscissa in Figures 18 through 38. The equivalence ratio was determined using two techniques; a) the measured fuel and air flow and b) calculated from the exhaust gas composition using the method of Stivender⁽⁸⁾. Data was considered reliable when the difference between these two values was less than 0.025. A deviation greater than this was always traced to operator error, air leaks or faulty equipment. The engine was not operated at fuel air ratios above stoichiometric. Previous experience with this engine has shown that any performance gain above $\phi = 1.0$ are achieved with substantially

increased hydrocarbons, CO and degraded fuel economy⁽⁵⁾.

Engine Performance with Iso-Octane and Wide Boiling Point Fuel:

The indicated mean effective pressure (IMEP) versus equivalence ratio for iso-octane and the 100-600, wide boiling point fuel are shown in Figures 18 and 19. The maximum IMEP is not developed, with either fuel, in the range of equivalence ratios shown; rather, the effective upper limits for engine operation are determined by a "smoke limit" near $\phi = 1.0$. In addition, there is a distinct flattening of the power curve near stoichiometric conditions. The secondary dependence on RPM exhibited by the IMEP curves can be traced to several factors. The volumetric efficiency increases with speed in the range tested as shown in Figure 39. PV^γ plots also show a slight decrease in heat transfer with increasing speed during the heat transfer dominated phase of combustion. As will be discussed in the following chapter, the burning angle appears to decrease slightly with increasing RPM, and this would also serve to increase the IMEP. The data for iso-octane and 100-600 split differently with speed. Similar results have been observed by Texaco⁽⁹⁾. This difference cannot be satisfactorily explained with the basic data comparison presented in this thesis and additional study to resolve this potential conflict is recommended.

The indicated specific fuel consumption (ISFC) is shown for

iso-octane in Figure 20 and for 100-600 in Figure 21. The data sets are of similar character with a clear minimum at an equivalence ratio near $\phi = 0.3$ and a steep rise at leaner equivalence ratios. This rise in ISFC at lean fuel air ratios is accompanied by increased cyclic variations and incomplete combustion; and appears to be a characteristic of the fuel injection system used with this engine.

The indicated thermal efficiency (η_i) provides the best comparison of the actual combustion process since it properly accounts for the different heating values of the three fuels used in these experiments. The indicated thermal efficiency is equal to the reciprocal of the ISFC x lower heating value and the indicated thermal efficiency is equivalent for engine operation on both fuels, with a maximum value of approximately 50% reached near $\phi = 0.3$ as shown in Figures 22 and 23.

The volumetric efficiency (η_v) changes with load to reflect changes in the quantity, composition and state of the residual gas in the combustion chamber as shown in Figures 22 and 23. The effect of engine speed is shown in Figures 22, 23 and 39. The effect of load is shown in brackets on Figure 39.

The exhaust temperature data follows the same trends as described for the IMEP data as shown in Figures 24 and 25.

The friction mean effective pressure (FMEP) versus RPM

for the single cylinder test engine is shown in Figure 39. This data is representative and the actual FMEP showed little variation throughout the test series.

Emissions with Iso-Octane and Wide Boiling Point Fuel:

The TCCS concept is designed to burn the fuel immediately after injection in a fuel rich, mixing controlled plume in order to achieve multifuel capability and low emissions. In the course of these experiments, it was consistently observed that emissions, particularly hydrocarbon and carbon monoxide, are more sensitive to small variations in engine operating conditions than the basic performance data. Careful system timing is required to obtain satisfactory emissions levels and the convention adopted places the start of ignition immediately ahead of injection. However, if timing is adjusted so that fuel injection precedes ignition higher IMEP levels are achieved with a corresponding significant increase in hydrocarbon emissions at equivalence ratios of $\phi > 0.6$. This system sensitivity is thought to be the source for data scatter at high load conditions and all lines were drawn using a least square regression analysis technique.

The increased cyclic variations and degraded emissions observed at very low load test conditions are thought to be caused by an injection - ignition system phenomena. Two

potential mechanisms for cyclic variations are advanced. High speed movies of TCCS combustion in a Rapid Compression Machine show that the ignition arc discharge time is short compared to the arc cycle time⁽¹⁰⁾. This ignition characteristic suggests that the initial fuel jet may pass the spark plug in the interval between ignition pulses and a stable flame front may not be formed in the leading edge of the fuel jet. This mechanism introduces the possibility of cycle variation in the initial stages of combustion. At light load conditions the injection duration is less than the ignition duration, and with small injection quantities, the unburnt fuel vapor that passes the electrodes before a stable flame front is formed can rapidly mix to a fuel air ratio below the limit of combustion. This mechanism may partially account for the degradation of hydrocarbon emissions at low load.

A second possible mechanism is traced to fuel injector characteristics. As indicated in Figure 13, needle lift is not always crisp and there is often a 2 CA^0 period at the start of injection when the needle opens only a small amount. This starting transient may have substantially influenced the initial stages of fuel jet formation. As shown by Jain, a low momentum jet would be swept outside of the electrode radius by air swirl. The percentage of fuel vapor missing the plug electrodes would increase for light load conditions with the

smaller fuel quantities required. As in the previous case, this phenomenon introduces a mechanism for cycle variation and hydrocarbon and CO formation in the combustion chamber.

Carbon monoxide emissions are shown in Figure 26 for iso-octane and in Figure 27 for 100-600. The lowest CO levels are obtained at an equivalence ratio near $\phi = 0.45$. The CO levels observed with iso-octane are approximately 50% lower than observed with 100-600 at a given equivalence ratio. The mean minimum value observed with iso-octane 4 gr/ihp-hr or 3.5 gr/ihp-hr less than that observed with 100-600.

The hydrocarbon emissions show a sharp increase at equivalence ratios less than $\phi = 0.3$ for both fuels, as seen in Figures 28 and 29. This sharp rise is accompanied by increased cyclic variations which are attributed to the injection and ignition dynamic effects discussed previously. A small rise in HC emissions is also observed near stoichiometric equivalence ratios.

Nitric oxide emissions are shown in Figures 30 and 31. The trends indicated by the data have the same characteristic shape as demonstrated in homogeneous charge spark ignition engines; however, the peak occurs near an overall equivalence ratio of $\phi = 0.6$ whereas in a homogeneous charge engine the measured levels are generally higher and the maximum level occurs near stoichiometric fuel-air ratios.

Methanol Performance and Emissions:

Methanol was chosen as the third test fuel because it represented a severe test of TCCS multifuel capability. The fuel properties of methanol are significantly different from iso-octane or the wide boiling point fuel. Methanol has a much lower specific heating value and a higher stoichiometric air-fuel ratio and thus requires injection quantities nearly twice as large to achieve the same equivalence ratio. A Bosch injection system was used in these tests and the pump and nozzle geometry were selected for the reference fuels. No attempt was made to modify the pump or nozzle for the methanol experiments. As a result, the fuel system was operated off design.

The performance and emissions data for methanol are presented in Figures 32 through 38. Since the fuel system was not optimized for this fuel, wide scatter in emissions data was observed. The basic performance plots in Figures 32 through 35 show the trends to be expected with a properly matched fuel injection system. Figure 32 showing IMEP data exhibits no sensitivity to RPM; however, "misfire" increased with higher RPM at high load conditions. The indicated specific fuel consumption, volumetric efficiency, and thermal efficiency data, as shown in Figures 33 and 34 has trends very similar to the

corresponding trends observed with iso-octane and 100-600 fuel. The indicated thermal efficiency (η_i) is almost identical to Figures 22 and 23; the maximum value of approximately 50% occurs at an equivalence ratio near $\phi = 0.3$. This demonstrates that the Texaco controlled combustion process is compatible with alcohol fuels; however, fuel system modifications are necessary to properly match the engine with this fuel type.

Comparison of M.I.T. and Texaco Data

The single cylinder engine emissions and performance data compare favorably with the TCCS engine data observed at the Texaco Engine Development Laboratory⁽⁹⁾. The maximum IMEP observed at MIT with 100-600 fuel exceeded the values observed at Texaco by nearly 5% at a given equivalence ratio. The two engines exhibited identical values of volumetric efficiency at each given operating point. Comparative plots by Lazarewicz showed good agreement with all emissions data except hydrocarbon emissions⁽⁵⁾. In these experiments, the level of hydrocarbon emissions observed was considerably reduced when compared to values obtained by Lazarewicz; however, the level is still higher than observed at Texaco. This difference in HC levels can be explained by the different sampling techniques used at the two facilities. The Texaco data was acquired in bag samples before analysis, while at the Sloan Laboratory a heated teflon line is used to sample directly from the exhaust tank. The heated

sampling line used at MIT eliminates the potential for condensation of hydrocarbons, and in general, higher hydro carbon levels are measured in experiments with a heated sampling line.

IV ANALYSIS OF PRESSURE VOLUME DATA

Accurate records of cylinder pressure-volume data are an important tool for evaluating performance. The indicated mean effective pressure and pumping mean effective pressure can be computed by integrating the average pressure-volume diagram. In addition, logarithmic plots of P, V data provide estimates of the combustion delay time, the duration of effective heat release, and the ratio of specific heats, γ , during the isentropic compression and expansion phases. Finally, pressure-volume data is required as an input for the thermodynamic models used to compute heat release and fuel burning rates.

Logarithmic Pressure Volume Diagrams:

A matrix of comparable test data for engine operation on iso-octane and 100-600 is presented in Table 6 and logarithmic P-V diagrams are shown in Figures 40 through 57. When pressure-volume data is plotted on a logarithmic diagram, the isentropic portions of the compression and expansion process appear as straight lines. The slope of the linear segments is equal to $(-1) \cdot \gamma$, where γ is the ratio of specific heats. The beginning and end of combustion are marked by a departure from and return to the straight isentropic compression and expansion lines; since the effect of combustion is equivalent to heat being added

with a consequent change in γ . These points are indicated in Table 6. The apparent burning time for the iso-octane and 100-600 fuels is nearly the same and decreases with increasing RPM. The apparent average burning time is 5.2 ms at 1500 RPM, 3.5 ms at 2000 RPM and 2.7 ms at 2500 RPM. Decreases in engine load only slightly decrease the time required for burning.

The combustion delay time can be determined if the start of injection is known. The injection is tabulated in Table 6 and indicated in each figure. In previous work, this delay has been attributed to the required jet transit time of the fuel from the injector to the stable flame front established at the spark plug electrodes⁽³⁾. However, as shown in Table 6 the fuel used also influences the delay time. This indicates droplet evaporation rates may also influence the combustion process. The small dip in the log P log V diagrams during the injection period also indicates the effects of fuel vaporization and this dip is more pronounced when the engine is operated on iso-octane due to its higher latent heat of vaporization.

Heat Release Calculations:

The rate of fuel burning is a basic parameter in most engine models and techniques for calculating fuel burning rates from engine pressure data have received considerable attention. Our understanding of combustion in homogeneous fuel air mixtures

is well developed; however, the increased complexity of heterogeneous charge engine combustion precludes a strictly thermodynamic solution which does not account for mixing in the combustion chamber. This statement applies to both stratified charge and diesel engines and most of the previous work has been done with diesel combustion systems. Until recently, efforts to predict heat release rates in a diesel engine were highly empirical. Lyn has developed relationships to predict heat release rates in an open chamber diesel based on the fuel injection rates⁽¹¹⁾. Borman and Kreigher have developed a thermodynamic model to predict burning rates from diesel engine pressure data⁽¹²⁾. In the Borman model, the fuel was assumed to be homogeneously mixed at each time step. This assumption implies very lean equivalence ratios at the start of injection which increase to the overall equivalence ratio. This is physically inconsistent since mixing considerations of the fuel jet imply initially rich combustion followed by progressive mixing down to the final lean overall equivalence ratio. Still other investigations have assumed micro mixtures of burning droplets in which all combustion takes place at stoichiometric considerations⁽¹³⁾. The TCCS performance model developed by Jain assumed that burning took place at equivalence ratios determined by jet mixing and air entrainment and used a specified constant equivalence ratio for the burnt products during its

rapid combustion phase⁽³⁾. These assumptions are critical and control the shape of the burning rate diagram computed from pressure-volume data.

The thermodynamic model used in these experiments to predict the cumulative mass of fuel burnt from pressure-volume data is an extension of the two zone homogeneous charge combustion model as outlined below. The closed system is defined as all air, residual gas and fuel vapor in the cylinder prior to ignition. The mass conservation equation can be written as:

$$\bar{v} = v/M = x\bar{v}_b + (1-x)\bar{v}_u \quad 4.1$$

and the first law as:

$$\bar{e} = (E_o - W - Q)/M = x\bar{e}_b + (1-x)\bar{e}_u \quad 4.2$$

where

x = charge mass burnt/total charge mass

E_o = total energy of the charge at time t_o

M = the total charge mass, air + fuel + residual gas

Q = the cumulative heat since t_o

v = the combustion chamber volume

W = the work done since t_o

$\bar{e}$ = the average specific energy

$\bar{v}$ = the average specific internal energies

$\bar{e}_b, \bar{e}_v$ = the appropriate average specific volumes

$\bar{v}_b, \bar{v}_u$ = the appropriate average specific internal energies

Subscripts:

b refer to the burnt zone

u refer to the unburnt zone

Further more at a given equivalence ratio ϕ ;

$$\bar{v}_u = \bar{v}_u (P, T_u) \quad 4.3$$

$$\bar{v}_b = \bar{v}_b (P, T_b) \quad 4.4$$

$$\bar{e}_u = \bar{e}_u (P, T_u) \quad 4.5$$

$$\bar{e}_b = \bar{e}_b (P, T_b) \quad 4.6$$

where

P = the cylinder pressure

T_u, T_b = the appropriate average zone temperatures.

Assuming the unburnt zone undergoes adiabatic quasistatic compression and expansion, T_u is calculated from;

$$\left(\frac{\partial T}{\partial P} \right)_s = \left[v_u (P, T) - \left(\frac{\partial h_u}{\partial P} \right)_T \right] \quad 4.7$$

Equations 4.1 and 4.2 can be combined to eliminate x , $\bar{T}_b$ is then found by iterative technique. Once $\bar{T}_b$ is known, x , the mass fraction burnt can then be calculated from either 4.1 or 4.2.

This model has been expanded by Martin for use in a heterogeneous charge engine. The burnt zone is considered as burnt products + residual gas uniformly mixed at an externally designated equivalence ratio ϕ_b at each time step. The unburnt zone is divided into two components; unburnt air + residual gas, and the injected but unburnt fuel vapor. Heterogeneous combustion models require a relationship between the fuel fraction burnt and the charge mass burnt since combustion takes place at other than the overall equivalence ratios. The following ratios can be defined:

y = unburnt fuel mass/charge mass

z = fuel mass burnt/total fuel mass

The equation for specific volume and specific energy of the unburnt zones are then written as:

$$\bar{v}_u = (y\bar{v}_{uf} + (1-x-y)\bar{v}_{ua})/(1-x) \quad 4.8$$

$$\bar{e}_u = (y\bar{e}_{uf} + (1-x-y)\bar{e}_{ua})/(1-x) \quad 4.9$$

Equations for y and z are then expressed in dimensionless ratios.

$$y = \frac{F\bar{\phi}(1-R)}{1 + F\bar{\phi}} - \frac{F\phi_b(1-R)}{1 + RF\bar{\phi} + (1-R)F\phi_b} x \quad 4.10$$

$$z = \frac{\phi_b(1+F\bar{\phi})}{\bar{\phi}(1+RF\bar{\phi} + (1-R)F\phi_b)} x \quad 4.11$$

where

ϕ_b = the burnt zone equivalence ratio at time t

$\bar{\phi}$ = the average overall equivalence ratio at time t

F = the stoichiometric fuel-air ratio

R = the residual fraction

The computational procedures used to solve for x is the same as in the homogeneous charge model; and z can then be found with Equation 4.11; however, particular attention must be paid to the change in $\bar{\phi}$ and ϕ_b with time. The overall equivalence ratio only varies during the injection process, and its change is directly related to the fuel injected in each time step. But it will be shown that proper selection of the burnt zone equivalence ratio is not straightforward.

As originally developed by Martin, the modified model assumed a constant unburnt equivalence ratio equal the final overall equivalence ratio and that fuel burned immediately upon injection⁽⁴⁾. Early efforts to use the model in this form with ϕ_b held constant predicted a slow start of combustion prior to

the actual rapid combustion phase, and a final burnt fuel fraction greater than one. The model has been refined by including the variations in unburnt equivalence ratio during injection, and by assuming that the injected but unburnt fuel can be treated as fuel vapor. Procedures for allowing the burnt zone equivalence ratio to change with time have also been included in the computer program.

Sensitivity of the thermodynamic model to ϕ_b is shown in Figure 58. These computations assume no mixing, and the burnt gas equivalence ratio ϕ_b is held constant. The computations are based on pressure-volume data and on overall equivalence ratio of $\bar{\phi} = 0.45$ at 1500 RPM. Four values of ϕ_b are shown, the overall average equivalence ratio, stoichiometric and two rich mixtures. When burning is assumed to take place at the overall equivalence ratio $\bar{\phi} = 0.45$, the fuel fraction burnt does not reach 1.0 and the burning time is much larger than predicted by the log P - log V diagram. This homogeneous premixed case is clearly one limiting example. With either rich or stoichiometric burnt gas equivalence ratio, the rapid combustion phase does not significantly vary, however, the curves diverge widely and exceed a value of unity during the mixing controlled combustion. During this period, the mixing rates and burning rates are comparable, by definition, and a mixing model is clearly needed

to account for the change in ϕ_b due to air entrainment by the burning plume if the mass burned is to be correctly related to the physical processes in the engine.

The fuel-air mixtures in the combustion chamber is heterogeneous, and combustion is not limited, a priori to any single equivalence ratio at a given time, the burnt and unburned gases may continually mix throughout the combustion process. As already noted the choice of ϕ_b for each time step during the mixing controlled combustion phase is important and an accurate entrainment model is required. The air entrainment model proposed by Blizard and Keck and developed for the TCCS engine by Jain⁽³⁾ is used to calculate the mass burned for the same PV data used in the sensitivity study as shown in Figure 59. Entrainment rates predicted by this model were high and the overall equivalence ratio was reached in 15 CA⁰, introducing an unrealistic dip in the mass fraction burnt curve. As indicated by the two previous examples, the calculation of burning rates in a stratified charge engine requires additional development to include mixing before plausible results will be obtained. We postulate that a model developed to predict NO may serve as a tool to aid in untangling the mixing phenomena. The mechanisms of NO formation in homogeneous charge engines are relatively well understood⁽¹⁴⁾; and the extension of a homogeneous model to

stratified charge engines appears to be plausible.

PV^γ Results

An examination of the value of PV^γ just before, during and after combustion gives a very good idea of the net heat input or output to the working fluid due to heat release as a result of chemical reaction and/or heat loss⁽³⁾. Figure 60 is a plot of PV^γ for the same pressure time data as analyzed in Figures 58 and 59. The cylinder pressure and volume at the start of injection is used as the reference (P_oV_o). The values of the specific heat ratio before and after combustion were determined from Figure 41. The solid line represents heat release at constant γ_u while the dashed line represents heat release at γ_b. When the end boundary conditions are applied, namely that the process must start as unburnt and end with its maximum coincident with the burnt maximum, the lines define a very narrow region within which the true heat release curve must fall. The dotted line represents the results of the thermodynamic program discussed in the last section with the burnt products equivalence ratio held at stoichiometric. The rise of this line above the peak value evident in the burnt curve is explained by the rise in the value of fuel mass fraction burnt in Figure 58 to greater than 1.0.

Several conclusions can be drawn from plots of this nature.

The dip in the unburnt curve during the injection period provides further evidence of fuel vaporization, a fact also discussed in the section covering logarithmic data plots. If the above curves are normalized using the maximum difference in burnt and unburnt curves, a line starting as unburnt and changing to the burnt curve near TDC closely approximates the actual cumulative fuel fraction burnt curve. PV^γ plots with γ determined from $\log P$, $\log V$ plots can be used to qualify results from a more complete thermodynamic analysis. Note that when normalized PV^γ curves are compared to the results of the Figure 58, only the fuel fraction burnt curves in which $0.95 < \phi_b < 1.1$ during the rapid combustion phase fall within the defined boundary region.

The method discussed above can, with careful normalization, provide a very good estimate of cumulative heat release. These estimates can, by comparison with data from detailed thermodynamic, be used to qualify assumptions made in the necessary mixing models.

V CONCLUSIONS AND RECOMMENDATIONS

1. The multifuel capability of the TCCS concept has been demonstrated by tests with iso-octane, a wide boiling point fuel and methanol. The thermal efficiency of the engine is independent of the fuel used. However, proper matching of the fuel injection system is required to achieve satisfactory exhaust emissions levels.
2. The limits on engine operating range are determined by hydrocarbon and CO emissions. The equivalence ratio upper limit is determined by a "smoke limit" near stoichiometric and the lower limit near $\phi = 0.3$ is determined by cyclic variations and high hydrocarbon emissions.
3. Detailed emissions data has been acquired for the three test fuels. Emissions with iso-octane and the wide boiling point fuel exhibit similar trends and compares favorably with previous available data.
4. Further research is required to explain the effects of RPM and different fuel types on indicated mean effective pressure at high load conditions with the TCCS system.

5. Techniques for obtaining online digital data with a small laboratory computer have been demonstrated. The pressure-volume data obtained has been shown to be sufficiently accurate for use in performance models.
6. It has been shown that accurate pressure-volume data can be used to provide a good estimate of cumulative heat release through the use of logarithmic and PV^γ plots.
7. The problems involved in predicting heat release rates have been discussed and the importance of mixing in diesel and stratified charge combustion clearly demonstrated. A detailed thermodynamic analysis of burning rates will require better modelling, both for the mixing of the fuel jet with air before it is entrained in the flame front and for the entrainment of air by the burning plume.
8. It is recommended that a NO_x prediction model be developed for this engine. This model will aid in understanding the role of mixing in stratified charge combustion and can be used to qualify mixing models developed for heat release calculations.

9. Parametric studies involving off design operation are required to explain the sensitivity of hydrocarbon emissions to small variations in injection and ignition phasing.

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APPENDIX I

PERFORMANCE AND EMISSIONS DATA REDUCTION PROGRAM

An interactive data reduction program was written for the Sloan Laboratory PDP 11/10 data analysis facility. The program consists primarily of I/O and is designed specifically for the TCCS engine; however, modifications for other single cylinder engines are possible. All inputs are requested in the same units that are used on the experimental data sheet. Equations used to compute air flow rate in grams/second, coolant flow rate, volumetric efficiency, brake horsepower, and engine emissions require clarification.

Air Flow:

The equation for the flow rate of air through the ASME square edged orifice meter with flange taps is given by the following equation (15).

$$W = 51.94 D_2^2 KY \sqrt{\frac{P_1}{T_1}} \text{ Gy } \Delta P$$

w = mass flow rate grams/second

P_2 = orifice diameter inches

K = flow coefficient

Y = expansion factor

P_1 = static pressure before orifice in in. Hg

T_1 = temperature before orifice $^{\circ}\text{R}$

G = specific gravity of gas

y = super compressibility factor

p = pressure drop across orifice in in. H₂O

The computer form of this equation will work with two orifice diameters D₂ = 0.515 and D₂ = 0.71. The program assumes the following variable values:

$$Y = 1 - 7.3 \times 10^{-4} \Delta p$$

$$G_{\text{wet}} = G_{\text{dry}} \left[\frac{1+w}{1+1.608w} \right]$$

$$Y = 1$$

The maximum and minimum Reynolds number can be written as functions of Y and D₂ with N_v = 0.85, RPM Max = 3000 RPM Min = 1000, and inlet air temperature = 90°F

$$Re_{\text{min}} = \frac{17174.72}{D_2} \quad Re_{\text{Max}} = \frac{68701.3}{D_2}$$

and appropriate values of K as a function of D₂ determined

$$K = 0.6152 D_2^{0.0366}$$

Coolant Flow Rates:

The equation for coolant flow rates was determined by linear regression analysis of calibration data points. 46°F water was used and a density correction was applied to obtain the least squared curve fit given below, good at 175°F.

$$\dot{m} = 0.0479 (h) - 0.0081$$

$$r = 0.994$$

$$\dot{m} = \text{lbm/sec}$$

$$h = \text{rotameter height}$$

$$r = \text{goodness of fit}$$

Volumetric Efficiency:

The engine volumetric efficiency is strictly a function of engine dimensions and operating conditions as shown below:

$$\eta_v = \frac{\dot{m} \left(\frac{2}{N} \right)}{\frac{P_I V}{\left(\frac{T_I R}{T_I} \right)}}$$

$$\dot{m} = \text{air flow rate in lbm/min}$$

$$N = \text{revolutions/min}$$

$$P_I = \text{inlet air pressure}$$

$$V = \text{cylinder volume}$$

$$R = \text{specific gas constant}$$

$$T_I = \text{inlet air temperature}$$

after the inclusion of engine geometry and unit conversions

$$\eta_v = \frac{3. \text{TD} \dot{m}_a (T_I + 460)}{N [0.0193 P_{\text{atm}} - 0.361 P_I]}$$

Engine Power Output:

The mean effective pressure and horsepower are determined from the following equations (16).

$$hp = \frac{mep LAN}{66000}$$

$$hp = \frac{N\Delta h}{K}$$

After including specific engine geometry and an overall dynamometer constant of $K = 6000$

$$mep = 2.88847\Delta h$$

$$hp = \frac{N\Delta h}{6000}$$

where

A = area of engine piston, in.²

L = stroke, ft.

N = engine RPM

mep = mean effective pressure, psi.

Δh = dynamometer scale height, in Hg.

Specific Emissions:

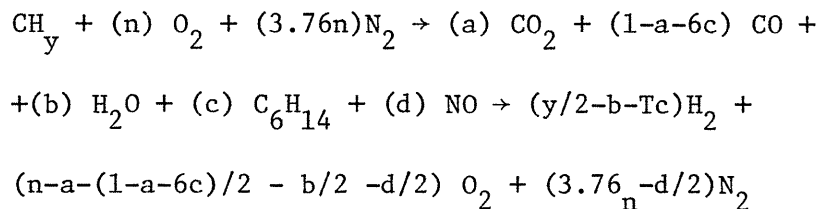
The average exhaust composition is a function of the equivalence ratio. A model developed by Stivender (8) is used to determine the exhaust based equivalence ratio as a check of the equivalence ratio measured from inlet flow rates; and to compute the engine emissions in grams of pollutant/indicated

horsepower hour. Required inputs are the indicated specific fuel consumption (ISFC), emissions concentrations on a volume basis and the fuel carbon:hydrogen ratio. The model as presented does not apply to alcohol fuels and a method presented by Spindt (17) was used for the methanol experiments.

The model fits one undetermined equilibrium constant for the water-gas reduction to direct measurements:

$$K = \frac{[H_2O] [CO]}{[CO_2] [H_2]} = 3.8$$

The combustion reaction for a typical hydrocarbon fuel with air may be expressed in the following form:



The molecular weight of fuel as it appears in the above equation can be written as

$$M_f = 12.01 + 1.008 y$$

The molecular weight of air is assumed as

$$M_a = 28.96$$

The air fuel ratio can then be written by a carbon and oxygen balance as

$$\frac{A}{F} = 4.76 \frac{M_e}{M_a} \left[\frac{[CO_2] + [O_2] \frac{[CO] \rightarrow [H_2O] + [NO]}{2}}{[HC] + [CO] + [CO_2]} \right]$$

The HC concentration is measured wet. All other pollutant concentrations are dry and must be corrected by the following relationship

$$[]_{\text{wet}} = []_{\text{dry}} (1 - [H_2O])$$

An empirical correlation used to determine the exhaust water concentration where the concentrations were wet and $K = 3.8$, as shown below

$$[H_2O] = \frac{.5y([CO_2] - [CO])}{\left(\frac{[CO]}{3.8[CO_2]} + 1\right)}$$

Specific pollutant emissions can be written as

$$\text{IS "X" (gr/ihp-hr)} = \frac{M_x}{M_f} \left[\frac{[X]_{\text{wet}}}{[HC] + [CO] + [CO_2]} \right] \text{ISFC}$$

where "X" is the species of interest. When the above equation is used to indicate C_6H_{14} emissions the ["X"] term is $[HC]/6$ since $[HC]$ is determined by a count of single carbons.

For output consistency fuel consumption is based on the observed air flow and the equivalence ratio calculated from the exhaust products. The computer program listing is included in Appendix III.

APPENDIX II

ONLINE DIGITAL PRESSURE DATA ACQUISITION

Accurate pressure volume data was required and an online digital acquisition system was developed for these experiments. The advantages of direct data acquisition include improved accuracy and speed. With these routines, a large number of data records can be collected and statistically analyzed. Consequently, failure of the experimental techniques can be detected by immediate review and preliminary analysis of the digital data. The online data acquisition system and program described in this appendix is based on a Digital Equipment Company (DEC) 11/10 computer with 16 K of core memory, a DEC RK -05 random access disk, two teletype terminals and the DEC Laboratory Peripheral System (LPS). The DEC LPS consists of an 8 channel multiplexed analog to digital converter with variable gain preamplifiers, and internal timing clock, and two Schmidt triggers. This system has the capability to sample each channel along with its multiplexed pair simultaneously and then perform sequential conversion on the two signals. The sample window length is 5 nano-seconds and each signal conversion takes 25 μ S. Maximum sampling rate on a single channel is 45 Hz, with 12 bit conversion.

A schematic of the data acquisition system is shown in Figure 17. The reference marker pulse at the start of the compression

stroke is input to channel 0 with the cylinder pressure input to channel 10. Marker pulses every 5 CA° are used as an input to the Schmidt trigger. It appears that further system refinements will permit 1 CA° sampling increments for a single pair of inputs.

Accurate pressure records must be matched with accurate crankangle records to be of further use and variations in crankshaft angular velocity precludes accurate determination of the cylinder volume when the pressure signal is only logged against time. Consequently, combustion pressure and crankangle position signals make up a data pair and are synchronized with the aid of the Schmidt trigger. Each sample interval consists of 144 data pairs comprising two engine revolutions. The actual crankangle position is not known at the start of a sampling interval and the sampled data is reordered at the end of each data sample interval using a reference signal at 185° before top dead center.

Two techniques can be proposed for obtaining average engine performance. The first involves a complete heat release analysis of individual combustion records followed statistical averaging of these results. The extended interval between sampled data sets and the computational expense required by this method precludes its use. Consequently, a second technique involving the computation of mean cylinder pressure records from consecutive data sets was used. These mean records are then analyzed to obtain engine performance. If a Gaussian distribution

is assumed, the probability density function can be expressed as:

$$\rho(X) = \frac{1}{\sqrt{2\pi\sigma}} \exp \left[-\frac{(X_o - \bar{X})^2}{2\sigma^2} \right]$$

The following equations are used to calculate the statistical properties of data variations from N records of data:

$$\text{Mean } (\mu_1) \quad \bar{X}_i = \frac{1}{N} \sum_{j=1}^N X_{ij}$$

$\bar{X}_i$ represents the average value of the i the element of the data vector X.

$$\text{Variance: } (\sigma^2) \quad S_i^2 = \frac{1}{(N-1)} \sum_{j=1}^N (X_{ij} - \bar{X}_i)^2$$

Rearranging these equations, the standard deviation can be computed with a single pass of the data:

$$S_i = \sqrt{\frac{1}{N-1} \left[\sum_{j=1}^N X_{ij}^2 - \frac{1}{N} \left(\sum_{j=1}^N X_{ij} \right)^2 \right]}$$

This routine permits calculation without an unmanageable number of element arrays. However, the standard deviation as calculated is not normalized and can only be expressed as a percent of the

observed element mean.

Assuming that we are sampling from a normal population it is possible to construct exact confidence intervals for μ , the true mean, even when σ is unknown, by use of the Student - t distribution. A $1-\alpha$ confidence interval for μ_i is expressed as:

$$\bar{X}_i - t_{\alpha/2} \left(\frac{S_i}{\sqrt{N}} \right) < \mu_i < \bar{X}_i + t_{\alpha/2} \left(\frac{S_i}{\sqrt{N}} \right)$$

For a large sample size the distribution of S_i can be closely approximated as normal and a $1-\alpha$ confidence interval is:

$$\frac{S_i}{1 + \frac{Z_{\alpha/2}}{\sqrt{2N}}} < \sigma_i < \frac{S_i}{1 - \frac{Z_{\alpha/2}}{\sqrt{2N}}}$$

where

$$Z_i = \frac{S_i - \sigma_i}{(\sigma_i / \sqrt{2N})}$$

In addition to the statistical information outlined above, the outline data acquisition program integrates the mean pressure volume diagram to calculate the indicated mean effective pressure and the pumping mean effective pressure by using Simpson's Rule

for non evenly spaced ordinates as shown below:

$$W = \sum_{j=1,3,5..}^N [(V_{j+2}(\theta) - V_j(\theta) (5P_j(\theta) + 8P_{j+1}(\theta) - P_{j+2}(\theta))]$$

Note that cylinder volume is a geometric function of crankangle position.

Log P and Log V vectors are also displayed for cycle evaluation and the program listing containing in stream documentation is included in Appendix III. The assembly language commands for the sampling subprogram are explained in Reference(18).

APPENDIX III

COMPUTER ANALYSIS PROGRAMS

Listings for all computer programs and subroutines used in these experiments are included in this appendix. The programs and subroutines can be grouped in four areas as indicated by Tables A-1 through A-4. All programs contain in-stream documentation of major equations and computational schemes and each subroutine contains a brief section describing its purpose, calling sequence, and the definition and dimensions of arguments. All programs with the exception of subroutine SAMPLE are written in ANS Fortran IV. Subroutine SAMPLE is written in DEC Assembly Language.

Table A-1

Summary of Interactive Data Acquisition and Reduction Programs

<u>Program</u>	<u>Purpose</u>
REZLTS	Calculates basic performance and emissions from experimental data
ONLINE	Performs online pressure data ac- quisition and calculates mean pressure crankangle statistics
<u>Subroutine</u>	
SAMPLE	Provides assembly language commands used to control analog to digital conversion

Table A-2

Summary of Pressure Crankangle Data
File Preparation and Control Programs

<u>Program</u>	<u>Purpose</u>
ANALIZ	Prepares pressure crankangle data files and basic performance information for additional thermodynamic analysis.
<u>Subroutine</u>	
RECALL	Returns pressure-crankangle data from ONLINE for further calculations.
XPRNT1, XPRNT2	Provides printout of internal variables in XCLC2 for each time increment.
STORE	Provides file storage options for output from ANALIZ.

Table A-3

Summary of TCCS Combustion Analysis Program

<u>Subroutine</u>	<u>Purpose</u>
XCLC2	Calculates fuel fraction burnt, and PVY versus crankangle from pressure- crankangle data
GASVEL	Calculates the average gas velocities at the periphery of the piston cup*
HEAT2	Calculates heat transfer rate in TCCS engine during combustion
PLUME	Calculates air entrainment rates for burning gas plume**

* Appendix B, Reference (4).

**Appendix II, Reference (3).

Table A-4

Summary of General Thermodynamic Property Subroutines*

<u>Subroutine</u>	<u>Purpose</u>
AFTEMP	Calculates adiabatic flame temperature from given initial state
CLDPRD	Calculates burnt gas properties at low (<1000°K) temperatures
DERIVS	Calculates derivatives of properties; for HPROD
HPROD	Calculates burnt gas properties at temperatures >1100°K
TEMP	Calculates T(h,P) for burnt gas
TSUBU2	Calculates T(P) from given initial state of unburnt gas following an isentropic process (assumes no fuel vapor)
UPROPZ	Calculates properties of unburnt gas (assumes no fuel vapor)

*Appendixes C and D; Reference (4)

```

C
C
C
C
C
C
      REZLTS

      THIS PROGRAM WILL REDUCE THE EXPERIMENTAL DATA AS IT IS
      REQUESTED. ALL INPUTS WILL BE PROMPTED.

      DIMENSION T(5), FULFLO(5)
      INTEGER RUN
      REAL MECEFF, NO, IHP, IMEP, ISFC, ITEFF, ISCO, ISNO,NL,ISHC
      DATA DORF/0.71 /
      TYPE 500
      FORMAT('          THE FOLLOWING INPUTS ARE REQUIRED TO REDUCE THE',
1' ENGINE DATA')
      TYPE 514
      FORMAT('          ENTER THE FUEL DATA AS REQUESTED'/' WHAT IS THE ',
1' H:C RATIO')
      ACCEPT 111,HCR
      FORMAT(F15.7)
      TYPE 515
      FORMAT('          WHAT IS THE STOIC FUEL AIR RATIO? ')
      ACCEPT 111, STOIC
      TYPE 516
      FORMAT('          WHAT IS THE LOWER HEAT OF COMBUSTION? ')
      ACCEPT 111, QC
      TYPE 517
      FORMAT('          WHAT IS THE FUEL SPECIFIC GRAVITY AT TEST',
1' TEMP.? ')
      ACCEPT 111, SPGR
      DO 11 I=1, 23
      TYPE 200
      FORMAT(/)
      RFML = 100.
      ACCEPT 5011, NULL
      FORMAT(I2)
      TYPE 501
      FORMAT('          ENTER THE RUN #(I2)      ',*)

```

```
100 ACCEPT 100, RUN
    FORMAT(I2)
    IF ( RUN .EQ. 0 ) GO TO 99
    TYPE 502
    FORMAT('      THE DATE(A8) ', $)
101 ACCEPT 101, DA, TE
    FORMAT(A4, A4)
    TYPE 503
    FORMAT('      THE FUEL USED (A8) ', $)
103 ACCEPT 101, FU, EL
    TYPE 504
    FORMAT('      ENTER THE RPM (F5.0) ', $)
104 ACCEPT 111, RPM
    TYPE 505
    FORMAT('      THE INJECTION START (I3) ', $)
102 ACCEPT 102, INJS
    FORMAT(I3)
    TYPE 506
    FORMAT('      THE END OF INJECTION (I2) ', $)
103 ACCEPT 103, INJF
    FORMAT(I3)
    TYPE 507
    FORMAT('      THE INJECTOR CRACKING PRESSURE (I4) ', $)
104 ACCEPT 104, INJP
    FORMAT(I4)
    TYPE 508
    FORMAT('      THE AMOUNT OF NEEDLE LIFT ', $)
105 ACCEPT 111, NL
    TYPE 509
    FORMAT('      THE IGNITION START (I3) ', $)
106 ACCEPT 102, IGNS
    TYPE 510
    FORMAT('      THE END OF IGNITION (I2) ', $)
107 ACCEPT 103, IGNE
    IF ( RPM .EQ. RFML ) GO TO 2
```

```

511 K=0
    TYPE 511
    FORMAT( 'WHAT IS THE ATMOSPHERIC PRESSURE IN MM OF HG ',#)
    ACCEPT 111, PATM
512 TYPE 512
    FORMAT( 'HOW MANY GRAINS OF WATER VAPOR ARE ',
    1' THERE ',#)
    ACCEPT 111, WGR
    TYPE 5161
5161 FORMAT( 'WHAT IS THE PRESS INTO THE ORIFICE IN IN OF H2O ',#)
    ACCEPT 111, PINOR
    GO TO 3
2 K = 1
3 RPML = RPM
    TYPE 5171
5171 FORMAT( 'WHAT IS THE PRESS DROP ACROSS THE ORIFICE IN IN OF ',
    1'H2O ',#)
    ACCEPT 111, PDEL
    TYPE 518
518 FORMAT( 'WHAT IS THE PRESS DROP IN THE INTAKE MANIFOLD IN IN ',
    1'OF H2O? ',#)
    ACCEPT 111, PINL
    TYPE 519
519 FORMAT( 'WHAT ARE THE DYNO PRESSURES IN INCHES OF HG'/
    1' FOR BRAKE ',#)
    ACCEPT 111, PDYB
    TYPE 520
520 FORMAT( 'FOR FRICTION ',#)
    ACCEPT 111, PDYF
    TYPE 521
521 FORMAT( 'FOR BRAKE ZERO ',#)
    ACCEPT 111, PDYBZ
    TYPE 522
522 FORMAT( 'FOR FRICTION ZERO ',#)
    ACCEPT 111, PDYFZ

```

```

523 TYPE 523
    FORMAT('          WHAT ARE THE FOLLOWING TEMPERATURES IN DEG F')
    1'      WATER IN ', $)
    ACCEPT 111, TWIN
    TYPE 524
    FORMAT('          WATER OUT ', $)
    ACCEPT 111, TWOUT
    TYPE 525
    FORMAT('          ORIFICE INLET ', $)
    ACCEPT 111, TORIN
    TYPE 526
    FORMAT('          INLET MANIFOLD ', $)
    ACCEPT 111, TAIRIN
    TYPE 527
    FORMAT('          EXHAUST ', $)
    ACCEPT 111, TEXH
    TYPE 528
    FORMAT('          WHAT IS THE WATER FLOW RATE -SCALE READING- ', $)
    ACCEPT 111, WTRFLO
    TYPE 529
    FORMAT('          HOW MANY FUEL CHECKS WERE MADE? ', $)
    ACCEPT 1041, NCK
    1041 FORMAT(I1)
    TYPE 530
    FORMAT(' ENTER THE FUEL FLOW DATA, MASS IN GRAMS, TIME IN SEC, ',
    1'FOR EACH CHECK (2F10.2)')
    DO 12 I=1, NCK
    12  ACCEPT 105, FULFLO(I), T(I)
    105  FORMAT(2F10.2)
    TYPE 531
    FORMAT('          WHAT ARE THE EMISSIONS DATA, HC IN PPM, NO IN ',
    1'PPM, O2, CO2 AND CO IN % (F10.2/))')
    ACCEPT 111, HC
    ACCEPT 111, NO
    ACCEPT 111, O2

```

THIS EQUATION IS DERIVED FROM THE PAPER "THE METERING OF GASES BY MEANS OF THE ASME SQUARE EDGED ORIFICE WITH FLANGED TAPS." BY LEARY W. A.

```
W=31.76*DOREF**2.0366*((PATM*.03937-PINOR*.07369)
1*(1. + WGR/7000.)/(1. + 1.608*WGR/7000.))*FDEL/
1(TORIN + 460. )**0.5
```

THIS CALCULATES THE AIR FLOW IN GRAMS PER SEC

$$\begin{array}{c} \diamond \\ \text{O} \\ \text{I} \\ \text{F} \end{array} \quad \begin{array}{c} \diamond \\ \text{O} \\ \text{I} \\ \text{F} \end{array}$$

NO 13 I=1,NCK

$$T_i = FULFLO(I)/T(I)$$



$$FM = F/ \text{FLOAT}(NCK)$$

THIS IS THE MEASURED FUEL FLOW RATE

FAR = FM/W

THIS IS THE MEASURED FUEL AIR RATIO

PHIM = FAR / STOIC

THIS IS THE MEASURED EQUIVALENCE RATIO

$$\text{FPERST} = \text{FM} * 120000.0 / (\text{RFM} * \text{SFGR})$$

THIS IS THE FUEL INJECTED PER STROKE IN MM**3

CALCULATE THE WATER FLOW RATE USING A LEAST SQUARES
FIT FOR THE ROTAMETER CALIBRATION DATA ON 28 JAN 76

WTRFLO = 0.0479 * WTRFLO - 0.0081
HREJ = WTRFLO * 60. * (TWOUT-TWIN)
BMEP = 2.88847 * (PDYB-PDYBZ)
FMEP = 2.88847 * (PDYFZ-PDYF)
IMEP = BMEP + FMEP
RHP = RPM * (PDYB-PDYBZ)/6000.0
FHP = RPM * (PDYFZ-PDYF)/6000.0
IHP = BHP + FHP
MECEFF= BMEP/IMEP
VOLEFF= W * 3.707 * (TAIRIN + 460.)/(RPM * (PATM * 0.01934
1-PINL * 0.0361))
SAC =W* 3600./(453.592*IHP)

ALL EMISSION EQUATIONS ARE BASED ON SAE PAPER 710604
BY D. L. STIVENNER ----- NOTE THAT THE HC ARE MEASURED
IN TERMS OF CARBON ATOMS AND THAT AS MEASURED HC IS
WET WHILE ALL OTHER QUANTITIES ARE MEASURED DRY.

HC = HC/10000.0
NO = NO/10000.0
FMWT = 12.01 + 1.008 * HCR
CH20 = HCR * 0.5 * (CO2 + CO)/(CO/(CO2 * 3.8) + 1.0)
CH20 = CH20/100.0
H20 = CH20/(1.0 + CH20)
WDR = 1.0 - H20
H20 = H20 * 100.0

AFR=4.76*(28.96/FMWT)*((CO2+O2+(CO+NO)*0.5)
1*WDR+0.5*H20)/(HC+(CO+CO2)*WDR)
FAREX = 1.0/AFR

THIS IS THE CALCULATED FUEL AIR RATIO

PHIEX = FAREX/STOIC

THIS IS THE CALCULATED EQUIVALENCE RATIO

CALCULATE THE FUEL CONSUMPTION BASED ON THE AIR FLOW
AND THE CALCULATED AFR TO MAKE THE EMISSIONS OUTPUT CONSISTENT.

```

FM = W * FAREX
SFC = FM * 3600.0 / IHP
ISFC = SFC / 453.592
BSFC = ISFC * IHP / BHP
ITEFF = 2545.0 / (ISFC * QC )
DEM = 1. / ( HC + CO *WDR + CO2*WDR )
ISCO = (28.01/FMWT) * DEM * WDR * CO * SFC
ISNO = ( 48.008/FMWT) *DEM *NO * WDR * SFC
ISHC = ( 83.25/FMWT ) * DEM * (HC/6.) * SFC

```

COMMENCE OUTPUT

```
IX = 13+K*3
DO 14 I=1,IX
```

TYPE 200

TYPE 5311, RUN, DA, TE, FU, EL

PERFORMANCE SUMMARY FOR THE TCCS ENGINE//
FORMAT//

```
1' TEST RUN ',I2,5X,A4,A4,' USING ',A4,A4,' FUEL,')
```

TYPE 532

FORMAT	RPM	INJ START	INJ FINISH	INJ PRESS
--------	-----	-----------	------------	-----------

1'NEEDLE LIFT IGN START IGN FINISH')

TYPE 533, RPM, INJS, INJF, INJF, NL, IGNS, IGNF

```
FORMAT(' ',F5.0,7X,I3,I2X,I3,I1X,I4,I2X,F5.3,10X,I3,I2X,I3)
```

TYPE 534, FHIM, FHIX

```

FORMAT( '
THE MEASURED EQUIVALENCE RATIO= ',F5.3'

```

1' THE CALCULATED EQUIVALENCE RATIO= 'F5.3)

TYPE 535, IMEP, BMEP, FMEP

```
FORMAT('IMEP= ',F10.2,'3X','PSI',5X,'BMEP= ',F10.2,
```

14

5311

532

533

534

535

```

1 3X,'PSI',5X,'FMEP=',F10.2,3X,'PSI')
TYPE 536, IHP, BHP, FHP
FORMAT('      IHP = ',F10.2,11X,'BHP = ',F10.2,11X,'FHP = ',
1 F10.2)
TYPE 537, MECEFF, ITEFF, VOLEFF
FORMAT('      MECH EFF = ',F10.3,'      IND THERM EFF = ',F10.3,' VOLUME',
1 'TRIC EFF=',F10.3)
TYPE 538, HREJ, TEXH
FORMAT('      HEAT REJECTION TO H2O=',F10.2,' BTU/MIN',5X,'EXH',
1 'AUST TEMP=',F10.1,3X,'DEG F')
TYPE 539, FPERST
FORMAT('      THE FUEL INJECTED / STROKE = ',F10.5,3X,'MM**3' )
TYPE 540, ISFC, BSFC, SAC
FORMAT('      ISFC=',F10.3,5X,'BSFC=',F10.3,5X,
1 'ISAC=',F10.3,5X,'( LBM/HP-HR )')
TYPE 541, ISCO, ISNO, ISHC
FORMAT('      ISCO=',F10.2,5X,'ISNO=',F10.2,5X,
1 'ISHC=',F10.2,5X,'( GR/IHP-HR )')
TYPE 542
FORMAT('      NOX IS IN TERMS OF NO2 AND THE HC IS IN ',
1 'TERMS OF EQUIVALENT HEXANE')
DO 15 I=1,13
TYPE 200
CONTINUE
GO TO 1
STOP
END

```

536

537

538

539

540

541

542

15

99


```

804 TYPE 804
    FORMAT(/, 'WHAT ANGLE DOES THE BALANCE PRESSURE INDICATOR',
1' CORRESPOND TO (NEAREST 5 DEGREE) ? (I4) ', $ )
807 ACCEPT 807, IBPI
    FORMAT(I4)
    TYPE 808
808 FORMAT(/, 'WHAT PRESSURE IS THE BALANCE PRESSURE INDICATOR',
1' SET AT ? (F5.2) ', $ )
    ACCEPT 809, BPI
809 FORMAT(F5.2)
    BPI = BPI + CNTP
    TYPE 8111
8111 FORMAT(' WHAT IS THE RPM ? ', $)
    ACCEPT 8112, RPM
8112 FORMAT(F10.3)
500 TYPE 812
812 FORMAT(/, 'HOW MANY SAMPLES DO YOU WANT ? (I3) ', $ )
    ACCEPT 813, ISAMP
813 FORMAT(I3)
    TYPE 810
810 FORMAT(/, 'DO YOU WANT TO SEE A FULL CYCLE ? YES=1 NO=0 ', $)
    ACCEPT 906, LOOK1
8131 FORMAT('
                                RELEASE WHEN READY TO RUN', $)
8132 ACCEPT 8132, NULL
    FORMAT(I2)
    TYPE 8133
8133 FORMAT('
                                ONLINE SAMPLING UNDERWAY DO NOT DISTURB'////)
    ICOUNT = 0
    DO 5 I= 1, 288
        IBUF(I) = 0
5    CONTINUE
    DO 6 I = 1, 144
    DO 6 J = 1, 2
        PSTAT(I,J) = 0.0

```

```

6      CONTINUE
      LOOK=0
      DO 1 I=1,288
1       IBUF(I)=0
C
C      JUMP ON BOARD AND COLLECT SAMPLES FOR 2 REVOLUTIONS USING CHANNEL
C      0 AND 10 (OCTAL)
C
C      CALL SAMPLE(IBUF,144)
C
C      FIND THE REF PULSE ON CHANNEL 0
C
C      IR = 1
C      IMAX = IBUF(1)
C      DO 2 I=3,287,2
C      IF (IBUF(I) .LT. IMAX) GO TO 2
C      IMAX = IBUF(I)
C      IR = I
C      CONTINUE
2
C
C      REORDER THE PRESSURE DATA STARTING AT THE REF PULSE
C
C      IR = IR +1
C      J = 0
C      DO 3 I=IR,288,2
C      J=J+1
C      IPRES(J) = IBUF(I)
3
C      DO 4 I=2,IR,2
C      J=J+1
C      IPRES(J)= IBUF(I)
C      ICOUNT =ICOUNT + 1
C      IF (ICOUNT .EQ. ISAMP) LOOK=LOOK+LOOK1
4
C
C      CALIBRATE THE DATA USING BPI, IBPI, PSCALE AND STORE THE ARRAY TO
C      COMPUTE THE FINAL PRESSURE STATISTICS
C

```

```

C
IF(LOOK.EQ.0) GO TO 41
TYPE 701, ICOUNT
FORMAT(//, ICOUNT= ',I3)
CONTINUE
I = (185 + IBPI) / 5 + 1
RBPI = (FLOAT( IPRES(I))-2047.)/409.5
TH=-185.0
DT= 5.0
DO 10 I= 2,74
  TH=TH + DT
  K=I-1
  TH1(K)=TH
  PRESS= ((FLOAT(IPRES(I))-2047.)/409.5-RBPI) * FSCALE + BPI
IF(LOOK.EQ.0) GO TO 42
TYPE 702, TH, PRESS
1  FORMAT(' THETA= ',F5.0, 5X,' PRESSURE = ',F7.3,3X,
CONTINUE
42  TH1(K)=TH
    PSTAT(K,2) = PSTAT(K,2) + PRESS
    PSTAT(K,1) = PSTAT(K,1) + PRESS**2
10  CONTINUE
    TH=0.0-TH
    DO 11 I=75,144
      K=I-1
      TH=TH + DT
      TH1(K)=TH
      PRESS= ((FLOAT(IPRES(I))-2047.)/409.5-RBPI) * FSCALE + BPI
      PSTAT(K,2) = PSTAT(K,2) + PRESS
      PSTAT(K,1) = PSTAT(K,1) + PRESS**2
IF(LOOK.EQ.0) GO TO 43
TYPE 702, TH, PRESS
CONTINUE
43  CONTINUE
11  DO 12 I=1,1

```

```

44 TH=TH +DT
12 PRESS= ((FLOAT(IPRES(I))-2047.)/409.5-REPI) * PSCALE + BPI
    K=144
    TH1(K)=TH
    PSTAT(K,2) = PSTAT(K,2) + PRESS
    PSTAT(K,1) = PSTAT(K,1) + PRESS**2
    IF(LOOK .EQ. 0 ) GO TO 44
    TYPE 702, TH, PRESS
    CONTINUE
    CONTINUE
    IF ( ICOUNT .EQ. ISAMP ) GO TO 400
    THIS CHECKS TO SEE HOW MANY SAMPLE DATA SETS HAVE BEEN COLLECTED
    IF NOT MAX COLLECT AGAIN
    GO TO 100
    PROCESS THE PSTAT ARRAYS TO DETERMINE THE PRESSURE STATISTICS
    SAMP = FLOAT(ISAMP)
    DO 30 I = 1,144
    PSTAT(I,1)=SQRT(ABS(1./((SAMP-1.)*(PSTAT(I,1)-PSTAT(I,2)**2/SAMP)))
    PSTAT(I,2) = PSTAT(I,2)/SAMP
    CONTINUE
    CALCULATE THE MEAN EFFECTIVE PRESSURE, LIST THE OUTPUT AND PREPARE
    DATA FILES FOR STORAGE ON THE DISK.
    THE FOLLOWING SECTION CALCULATES THE CYLINDER VOLUME AND THE WORK AT
    EACH INCREMENT AND PROVIDES FOR PRINT OUT
    VDSP = 2. * B1
    TYPE 900
    FORMAT(////////// ON LINE DATA PROGRAM SUMMARY ')
900

```

```

901 TYPE 901, IRUN, DAT(1), DAT(2), DAT(3), RPM
    FORMAT(' RUN NUMBER ', I2, 5X, A4, A4, 5X, F7.2, 3X, 'RPM')
902 TYPE 902
    FORMAT('/', THETA, VOLUME/VOLUME MAX, MEAN PRESSURE,
1'STAND DEVIATION, LOG(VOL/VOL MAX), LOG(PRESS ATM))
C
DO 40 I = 1, 73
    CYVOL = VOL(TH1(I)*DTR)/(VDSF+VTDC)
    CYLN = ALOG10(CYVOL)
    PRLN = ALOG10(PSTAT(I,2)/ATM)
40 TYPE 903, TH1(I), CYVOL, PSTAT(I,2), PSTAT(I,1), CYLN, PRLN
903 FORMAT(6X, F5.0, 10X, F7.4, 12X, F7.3, 13X, F8.5, 10X, F8.5)
C
IF( LOOK.EQ. 0 ) GO TO 402
DO 401 I = 74, 144
    CYVOL = VOL(TH1(I)*DTR)/(VDSF+VTDC)
    CYLN = ALOG10(CYVOL)
    PRLN = ALOG10(PSTAT(I,2)/ATM)
401 TYPE 903, TH1(I), CYVOL, PSTAT(I,2), PSTAT(I,1), CYLN, PRLN
402 CONTINUE
    W=0.0
DO 51 I=1, 71, 2
    V01=VOL(TH1(I)*DTR)
    V02=VOL(TH1(I+2)*DTR)
    F=( V02-V01 ) * CCTIN3/12.
    F=F * ( 5.*PSTAT(I,2)+8.*PSTAT(I+1,2)-PSTAT(I+2,2) )
    W=W+F
51 WP=0.0
DO 52 I=73, 141, 2
    V01=VOL(TH1(I)*DTR)
    V02=VOL(TH1(I+2)*DTR)
    F=( V02-V01 ) * CCTIN3/12.
    F=F * ( 5.*PSTAT(I,2)+8.*PSTAT(I+1,2)-PSTAT(I+2,2) )
    WP=WP+F
52 V01=VOL(TH1(143)*DTR)

```

```

V02=VOL(TH1(1)*DTR)
F=( V02-V01 ) * CCTIN3/12.
F=F * (5.*PSTAT(143,2)+8.*PSTAT(144,2)-PSTAT(1,2))
WP=WP+F
PMEP=WP/(VDSP*CCTIN3)

C
MEP = W/(VDSP*CCTIN3)
HP = W/RPM/792000.0
TYPE 904, MEP, PMEP, HP
904 FORMAT(// THE IMEP = ',F6.2,10X,'THE PMEP = ',F7.2,10X,
1'THE IHP = ',F6.3//////////)
ISTR=1
TYPE 905
905 FORMAT(// ' DO YOU WANT TO STORE THE DATA? 1=YES 0=NO (I1) ', $)
ACCEPT 906, ISTR
906 FORMAT(I1)
IF (ISTR.EQ. 0 ) GO TO 97
TYPE 909
909 FORMAT(// ASSIGN A FILE TO THE DATA, IN THE FORM DEV:RUN#.DAT'//)
CALL ASSIGN(11,'DEV:FILE.EXT',-1)
DEFINE FILE 11(150,2,U,IT)

C
STACK ALL DATA INTO ONE ARRAY FOR STORAGE ON THE DISK
C
C
DO 80 I=1,2
DO 80 J=1,73
IX = J + 73*(I-1)
80 WRITE(11,IX) PSTAT(J,I)
WRITE(11,147) MEP
WRITE(11,148) HP
WRITE(11,149) RPM
WRITE(11,150) PMEP
C
GO TO 99
97 TYPE 910

```

910 FORMAT(// DO YOU WANT TO COLLECT MORE DATA? 1=YES 0=NO', \$)
 ACCEPT 906, ITALK
 IF (ITALK .EQ. 1) GO TO 500

C
99 STOP
 END

```
14:      .TITLE      ONLINE DATA ACQUISITION PROGRAM "SAMPLE"
      .MCALL
      .REGDEF
      .CSECT  SAMPLE
      LPSADS=170400
      LPSADB=170402
      TST (R5)+
      MOV (R5)+, R0
      MOV @ (R5)+, R2
      CLR @#LPSADS
      CLR @#LPSADB
      MOV #40020, @#LPSADS
      TSTB @#LPSADS
      BFL 1$
      INC @#LPSADS
      MOV @#LPSADR, (R0)+
      TSTB @#LPSADS
      BFL 2$
      MOV @#LPSADR, (R0)+
      DEC R2
      BGT 1$
      CLR @#LPSADS
      CLR @#LPSADR
      RTS PC
      .END

      ;VECTOR STATUS ADDRESS
      ;VECTOR BUFFER ADDRESS
      ;GET BUFFER POINTER
      ;GET NUMBER OF POINTS

      ;OPEN CH 0&10 DUAL SAMPLE & HOLD + ST1
      ;WAIT FOR THE FIRST SAMPLE CONVERSION

      ;WAIT FOR THE SECOND CH CONVERSION

      ;DECREMENT COUNTER
      ;GO WAIT FOR ST1 AGAIN
```

```

C ANALIZ
C
C THIS PROGRAM WILL PREPARE DATA FILES FOR XCLC2
C USING SUBROUTINE RECALL AND STORE & LIS-183 ENGINE DATA
C
C
C DIMENSION P(100), TH(100), Z(100), W(100), Q(100), PHITAB(100)
C DIMENSION P2(100), TH2(100), GAMMA(100), FVG(100)
C LOGICAL TALK
C INTEGER UNIT
C COMMON /CHARGE/ PHIAY, DEL, PSI, RESFRK, CHMASS, QLOWER, CFUEL
C COMMON /ENGINE/ BORE, STROKE, CONLEN, VTDC, HTDC, VCUP, ACUP,
C * RSUBC, RTICAP, RTSML, DSUBC, WO, RPM, TWALL
C COMMON /VERBOS/ TALK, UNIT
C COMMON /HTDATA/ P1, T1, V1, PM
C COMMON /XFRNTC/PRES, THETA, VBAR, WOVRM, QOVRM, VUAV, VBAV, VB,
C * EUAV, EB, TU, TBAV, TB
C
C DATA NREAD, NWRITE, NPNCH / 5, 5, 7 /
C
C READ IN PRESSURE DATA, AND SET UP ARRAY OF CRANK ANGLES
C
C CALL RECALL(P2,TH2,RPM)
C TYPE 107
C FORMAT(//// WHAT IS THE FUEL H:C RATIO ', $)
C ACCEPT 901, XCR
C DEL=1./XCR
C TYPE 108
C FORMAT(' WHAT IS THE LOWER HEATING VALUE FOR THE FUEL ', $)
C ACCEPT 901, QLOWER
C TYPE 101
C FORMAT(' WHAT IS THE ISFC ', $)
C ACCEPT 901, SFC
C TYPE 102
C FORMAT(' WHAT IS THE ISAC ', $)

```

```

103 TYPE 103
    FORMAT(' WHAT IS THE MEASURED IHP ', '$')
    ACCEPT 901, XHP
C
C
C    CALCULATE THE FUEL AND AIR MASS
    FMASS = SFC*XHP*453.592/(30.*RPM)
    AMASS = SAC*XHP*453.592/(30.*RPM)
    STOIC = (12.01+1.008*XCR)/(1.+XCR/4.)*137.965)
    PHIIV = (SFC/SAC)/STOIC
C
90 TYPE 104
104 FORMAT(' WHAT IS THE BURNT PRODUCTS EQUIVALENCE RATIO ', '$')
    ACCEPT 901, PHITR
    PSI = 3.764
    CFUEL = 0.00058
C
    BORE = 9.843
    STROKE = 9.843
    CONLEN = 16.83
    VTDC = 74.89
    HTDC = .124
    VCUP = 62.19
    ACUP = 72.5
    RSURC = 2.464
    RTCAP = 1.346
    RTSML = 1.118
    DSURC = 2.159
C
    TWALL = 400.
C
    TALK = .TRUE.
    UNIT = 5
105 TYPE 105
    FORMAT(' WHEN WAS THE START OF INJECTION ', '$')

```

00000170
00000210
00000220
00000230
00000240
00000250
00000260
00000270
00000280
00000290
00000300
00000310
00000320
00000330
00000340
00000370
00000380
00000390
00000400

```

1050 ACCEPT 901,THINJ
      TYPE 1050
      FORMAT(' WHEN WAS THE END OF INJECTION ',#)
106  ACCEPT 901,EINJ
      TYPE 106
      FORMAT(' WHAT DO YOU THINK THE RESIDUAL FRACTION WAS ',#)
      ACCEPT 901,RESFRK
      QLOWER=QLOWER/1800.
      W0 = RPM * 0.37803832
      CHMASS = AMASS+FMASS
      CHMASS = CHMASS/(1.-RESFRK)

C
C FIND THE START OF INJECTION AND THE NUMBER OF POINTS BEFORE
C THE EXHAUST VALVE OPENS
C
DO 10 I=1,73
IF(TH2(I) .LT. THINJ ) GO TO 10
K = I
GO TO 11
CONTINUE
DO 12 I=K,73
IF(TH2(I) .LT. 130.) GO TO 12
KN=I
GO TO 13
CONTINUE
I1=0
DO 14 I=K,KN
I1=I1+1
TH(I1) =TH2(I)
P(I1) = P2(I)
CONTINUE
NPTS = I1
DO 15 I=1,I1
IF(TH(I) .LE. EINJ ) GO TO 15
I3=I

```

```

15      GO TO 16
C      CONTINUE
C      INITIALIZE ARRAY CONTAINING BURNT PRODUCT PHI'S
C
16      DO 20 I = 1, NPTS
          PHITAB(I) = PHITB
C      20 CONTINUE
          CALL XCLC2 (P, TH, PHITAB, NPTS, I3, Z, W, Q, GAMMA, PVG )
901      FORMAT(F15.6)
C      TYPE 109
109      FORMAT(////)
          CALL STORE(P, TH, Z, GAMMA, PHITAB, PVG, NPTS)
1000     CALL EXIT
          END
          00000500
          00000510
          00000520
          00000530
          00000540
          00000550
          00000560
          00000600
          00000610

```



```

9  FORMAT(' DO YOU WANT TO SEE THE DATA YES=1 NO=0 ',#)
8  ACCEPT 8, MF
   FORMAT(I1)
11 IF(MP.EQ. 0) GO TO 16
   TYPE 11
   FORMAT('//          DATA SUMMARY'//
1'      THETA      PRESSURE      STANDARD DEVIATION')
13 TYPE 13, (TH(I), PSTAT(I,2), PSTAT(I,1), I=1,73)
   FORMAT(8X,F6.1,7X,F7.2,14X,F7.3)
14 TYPE 14, XMEP, PMEP, XHP, RPM
   FORMAT('      IMEP= ',F10.3,3X,'PMEP= ',F10.3,3X,'HP= ',
1F10.2,3X,'RPM= ',F7.2)
   C
   C
   C
   CONVERT PRESSURE TO ATM
16 DO 15 I=1,73
15 P(I) = PSTAT(I,2)/ATM
   RETURN
   END

```

```

C      PRINT HEADER INFORMATION FOR THIS INVOCATION OF XCLC
SUBROUTINE XPRNT1 (ENOT)
COMMON /XPRNTC/ P, TH, VOVRM, WOVRM, GOVRM, VUAV, VB,
      EUAV, EB, EB, TU, TRAV, TB
*
COMMON /VERBOS/ TALK, NRITE
COMMON /CHARGE/ PHI, DEL, PSI, RESFRN, CHMASS, GLOWER, TREF, CFUEL
C
      WRITE (NRITE,100) PHI,CHMASS,ENOT
100 FORMAT (1H, 'PHI =',F5.2,'SX', 'CHARGE MASS =',F7.4,
1      ' GRAMS', 'SX', 'INITIAL ENERGY =',F6.1, ' CAL/G'//)
C
      PRINT OUT TABLE HEADINGS AND FIRST LINE
C
      WRITE (NRITE,200)
200 FORMAT (1H, ' THETA',4X, 'P',6X, 'V/M',5X, 'W/M',6X, 'B/M',
      'SX', 'VULAV',5X, 'VBLAV',5X, 'EULAV',4X, 'EB',4X,
      ' TU',6X, 'TRAV',5X, 'GAMMA',5X, 'PHIBT',4X, 'PV',6X,
      'Z',1H, ' (DEG) (ATM) (CC/G) (CAL/G) (CAL/G)' ,
      ' (CC/G) (CC/G) (CAL/G) (CAL/G) (DEG N)' ,
      ' (DEG N) ' )
      RETURN
      END
C
C      PRINT PROPERTIES FOR MIXED CASE
SUBROUTINE XPRNT2 (X,GAMMA,PHITB,PVG)
COMMON /XPRNTC/ P, TH, VOVRM, WOVRM, GOVRM, VUAV, VB,
      EUAV, EB, EB, TU, TRAV, TB
*
COMMON /VERBOS/ TALK, NRITE
COMMON /CHARGE/ PHI, DEL, PSI, RESFRN, CHMASS, GLOWER, TREF, CFUEL
WRITE (NRITE,500) TH,P,VOVRM,WOVRM,GOVRM,VUAV,VB,EUAV,EB,
      TU,TRAV,GAMMA,PHITB,PVG,X
1
500 FORMAT (1H, 'F6.1,F7.2,F8.2,F9.1,F9.2,F9.1, 4F8.3)
      RETURN
      END
C
C

```

```

C*****
C
C SUBROUTINE STORE(P, TH, Z, GAMMA, PHITAB, FVG, NPTS )
C
C
C THIS ROUTINE WILL ASSIGN A FILE AND STORE THE OUTPUT FROM TEXJOB
C AND XCLC2
C*****
C SUBROUTINE STORE(P, TH, Z, GAMMA, PHITAB, FVG, NPTS )
C DIMENSION P(50), TH(50), Z(50), GAMMA(50), PHITAB(50), FVG(50)
C
C TYPE 100
C FORMAT(' DO YOU WANT TO STORE THE DATA YES=1 ', $)
C ACCEPT 200, NO
C FORMAT(I1)
C IF(NO.EQ. 0 ) GO TO 99
C TYPE 101
C FORMAT(' ASSIGN A FILE TO THE DATA'//)
C CALL ASSIGN(13, 'DEV:FILE.EXT', -1)
C DEFINE FILE 13(301,2,U,IT)
C XNPT = FLOAT(NPTS)
C XNPT = XNPT + 0.01
C
C STACK ALL THE DATA
C
C WRITE(13,1)XNPT
C IX = 1
C DO 10 I=1,NPTS
C IX=IX+1
C WRITE(13,IX) TH(I)
C DO 11 I=1,NPTS
C IX = IX + 1
C WRITE(13,IX) P(I)
C DO 12 I=1,NPTS

```

```
12      IX = IX + 1  
      WRITE(13,IX) Z(I)  
      DO 13 I=1,NPTS  
13      IX = IX + 1  
      WRITE(13,IX) PHITAB(I)  
      DO 14 I=1,NPTS  
14      IX = IX + 1  
      WRITE(13,IX) GAMMA(I)  
      DO 15 I=1,NPTS  
15      IX = IX + 1  
      WRITE(13,IX) FVG(I)  
      RETURN  
      END
```

```

C***** VERSION 2.0 *** 03-24-76 *****
C
C SUBROUTINE XCLC2
C
C PURPOSE:
C   TO CALCULATE MASS FRACTION OF FUEL BURNED VERSUS CRANK
C   ANGLE FOR A TCCS STRATIFIED CHARGE ENGINE FROM GIVEN
C   PRESSURE-TIME DATA
C
C USAGE:
C   CALL XCLC2 (P, TH, PHITAB, NPTS, INJ, Z, W, Q, GAMMA, FVG )
C
C DESCRIPTION OF PARAMETERS:
C   GIVEN:
C     P - A VECTOR OF MEASURED COMBUSTION CHAMBER PRESSURES
C         (ATM ABSOLUTE)
C     TH - A VECTOR OF CRANK ANGLES (DEGREES ATDC) AT WHICH
C           THE CORRESPONDING PRESSURE DATA POINTS WERE TAKEN
C     PHITAB- VECTOR OF AVERAGE BURNED PRODUCT EQUIVALENCE RATIOS
C              CORRESPONDING TO THE ANGLES TH(I) DURING INJECTION
C     NPTS - NUMBER OF DATA POINTS IN THE VECTORS P, TH, X, W, & Q
C           INJ - THE END OF THE INJECTION PERIOD
C           GIVEN IN COMMON AREA /CHARGE/ :
C     PHIAV - AVERAGE EQUIVALENCE RATIO OF THE CHARGE
C     DEL - MOLAR C:H RATIO OF THE FUEL
C     FSI - MOLAR N:O RATIO OF THE CHARGE (APPROX 3.76 FOR AIR)
C     RESFRK- MASS FRACTION OF THE CHARGE THAT IS RESIDUAL
C     CHMASS- TOTAL MASS OF CHARGE (GRAMS)
C     QLOWER- LOWER HEATING VALUE OF THE FUEL (KCAL/G) AT 293 DEG K
C     CFUEL - SPECIFIC HEAT (KCAL/G-DEG K) OF THE LIQUID FUEL
C           GIVEN IN COMMON AREA /ENGINE/ :
C     BORE - ENGINE BORE (CM)
C     STROKE- ENGINE STROKE (CM)
C     CONLEN- CONNECTING ROD LENGTH (CM) CENTER TO CENTER
C     VTDC - VOLUME OF THE CHAMBER AT TDC (CM**3)
C
000000010
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000000080
000000090
000000100
000000110
000000120
000000130
000000140
000000150
000000160
000000170
000000180
000000190
000000200
000000210
000000220
000000230
000000240
000000250
000000260
000000270
000000280
000000290
000000300
000000310
000000320
000000330
000000340

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C      HTDC - PISTON CLEARANCE HEIGHT AT TOP DEAD CENTER (CM)      00000350
C      VCUP - CUP VOLUME (CM**3)                                     00000360
C      ACUP - CUP SURFACE AREA (CM**2)                             00000370
C      RSUBC - CUP RADIUS (CM)                                     00000380
C      RTCAP - RADIUS FROM CUP CENTER TO CENTER OF TORUS CROSS    00000390
C              SECTION (CM)                                       00000400
C      RTSML - RADIUS OF TORUS CROSS SECTION (CM)                 00000410
C      DSUBC - CUP DEPTH FROM TOP TO TORUS MIDPLANE (CM)          00000420
C      W0 - BDC SWIRL RATE (RAD/SEC)                               00000430
C      RPM - ENGINE SPEED (REVOLUTIONS PER MINUTE)                00000440
C      TWALL - CYLINDER WALL TEMPERATURE (DEG K)                  00000450
C      GIVEN IN COMMON AREA /VERBOS/ ;                             00000460
C      TALK - A LOGICAL*4 VARIABLE , USED TO SET PRINTOUT MODE    00000470
C              IF TRUE, DETAILED LISTINGS OF PROPERTIES OF BURNED AND
C              UNBURNED ELEMENTS WILL BE PRODUCED ON THE FORTRAN FILE 00000480
C              WHOSE NUMBER IS GIVEN BY THE VARIABLE "UNIT"
C              IF FALSE, NO LISTINGS ARE PRODUCED
C      UNIT - AN INTEGER*4 VARIABLE GIVING THE FORTRAN FILE NUMBER 00000500
C              TO WHICH LISTINGS ARE TO BE WRITTEN                 00000510
C
C      RETURNS:
C      Z - VECTOR OF CUMULATIVE MASS FRACTION BURNED AT TIME TH(I) 00000520
C      W - VECTOR OF CUMULATIVE WORK DONE AT TIME TH(I) (CAL)      00000530
C      Q - VECTOR OF CUMULATIVE HEAT LOSS (CAL)                     00000540
C
C      PHITAB- VECTOR OF AVERAGE BURNT PRODUCT EQUIVALENCE RATIOS 00000550
C              CORRESPONDING TO THE ANGLES TH(I)
C      GAMMA - VECTOR OF WEIGHTED GAMMA                             00000560
C      PVG - VECTOR OF P*VOL**GAMMA                                00000570
C
C      REMARKS:
C      1) REPORT ANY PROBLEMS TO GORDON MARSH AT 253-3356           00000580
C      2) BURNT ZONE ASSUMED UNIFORM (FULLY MIXED)                 00000590
C      3) ANY EGR ASSUMED TO BE AT AVERAGE EQUIVALENCE RATIO OF CHARGE 00000600
C              00000610
C      SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED:               00000620
C              00000630
C              00000640
C              00000650
C              00000660
C              00000670
C              00000680

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C      HPROD, ATEMP, UPROP2, ADCOMP, TSUBU2, HEAT2, XPRINT2, GASVEL      00000690
C      00000700
C      00000710
C      00000720
C      00000730
C      00000740
C      00000750
C*****
C      SUBROUTINE XCLC2 (P, TH, PHITAB, NPTS, INJ, Z, W, Q, GAMMA, PUG ) *****00000760
C
C      DIMENSION P(NPTS), TH(NPTS), Z(NPTS), W(NPTS), Q(NPTS),      00000780
C      PHITAB(NPTS), GAMMA(NPTS), PUG(NPTS)      00000790
C      *      00000800
C      COMMON /CHARGE/ PHIAV, DEL, PSI, RESFRK, CHMASS, QLOWER, CFUEL      00000820
C      COMMON /ENGINE/ BORE, STROKE, CONLEN, VTDC, HTDC, VCUP, ACUP,      00000830
C      *      RSUBC, RTCAF, RTSML, DSUBC, W0, RPM, TWALL      00000840
C      COMMON /VERBOS/ TALK, UNIT      00000850
C      COMMON /HTDATA/ P1, T1, V1, PM      00000860
C      COMMON /XPRNTC/ PRES, THETA, VBAR, WOVRM, QOVRM, VUAV, VBAV, VB,      00000870
C      *      EUAV, ERAV, EB, TU, TRAV, TB      00000880
C
C      LOGICAL FIRST, TALK      00000890
C      REAL K1, K2, K3      00000900
C      INTEGER UNIT      00000910
C
C      DATA ERLIM /.001/, MAXITS /20/, MAXHTR /3/      00000940
C      DATA PIOVR8 /.39269908/, DTR /.01745329/      00000950
C      DATA R /1.9869/, FSCALE /2.42173E-2/      00000960
C      DATA TBMIN, TBMAX /400., 4000./      00000961
C
C      SET UP STATEMENT FUNCTIONS FOR COMBUSTION CHAMBER VOLUME, THE      00000970
C      DERIVATIVE OF VOLUME WITH RESPECT TO CRANK ANGLE, AND PISTON      00000980
C      CLEARANCE HEIGHT. ALSO ONE TO LIMIT O <= X <= 1      00000990
C
C      VOL(THR) = VTDC + B1*(B3 - COS(THR) - SQRT(COS(THR)**2 + B2))      00001020
C      DVDTHR(THR) = B1*SIN(THR)*(1. + COS(THR))/SQRT(COS(THR)**2 + B2))      00001030

```

```

C      HT(THR) = HTDC + S1*(R3 - COS(THR) - SQRT(COS(THR)**2 + B2))
C      CLIP(XX) = AMAX1(0.0 , AMIN1(1.0,XX))
C
C      SET UP PARAMETERS FOR THE STATEMENT FUNCTIONS AND COMPUTE WORK
C      DONE
C
C      R1 = P10VR8*BORE*BORE*STROKE
C      R2 = (CONLEN*2./STROKE)**2 - 1.0
C      R3 = 1.0 + 2.*CONLEN/STROKE
C      S1 = STROKE/2.0
C      GAMMAR = 0.
C
C      W(1) = 0.
C      FLAST = P(1)*PSCALE*DVDTTHR(DTR*TH(1))
C      DO 10 I = 2, NPTS
C      F = P(I)*PSCALE*DVDTTHR(DTR*TH(I))
C      W(I) = W(I-1) + .5*(FLAST + F)*(TH(I) - TH(I-1))*DTR
C      FLAST = F
C      10 CONTINUE
C
C      COMPUTE AMASS, FMASS, AND RMASS
C
C      EPS = (4.0*DEL)/(1.0 + 4.0*DEL)
C      F = (8.*EPS + 4.)/(28.*PSI + 32.)
C      AMASS = (1.-RESFRK)*CHMASS/(1.+PHIAV*F)
C      FMAST = AMASS * F * PHIAV
C      RMASS = CHMASS - AMASS - FMAST
C      DMASS = FMAST / FLOAT(INJ)
C      RESID = RESFRK
C
C      SET FMASS = THE FIRST INJECTION INCREMENT
C
C      FMASS = DMASS
C      CHMASS = AMASS + RMASS + FMASS
C      RESFRK = RMASS/CHMASS

```

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00001170
00001180
00001190
00001200
00001210

00001350
00001360

```

C
C
C
      PHIAT = PHIAY
      SET UP INITIAL VALUES BEFORE LOOPING THROUGH TIME
      Z(1) = 0.
      Q(1) = 0.
      THETA = TH(1)
      PHIB = PHITAB(1)
      PRES = P(1)
      CVOL = VOL(DTR*THETA)
      VBAR = CVOL/CHMASS
      INITIALIZE CONSTANTS RELATING X, Y, AND Z
      CALCULATE INITIAL TEMPERATURE OF UNBURNED CHARGE
      RHO = ( AMASS + RMASS )/CVOL
      TMOL = PSI + (1.0 - RESFRK)
      IF (PHIAY .LE. 1.0) TMOL = TMOL + (1.0 + PHIAY*(1.-EPS))*RESFRK
      IF (PHIAY .GT. 1.0) TMOL = TMOL + (2.0 - EPS)*PHIAY*RESFRK
      XMAV = (32. + 28.*PSI + (8.*EPS + 4.)*PHIAY*RESFRK)/TMOL
      TU = PRES*FSCALE*XMAV/(RHOXR)
      GET INITIAL PROPERTIES OF THE FUEL
      VUFAY = TUX82.057*DEL/(96.08*DEL + 8.06)/PRES
      EUFAY = (ABS(QLOWER) - (115.596-21.542*EPS)/(8.*EPS + 4.))*1000.
      GET INITIAL PROPERTIES OF UNBURNED CHARGE
      CALL UPROP2 (PRES, TU, PHIAY, DEL, PSI, RESID, ENTHLP, CSUBP,
      *          CSURT, RHO, DRHODT, DRHODF)
      EO = ENTHLP*1000. - PRES*FSCALE/RHO
      VUAV = 1.0/RHO
      EUAV = EO
      00001220
      00001230
      00001240
      00001250
      00001260
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      00001590
      00001600
      00001610
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      00001630
      00001631
      00001632

```

```

C
C
C
GAMMAU = (TU*DRHODT*DRHODT*FSCALE)/(RHO*RHO*DRHODP*CSUBP)
GAMMAU = 1.0 / (1.0 - GAMMAU)
GAMMA(1) = GAMMAU
PNOT = PRES
UNOT = CVOL
PVG(1) = 1.0
IF (TALK) CALL XPRNT1 (E0)
00001660
00001670
00001860

GET THE ACTUAL PHIIV AT CURRENT THETA
PHIAV = FMASS / ( AMASS * F )
C1 = (1.0 + PHIIV*F)/(AMASS+FMASS)/CHMASS
C2SAVE = (1.0 + F*PHIAV*RESFRK)/(1.0 - RESFRK)
C2 = C2SAVE + F*PHIB
K1 = F*PHIAV/C1
K2 = F*PHIB/C2
K3 = K2/K1
00001380

GET INITIAL HEAT TRANSFER RATE
P1 = PRES
V1 = CVOL
T1 = TU
PM = PRES
CALL AFTEMP (PRES, TU, TU, 298., CFUEL, GLOWER, PHIB, DEL,
*          PSI, RESFRK, TRAV)
CALL HEAT2 (PRES, THETA, TU, TRAV, 0.0, DQBNTL, DQUDTL)
CALL HPROD (PRES, TRAV, PHIB, DEL, PSI, ENTHLP, CSUBP, CSURT, RHO, 00001780
*          DRHODT, DRHODP)
VRVAV = 1.0/RHO
EBAV = ENTHLP*1000. - PRES*FSCALE/RHO
GOVRM = 0.
WOVRM = 0.
00001790
00001800
00001810
00001820
00001830
00001850

IF (TALK) CALL XPRNT2 (Z(1), GAMMA(1), PHITAB(1), PVG(1))

```

```
START LOOP THROUGH TIME; INITIALIZE PROPERTIES CONSTANT FOR
GIVEN TIME
```

NO 2001 = 2, NPTS

CORRECT THE CHARGE MASS DURING INJECTION

```

IF(I .GT. INJ) GO TO 88
FMASS = FMASS + IMASS
CHMASS = FMASS + AMASS + RMASS
PHIAV = FMASS/(AMASS*F)
PRESFRK = RMASS/CHMASS
PHITAB(I) = PHITAB(I-1)
MAE = FMASS / (PHITAB(I)*F)
IF(I .LT. (INJ+3)) GO TO 87
CHT = HT(DTR*TH(I-1))

```

```

CX = CLIP(X)
CALL PLUME( CHT, DELT, VBAV, VUAV, CX, AENT )
MAE = MAE + AENT
PHITAB(I) = FMAS / (MAE*F)
IF (PHITAB(I) .LT. PHIAT ) PHITAB(I) = PHIAT
CONTINUE

```

00001960
00001970
00001980
00001990
00002000
00002010
00002020
00002030

```
TELAST = TRAV
QLAST  = Q(I - 1)
FLAST  = PRES
TULAST = TU
```

```

THETA = TH(I)
PRES = P(I)
DELT = (THETA - TH(I-1))/(6.0*RFM)

```

```

CVOL = VOL(DTR*THETA)
PM = P1*(V1/CVOL)**GAMMAU
VBAR = CVOL/CHMASS
WVRM = W(I)/CHMASS
QVRM = (QLAST + QBDTL*DELT)/CHMASS
TU = TSUBU2 (PRES, PLAST, TULAST, ERLIM)
VUFV = TU * 82.057 * DEL/(96.08*DEL+8.06)/PRES
PHIB = PHITAB(I)
C1 = (1. + PHIAV*F)/((AMASS+FMASS)/CHMASS)
C2SAVE = (1.0 + F*PHIAV*RESFRN)/(1.0 - RESFRN)
C2 = C2SAVE + F*PHIB
N2 = F*PHIB/C2
N3 = (PHIB*C1)/(PHIAV*C2)

CALCULATE AVERAGE PROPERTIES OF UNBURNED CHARGE

CALL UPROP2 (PRES, TU, PHIAV, DEL, PSI, RESID, ENTHLP, CSUBP,
             CSUBT, RHO, DRHOOT, DRHOOP)
VUAV = 1.0/RHO
EUAV = ENTHLP*1000. - PRES*PSCALE/RHO
VUITL = N1*VUFV + (1.0 - N1)*VUAV
VU2TL = N2*VUFV + (1.0 - N2)*VUAV
EUITL = N1*EUAV + (1.0 - N1)*EUAV
EU2TL = N2*EUAV + (1.0 - N2)*EUAV
EBAR = E0 - WVRM - QVRM

SOLVE CONSERVATION EQUATIONS.
FIRST ITERATE TO GET AVERAGE BURNED GAS TEMPERATURE

DO 100 THEAT = 1, MAXHTR
DO 110 NCOUNT = 1, MAXITS
CALL HPROD (PRES, TELAST, PHIB, DEL, PSI, ENTHLP, CSUBP,
            CSUBT, RHO, DRHOOT, DRHOOP)
DVBDB = -DRHOOT/(RHO*RHO)
DEBDB = CSUBP - PRES*PSCALE*DVBDB

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00002110
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00002200
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00002211
00002212
00002213
00002214
00002230
00002240
00002250
00002260
00002270
00002280
00002290
00002300
00002310
00002321
00002322

```

C
C
C

C
C
C
C

100

*

```

110      VBAV = 1./RHO
      EBAV = ENTHLF*1000. - PRES*PSCALE/RHO
      DGDTR = (VBAR - VUITL)/(EBAR - EUITL)*(VBAV-VU2TL)**2)
      G      = ((VBAV - VU2TL)*DGDTR - (EBAR - EU2TL)*DGDTR)/
      *      = (VBAR - VUITL)*(EBAR - EU2TL)/
      *      = ((EBAR - EUITL)*(VBAV - VU2TL)) - 1.0
      TBAV = TBLAST - G/DGDTR
      IF (ABS(1. - TBAV/TBLAST) .LT. ERLIM) GO TO 120
      TBAV = AMAX1 (TU , AMIN1 (TBMX,TBAV))
      TBLAST = TBAV
      CONTINUE
      THEN CALCULATE X DIRECTLY, AND UPDATE HEAT TRANSFER
      ESTIMATE
      X = (VBAR - VUITL)/(VBAV - VU2TL)
      CALL HEAT2 (PRES, THETA, TU, TBAV, VBAV*CHMASS*CLIP(X),
      *      DQBDT, DQUDT)
      Q(I) = QLAST + .5*(DQBDT + DQBDTL)*DELT
      QOVRM = Q(I)/CHMASS
      EBAR = EO - WOVRM - QOVRM
      TBLAST = TBAV
      CONTINUE
      GAMMAB=TBLAST*DRHODT*DRHODT*FSCALE/(RHO*RRHO*DRHODP*CSUBP)
      GAMMAB = 1. / (1. - GAMMAB)
      DQBDTL = DQBDT
      Z(I) = K3**FMASS/FMAST
      XF=CLIP(Z(I))
      GAMMA(I) = ((1.-XF)*GAMMAU+XF*GAMMAB)
      PVG(I) = (P(I)*CVOL**GAMMA(I))/(PNOT*VNUT**GAMMA(I))
      IF (TALN) CALL XFRNT2(Z(I),GAMMA(I),PHITAB(I),PVG(I))
      CONTINUE
      RETURN
      END

```



```

SINTH = SIN (DIR*THETA)
S = SQRT (COSTH*COSTH + M)
TEMP = LOVAP1 - COSTH - S
C
HT = HTDC + .5*STROKE*TEMP
CVOL = VTDC + .5*STROKE*PI*RR*TEMP
UPRAT = - SINTH*(1.0 + COSTH/S)/VSCALE
C
X = HT/K
BTOM2 = 1.0/(B*K)
C
CALCULATE DIMENSIONLESS VELOCITY RATIOS AS IN NOTES
C
URRAT = (BTOM2 - 1.0)*UPRAT*RSUBC/(2.0*K*XX*(1.0 + X))
VZRAT = (BTOM2 - 1.0)*VPRAT/((1.0 + X)*(1.0+ B*B*XX))
VTRAT = BTOM2 - (BTOM2 - 1.0)*(X*(1.0+X0))/(X0*(1.0+X))
C
GET APPROPRIATE MAXIMUM PISTON SPEED AND CALCULATE VELOCITIES
C
VFMAX = PI*RRPM*STROKE*VSCALE/30.
VR3 = URRAT*VFMAX
VT3 = VTRAT*W0*RSUBC
VZ3 = VZRAT*VFMAX
C
RETURN
END

```

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00000720
00000730
00000740
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00000790
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00000810
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00000870
00000880
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00000940
00000950

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```

C***** VERSION 1.0 *** 11-03-74 *****00000010
C SUBROUTINE HEAT2                                00000020
C                                                    00000030
C                                                    00000040
C PURPOSE:                                         00000050
C   TO CALCULATE HEAT TRANSFER IN A TCCS STRATIFIED CHARGE ENGINE 00000060
C                                                    00000070
C USAGE:                                           00000080
C   CALL HEAT2 (P, THETA, TU, TR, VOLB, DQBDT, DQDUT) 00000090
C                                                    00000100
C DESCRIPTION OF PARAMETERS:                      00000110
C GIVEN:                                           00000120
C   P - ABSOLUTE CYLINDER PRESSURE (ATM)          00000130
C   THETA - CORRESPONDING CRANK ANGLE (DEG ATDC)  00000140
C   TU - AVERAGE UNBURNED GAS TEMPERATURE (DEG K) 00000150
C   TR - AVERAGE BURNED GAS TEMPERATURE (DEG K)  00000160
C   VOLB - VOLUME OF THE BURNED GAS (CM**3)       00000170
C   GIVEN IN COMMON AREA /ENGINE/ :              00000180
C   BORE - ENGINE BORE (CM)                       00000190
C   STROKE - ENGINE STROKE (CM)                   00000200
C   CONLEN - CONNECTING ROD LENGTH (CM) CENTER TO CENTER 00000210
C   VTDC - VOLUME OF THE CHAMBER AT TDC (CM**3)   00000220
C   HTDC - CLEARANCE HEIGHT AT TDC (CM)           00000230
C   VCUP - CUP VOLUME (CM**3)                    00000240
C   ACUP - CUP SURFACE AREA (CM**2)              00000250
C   RSUBC - CUP RADIUS (CM)                      00000260
C   RTCAP - RADIUS FROM CUP CENTER TO CENTER OF TORUS CROSS 00000270
C   SECTION (CM)                                  00000280
C   RTSML - RADIUS OF TORUS CROSS SECTION (CM)   00000290
C   DSUBC - CUP DEPTH FROM TOP TO TORUS MIDPLANE (CM) 00000300
C   W0 - BDC SWIRL RATE (RAD/SEC)                 00000310
C   RPM - ENGINE SPEED (REVOLUTIONS PER MINUTE) (NOT USED) 00000320
C   TWALL - CYLINDER WALL TEMPERATURE (DEG K)    00000330
C   GIVEN IN COMMON AREA /HTDATA/ :              00000340
C   P1 - PRESSURE AT REFERENCE TIME (ATM)        00000350

```

```

C      P1 - TEMPERATURE AT REFERENCE TIME (DEG K)
C      V1 - VOLUME AT REFERENCE TIME (CM**3)
C      PM - EQUIVALENT PRESSURE IN THE MOTORING ENGINE (ATM)
C
C      RETURNS:
C      DQBDT - HEAT TRANSFER RATE FROM BURNED GAS TO THE WALL
C              (CAL/SEC)
C      DQUDT - HEAT TRANSFER RATE FROM UNBURNED GAS TO THE WALL
C              (CAL/SEC)
C
C      SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED:
C      GASVEL
C
C      REMARKS:
C      1) ASSUMED TOROIDAL FLAME FRONT
C      2) REPORT ANY PROBLEMS TO MIKE MARTIN AT 253-2411
C
C      METHOD:
C      WOSCHNI'S CORRELATION (SEE SAE PAPER NUMBER 670931)
C
C      *****
C      SURROUTINE HEAT2 (P, THETA, TU, TB, VOLB, DQBDT, DQUDT)
C      COMMON /ENGINE/ BORE, STROKE, CONLEN, VTDC, HTDC, VCUP, ACUP,
C      *          RSUBC, RTCAF, RTSML, DSUBC, WO, RPM, TWALL
C      COMMON /HTDATA/ P1, T1, V1, PM
C
C      DATA PI /3.14159265/, DTR /.01745329/
C      DATA PSCL /.967836/
C      DATA ERLIM /.005/, MAXITS /50/
C
C      VOL(THR) = VTDC + VDSP*(H1 - COS(THR) - SQRT(COS(THR)**2 + H2))
C      HT(THR) = HTDC + HDSP*(H1 - COS(THR) - SQRT(COS(THR)**2 + H2))
C
C      H1 = 1.0 + 2.0*CONLEN/STROKE
C      H2 = (2.0*CONLEN/STROKE)**2 - 1.0
00000360
00000370
00000380
00000390
00000400
00000410
00000420
00000430
00000440
00000450
00000460
00000470
00000480
00000490
00000500
00000510
00000520
00000530
00000540
00000550
00000560
00000570
00000580
00000590
00000600
00000610
00000620
00000630
00000640
00000650
00000660
00000670
00000680
00000690
00000700

```

```

C      VDSP = STROKE*PI*BORE*BORE/8.0
C      HDSP = STROKE/2.0
C      CALCULATE HEAT TRANSFER AREAS.  FOR NOW, USE SIMPLE APPORTIONMENT
C
C      RAD = BORE/2.0
C      CHT = HT(DTR*THETA)
C      CVOL = VOL(DTR*THETA)
C      VR = AMINI ( CVOL, AMAXI(0.,VOLB))
C      AREA = ACUP + PI*RAD*(RAD + 2.0*CHT)
C      AB = ACUP
C      IF (VR .LE. VCUP)  AB = ACUP*(VR/VCUP)**.6666666666
C      AU = AREA - AB
C
C      GET GAS VELOCITIES INSIDE THE CUP
C
C      CALL GASVEL (THETA, VOLB, VR3, VT3, VZ3)
C
C      CALCULATE THE HEAT TRANSFER COEFFICIENT USING WOSCHNI'S EQUATION
C      (CONVERT TO CAL/CM**2 SEC DEG_K)
C
C      C1 = 2.28
C      C2 = 3.24E-3
C      CM = .01*SQRT(VT3*VT3 + VR3*VR3 + VZ3*VZ3)
C
C      DELP = AMAX1(P - PM , 0.)
C      FACTR = 110.*(BORE/100.)**(-.2)*(P*P*SCL)**(.8)
C      FACTR = FACTR*((C1*CM + C2*TI*(CVOL/V1)*(DELP/P1))**(.8))
C
C      HB = FACTR*(TB**(-.53))/36000.
C      HU = FACTR*(TU**(-.53))/36000.
C
C      THEN CALCULATE HEAT TRANSFER RATES AND RETURN
C
00000710
00000720
00000730
00000740
00000750
00000760
00000770
00000780
00000790
00000800
00000810
00000820
00000830
00000840
00000850
00000860
00000870
00000880
00000890
00000900
00000910
00000920
00000930
00000940
00000950
00000960
00000970
00000980
00000990
00001000
00001010
00001020
00001030
00001040
00001050

```

DQEDT = AB*HE*(TB - TWALL)
DQUDT = AUXHU*(TU - TWALL)

RETURN
END

00001060
00001070
00001080
00001090

C*****

SUBROUTINE PLUME

THIS ROUTINE WILL CALCULATE THE AMOUNT OF AIR ENTRAINED
IN THE BURNING PLUME OF COMBUSTION PRODUCTS IN A TCCS ENGINE
USING THE MIXING MODEL PROPOSED BY JAIN.

USAGE:

CALL PLUME(CHT, DELT, VBAV, VUAV, CX, AENT)

DESCRIPTION OF PARAMETERS:

GIVEN:

CHT -COMBUSTION CHAMBER HEIGHT
DELT -TIME INTERVAL FOR ENTRAINMENT
VBAV -SPECIFIC VOLUME OF THE BURNT GAS
VUAV -SPECIFIC VOLUME OF THE AIR AND RESIDUAL
CX -A CLIPPED FRACTION OF CHARGE MASS BURNT

RETURNS:

AENT -THE MASS OF AIR ENTRAINED IN THAT TIME STEP

INTERNALLY DEFINED VALUES:

RSP -THE SPARK PLUG RADIUS
DVAL -THE INTAKE VALVE DIAMETER
LVAL -THE INTAKE VALVE LIFT
EFFV -THE AVERAGE VOLUMETRIC EFFICIENCY
ALPHA -AN ADJUSTABLE ENTRAINMENT COEFFICIENT

C*****

SUBROUTINE PLUME(CHT, DELT, VBAV, VUAV, CX, AENT)
COMMON/CHARGE/PHIAV,DEL,PSI,RESFRK,CHMASS,QLOWR,CFUEL
COMMON/ENGINE/BORE,STROKE,CONLEN,VTDC,HTDC,VCUP,ACUP,
* RSUBC,RTCAP,RTSML,DSUBC,W0,RPM,TWALL

```

REAL LVAL
RSP = 1.9
DVAL = 4.0
LVAL = 1.558
EFFV = 0.87
ALPHA = 0.05
PL = RSUBC - RSP
DCP = 2.*RSUBC
RPL1 = PL
RPL2 = RSP
RPL3 = BORE/2. - RSP
VB1 = 19.75 * RSP * FL**2
VB2 = 12.57 * CHT * RSP**2 + 0.7854 * (RSUBC - CHT)*DCP**2
VB3 = 0.785 * CHT * DORE**2 + 0.7854*(BORE/2.-RSP+PL-CHT)
J*DCP**2
VBA = VBAV * CHMASS * CX
IF ( VBA .LE. VB1) GO TO 120
IF ( VBA .LE. VB2) GO TO 110
IF ( VBA .LE. VB3) GO TO 100
SE3 = 0.7854 * DCP**2
SE = SE3
GO TO 900
100 RPL = RPL2+(RPL3-RPL2)*((VBA-VB2)/(VB3-VB2))*0.333
SE = 6.20 * (RSP + RPL ) * CHT +0.7854 * DCP**2
GO TO 900
110 RPL = RPL1 + (RPL2-RPL1)*((VBA-VB1)/(VB2-VB1))*0.333
SE=6.20*(RSP+RPL)*CHT + 3.14 * (3.*(RSP-RPL)+RSUBC)*(RPL+PL)
GO TO 900
120 RPL = SQRT(VBA/19.75*RSP)
SE = 39.4 * RSP* RPL
UE = 0.23*EFFV*STROKE*RPM*BORE**2/(DVAL*LVAL)*0.5
AENT = ALPHA * SQRT(1./(VBAV*VUAV))*SE*UE*DELT
RETURN
END

```



```

C      IN THE PRESENT IMPLEMENTATION THE ENTHALPIES OF FORMATION
C      OF CO2 AND H2O ARE ASSUMED TO BE TEMPERATURE INDEPENDENT
C
C      METHOD:
C      SEE MATHEMATICAL NOTES
C
C*****
C      SUBROUTINE AFTMP (P,TA,TR,TF,TREF,CFUEL,QLOWER,PHI,DEL,PSI,
C      1      RESFRK,TPROD)
C
C      DATA ROVR2/.99345E-3/,CPGUES/.30E-3/
C      DATA DHC02,DHH20/-94.054,-57.798/
C
C      STATEMENT FUNCTION FOR ENTHALPY OF AIR
C      HSUBA(T) = (7.*(1. + PSI)*T + 4460.)/(EXP(2230./T) - 1.)
C      1      + PSI*6680./(EXP(3340./T)- 1.)) * ROVR2/AIRWT
C
C      EPS = (4.*DEL)/(1. + 4.*DEL)
C      AIRWT = 32. + 28.*PSI
C      FUELWT = (8.*EPS + 4.)*PHI
C      TOTWT = AIRWT + FUELWT
C
C      GET ENTHALPY OF THE RESIDUAL
C
C      CALL HPROD(P,TR,PHI,DEL,PSI,HSUBP,DUMY,DUMY,DUMY,DUMY,DUMY)
C      HSURP = RESFRK*HSUBP
C
C      ADD THE ENTHALPY OF THE AIR
C
C      HSURP = HSURP + HSUBA(TA)*(1.0 - RESFRK)*AIRWT/TOTWT
C
C      GET HEAT OF FORMATION OF THE FUEL AND ADD TOTAL FUEL ENTHALPY
C
C      DHFUEL = ABS(QLOWER) + (EPS*DHC02 + 2.*(1.-EPS)*DHH20)/FUELWT*PHI
C      HSURP = HSURP + (1.- RESFRK)*(DHFUEL + CFUEL*TF)*FUELWT/TOTWT

```

```

C
C
C      SET PARAMETERS FOR TEMP
      TGUSS = TA + ABS(QLOWER)/CPGUES*FUELWT/TOTWT
      ERMAX = .001
      MAXITS = 50
C
C      CALL TEMP(P,TGUSS,PHI,DEL,PSI,HSUBP,TPROD,ERNAX,MAXITS,IER)
      RETURN
      END
      AFTP 720
      AFTP 730
      AFTP 740
      AFTP 750
      AFTP 760
      AFTP 770
      AFTP 780
      AFTP 790
      AFTP 800
      AFTP 810

```

```

C***** VERSION 1.1 *** 8/01/74 *****CLDP 10
C SUBROUTINE CLDPRD CLDP 20
C CLDP 30
C CLDP 40
C CLDP 50
C CLDP 60
C CLDP 70
C CLDP 80
C CLDP 90
C CLDP 100
C CLDP 110
C CLDP 120
C CLDP 130
C CLDP 140
C CLDP 150
C CLDP 160
C CLDP 170
C CLDP 180
C CLDP 190
C CLDP 200
C CLDP 210
C CLDP 220
C CLDP 230
C CLDP 240
C CLDP 250
C CLDP 260
C CLDP 270
C CLDP 280
C CLDP 290
C CLDP 300
C CLDP 310
C CLDP 320
C CLDP 330
C CLDP 340
C CLDP 350

PURPOSE:
  TO CALCULATE THE SPECIFIC ENTHALPY OF THE PRODUCTS OF HC-AIR
  COMBUSTION AT TEMPERATURES AND PRESSURES WHERE DISSOCIATION
  OF THE PRODUCT GASES MAY BE IGNORED. THE DENSITY OF THE
  PRODUCT GAS IS ALSO CALCULATED, AS ARE THE PARTIAL
  DERIVATIVES OF BOTH OF THESE QUANTITIES WITH RESPECT TO
  PRESSURE AND TEMPERATURE.

USAGE:
  CALL CLDPRD(P,T,PHI,DEL,PSI,ENTHLP,CSUBP,CSURT,RHO,DRHODT,
              DRHODP,IER)

DESCRIPTION OF PARAMETERS:
  GIVEN:
    P - ABSOLUTE PRESSURE OF PRODUCTS (ATM)
    T - TEMPERATURE OF PRODUCTS (DEG K)
    PHI - EQUIVALENCE RATIO (FUEL/AIR RATIO DIVIDED BY THE
          CHEMICALLY CORRECT FUEL/AIR RATIO)
    DEL - MOLAR C:H RATIO OF THE PRODUCTS
    PSI - MOLAR N:O RATIO OF THE PRODUCTS

  RETURNS:
    ENTHLP- SPECIFIC ENTHALPY OF THE GAS (KCAL/G)
    CSUBP - PARTIAL DERIVATIVE OF ENTHLP WITH RESPECT TO T
             AT CONSTANT P (CAL/G-DEG K)
    CSURT - PARTIAL DERIVATIVE OF ENTHLP WITH RESPECT TO P
             AT CONSTANT T (CC/G)
    RHO - DENSITY OF THE MIXTURE (G/CC)
    DRHODT- PARTIAL DERIVATIVE OF RHO WITH RESPECT TO T AT
             CONSTANT P (G/CC-DEG K)
    DRHODP- PARTIAL DERIVATIVE OF RHO WITH RESPECT TO P AT
             CONSTANT T (G/CC-ATM)

```

```

C IER - FLAG, SET TO 1 FOR T<100 DEG K
C 2 FOR T> 6000 DEG K
C 0 OTHERWISE
C
C REMARKS:
C 1) ENTHALPY DATUM STATE IS AT T = 0 ABSOLUTE WITH
C 02,N2,H2 GASEOUS AND C SOLID GRAPHITE
C 2) IN CASE OF PROBLEMS CONTACT MIKE MARTIN AT 253-2411
C (ROOM 3-339 D)
C
C SUBROUTINES AND FUNCTION SUBPROGRAMS NEEDED: NONE
C
C METHOD:
C DESCRIBED IN APPENDIX IV OF WRITEUP
C
C*****
C SUBROUTINE CLDPD(P,T,PHI,DEL,PSI,ENTHLP,CSUBF,CSURT,RHO,
C 1 DRHODT,DRHODP,IER)
C
C LOGICAL RICH,LEAN
C DIMENSION A(6,6,2),X(6)
C DIMENSION A1(36),A2(36)
C EQUIVALENCE (A1(1),A(1,1,1)),(A2(1),A(1,1,2))
C REAL*4 MBAR,K
C
C INITIALIZE PARAMETERS, AND CHECK TO SEE IN WHAT TEMPERATURE
C RANGE WE ARE SO THAT THE CORRECT FITTED COEFFICIENTS WILL BE
C USED. FLAG TEMPERATURES TOO BIG OR TOO SMALL
C
C DATA A1/11.94033,2.088581,-0.47029,.037363,-.589447,-97.1418,
C 1 6.139094,4.60783,-.9356009,.06669498,.0335801,-56.62588,
C 2 7.099556,1.275957,-.2877457,.022356,-.1598696,-27.73464,
C 3 5.555680,1.787191,-.2881342,.01951547,.1611828,.76498,
C 4 7.865847,.6883719,-.031944,-.00268708,-.2013873,-.893455,
C 5 6.807771,1.453404,-.328985,.02561035,-.1189462,-.331835/
C
C CLDP 360
C CLDP 370
C CLDP 380
C CLDP 390
C CLDP 400
C CLDP 410
C CLDP 420
C CLDP 430
C CLDP 440
C CLDP 450
C CLDP 460
C CLDP 470
C CLDP 480
C CLDP 490
C CLDP 500
C*****CLDP 510
C CLDP 520
C CLDP 530
C CLDP 540
C CLDP 550
C CLDP 560
C CLDP 570
C CLDP 580
C CLDP 590
C CLDP 600
C CLDP 610
C CLDP 620
C CLDP 630
C CLDP 640
C CLDP 650
C CLDP 660
C CLDP 670
C CLDP 680
C CLDP 690
C CLDP 700

```

```

DATA A2/4.737305,16.65283,-11.23249,2.828001,.00676702,-93.75793,
7 7.809672,-.2023519,3.418708,-1.179013,.00143629,-57.08004,
8 6.97393,-.8238319,2.942042,-1.176239,.0004132409,-27.19597,
9 6.991878,.1617044,-.2182071,.2968197,-.01625234,-.118189,
8 6.295715,2.388387,-.0314788,-.3267433,.00435925,.103637,
- 7.092199,-1.295825,3.20688,-1.202212,-.0003457938,-.013967/

C
RICH = PHI .GT. 1.0
LEAN = .NOT. RICH
EPS = 4.*DEL/(1. + 4.*DEL)
IER = 0
IF (T .LT. 100.) IER = 1
IF (T .GT. 6000.) IER = 2
IR = 1
IF (T .LT. 500.) IR = 2

C
C
C
GET THE COMPOSITION IN MOLES/MOLE OXYGEN

IF (RICH) GO TO 10
X(1) = EPS*PHI
X(2) = 2.*(1. - EPS)*PHI
X(3) = 0.
X(4) = 0.
X(5) = 1. - PHI
GO TO 20
10 Z = 1000./T
K = EXP(2.743 + Z*(-1.761 + Z*(-1.611 + Z*.2803)))
ALPHA = 1. - K
BETA = (2.*(1. - EPS*PHI) + K*(2.*(PHI - 1.) + EPS*PHI))
GAMMA = 2.*K*EPS*PHI*(PHI - 1.)
C = (- BETA + SQRT(BETA*BETA + 4.*ALPHA*GAMMA))/(2.*ALPHA)
X(1) = EPS*PHI - C
X(2) = 2.*(1. - EPS*PHI) + C
X(3) = C
X(4) = 2.*(PHI - 1.) - C
CLDP 710
CLDP 720
CLDP 730
CLDP 740
CLDP 750
CLDP 760
CLDP 770
CLDP 780
CLDP 790
CLDP 800
CLDP 810
CLDP 820
CLDP 830
CLDP 840
CLDP 850
CLDP 860
CLDP 870
CLDP 880
CLDP 890
CLDP 900
CLDP 910
CLDP 920
CLDP 930
CLDP 940
CLDP 950
CLDP 960
CLDP 961
CLDP 970
CLDP 980
CLDP 990
CLDP1000
CLDP1010
CLDP1020
CLDP1030
CLDP1040

```


DRHODT = -RHO/T
DRHODP = RHO/P
ALL DONE
RETURN
END

CLDP1400
CLDP1410
CLDP1420
CLDP1430
CLDP1440

C
C


```

C
DYDTP = DYDX*DXDADADTP
DYDPT = DYDX*DXDADADPT
DUDTP = DUDXFT*DXDADADTP + DUDTPX
DUDPT = DUDXFT*DXDADADPT + DUDPTX

DHFDPT = C3*DYDPT + C4*DUDPT
DC2DPT = -2.*(3.*DYDPT + DUDPT)
DC1DPT = 5.*DYDPT + 3.*DUDPT
DHFDTP = C3 * DYDTP + C4*DUDTP
DC2DTP = -2.*(3.*DYDTP + DUDTP)
DC1DTP = 5.*DYDTP + 3.*DUDTP

TV0 = (3000. - 2000.*EPS + 300.*PSI)/(1. - .5*EPS + .09*PSI)
EARG = EXP(TV0/T)
TV = TV0/(EARG - 1.)
DTVDT = TV0*EARG/(1*(EARG - 1.))*2 *TV0

AMCP = (8.*EPS + 4.)*PHI + 32. + 28.*PSI
C1 = 7.*PSI + 5.*Y + 3.*U
C2 = 2.*(PSI - 3.*Y - U)
IF (LEAN) C1 = C1 + 7. + (9. - 8.*EPS)*PHI
IF (RICH) C1 = C1 + 2. + 2.*(7. - 4.*EPS)*PHI
IF (LEAN) C2 = C2 + 2.*(1. + (5. - 3.*EPS)*PHI)
IF (RICH) C2 = C2 + 2.*(4. + (2. - 3.*EPS)*PHI)

CSURP = ROVR2/AMCP*(C1 + T*DC1DTP + C2*DTVDT + TV*DC2DTP
1      + DHFDTP)
CSURT = ROVR2/AMCP*(T*DC1DTP + TV*DC2DTP + DHFDTP)*SCALF

C
IF (LEAN) G = 1. + (1.-EPS)*PHI + PSI + Y + U
IF (RICH) G = (2.- EPS)*PHI + PSI + Y + U
G = -AMCP/G**2
DMDTP = G*(DYDTP + DUDTP)
DMDPT = G*(DYDPT + DUDPT)

C
DRVS 360
DRVS 370
DRVS 380
DRVS 390
DRVS 400
DRVS 410
DRVS 420
DRVS 430
DRVS 440
DRVS 450
DRVS 460
DRVS 470
DRVS 480
DRVS 490
DRVS 500
DRVS 510
DRVS 520
DRVS 530
DRVS 540
DRVS 550
DRVS 560
DRVS 570
DRVS 580
DRVS 590
DRVS 600
DRVS 610
DRVS 620
DRVS 630
DRVS 640
DRVS 650
DRVS 660
DRVS 670
DRVS 680
DRVS 690
DRVS 700

```

DRHODT = .012187*F/T*(DMDTF - AMWT/T)
DRHODP = .012187/T*(AMWT + F*DMDFT)

RETURN
END

DRVS 710
DRVS 720
DRVS 730
DRVS 740

```

C***** VERSION 1.0 *** 5/29/74 *****HPRD 010
C
C SUBROUTINE HPROD HPRD 020
C
C
C HPRD 030
C
C HPRD 040
C
C HPRD 050
C
C HPRD 060
C
C HPRD 070
C
C HPRD 080
C
C HPRD 090
C
C HPRD 100
C
C HPRD 110
C
C HPRD 120
C
C HPRD 130
C
C HPRD 140
C
C HPRD 150
C
C HPRD 160
C
C HPRD 170
C
C HPRD 180
C
C HPRD 190
C
C HPRD 200
C
C HPRD 210
C
C HPRD 220
C
C HPRD 230
C
C HPRD 240
C
C HPRD 250
C
C HPRD 260
C
C HPRD 270
C
C HPRD 280
C
C HPRD 290
C
C HPRD 300
C
C HPRD 310
C
C HPRD 320
C
C HPRD 330
C
C HPRD 340
C
C HPRD 350

PURPOSE:
  TO CALCULATE THE SPECIFIC ENTHALPY OF THE PRODUCTS OF HYDRO-
  CARBON-AIR COMBUSTION AS A FUNCTION OF TEMPERATURE AND PRES-
  SURE, USING AN APPROXIMATE CORRECTION FOR DISSOCIATION,
  THE PARTIAL DERIVATIVES OF H WITH RESPECT TO THESE VARIABLES
  ARE ALSO CALCULATED, ALONG WITH THE GAS DENSITY AND ITS PAR-
  TIAL DERIVATIVES

USAGE:
  CALL HPROD(P,T,PHI,DEL,FSI,ENTHLP,CSURF,CSUBT,RHO,DRHODT,
             DRHODP)

DESCRIPTION OF PARAMETERS:
  GIVEN:
    P - ABSOLUTE PRESSURE OF PRODUCTS (ATM)
    T - TEMPERATURE OF PRODUCTS (DEG K)
    PHI - EQUIVALENCE RATIO (FUEL/AIR RATIO DIVIDED BY THE
          CHEMICALLY CORRECT FUEL/AIR RATIO)
    DEL - MOLAR C:H RATIO OF THE PRODUCTS
    FSI - MOLAR N:O RATIO OF THE PRODUCTS
  RETURNS:
    ENTHLP - SPECIFIC ENTHALPY OF THE PRODUCTS (KCAL/G)
    CSURF - PARTIAL DERIVATIVE OF ENTHLP WITH RESPECT TO T
             AT CONSTANT P (CAL/G-DEG K)
    CSUBT - PARTIAL DERIVATIVE OF ENTHLP WITH RESPECT TO P
             AT CONSTANT T (CC/G)
    RHO - DENSITY OF THE PRODUCTS (G/CC)
    DRHODT - PARTIAL DERIVATIVE OF RHO WITH RESPECT TO T AT
             CONSTANT P (G/CC-DEG K)
    DRHODP - PARTIAL DERIVATIVE OF RHO WITH RESPECT TO P AT
             CONSTANT T (G/CC-ATM)

```



```

C
RCVT = 2. + 2.*(7. - 4.*EPS)*PHI + T1
RCVV = 4. + (2. - 3.*EPS)*PHI + T2
XC02 = 2. - (2. - EPS)*PHI
XCO = 2.*(PHI - 1.)
ENTFOR = ENTFOR - 1000.*ROVR2*.5*(PHI - 1.)/EPS
GO TO 20

C
10 RCVT = 7. + (9. - 8.*EPS)*PHI + T1
RCVV = 1. + (5. - 3.*EPS)*PHI + T2
XCO = 0.
XC02 = EPS*PHI

C
20 ENTFOR = ENTFOR + (XC02*AHFCO2 + XH20*AHFH20 + XCO*AHFCO)

C
C ADD IN TRANSLATIONAL, VIBRATIONAL, AND ROTATIONAL TERMS TO GET
C TOTAL ENTHALPY
C
TV = (3000. - 2000.*EPS + 300.*PSI)/(1. - .5*EPS + .09*PSI)
TV = TV/(EXP(TV/T) - 1.)
AMCP = (8.*EPS + 4.)*PHI + 32. + 28.*PSI

C
ENTHLP = (ROVR2*(RCVT*T + RCVV*TV*2.) + ENTFOR)/AMCP

C
C CALCULATE AVERAGE MOLECULAR WEIGHT, AND GET DENSITY BY
C USING THE PERFECT GAS LAW
C
IF (LEAN) AMWT = AMCP/(1. + (1. - EPS)*PHI + PSI + Y + U)
IF (RICH) AMWT = AMCP/((2. - EPS)*PHI + PSI + Y + U)
RHO = .012187*AMWT*P/T

C
C GET PARTIAL DERIVATIVES BY WAY OF A SUBROUTINE CALL
C
CALL DERIVS(P,T,PHI,EPS,PSI,A,X,Y,U,AMWT,CSUBP,CSUBT,DRHOOT,
1 DRHODP)
C

```

HPR01060
 HPR01070
 HPR01080
 HPR01090
 HPR01100
 HPR01110
 HPR01120
 HPR01130
 HPR01140
 HPR01150
 HPR01160
 HPR01170
 HPR01180
 HPR01190
 HPR01200
 HPR01210
 HPR01220
 HPR01230
 HPR01240
 HPR01250
 HPR01260
 HPR01270
 HPR01280
 HPR01290
 HPR01300
 HPR01310
 HPR01320
 HPR01330
 HPR01340
 HPR01350
 HPR01360
 HPR01370
 HPR01380
 HPR01390
 HPR01400


```

C
IER = 0
DO 10 I = 1, MAXITS
  CALL HPROD(P, T, PHI, DEL, PSI, AHG, CSUBP, CSUBT, RHO, DRHODT, DRHODP)
  TOLD = T
  T = T + (ENTHLP - AHG) / (CSUBP * 1.0E-3)
  IF (ABS((T - TOLD) / T) .LE. ERMAL) GO TO 20
10 CONTINUE
C
IER = 1
20 RETURN
END
TEMP 360
TEMP 370
TEMP 380
TEMP 390
TEMP 400
TEMP 410
TEMP 420
TEMP 430
TEMP 440
TEMP 450
TEMP 460

```

```

C***** VERSION 1.0 *** 11/13/74 *****00000010
C
C FUNCTION TSUBU20000020
C00000030
C00000040
C00000050
C00000060
C00000070
C00000080
C00000090
C0000100
C0000110
C0000120
C0000130
C0000140
C0000150
C0000160
C0000170
C0000180
C0000190
C0000200
C0000210
C0000220
C0000230
C0000240
C0000250
C0000260
C0000270
C0000280
C0000290
C0000300
C0000310
C0000320
C0000330
C0000340
C0000350

PURPOSE:
TO CALCULATE THE TEMPERATURE OF UNBURNED CHARGE IN A TCCS
STRATIFIED CHARGE ENGINE FOLLOWING AN ISENTROPIC EXPANSION
OR COMPRESSION

USAGE:
TEMPU = TSUBU2 (P, PNOT, TNOT, EMAX)

DESCRIPTION OF PARAMETERS:
GIVEN:
P - ABSOLUTE PRESSURE (ATM) AT END OF PROCESS
PNOT - ABSOLUTE PRESSURE (ATM) AT START OF PROCESS
TNOT - ABSOLUTE TEMPERATURE (DEG K) AT START OF PROCESS
EMAX - MAXIMUM ALLOWABLE RELATIVE ERROR IN TSUBU2
GIVEN IN COMMON AREA /CHARGE/ :
PHI - AVERAGE EQUIVALENCE RATIO OF THE RESIDUAL
DEL - MOLAR C:H RATIO OF THE FUEL
PSI - MOLAR N:O RATIO OF THE CHARGE (APPROX 3.76 FOR AIR)
RESFRK - MASS FRACTION OF THE CHARGE THAT IS RESIDUAL
CHMASS - TOTAL MASS OF CHARGE (GRAMS)
QLOWER - LOWER HEATING VALUE OF THE FUEL (KCAL/G) AT 293 DEG K
CFUEL - SPECIFIC HEAT AT CONSTANT PRESSURE (CAL/G-DEG K) OF
THE FUEL VAPOR

RETURNS:
TSUBU2 - FINAL TEMPERATURE (DEG K)

SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED:
UPROP2

REMARKS:

```

```

C      1) REPORT ANY PROBLEMS TO MIKE MARTIN AT 253-2411
C      OR ROOM 3-339D
C
C      METHOD:
C      ADAPTIVE PREDICTOR-CORRECTOR METHOD
C*****
C      FUNCTION TSUBU2 (P, PNOT, TNOT, EMAX)
C      COMMON /CHARGE/ PHI, DEL, PSI, RESFRK, CHMASS, GLOWER, CFUEL
C
C      DATA FSCALE /2.42173E-2/
C
C      LOGICAL DONE
C      DONE = .FALSE.
C
C      INITIALIZE PARAMETER VALUES
C
C      TSUBU2 = TNOT
C      IF (P .EQ. PNOT) RETURN
C      DELP = SIGN(.1, P - PNOT)
C      FOLD = PNOT
C      TOLD = TNOT
C      EMIN = EMAX/10.
C
C      CHECK STEPSIZE
C
C      10 IF (ABS(P - FOLD) .GT. ABS(DELP)) GO TO 20
C
C      IF TOO BIG, REDUCE AND SIGNAL DONE
C
C      DELP = P - FOLD
C      DONE = .TRUE.
C
C      DO PREDICTOR-CORRECTOR
C
00000360
00000370
00000380
00000390
00000400
00000410
00000420
00000430
00000440
00000450
00000460
00000470
00000480
00000490
00000500
00000510
00000520
00000530
00000540
00000550
00000560
00000570
00000580
00000590
00000600
00000610
00000620
00000630
00000640
00000650
00000660
00000670
00000680
00000690
00000700

```

```

20 CALL UPROP2 (POLD, TOLD, PHI, DEL, PSI, RESFRK, XH, CP, CT, RHO,
*      RT, RP)
    G1 = (1./RHO - CT)/CP
    TSTAR = TOLD + DELP*G1*PSCALE
    PNEW = POLD + DELP
    CALL UPROP2 (PNEW, TSTAR, PHI, DEL, PSI, RESFRK, XH, CP, CT, RHO,
*      RT, RP)
    G2 = (1./RHO - CT)/CP
    TNEW = TOLD + DELP*PSCALE*(G1 + G2)/2.
    ERROR = ABS((TNEW - TSTAR)/TNEW)
    IF ERROR TOO LARGE, CHANGE STEP SIZE
    IF (ERROR .LT. EMAX) GO TO 30
    DONE = .FALSE.
    DELP = DELP*.8
    GO TO 20
    OTHERWISE, UPDATE P AND T
30 POLD = PNEW
    TOLD = TNEW
    IF (DONE) GO TO 40
    SEE IF ERROR TOO SMALL TO JUSTIFY THIS STEP SIZE
    IF (ERROR .GE. EMIN) GO TO 10
    IF SO, INCREASE STEP SIZE
    DELP = DELP*.25
    GO TO 10
40 TSUBU2 = TOLD
    RETURN
    END

```

```

C***** VERSION 1.0 *** 11/13/74 *****00000010
C
C SUBROUTINE UPROP2 00000020
C 00000030
C 00000040
C TO CALCULATE THE ENTHALPY AND DENSITY OF A HOMOGENEOUS MIXTURE 00000050
C OF AIR AND RESIDUAL GAS AS A FUNCTION OF TEMPERATURE AND 00000060
C PRESSURE FOR GIVEN EQUIVALENCE RATIO OF THE RESIDUAL 00000070
C 00000080
C 00000090
C USAGE:
C CALL UPROP2 (P, T, PHI, DEL, PSI, RESFRK, ENTHLP, CSURP, CSURT, 00000100
C RHO, DRHODT, DRHODP) 00000110
C 00000120
C 00000130
C 00000140
C 00000150
C 00000160
C 00000170
C 00000180
C 00000190
C 00000200
C 00000210
C 00000220
C 00000230
C 00000240
C 00000250
C 00000260
C 00000270
C 00000280
C 00000290
C 00000300
C 00000310
C 00000320
C 00000330
C 00000340
C 00000350

      TO CALCULATE THE ENTHALPY AND DENSITY OF A HOMOGENEOUS MIXTURE
      OF AIR AND RESIDUAL GAS AS A FUNCTION OF TEMPERATURE AND
      PRESSURE FOR GIVEN EQUIVALENCE RATIO OF THE RESIDUAL

      USAGE:
      CALL UPROP2 (P, T, PHI, DEL, PSI, RESFRK, ENTHLP, CSURP, CSURT,
      RHO, DRHODT, DRHODP)

      DESCRIPTION OF PARAMETERS:
      GIVEN:
      P - ABSOLUTE PRESSURE OF MIX (ATM)
      T - TEMPERATURE OF MIX (DEG K)
      PHI - EQUIVALENCE RATIO OF THE RESIDUAL GAS
      DEL - MOLAR C:H RATIO OF THE RESIDUAL GAS
      PSI - MOLAR N:O RATIO OF THE MIX

      RETURNS:
      ENTHLP- SPECIFIC ENTHALPY OF THE MIX (KCAL/G)
      CSURP - PARTIAL DERIVATIVE OF ENTHLP WITH RESPECT TO T
      AT CONSTANT P (CAL/G-DEG K)
      CSURT - PARTIAL DERIVATIVE OF ENTHLP WITH RESPECT TO P
      AT CONSTANT T (CC/G)
      RHO - DENSITY OF THE PRODUCTS (G/CC)
      DRHODT- PARTIAL DERIVATIVE OF RHO WITH RESPECT TO T AT
      CONSTANT P (G/CC-DEG K)
      DRHODP- PARTIAL DERIVATIVE OF RHO WITH RESPECT TO P AT
      CONSTANT T (G/CC-ATM)

      REMARKS:
      1) ENTHALPY DATUM STATE IS AT T = 0 ABSOLUTE WITH
      O2,N2,H2 GASEOUS AND C SOLID GRAPHITE
      2) REPORT ANY PROBLEMS TO MIKE MARTIN AT 253-2411

```

```

C      (ROOM 3-339 D)
C
C      SUBROUTINES AND FUNCTION SUBPROGRAMS NEEDED:  NONE
C
C      METHOD:
C      ZERO ORDER EQUILIBRIUM MODEL (MAJOR SPECIES ONLY)
C
C*****
C      SUBROUTINE UPROP2 (F, T, PHI, DEL, PSI, RESFRK, ENTHLF, CSURF,
C      *      CSUBT, RHO, DRHODT, DRHODF)
C      LOGICAL  RICH,LEAN
C      DIMENSION A(6,6,2), X(6)
C      DIMENSION A1(36), A2(36)
C      EQUIVALENCE (A1(1),A(1,1,1)), (A2(1),A(1,1,2))
C      REAL  MBAR,K
C
C      INITIALIZE PARAMETERS, AND CHECK TO SEE IN WHAT TEMPERATURE
C      RANGE WE ARE SO THAT THE CORRECT FITTED COEFFICIENTS WILL BE
C      USED. FLAG TEMPERATURES TOO BIG OR TOO SMALL
C
C      DATA A1/11.94033, 2.088581, -0.47029, .037363, -.589447, -97.1418, 00000550
C      1 6.139094, 4.60783, -.9356009, .06669498, .0335801, -56.62588, 00000570
C      2 7.099556, 1.275957, -.2877457, .022356, -.1598696, -27.73464, 00000580
C      3 5.555680, 1.787191, -.2881342, .01951547, .1611828, .76498, 00000590
C      4 7.865847, .6883719, -.031944, -.00268708, -.2013873, -.893455, 00000600
C      5 6.807771, 1.453404, -.328985, .02561035, -.1189462, -.331835, 00000610
C      DATA A2/4.737305, 16.65283, -11.2325, 2.828, .00676702, -.93.75793, 00000620
C      7 7.809672, -.2023519, 3.418708, -1.179013, .00143629, -57.08004, 00000630
C      8 6.97393, -.8238319, 2.942042, -1.176239, .0004132409, -27.19597, 00000640
C      9 6.991878, .1617044, -.2182071, .2968197, -.01625234, -.118189, 00000650
C      8 6.295715, 2.388387, -.0314788, -.3267433, .00435925, .103637, 00000660
C      - 7.092199, -1.295825, 3.20688, -1.202212, -.0003457938, -.013967/00000670
C      00000680
C      RICH = PHI .GT. 1.0
C      LEAN = .NOT. RICH
C      00000690
C      00000700

```

```

EPS = 4.*DEL/(1. + 4.*DEL)
IER = 0
IF (T.LT. 100.) IER = 1
IF (T.GT. 6000.) IER = 2
IR = 1
IF (T.LT. 500.) IR = 2

C
C
C
GET THE COMPOSITION IN MOLES/MOLE OXYGEN

PCTRES = RESFRK
PCTNEW = 1.0 - RESFRK
IF (RICH) GO TO 10

C
X(1) = EPS*PHI*PCTRES
X(2) = 2.*(1.0 - EPS)*PHI*PCTRES
X(3) = 0.
X(4) = 0.
X(5) = (1. - PHI)*PCTRES + PCTNEW
GO TO 20

C
10 Z = 1000./T
K = EXP(2.743 + Z*(-1.761 + Z*(-1.611 + Z*.2803)))
ALPHA = 1.0 - K
BETA = 2.*(1. - EPS*PHI) + K*(2.*(PHI - 1.) + EPS*PHI)
GAMMA = 2.*K*EPS*PHI*(PHI - 1.)
C = (-BETA + SQRT(BETA*BETA + 4.*ALPHA*GAMMA))/(2.*ALPHA)
X(1) = (EPS*PHI - C)*PCTRES
X(2) = (2.0*(1. - EPS*PHI) + C)*PCTRES
X(3) = C*PCTRES
X(4) = (2.0*(PHI - 1.) - C)*PCTRES
X(5) = PCTNEW
20 X(6) = PSI

C
C
C
CONVERT COMPOSITION TO MOLE FRACTIONS AND CALCULATE AVERAGE
MOLECULAR WEIGHT
00000710
00000720
00000730
00000740
00000750
00000760
00000770
00000780
00000790
00000800
00000810
00000820
00000830
00000840
00000850
00000860
00000870
00000880
00000890
00000900
00000910
00000920
00000930
00000940
00000950
00000960
00000970
00000980
00000990
00001000
00001010
00001020
00001030
00001040
00001050

```

```

C
IF (LEAN) TMOLES = PSI + PCTNEW + PCTRES*(1. + PHI*(1.-EPS))
IF (RICH) TMOLES = PSI + PCTNEW + PCTRES*( PHI*(2. - EPS))
DO 30 J = 1, 6
  X(J) = X(J)/TMOLES
30 CONTINUE
MBAR = ((8.*EPS + 4.)*PHI + 32. + 28.*PSI)/TMOLES
C
  CALCULATE H, CP, AND CT AS IN WRITEUP, USING FITTED
  COEFFICIENTS FROM JANAF TABLES
  ENTHLP = 0.
  CSURF = 0.
  CSURT = 0.
  ST = T/1000.
DO 40 J = 1, 6
  TH = ((( A(4,J,IR)/4.*ST + A(3,J,IR)/3. ) *ST
    + A(2,J,IR)/2.)*ST + A(1,J,IR) ) *ST
  TCP = (( A(4,J,IR)*ST + A(3,J,IR) ) *ST
    + A(2,J,IR))*ST + A(1,J,IR)
  TH = TH - A(5,J,IR)/ST + A(6,J,IR)
  TCP = TCP + A(5,J,IR)/(ST*ST)
  ENTHLP = ENTHLP + TH*X(J)
  CSURF = CSURF + TCP*X(J)
40 CONTINUE
  ENTHLP = ENTHLP/MBAR
  CSURF = CSURF/MBAR
C
  NOW CALCULATE RHO AND ITS PARTIAL DERIVATIVES
  USING PERFECT GAS LAW
C
  RHO = .012187*MBAR*P/T
  DRHODT = -RHO/T
  DRHODP = RHO/P
C
00001060
00001070
00001080
00001090
00001100
00001110
00001120
00001130
00001140
00001150
00001160
00001170
00001180
00001190
00001200
00001210
00001220
00001230
00001240
00001250
00001260
00001270
00001280
00001290
00001300
00001310
00001320
00001330
00001340
00001350
00001360
00001370
00001380
00001390
00001400

```

C ALL DONE
RETURN
END

00001410
00001420
00001430

Table 1

Engine Specifications

DIMENSIONS*

bore	3.875 in.
stroke	3.875 in.
connecting rod	6.625 in.
clearance volume	4.570 in. ³

VALVE TIMINGS

	OPENS	CLOSES
inlet valve	10 BTDC (1)	55 ABDC (2)
	0 (2)	45 (1)
exhaust valve	55 BBDC (1)	10 ATDC (2)
	45 (2)	0 (1)

(1) at 0.006 in. valve lift (2) valve face flush with head

* defined in Figure () and Appendix B of ()

Table 2

Injection System

PUMP

pump: APE - B Bosch

cam: 6/1

plunger: 7mm.

reaction valve: 20 mm³

NOZZLE

nozzle: Roosa-Master XNM 1029

orifice diameter .023 in.

orifice L/D 1.0

nozzle cracking pressure 2000

needle lift .010 in.

Table 3

Summary of Instrumentation

Temperatures

Air Orifice Inlet	Water Outlet	Bearing Oil
Air Inlet	Exhaust	Fuel Inlet
Water Inlet	Crankcase Oil	Fuel Returns

Instrument - All Points

Chromel - Alumel Thermocouple

Omega DS - 500 Digital Readout

Resolution 1°F

Pressures

	Method	Resolution
Inlet Air	Water Manometer	.1 in.
Crankcase Vacuum	Water Manometer	.1 in.
Oil Pressure	Panel Gage	2 PSI
Exhaust	Mercury Manometer	.1 in.
Dynamometer Load	Mercury Manometer	.1 in.
Injection Line	Kistler 601 Piezoelectric transducer, Kistler 504E Charge Amplifier	30 PSI*
Combustion Chamber	Kistler 609A Piezoelectric Transducer, Kistler 503D Charge Amplifier	.2 PSI**

Table 3 (cont)

<u>Flow Rates</u>		
	Method	Resolution
Air Inlet	ASME Square Edged Orifice	
	with water manometers	0.05 g/sec
Fuel	Laboratory Scale and Timer	0.01 g/sec
Cooling Water	Rotameter	.2 lbm/sec
Position		
Crankangle	Trump Ross Rotary Pulse Generator	
	720 pulses per revolution	
	plus Marker	.2 CA ^o
Fuel Injector		
Needle Lift	AVL NH1 - 100 B LDT	1 μ m
<u>Gas Analysis Cart</u>		
Exhaust		
Hydrocarbons	Scott Model 215 FID HC Analyzer	
Nitric Oxides	TELCO Model 10 A Chemilumenscent NO Analyzer	
Carbon Dioxide	Beckman Model 315A NDIR CO ₂ Analyzer	
Carbon Monoxide	Beckman Model 315A NDIR CO Analyzer	
Oxygen	Scott Model 150 Paramagnetic O ₂ Analyzer	

* Accuracy is effectively limited by the system transfer function and the 565 oscilloscope.

** See Text

Table 4

Summary of Fuel Properties

	Methanol CH_3OH	Iso-Octane C_8H_{18}	Cross-cut Distillate
Molecular Wt.	32	114	~125
H:C Ratio	4:0	2.25	1.828
Specific Gravity	.796	.692	.80
Boiling Point °F	149	211	(106-648)
Lower Heating Value (Btu/lbm)	8580	19080	18038
Stoichiometric F/A Ratio	0.155	0.0665	0.0692

FIA - %

Aromatics	29.5
Olefins	3.0
Saturates	67.5

Octane No. RON	106	100	76.6
Cetane No.			28.3

Table 5

Engine Operating Conditions for Emission Results

RPM	ϕ	θ_s	IMEP	ISFC
1500	0.759	-24	104.7	0.384
	0.625	-23	93.2	0.358
	0.446	-23	81.9	0.290
	0.278	-23	56.8	0.284
	0.261	-23	53.6	0.263
	0.172	-23	39.1	0.249
	0.143	-20	24.7	0.331
	0.113	-23	17.5	0.379
2000	0.828	-26	122.2	0.353
	0.650	-26	108.9	0.320
	0.475	-26	91.3	0.289
	0.348	-24	73.1	0.269
	0.218	-23	44.2	0.285
	0.161	-24	25.9	0.362
2500	0.811	-29	130.3	0.349
	0.639	-28	119.3	0.349
	0.524	-28	105.4	0.286
	0.371	-28	82.0	0.262
	0.249	-28	55.5	0.265
	0.193	-28	38.1	0.306
	0.124	-28	21.7	0.344

θ_s = Start of Injection

Ignition Always Preceeded by 2 CA^o

Table 5 (con't)

RPM	<u>Cross Cut Distillate</u>			
	ϕ	θ_s	IMEP	ISFC
1500	0.924	-22	112.1	0.432
	0.762	-20	105.4	0.392
	0.600	-20	93.0	0.358
	0.442	-19	79.7	0.299
	0.426	-20	76.3	0.317
	0.282	-19	55.5	0.284
	0.211	-19	41.3	0.290
	0.129	-18	22.8	0.327
2000	0.927	-25	112.9	0.416
	0.859	-23	112.4	0.390
	0.692	-23	98.5	0.372
	0.472	-23	88.4	0.296
	0.334	-23	63.6	0.303
	0.258	-23	51.4	0.290
	0.180	-23	34.9	0.304
	0.184	-20	32.4	0.338
2500	1.000	-26	122.5	0.439
	.850	-26	120.7	0.391
	.685	-25	108.9	0.353
	.546	-26	95.6	0.324
	.367	-25	69.3	0.303
	.291	-26	56.6	0.300
	.212	-23	39.7	0.314
	.218	-20	19.4	0.387

Table 5 (cont)

RPM	<u>Methanol</u>			
	ϕ	θ_s	IMEP	ISFC
1500	0.767	-25	106.9	0.878
	0.636	-28	101.7	0.755
	0.486	-26	89.0	0.676
	0.394	-26	77.7	0.637
	0.324	-26	66.4	0.616
	0.261	-24	50.8	0.655
	0.219	-24	40.7	0.697
2000	0.811	-28	108.9	0.900
	0.741	-28	106.9	0.838
	0.654	-28	104.6	0.766
	0.591	-28	100.5	0.731
	0.504	-28	92.7	0.682
	0.414	-28	84.6	0.632
	0.364	-25	72.5	0.643
	0.291	-25	58.6	0.640
2500	0.221	-25	26.9	1.077
	0.696	-35	106.3	0.824
	0.641	-35	102.3	0.795

Table 6

Matrix of Averaged Pressure Crankangle

Iso-Octane

RPM	ϕ_e	ϕ_e	IMEP _m	IMEP _i	θ_{is}	θ_{ie}	θ_{bs}	θ_{be}
1500	0.77	0.76	104.7	106.6	-24	9	-12	35
	0.46	0.45	81.9	82.3	-23	0	-13	35
	0.29	0.28	56.8	60.0	-23	-3	-12	24
2000	0.83	0.83	122.2	118.3	-25	13	-12	28
	0.49	0.48	91.3	88.5	-24	3	-9	24
	0.22	0.22	44.2	44.3	-23	-5	-7	23
2500	0.78	0.81	130.3	122.4	-29	15	-8	30
	0.52	0.52	105.4	99.6	-28	7	-9	30
	0.25	0.25	55.4	47.4	-28	-4	-9	29

Subscript Nomenclature

o = Observed from fuel air flow

e = Measured from exhaust gas composition

M = Dynamometer measurement

i = Integrated average pressure data

is = Injection start

ie = Injection end

bs = Start of heat release from Log P Log V plots

be = End of effective heat release from Log P Log plots

Table 6 (cont)

Cross Cut Distillate

RPM	ϕ_o	ϕ_e	IMEP _M	IMEP _i	θ_{is}	θ_{ie}	θ_{bs}	θ_{be}
1500	0.76	0.78	105.4	99.2	-20	10	-11	35
	0.43	0.43	76.3	73.3	-20	4	-13	36
	0.27	0.27	51.4	47.2	-20	-5	-11	35
2000	0.87	0.85	121.0	114.6	-24	15	-14	29
	0.49	0.47	88.4	84.9	-23	-2	-14	26
	0.26	0.26	51.4	46.5	-23	-12	-15	31
2500	0.83	0.82	121.3	124.8	-26	15	-14	31
	0.52	0.50	95.0	100.1	-26	0	-14	24
	0.29	0.28	56.1	59.7	-26	-9	-13	26

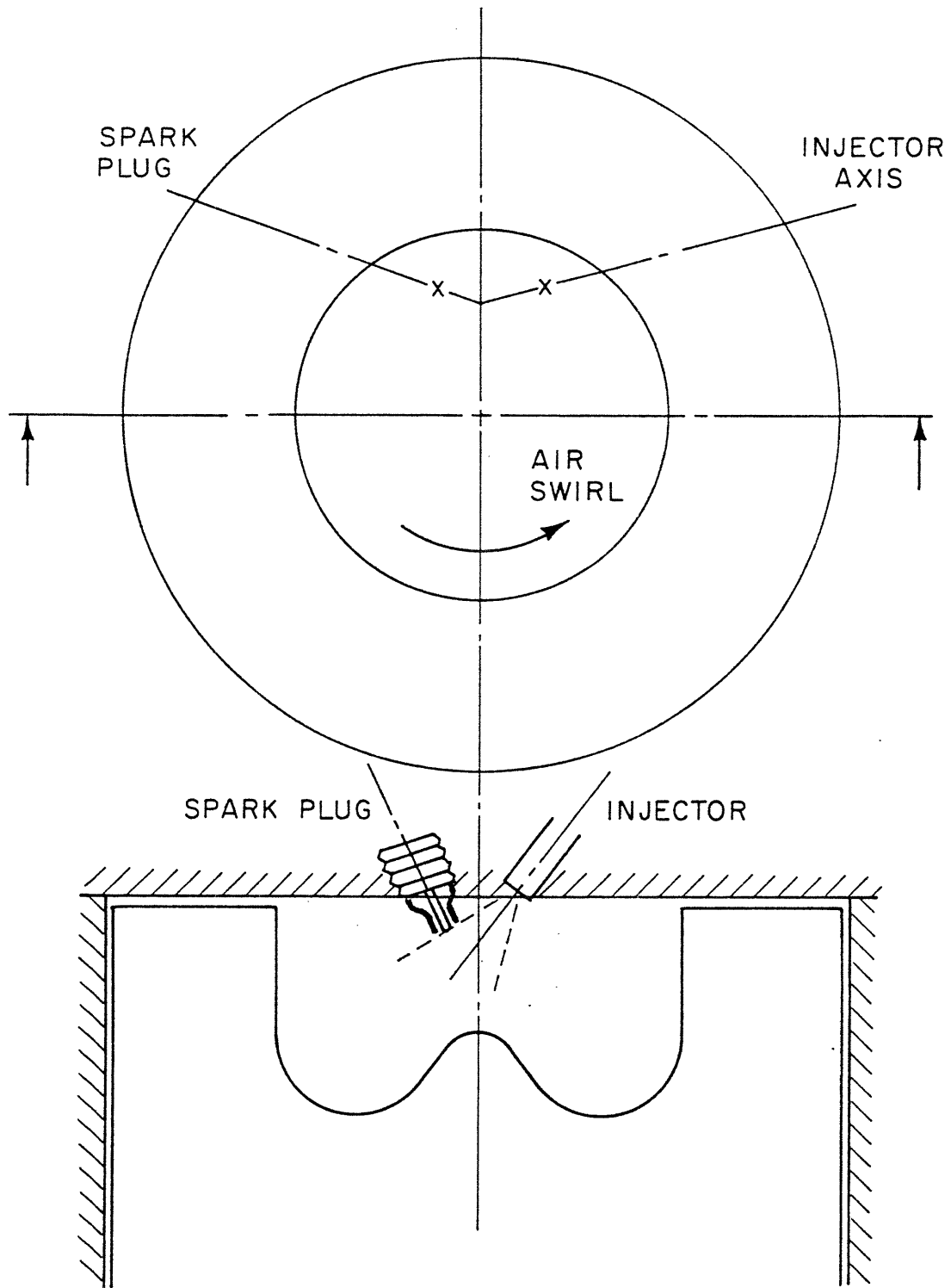


FIG. 1 TEXACO CONTROLLED COMBUSTION
SYSTEM (SCHEMATIC)

CRACKING PRESSURE ADJUSTMENT SCREW

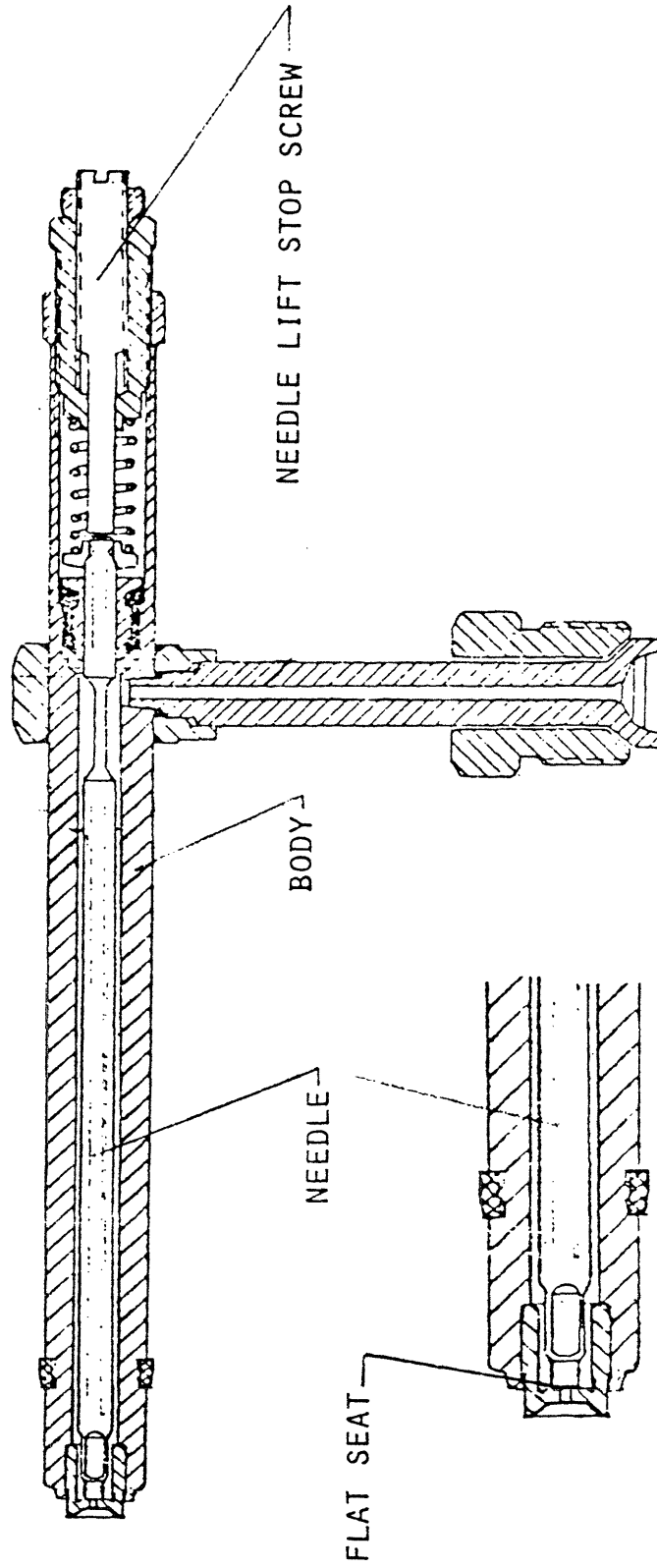
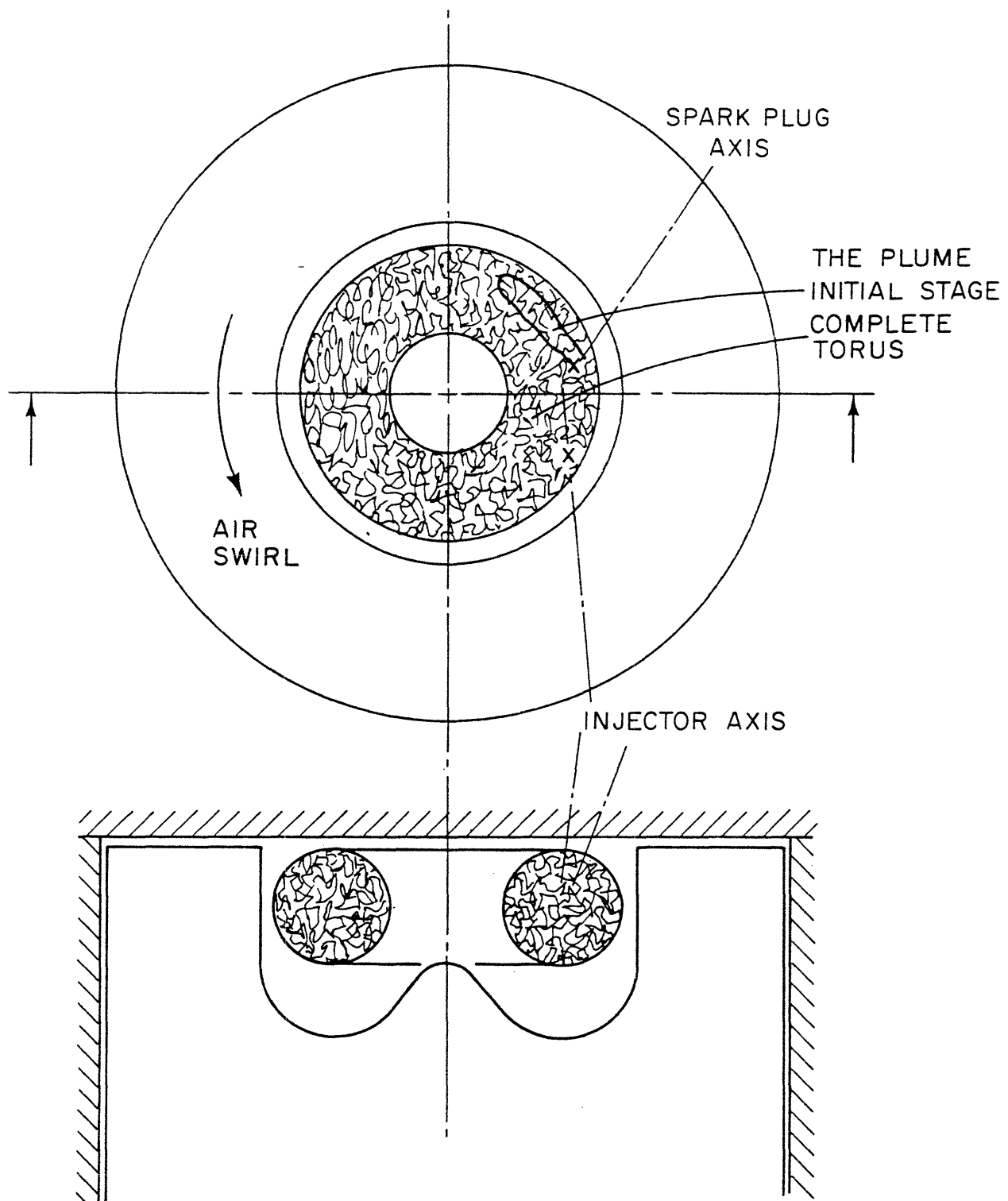


FIG. 2 ROOSA-MASTER INJECTION NOZZLE



SCHEMATIC OF THE COMBUSTION PROCESS

FIG. 3

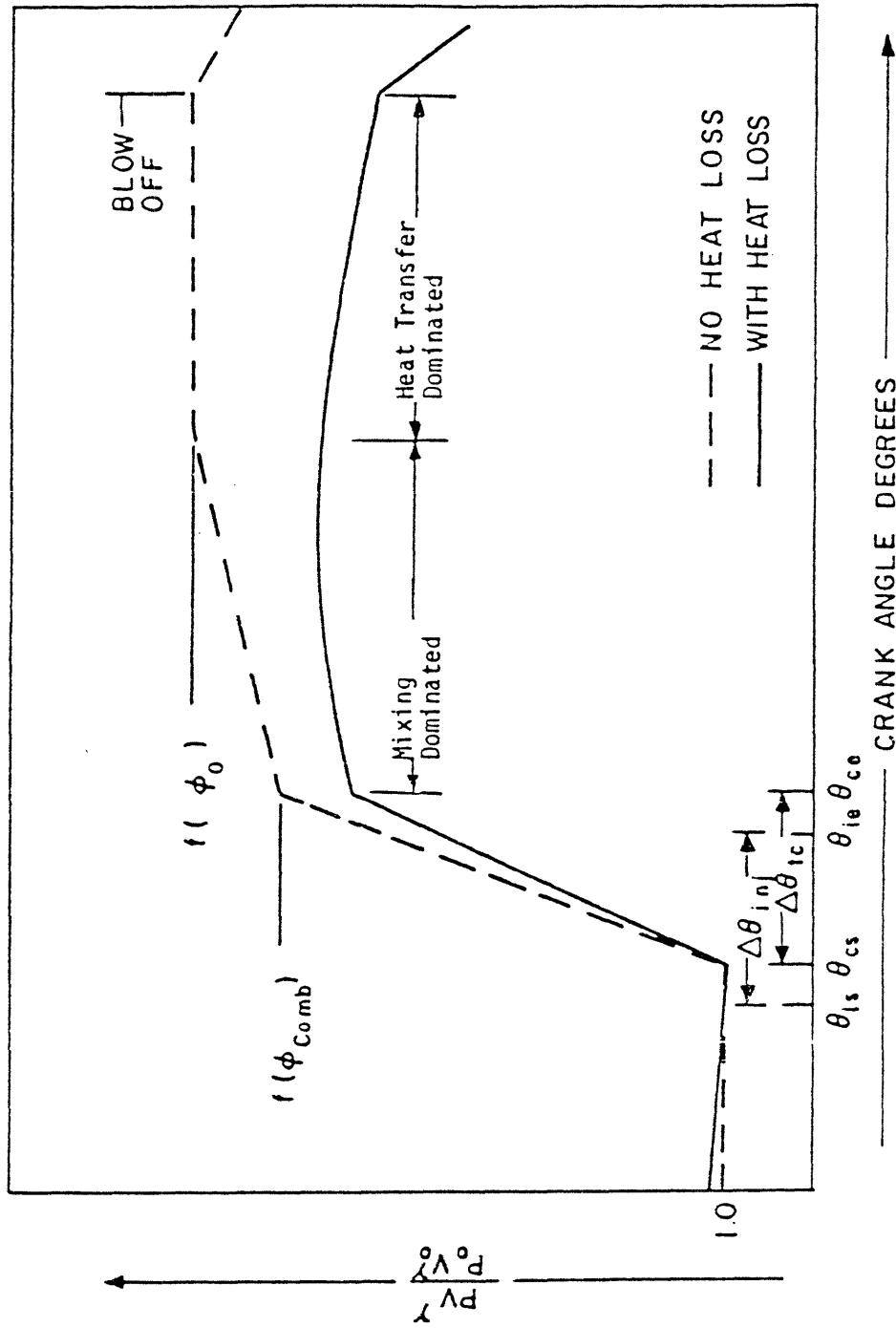


FIG. 4 Simplified PV plot (Theory). $\Delta\theta_{inj}$ and $\Delta\theta_{rc}$ are injection and rapid combustion durations respectively.

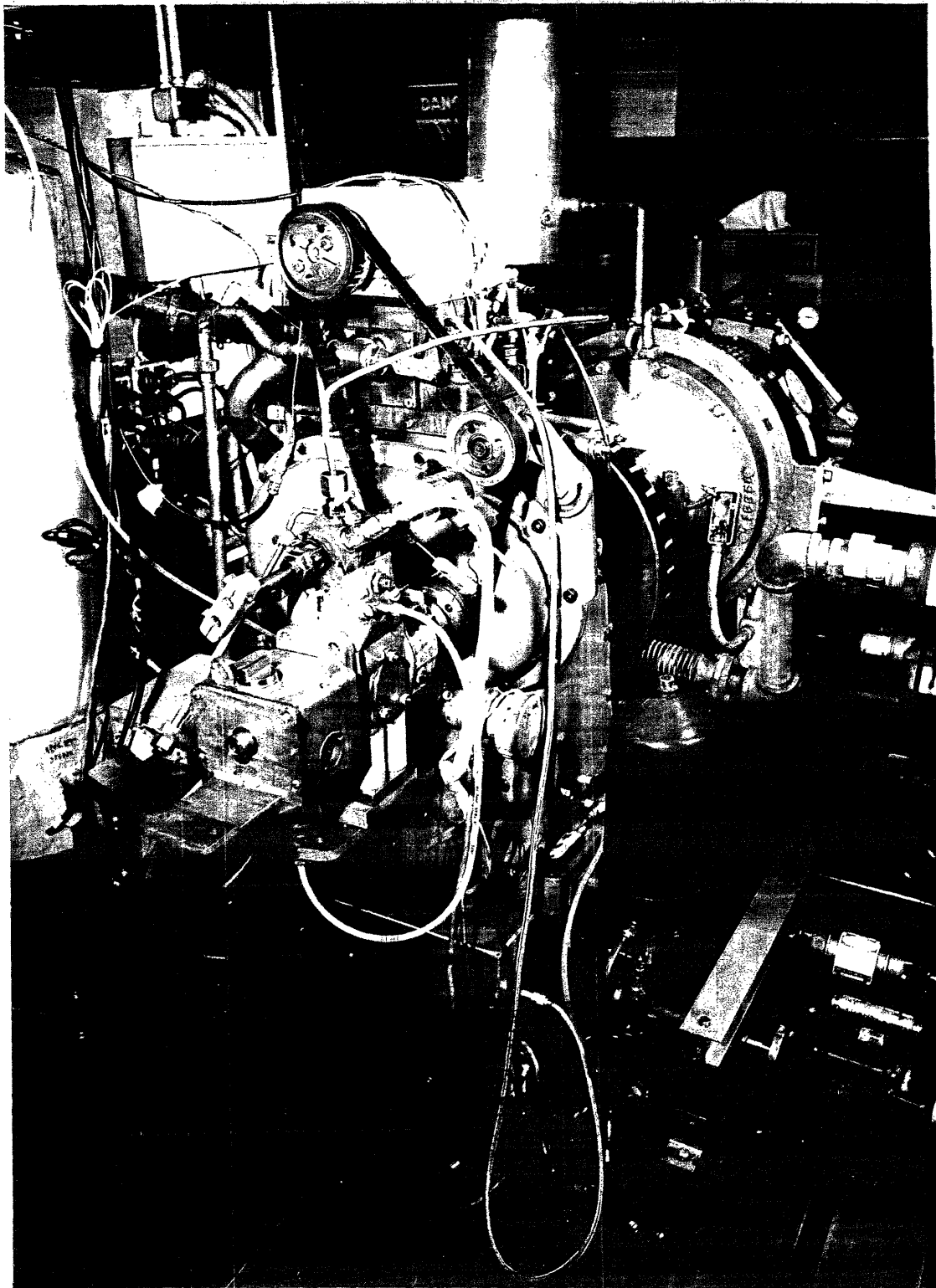
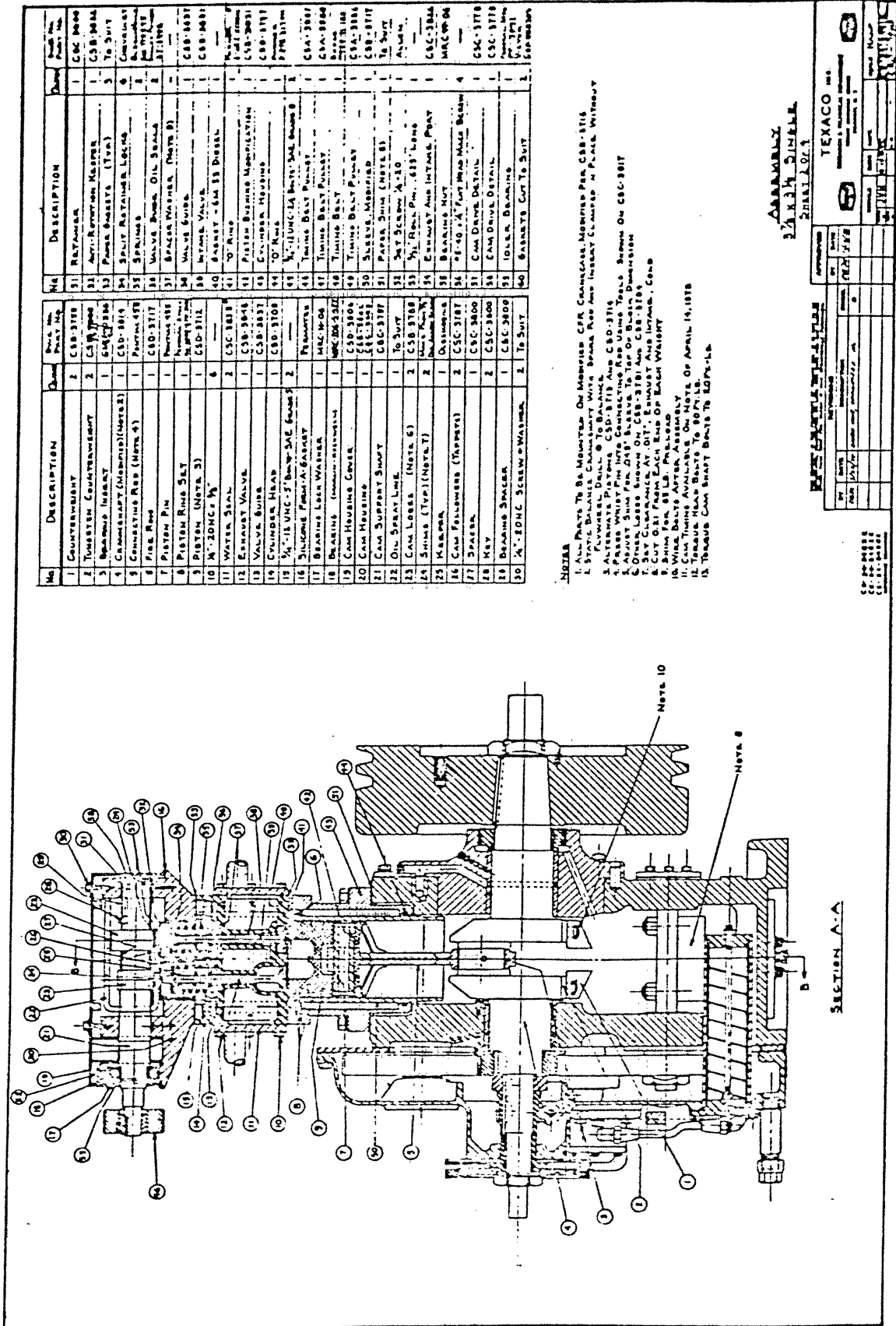


FIGURE 5 PHOTOGRAPH OF TEST INSTALLATION



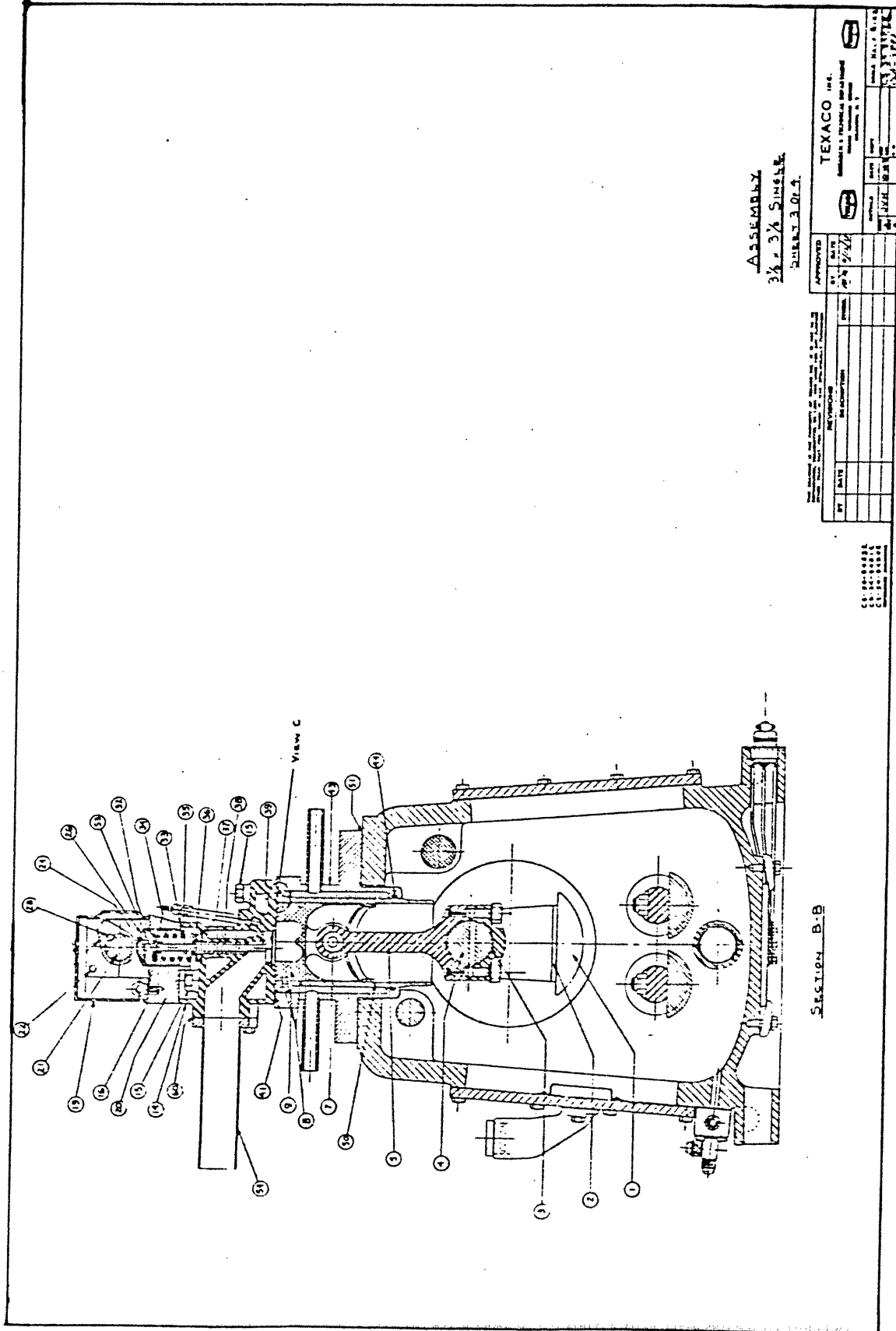


FIG. 6b SINGLE CYLINDER TEST ASSEMBLY

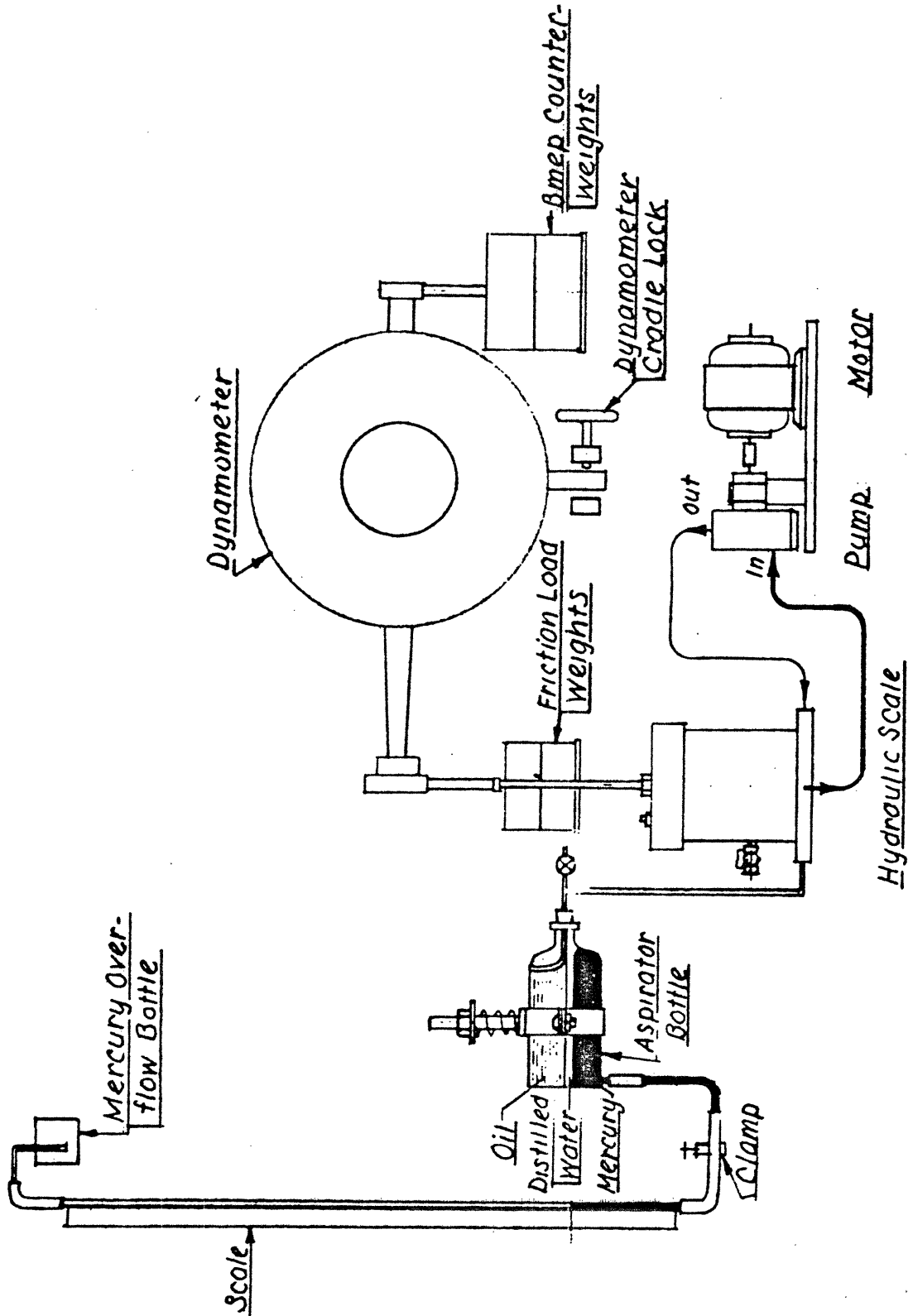


FIG. 7 DYNAMOMETER HYDRAULIC SCALE

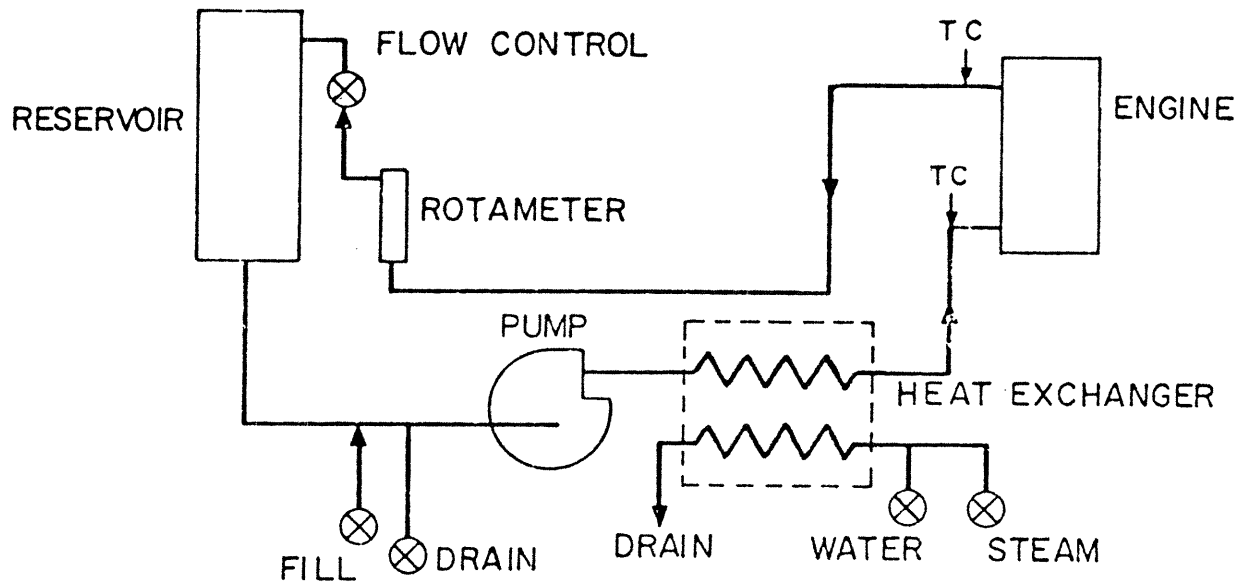


FIG. 8 COOLING SYSTEM

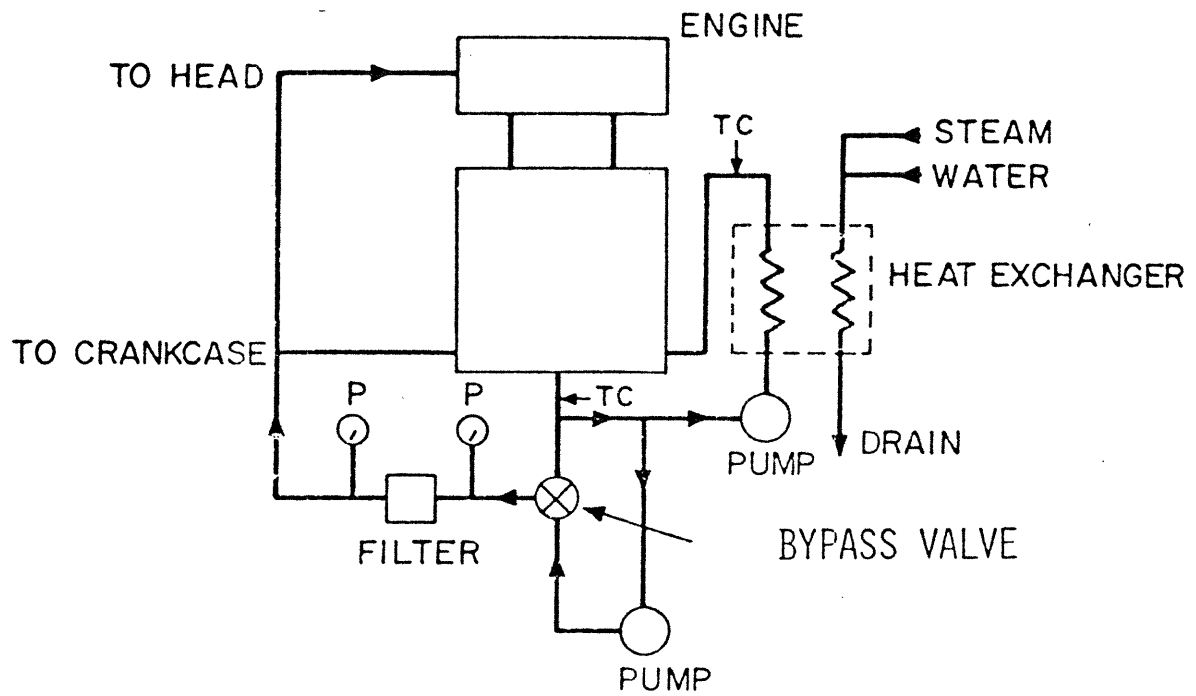


FIG. 9 LUBRICATION SYSTEM

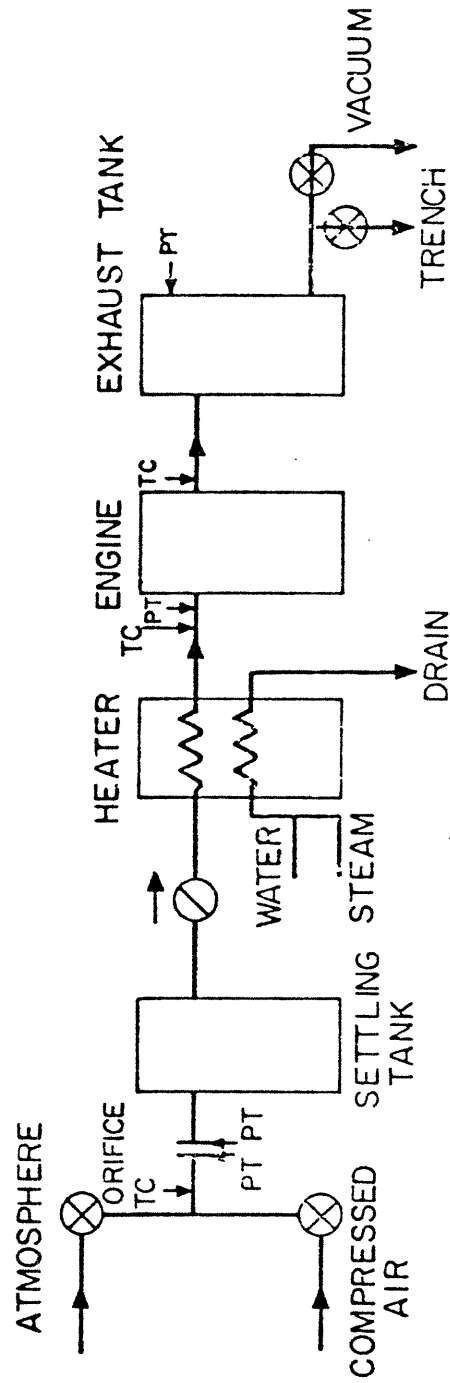


FIG. 10 INLET AND EXHAUST SYSTEM

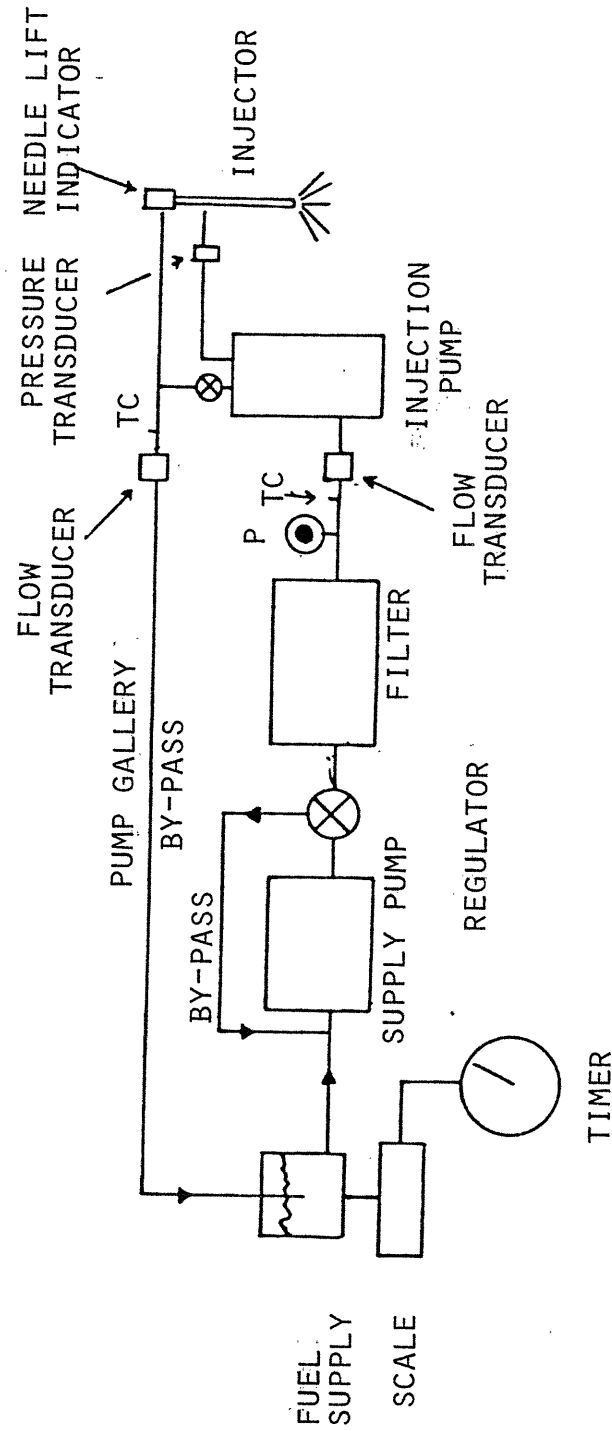


FIG.11 FUEL SYSTEM

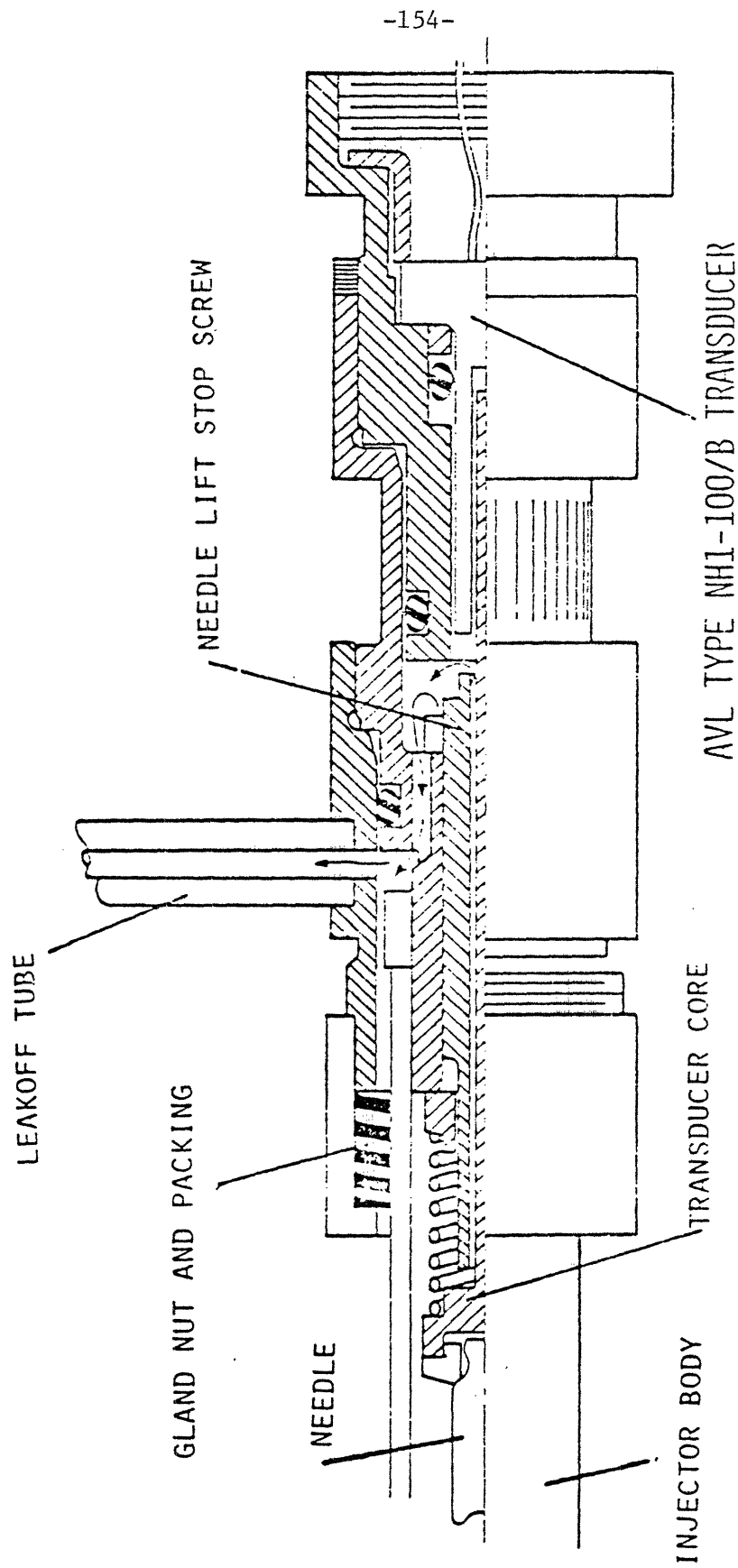
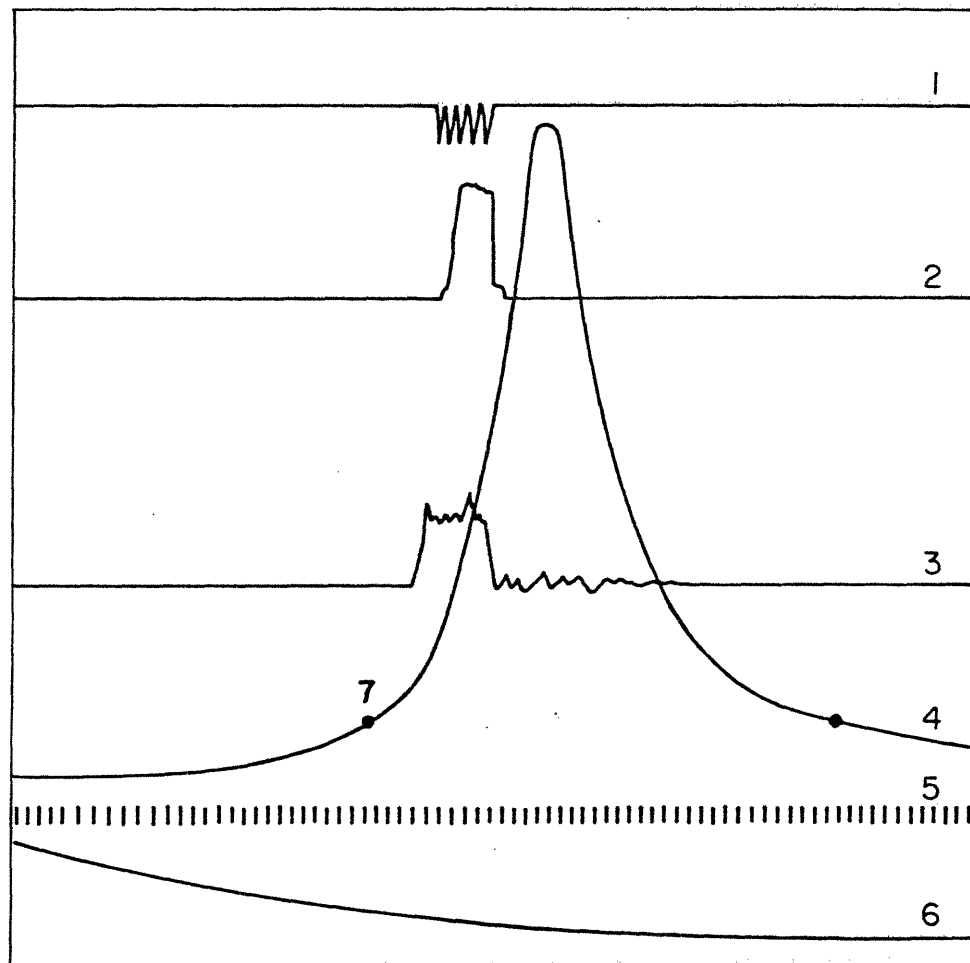


FIG. 12 INJECTOR LIFT TRANSDUCER ASSEMBLY



1. IGNITION DURATION
2. FUEL INJECTOR NEEDLE LIFT
3. FUEL INJECTION LINE PRESSURE
4. CYLINDER PRESSURE
5. CRANKANGLE INDICATOR, $1/5$ CA⁰
6. 185 CA⁰ BTDC REFERENCE SIGNAL
7. BALANCE PRESSURE INDICATOR

FIG.13-TYPICAL OSCILLOSCOPE TRACE

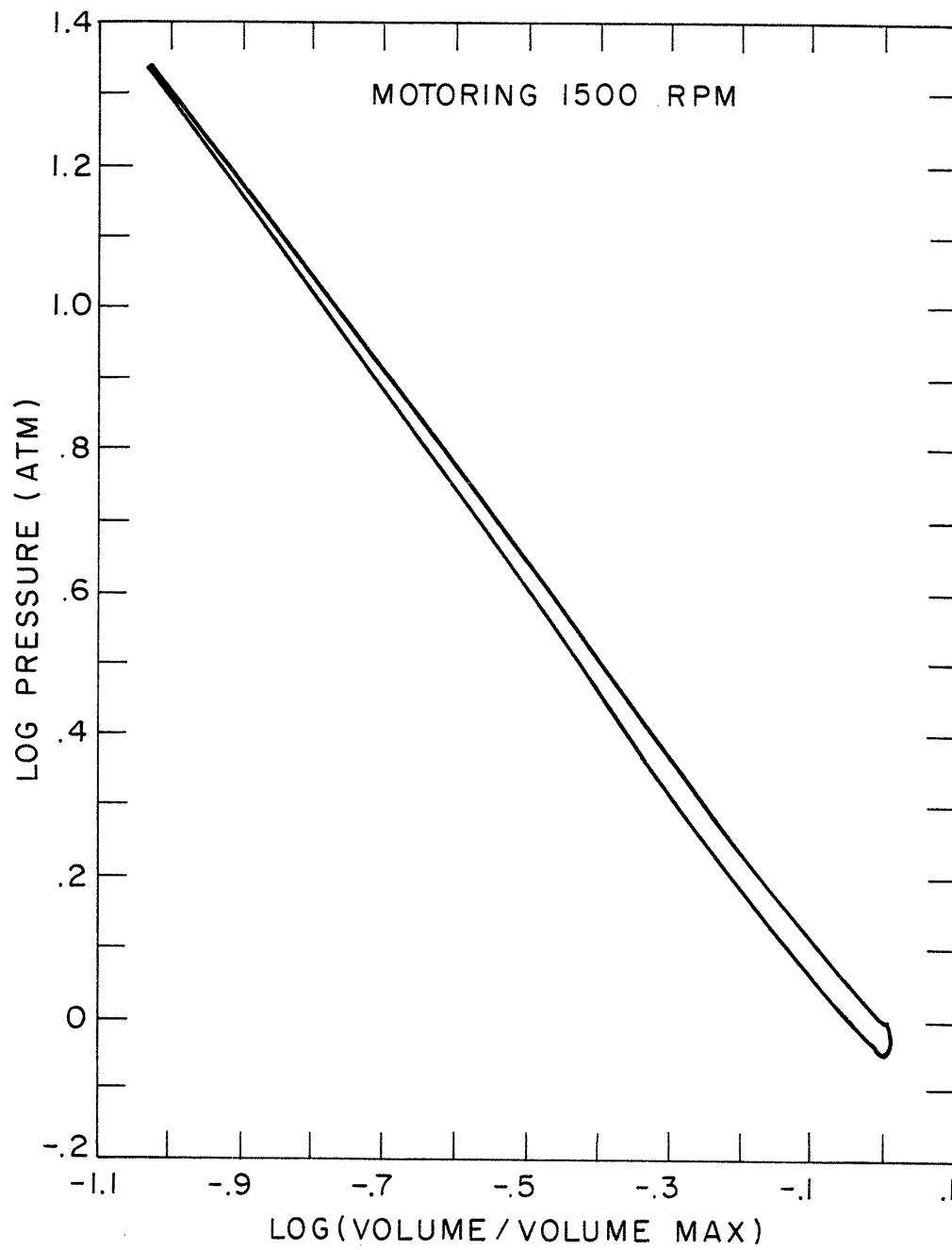


FIG.14 1500 RPM MOTORING LOG P vs LOG V

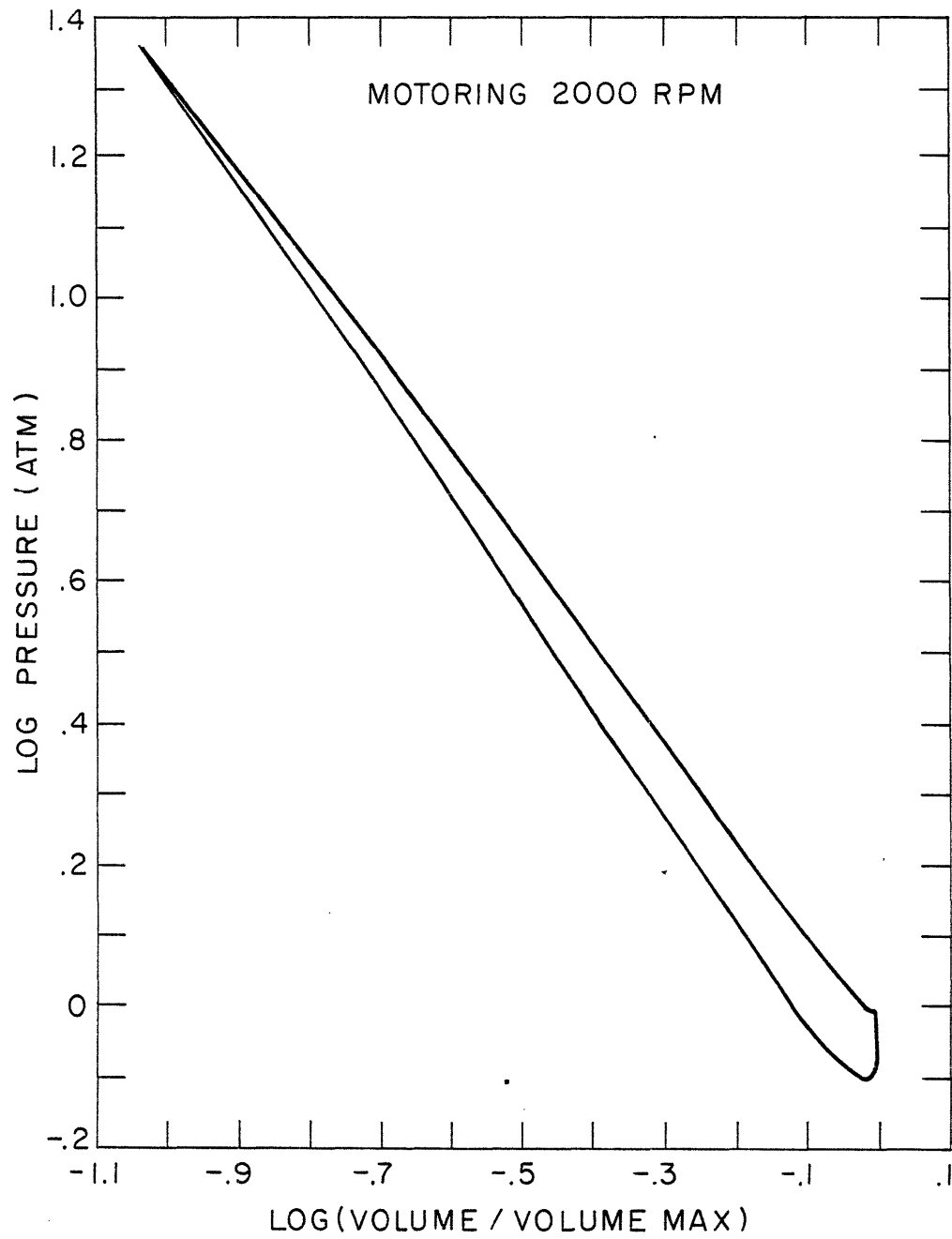


FIG. 15 2000 RPM MOTORING LOG P vs LOG V

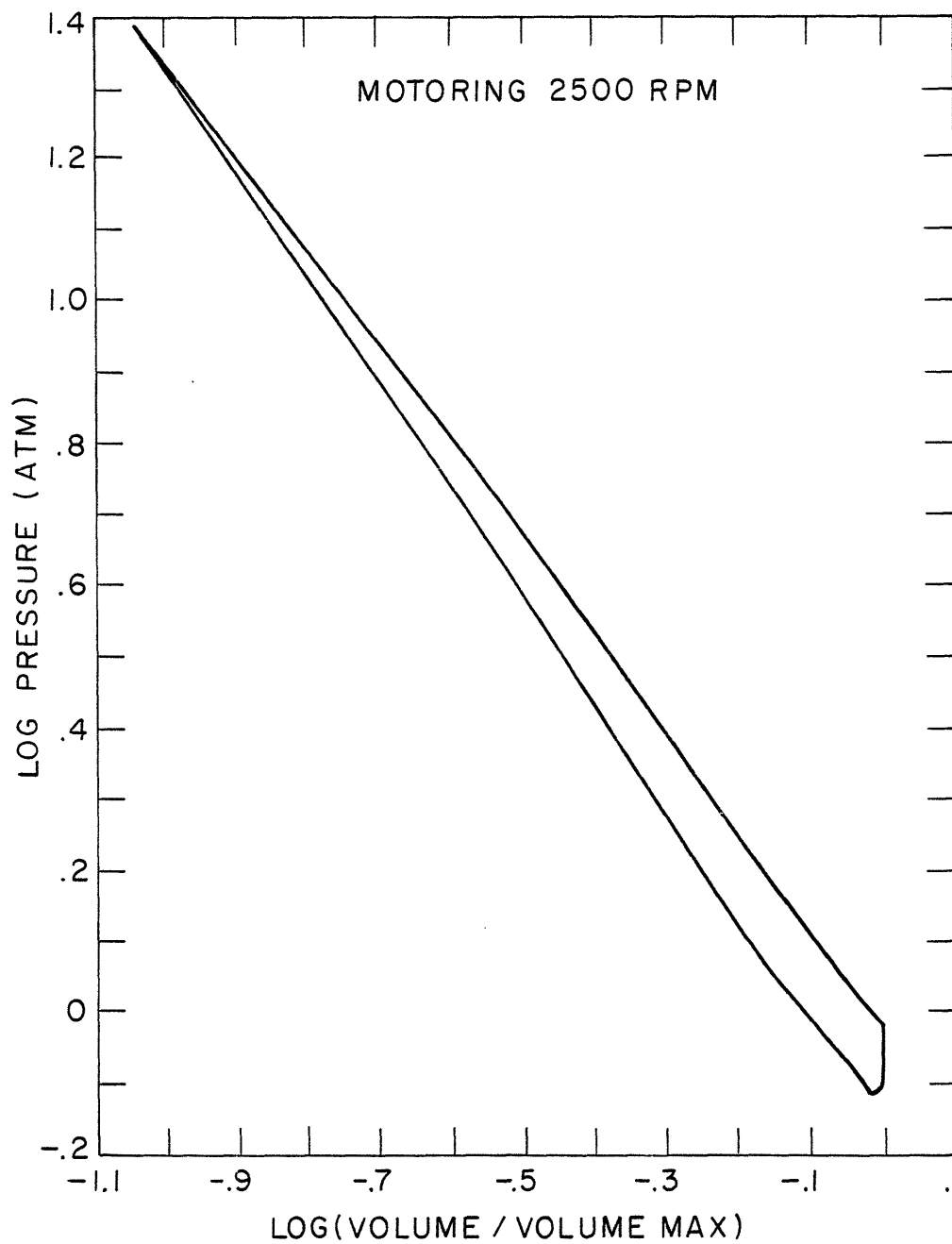


FIG.16 2500 RPM MOTORING LOG P vs LOG V

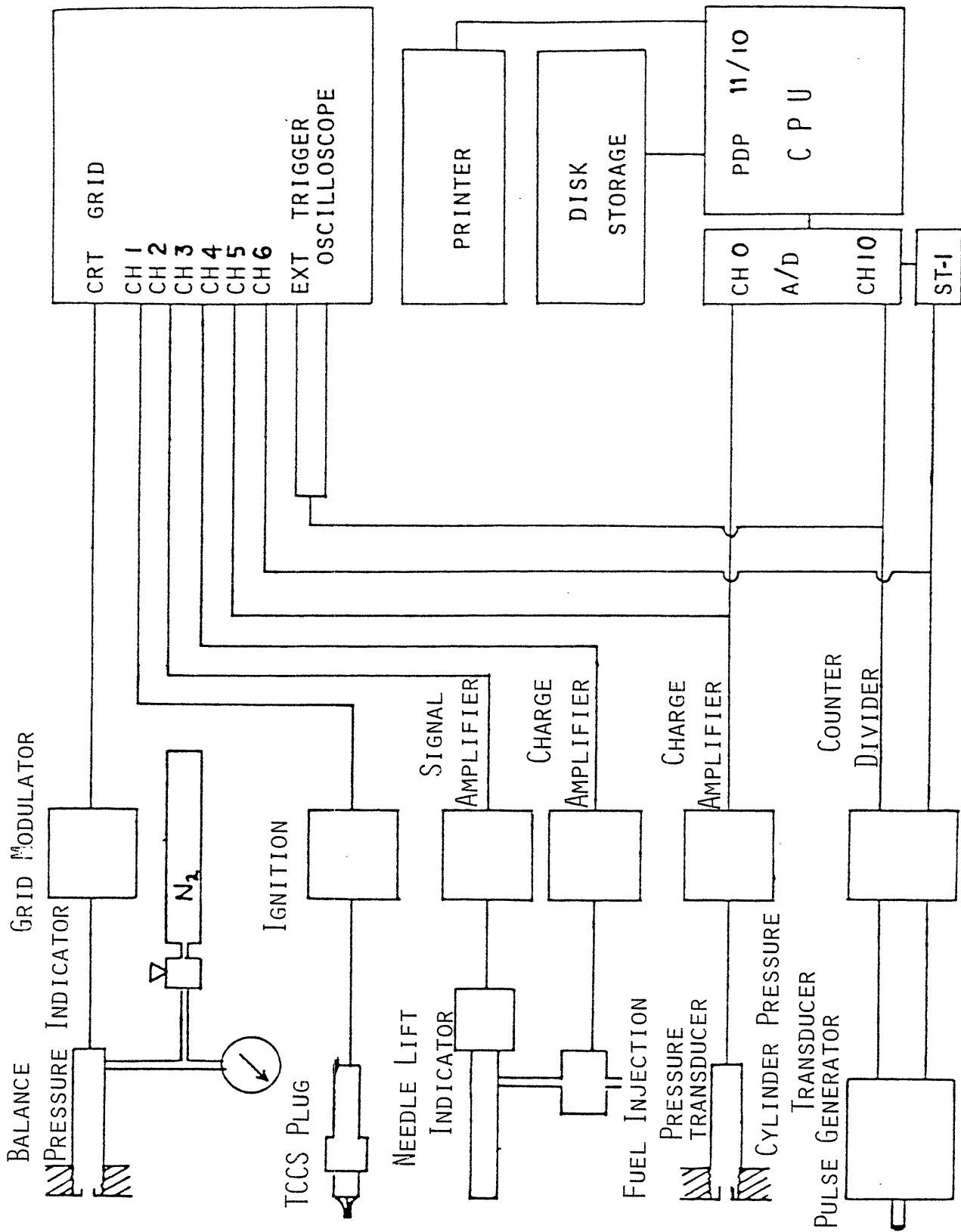


FIG. 17 SCHEMATIC OF DATA ACQUISITION SYSTEM

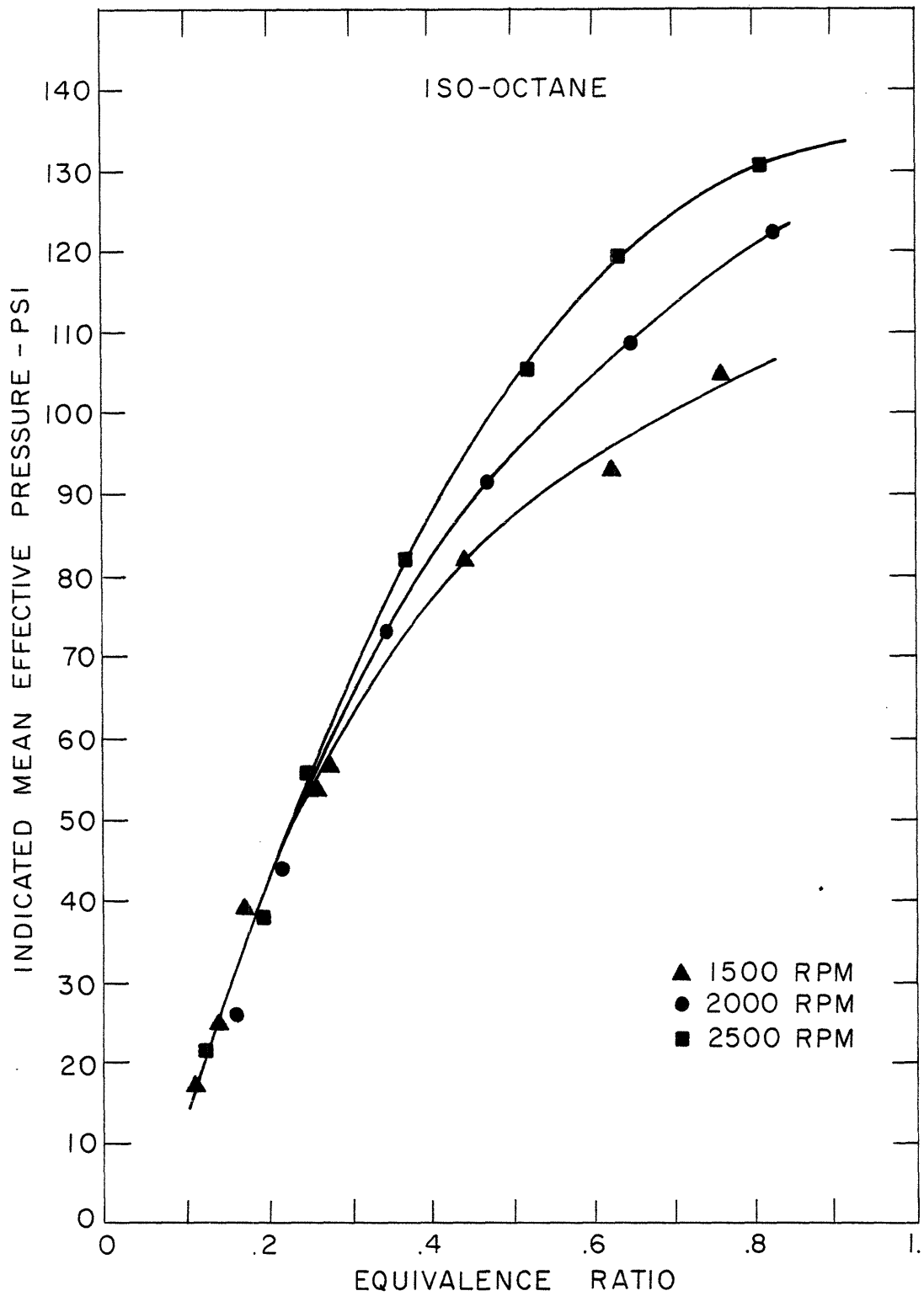


FIG. 18 INDICATED MEAN EFFECTIVE PRESSURE VS
EQUIVALENCE RATIO, FOR ISO-OCTANE

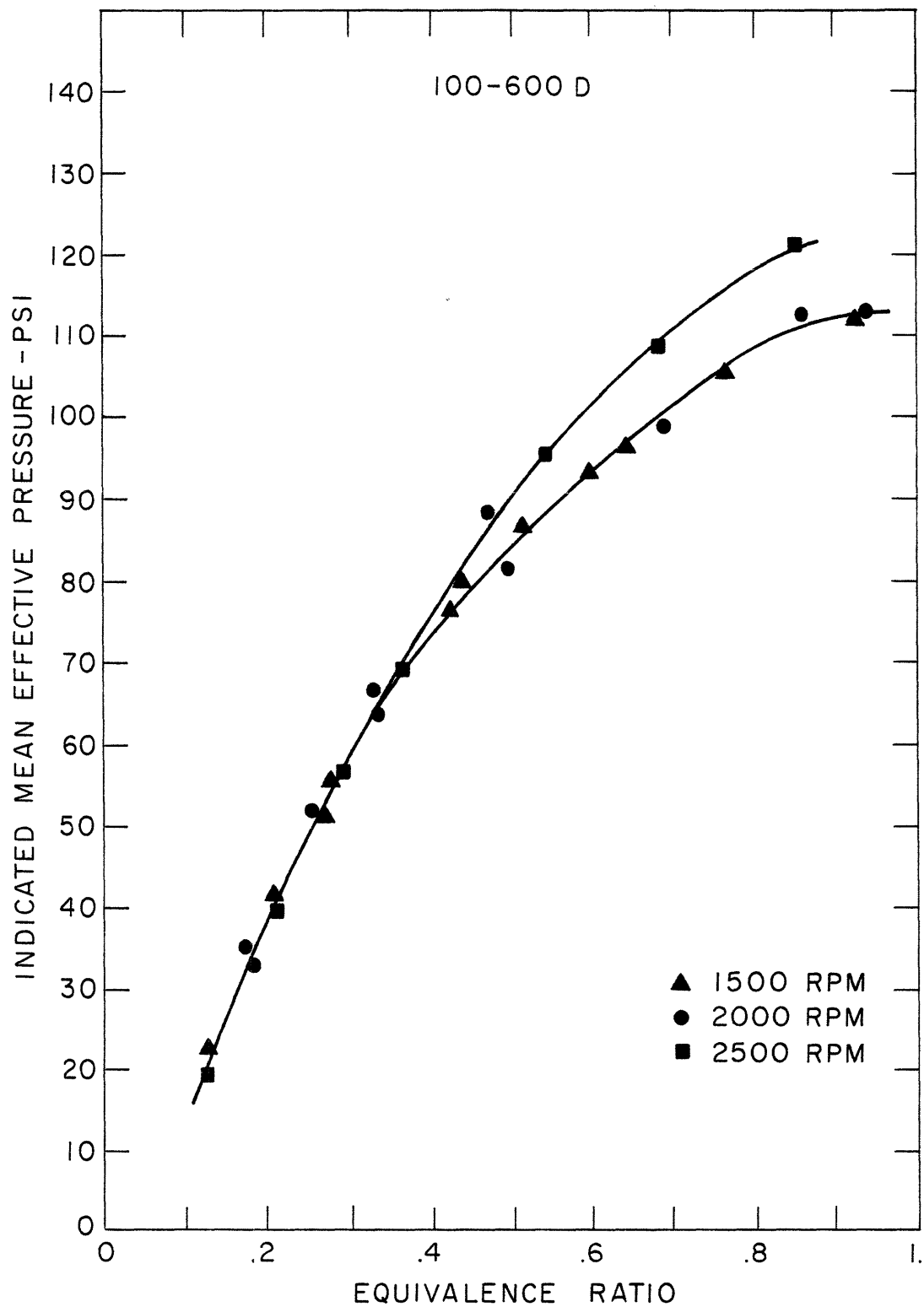


FIG. 19 INDICATED MEAN EFFECTIVE PRESSURE VS
EQUIVALENCE RATIO, FOR 100-600 FUEL

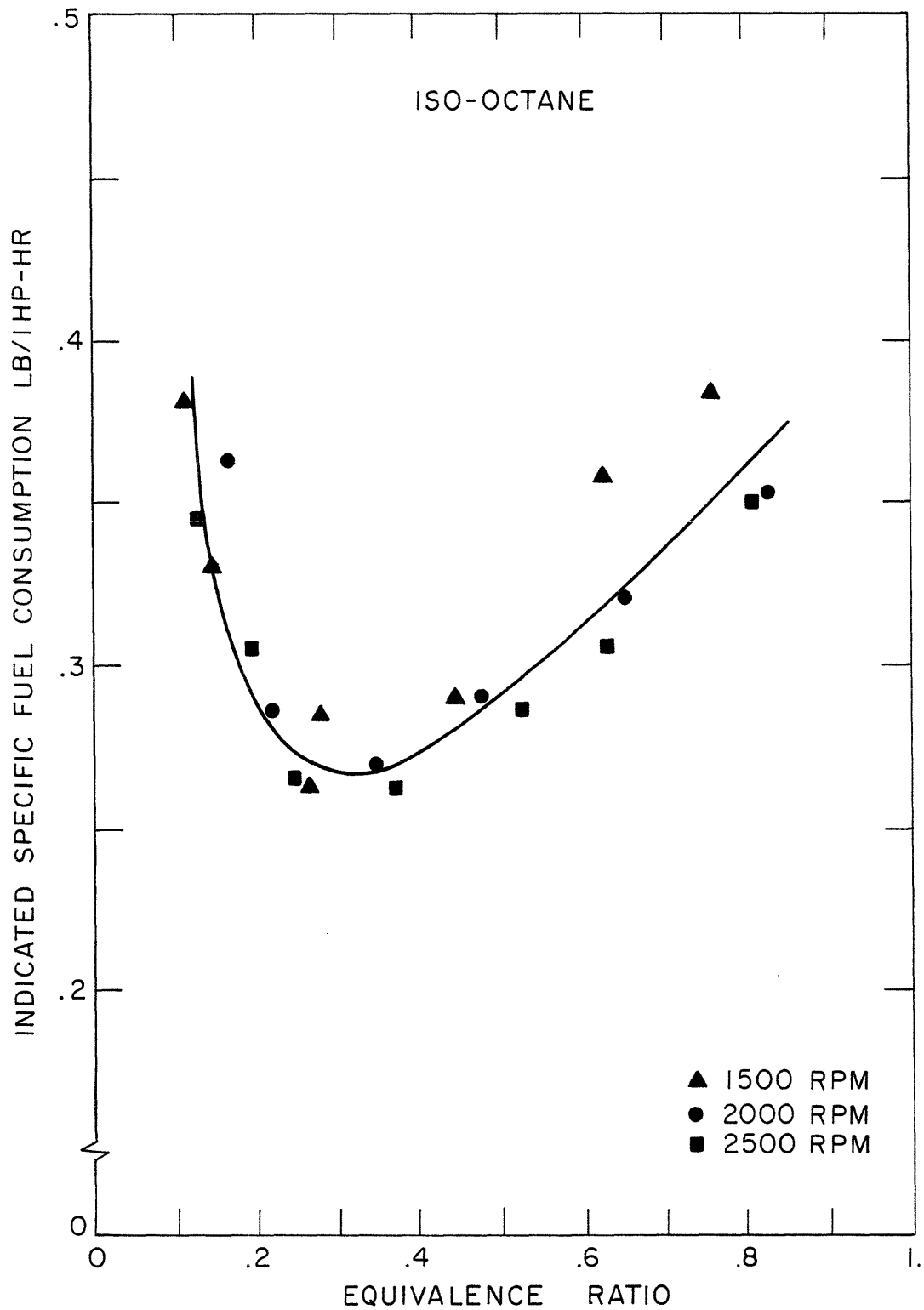


FIG. 20 INDICATED SPECIFIC FUEL CONSUMPTION VS
EQUIVALENCE RATIO, FOR ISO-OCTANE

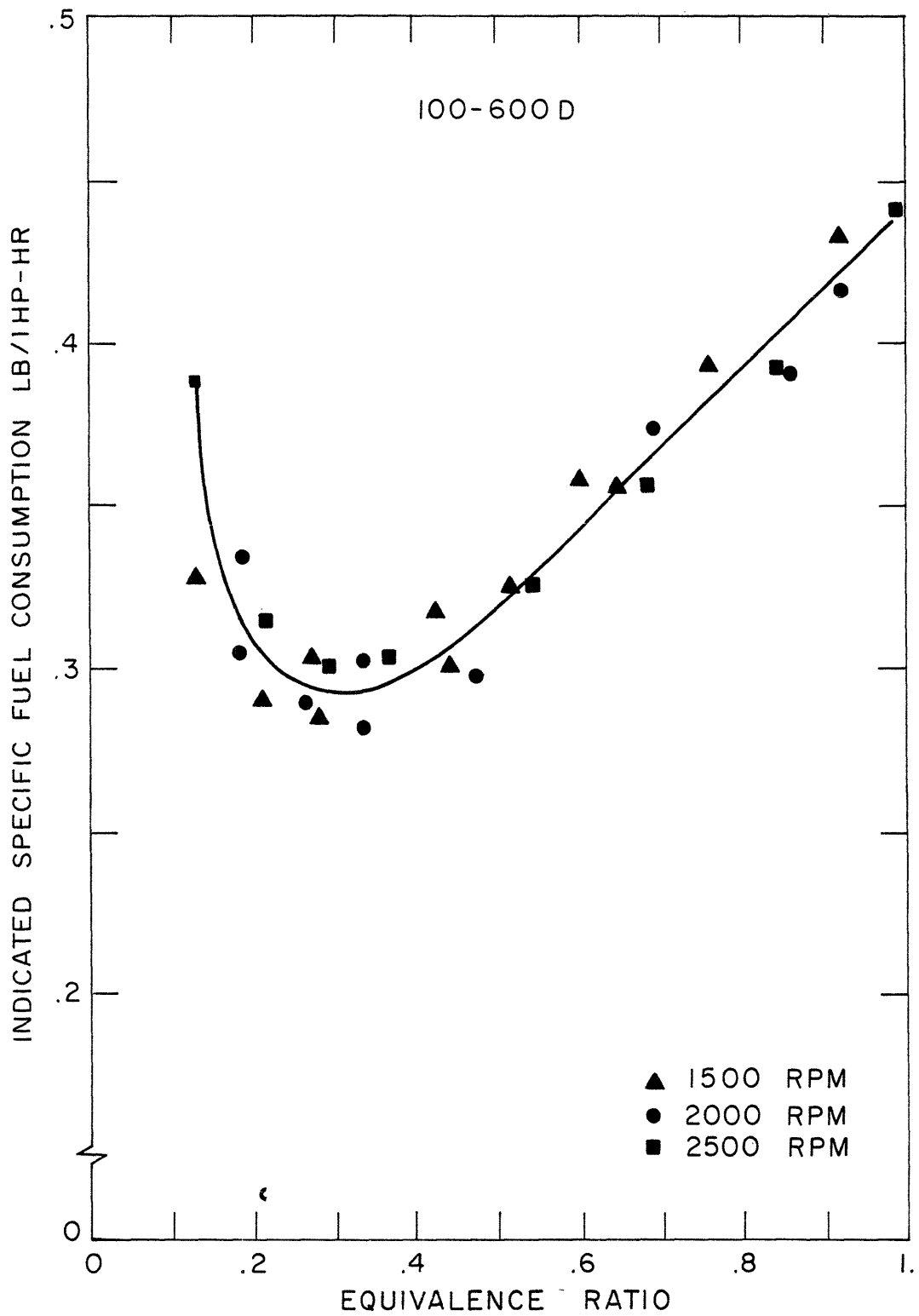


FIG. 21 INDICATED SPECIFIC FUEL CONSUMPTION VS
EQUIVALENCE RATIO, FOR 100-600 FUEL

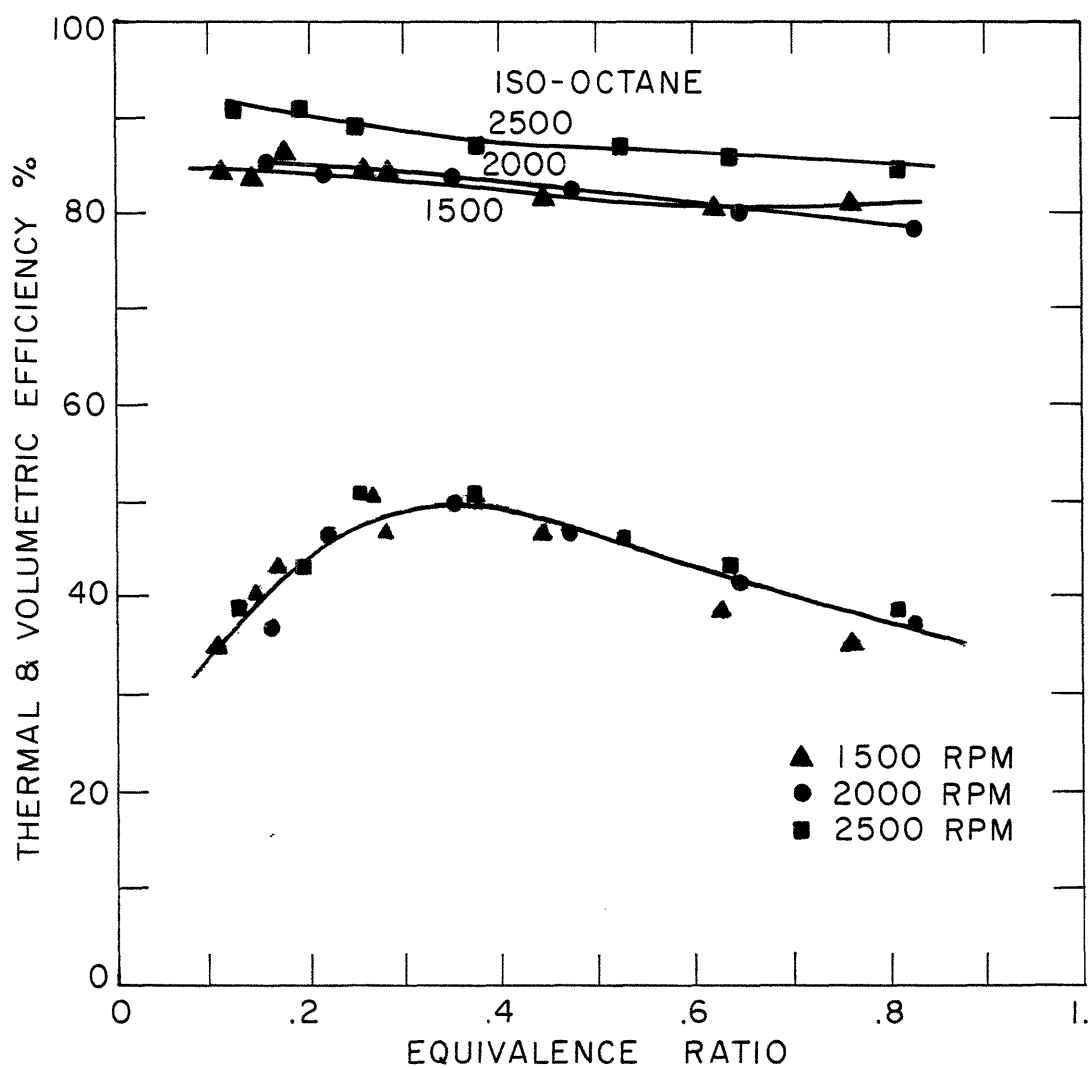


FIG. 22 INDICATED THERMAL AND VOLEMETRIC EFFICIENCY
VS EQUIVALENCE RATIO FOR ISO-OCTANE

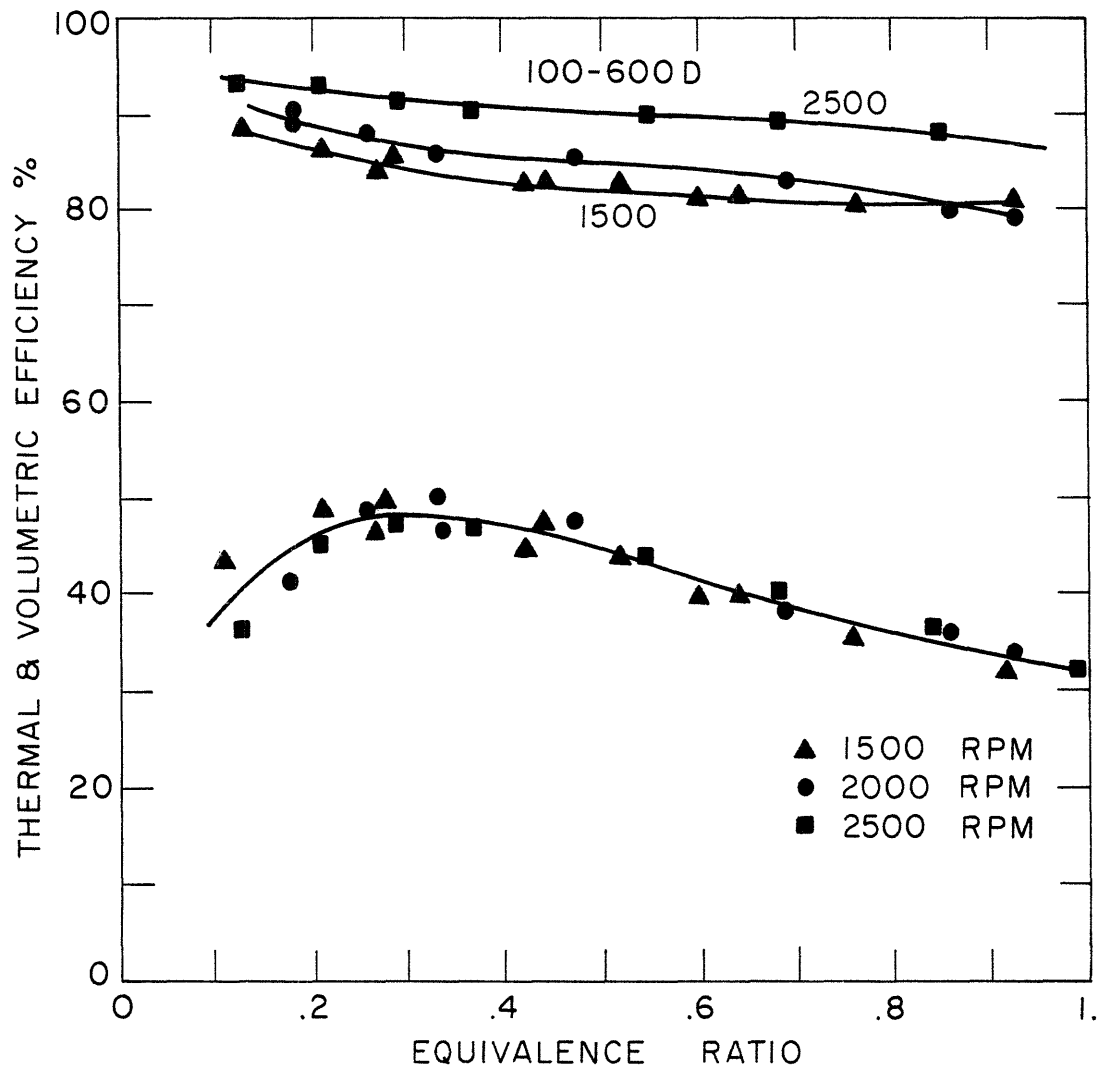


FIG. 23 INDICATED THERMAL AND VOLUMETRIC EFFICIENCY
VS EQUIVALENCE RATIO FOR 100-600 FUEL

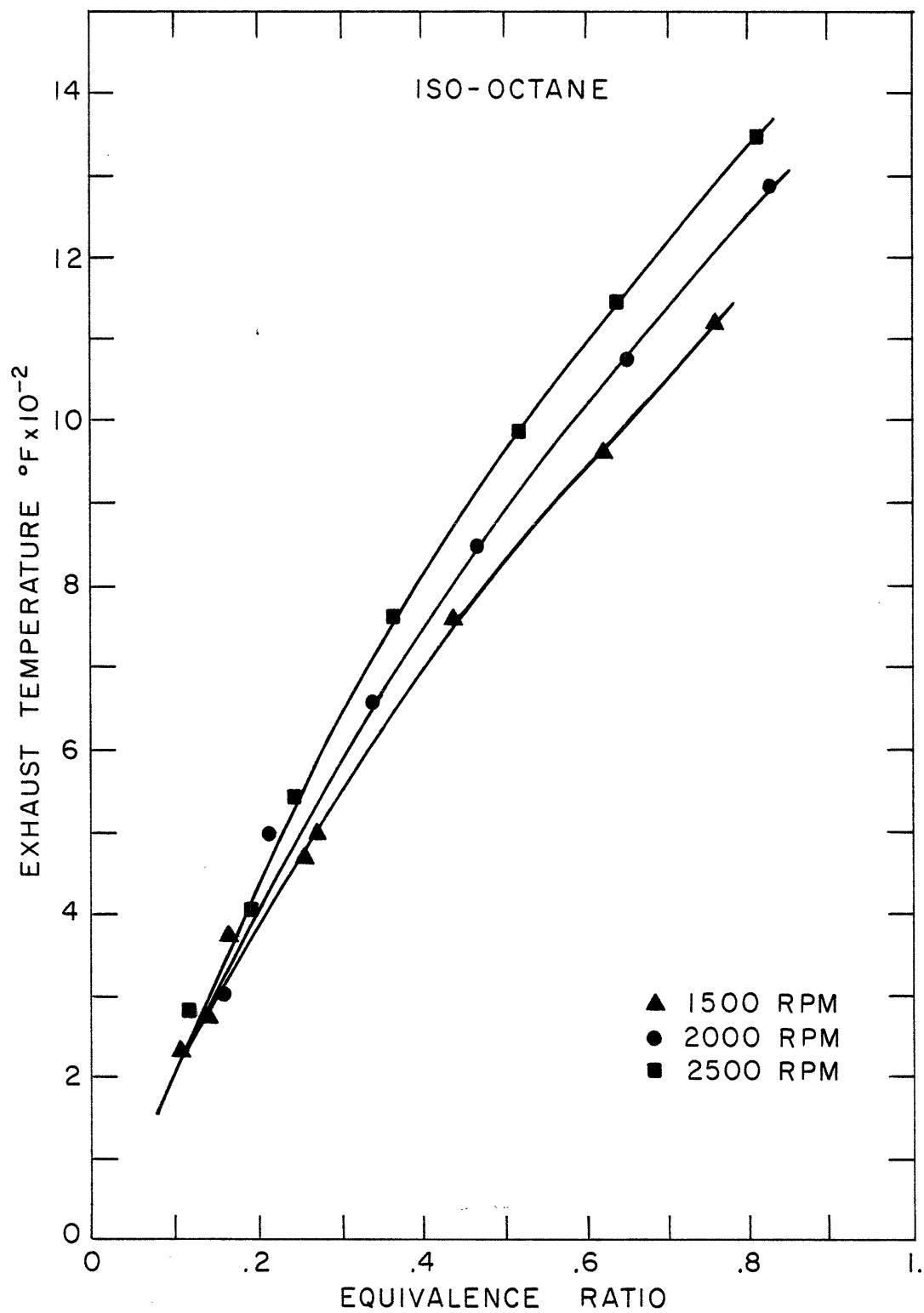


FIG. 24 EXHAUST TEMPERATURE VS EQUIVALENCE RATIO
FOR ISO-OCTANE

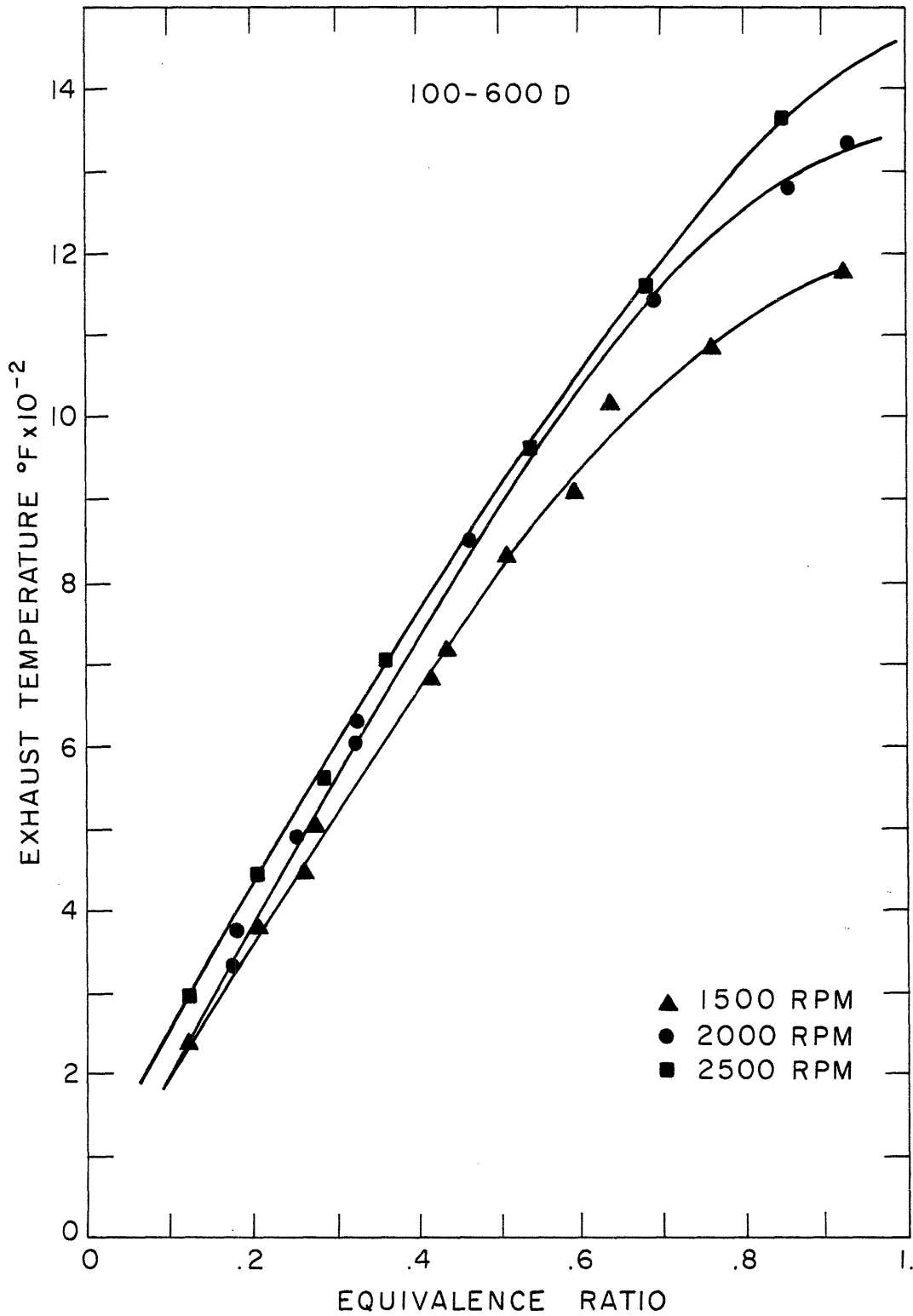


FIG. 25 EXHAUST TEMPERATURE VS EQUIVALENCE RATIO FOR 100-600 FUEL

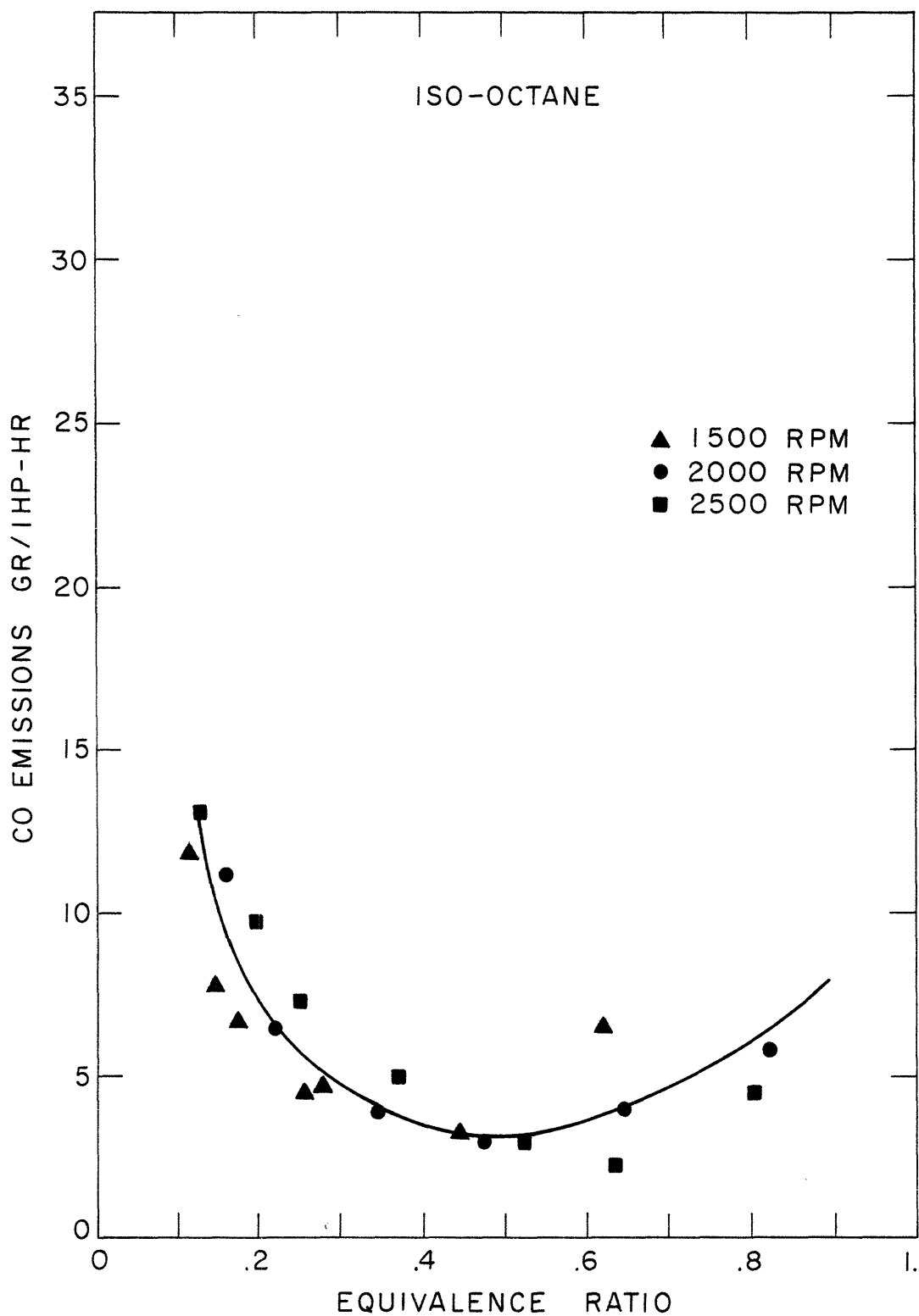


FIG. 26 CARBON MONOXIDE EMISSIONS VS EQUIVALENCE RATIO FOR ISO-OCTANE

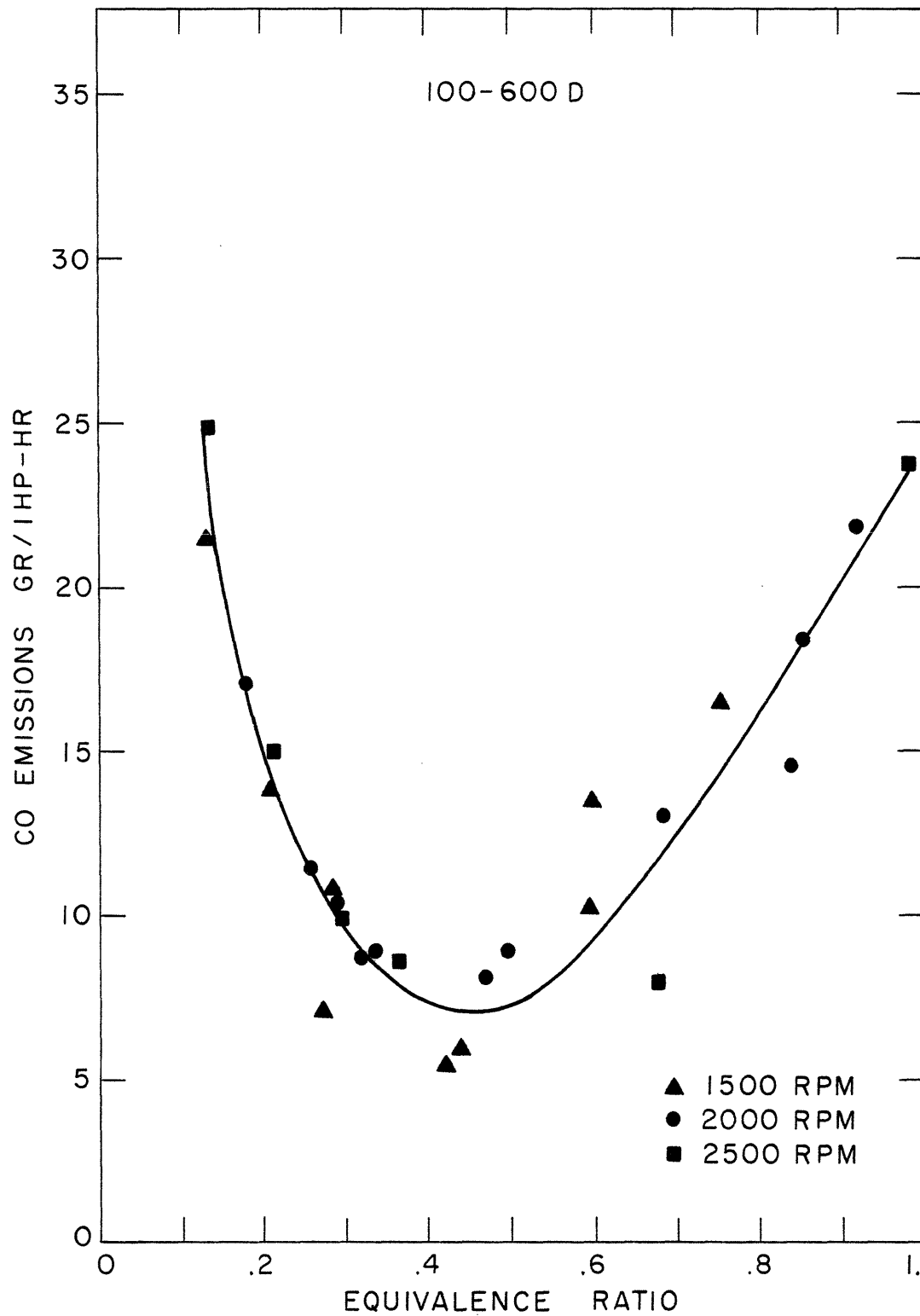


FIG. 27 CARBON MONOXIDE EMISSIONS VS EQUIVALENCE RATIO FOR 100-600 FUEL

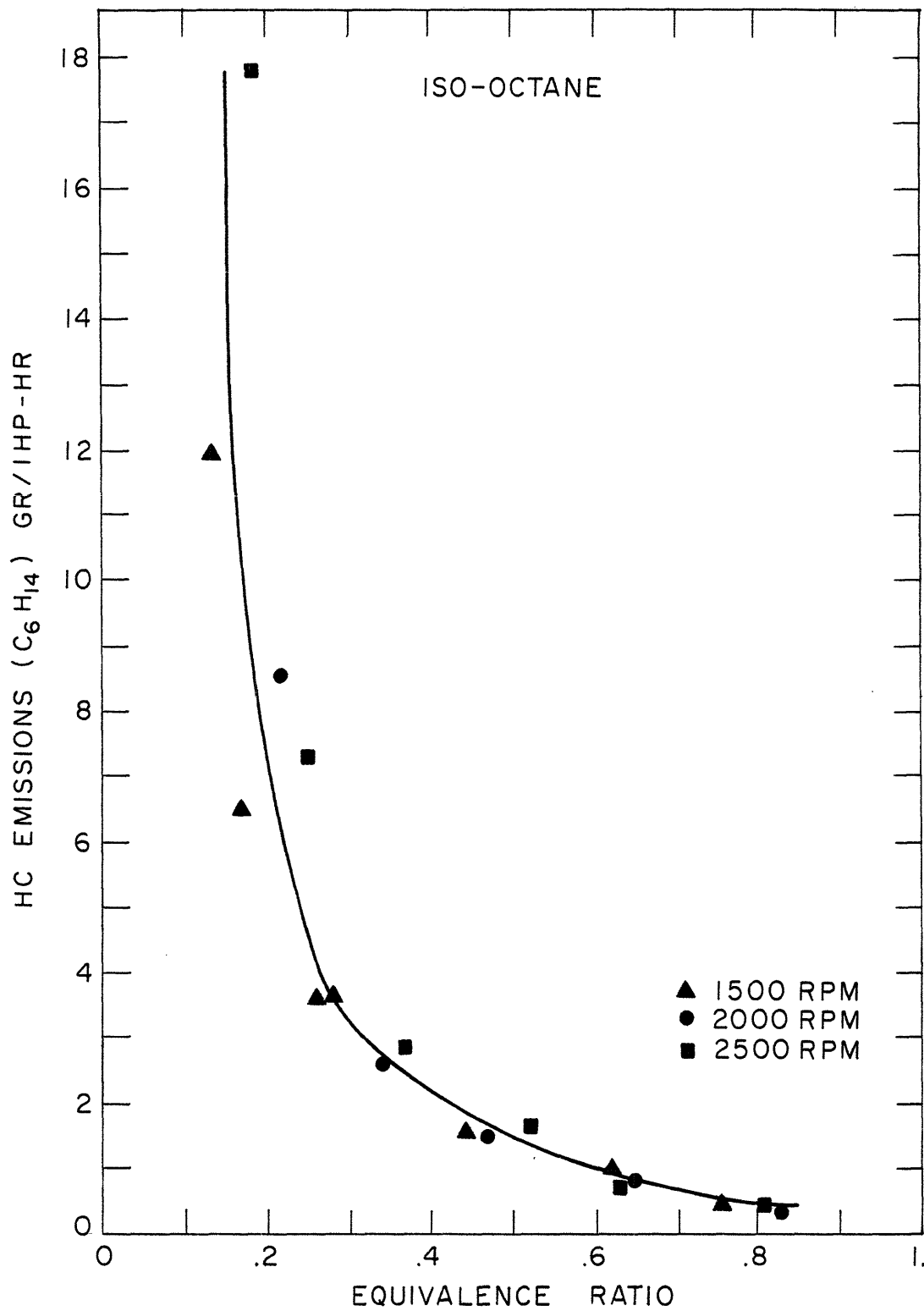


FIG. 28 HYDROCARBON EMISSIONS VS EQUIVALENCE RATIO FOR ISO-OCTANE

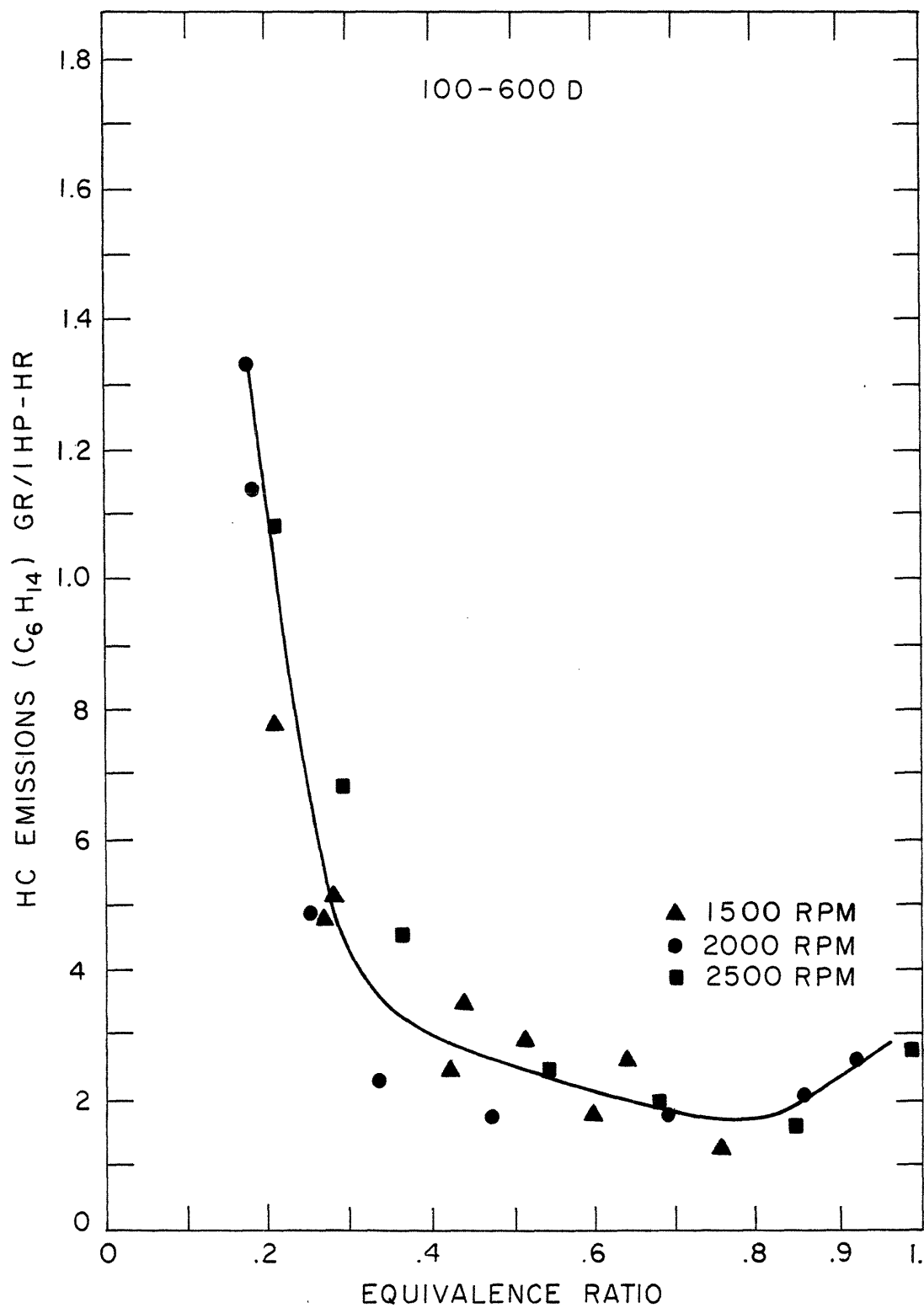


FIG. 29 HYDROCARBON EMISSIONS VS EQUIVALENCE RATIO FOR 100-600 FUEL

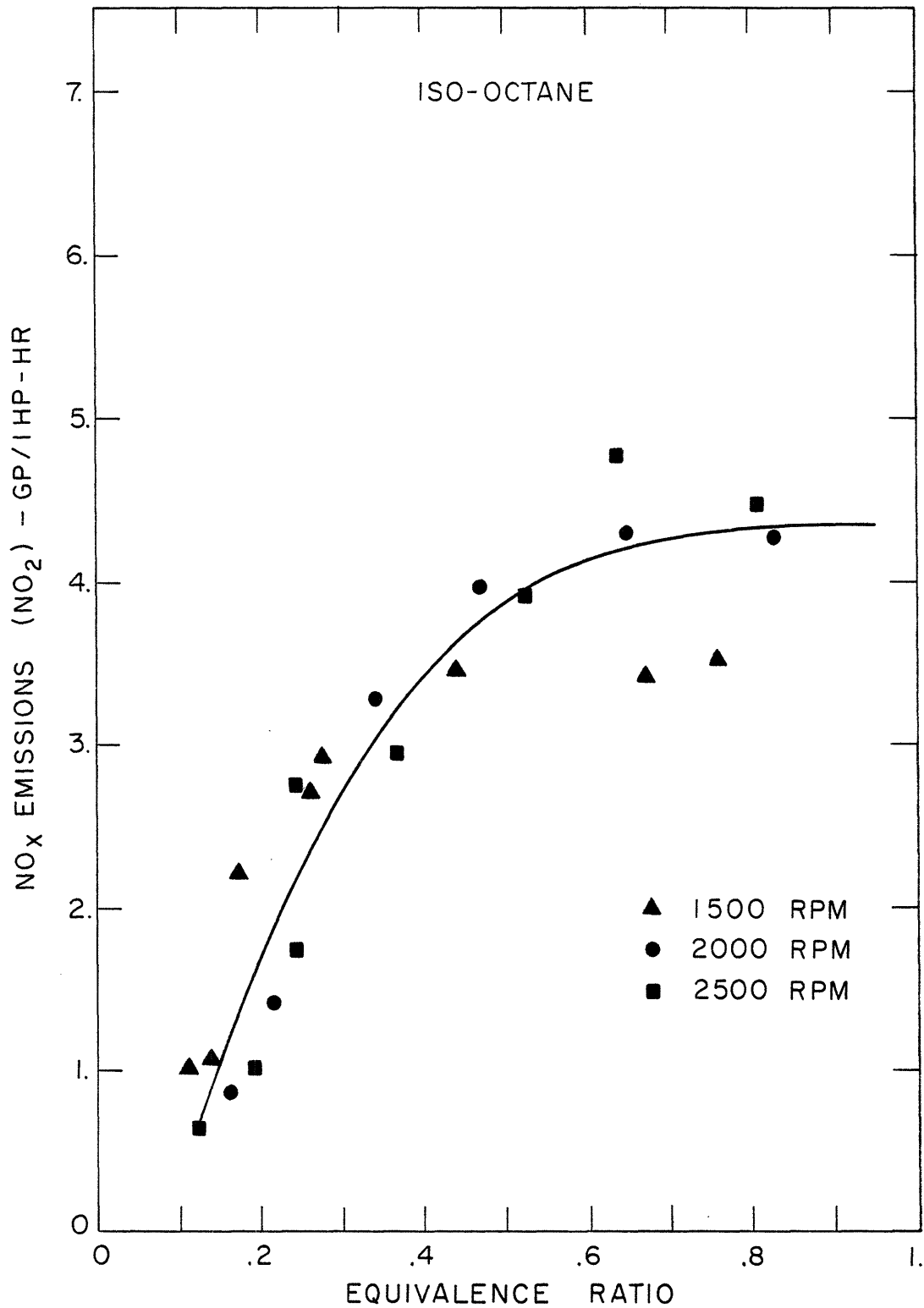


FIG. 30 NITRIC OXIDE EMISSIONS VS EQUIVALENCE RATIO FOR ISO-OCTANE

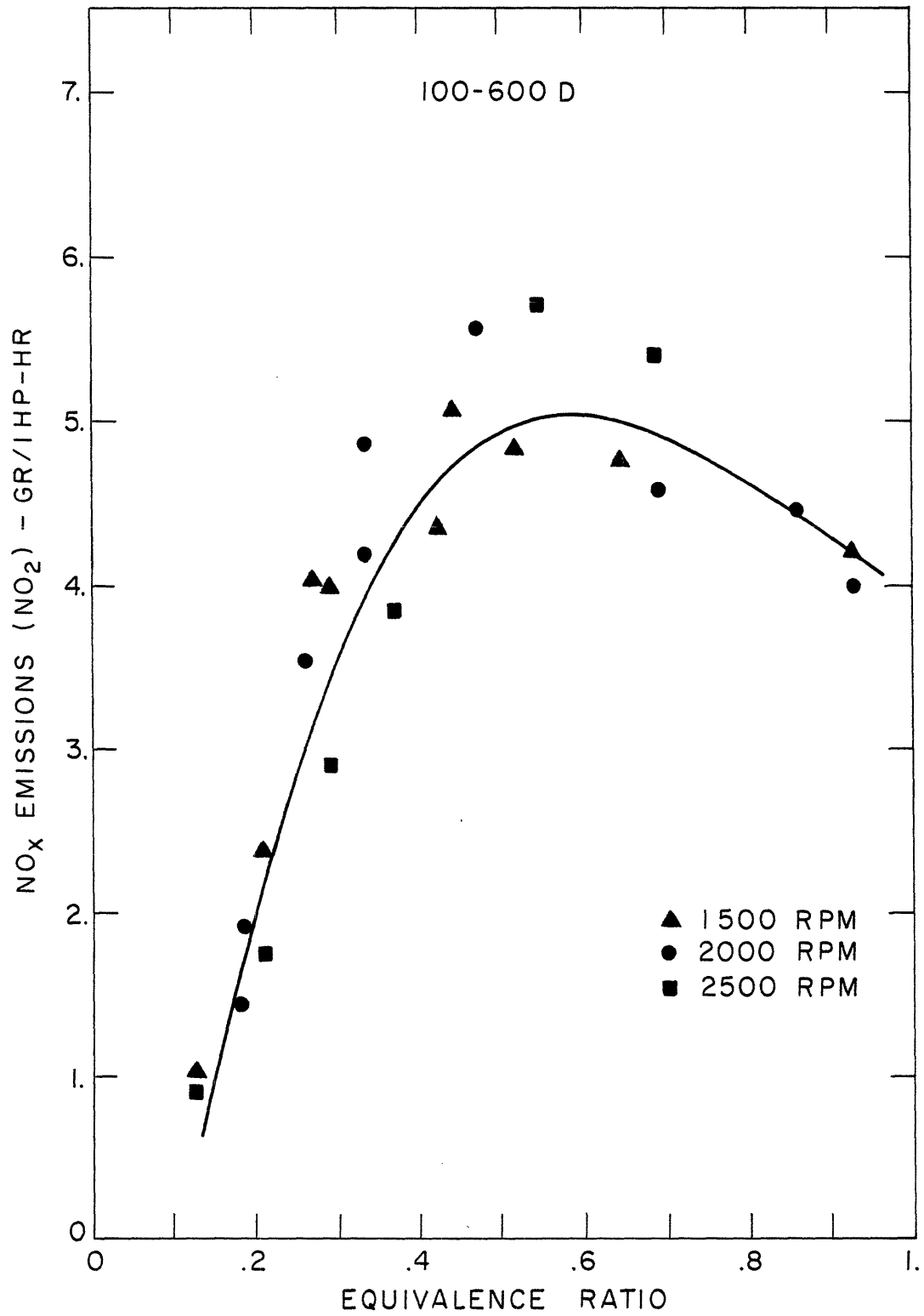


FIG. 31 NITRIC OXIDE EMISSIONS VS EQUIVALENCE RATIO FOR 100-600 FUEL

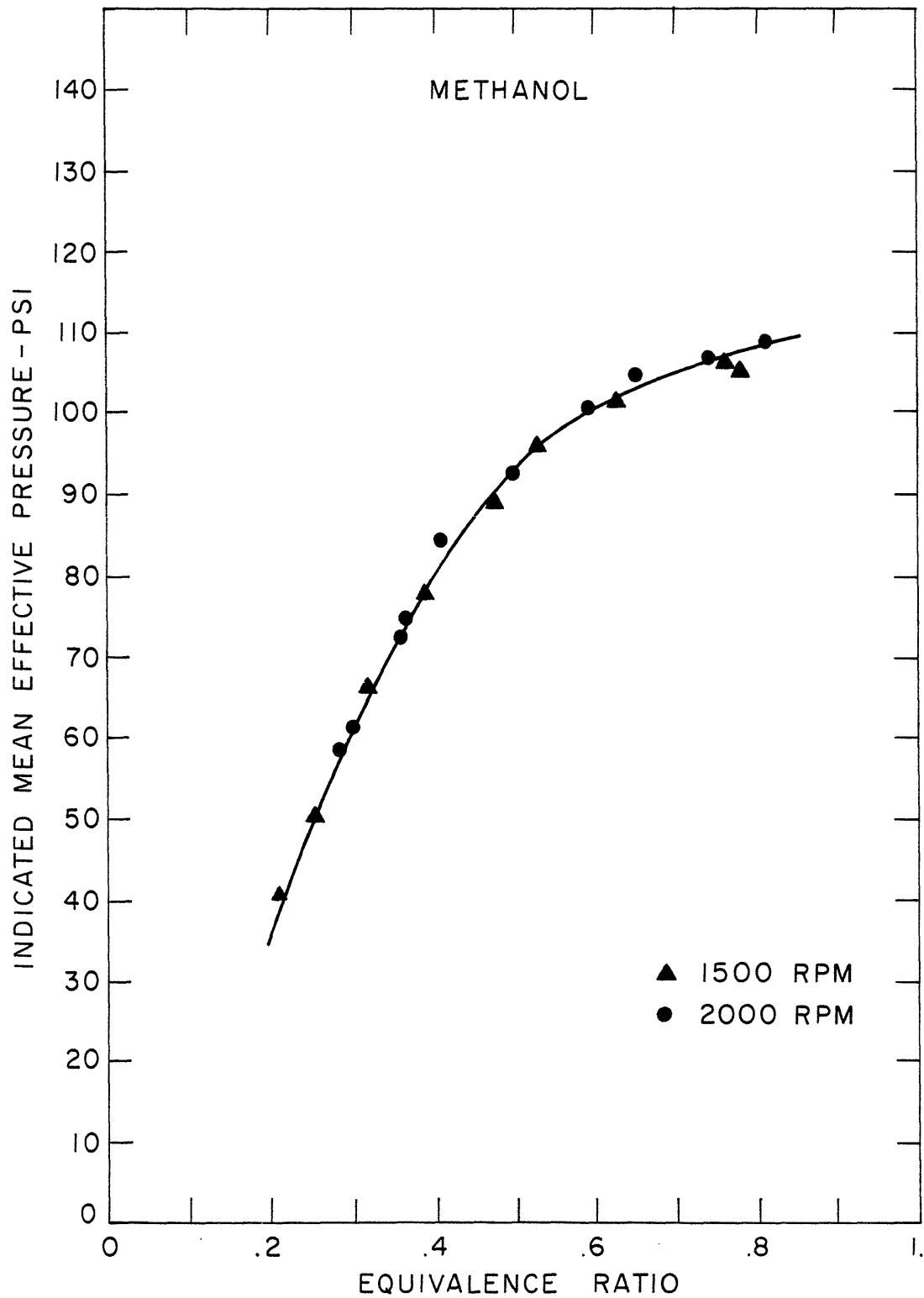


FIG. 32 INDICATED MEAN EFFECTIVE PRESSURE VS
EQUIVALENCE RATIO FOR METHANOL

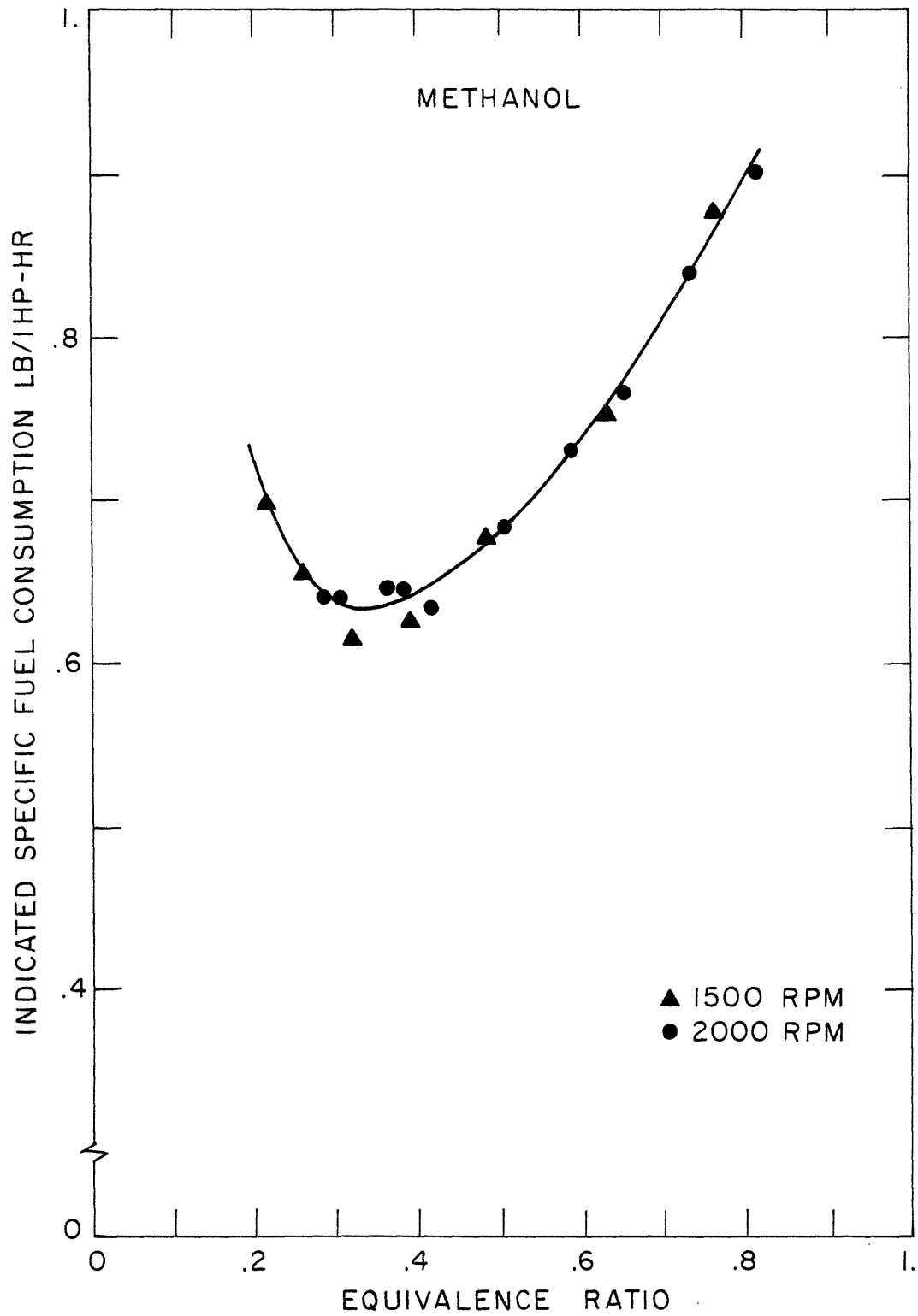


FIG. 33 INDICATED SPECIFIC FUEL CONSUMPTION FOR METHANOL

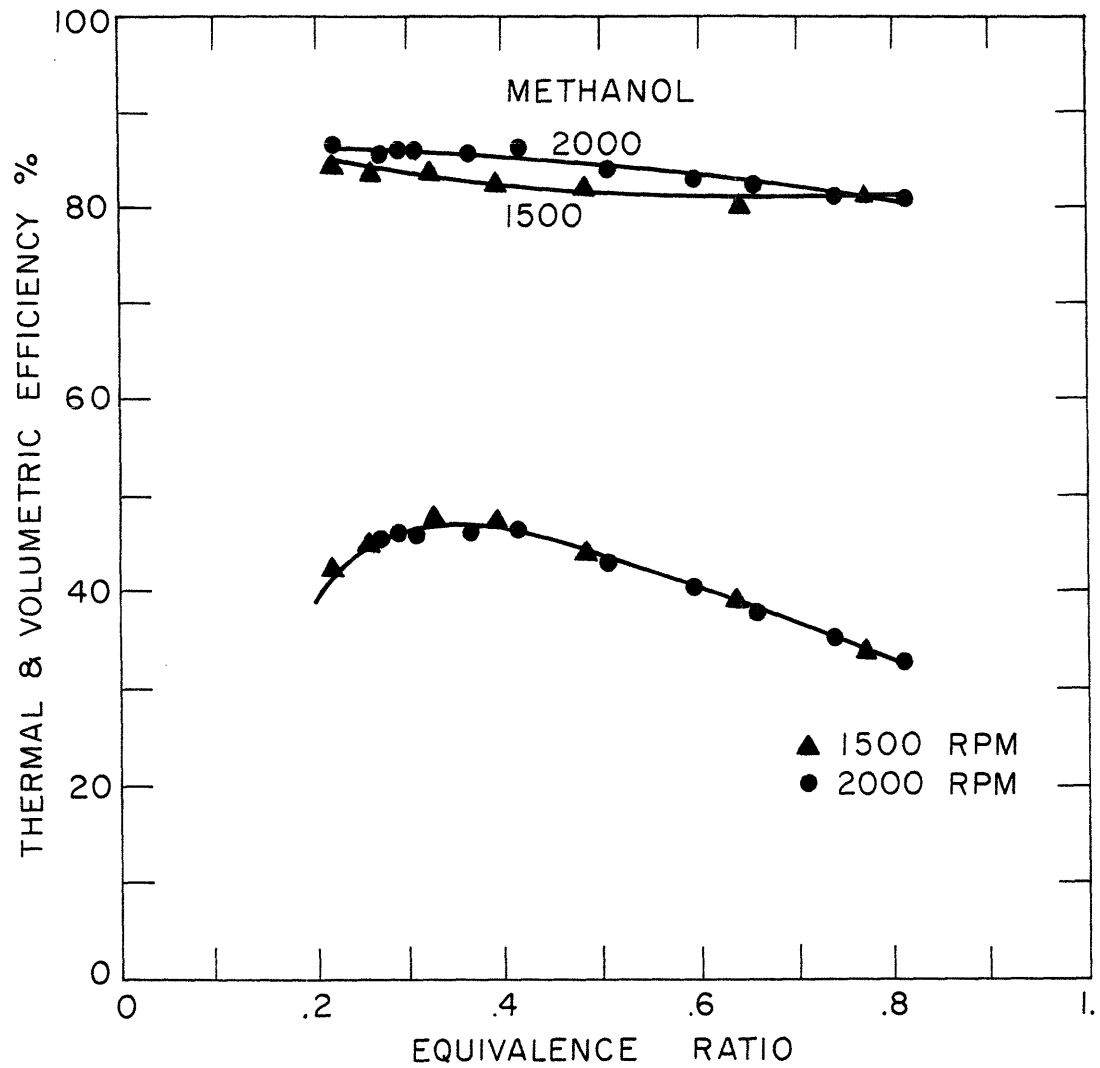


FIG. 34 INDICATED THERMAL AND VOLUMETRIC EFFICIENCY VS EQUIVALENCE RATIO FOR METHANOL

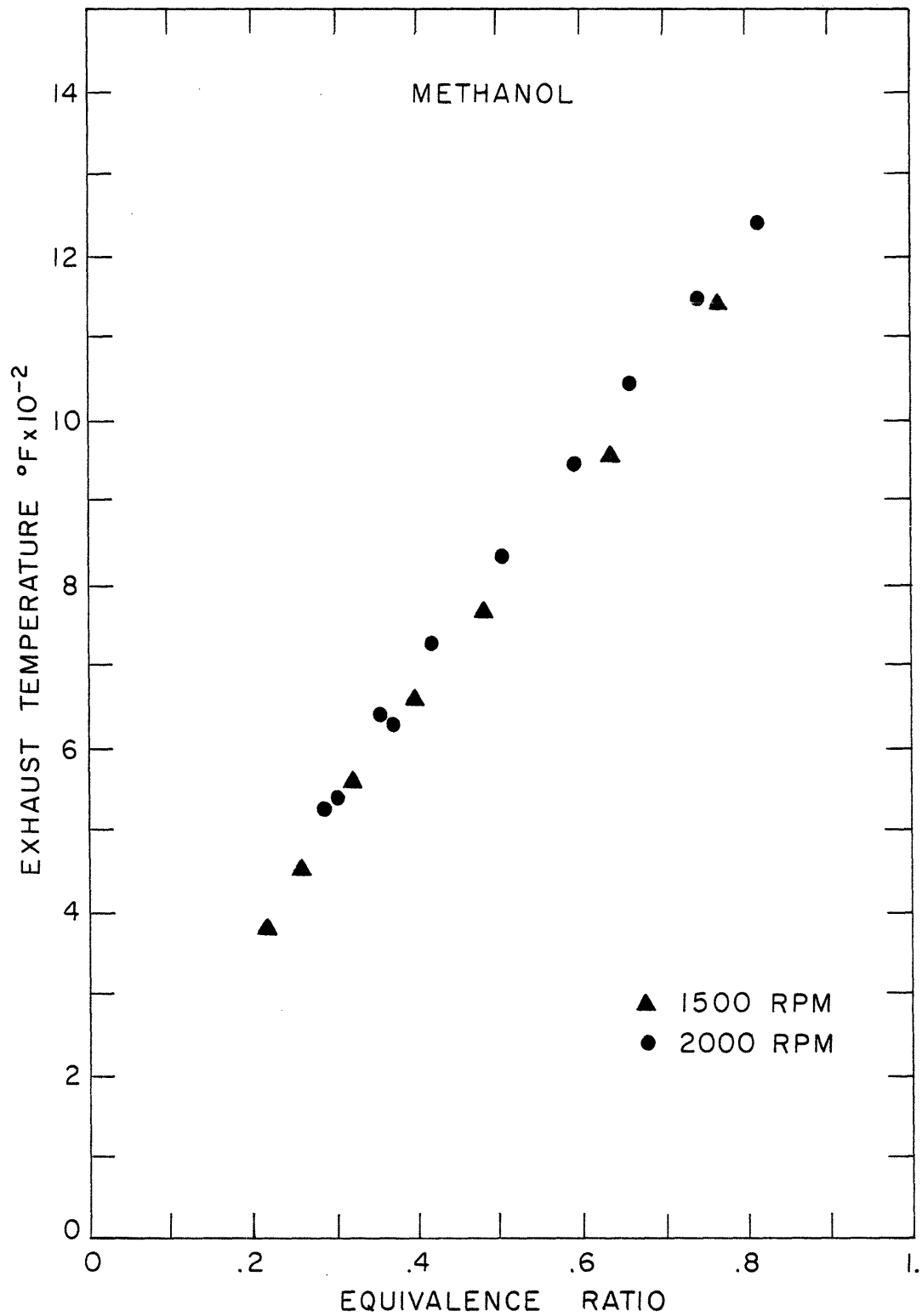


FIG. 35 EXHAUST TEMPERATURE VS EQUIVALENCE RATIO FOR METHANOL

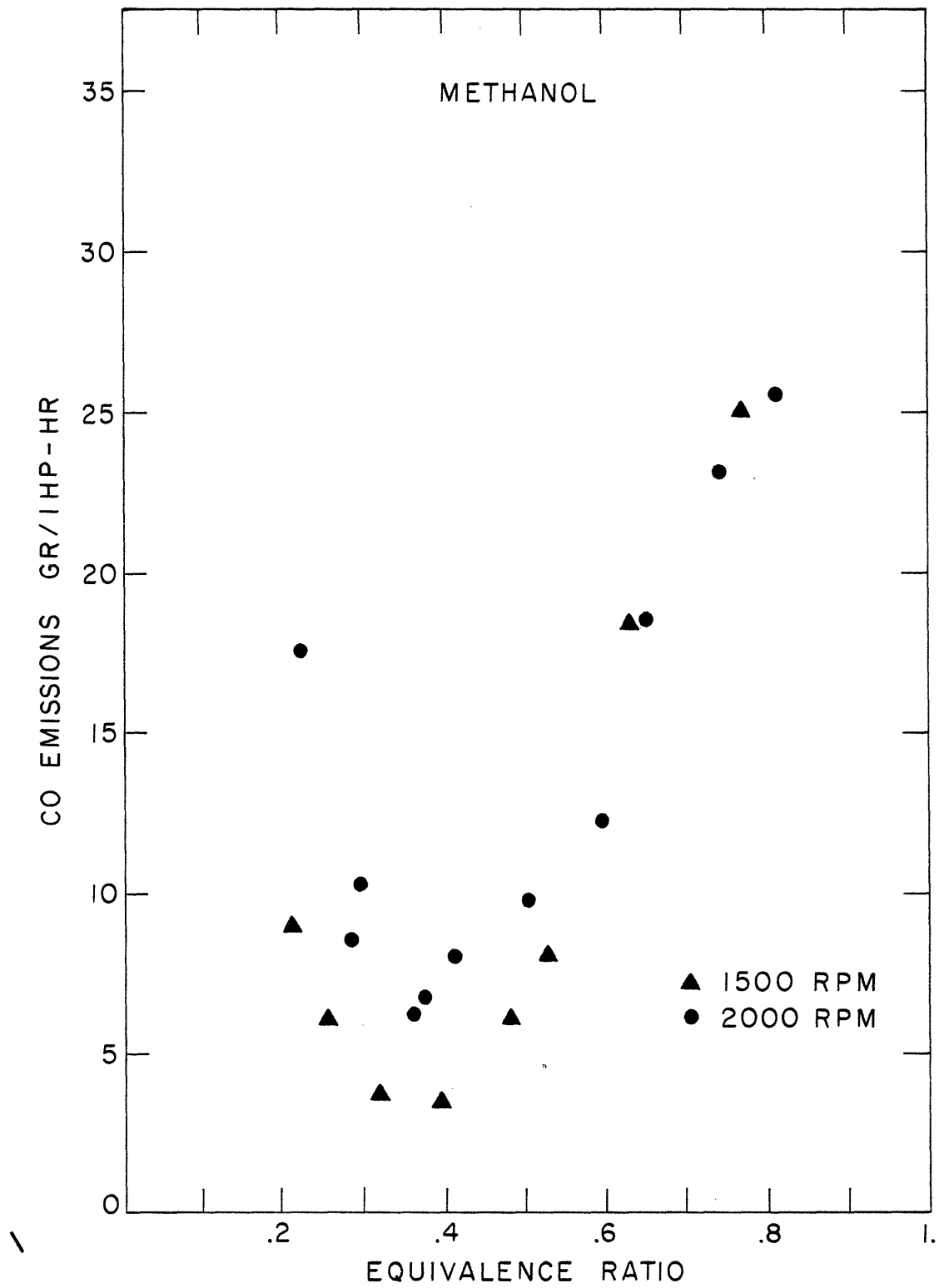


FIG. 36 CARBON MONOXIDE EMISSIONS VS EQUIVALENCE RATIO FOR METHANOL

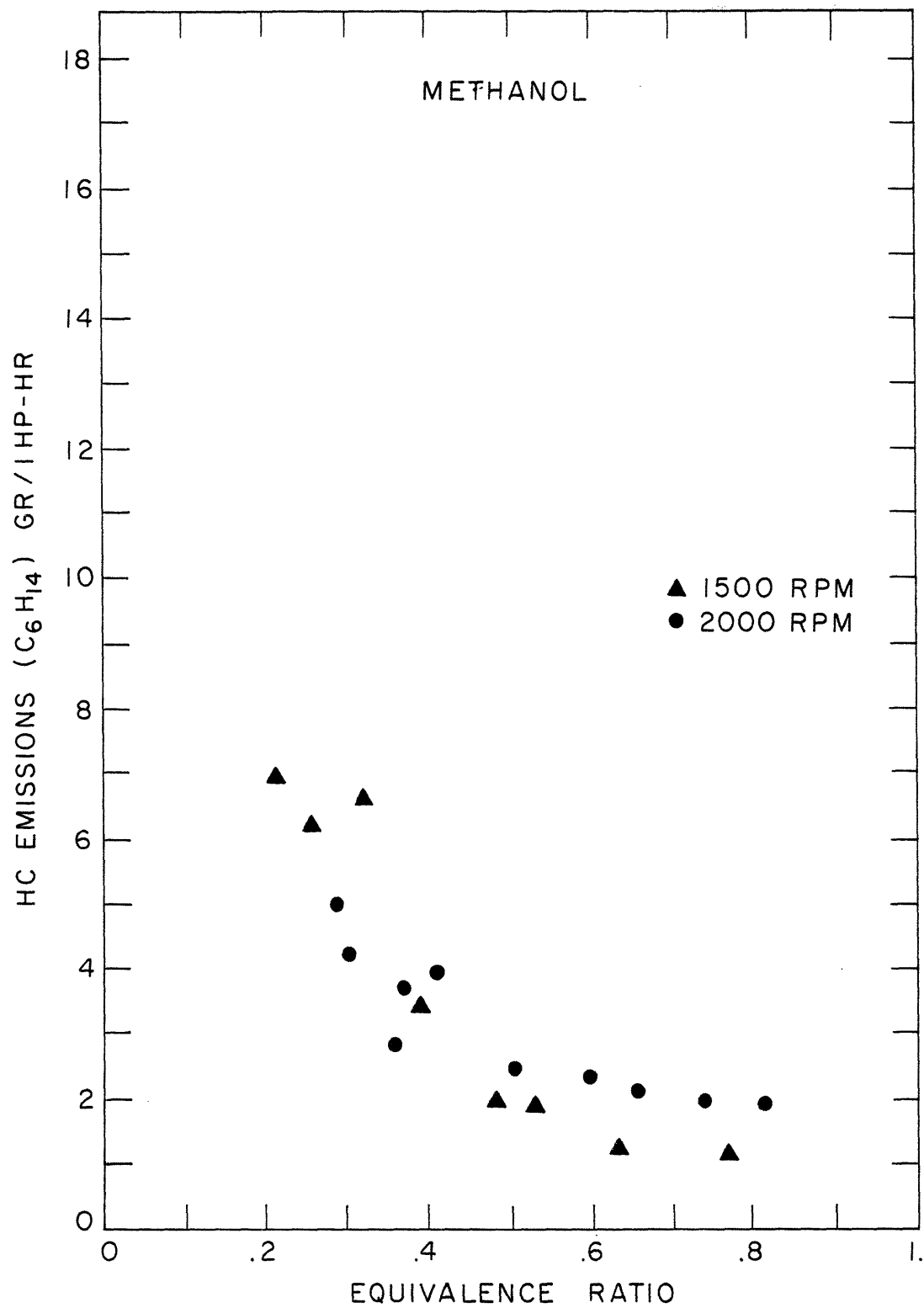


FIG. 37 HYDROCARBON EMISSIONS VS EQUIVALENCE RATIO FOR METHANOL

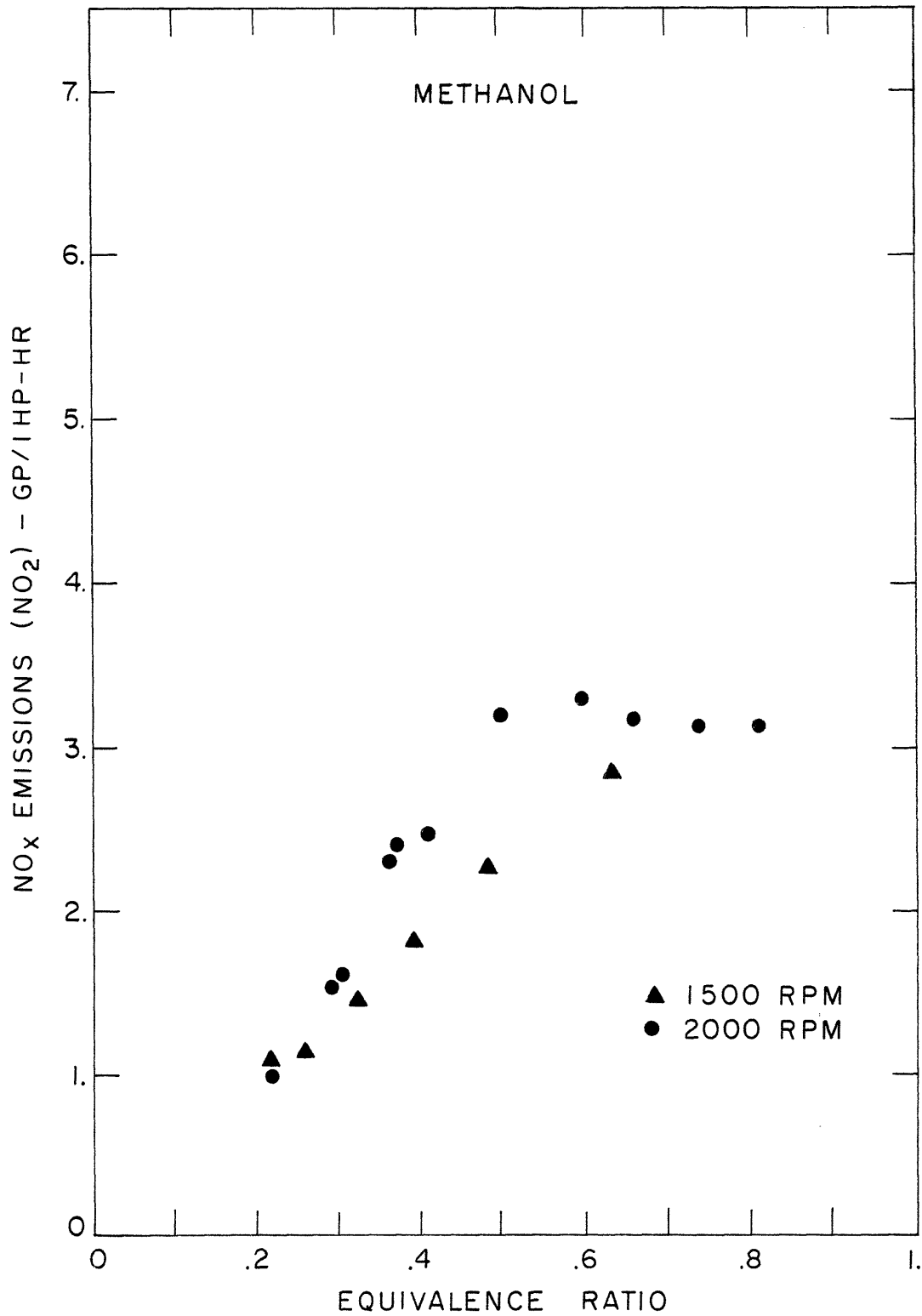


FIG. 38 NITRIC OXIDE EMISSIONS VS EQUIVALENCE RATIO FOR METHANOL

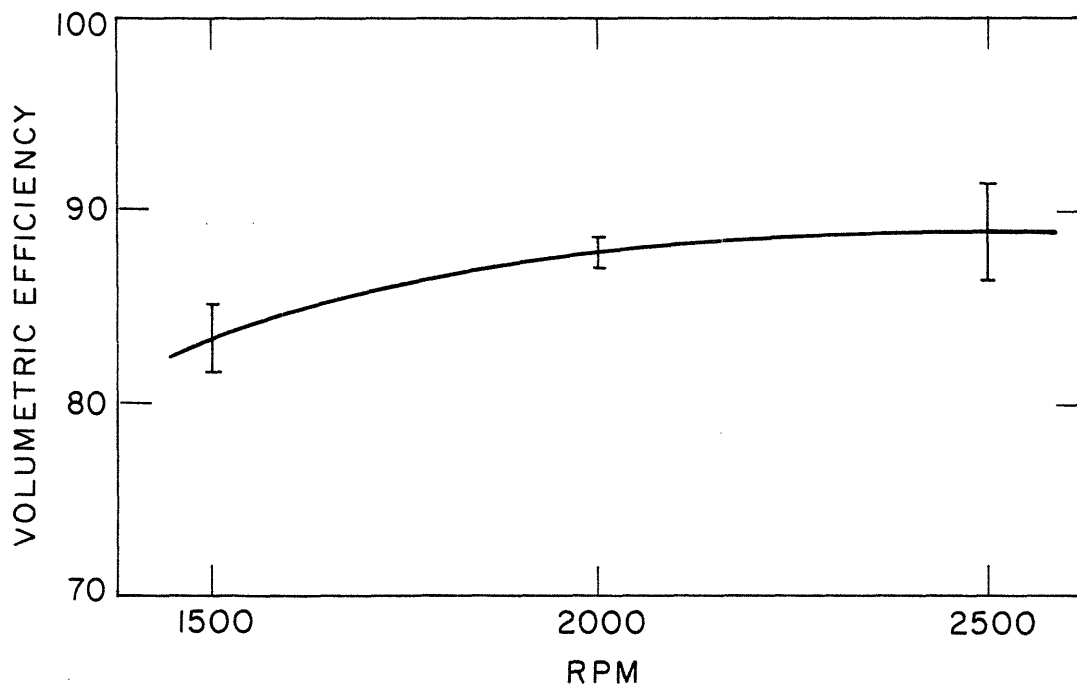


FIG. VOLUMETRIC EFFICIENCY VS ENGINE RPM

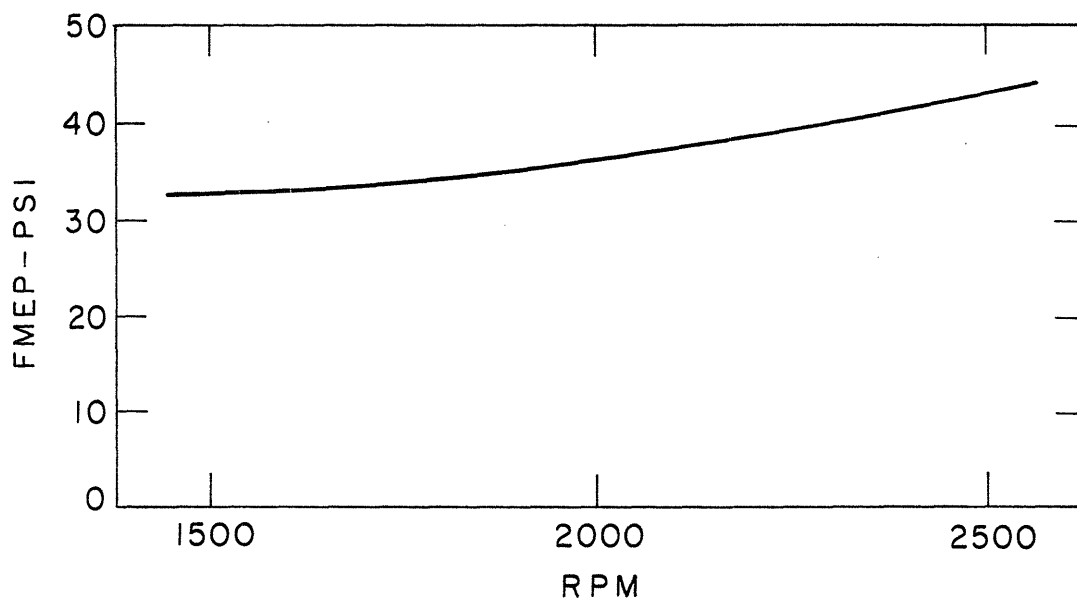


FIG. 39 FRICTION MEAN EFFECTIVE PRESSURE
VS ENGINE RPM

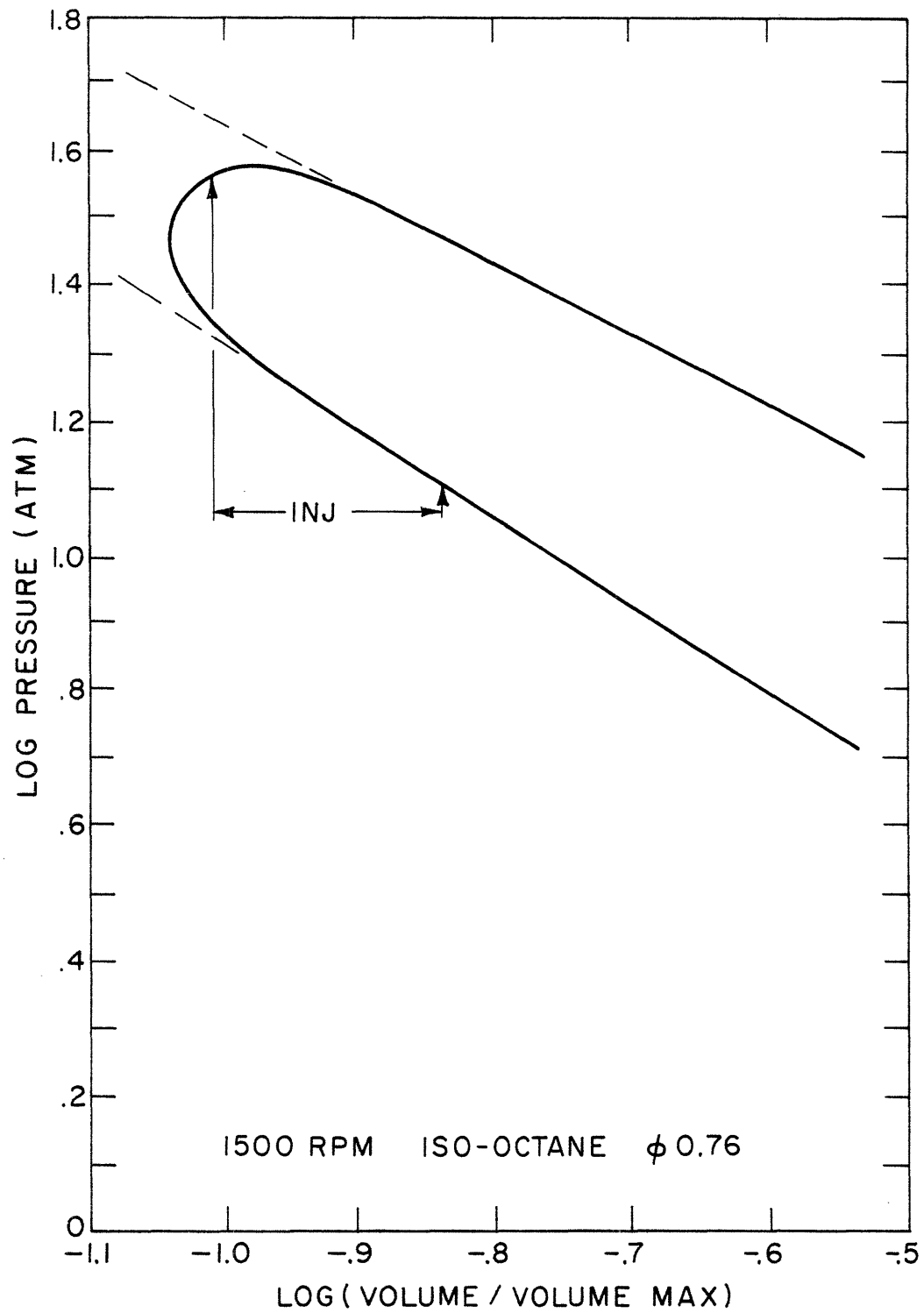


FIG. 40 Log P vs Log V for Iso-octane,
 $\phi = 0.76$, 2500 RPM

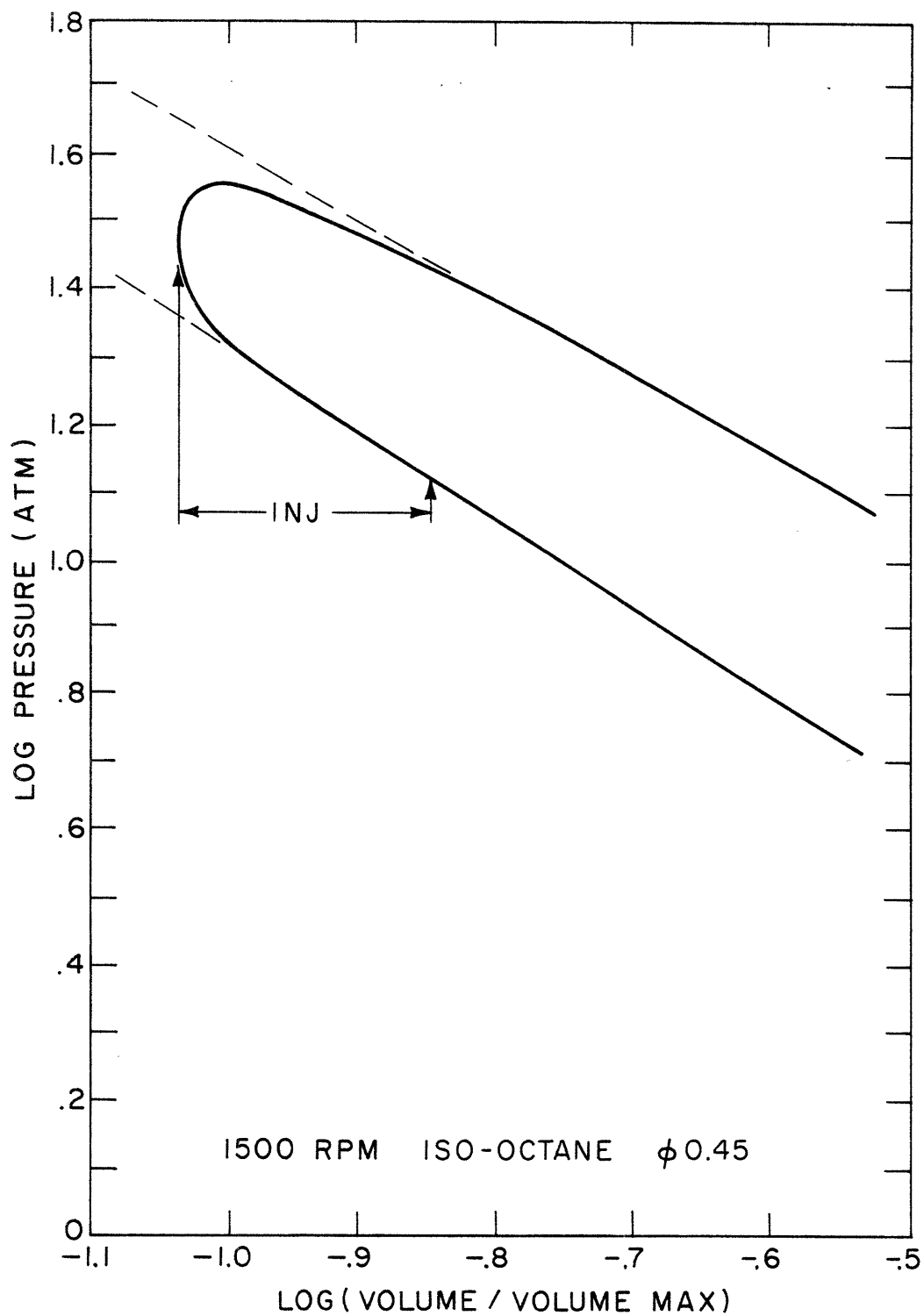


FIG. 41 LOG P vs LOG V FOR ISO-OCTANE,
 $\phi = 0.45$, 1500 RPM

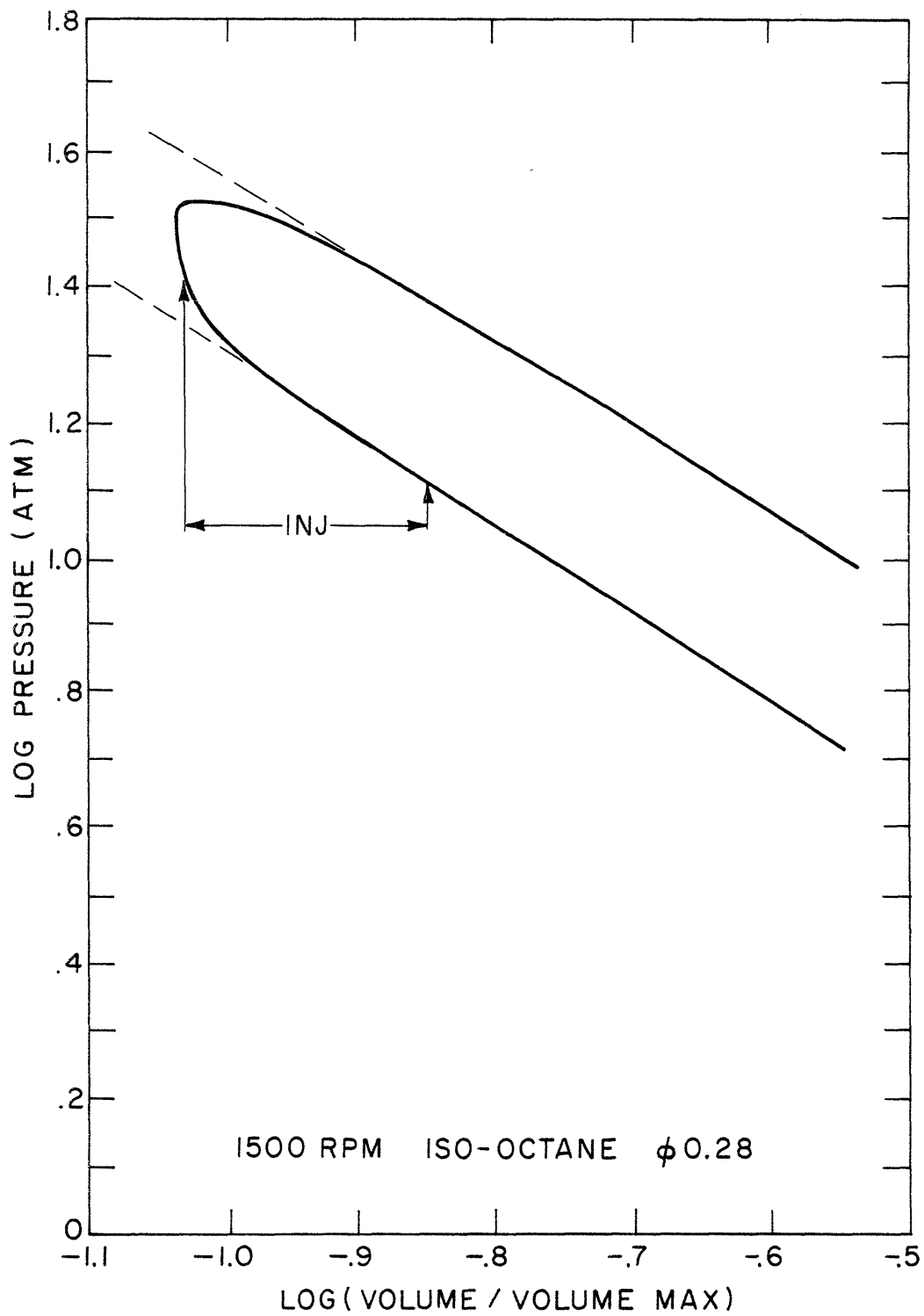


FIG. 42 Log P vs Log V FOR ISO-OCTANE,
 $\phi = 0.28$, 1500 RPM

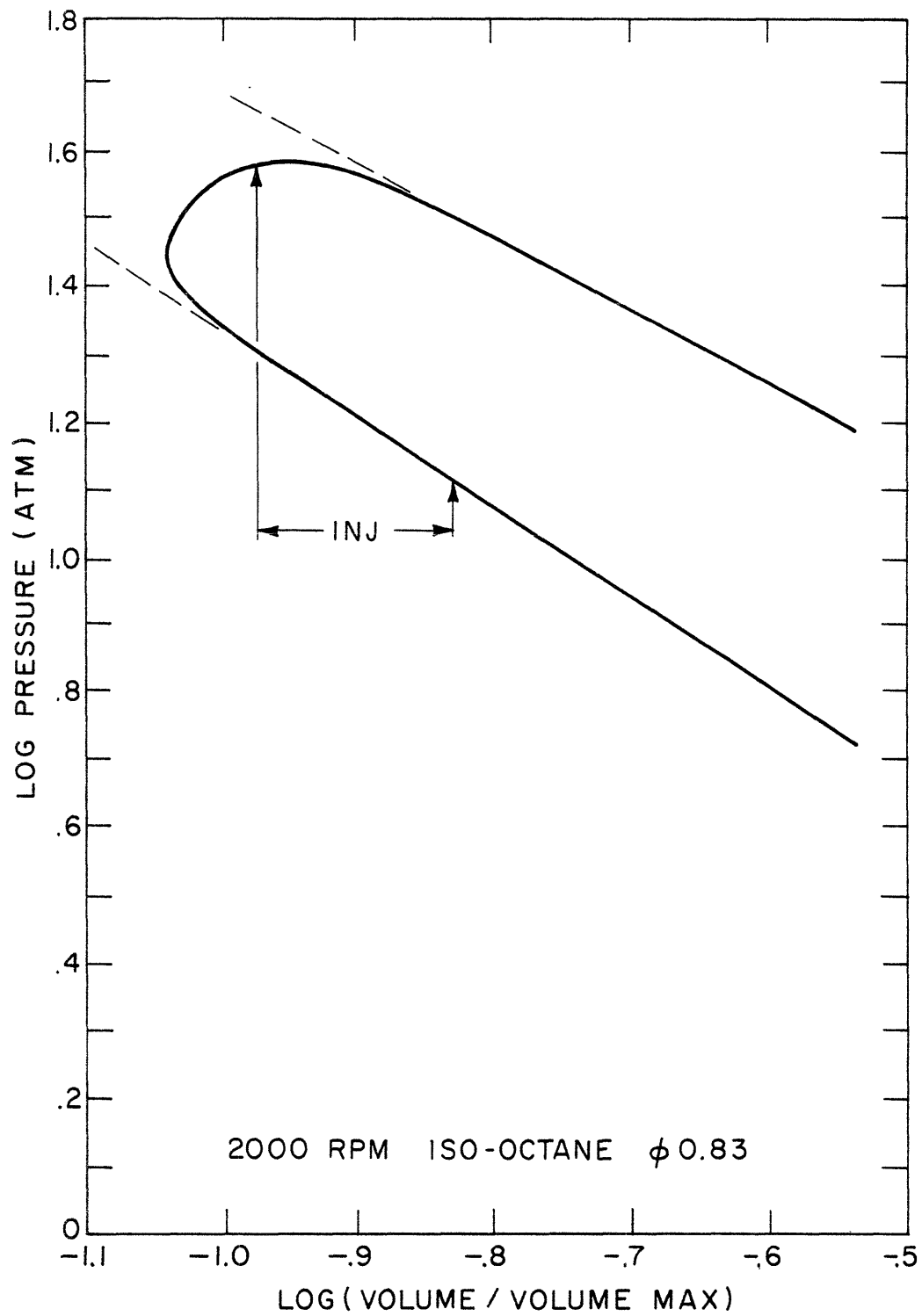


FIG. 43 LOG P vs LOG V FOR ISO-OCTANE,
 $\phi = 0.83$, 2000 RPM

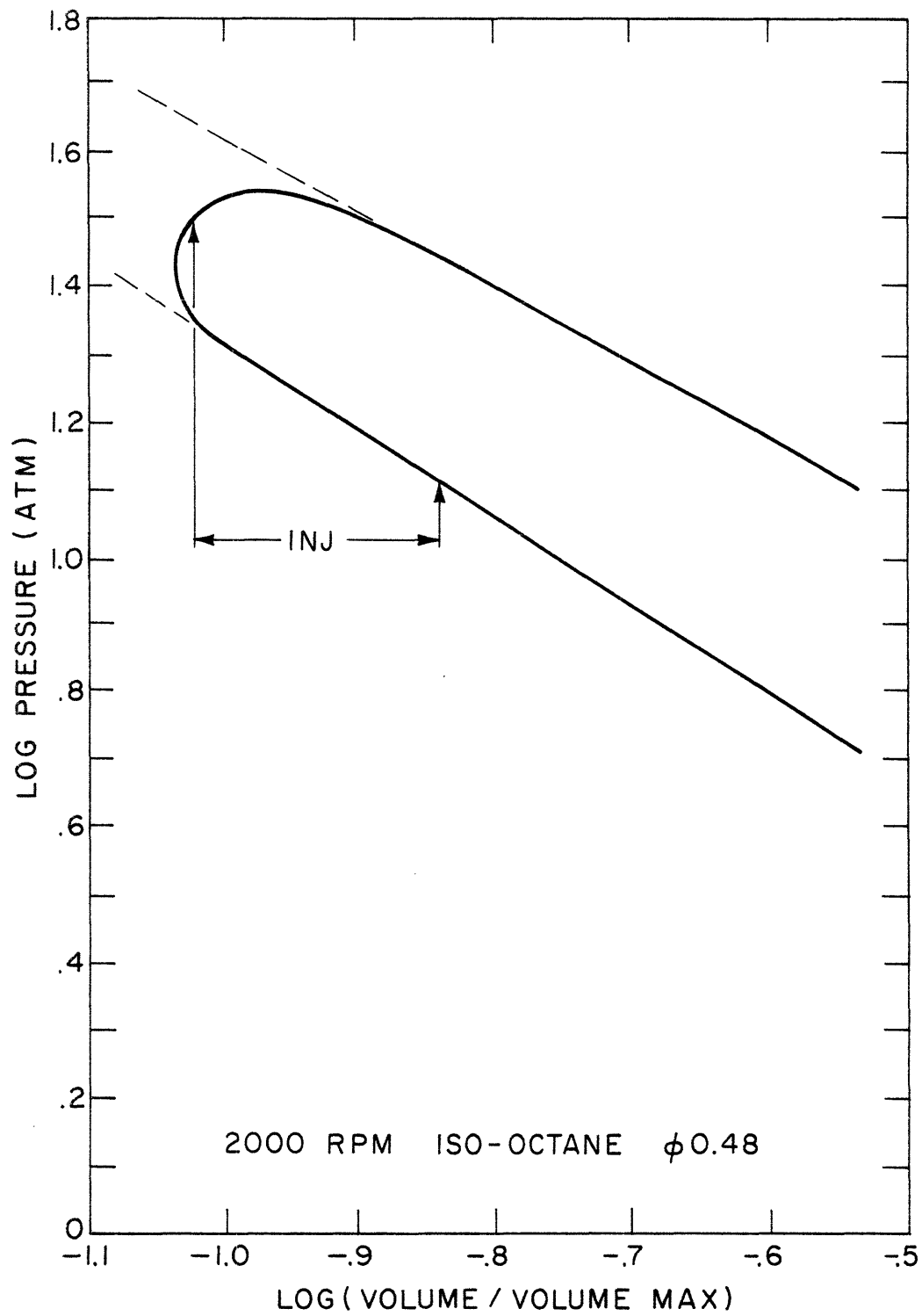


FIG. 44 Log P. vs Log V FOR ISO-OCTANE,
 $\phi = 0.48$, 2000 RPM

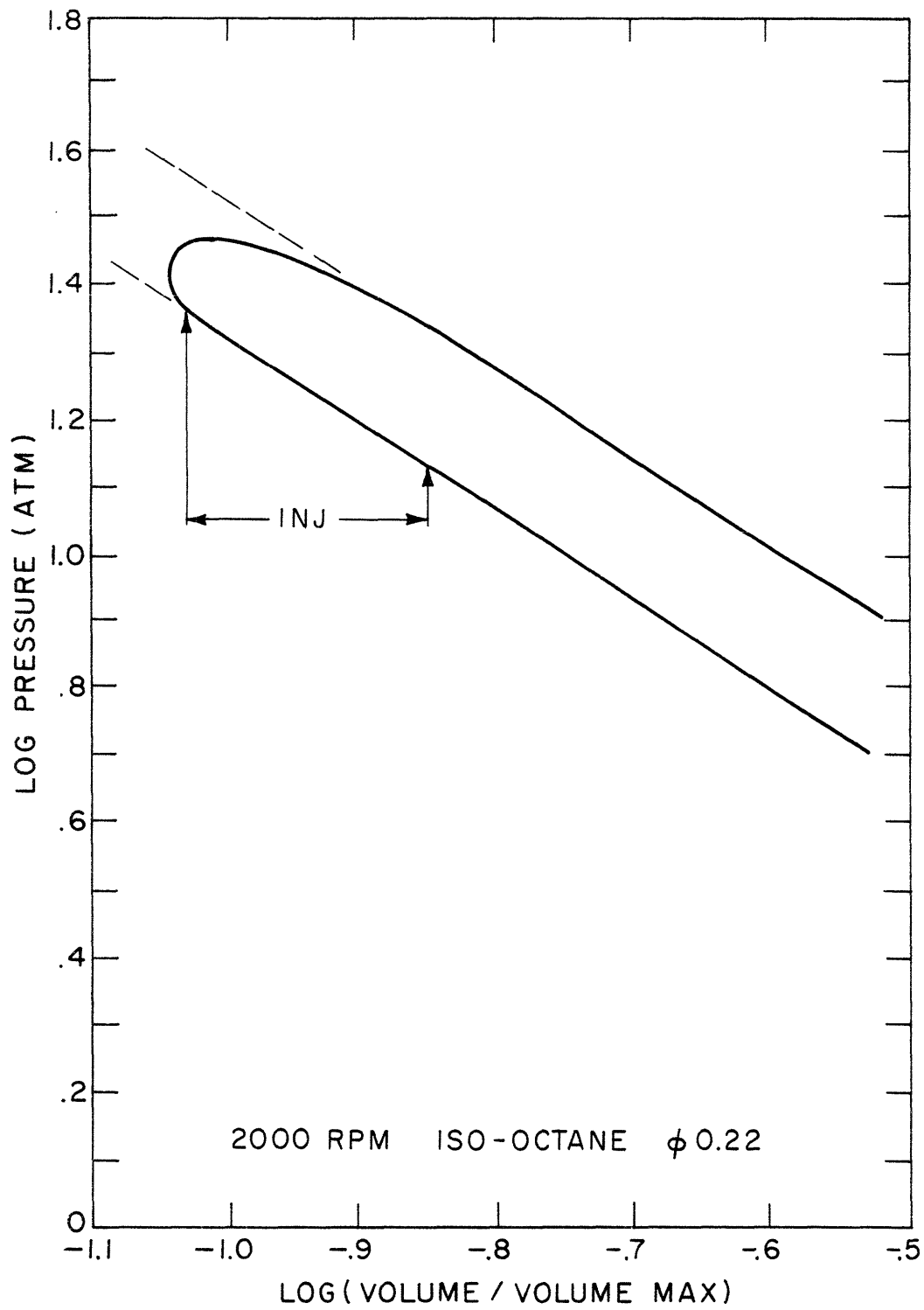


FIG. 45 Log P vs Log V FOR ISO-OCTANE,
 $\phi = 0.22$, 2000 RPM

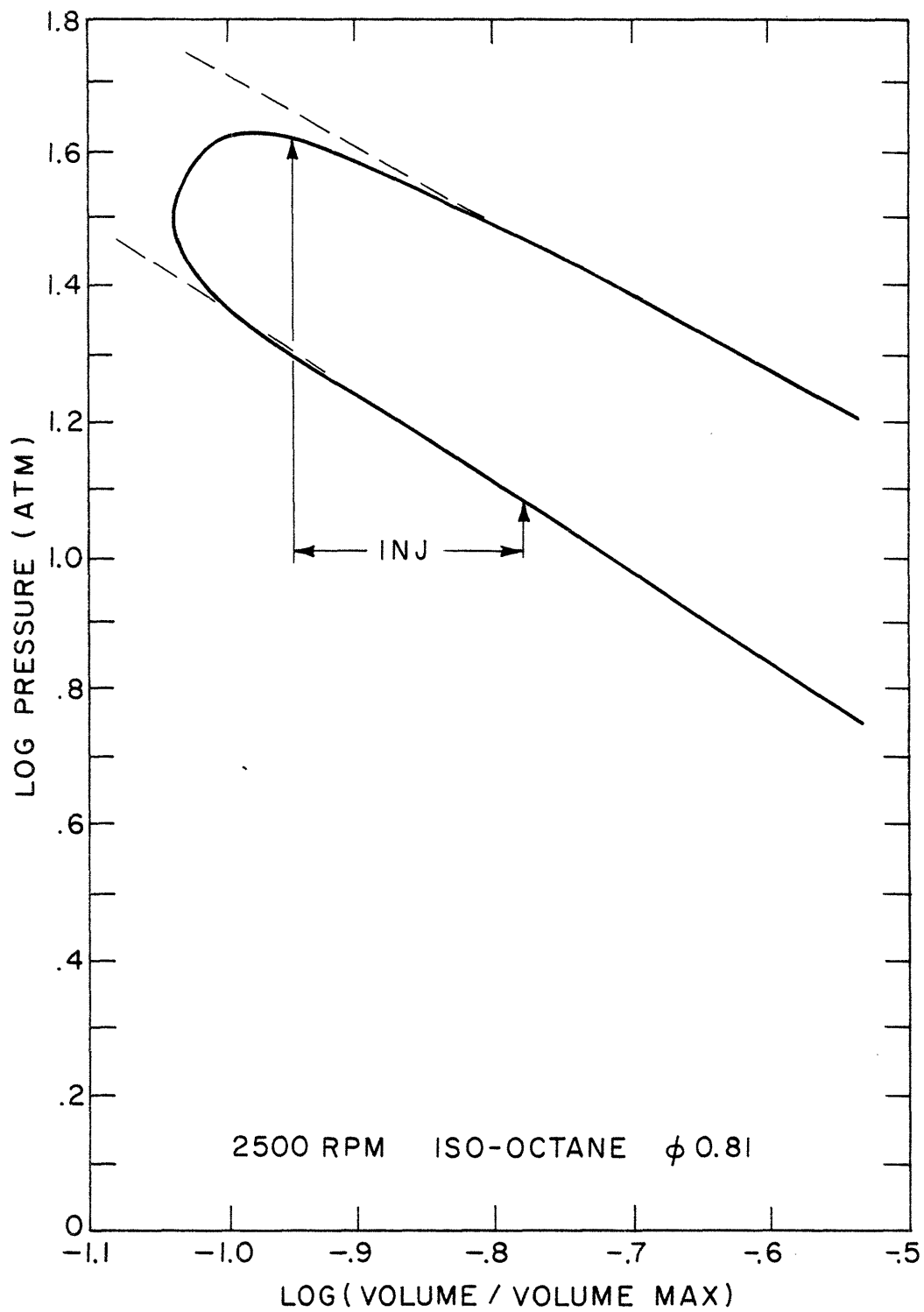


FIG. 46 LOG P vs LOG V FOR ISO-OCTANE,
 $\phi = 0.81$, 2500 RPM

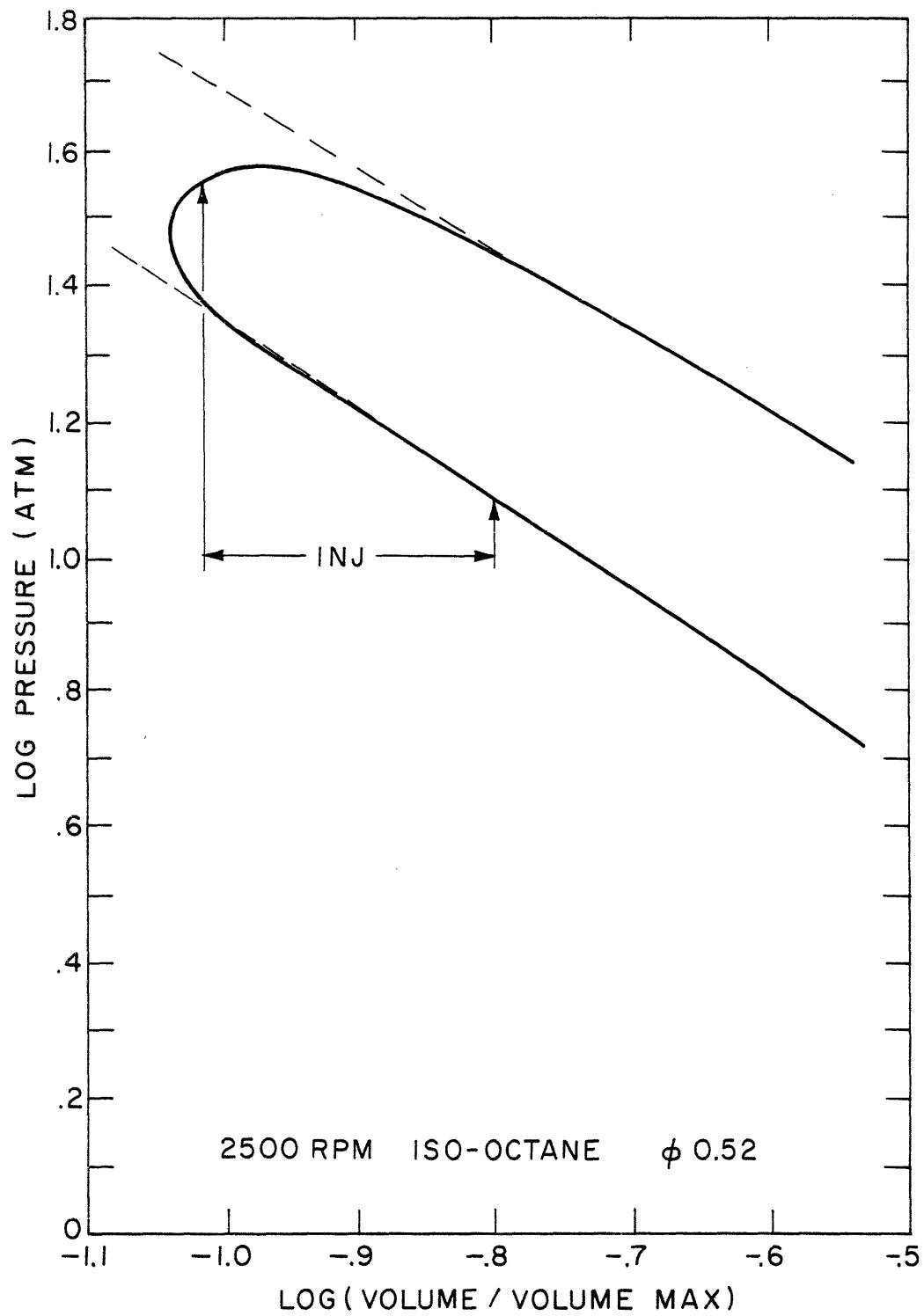


FIG. 47 Log P vs Log V FOR ISO-OCTANE,
 $\phi = 0.52$, RPM

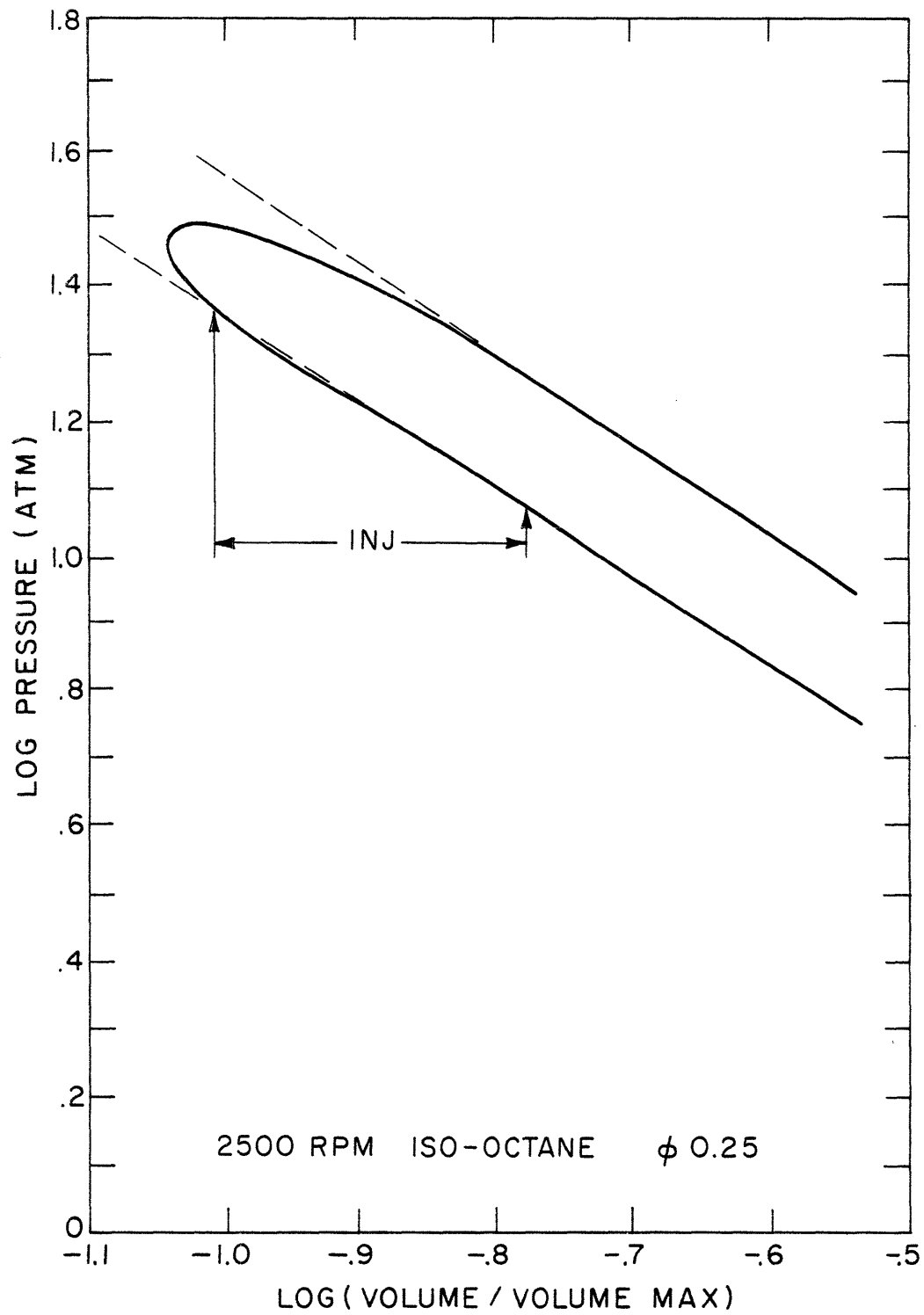


FIG. 48 LOG P vs LOG V FOR ISO-OCTANE,
 $\phi = 0.25$, 2500 RPM

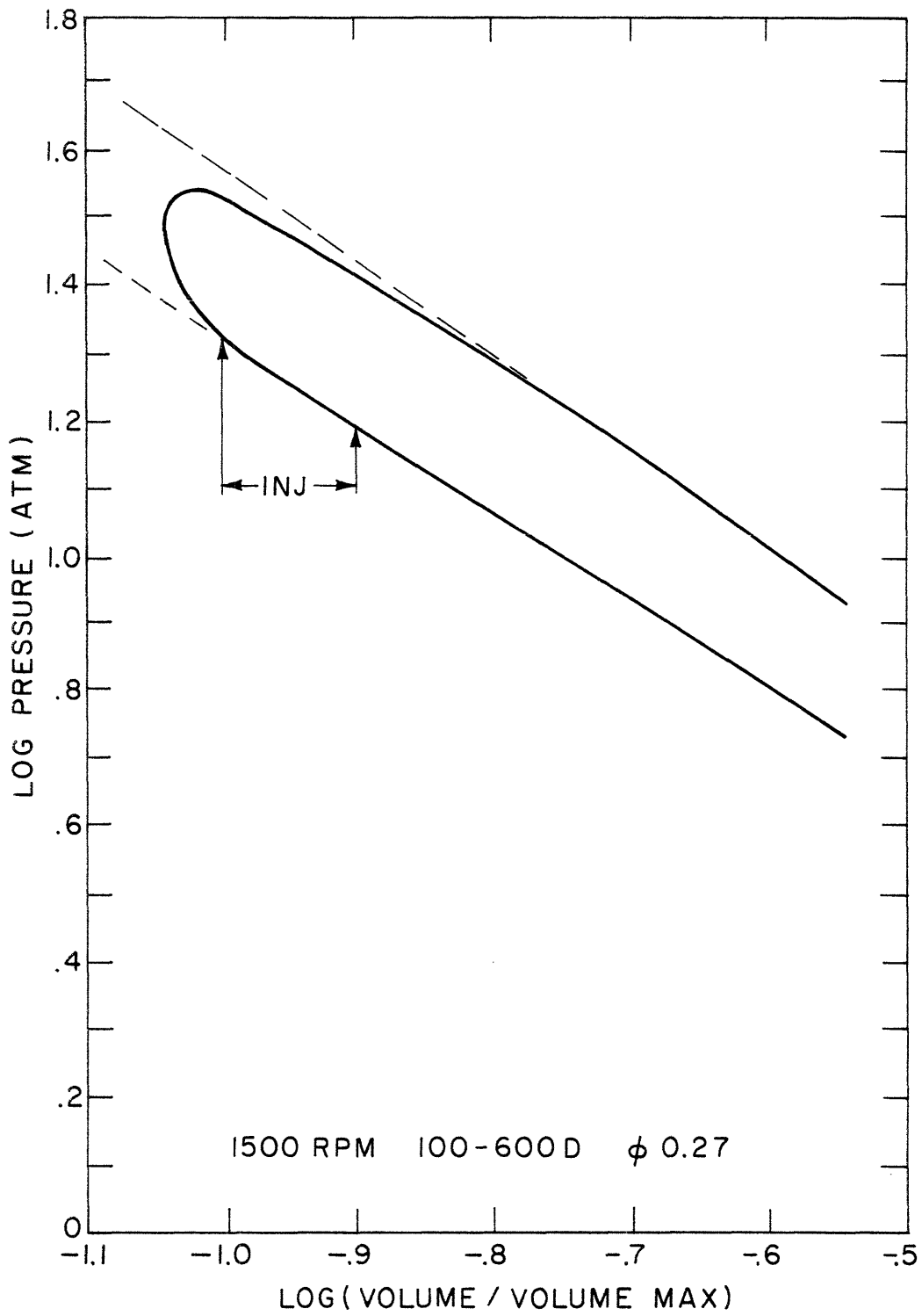


FIG. 49 Log P vs Log V FOR 100-600,
 $\phi = 0.77$, 1500 RPM

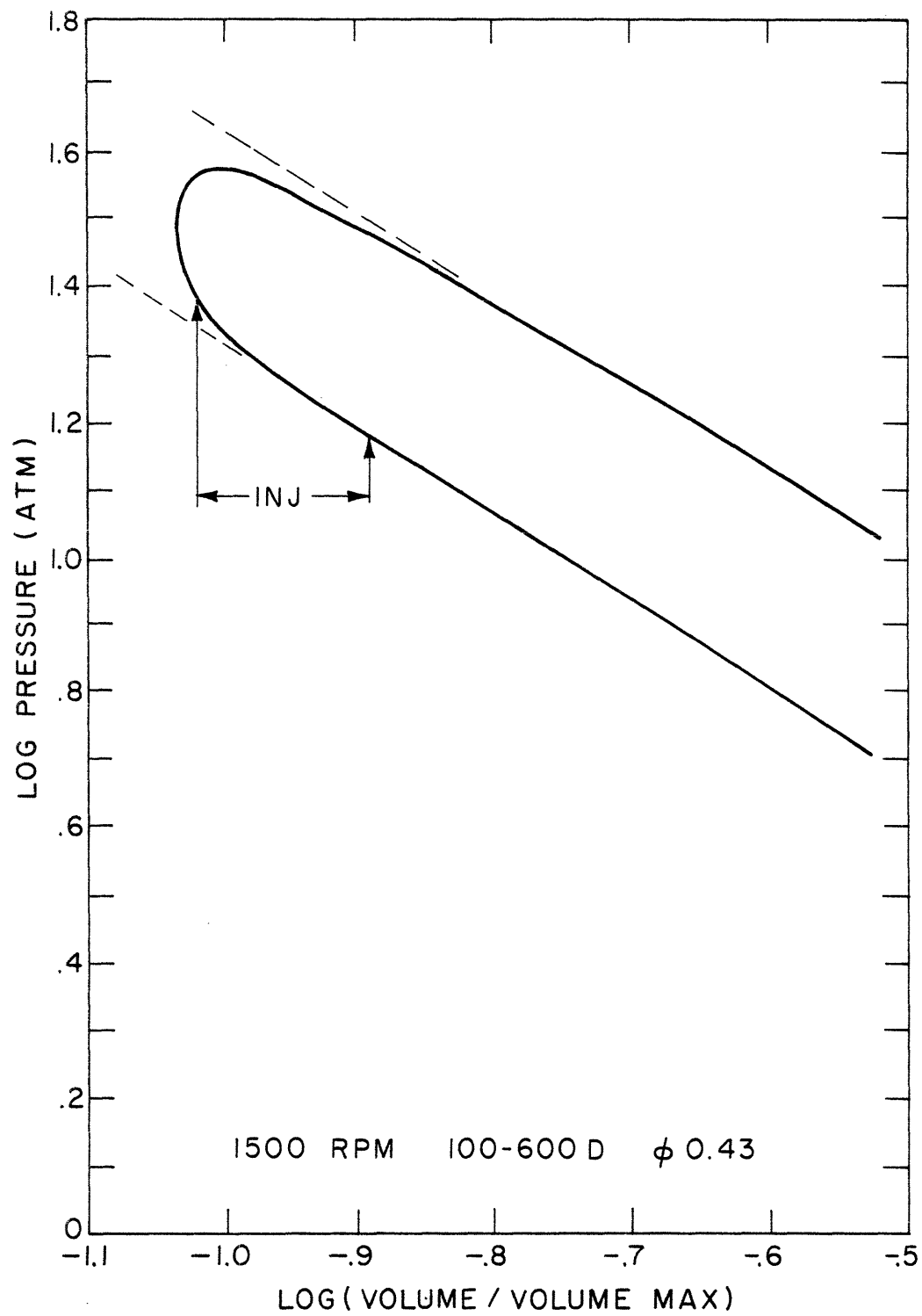


FIG. 50 LOG P vs LOG V FOR 100-600,
 $\phi = 0.43$, 1500 RPM

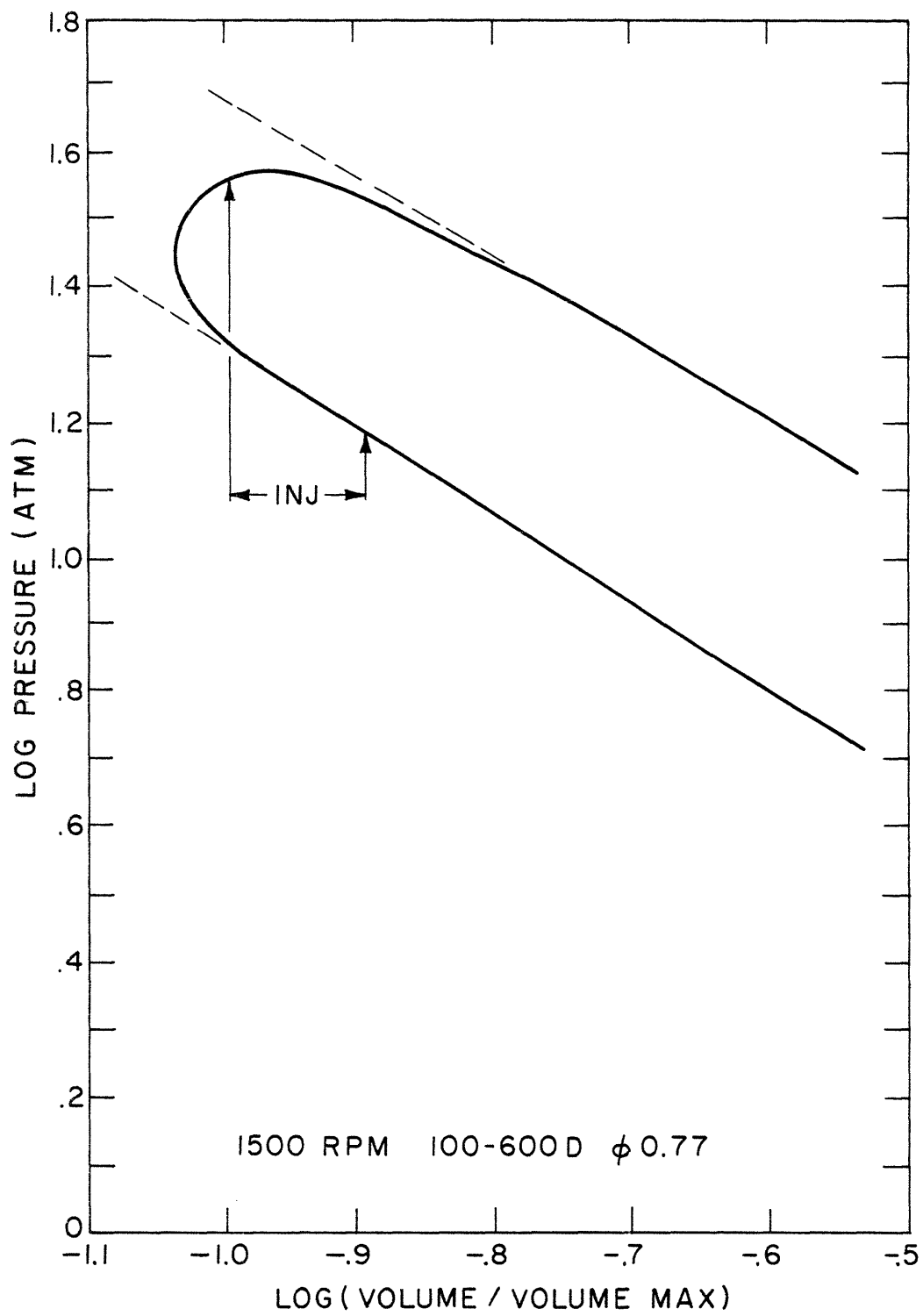


FIG. 51 LOG P vs LOG V FOR 100-600,
 $\phi = 0.27$, 1500 RPM

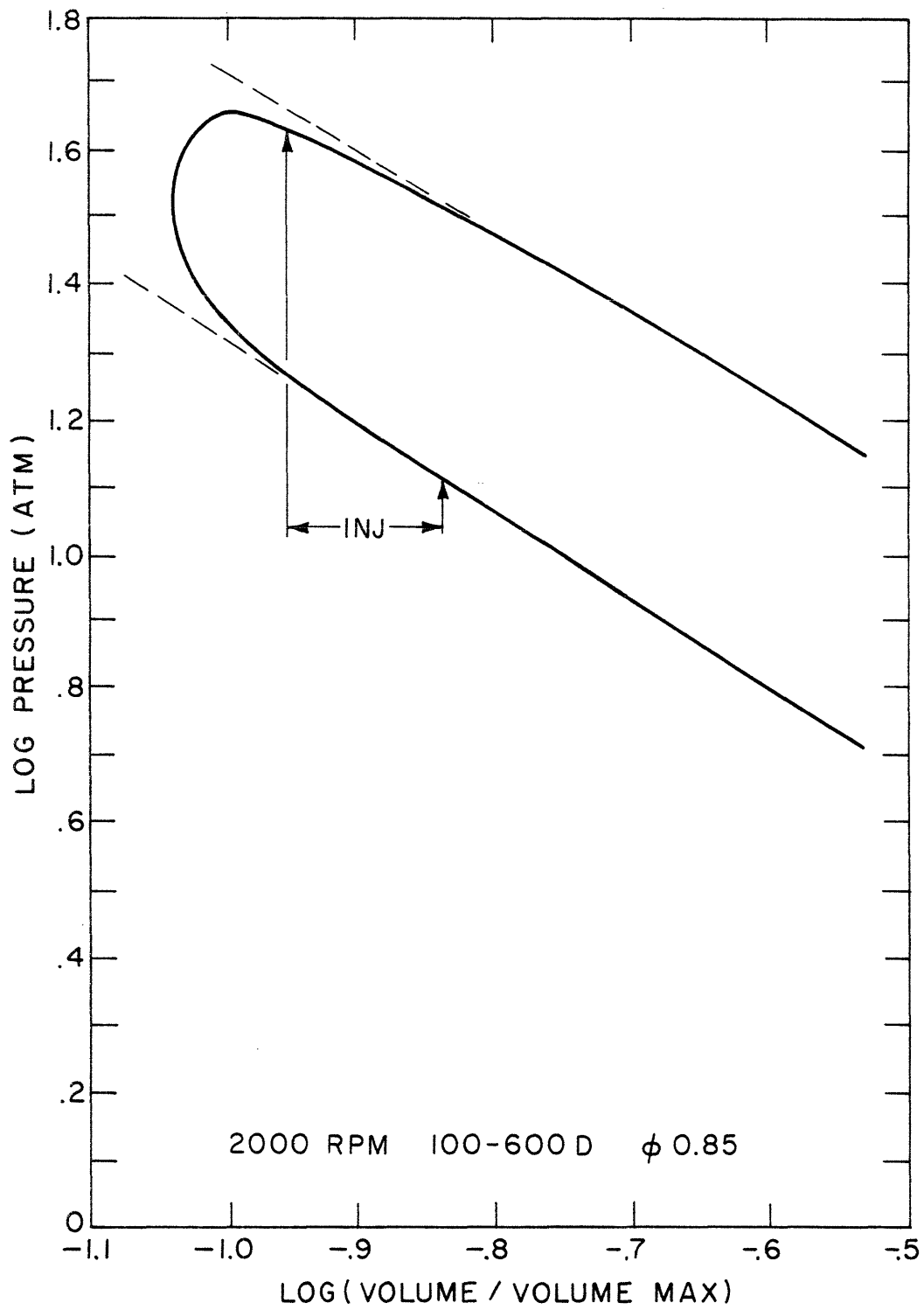


FIG. 52 Log P vs Log V FOR 100-600,
 $\phi = 0.85$, 2000 RPM

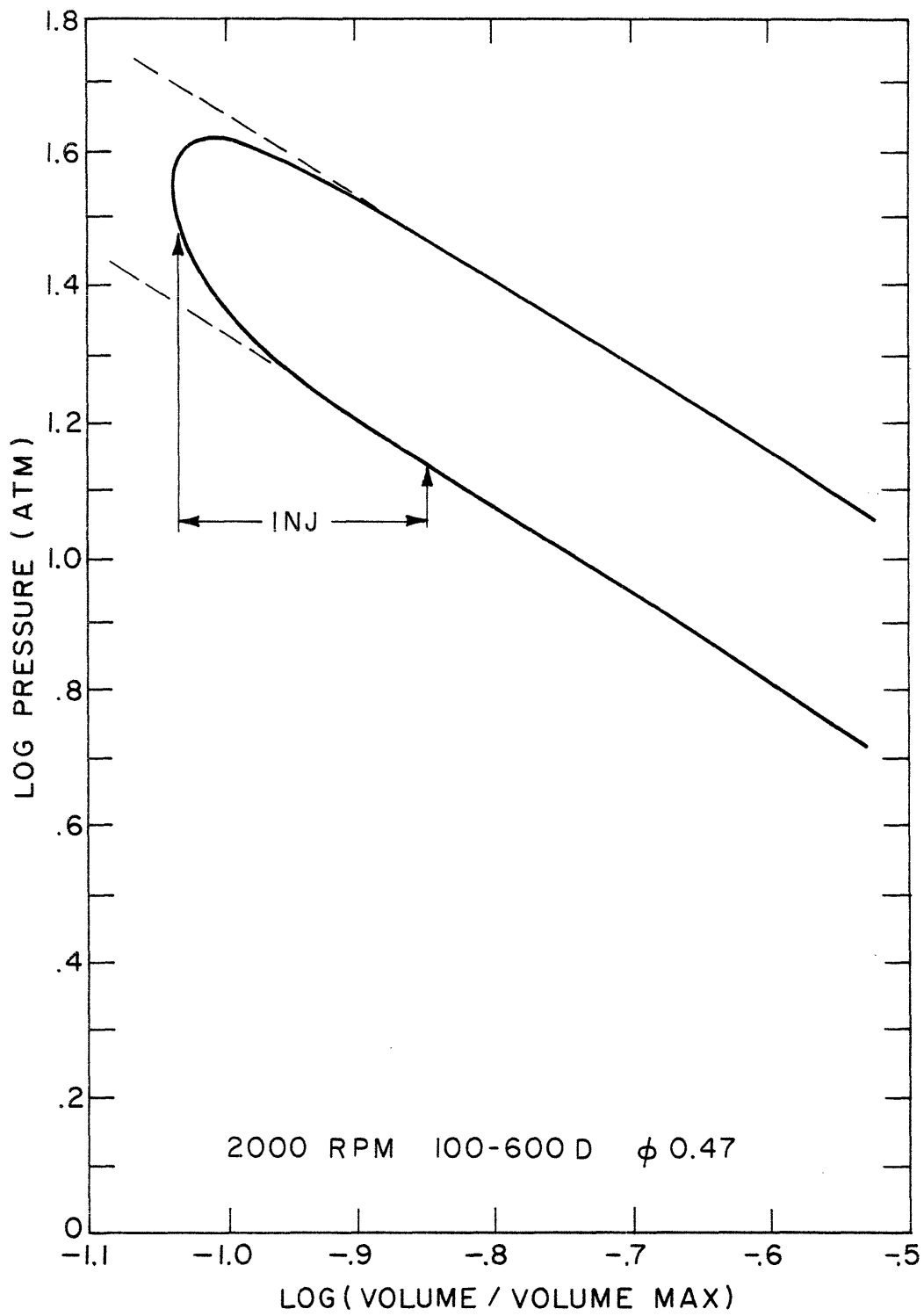


FIG. 53 Log P vs Log V FOR 100-600,
 $\phi = 0.47$, RPM

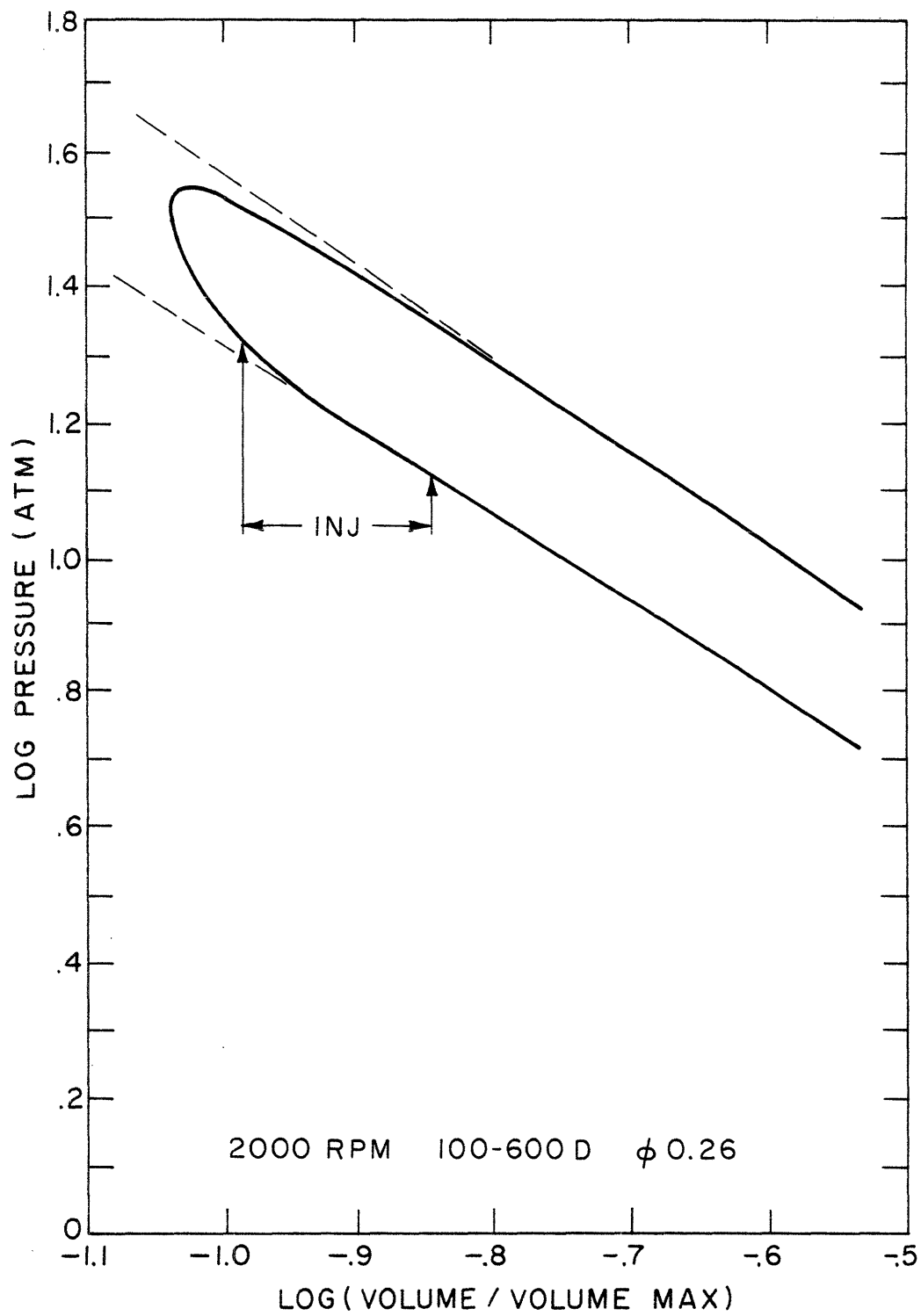


FIG. 54 LOG P vs LOG V FOR 100-600,
 $\phi = 0.26$, 2000 RPM

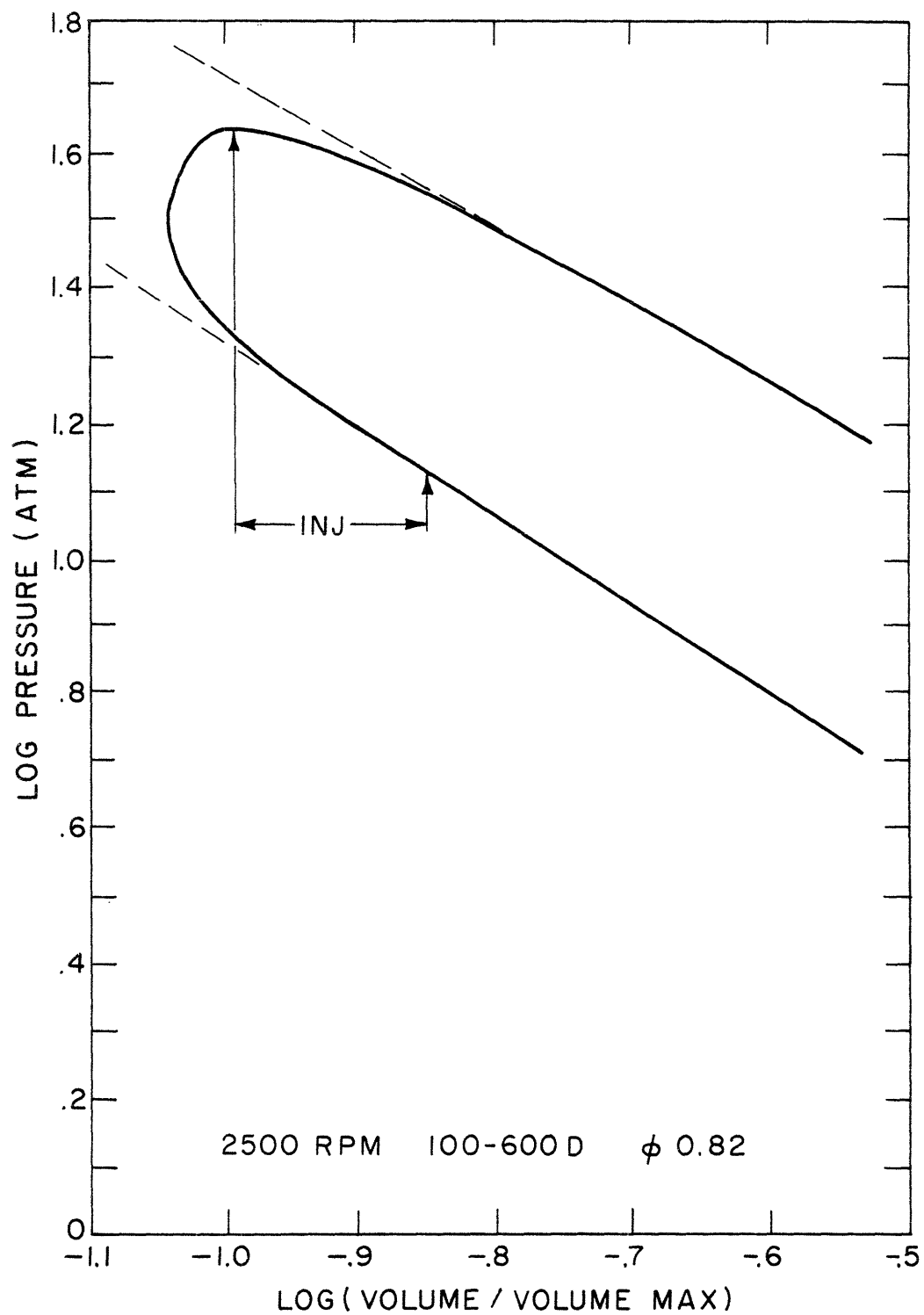


FIG. 55 LOG P vs LOG V FOR 100-600,
 $\phi = 0.82$, 2500 RPM

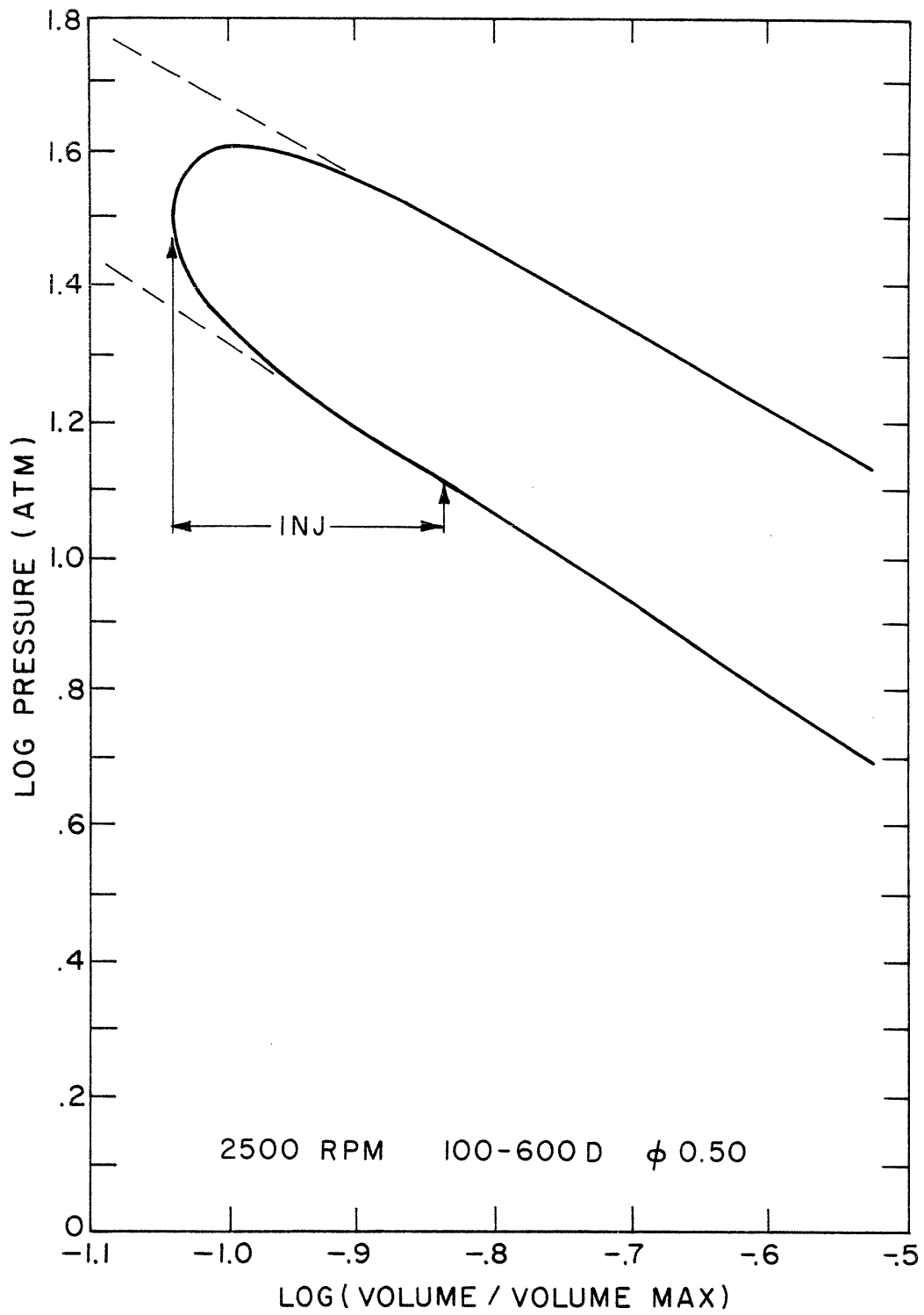


FIG. 56 LOG P vs LOG V FOR 100-600,
 $\phi = 0.50$, 2500 RPM

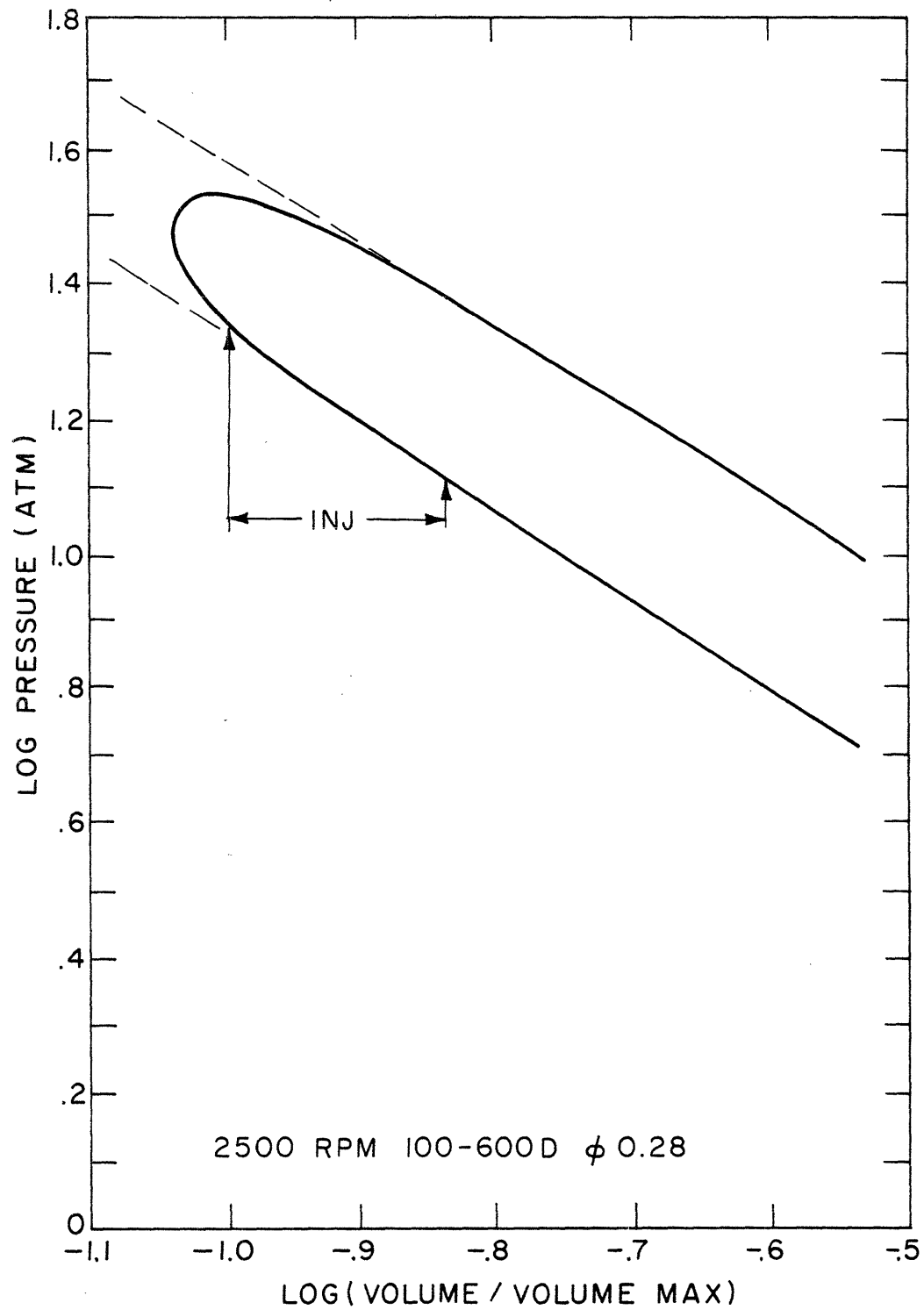


FIG. 57 LOG P vs LOG V FOR 100-600,
 $\phi = 0.28$, 2500 RPM

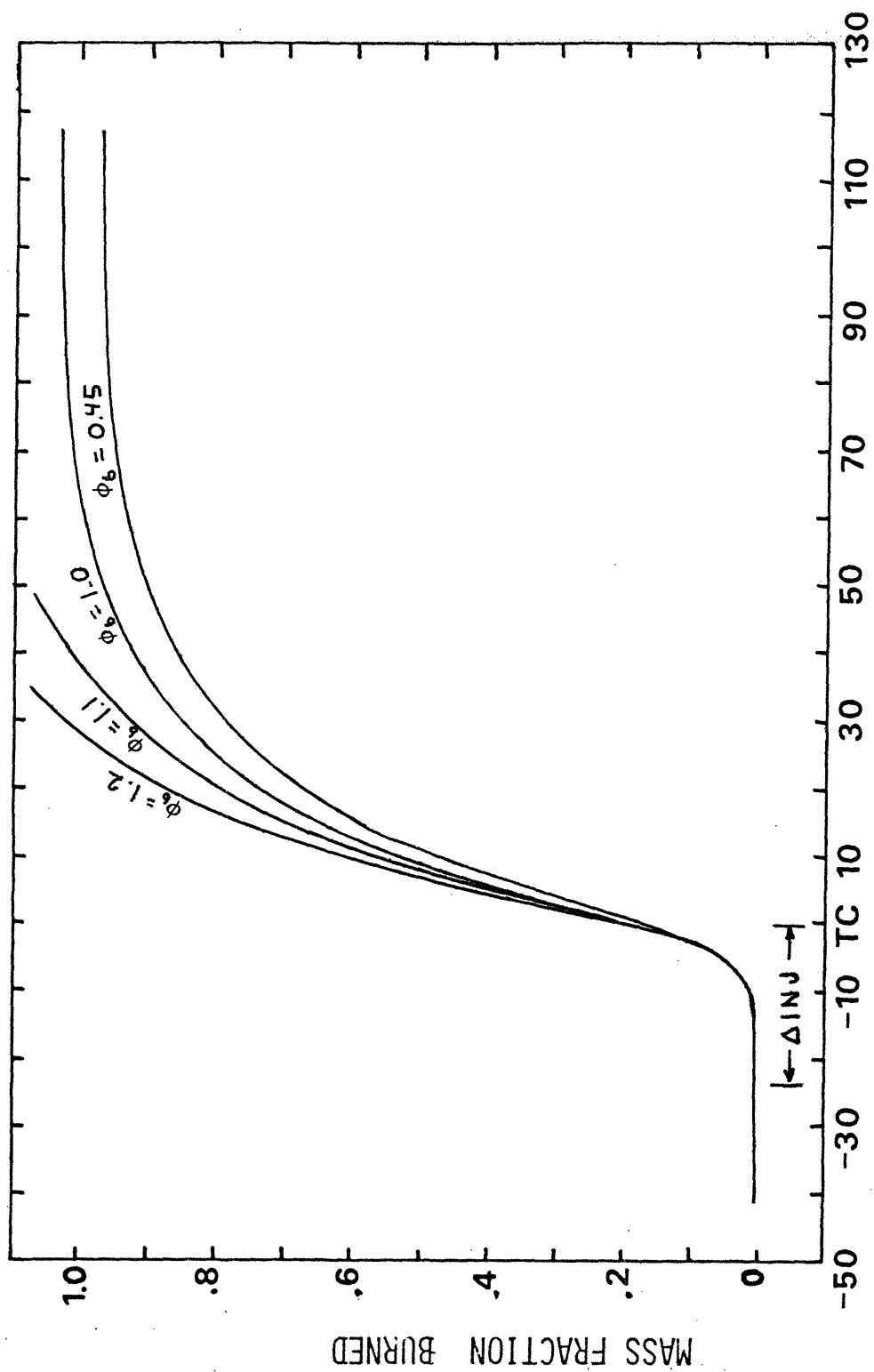


FIG. 58 FUEL MASS FRACTION BURNED VS CRANKANGLE FOR FIXED ϕ_B

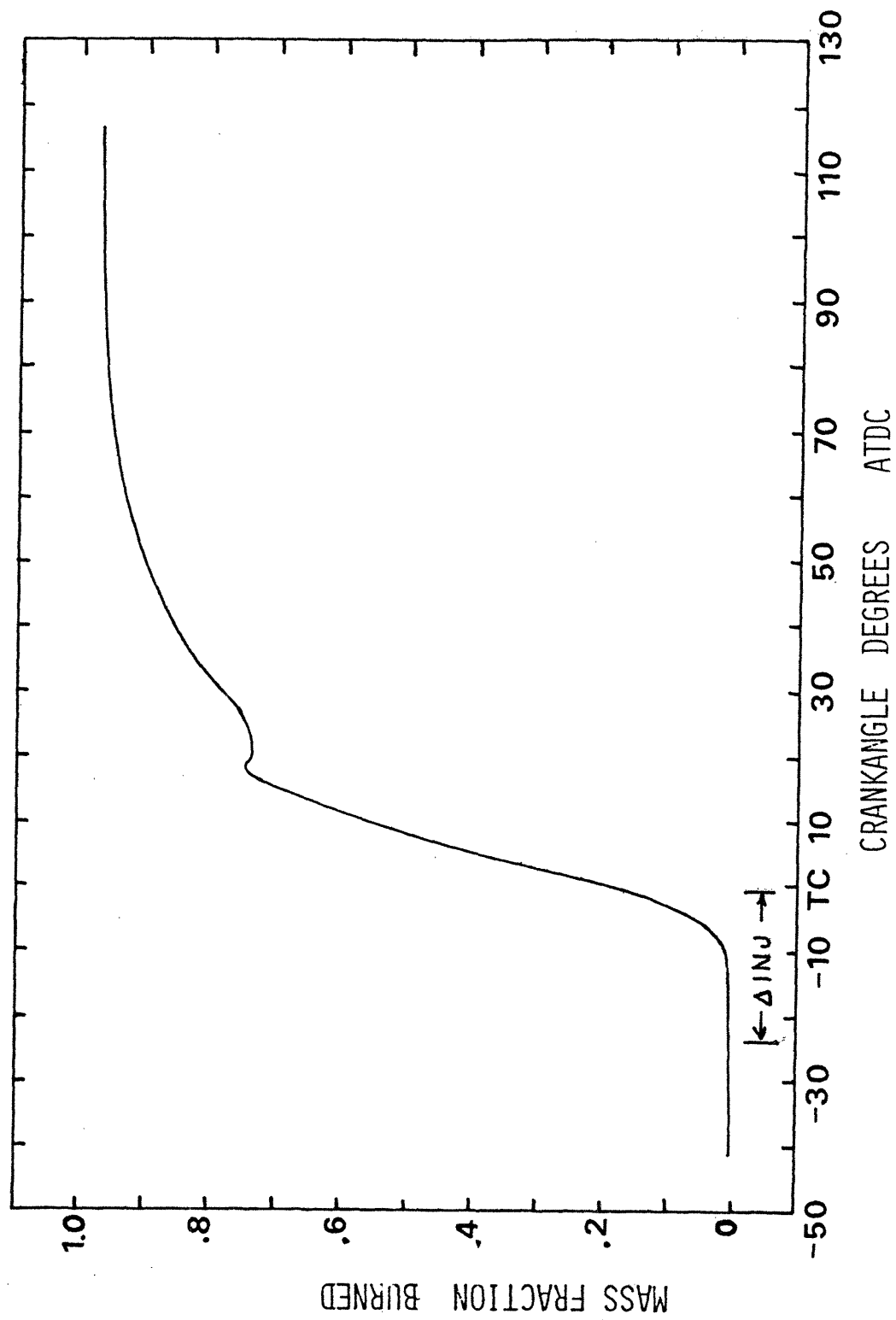


FIG. 59 FUEL MASS FRACTION BURNED VS CRANKANGLE FOR VARIABLE ϕ_B

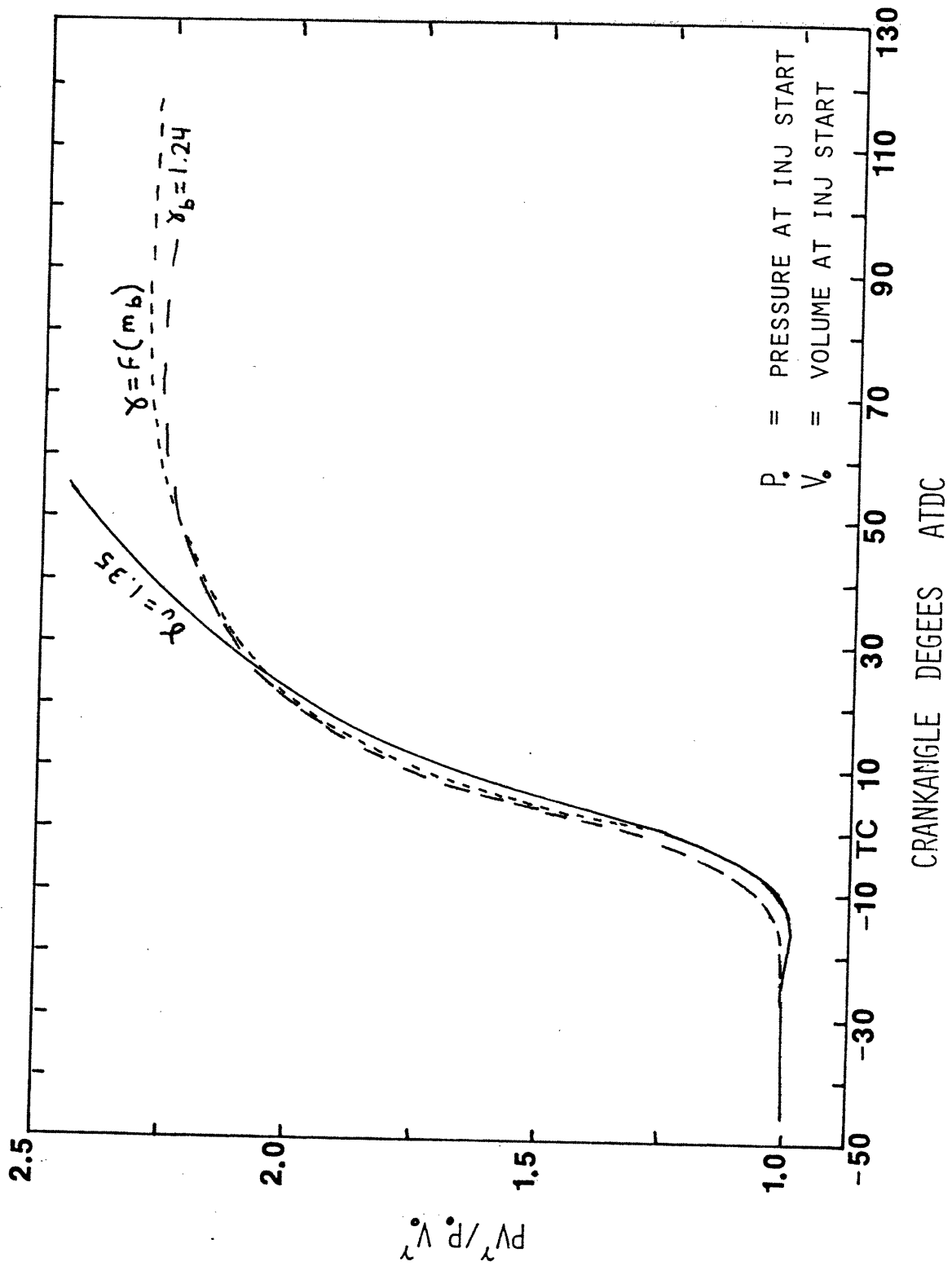


FIG. 60 PV^γ VS CRANKANGLE WITH BURNT AND UNBURNT GAMMA VALUES