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A single cylinder engine study of lean supercharged operation for spark ignition engines

Kenneth Robert Schmid

A SINGLE CYLINDER ENGINE STUDY OF LEAN SUPERCHARGED OPERATION FOR SPARK IGNITION ENGINES

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ABSTRACT

A comprehensive single cylinder engine test program to evaluate Lean Supercharged Operation (LSO) for spark ignition engines was conducted. The evaluation involved an experimental program studying the power, emissions, and efficiency of a single cylinder engine. The relationships between engine power, efficiency, and emissions and the engine operating variables such as absolute intake manifold pressure, Exhaust Gas Recirculation rates, and spark timing were studied.

Results of the experimental work indicated that LSO has the potential of improved engine efficiency and NO_x emissions comparable to, or lower than, the naturally aspirated engine. For equal power output from the engine, efficiency increases of 14% were accompanied by reductions in Brake Specific NO_x ($BSNO_x$) emissions of approximately 76%. For a case of equal $BSNO_x$ emissions, an efficiency improvement of 6.4 points or over 40% was observed. The combustion process is improved and the lean misfire limit is extended with Lean Supercharged Operation. The hydrocarbon and carbon monoxide emissions are not significantly different, from the naturally aspirated engine, by operation at realistic lean supercharged conditions.

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I. INTRODUCTION

Increased concern about air pollution in the 1960's led to federal regulations restricting crankcase and exhaust emissions from all 1968 and later model year light duty vehicles. Two studies conducted by the National Research Council between 1971 and 1974 contributed to current crankcase and exhaust emissions regulations for light duty vehicles. The exhaust emission requirements for the 1981 and the 1982 model year vehicles are 0.41/3.4/1.0 grams per mile for HC/CO/NOx respectively. Exhaust emission requirements for the 1981 model year are to be met at all possible idle mixtures and choke settings. For the 1982 model year, the exhaust emissions requirements are to be met for all possible settings of idle mixtures, idle speeds, spark timing, and choke settings.

Due to the recent shortage of petroleum fuels, beginning with the 1978 model year, the automobile manufacturers are required to meet "Corporate Average Fuel Economy" (CAFE) requirements, in addition to the crankcase and exhaust emissions requirements. The CAFE requirement for 1981 is 22 miles per gallon, an improvement of 83% compared with the 1974 average fuel economy for the United States (1). To meet these increasingly severe fuel economy and exhaust emissions requirements the need for a clean, efficient engine appears to be mandatory. Currently the automobile manufacturers are using and investigating various techniques to improve vehicle fuel economy and exhaust emissions. Techniques include: the use of lightweight materials to produce a lighter vehicle, aerodynamic refinements to reduce air resistance, lock up torque convertors to improve transmission efficiency, and engine modifications for improved efficiency. Spark ignition engine modifications being investigated include: computer control of the engine, electronic fuel injection, combustion chamber design, reducing internal friction, variable displacement engines, turbocharging engines, and lean operation.

Some extensions of the lean limit of a naturally aspirated engine were accomplished by increased compression ratio and increased air inlet temperature in work conducted by Quader (2). Turbo-supercharging (turbocharging) the spark ignition engine generally increased the effective compression ratio and inlet air temperature. The study of previous investigators work indicates that lean operation with supercharging would provide extensions of the lean limit.

The intent of this study was to examine the extension of the lean limit by supercharged operation of a spark ignition engine. The intake manifold pressure and temperature, and exhaust pressure were controlled to simulate the addition of a turbocharger to the engine. Estimates were made to determine if sufficient energy existed in the exhaust to operate an exhaust turbine for turbocharging under lean operation. The effects of spark timing and EGR were examined for supercharged operation. Also, pressure-crank angle data were obtained to allow a simplified cycle analysis.

II. REVIEW OF LITERATURE

A. TURBOCHARGING

The invention of turbocharging is credited to Dr. A. J. Buchi. In 1905, Buchi received a patent (U.S. #1,006,902) which describes a combustion engine equipped with an axial compressor on the intake system, an axial turbine on the exhaust system, and the three units mechanically coupled together with a common shaft. Dr. Buchi received another patent in 1915 (U.S. #1,138,007) which removes the mechanical connection between the engine and the compressor-turbine assembly establishing the principle of exhaust turbocharging as it is used today (3). The first use of the turbocharger was in the late 1920's on marine and railroad engines. Increased use of the turbocharger occurred in the 1940's with the application to diesel truck engines and airplane engines. Historically, turbocharging of spark ignition engines has been primarily for racing and high performance applications. Limited applications of turbochargers were made to production automobile engines in the 1960's. However, the turbocharging of the spark ignition engine is receiving renewed interest with the advent of increasingly stricter governmental regulations regarding exhaust emissions and fuel economy for the automobile.

Several authors have investigated the use of a turbocharged engine to obtain lower exhaust emissions and improved fuel economy. Schweikert and Johnson (4) examined a turbocharged thermal reactor system with a multi-cylinder engine coupled to an engine dynamometer. These investigators studied a naturally aspirated engine and a turbocharged engine, each equipped with thermal reactors and secondary air injection. The nominal engine air/fuel ratio investigated was between 12 and 14 to one. With this rich engine operation, there was little difference in fuel economy and exhaust emissions between the two engines. Schweikert and Johnson predicted better fuel economy and reduced mass emissions with the use of a small displacement turbocharged engine to replace a larger naturally aspirated engine with equivalent power output.

Engine operation near stoichiometric conditions with a 4-cylinder engine equipped with a turbocharger-thermal reactor system was investigated by Goggard, et. al. (5). These investigators were primarily concerned with developing the thermal reactor system for the turbocharged engine. They found the addition of secondary air injection to the thermal reactors provided rapid reactor warm-up, a reduction in exhaust emissions, and a torque increase. The best secondary air injection settings were found to be those which provided 2-3% excess oxygen in the exhaust to achieve rapid warm-up and reduction in exhaust emissions. The torque increase was obtained from the higher mass flow through the turbine providing a higher boost from the compressor.

Initial vehicle test results were reported by Emmenthal, et. al. (6) using small displacement turbocharged engines for improved fuel economy. Two engines were selected and installed in test vehicles, a 4-cylinder 1.6 L engine and 5-cylinder 2.2 L engine. Boost pressure was controlled by a wastegate, with 40 kPa to 50 kPa maximum boost pressure. The engines were equipped with two-stage feedback carburetors. The jets were selected to provide a slightly lean air/fuel mixture. The air/fuel mixture was enriched to stochimetric by throttling the bleed air for idle, first stage, and second stage systems of the carburetor. An oxygen sensor provided the necessary feedback signal to the exhaust treatment. The exhaust emissions did not meet the engineering goals of 0.41/3.4/1.0 gpm HC/CO/NO_x. The investigators suggest the addition of secondary air and a clean-up catalyst. The fuel economy was approximately 33 mpg for a 100 HP/3000 lbm inertia weight vehicle.

Recently some of the automotive manufacturers have started manufacturing and installing small displacement turbocharged engines (7,8,9) in automobiles. The manufacturers have given special attention to the problems of turbocharger lag and engine detonation. The problem of turbocharger lag has been minimized by careful matching of the turbocharger unit and careful selection of the nominal engine compression ratio to provide good part load engine operation. The nominal compression ratio ranges from 7.1 to 9.1 with maximum boost pressures from 80 kPa (11.4 psig) to 40 kPa (5.5 psig) respectively.

To avoid detonation in the combustion chamber of the engine, Porsche uses a lower nominal engine compression ratio and an after-cooler on the air system (8). The technique used by Ford and Buick is to control the spark timing advance. Ford's spark timing advance control system uses a dual mode ignition module and a conventional breakerless distributor with mechanical and vacuum advance. The dual ignition module retards the spark timing based upon signals received from intake manifold pressure sensors. The ignition module retards the spark timing a preset amount in two steps (9). Buick's spark timing advance control system uses an electronic spark control with detonation feedback and a conventional breakerless distributor. Two special components are used in the electronic control system - a detonation sensor and a controller. The detonation sensor is mounted to the intake manifold and provides an electrical signal corresponding to the intake manifold vibrations. Normal engine vibrations are treated as background noise by the controller. The controller continuously monitors and updates the background noise information. When cylinder detonation occurs, the sensor produces a voltage signal proportional to the intensity of the detonation. The controller compares the detonation voltage signal and the engine background noise voltage signal to determine the amount of spark retard, which is transmitted to the distributor. The spark timing is restored at a fixed predetermined rate.

To control the maximum intake manifold pressure manufacturers are using a wastegate on the turbocharger turbine (7,8,9). Basically the wastegate is a valve, which permits a controlled amount of the exhaust gas to by-pass the turbine. This allows the turbocharger speed, and thus the intake pressure, to be controlled. The wastegate is operated by a spring-loaded diaphragm actuator connected to the intake manifold pressure.

B. LEAN OPERATION

Theoretically, the lean operation of the spark ignition engine has two advantages: the thermal efficiency of the engine is generally higher and the oxides of nitrogen (NO_x) emissions are lower at leaner air/fuel ratios. A considerable amount of investigation has been performed on operating the spark ignition engine in the lean region and on extending the lean misfire limit. These studies have examined primarily two areas: spark and flame characteristics, and mixture turbulence and preparation.

Several investigations have been performed studying spark and flame characteristics to improve lean operation of the spark ignition engine. Tanuma, et. al. (10) examined, modifications to both the ignition and intake systems. The study was performed on a 4-cylinder 1982 cc displacement engine. Various spark plug modifications were examined. The spark gap was varied from 0.5 to 2.5 mm, the center electrode diameter from 0.5 to 2.9 mm, and the gap projection from 3.5 to 13 mm. Spark energy effects were examined at values of 30 and 100 millijoules, and the intake system was modified by the addition of 6 vanes to the intake valve seat to increase mixture turbulence. In this case, increasing the spark energy, gap projection, and center electrode diameter improved the lean operation of the engine. The lean limit was also extended by the addition of the intake valve seat vanes to increase mixture turbulence. Ryan, et. al. (11) further examined ignition and intake system modifications using a single cylinder CFR engine equipped with a removable dome head. Two types of ignition systems were used, a typical automotive inductive discharge system and a Texaco ignition system. The Tecaco ignition system provided a high energy a-c, controlled duration spark. These investigators ranked, in descending order, the ability of the various modifications toward extending the lean limit as follows: increased gap width, increased spark duration, increased gap projection, and increased mixture turbulence.

Novel ignition systems designs have also been investigated. The testing and development of a plasma jet ignition system is described by Wyczalek, et. al. (12). This ignition system was tested on both a single cylinder and a 4-cylinder engine which was equipped with a transparent piston. The photographs showed that the plasma jet provided an ignition source which traveled ahead of the initial flame front. In some recent work performed by Quader (2), extensions of the lean misfire limit were obtained with a more central spark plug location and multiple spark plugs. A dual spark plug ignition system was examined by Oblander, et. al. (13). Tests were performed on both a single-cylinder and a 6-cylinder engine. The dual spark plug ignition system gnerally allowed leaner operation by 0.1 to 0.15 air/fuel equivalence ratios. Also, the two plug ignition system provided lower fuel consumption, lower exhaust emissions, and less tendency for engine knock.

Quader (14) reported the results of two single cylinder engine experiments investigating flame initiation and flame propagation under lean operation. The first experiment investigated flame initiation by advancing and retarding the spark timing from MBT spark timing. The advanced spark timing allowed determination of an ignition limit or failure of flame initiation to occur. The retarded spark timing provided a partial burn limit where failure of the flame to propagate occurred. The flame propagation experiments were conducted by the addition of an instrumented spacer installed between the cylinder block and the head. Quader concluded that both the flame initiation and the flame propagation constrained the spark timing in an engine.

Another area of investigations has been mixture turbulence and mixture preparation. The effects of various engine variables on lean engine operation were examined by Quader (2). Quader obtained extensions of the lean misfire limit by increasing the mixture homogeneity, increased compression ratio, increased air inlet temperature, decreased charge dilution, and decreased engine speed. The generation of a vortex to improve the lean operation of the spark ignition engine was examined by Lucas, et. al. (15). These investigators found that the vortex generator improved lean operation and that a variable vortex generator would be desirable to replace the throttle. Recent work conducted by Peters and Quader (16) investigated the mixture preparation for leaner operation. A heterogeneous mixture and a homogeneous mixture were examined. The heterogeneous mixture and a homogeneous mixture were examined. The heterogeneous mixture was obtained by port fuel injection and the mixture was changed by varying the injection timing with respect to the intake valve opening. The homogeneous mixture was obtained by premixing and fully vaporizing the air/fuel mixture. The results showed that the heterogeneous charge allowed leaner engine operation than the homogeneous charge. John discussed the current design and development of various manufacturers' carburetor and intake manifolds intended for lean operation (17). Adam, et. al. (18) discuss the development and operation of an intake manifold, termed a Turbulent Intake Manifold. The manifold was designed to improve mixing and distribution of the air/fuel mixture. The study included the equipping of various automobiles with the Turbulent Intake Manifold and carburetors adjusted for lean operation. The results indicated lower exhaust emissions, improved fuel economy, cylinder to cylinder mixture variations reduced by two-thirds, and good driveability.

III. EXPERIMENTAL APPARATUS AND PROCEDURE

A single cylinder engine was selected in preference to a multicylinder automotive production engine for several reasons. The single cylinder engine allows better control of engine variables so the variable of interest can be held constant or changed. The amount of fuel needed is substantially less, and air/fuel distribution problems are eliminated.

A. SINGLE CYLINDER ENGINE APPARATUS

The test engine used was a split-head Cooperative Fuel Research (CFR) engine with a high speed crankcase. The cylinder bore of 82.6 mm (3.25 in) and a stroke of 114.3 mm (4.50 in) provided a displacement volume of 0.611 L (37.33 cu.in). The engine was equipped with a shrouded intake valve installed to provide a counter-clockwise swirl inside the combustion chamber. A standard breaker-point ignition system was used with a Champion type D-16 spark plug. The engine was coupled to a 11 Kw dynamometer which provided engine load and speed regulation. Dynamometer control was accomplished by using a Digalog Corp., Model 1022, Dynamometer Controller regulating the dynamometer field voltage. A 60-tooth gear mounted on the dynamometer shaft and a magnetic pick-up provided the necessary shaft speed input. Intake mixture and exhaust temperatures were measured with chromel-alumel thermocouples. The intake mixture thermocouple was located approximately 40 cm (15.7 in) upstream of the intake valve, and the exhaust thermocouple was located approximately 9 cm (3.55 in) downstream of the exhaust valve. The intake manifold pressure was measured with an absolute pressure gauge connected approximately 9 cm (3.55 in) upstream of the intake valve. The exhaust pressure was measured downstream of the exhaust valve approximately 60 cm in a 13.55 L

(827 cu.in) stilling chamber. A control valve installed downstream of the stilling chamber provided exhaust pressure control. A schematic of the test set-up is shown in figure 1.

B. AIR AND FUEL METERING

An air system, shown in figure 1, supplied dry, oil free air to the intake manifold through a calibrated critical flow nozzle. This arrangement allowed engine operation with vacuum or boost pressure in the intake manifold. The air system was equipped with a normally closed solenoid valve and a normally open vent valve. With the valves energized, the engine air flow passed through the critical flow nozzle. With the valves de-energized, the intake manifold was vented to the atmosphere, and the engine air flow entered through the vent valve.

The fuel was metered using an American Bosch injection pump, Type APE, driven by the camshaft. The injection pump was equipped with a modified 5 mm plunger and barrel assembly. The fuel was delivered to an American Bosch injector, Model Akb50563p, which was mounted for port injection. The injection timing was set at 102.5 ATDC on the intake stroke to provide the best lean limit operation following the ideas of Peters and Quader (16). The fuel flow rate was determined on a gravimetric basis using a digital stopwatch, a precision balance, and calibrated weights.

C. EXHAUST GAS RECIRCULATION

Exhaust Gas Recirculation (EGR) was provided by stainless steel tubing, 12.7 mm o.d. (0.5 in), installed between the exhaust stilling chamber and the intake manifold, as shown in figure 1. The stainless steel tubing was connected into the intake system approximately 88 cm upstream of the intake valve. A needle valve allowed control of the amount

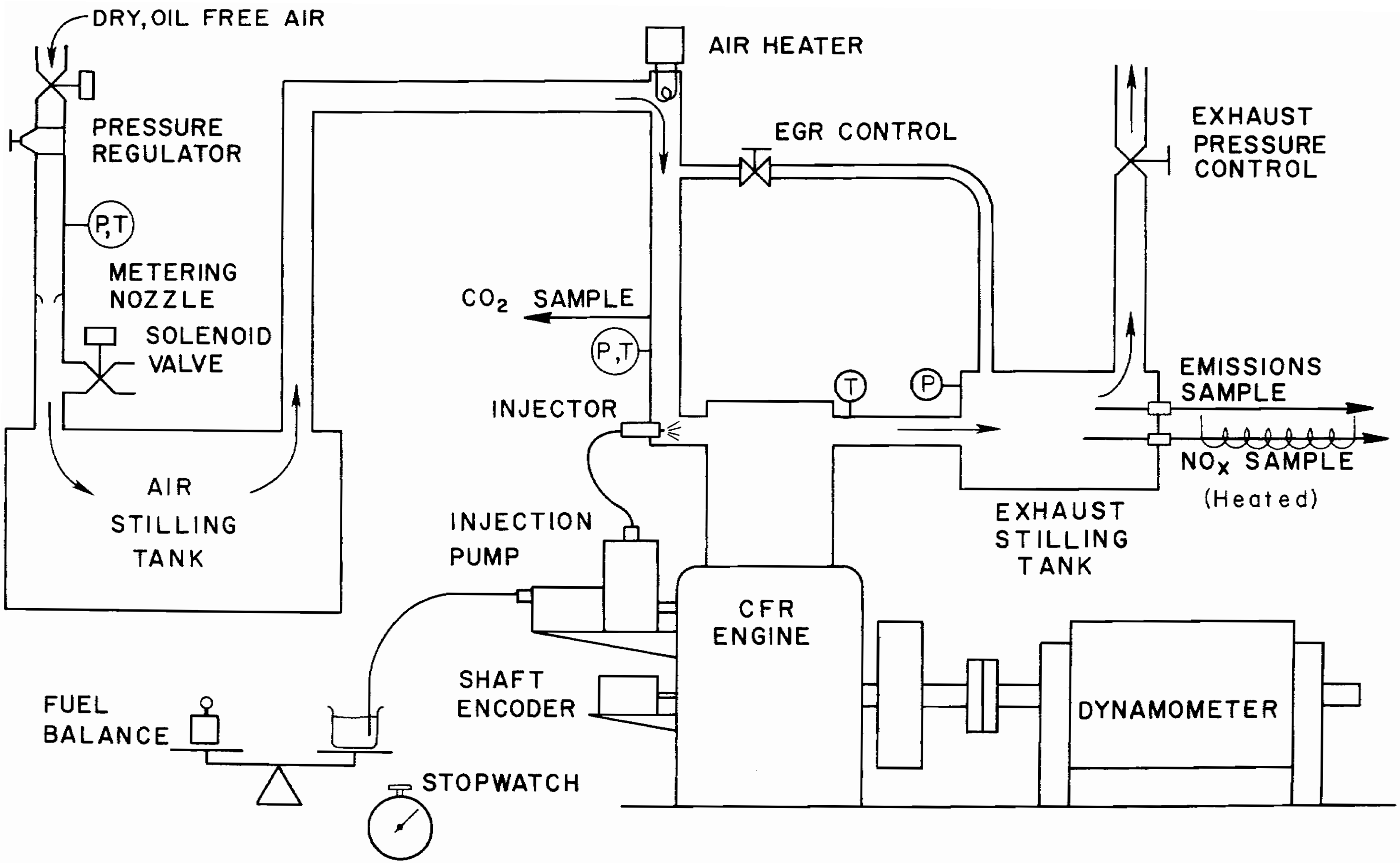

Figure 1. Schematic Diagram, Single Cylinder CFR Engine Apparatus

of exhaust gas recirculated. The percent EGR was determined from the intake manifold carbon dioxide (CO_2) concentration and the exhaust CO_2 concentration. The carbon dioxide concentration in the intake manifold was measured approximately 48 cm (19 in) upstream of the intake valve. Appendix B details the EGR calculation.

D. EXHAUST EMISSIONS SAMPLING AND INSTRUMENTATION

The exhaust emissions were sampled from the stilling chamber located approximately 60 cm (24 in) downstream of the exhaust valve. A schematic of the exhaust emissions bench is shown in figure 2. The exhaust sample was passed through a condenser to trap any water present before passing through the following equipment: Beckman Model 864 Non-dispersive infrared (NDIR) analyzers for carbon monoxide and carbon dioxide, a Thermo Electron Model 10A chemiluminescent analyzer for oxides of nitrogen, a Beckman Model 742 polarographic analyzer for excess oxygen, and a Scott Model 116 Flame Ionization Detector (FID) for unburned hydrocarbons. The instruments were calibrated with certified standard span gas mixtures. Dry nitrogen was used for zero gas. The instrument calibrations were checked before each data run.

Special attention was given to the sampling of oxides of nitrogen (NO_x). Usually the nitrogen dioxide level from the spark ignition engine is less than 10 ppm and nitric oxide is assumed the major component of the oxides of nitrogen. However, with very lean engine operation the potential for higher nitrogen dioxide emissions exists. Since nitrogen dioxide (NO_2) is very soluble in water, the water in the exhaust sample must not be allowed to condense and possibly remove some of the NO_2. To minimize this problem, a heated sample line, operated at 100°C, and a separate sampling pump were installed between the exhaust stilling chamber and the

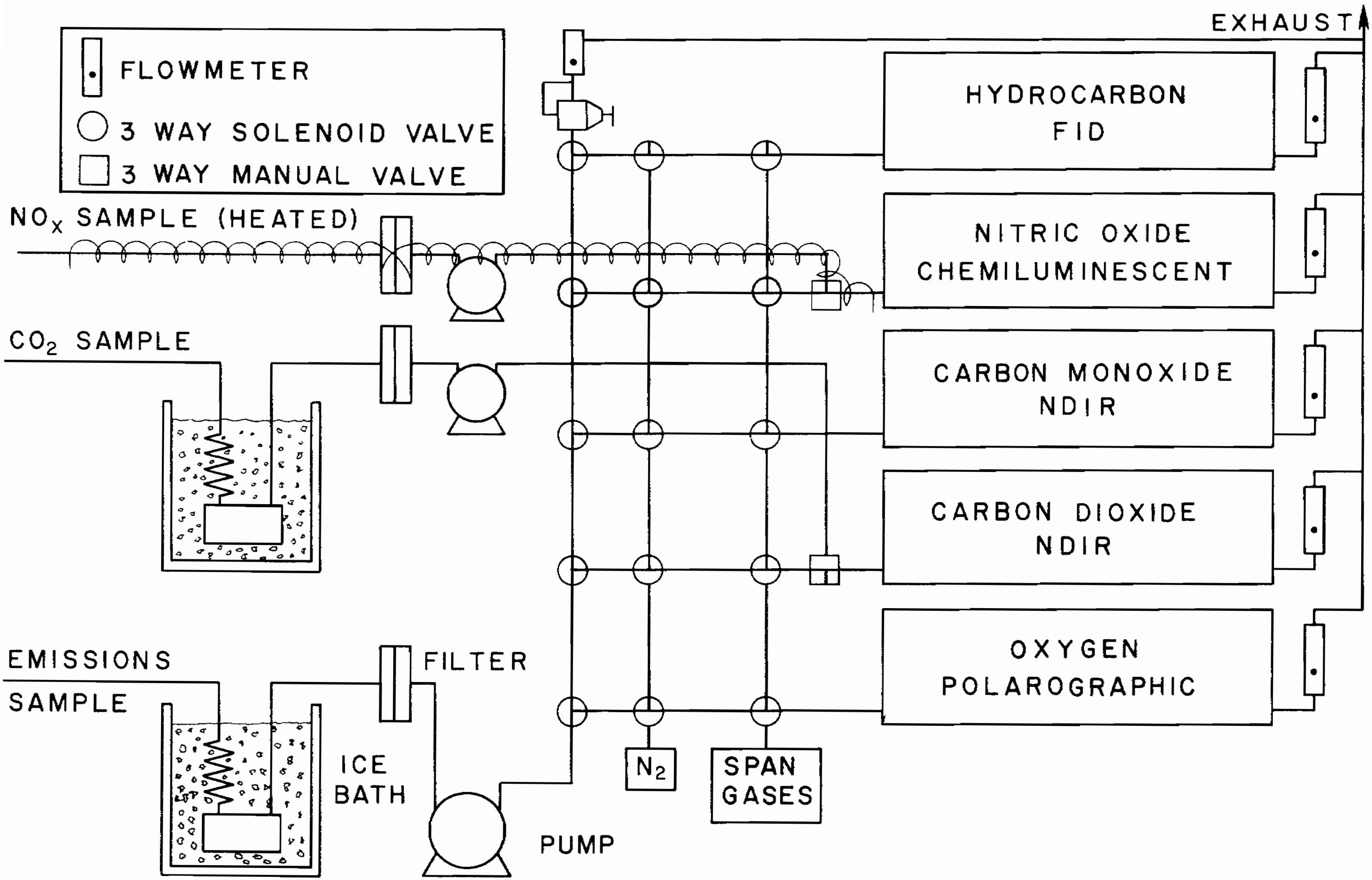

Figure 2. Schematic Diagram, Exhaust Emissions Sampling and Instrument System

NO_x analyzer. To prevent the problem of condensate build-up inside the NO_x instrument, the instrument lines were wrapped with heat tape and the heated sample was obtained in a grab sampling technique.

To determine the percent EGR, the carbon dioxide concentration in the intake manifold was required. A sample was obtained from the intake manifold at approximately 48 cm (19 in) upstream of the intake valve. The sample was passed through a separate condensate trap and pump. A 3-way valve on the carbon dioxide instrument allowed selection of intake or exhaust sample for CO_2 measurement.

E. CYLINDER PRESSURE CYCLE MEASUREMENTS

The engine was instrumented to provide acquisition of pressure-crank angle data. A schematic of the pressure-crank angle instrumentation is shown in figure 3. A quartz pressure transducer, Kistler Model 601A, was installed in a water cooled adaptor. The transducer and adaptor assembly was mounted in the detonation access hole in the cylinder head. The pressure transducer was connected to a charge amplifier, Kistler Model 566. A Trump-Ross shaft encoder, Model UM-0360-5se-1, was coupled to the engine crankshaft. The shaft encoder provided two channels of output. One channel, referred to as the clock channel, produced one electrical pulse per degree of rotation and the other channel produced an electrical marker pulse once per revolution. The marker pulse was statically aligned with TDC of the engine. The charge amplifier and the shaft encoder outputs were connected to the data acquisition system of a Data General Nova 3 Minicomputer. A Fortran callable assembler subroutine was used to acquire the pressure-crank angle data. The assembler subroutine waits for the marker pulse when the cylinder pressure is low. This point corresponds with

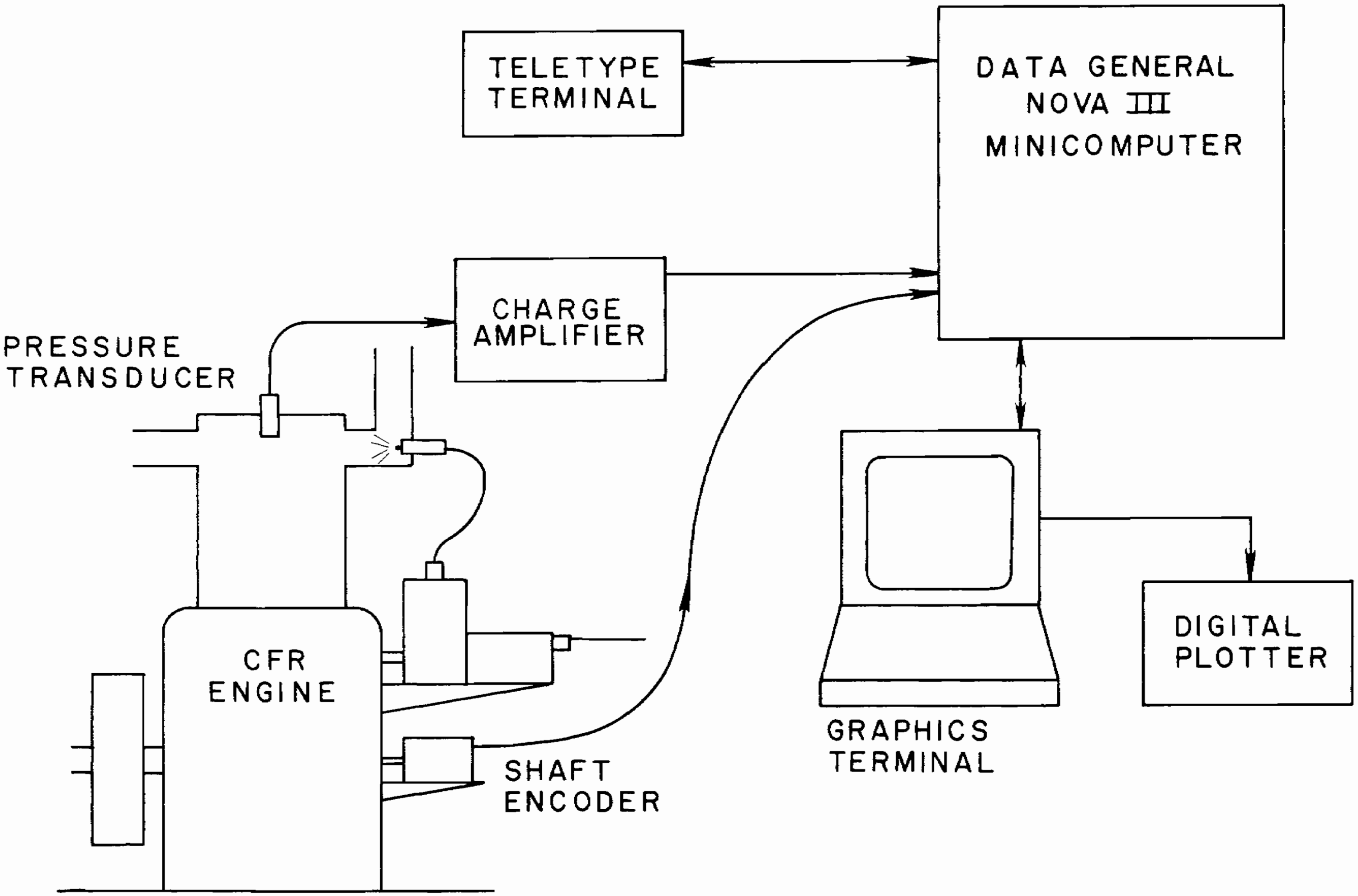

Figure 3. Schematic Diagram, Cylinder Pressure, Cycle Measurement Apparatus

the beginning of the intake stroke. From this point the computer takes a pressure reading each degree of crankshaft rotation, based upon the input from the shaft encoder clock channel. Each pressure reading is stored in the memory of the computer. When the data acquisition is complete, the data is written into a disk data file. Due to the memory size of the minicomputer, only 30 consecutive engine cycles were obtained for each operating point. The analysis of the pressure-crank angle data will be discussed in a later section.

F. TEST PROCEDURE

After an initial warm up, the engine was operated at the conditions listed in table I using a test condition selected from those listed in table II. The supercharged operating points listed in table II were based upon preliminary vehicle tests conducted on a chassis dynamometer at the University of Missouri-Rolla with a 1979 Buick Century with a 3.8 L turbocharged V-6 engine and from engine data provided by the Buick Division of General Motors Corporation.

The intake manifold pressure was controlled by adjusting the upstream air pressure of the critical flow nozzle. The air/fuel ratio was controlled by adjusting the fuel delivered to the injector from the injection pump and was varied from slightly rich to the lean limit. In addition to using air flow and fuel flow measurements, the air/fuel ratio was determined from the exhaust emissions using a carbon and oxygen balance procedure (19). The lean misfire limit for this study, lacking the instrumentation to determine the misfire frequency, was the operating point at which both hydrocarbon emissions and obvious misfires of the engine indicated engine operation was unstable.

TABLE I - ENGINE OPERATING CONDITIONS

Compression Ratio	8.0 to 1
Engine Speed	1200 RPM
Oil Temperature	65 ± 1°C
Coolant Temperature	98 ± 1°C
Spark Plug	Champion D-16
Plug Gap	1 mm
Fuel Type	Indolene H.O.
Fuel Temperature	40°C Nominal

TABLE II - ENGINE TEST CONDITIONS

INTAKE MANIFOLD PRESSURE (kPa)	MIXTURE TEMP. (°C)	EXHAUST PRESSURE (kPa)	ASSUMED* COMPRESSOR EFFICIENCY (%)
68.9	52	119.3	----
89.6	52	119.3	----
112.4	76.7	133.0	50
126.4	91.1	146.8	60
140.0	115.6	153.7	55

*Compressor efficiency used in estimating mixture temperatures for given intake manifold pressures.

Three possible spark timing settings were used during the test procedure. The spark timing settings were: Minimum spark advance for best torque, 5% power loss spark, and knock limited spark. Minimum spark advance for Best Torque (MBT spark) is the spark timing which provides the maximum torque output. A detailed procedure for determination of MBT spark is given in Appendix - A. Knock Limited spark (K.L. spark) is the spark timing achieved by retarding the spark timing two degrees from the timing which produced steady audible knocking. This timing was used in cases where knocking was produced before the spark timing could be advanced to achieve MBT spark timing. 5% power loss spark timing (5% P.L.) is the spark timing, retarded from MBT or Knock Limited spark, that produces 5% less indicated power output from the engine. Engine torque, airflow, exhaust emission concentrations, and pressure-crank angle data were obtained at spark settings of MBT (or K.L. spark) and 5% power loss. Also, with the spark timing set at MBT, the fuel flow was shut off and the engine motored to determine the frictional losses and obtain motored pressure-crank angle data. After obtaining a complete set of data, the air/fuel ratio, EGR rate, or manifold pressure were changed and the procedure repeated.

IV. EXPERIMENTAL RESULTS

Because of the high frictional losses inherent in the CFR crankcase, indicated power is often used to report results of single cylinder studies using the CFR engine. However, for this study it was decided to report the results on a brake power basis since supercharging can substantially alter pumping and frictional losses in the engine. The exhaust emissions data were reduced to a mass specific basis using a carbon balance technique developed by Stivender (19), and were expressed as micrograms of constituent per joule of energy output produced by the engine. The air/fuel equivalence ration, ϕ_{AF}, used in this study is defined as:

$$\phi_{AF} = \frac{\text{Actual Air/Ratio}}{\text{Stoichiometric Air/Fuel Ratio}}$$

This gives ϕ_{AF} a value greater than one for lean operation. Most of the results examined were at MBT or Knock Limited spark timing.

Two intake manifold pressures were selected to simulate naturally aspirated engine operation: moderate load operation, 68.94 kPa (10.0 psia), and full load operation, 89.6 kPa (13.0 psia). This is referred to as the base engine operation and is used for comparison purposes. Three intake manifold pressures were selected for supercharged operation at lean air/fuel mixtures: 112.2 kPa (+2 psig), 126.2 kPa (+4 psig), 140 kPa (+6 psig). The operation of the engine with a lean mixture and positive manifold pressure is referred to as Lean Supercharged Operation (LSO).

A. ENGINE POWER, EFFICIENCY, AND EXHAUST EMISSIONS

The power, efficiency, and emissions data are graphically presented in figures 4 to 12 with the intake manifold parameter. Each figure, divided into three parts, shows the data for 0%, 5%, and 10% EGR rate to illustrate the effects of EGR on the engine operation.

Brake Power produced by the engine as a function of the air/fuel equivalence ratio is shown in figure 4. The decrease in brake power output with increasing $\emptyset_{AF}$ is predictable. Since the frictional losses and the charge volume are essentially fixed, decreasing fuel energy input leads to reduced brake power. The base engine brake power output, at 0% EGR, ranged between 0.55 Kw and 2.08 Kw. The LSO engine brake power output, at 0% EGR, ranged from 1.53 Kw to 3.07 Kw, an increase of approximately 48% over the base engine.

Engine efficiency is shown in figure 5 as a function of $\emptyset_{AF}$. When compared with the base engine at full load and 0% EGR, an increase of approximately 28% in the brake efficiency was observed with LSO. The decreasing brake efficiency with increasing $\emptyset_{AF}$ is due to the lower energy input and the fixed frictional and pumping losses in the engine. The base engine at part load showed a decrease in brake efficiency with the addition of EGR. However, the naturally aspirated engine at full load and the LSO engine showed less than 5% decrease in the brake efficiency with the introduction of EGR.

MBT spark and Knock Limited spark timing data are shown in figure 6 as a function of $\emptyset_{AF}$. The data are provided to show where Knock Limited spark timing was used (which will effect the exhaust emissions) and to show the effects of intake manifold pressure and EGR on the spark timing. The increased spark advance with increased $\emptyset_{AF}$, at fixed intake manifold pressure, was anticipated due to the slower combustion and longer flame kernel formation times for lean mixtures. at fixed $\emptyset_{AF}$, the degrees of spark advance were reduced with increasing intake manifold pressure, primarily due to the increased charge density and resulting faster flame speed. The addition of EGR produces a diluting effect and reduced flame speeds requiring more spark advance for MBT timing.

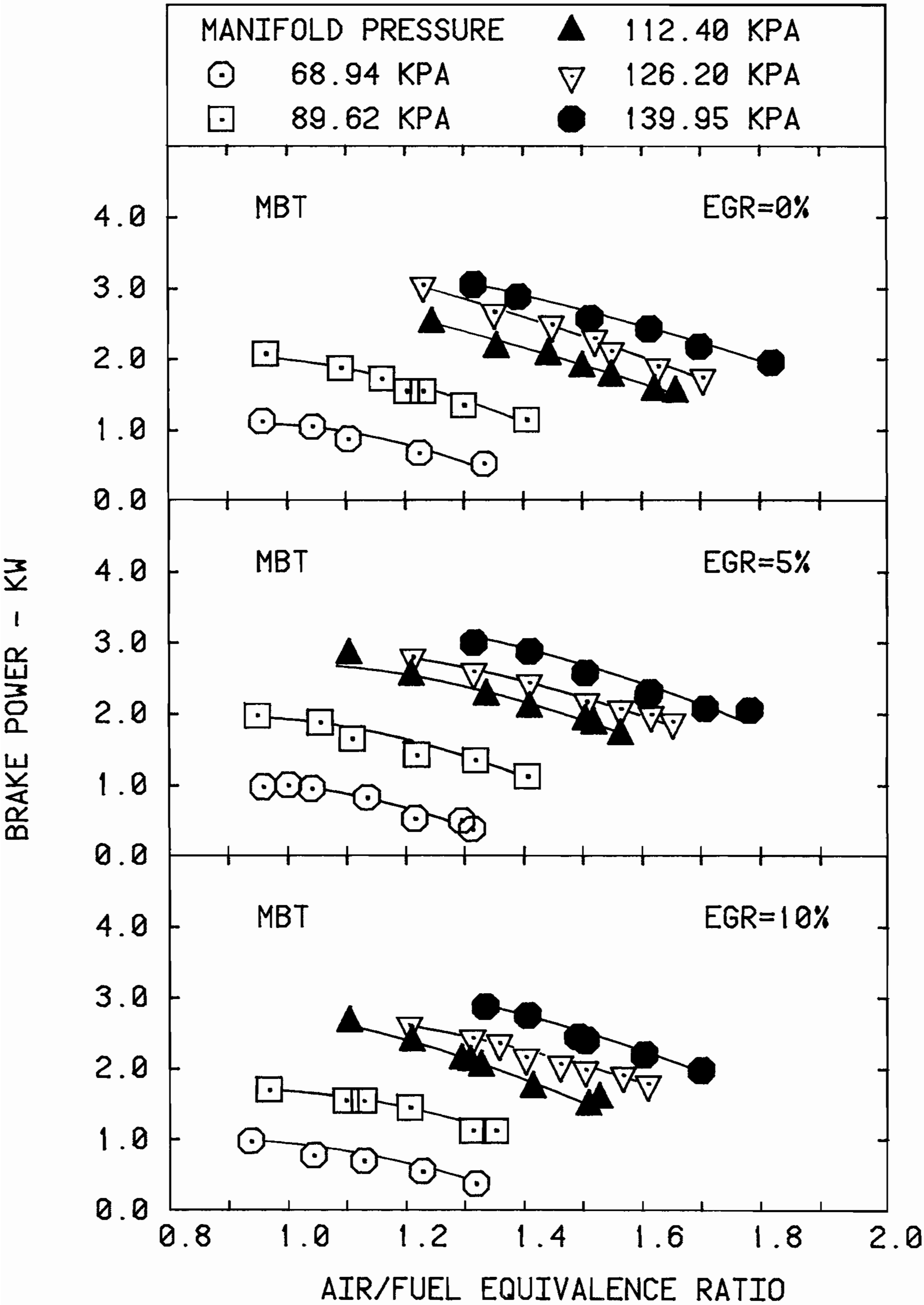

Figure 4. Brake Power for Single Cylinder Engine

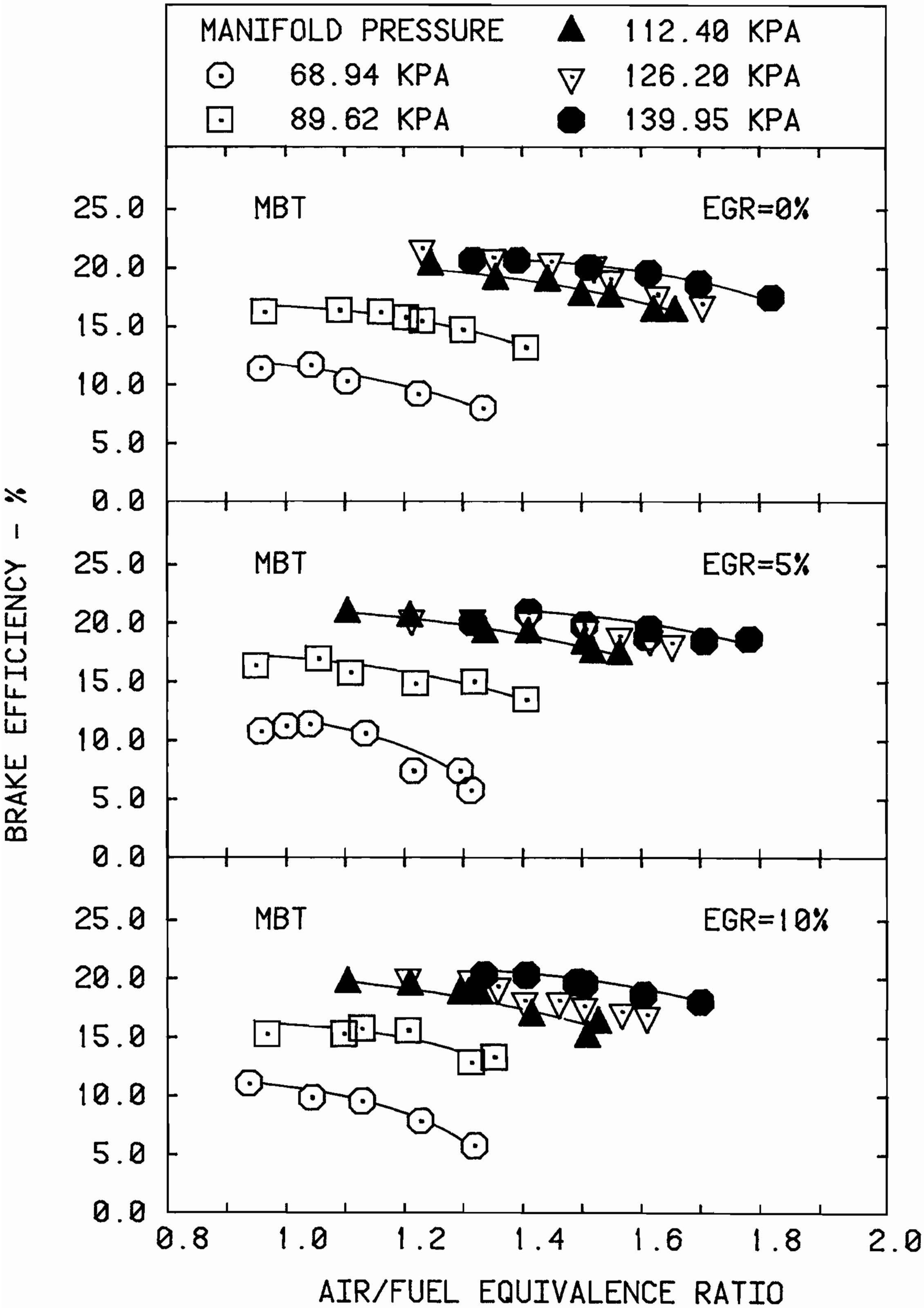

Figure 5. Brake Efficiency for Single Cylinder Engine

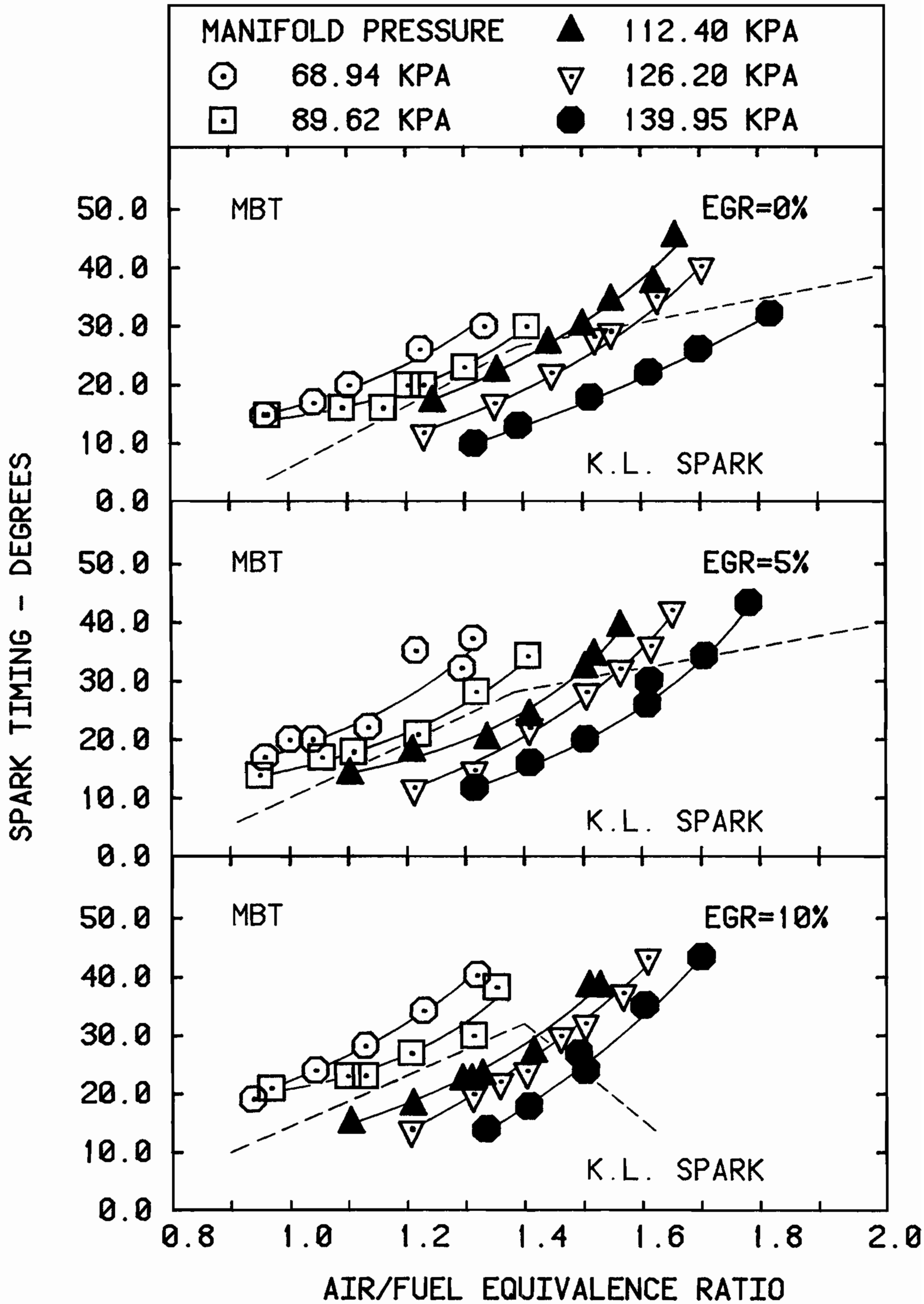

Figure 6. Engine Spark Timing for Single Cylinder Engine

Carbon Monoxide as a function of $\emptyset_{AF}$ is displayed in figure 7. Generally, the results are those anticipated in that the Brake Specific Carbon Monoxide (BSCO) is primarily a function of $\emptyset_{AF}$ and little else. BSCO emissions are very high for rich operation ($\emptyset_{AF}$=1.0) and reduce sharply to a low value for lean operation. For the lean operation data shown in figure 7, a significant increase in BSCO emissions can be observed for the naturally aspirated engine operating at part load. A similar, but less pronounced, trend can be observed for the full load and LSO data as well. This effect is assumed to be due to a combination of decreasing brake power output and a deterioration of combustion at the leaner air/fuel conditions. Other than reducing the lean limits of operation, EGR flow seemed to have little effect on the BSCO emissions.

Unburned Hydrocarbon emissions data are presented in figure 8. The Brake Specific Hydrocarbon (BSHC) emissions were significantly changed by increased intake manifold pressure. The reduced BSHC emissions shown in figure 8 are due to two major effects: improved combustion due to increased charge density, and increased engine power causing a reduction in BSHC in addition to the reductions in the concentration of hydrocarbons in the engine exhaust. This change in the BSHC emissions due to changes in the engine power can also be seen in the gradual increase of these emissions with increasing $\emptyset_{AF}$, in that the reduced power associated with increasing $\emptyset_{AF}$ contributes to the apparent increase of these emissions. Near the lean misfire limit, deterioration of the combustion process also contributes to the rate of increase of the BSHC emissions.

Oxides of Nitrogen emissions as a function of $\emptyset_{AF}$ are presented in figure 9. The oxides of nitrogen emissions follow typical data with the peak $BSNO_x$ at about 10% lean ($\emptyset_{AF}$ = 1.10). For a constant EGR rate, both the naturally

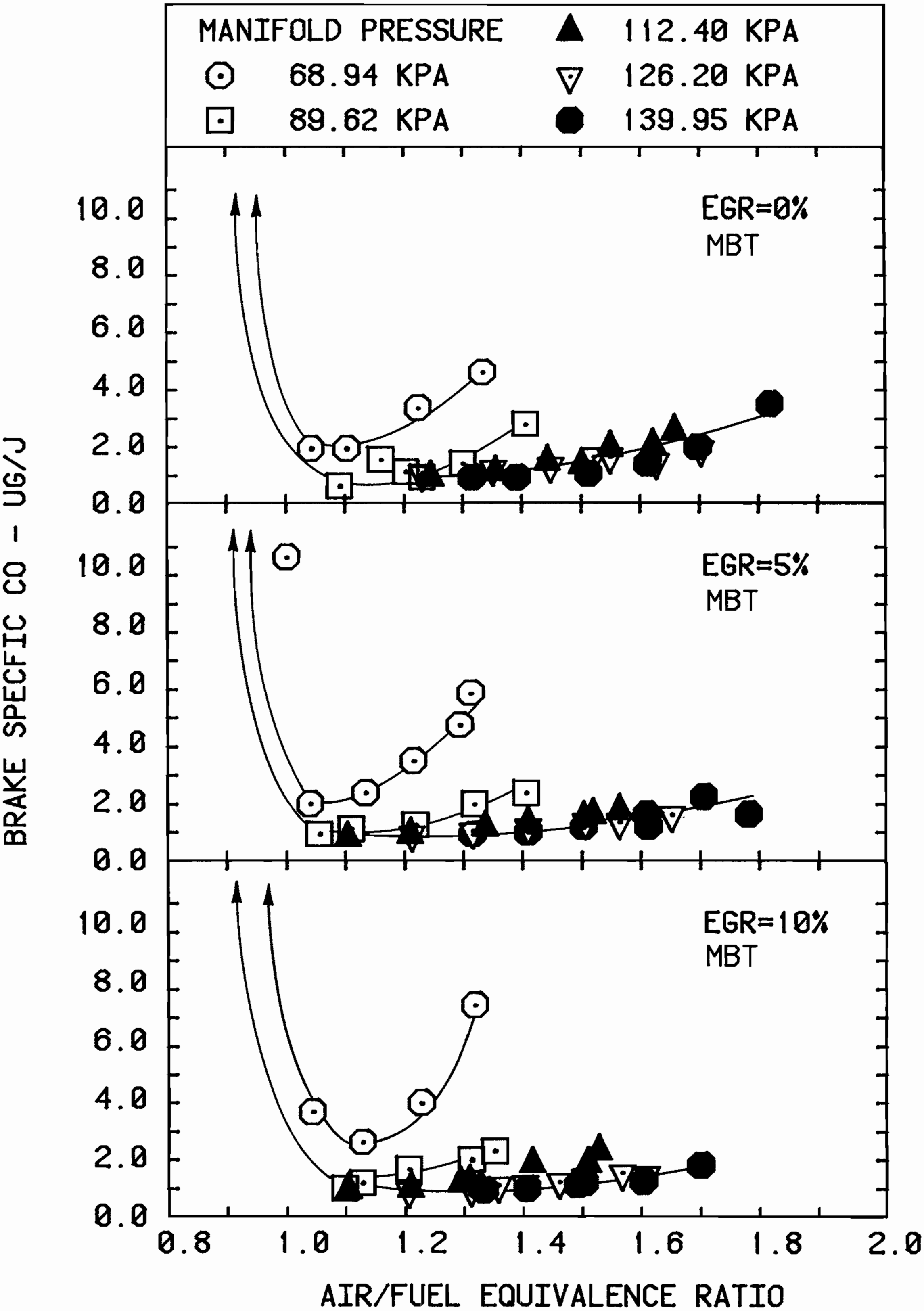

Figure 7. Brake Specific CO Emissions for Single Cylinder Engine

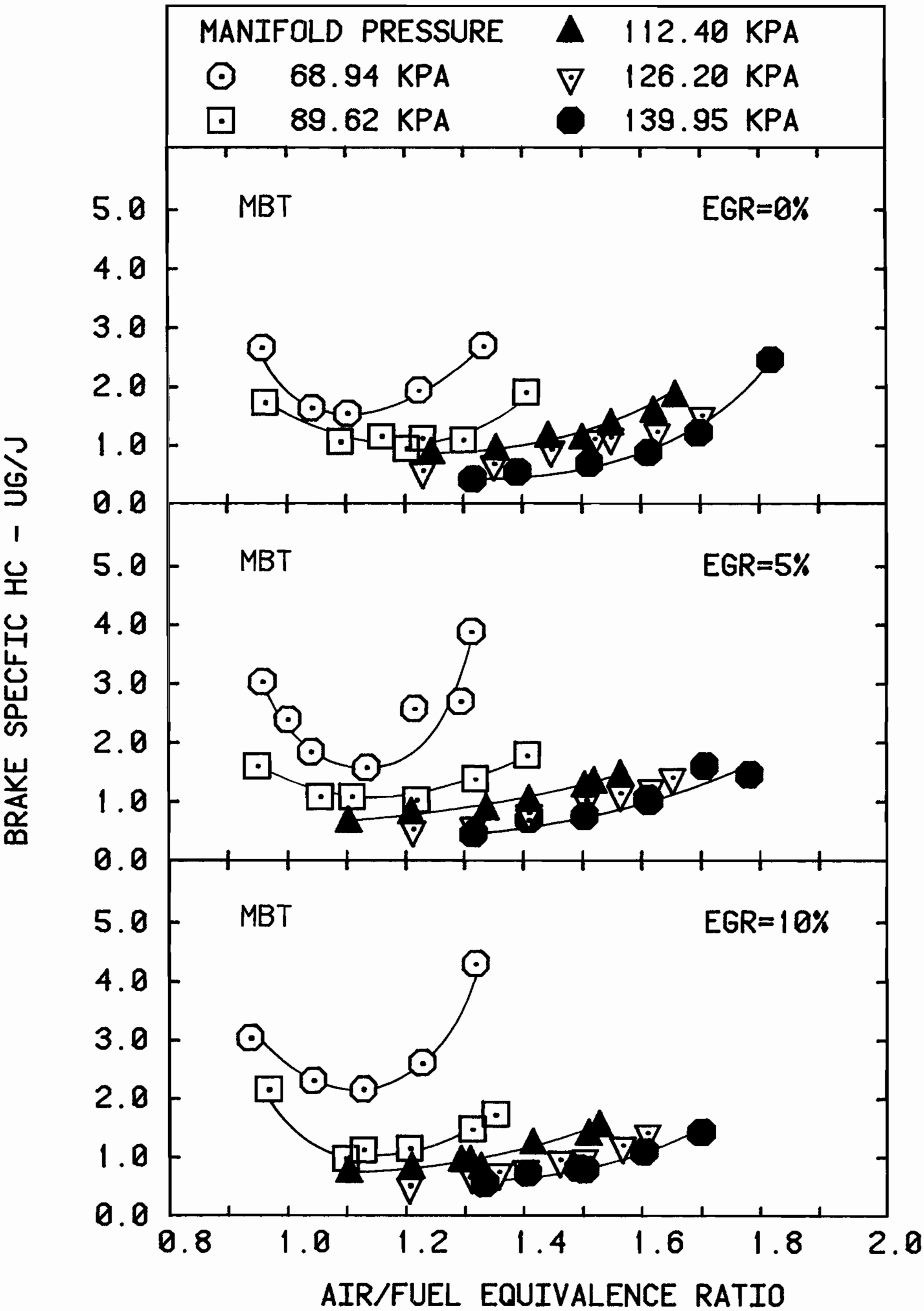

Figure 8. Brake Specific HC Emissions for Single Cylinder Engine

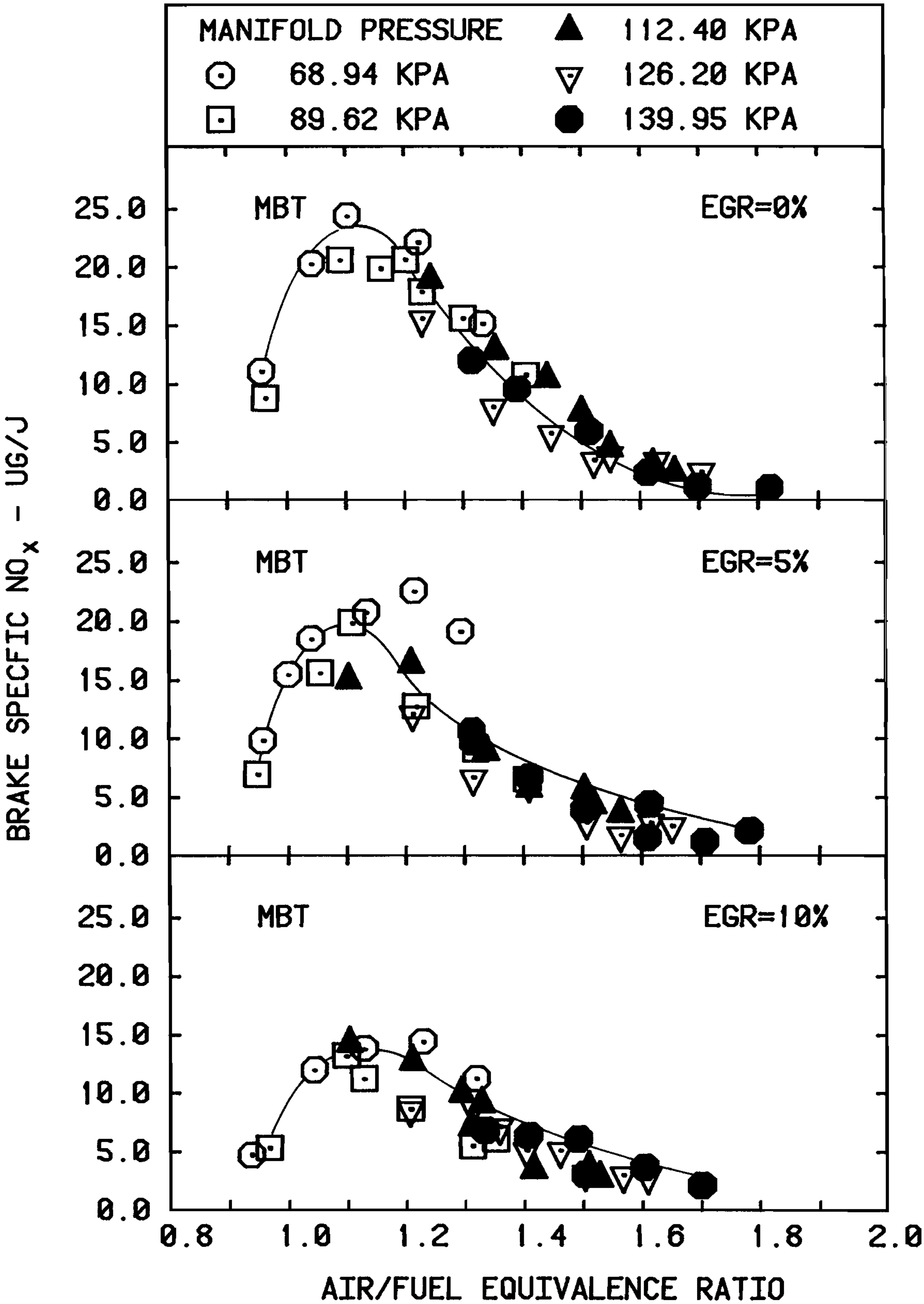

Figure 9. Brake Specific NO_x Emissions for Single Cylinder Engine

aspirated and LSO data tend to follow the same curve. The addition of EGR has a substantial effect in reducing the $BSNO_x$ emissions for $\emptyset_{AF}$ between 1.00 and 1.3; however, for equivalence ratios greater than about 1.3, EGR has little effect upon the $BSNO_x$ emissions. Some of the deviations in the $BSNO_x$ emissions data can be traced to variations in engine test conditions. In particular, deviation of the actual EGR rate from the desired value, and Knock Limited spark timing rather than MBT operation. The $BSNO_x$ emissions appear to have substantial sensitivity to EGR rates when operating at an equivalence ratio near peak NO_x. Spark timing appears to have an influence on NO_x emissions at virtually all lean operating conditions.

Further analysis of the exhaust emissions data involves some crossplots of the data (figures 10 to 12). The BSHC emissions as a function of the brake efficiency are shown in figure 10. The trend of the data follows a negative slope as the intake manifold pressure increases. The trend indicates that the best operating conditions for lower BSHC emissions and higher engine efficiency are in the LSO regime.

Figure 11 is a crossplot of $BSNO_x$ emissions and brake efficiency. Two points can be illustrated by this figure. First, for a given level of $BSNO_x$ emissions, LSO provides definite gains in the efficiency. For example, at an $BSNO_x$ emission level equal to 10.0 μg/J, the base engine at full load has an efficiency of 16.2%. For LSO with 0% EGR, efficiency ranges between 18.1% and 21.%, an increase of 11 to 29 percent. Second, several possible LSO operation points have higher brake efficiency and lower $BSNO_x$ emissions than the base engine, even with EGR.

Figure 12 is a crossplot of BSHC and $BSNO_x$ emissions for lean operating conditions. This plot is included to examine the typical inverse relationship between $BSNO_x$ and BSHC emissions. The relationship between these variables

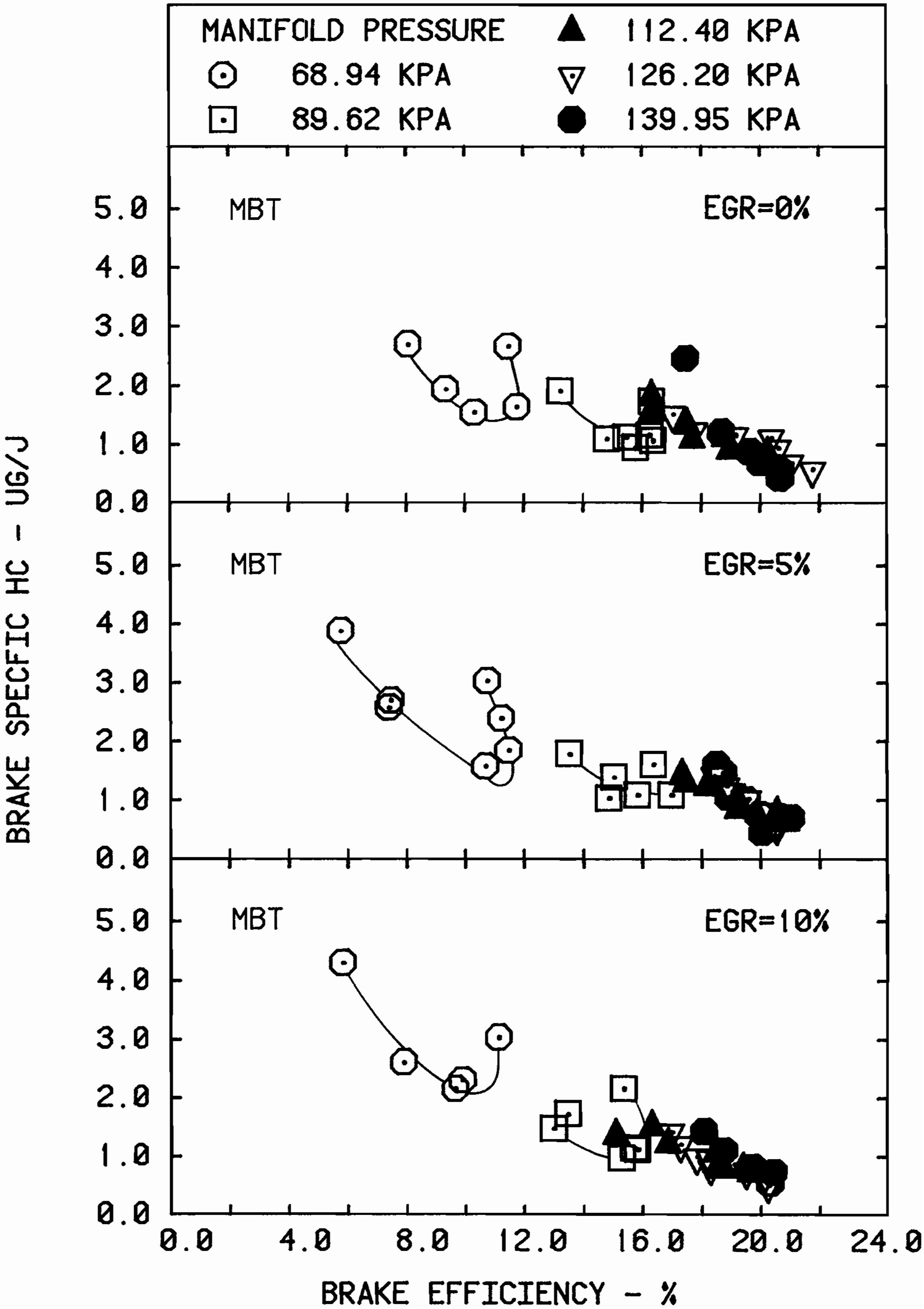

Figure 10. Brake Specific HC as a Function of Efficiency

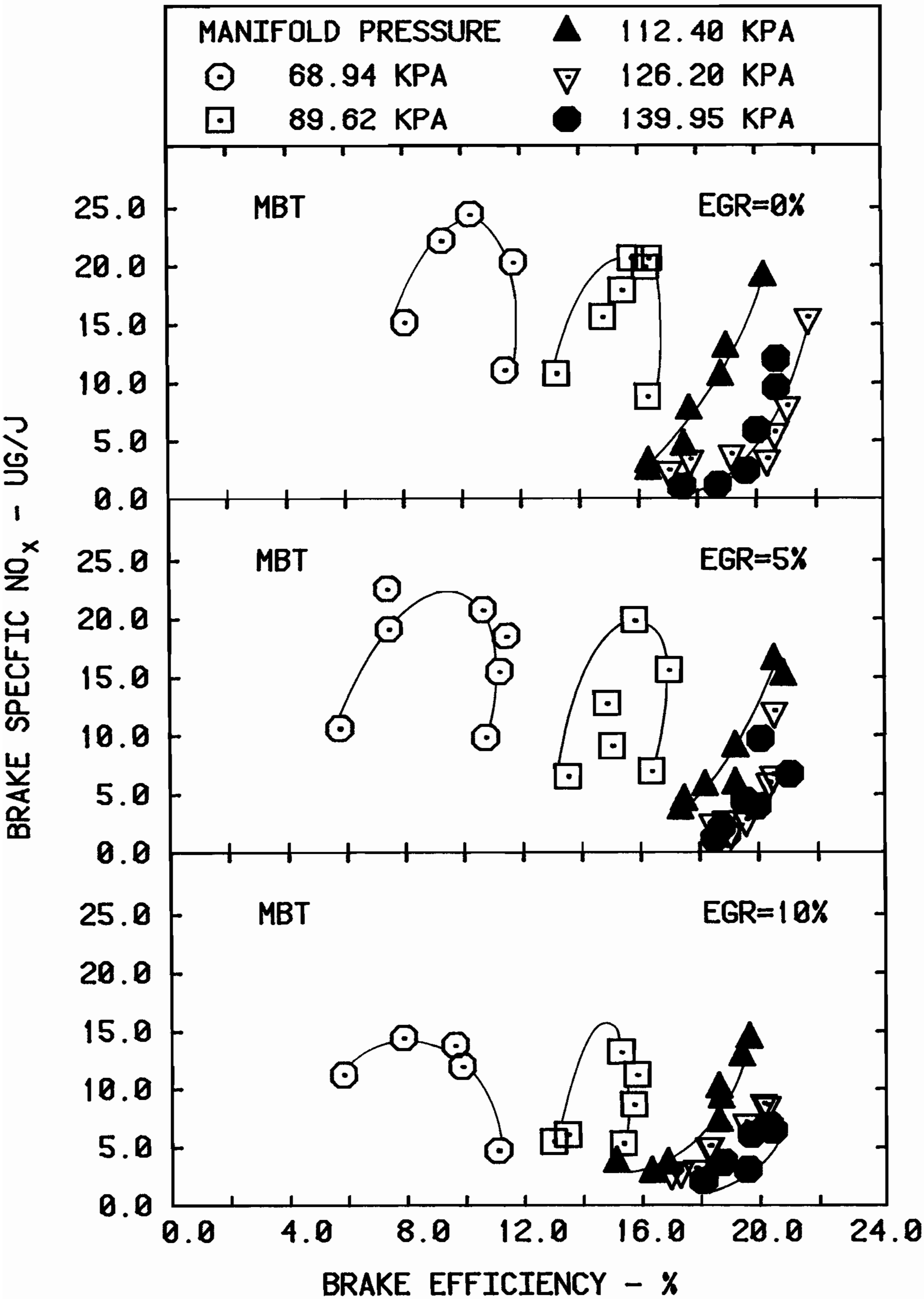

Figure 11. Brake Specific NO_x as a Function of Efficiency

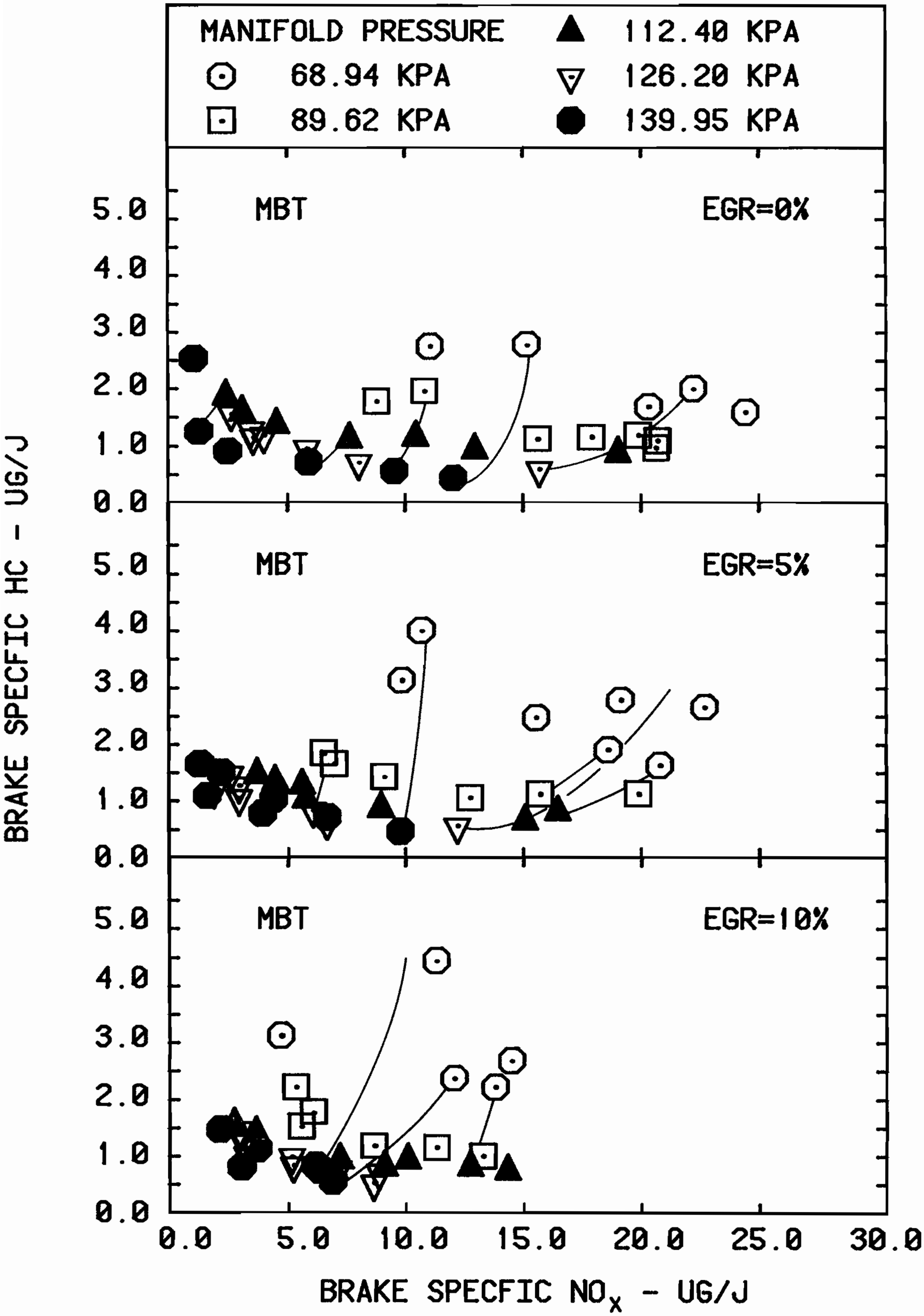

Figure 12. Brake Specific HC vs. Brake Specific NO_x

is dependent on both the manifold pressure (i.e. charge density) and the air/fuel equivalence ratio. Figure 12 clearly shows that the manifold pressure has a significant influence in reducing BSHC for a given level of $BSNO_x$. In fact, at the LSO conditions, BSHC emissions change very little from the range of 1.0 microgram per joule for a wide range of $BSNO_x$ emissions. It is also obvious that the $BSNO_x$ emissions are virtually independent of manifold pressure and highly dependent on the air/fuel equivalence ratio, particularly at the LSO test conditions. EGR flow has a detrimental effect on the BSHC emissions for the two lower manifold pressure conditions representing the naturally aspirated engine. However, the influence of EGR flow on the BSHC emissions for the LSO conditions seems to be negligible. From these data it is apparent that Lean Supercharged Operation reduces the inverse relationship between BSHC and $BSNO_x$ emissions. BSHC emissions are stabilized in a range near 1.0 microgram per joule and $BSNO_x$ emissions are strongly dependent on the air/fuel equivalence ratio.

B. ENERGY AVAILABILITY IN EXHAUST GASES

An objective of this study was to determine available exhaust gas energy for possible turbocharger operation. Estimates of the compressor power needed to provide LSO and the power available from an exhaust driven gas turbine were calculated. These calculations provided data regarding the conditions for which LSO would be possible with a turbocharger. A description of the calculation is given in Appendix - C. Figures 13 and 15 show the necessary compressor power and available power from a turbine at MBT spark and 0% EGR.

The compressor power was calculated for two inlet air pressures: 89.6 kPa and 98.6 kPa. These two compressor inlet air pressures were used to simulate having the

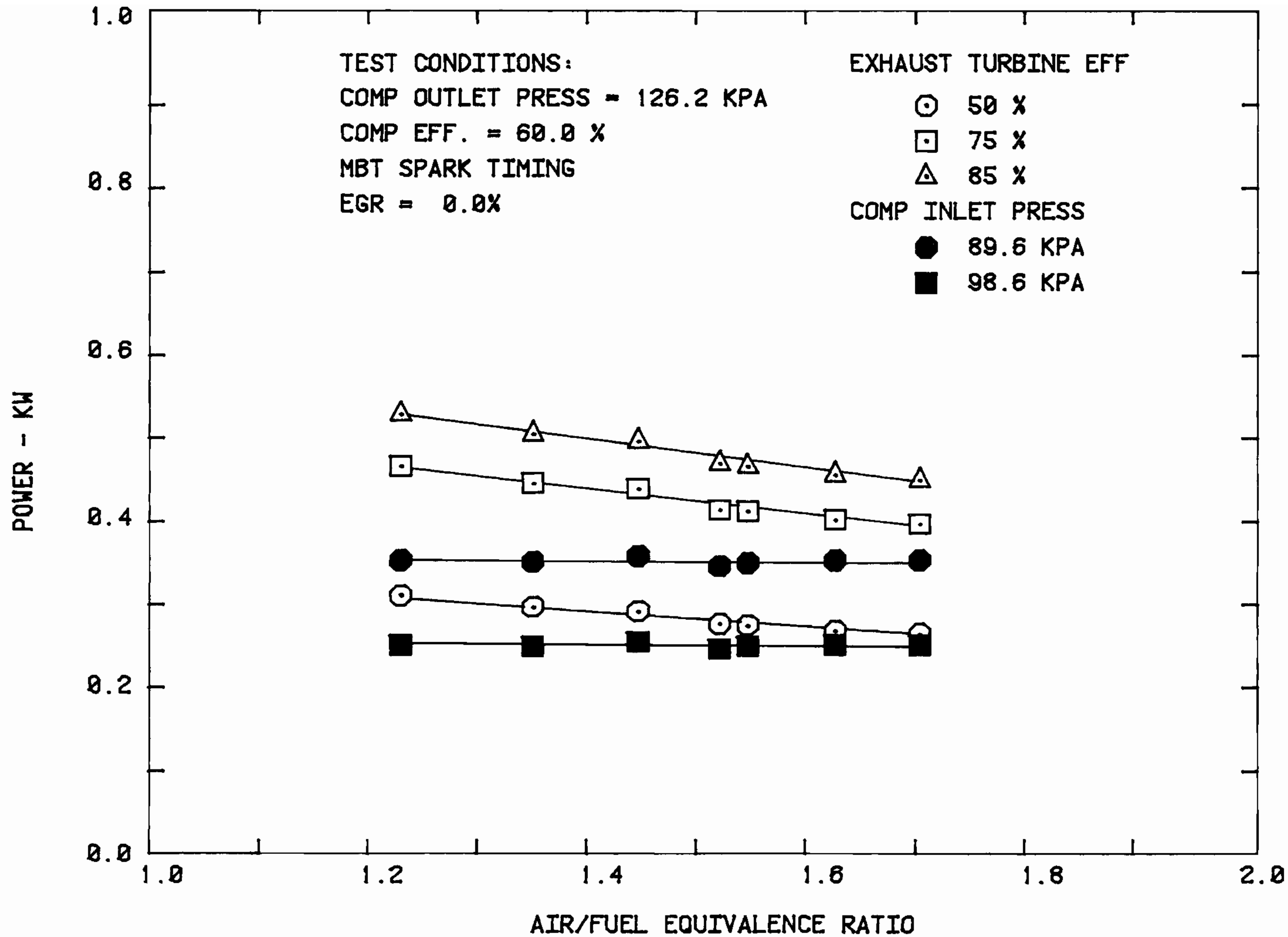

Figure 13. Estimates, Turbine and Compressor Power for 60% Compressor Efficiency

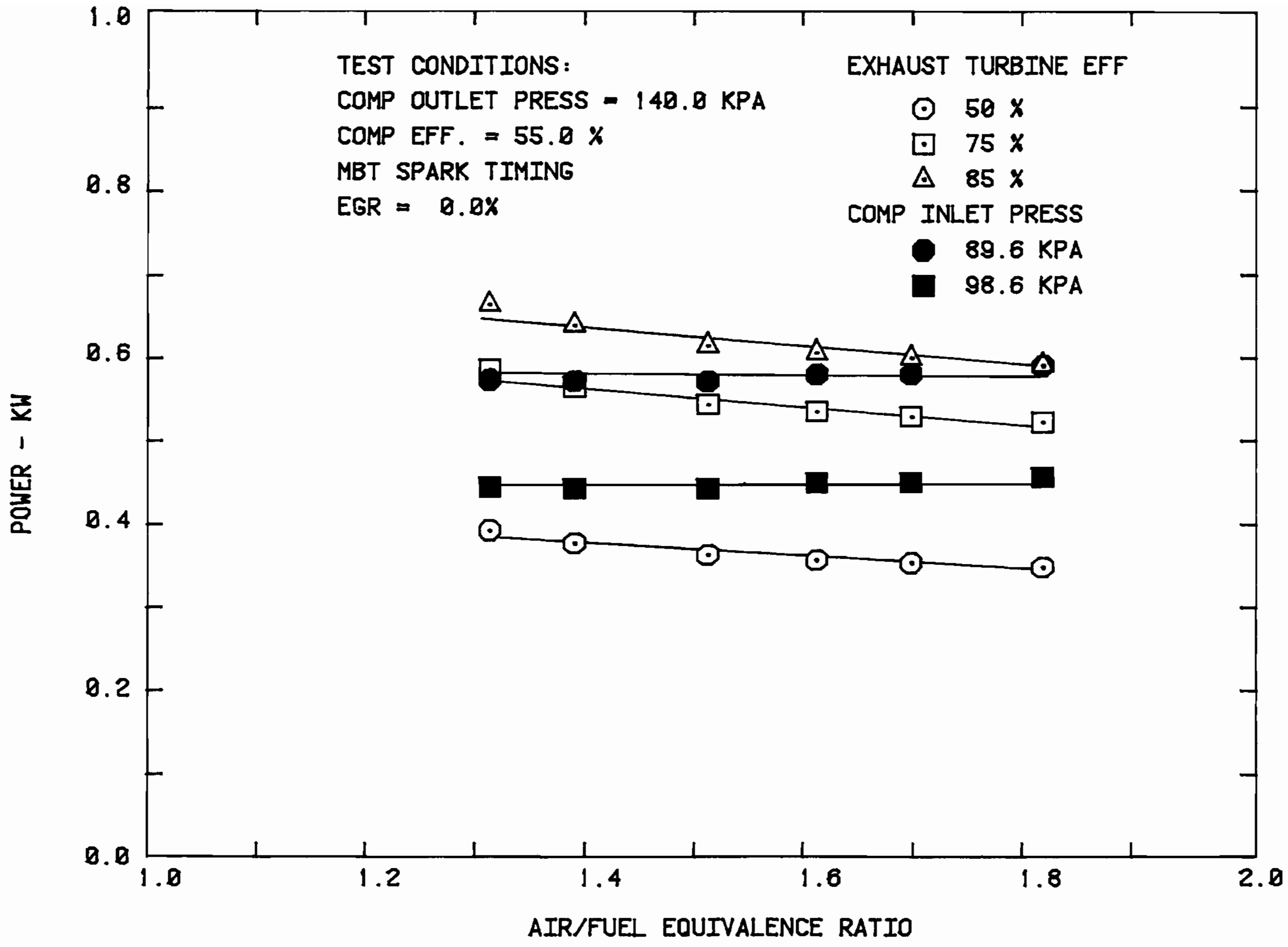

Figure 14. Estimates, Turbine and Compressor Power for 55% Compressor Efficiency

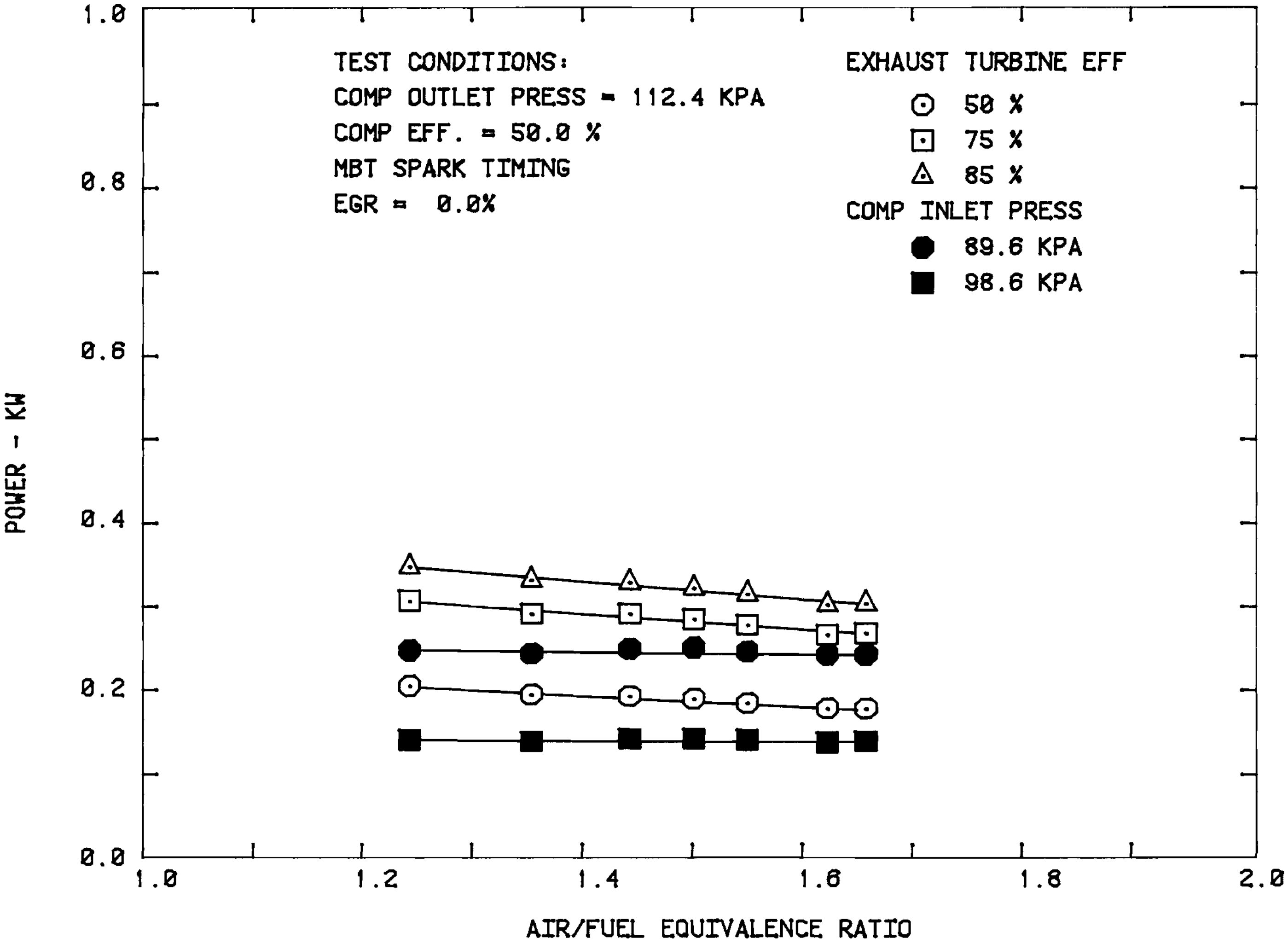

Figure 15. Estimates, Turbine and Compressor Power for 50% Compressor Efficiency

compressor located upstream or downstream of the throttle plates in calculating the compressor power. Current practice is to locate the compressor downstream of the carburetor. The major reason for this location is to avoid having the carburetor operate under postive pressure, requiring shaft seals, and more complicated fuel metering due to a wide range of operating pressures.

The exhaust turbine power was calculated for three (3) efficiencies, 50%, 75%, and 85%. The 50% efficiency value was used as the worst possible efficiency, and the 75% and 85% efficiencies were used as more realistic values.

The addition of EGR decreased the needed compressor power slightly (approximately 5% for 10% EGR) due to reduced mass airflow needed by the engine at constant equivalence ratio. This condition is correct only in the case where the EGR does not flow through the compressor. Should the EGR flow through the compressor, the compressor power needed will be the same, with or without EGR. Also, the addition of EGR decreased the available power from the exhaust turbine due to lower exhaust temperatures. The 5% P.L. spark timing slightly increased (approximately 4%) the available power from the exhaust turbine due to higher exhaust temperatures.

Assuming a downstream compressor location, the compressor power required for LSO (0% EGR, MBT spark) is between 0.24 Kw and 0.57 Kw for intake manifold pressures of 112.2 kPa and 140 kPa respectively. To obtain this power from an exhaust turbine requires a turbine efficiency between 64% and 80% respectively. Thus, a turbine efficiency of 80% would be needed to provide a maximum manifold pressure of 140 kPa.

C. CYCLE ANALYSIS DEVELOPMENT

The fact that lean operation of the spark ignition means that any approach to lean operation must in some way attempt to examine the behavior of the combustion process. In this work, pressure-volume data from the single cylinder engine operating at lean supercharged conditions are used to obtain information about the combustion process. The instrumentation used in gathering pressure-crank angle data for analysis was described in an earlier section of this thesis. The purpose of this section is to describe the methods used in analyzing these data.

Since several different steps are involved in the reduction and processing of the pressure-crank angle data, a flow diagram for the process is shown in figure 16. Each of the blocks in the diagram represents a data reduction or presentation step and the names in the blocks are for the computer programs used. The first block at the top of the diagram represents the pressure-crank angle data files produced by the minicomputer data acquisition system. The first use of this information is in the laboratory using program PRELIST. This program prints out the pressure data for the first cycle (720 points) of the 30 consecutive cycles stored in the data file to determine if any obvious problems exist in the data. Since this step is done while the engine is running, additional data sets may be taken to insure that a good set is obtained for further analysis.

Once a satisfactory set of pressure-crank angle data has been taken, data reduction and analysis proceed with the calculation of the average and standard deviation across the 30 cycles at each of the 720 crank angle degrees in a cycle. The average and standard deviation cycles calculated in this step are then stored in individual data files. Two primary reasons for averaging the pressure data are given by Lancaster, et. al. (20). The first is that the engine is an averaging device which responds to mean values of fuel and air flows in delivering power output. The second reason

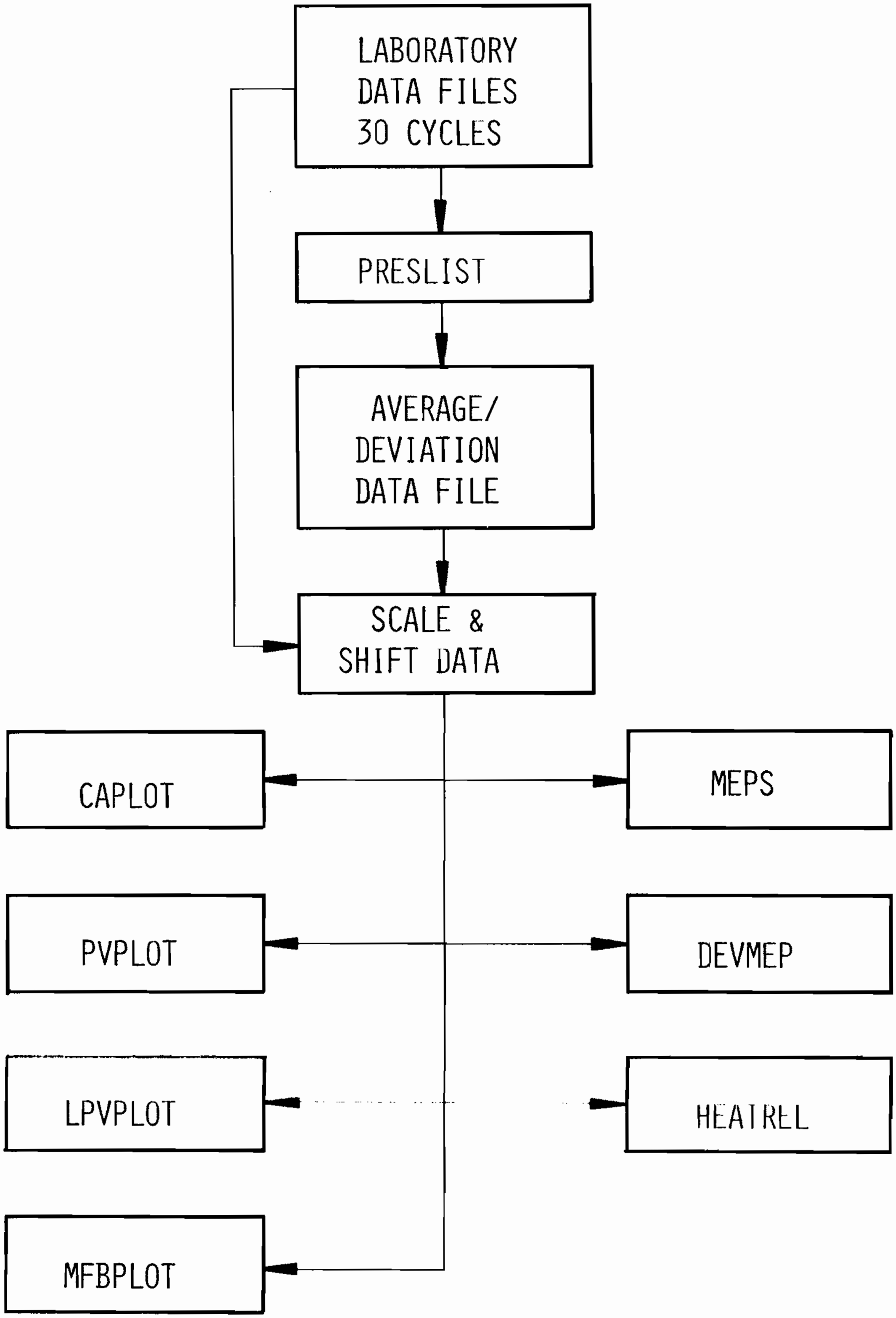

Figure 16. Cycle Analysis, Data Reduction Flow Chart

is statistical: For a given crank angle, the pressure averaged across many cycles is a better estimator of the nominal cylinder pressure than any individual cycle measurement.

In order to make pressure-crank angle information more useful, several computer programs were written to plot the data in different formats. The three most valuable forms of the graphical presentation used in this work were produced by the computer programs named CAPLOT, PVPLOT, and LPVPLOT. These three programs are shown as output blocks in figure 16. The program CAPLOT was used to plot any number of the 30 original data cycles. This information was useful in tracing down any discrepancies in the results that might be attributable to a problem in the original data, such as complete misfires. Figure 17 is an example of this type of information. As shown in figure 18, the PVPLOT program was used to obtain a classical P-V plot from the average pressure-crank angle cycle. LPVPLOT was a modified version of PVPLOT that produced Log-pressure vs. Log-volume plots for use in final calibration and correction of the pressure-crank angle data. Figure 19 is an example of the graphical output from this program.

Before the averaged data can be used quantitatively, they must be properly scaled and phased. A detailed description of pressure data scaling, phasing, and analysis was made by Lancaster, et. al. (20) and those techniques have been used in this work. The pressure scaling involves converting the binary number stored in the average data file to a relative pressure using the calibration factors for the pressure transducer and data acquisition system. The relative pressures are then shifted by a constant to obtain absolute cylinder pressures. This constant is a reference pressure assigned to one point in the cycle where an accurate estimate of the absolute cylinder pressure can be made. For

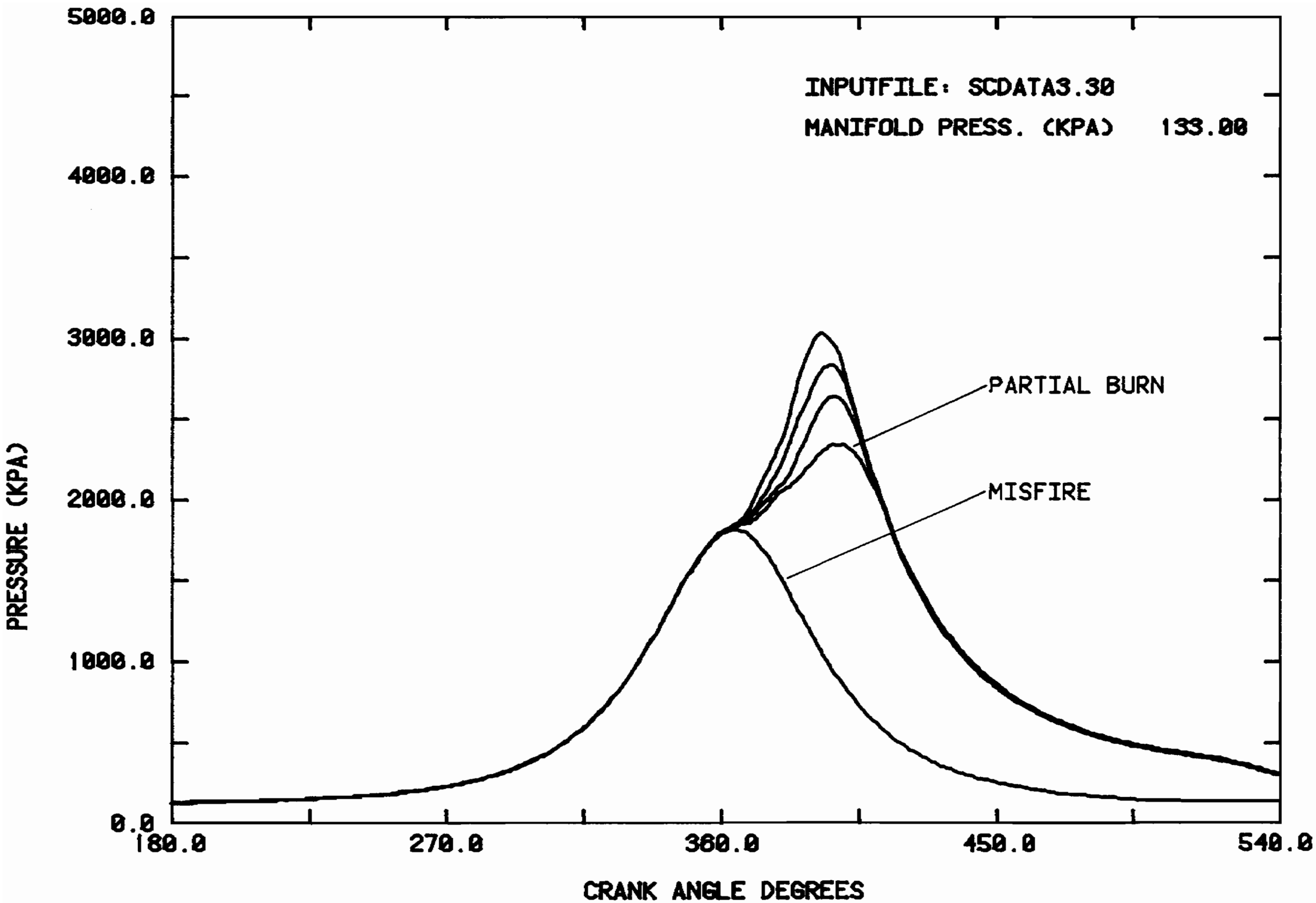

Figure 17. Typical Output from CAPLOT Program Showing Partial Burns and Misfire

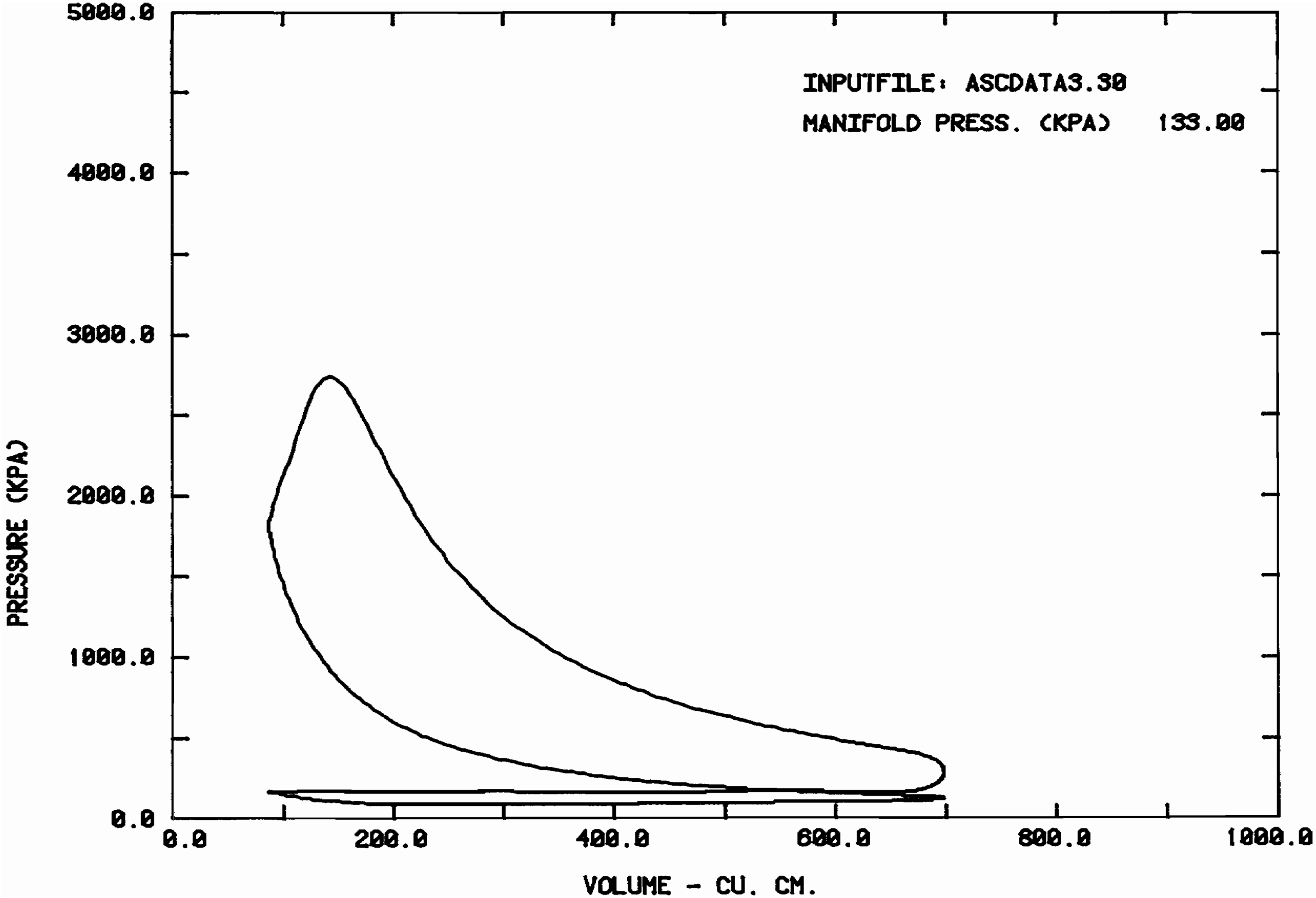

Figure 18. Typical Pressure-Volume Plot Produced by Program PVPLOT

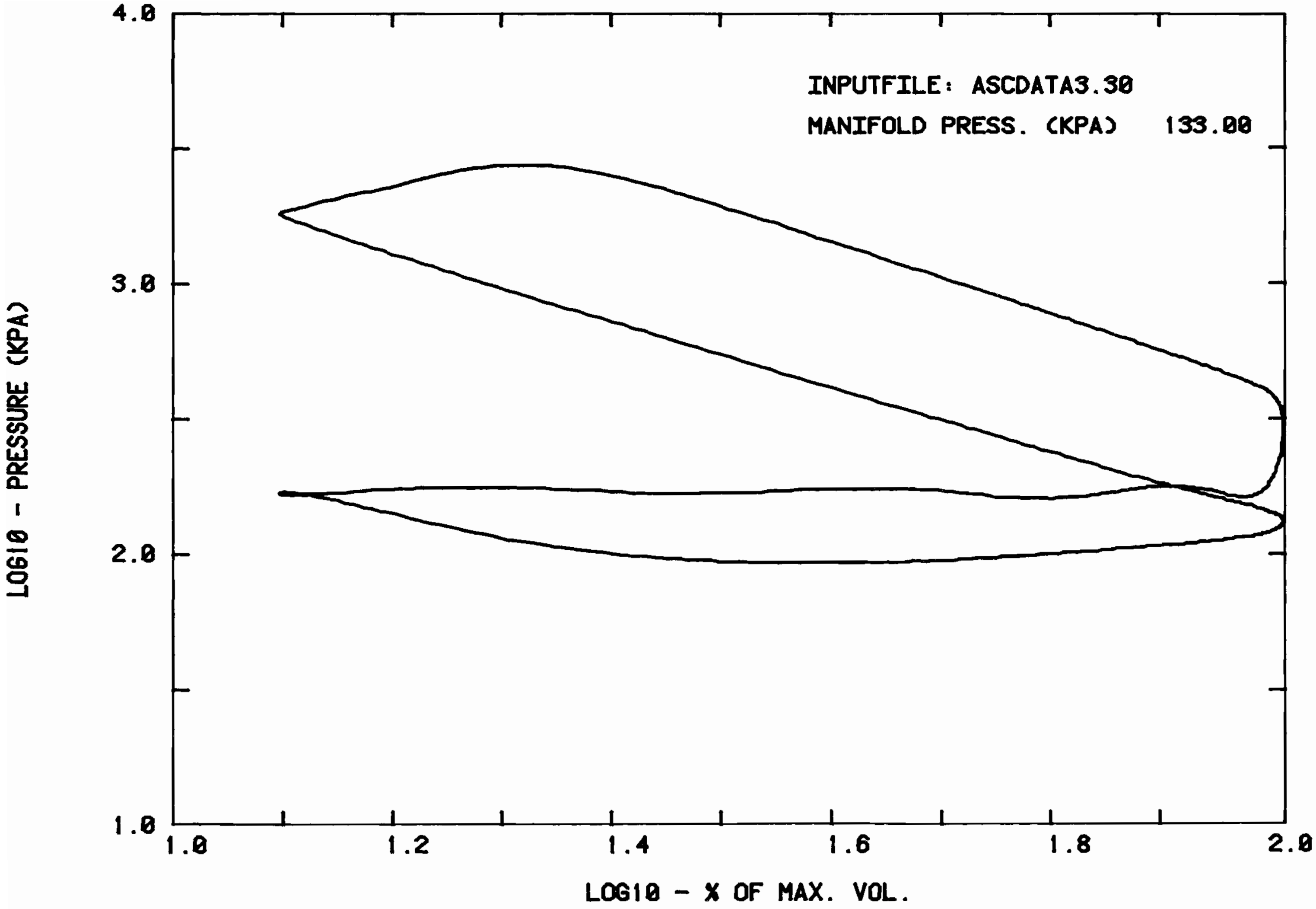

Figure 19. Typical Log-pressure vs. Log-volume Plot Produced by Program LPVPLOT

this case, the intake manifold absolute pressure was assigned to the point corresponding to Bottom Dead Center of the piston on the intake stroke. Once this reduction of the average data was complete, a plot of Log-pressure vs. Log-volume was made. From this graphical output of the data, corrections to the assigned reference pressure were made to obtain a straight line for the compression stroke of the Log-pressure vs. Log-volume plot. The lower reference pressure obtained using this procedure was assumed to have been due to a pressure drop across the shrouded intake valve.

A second correction to the pressure-crank angle data was a "phasing" adjustment to insure that the pressure and crank angle information were concurrent. This correlation is extremely important since minor errors in the pressure-crank angle relationship can produce significant errors in later calculations based upon areas under this curve. The phasing correction is necessary even though great care was exercised in calibrating the engine crankshaft position encoder to identify TDC for the piston. The elastic behavior of the engine parts under load, changes in bearing clearances, and dynamic effects can cause the location of piston TDC to vary a few degrees from that indicated by the crankshaft encoder. The correction for these effects is determined by using a Log-pressure vs. Log-volume plot for motored (non-firing) cycle data. The compression-expansion portion of the motored cycle should contain almost zero area. The pressure-crank angle data were shifted to produce a minimum area between the compression and expansion lines of the Log-pressure vs. Log-volume plot for the motored data. For the test conditions examined in this project, this shift was determined to be 2 crank angle degrees.

Once the average pressure-crank angle data file had been fully calibrated and corrected, useful information from this data could be obtained. The final four blocks in figure 16 are to identify the data analysis programs which use the final pressure-crank angle data. These programs are MEPS, DEVMEP, HEATREL, and MFBPLOT. Numerical integration of the area under the P-V data using program MEPS provides indicated pumping, and frictional mean effective pressures for the average cycle data examined. The definitions of Lancaster, et. al. (20) were used for these computations. The program DEVMEP provides average and standard deviation values for indicated and pumping mean effective pressures. HEATREL is a program for the approximate calculation of heat release rates and mass fractions burned from the P-V data and other operating conditions. MFBPLOT is a plotting program to graphically display the useful results from the heat release calculations.

In examining the data from these analysis programs, several interesting results were observed. The results from the MEPS program using the pressure data were consistently lower (3 to 6%) than the estimate of Indicated Mean Effective Pressure from the engine dynamometer data. Lancaster, et. al. (20) state that this slight discrepancy is primarily due to the non-zero value of the motoring IMEP (the area between compression and expansion lines for the motored engine), which is assumed to be zero in the computations. The consistent correlation between IMEP calculated from the pressure-crank angle data and that estimated from the dynamometer results was considered to have an important bearing on the validity of the heat release and mass fraction burned computations. A poor correlation would certainly cast some doubt on the usefulness of computations based upon the data.

Cycle-to-cycle variations in the P-V data for the engine are indicative of the quality of the combustion process. The smaller the variation between cycles, the more consistent the quality of the combustion. Program DEVMEP finds the standard deviation of the indicated and pumping mean effective pressures for the 30 data cycles. Variations in the IMEP are indicative of combustion quality, partial burns, and misfires. The standard deviation for the IMEP as a function of ϕ_{AF}, for the range of conditions examined in this program, is shown in figure 20. The data follow roughly the same trend for full load naturally aspirated operation or Lean Supercharged Operation. As ϕ_{AF} increases, the standard deviation increases, indicating increased cyclic variations and deterioration of the combustion process. Although not shown in figure 20, the use of EGR and the 5% P.L. condition with retarded spark also contribute to the increase of the standard deviation of the IMEP and therefore they also contribute to degrading the combustion process.

An approximate heat release curve was calculated from the pressure data following an empirical technique described by Young and Lieneson (21). The authors indicate that the resulting curve compared favorably with detailed heat release analysis, particularly for mass burned fractions of less than 50%. Figure 21 is an example of the Mass Fraction Burned (MFB) results from this approximate heat release computation. The slope of the MFB curve is also presented since it is a measure of the heat release rate, and thus indicative of the flame speed for the charge. A more detailed discussion of the meaning of this information is contained in the following section.

D. CORRELATION OF CYCLE ANALYSIS AND ENGINE PERFORMANCE

The Mass Fraction Burned (MFB) rate provides an indicator for changes in the combustion process. For this reason, it was anticipated that examination of the MFB rates would provide some explanation of the observed engine performance for Lean Supercharged Operation. Because MFB rate varies

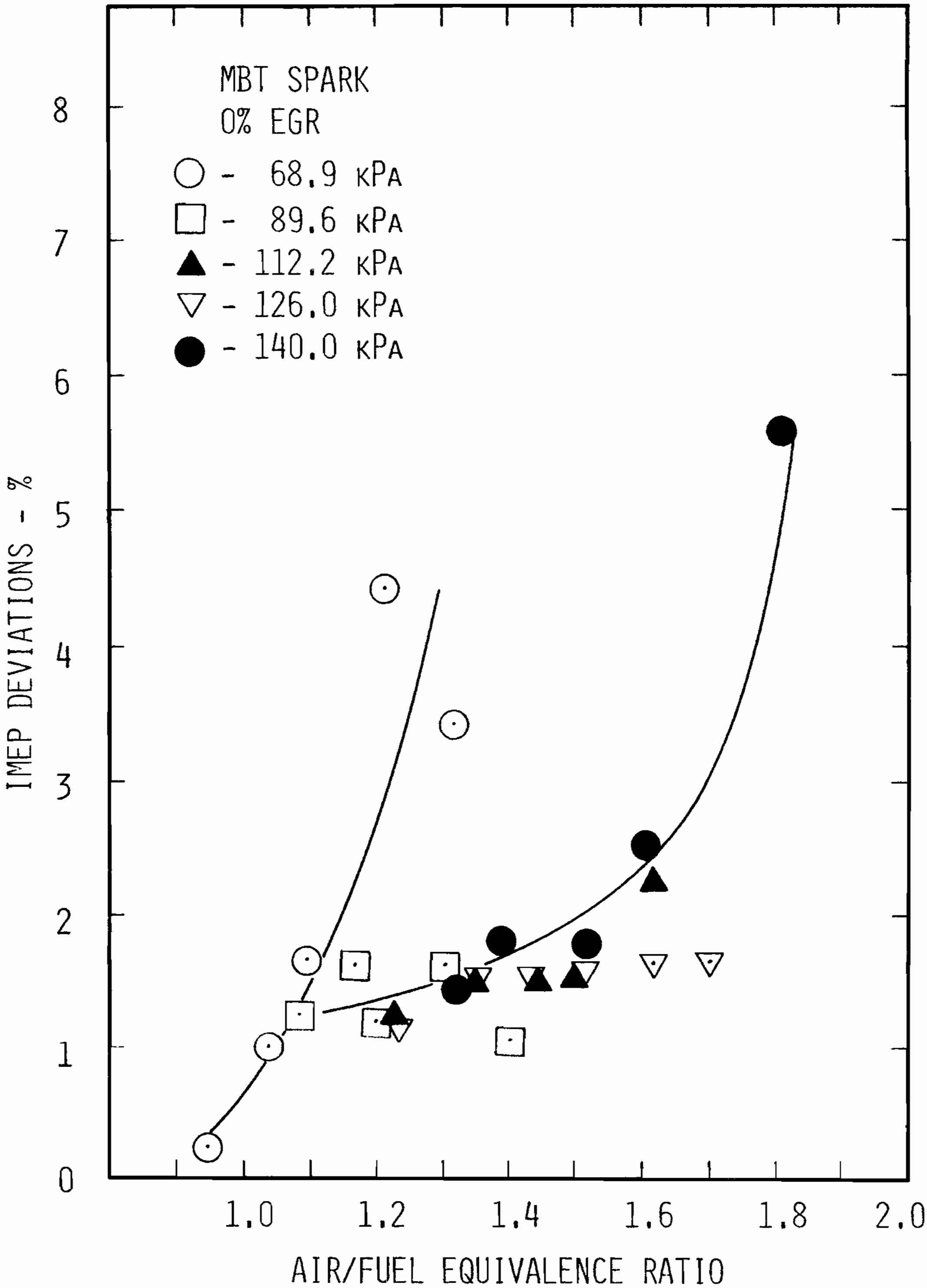

Figure 20. Influence of Equivalence Ratio on IMEP Deviations

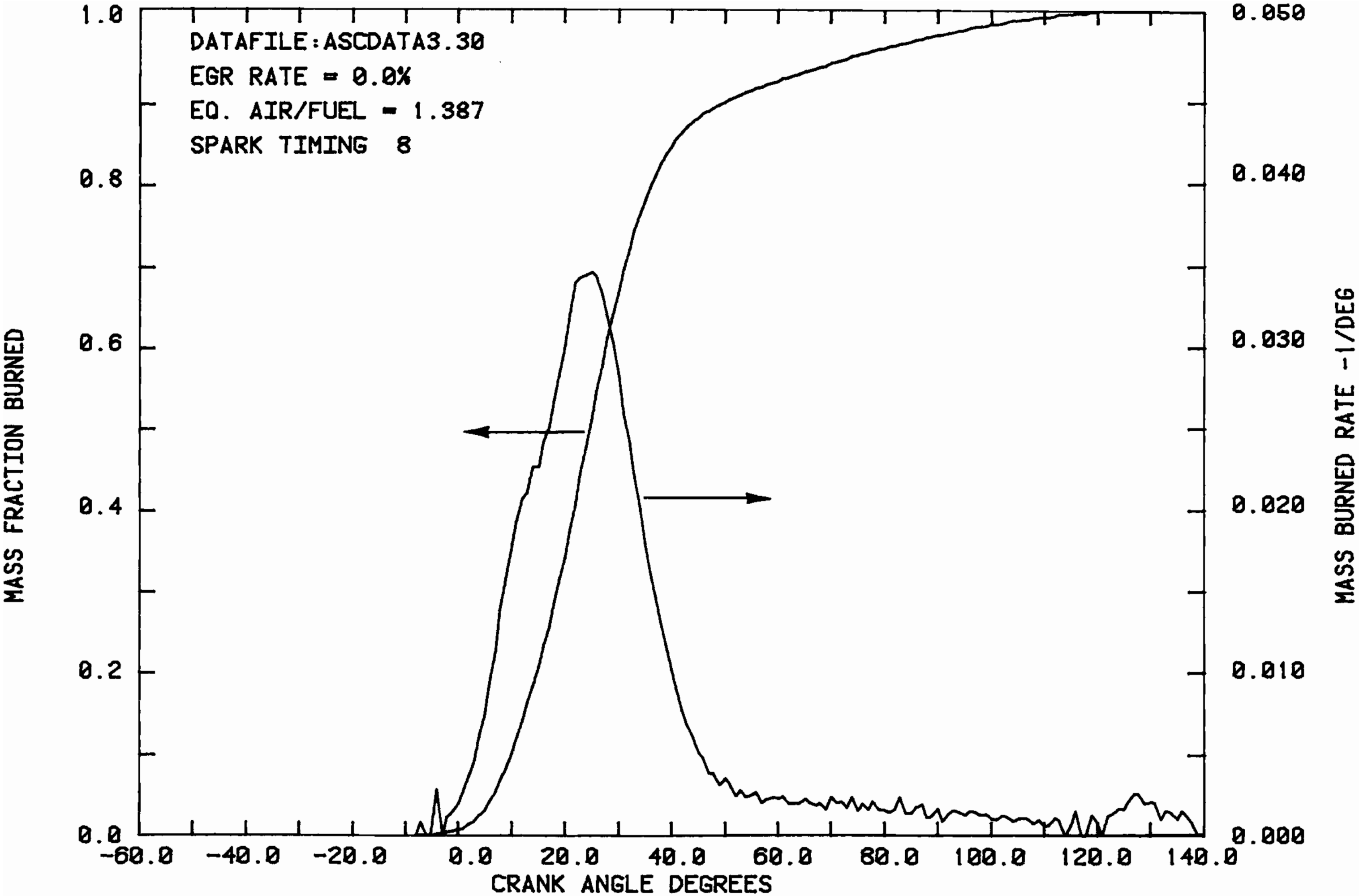

Figure 21. Typical Mass Fraction Burned and Mass Burned Rate Plots

continuously as a function of crankshaft rotation, arbitrary single point for comparisons was selected. The point chosen was the MFB rate that corresponded to a Mass Fraction Burned of 25%. This choice was based upon the fact that the approximate heat release calculation used was known to be reasonably accurate for MFB's less than 50%. Also, this choice was at a point where the flame is fully established and partial burns and wall quenching effects should be minimal. Figure 22 shows the influence of air/fuel equivalence ratio and supercharge conditions on the MFB rate at the 25% MFB point. The conditions presented in this figure are for MBT spark timing and no EGR flow.

The trends demonstrated in figure 22 are those anticipated from the inception of this program and from the engine performance data. Basically, the MFB rate decreases with increasing $\emptyset_{AF}$, a condition expected due to the slower flame speeds associated with lean combustion. However for a fixed value of $\emptyset_{AF}$, the MFB rate increases with increased intake manifold pressure. This is a clear sign that the increased charge density at the supercharged condition is contributing to increased flame speed. This conclusion is reinforced by both spark timing and efficiency data. Figure 6, in section IV-A illustrates that increased intake manifold pressure at a fixed value for $\emptyset_{AF}$, reduces the spark advance needed for MBT conditions. This effect implies a more rapid combustion process near piston TDC, or increased flame speed. Since the increased flame speed allows more of the combustion process to take place near piston TDC, more energy should be extracted during the expansion process and improved thermal efficiency should result. Figure 5 in section IV-A shows that the thermal efficiency is indeed improved as intake manifold pressures are increased at constant $\emptyset_{AF}$.

In figure 22, the data for the 140 kPa intake manifold pressure do not follow the general trend in increasing the

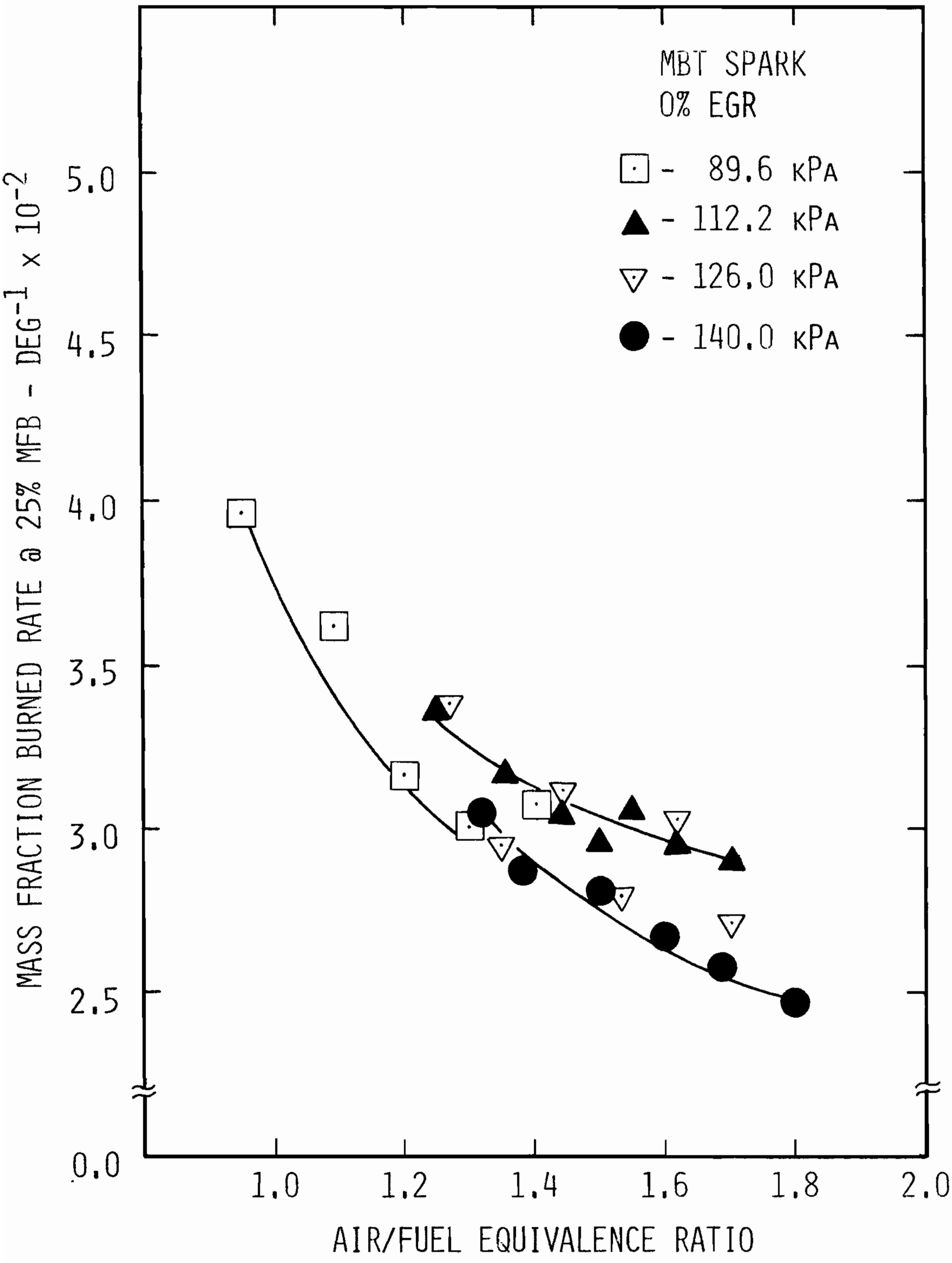

Figure 22. Burn Rates at 25% Mass Fraction Burned

MFB rate. This discrepancy can be attributed to the fact that virtually all the data at the 140 kPa test condition were taken at knock limited, rather than MBT spark conditions. The effects due to this retarded spark timing are also noted in section IV-A for figure 5 and 6. It should also be noted that the data for operation with EGR flow and/or 5% P.L. spark timing show decreases in the MFB Rate and comparable changes in engine efficiency.

One additional trend that should be noted from figure 22 is that the increased charge density due to supercharging allows extension of the lean operation limits. The data in this figure clearly show that the engine is operating at significantly lower MFB rates for Lean Supercharged Operation than are possible for the naturally aspirated engine.

V. CONCLUSIONS

The results of this experimental study of Lean Supercharged Operation of a spark ignition engine have been positive. Many of the assumptions made concerning how supercharged operation with lean mixtures would influence efficiency and emissions have been verified. Specific conclusions are as follows:

1. Brake Power - Increases in the brake power output were obtained for supercharged operation, even at very lean operating conditions. The power available from the lean supercharged engine was at least equal to that available from the naturally aspirated engine. For the more realistic operating conditions, the power output from the lean supercharged engine was greater than that from the naturally aspirated engine.

2. Engine Efficiency - One of the major incentives for examining Lean Supercharged Operation of the spark ignition engine was the potential for increased engine efficiency. The results from this single cylinder engine test program indicate that, if the engine is operated at high intake manifold pressure conditions, significant increases in engine efficiency are possible. These gains are particularly impressive for conditions that have equal NO_x emissions rates, as illustrated in figure 23.

3. HC and CO Emissions - The HC and CO emissions produced by the singly cylinder engine operating at lean supercharged conditions were comparable to those for the naturally aspirated engine operating at normal lean air/fuel ratios. As expected, CO emissions were primarily a function of the air/fuel

equivalence ratio. HC emissions were a function of both the equivalence ratio and the intake manifold pressure for supercharged operation. Greater supercharge (increased manifold pressure) reduced BSHC emissions. Generally, operation at lean supercharged conditions produced CO and HC emissions that were comparable to or less than the naturally aspirated engine operating at nominal lean conditions. Figure 23 demonstrates this effect for operation at equal NO_x levels.

4. NO_x Emissions - The second major incentive for examining Lean Supercharged Operation of the spark ignition engine was the potential for a reduction in NO_x emissions at lean operating conditions. The results of this program have clearly shown that, for MBT spark timing and fixed EGR flow, operation at lean supercharged conditions ($\phi_{AF}>1.4$) provides greatly reduced NO_x emissions at high engine efficiency. This fact is illustrated in figure 24 for equal engine power levels.

5. Exhaust Energy - One of the major concerns of simulating lean turbocharged operation with a single cylinder engine was that conditions not representative of turbocharger operation might be used, leading to erroneous conclusions. The exhaust energy studies performed at the lean supercharged conditions selected for testing indicate that sufficient exhaust energy is available to power a typical automotive type turbocharger.

6. Combustion Analysis - The analysis of the pressure-crank angle data to gain information as to how Lean Supercharged Operation influences combustion was very useful. The Mass Fraction Burned rates confirmed that supercharging at lean conditions

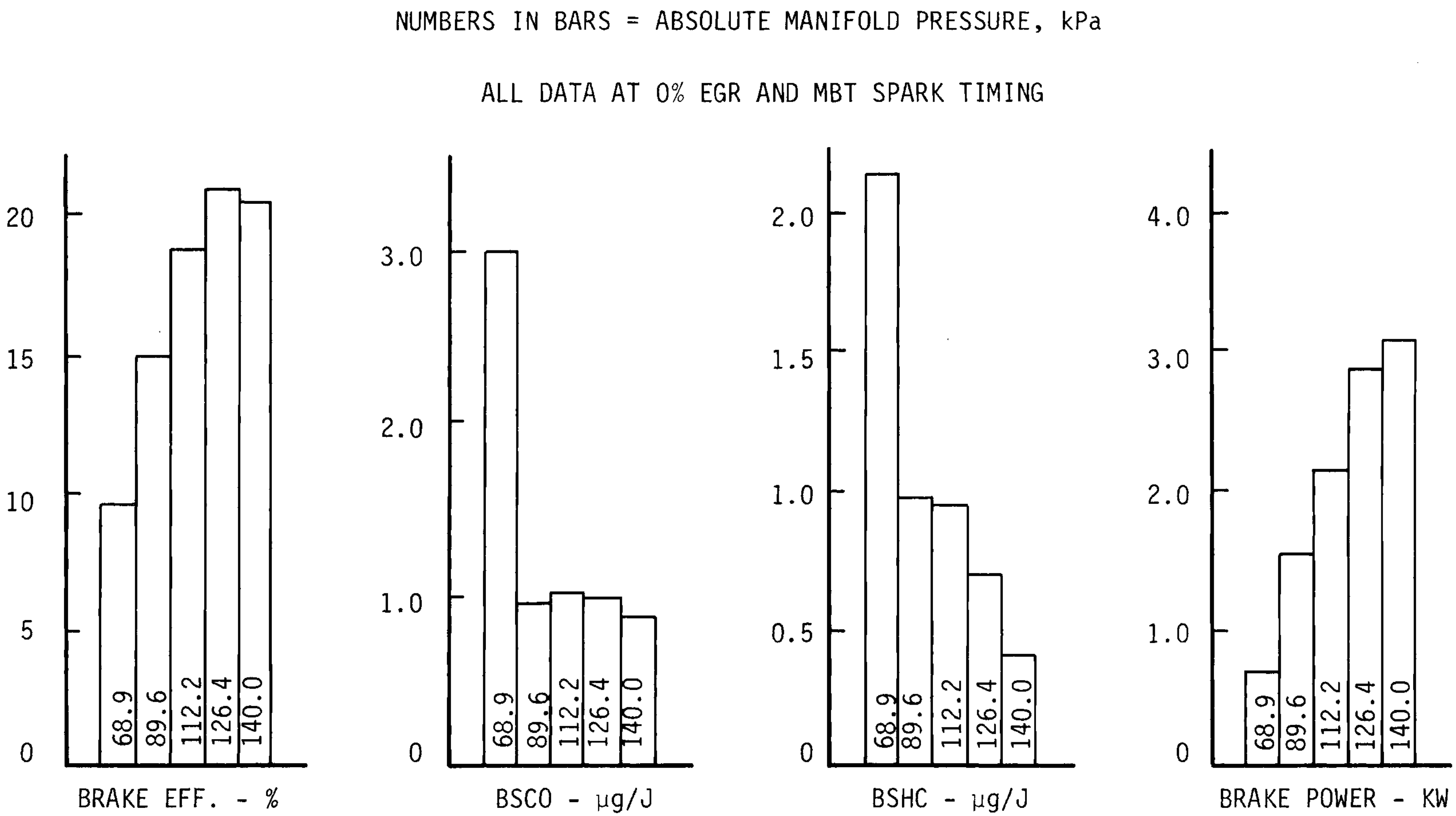

Figure 23. Comparison of Naturally Aspirated and Lean Supercharged Engines at Constant $BSNO_x$ = 13 µg/J

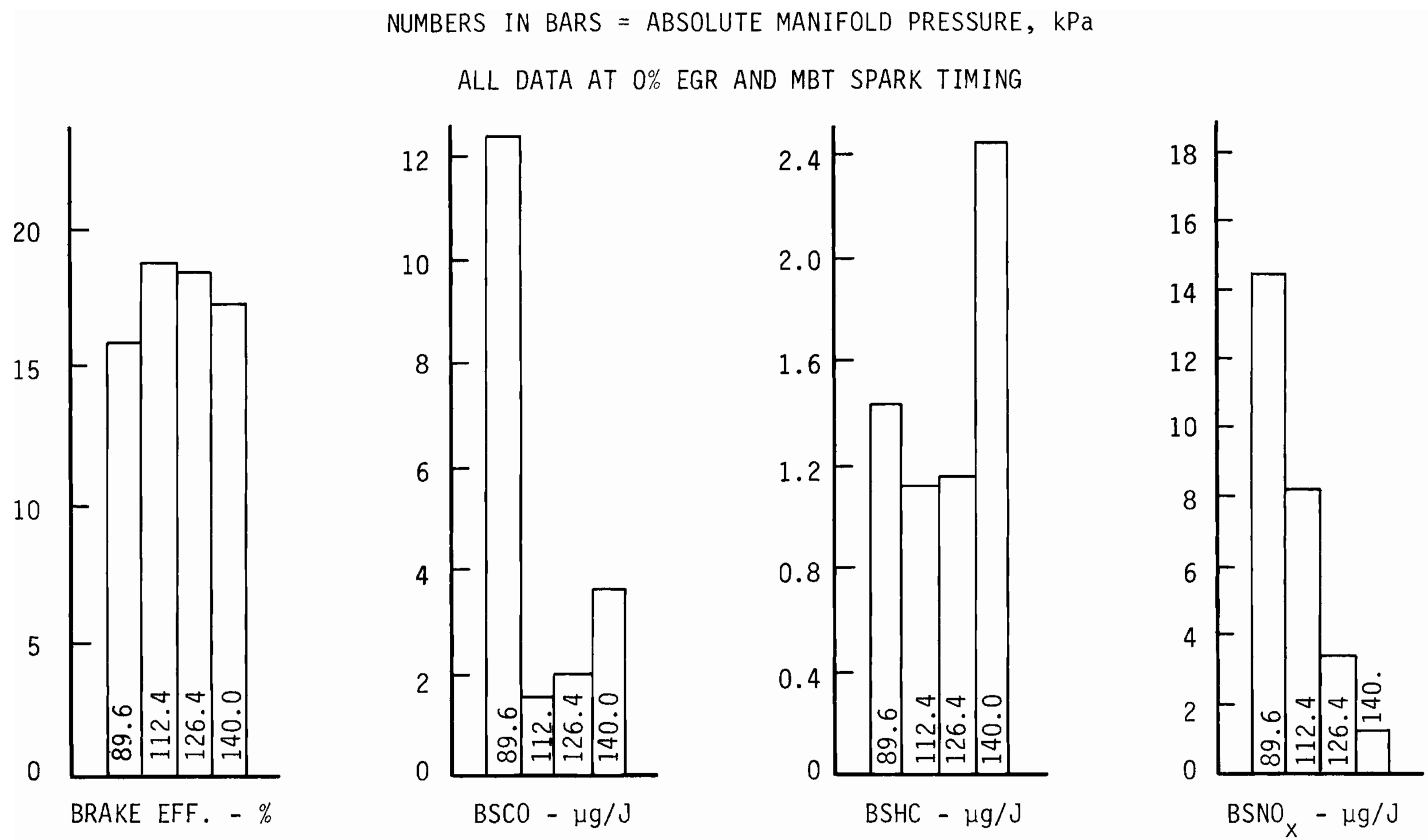

Figure 24. Comparison of Naturally Aspirated and Lean Supercharged Engines at Constant Power = 2.0 Kw

improves the flame speed, probably due to increased charge density. This conclusion was reinforced by the behavior of spark advance and efficiency data for the lean supercharged conditions.

Lean Supercharged Operation of the spark ignition engine has the potential of improved efficiency and reduced NO_x emissions when the operational range of the engine utilizes the higher intake manifold pressures. The combustion process it improved and the lean misfire limits are extended with Lean Supercharged Operation. HC and CO emissions are not greatly changed by operation at realistic lean supercharged conditions.

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VITA

Kenneth Robert Schmid was born on April 13, 1957 in Kansas City, Missouri. He obtained his primary and secondary education in the Center School District in Kansas City, Missouri. He performed his undergraduate studies at the University of Missouri-Rolla. He received a Bachelor of Science degree in Mechanical Engineering from the University of Missouri-Rolla in May 1979. He enrolled in Graduate School at the University of Missouri-Rolla in May 1979. Class work and experimental work were completed in August 1980. He has been employed, since September 1980, by the Mechanical Engineering Department at the University of Missouri-Rolla as a Research Specialist working on the undergraduate laboratories and performing research for Dr. R.T. Johnson.

APPENDICES

APPENDIX A

DETERMINATION OF MBT SPARK TIMING FOR SINGLE CYLINDER ENGINE

The following empirical technique was used to determine MBT spark timing: The spark timing was incremented in 2 degree intervals over a 10 to 12 degree range in the region where MBT spark timing was thought to exist. Dynamometer scale force and spark advance were recorded for each increment. A motoring run was performed to determine the motoring dynamometer scale force for the engine. A graph of the spark timing scale force was constructed from these data. (A more rigorous technique would use indicated power instead of scale force. However, with the test conducted at constant speed, the indicated power and scale force were directly proportional). Figure 25 is a typical graph for these data. Using the peak firing force to determine a 99% indicated force term. This 99% indicated force point was located on the graph and the associated spark advance noted. The MBT spark timing was arbitrarily set equal to this crank angle plus 5 degrees.

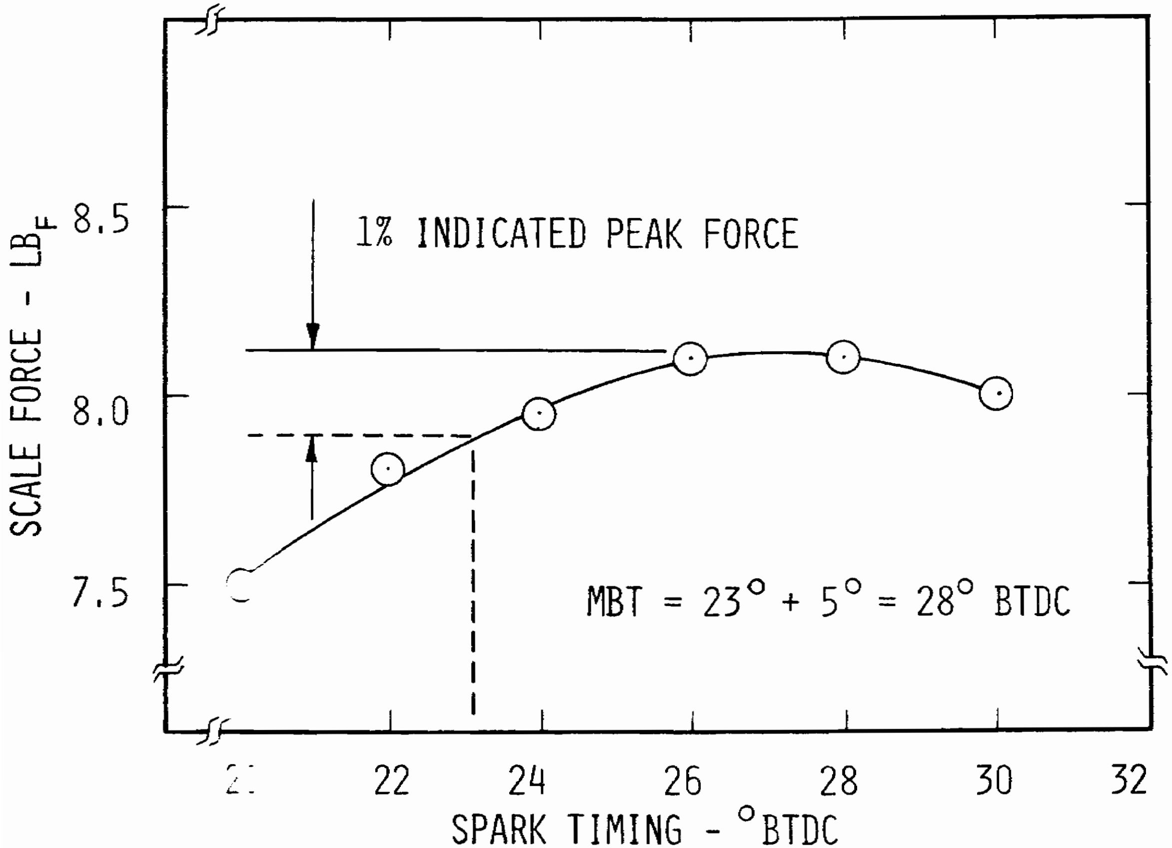

Figure 25. Scale Force as a Function of Spark Advance

APPENDIX B

EXHAUST GAS RECIRCULATION CALCULATION

The exhaust gas recirculation (EGR) rate was determined by a Carbon Dioxide Tracer Technique described by Wiers and Scheffler (22). The equation development to determine the percent EGR follows:

Nomenclature:

a	Moles of exhaust CO_2 in intake manifold
b	Moles of exhaust H_2O in intake manifold
c	Moles of exhaust O_2 in intake manifold
d	Moles of exhaust N_2 in intake manifold
ECO_2	Measured exhaust carbon dioxide (dry)
ICO_2	Measured intake carbon dioxide (dry)
m	Mass of constituent
M	Moles of constituent

Subscripts:

A	Air
E	Exhaust
F	Fuel
I	Intake manifold

The percent EGR was defined as:

$$\%\ EGR = \frac{\text{(moles exhaust in intake charge)}}{\text{(Total moles in intake charge)}} \times 100 \qquad \text{(B-1)}$$

Which can be written as:

$$\%\ EGR = \frac{M_E}{M_E + M_A + M_F} \times 100 \qquad \text{(B-2)}$$

The molar chemical description of the engine intake charge, including EGR, can be written in the following terms:

$$(M_F)CH_yO_x+(a)CO_2+(b)H_2O+(c)O_2+(d)N_2+z(O_2+3.76N_2) \quad \text{(B-3)}$$

where: z = moles O_2 in air/fuel mixture.

The moles of intake charge can be expressed as:

$$M_I = a + b + c + d + 4.76z + M_F \quad \text{(B-4)}$$

The measured intake CO_2, on a dry molar basis, is:

$$ICO_2 = \frac{a}{a + c + d + 4.76z} \quad \text{(B-5)}$$

Substituting equation B-5 into equation B-4 yields an expression for the moles of intake charge.

$$M_I = \frac{a}{ICO_2} + b + M_F \quad \text{(B-6)}$$

Assuming that the measured (dry) exhaust CO_2 can be expressed as:

$$ECO_2 \doteq \frac{a}{a + c + d}, \quad \text{(B-7)}$$

an expression for the moles of exhaust in the intake charge can be determined:

$$M_E = \frac{a}{ECO_2} + b \quad \text{(B-8)}$$

From equations B-1, B-6, and B-8:

$$EGR = \left(\frac{ICO_2}{ECO_2}\right) \cdot \frac{1 + (b/a)\ ECO_2}{1 + (b/a)\ ICO_2 + (M_F/a)\ ICO_2} \quad \text{(B-9)}$$

In this equation, ICO_2 and ECO_2 are the measured quantities and (b/a) and (M_F/a) must be evaluated before EGR can be determined. If ideal combustion is assumed, the reaction of a typical hydrocarbon fuel can be written in the form:

$$CH_yO_x + z(O_2 + 3.76N_2) \longrightarrow \qquad \text{(B-10)}$$

$$CO_2 + (y/2)\,H_2O + (3.76z)\,N_2 + (z - 1 - y/4 + x/2)O_2.$$

The reaction products are the engine exhaust. The molar ratio of H_2O to CO_2 in the exhaust should be the same as the molar ratio of H_2O to CO_2 in the exhaust gases in the intake manifold due to EGR. Therefore:

$$b/a = y/2. \qquad \text{(B-11)}$$

In the ideal combustion equation, B-10, one mole of fuel is assumed. Thus,

$$M_F = 1. \qquad \text{(B-12)}$$

In order to use equation B-9 to calculate EGR, the moles of exhaust CO_2 in the intake manifold, a, must be found. The quantity, a, can be expressed as:

$$a = \left(\frac{\text{moles of } CO_2 \text{ in Exhaust}}{\text{Total moles of Exhaust}}\right) \cdot M_E, \qquad \text{(B-13)}$$

For the one mole of fuel assumed in equation B-10, one mole of CO_2 will be produced in the exhaust. Also, the total moles of exhaust can be taken from the products in equation B-10, yielding:

$$a = \left(\frac{1}{1 + y/4 + x/2 + 4.76z}\right) \cdot M_E. \qquad \text{(B-14)}$$

Noting that

$$M_A = 4.76z,$$

equation B-14 can be expressed:

$$a = \left(\frac{1}{1 + y/4 + x/2 + M_A}\right) \cdot M_E. \qquad \text{(B-15)}$$

In order to evaluate a using this relationship, M_A and M_E must be determined. Taking the expression for air/fuel ratio (A/F),

$$A/F = \frac{M_A}{M_F} \bullet \frac{\text{molecular wt. of air}}{\text{molecular wt. of fuel}}, \qquad \text{(B-16)}$$

and rearranging it with the substitution of appropriate molecular weights yields:

$$M_A = (A/F) \left(\frac{12.01 + 1.008y + 16.0x}{28.96}\right). \qquad \text{(B-17)}$$

Since A/F can be found from the measured exhaust constituents and y and x for the given fuel are known, equation B-17 can be used to evaluate M_A. In order to find M_E, equation B-2 can be expressed for EGR in decimal form as follows:

$$EGR = \frac{M_E}{M_E = M_A + M_F}. \qquad \text{(B-18)}$$

Since M_F is taken as one and M_A can be found using equation B-17, M_E can be expressed as:

$$M_E = \frac{EGR\ (1 + M_A)}{(1 - EGR)}. \qquad \text{(B-19)}$$

Substitution of B-19 into B-15 gives the following expression for a:

$$a = \frac{EGR\ (1 + M_A)}{(1 - EGR)\ (1 + y/4 + x/2 + M_A)} \tag{B-20}$$

Using M_A from equation B-17, equation B-20, and b/a = y/2 in equation B-9, EGR can be evaluated. Since EGR must be known in order to evaluate a, an interactive process is used to compute EGR starting with a value EGR = ICO_2/ECO_2. The iteration is continued until the value of EGR changes less than 0.001.

APPENDIX C

COMPRESSOR AND TURBINE POWER CONSIDERATIONS FOR TURBOCHARGING

From the initiation of this program, one of the objectives was to examine the limits of Lean Supercharged Operation due to insufficient recoverable exhaust energy for operating a turbocharger. The basic problem was to insure that the energy in the exhaust gases was sufficient to drive a single shaft turbine and compressor, with appropriate efficiencies, such that the compressor output would supply the needed intake engine mass flow. The engine test conditions, discussed in section IV-F and listed in table II, were selected to simulate the addition of a turbocharger by adjusting both the intake manifold conditions and the exhaust pressure.

A computer program entitled ENERGY was written to perform two sets of calculations in evaluating the potential for exhaust turbocharging. One set of calculations was used to determine the power necessary to operate a compressor to obtain the desired LSO. This calculation was performed for two compressor inlet pressures to determine the power needed for locating the compressor either upstream or downstream of the throttle plate(s). The second set of calculations was used to estimate the possible exhaust turbine output. This calculation was performed at three turbine efficiencies; 50%, 75%, and 85%, to bracket reasonable operating regions. The general equations and constants used to compute the exhaust turbine power available and the compressor power required are given by Taylor (23). The following equations and information were drawn from this source.

Nomenclature:

C_p = Specific heat at constant pressure

k = Ratio of specific heats

M = Mass flow rate through device

P = Absolute pressure

T = Absolute temperature

η = Efficiency

Subscripts:

1 = Inlet
2 = Outlet
c = Compressor
e = Exhaust
I = Intake
t = Turbine

Constants:

C_{PE} = 1.128 kJ/kg °K
C_{PI} = 1.003 kJ/kg °K
J = 2390 CAL/kJ
k_E = 1.343
k_I = 1.40

The power required to drive the compressor can be written:

$$P_c = J \dot{M}_c C_{PI} T_1 Y_c / \eta_c \tag{C-1}$$

Where:

$$Y_c = \left(\frac{P_2}{P_1}\right)^{\frac{k_I - 1}{k_I}} - 1 \tag{C-2}$$

The available power from the exhaust turbine can be written:

$$P_t = J \dot{M}_t C_{PE} T_1 Y_t \eta_t \tag{C-3}$$

Where:

$$Y_t = 1 - \left(\frac{P_2}{P_1}\right)^{\frac{k_E - 1}{k_E}} \tag{C-4}$$

APPENDIX D

COMPUTER PROGRAM LISTINGS

Comment statements were used in each individual program to provide necessary and useful program documentation. The first part of each program listing includes: a brief description of the program function, author(s), loading information, and variable name nomenclature. The following is a number system used for program statement numbers.

0 - 99	Program Branching
100 - 299	Do Loops
300 - 399	Format Statements for console input
400 - 499	Format Statements for program printed output
500 - 599	Format Statements for file input/output
600 - 699	Format Statements for plotter
700 - 799	Format Statements for line printer control

LISTING OF COMPUTER PROGRAMS

```
C ****** CAPLOT.FR ***********************************************
C
C THIS PROGRAM IS DESIGNED TO PLOT PRESSURE VS. CRANK ANGLE
C INFORMATION FROM A FILE CONTAINING VOLTS (PRESSURE) -
C CRANK ANGLE DATA.
C
C AUTHOR:        R. T. JOHNSON
C                MECHANICAL ENGINEERING DEPARTMENT
C                UNIVERSITY OF MO - ROLLA
C                ROLLA, MO 65401
C                (314) 341 4661
C
C                K. R. SCHMID
C                MECHANICAL ENGINEERING DEPARTMENT
C                UNIVERSITY OF MISSOURI - ROLLA
C                ROLLA, MO 65401
C
C REVISION HISTORY:
C                12/2/80 - CREATED ORIGINAL FROM PVPLOT.FR
C                12/4/80 - DEVIATION PLOTTING ADDED
C
C
C LOADING INFORMATION
C
C       RLDR CAPLOT SHIFT GRID VECTR.LB FORT.LB
C
C DEFINITIONS:
C
C       BORE    = ENGINE BORE (IN.)
C       CALB    = CALIBRATION FACTOR (PSI/VOLT)
C       CR      = COMPRESSION RATIO
C       DFILE   = FILENAME OF DEVIATION DATA FILE
C       IFILE   = FILENAME OF PRESSURE DATA
C       PREF    = REFERENCE PRESSURE
C       PRES    = CALIBRATED PRESSURE DATA
C       R       = ENGINE CRANK THROW (IN.)
C       RL      = CONNECTING ROD LENGTH (IN.)
C
C *****************************************************************
        DIMENSION IFILE(10),IHEADR(40),IDATA(720),VOLT(720)
        DIMENSION DFILE(10),JHEADR(40),IDEV(720)
        COMMON /PDATA/ PRES1(720,2),PRES(720,2)
C
        MCURVE = 0
        CALB = 91.274
        BORE = 3.250
        R = 2.250
        RL = 10.0
        CR = 8.0
C
10      CONTINUE
        WRITE(10,400)
400     FORMAT(/,1X," INPUT FILE :",Z)
        READ(11,300) IFILE(1)
        CALL FOPEN(0,IFILE)
        READ BINARY (0) IHEADR,ICYCLE
300     FORMAT (S18)
        WRITE(10,401)
401     FORMAT(/,1X," ABSOLUTE REFERENCE PRESSURE (KPA) : ",Z)
        READ(11,301) PREF
301     FORMAT(F6.2)
        WRITE(10,402)
402     FORMAT(/,1X," PRESSURE SHIFT (DEGREES) :",Z)
        ACCEPT JDEG
        WRITE(10,403)
403     FORMAT(/,1X," PLOT CRANK ANGLE 180-540 DEGREES
     & (1-YES;0-NO) ",Z)
        ACCEPT ICA
```

```
      ICA = ICA+1
      WRITE(10,404)
404   FORMAT(/,1X," PLOT DEVIATION DATA ?(1-YES;0-NO) ",Z)
      ACCEPT IPLOT
      IF(IPLOT.EQ.0)GO TO 15
      WRITE(10,405)
405   FORMAT(/,1X," DEVIATION FILENAME :",Z)
      READ(11,300)DFILE(1)
      CALL FOPEN(1,DFILE)
      READ BINARY (1) JHEADR,JCYCLE
      WRITE(10,410)JHEADR(1),JCYCLE
      JCYCLE=1
      NUM=1
      GO TO 16
C
C ***** WRITE FILE HEADER AND DESCRIPTIVE INFORMATION *****
C
15    CONTINUE
      WRITE(10,410) IHEADR(1),ICYCLE
410   FORMAT(/,10X,S78,//,10X,I2," CYCLES RECORDED")
      WRITE(10,411)
411   FORMAT(/,1X," NUMBER OF CYCLE TO BE PLOTTED = ? ",Z)
      ACCEPT JCYCLE
      WRITE(10,412)
412   FORMAT(/,1X," NUMBER OF CYCLES TO BE PLOTTED = ",Z)
      ACCEPT NUM
16    TYPE " "
      TYPE" READING DATA FILE"
C
C ***** READ AND SCALE PRESSURE DATA ****
C
      FACTOR = (CALB/3276.6)*6.895
      NCYCLE = JCYCLE-1
      DO 100 J=1,NCYCLE
      DO 110 I=1,720
      READ BINARY(0) IDATA(I)
110   CONTINUE
100   CONTINUE
      DO 112 KK=1,NUM
      DO 115 I=1,720
      READ BINARY(0) IDATA(I)
      PRES(I) = FLOAT(IDATA(I))
      PRES(I) = (PRES(I)-310.)*FACTOR
115   CONTINUE
      PRESC = PRES(180)-PREF
      DO 120 I=1,720
      PRES(I) = PRES(I)-PRESC
120   CONTINUE
C
      IF(KK.GT.1)GO TO 11
C
      WRITE(10,420)
420   FORMAT(//,1X," ****** TURN ON PLOTTER ***** ",/)
      PAUSE
C
      IF(MCURVE.EQ.1)GO TO 11
C
C ***** DRAW GRID *****
C
      WRITE(10,600)
600   FORMAT(1X,"(33)CI 40 75 ")
      GO TO(30,40)ICA
30    CALL GRID(0.0,720.0,180.0,1,0.0,5000.0,1000.,1,150,
     &900,130,730,1,1)
      GO TO 50
40    CALL GRID(180.0,540.0,90.0,1,0.0,5000.0,1000.0,1,150,
     &900,130,730,1,1)
50    CONTINUE
C
      CALL ANMDE(580,670)
```

```
      WRITE(10,610)IFILE(1)
610   FORMAT(1X,"INPUTFILE: ",S18)
      CALL ANMDE(580,640)
      WRITE(10,611)PREF
611   FORMAT(1X,"MANIFOLD PRESS. (KPA) ",F8.2)
      CALL ANMDE(430,75)
      WRITE(10,612)
612   FORMAT(1X,"CRANK ANGLE DEGREES")
      WRITE(10,613)
613   FORMAT(1X,"(33)CJ 90 ")
      CALL ANMDE(50,275)
      WRITE(10,614)
614   FORMAT(1X,"PRESSURE (KPA)")
      WRITE(10,615)
615   FORMAT(1X,"(33)CJ 0")
11    CONTINUE
C
C
C ***** READ AND SCALE DEVIATION DATA *****
C
      IF (IPLOT.EQ.0)GO TO 22
      DO 130 I=1,720
      READ BINARY(1) IDEV(I)
      PRES(I,2) =(FLOAT(IDEV(I)))/32767.0
      PRES(I,2) = PRES(I,2)*PRES(I,1)
130   CONTINUE
22    CONTINUE
C
      CALL SHIFT(JDEG)
      GO TO(35,45)ICA
C
C
C ***** PLOT PRESSURE VS. CRANKANGLE DATA *****
C
35    CALL DPORT(150,900,130,730,0.0,720.0,0.0,5000.0)
      ISTART = 2
      ISTOP = 720
      PRES2 = PRES(1,1)
      CALL MOVEA(0.0,PRES2)
      GO TO 55
45    CALL DPORT(150,900,130,730,180.0,540.,0.0,5000.0)
      ISTART = 181
      ISTOP = 540
      PRES2 = PRES(180,1)
      CALL MOVEA(180.0,PRES2)
55    CONTINUE
      DO 140 I=ISTART,ISTOP
      K = I-1
      CA = FLOAT(K)
      PRESY=PRES(I,1)
      CALL DRAWA(CA,PRESY)
140   CONTINUE
      IF(IPLOT.EQ.0)GO TO 25
C
C ***** PLOT (+) DEVIATION FROM THE AVERAGE PRESSURE DATA *****
C
      YDATA = PRES(180,1)+PRES(180,2)
      CALL MOVEA(180.0,YDATA)
      DO 150 I=180,540
      K=I-1
      CA=FLOAT(K)
      YDATA = PRES(I,1)+PRES(I,2)
      CALL DRAWA(CA,YDATA)
150   CONTINUE
C
C ***** PLOT (-) DEVIATION FROM THE AVERAGE PRESSURE DATA *****
C
      YDATA = PRES(180,1)-PRES(180,2)
      CALL MOVEA(180.,YDATA)
      DO 160 I=180,540
```

```
      K = I-1
      CA = FLOAT(K)
      YDATA = PRES(I,1)-PRES(I,2)
      CALL DRAWA(CA,YDATA)
160   CONTINUE
C
25    CONTINUE
112   CONTINUE
      CALL MVABS(150,130)
      REWIND 0
      CALL FCLOS(0)
      IF(IPLOT.EQ.0)GO TO 60
      REWIND 1
      CALL FCLOS(1)
60    CONTINUE
      CALL MVABS(0,0)
      WRITE(10,601)
601   FORMAT(1X,"(33) CN")
      CALL ANMDE(0,0)
      ACCEPT FAKE
C *** STOP TO TURN OFF PLOTTER ***
C *** HIT RETURN TO COMPLETE PROGRAM ****
      WRITE(10,430)
430   FORMAT(1X," PLOT A SECOND CURVE ? (NO-0,YES-1)",Z)
      READ(11,330)MCURVE
330   FORMAT(I1)
      IF(MCURVE.EQ.1)GO TO 10
      WRITE(10,431)
431   FORMAT(/,1X," REPEAT PROGRAM ? (NO-0,YES-1)",Z)
      READ(11,331)NCON
331   FORMAT(I1)
      IF (NCON.EQ.0)GO TO 13
      WRITE(10,440)
440   FORMAT(1X,"(33)(14)")
      GO TO 10
13    CONTINUE
      STOP
      END
```

```
C ***** CFRCALC.FR ******************************************************
C
C       DATA REDUCTION PROGRAM FOR SINGLE CYLINDER ENGINE DATA.
C
C AUTHOR:          R.T. JOHNSON
C                  MECHANICAL ENGINEERING DEPARTMENT
C                  UNIVERSITY OF MISSOURI - ROLLA
C                  ROLLA, MO 65401
C                  (314) 341 4661
C
C                  K.R. SCHMID
C                  MECHANICAL ENGINEERING DEPARTMENT
C                  UNIVERSITY OF MISSOURI - ROLLA
C                  ROLLA, MO 65401
C
C
C REVISION HISTORY:
C
C                   4/15/79 - CREATED ORGINAL
C                  12/10/79 - REVISED FOR LEAN SUPERCHARGE STUDY
C                  07/12/81 - SUBROUTINE EGR ADDED
C
C
C LOADING INFORMATION:
C
C                  RLDR CFRCALC EGR FORT.LB
C
C
C
C NOMENCLATURE:
C
C       AFLOW = MASS OF AIR FLOW,LB/MIN
C       AFS =   STOICHIOMERTIC A/F
C       BFUEL = BASE FUEL NAME, 8 CHARACTERS
C       BPRES = BAROMETRIC PRESSURE, IN.HG.
C       BRFR =  BEAM FORCE WHEN FIRING,LB
C       BTEMP = BAROMETRIC TEMPERATURE,F
C       CO =    CARBON MONOXIDE,%
C       CO2 =   CARBON DIOXIDE,%
C       CR =    COMPRESSION RATIO
C       EFF =   INDICATED OR BRAKE EFFICIENCY
C       FUFL =  MASS FUEL FLOW, LB/MIN
C       HC =    HYDROCARONS, PPM (PROPANE)
C       IKW =   INDICATED OR BRAKE POWER, KW
C       ISCO =  INDICATED OR BRAKE SPECFIC CO, UGM/J
C       ISFC =  INDICATED OR BRAKE SPECIFIC FUEL CONSUMPTON, GM/KJ
C       ISHC =  INDICATED OR BRAKE SPECIFIC HC, UGM/J
C       ISNO =  INDICATED OR BRAKE SPECIFIC NOX, UGM/J
C       LHV =   LOWER HEATING VALUE OF FUEL, BTU/LBM
C       MCO2 =  INTAKE MANIFOLD CO2, %
C       MPRES = INTAKE MANIFOLD PRESSURE, KPA
C       MTEMP = INTAKE MANIFOLD TEMPERATURE, DEG F
C       MTRFR = MOTORING BEAM FORCE, LB
C       NOX =   OXODES OF NITROGEN, PPM
C       NOZZLE =        NOZZLE NUMBER
C       NPRES = CRITICAL FLOW NOZZLE PRESSURE, PSIG
C       NTEMP = CRITICAL NOZZLE TEMPERATURE, DEG F
C       O2 =    OXYGEN, %
C       OTEMP = OIL TEMPERATURE, DEG F
C       PHIC =  CARBON BASED A/F EQUIVALENCE RATIO
C       PHIO =  OXYGEN BASED A/F EQUIVALENC RATIO
C       PHIX =  EXPERIMENTAL A/F EQUIVALENCE RATIO
C       RPM =   ENGINE SPPED, RPM
C       RUNNO = RUN NUMBER, 8 DIGIT NUMBER, 1ST 6 DIGITS = MO/DAY/YEAR
C               LAST 2 DIGITS = RUN FOR DAY
C       SG =    SPECIFIC GRAVITY OF FUEL, FM/ML
C       SPKT =  SPARK TIMING, DEG BTDC, ENTER DATA IN WHOLE DEGREE IDENTIFY
C               MBT BY ADDING DECIMAL > 0.10. EXAMPLE: 31.5 INDICATES MBT
C               SPARK TIMING OF 31 DEGREES.  20.0 = NON MBT SPARK TIMING
```

```
C              OF 20 DEGREES.
C       WTEMP = COOLANT TEMPERATURE, DEG. F
C       XTEMP = EXHAUST TEMPERATURE, DEG F
C       XPRES = EXHAUST PRESSURE, KPA
C       X =     MOLAR O/C RATIO OF FUEL
C       Y =     MOLAR H/C RATIO OF FUEL
C
C  FORMAT FOR DATA ENTRY INTO FILE SCD-:
C
C       BFUEL
C
C       LHV,AFS,Y,X,SG,CR,RPM,MPRES,MTEMP,OTEMP,WTEMP,XPRES,NOZZLE
C       RUNNO,BPRES,BTEMP,NPRES,NTEMP,FUFL,SPKT,BKFR,MTRFR
C       HC,NOX,CO2,CO,O2,MCO2,XTEMP
C       RUNNO,BPRES,PTEMP,NPRES,NTEMP,FUFL,SPKT,BKFR,MTRFR
C       HC,NOX,CO2,CO,O2,MCO2,XTEMP
C       0.,0.,0.,0.,0.,0.,0.,0.,0.
C
C       (ZEROS ARE PLACED AT END OF FILE AS END OF FILE INDICATORS)
C
C *****************************************************************
        DIMENSION BFUEL(3),FNAME(6),RNAME(6),IDATE(10),KDATE(3)
        DOUBLE PRECISION RUNNO
        COMMON /A/ CO2,MCO2,CO2B,AFC,AFO,XMF,Y
        REAL IKW,ISCO,ISHC,ISFC,ISNO,LHV,MTEMP,MTRFR,NOX,MPRES,MCO2
        REAL NPRES,NTEMP,NOZZLE
        TYPE " TYPE IN THE INPUT FILENAME:",
        READ(11,300)FNAME(1)
300     FORMAT(S10)
5       TYPE " TYPE IN THE OUTPUT FILENAME:",
        READ(11,300)RNAME(1)
        CALL CFILW(RNAME,2,IER)
        IF(IER.EQ.1)GO TO 15
        WRITE(10,400)
400     FORMAT(1X," FILE ALREADY EXISTS :",S20)
        GO TO 5
C
15      CONTINUE
        CALL OPEN(16,FNAME,1,IER)
        CALL FOPEN(17,RNAME)
        READ(16,500) BFUEL(1)
500     FORMAT(S8)
        READ(16) LHV,AFS,Y,X,SG,CR,RPM,MPRES,MTEMP,OTEMP,WTEMP,
     &XPRES,NOZZLE
        WRITE(10,410)
410     FORMAT(1X,//10X,"POWER ? (1-BRAKE,0-INDICATED : )",Z)
        READ(11,310) IPOWER
310     FORMAT (I1)
        WRITE(10,420)
420     FORMAT(1X,//10X," OUTPUT DEVICE (10-CONSOLE,12-PRINTER): ",Z)
        READ(11,320)IOUT
320     FORMAT(I2)
        IF (IOUT.EQ.10.OR.IOUT.EQ.12)GO TO 35
        GO TO 71
35      CONTINUE
        IF(IOUT.EQ.10)GO TO 36
        WRITE(12,700)
700     FORMAT(1X,"(33)(46)(153)(62)(123)")
C
C ***** OUTPUT HEADER *****
C
36      CONTINUE
        CALL FGTIM(IHR,IMIN,ISEC)
        CALL DATE(KDATE,IER)
        WRITE(IOUT,430)KDATE(1),KDATE(2),KDATE(3),IHR,IMIN,ISEC
430     FORMAT(/////,100X,"DATE :",I2,"/",I2,"/",I2,/,100X,
     &"TIME :",I2,":",I2,":",I2,/////)
        WRITE(IOUT,431)
431     FORMAT(//" FUEL CHARACTERISITICS :")
        WRITE(IOUT,432)BFUEL(1),LHV,AFS,Y,X,SG
```

```
432     FORMAT(/5X,"BASE FUEL ",11X,S8,/,5X,"LOWER HEATING VALUE",2X,
       &F6.0,/,5X,"STOICHIOMETRIC A/F ",2X,F6.3,/,5X,"FUEL MOLECULE ",
       &7X,"CH("F5.3,")O(",F5.3,")",/,5X,"SPECIFIC GRAVITY",5X,
       &F5.3,/)
        WRITE(IOUT)" ENGINE TEST CONDITIONS"
        WRITE(17,505)CR,RPM,MPRES,XPRES,MTEMP,OTEMP,WTEMP
505     FORMAT(1X,7F10.4)
        WRITE(IOUT,433)CR,RPM,MPRES,XPRES,MTEMP,OTEMP,WTEMP
433     FORMAT(/,5X,"COMPRESSION RATIO ",14X,F4.1,/,5X,"ENGINE
       &SPEED,RPM ",16X,F5.0,/,5X,"INTAKE MANIFOLD PRESSURE,KPA
       & ",4X,F6.2,/,5X,"EXHAUST PRESSURE, KPA ",11X,F5.2,/,5X,
       &"MIXTURE TEMP., DEG. F "11X,F4.0,/,5X,"OIL TEMP.,DEG. F
       & "16X,F4.0,/,5X,"COOLANT TEMP.,DEG., F",12X,F4.0,/)
        WRITE(IOUT,434)
        WRITE(IOUT,435)
        WRITE(IOUT,436)
        WRITE(IOUT,437)
434     FORMAT("1"," INPUT DATA "//)
435     FORMAT(1X,"RUN NO",4X,"ATM.",4X,"ATM.",4X,"NOZZLE",4X,"NOZZLE",
       &4X,"FUEL",4X,"SPARK",4X,"BRAKE",4X,"MOTOR",4X,"HC",4X,"NOX"
       &,4X,"CO2",4X,"CO",4X,"O2",4X,"INTAKE",4X,"EXHAUST")
436     FORMAT(1X,10X,"PRESS.",2X,"TEMP.",3X,"PRESS.",4X,"TEMP.",
       &5X,"FLOW",4X,"TIMING",3X,"FORCE",4X,"FORCE",46X,"TEMP.")
437     FORMAT(1X,10X,"IN.HG.",2X,"DEG-F",3X,"PSIG",6X,"DEG-F",5X,"LB/M",
       &5X,"DEG.",5X,"LB",7X,"LB",6X,"PPM",3X,"PPM",5X,"%",5X,"%",
       &6X,"%",5X,"CO2-%",4X,"DEG-F")
C
40      CONTINUE
        READ(16)RUNNO,BPRES,BTEMP,NPRES,NTEMP,FUFL,SPKT,BKFR,MTRFR
        IF (RUNNO.LT.10.0D0)GO TO 50
        READ(16)HC,NOX,CO2,CO,O2,MCO2,XTEMP
        WRITE(IOUT,440)RUNNO,BPRES,BTEMP,NPRES,NTEMP,FUFL,SPKT,BKFR,
       &MTRFR,HC,NOX,CO2,CO,O2,MCO2,XTEMP
440     FORMAT(/,1X,F10.0,1X,F5.2,3X,F3.0,4X,F4.1,5X,F5.0,5X,F5.4,4X,
       &F5.2,4X,F5.2,4X,F4.1,5X,F4.0,1X,F6.0,2X,F4.1,2X,F4.2,2X,F5.2,
       &3X,F4.2,5X,F5.0)
C
C ***** BAROMETRIC PRESSURE CORRECTION AND AIR FLOW CALCULATION *****
C
        C1=(9.08E-5)*(BTEMP-28.63)
        C2=1+(1.01E-4)*(BTEMP-32)
        CORR=(C1/C2)*BPRES
        ATM=(BPRES-CORR)*0.49076
        D = (NTEMP+460.0)**0.5
        IF(NOZZLE.EQ.2)GO TO 41
        AFLOW=0.2175*((ATM+NPRES)**1.0315)/D
        GO TO 42
41      AFLOW=0.468*((ATM+NPRES)**1.066)/D
42      CONTINUE
        AFMASS=AFLOW/FUFL
        PHIX=AFMASS/AFS
C
C ***** EXHAUST EMISSIONS AIR/FUEL CALCULATIONS
C
        XHC=HC/10000.0
        XNO=NOX/10000.
        XN=100./(3.*XHC+CO+CO2)
        H2O = (50.0*Y/XN-4.*XHC)/(CO/(3.8*CO2)+1.)
        XMF = 12.01+1.008*Y+16.*X
        A = (3.*XHC-CO/2.+1.5*H2O)*XN/100.
        AFC = (28.97/XMF)*(XN+A-(Y+X)/2.)
        PHIC = AFC/AFS
        B = CO2+CO/2.+H2O/2.+XNO/2.+O2
        C = (B*XN/100.)-X/2.
        AFO = 4.76*28.97/XMF*C
        PHIO = AFO/AFS
C
C ***** CALCULATION OF SPECFIC EMISSIONS
C
        IF(IPOWER.EQ.0) GOTO 44
```

```
      IKW=(BKFR)*RPM*0.746/5250
      GO TO 45
44    IKW=(BKFR+MTRFR)*RPM*0.746/5250
45    ISFC = (FUFL*4.535E05)/(60.0*IKW)
      EFF=((IKW*3412.14)/(LHV*FUFL*60.0))*100.0
      AD = ISFC/(XMF*(3.*XHC+CO+CO2))
      ISHC = 3.*XMF*XHC*AD
      ISNO = 46.0*XNO*AD
      ISCO = 28.01*CO*AD
      ISPK = SPKT
      SPKT1 = ISPK
      DIFF = SPKT-SPKT1
      IF(DIFF.LT.0.01)GO TO 46
      XMBT = SPKT1
46    RELMBT = SPKT1-XMBT
      MPRES1 = MPRES/6.894
      DENSITY = (MPRES1)/(640.*(MTEMP+460.0))
      THEAIR=33.330*RPM*DENSITY*0.5
      VOL = (AFLOW/THEAIR)*100.
C
      CO2B = 400.0
      CALL EGR(XEGR)
C
      WRITE(17,510)RUNNO
510   FORMAT(F10.0)
      WRITE(17,515)PHIX,PHIO,PHIC,RELMBT,XEGR,ISHC,ISCO,ISNO,IKW,
     &ISFC,EFF,VOL
515   FORMAT(1X,12F10.4)
      GO TO 40
50    CONTINUE
      RUNNO = 1.0D0
      WRITE(17,510)RUNNO
      CALL CLOSE(16,IER)
C
      REWIND 17
C
C ***** OUTPUT DATA ******
C
      WRITE(IOUT,448)FNAME(1),RNAME(1)
      IF(IPOWER.EQ.1)GO TO 60
      WRITE(IOUT,450)
      WRITE(IOUT,451)
      WRITE(IOUT,453)
      GO TO 61
60    CONTINUE
      WRITE(IOUT,449)
      WRITE(IOUT,452)
      WRITE(IOUT,453)
61    CONTINUE
C
448   FORMAT("1"," RESULTS CALCULATED FROM DATA IN FILE: ",S10,"ARE
     & STORED IN FILE: ",S10,//)
449   FORMAT(1X," POWER BASE USED - BRAKE ",/)
450   FORMAT(1X," POWER BASE USED - INDICATED ",/)
451   FORMAT(1X,"RUN NO",9X,"PHI",6X,"PHI",6X,"PHI",6X,"MBT",6X,"EGR"
     &,6X,"ISHC",6X,"ISCO",6X,"ISNO",6X,"POWER",6X,"ISFC",6X,"EFF"
     &,6X,"VOL")
452   FORMAT(1X,"RUN NO",9X,"PHI",6X,"PHI",6X,"PHI",6X,"MBT",6X,"EGR"
     &,6X,"BSHC",6X,"BSCO",6X,"BSNO",6X,"POWER",6X,"BSFC",6X,"EFF"
     &,6X,"VOL")
453   FORMAT(25X,"O2",7X,"CBN",6X,"REL",7X,"%",7X,"UG/J",6X,"UG/J",
     &6X,"UG/J",8X,"KW",7X,"UG/J",7X,"%",8X,"%")
C
      READ(17,505)CR,RPM,MPRES,XPRES,MTEMP,OTEMP,WTEMP
64    READ(17,510)RUNNO
      IF(RUNNO.LT.15.0D0)GO TO 65
      READ(17,515)PHIX,PHIO,PHIC,RELMBT,XEGR,ISHC,ISCO,ISNO,IKW,
     &ISFC,EFF,VOL
      WRITE(IOUT,460)RUNNO,PHIX,PHIO,PHIC,RELMBT,XEGR,ISHC,ISCO,ISNO
     &,IKW,ISFC,EFF,VOL
```

```
460     FORMAT(/,F10.0,5X,F5.3,4X,F5.3,4X,F5.3,4X,F5.1,3X,F5.2,6X,
       &F4.2,5X,F5.2,5X,F5.2,5X,F5.2,6X,F6.2,3X,F5.1,4X,F5.1)
        GO TO 64
65      CONTINUE
C
        REWIND 17
        CALL FCLOS(17)
        IF(IOUT.EQ.10)GO TO 66
        WRITE(12,701)
701     FORMAT(1X,"<33><14>")
        WRITE(12,702)
702     FORMAT(1X,"<33><46><153><60><123>")
66      CONTINUE
        STOP
70      TYPE " ERROR FOR OUTPUT DEVICE CODE"
        REWIND 17
        CALL CLOSE(16,IER)
        CALL FCLOS(17)
        STOP
        END
```

```
C ****** CROSSPLOT3.FR *********************************************************
C
C THIS PROGRAM IS DESIGNED TO READ THE RESULT FILE CREATED
C BY THE PROGRAM CFRCALC.FR AND PLOT THE DATA.
C
C  AUTHOR       K.R. SCHMID
C               MECHANICAL ENGINEERING DEPARTMENT
C               UNIVERSITY OF MO - ROLLA
C               ROLLA, MO 65401
C
C REVISION HISTORY:
C
C               6/30/80 - CREATED ORIGINAL
C               8/15/80 - SUBROUTINE GRID ADDED
C               10/7/81 - MODIFIED TO DO 3 PLOTS
C
C
C LOADING INFORMATION
C
C       RLDR CROSSPLOT SYMBOL GRID TITLE VECTR.LB FORT.LB
C
C ******************************************************************************
        DIMENSION BFUEL(3)
        DOUBLE PRECISION RUNNO
        COMMON IPOWER
        REAL MTRFR,MTEMP,OTEMP,NOX,MPRES,MCO2,NPRES,NTEMP
        REAL IKW,ISCO,ISHC,ISNO,ISFC,LHV,NOZZLE
        INTEGER XDATA,YDATA,RATE,TIMING,YDIV
        MPOINT=0
        RATE = 0
10      CONTINUE
        WRITE(10,400)
400     FORMAT(1X,"(33)(14)")
        WRITE(10,401)
401     FORMAT(/,1X," POWER BASE (0-BRAKE POWER;1-INDICATED POWER
     &) ",Z)
        READ(11,300) IPOWER
300     FORMAT (I1)
        WRITE(10,402)
402     FORMAT(1X,/," ***** MANIFOLD  PRESSURE *****  ",//,10X," CHANNEL 1 =
     & 10.0 PSIA",/,10X," CHANNEL 2 = 13.0 PSIA",/,10X," CHANNEL 3 = 16.3 PSIA",/,
     &10X," CHANNEL 4 = 18.3 PSIA",/,10X," CHANNEL 5 = 20.3 PSIA",/)
        WRITE(10,403)
403     FORMAT(1X," MANIFOLD PRESSURE CHANNEL :",Z)
        READ(11,303)J
303     FORMAT(I1)
        WRITE(10,404)
404     FORMAT(/,1X,"SPARK TIMING (1-5% POWER LOSS;0-MBT SPARK
     &TIMING)",Z)
        READ(11,304)TIMING
304     FORMAT(I1)
        IF(MPOINT.EQ.0)GO TO 15
        WRITE(10,430)
        PAUSE
15      CONTINUE
C
C ***** OPEN RESULT FILES FOR READING *****
C
        IF(IPOWER.EQ.0)GO TO 20
        IF(J.EQ.1)CALL OPEN(1,"RSLTIND10",1,IER)
        IF(J.EQ.2)CALL OPEN(2,"RSLTIND13",1,IER)
        IF(J.EQ.3)CALL OPEN(3,"RSLTIND16",1,IER)
        IF(J.EQ.4)CALL OPEN(4,"RSLTIND18",1,IER)
        IF(J.EQ.5)CALL OPEN(5,"RSLTIND20",1,IER)
        GO TO 30
20      CONTINUE
        IF(J.EQ.1)CALL OPEN(1,"RSLTBRK10",1,IER)
        IF(J.EQ.2)CALL OPEN(2,"RSLTBRK13",1,IER)
        IF(J.EQ.3)CALL OPEN(3,"RSLTBRK16",1,IER)
```

```
      IF(J.EQ.4)CALL OPEN(4,"RSLTBRK18",1,IER)
      IF(J.EQ.5)CALL OPEN(5,"RSLTBRK20",1,IER)
30    CONTINUE
      K = J+20
      GO TO (41,42,43,44,45)J
41    CALL OPEN(21,"DATA10.TC",1,IER)
      GO TO 40
42    CALL OPEN(22,"DATA13.TC",1,IER)
      GO TO 40
43    CALL OPEN(23,"DATA16.TC",1,IER)
      GO TO 40
44    CALL OPEN(24,"DATA18.TC",1,IER)
      GO TO 40
45    CALL OPEN(25,"DATA20.TC",1,IER)
40    CONTINUE
      READ(K,505)BFUEL(1)
505   FORMAT(S8)
      READ(K)LHV,AFS,Y,X,SG,CR,RPM,MPRES,MTEMP,OTEMP,WTEMP,
     &XPRES,NOZZLE
      READ(J,500)CR,RPM,MPRES,XPRES,MTEMP,OTEMP,WTEMP
500   FORMAT(1X,7F10.4)
C
      JSYM = J
      IF(J.EQ.5)JSYM = 1
C
      IF(MPOINT.GT.0)GO TO 50
      IF(RATE.EQ.5)GO TO 60
      IF(RATE.EQ.10)GO TO 70
C
C ***** INPUT DATA CHANNEL *****
C
C
C ***** X - AXIS INPUT DATA *****
C
      WRITE(10,406)
406   FORMAT(1X,/," ***** X-AXIS DATA INPUT ***** ",//)
      WRITE(10,407)
407   FORMAT(10X," CHANNEL 1 ISHC ",/,10X," CHANNEL 2 ISCO ",/,10X,
     &" CHANNEL 3 ISNO ",/,10X," CHANNEL 4 POWER ",/,10X,
     &" CHANNEL 5 A/F EQ. RATIO ",/,10X," CHANNEL 6 EFFICIENCY. ",/,
     &10X," CHANNEL 7 SPARK TIMING",/,10X," CHANNEL 8 EXHAUST TEMP.",/)
      WRITE(10,408)
408   FORMAT(1X," INPUT DATA CHANNEL :",Z)
      ACCEPT XDATA
      WRITE(10,409)
409   FORMAT(1X," X-AXIS STARTING COORDINATE =?",Z)
      ACCEPT XMIN
      WRITE(10,410)
410   FORMAT(1X" AXIS FULL SCALE = ?",Z)
      ACCEPT XMAX
      WRITE(10,411)
411   FORMAT(1X," AXIS DIVISION INCREMENT =?",Z)
      ACCEPT XINC
C
C ***** Y-AXIS DATA INPUT (0% EGR) ******
C
      WRITE(10,420)
420   FORMAT(/,1X," ***** Y-AXIS DATA INPUT ***** ",//)
      WRITE(10,407)
      WRITE(10,408)
      ACCEPT YDATA
      WRITE(10,419)
419   FORMAT(1X," Y-AXIS STARTING COORDINATE = ?",Z)
      ACCEPT YMIN
      WRITE(10,410)
      ACCEPT YMAX
      WRITE(10,411)
      ACCEPT YINC
      WRITE(10,430)
430   FORMAT(/," ******** TURN ON PLOTTER ******** ",/)
```

```
      PAUSE
C
C ***** DRAW GRID LINES *****
C
      WRITE(10,600)
600   FORMAT(1X"(33)CI40 75 ")
      CALL GRID(XMIN,XMAX,XINC,1,YMIN,YMAX,YINC,0,200,
     &600,500,700,0,1)
      CALL MVABS(200,700)
      CALL DWABS(200,780)
      CALL DWABS(600,780)
      CALL DWABS(600,700)
C
C ***** LABEL AXIS *****
C
      CALL TITLE(XDATA,0,275,50)
      CALL TITLE(YDATA,1,120,300)
C
C ***** WRITE OUT ENGINE TEST CONDITIONS *****
C
      CALL ANMDE(250,660)
      IF(TIMING.EQ.0)WRITE(10,620)
      IF(TIMING.EQ.1)WRITE(10,621)
620   FORMAT(1X,"MBT")
621   FORMAT(1X,"5% P.L.")
      CALL ANMDE(220,760)
      WRITE(10,623)
623   FORMAT(1X,"MANIFOLD PRESSURE")
      CALL MVABS(230,740)
      CALL SYMBOL(JSYM)
      CALL ANMDE(250,735)
      WRITE(10,624)MPRES
624   FORMAT(1X,F7.2," KPA")
      CALL ANMDE(500,660)
      WRITE(10,622)RATE
622   FORMAT(1X,"EGR=",I1,"%")
      GO TO 75
C
C ***** Y-AXIS DATA INPUT (5 % EGR) *****
C
60    CONTINUE
C
      CALL GRID(XMIN,XMAX,XINC,1,YMIN,YMAX,YINC,0,200,
     &600,300,500,0,0)
      CALL ANMDE(250,460)
      IF(TIMING.EQ.0)WRITE(10,620)
      IF(TIMING.EQ.1)WRITE(10,621)
      CALL ANMDE(500,460)
      WRITE(10,622)RATE
      GO TO 75
C
C ***** INPUT Y-AXIS DATA (10% EGR) *****
C
70    CONTINUE
C
      CALL GRID(XMIN,XMAX,XINC,1,YMIN,YMAX,YINC,0,200,
     &600,100,300,1,0)
      CALL ANMDE(250,260)
      IF(TIMING.EQ.0)WRITE(10,620)
      IF(TIMING.EQ.1)WRITE(10,621)
      CALL ANMDE(500,260)
      WRITE(10,632)RATE
632   FORMAT(1X,"EGR=",I2,"%")
      GO TO 75
C
50    CONTINUE
      IF(RATE.EQ.5.OR.RATE.EQ.10)GO TO 75
      WRITE(10,600)
      IF(MPOINT.EQ.1)GO TO 21
      IF(MPOINT.EQ.2)GO TO 22
```

```
      IF(MPOINT.EQ.3)GO TO 23
      IF(MPOINT.EQ.4)GO TO 24
      GO TO 25
21    CONTINUE
      CALL MVABS(230,715)
      CALL SYMBOL(JSYM)
      CALL ANMDE(250,710)
      WRITE(10,624)MPRES
      GO TO 25
22    CONTINUE
      CALL MVABS(425,765)
      CALL SYMBOL(JSYM)
      CALL ANMDE(445,760)
      WRITE(10,624)MPRES
      GO TO 25
23    CONTINUE
      CALL MVABS(425,740)
      CALL SYMBOL(JSYM)
      CALL ANMDE(445,735)
      WRITE(10,624)MPRES
      GO TO 25
24    CONTINUE
      CALL MVABS(425,715)
      CALL SYMBOL(JSYM)
      CALL ANMDE(445,710)
      WRITE(10,624)MPRES
25    CONTINUE
C
C ***** PLOT DATA *****
C
75    CONTINUE
      READ(J,510)RUNNO
510   FORMAT(F10.0)
      IF(RUNNO.LT.10.0D0)GO TO 95
      READ(J,511)PHIX,PHIO,PHIC,RELMBT,EGR,ISHC,ISCO,ISNO,IKW,
     &ISFC,EFF,VOL
511   FORMAT(1X,12F10.4)
      READ(K) RUN,BPRES,BTEMP,NPRES,NTEMP,FUFL,SPKT,BRKFR,MTRFR
      READ(K) HC,NOX,CO2,CO,O2,MCO2,XTEMP
      ISPARK = IFIX(SPKT)
C
C ***** CHECKING SPARK TIMING POINT *****
C
      IF(TIMING.EQ.0)GO TO 81
      IF(RELMBT.NE.0.0)GO TO 82
      GO TO 75
81    IF(RELMBT.EQ.0.0)GO TO 82
      GO TO 75
82    CONTINUE
C
C ***** CHECKING EGR RATE *****
C
      IF(RATE.EQ.0)GO TO 85
      IF(RATE.EQ.5)GO TO 86
      IF(EGR.GE.7.0.AND.EGR.LE.11.0)GO TO 90
      GO TO 75
85    IF(EGR.EQ.0.0)GO TO 90
      GO TO 75
86    IF(EGR.GE.3.0.AND.EGR.LE.6.500)GO TO 90
      GO TO 75
90    CONTINUE
C
C ***** DETERMINE X DATA POINT FOR PLOTTING *****
C
      IF(XDATA.EQ.1)XPOINT = ISHC
      IF(XDATA.EQ.2)XPOINT = ISCO
      IF(XDATA.EQ.3)XPOINT = ISNO
      IF(XDATA.EQ.4)XPOINT = IKW
      IF(XDATA.EQ.5)XPOINT = PHIO
      IF(XDATA.EQ.6)XPOINT = EFF
```

```
      IF(XDATA.EQ.7)XPOINT = ISPARK
      IF(XDATA.EQ.8)XPOINT = XTEMP
C
C ***** DETERMINE Y DATA POINT FOR PLOTTING *****
C
      IF(YDATA.EQ.1)YPOINT = ISHC
      IF(YDATA.EQ.2)YPOINT = ISCO
      IF(YDATA.EQ.3)YPOINT = ISNO
      IF(YDATA.EQ.4)YPOINT = IKW
      IF(YDATA.EQ.5)YPOINT = PHIO
      IF(YDATA.EQ.6)YPOINT = EFF
      IF(YDATA.EQ.7)YPOINT = ISPARK
      IF(YDATA.EQ.8)YPOINT = XTEMP
C
      IF(RATE.EQ.0) CALL DPORT(200,600,500,700,XMIN,XMAX,YMIN,YMAX)
      IF(RATE.EQ.5) CALL DPORT(200,600,300,500,XMIN,XMAX,YMIN,YMAX)
      IF(RATE.EQ.10) CALL DPORT(200,600,100,300,XMIN,XMAX,YMIN,YMAX)
      CALL MOVEA(XPOINT,YPOINT)
      CALL SYMBOL(JSYM)
C
      GO TO 75
95    CONTINUE
      REWIND K
      CALL CLOSE(K,IER)
      REWIND J
      CALL CLOSE(J,IER)
      CALL ANMDE(0,0)
      RATE= RATE+5
      IF(MPOINT.GT.0.AND.RATE.LE.10)GO TO 15
      IF(RATE.LE.10)GO TO 15
      ACCEPT FAKE
C ***** STOP TO TURN OFF PLOTTER *****
C ***** HIT RETURN KEY TO COMPLETE PROGRAM *****
      WRITE(10,450)
450   FORMAT(1X," PLOT MORE POINTS ?(0-NO;1-YES)",Z)
      ACCEPT MORE
      IF(MORE.EQ.0)GO TO 96
      MPOINT = MPOINT+1
      RATE = 0
      GO TO 10
96    CONTINUE
      WRITE(10,440)
440   FORMAT(1X,"(33)CN")
      WRITE(10,460)
460   FORMAT(/,1X," REPEAT PROGRAM ? (NO-0,YES-1)",Z)
      ACCEPT NCON
      IF(NCON.EQ.0)GO TO 97
      MPOINT = 0
      RATE = 0
      GO TO 10
97    CONTINUE
      STOP
      END
```

```
C ***** DEVMEP.FR ***************************************************************
C
C THIS PROGRAM IS DESIGNED TO CALCULATE DEVIATION OF
C THE MEAN EFFECTIVE PRESSURES FROM THE PRESSURE CRANK
C ANGLE DATA GENERATED BY PRESFILE.FR OR PRESAVE.FR AND
C  SHIFT THE DATA IN THE PROCESS.
C
C AUTHOR:         K.R. SCHMID
C                 MECHANICAL ENGINEERING DEPARTMENT
C                 UNIVERSITY OF MISSOURI - ROLLA
C                 ROLLA, MISSOURI 65401
C
C REVISION HISTORY:
C
C                 07/14/80 - CREATED ORIGINAL
C                 07/25/80 - REVISED FOR MULTIPLE RUNS
C                 12/29/80 - STANDARD DEVIATION ADDED
C                 03/08/81 - STANDARD DEVIATION CHANGED TO %
C                 07/12/81 - SUBROUTINE EGR ADDED
C
C LOADING INFORMATION:
C
C       RLDR DEVMEP EGR PHASE FORT.LB
C
C DEFINITIONS:
C
C       AIMEP   = AVERAGE INDICATED MEAN EFFECTIVE PRESSURE
C       APMEP   = AVERAGE PUMPING LOOP MEP
C       ATMEP   = AVERAGE THERMODYNAMIC MEP
C       BORE    = ENGINE BORE (IN.)
C       CALB    = CALIBRATION FACTOR (PSI/VOLT)
C       CR      = COMPRESSION RATIO
C       FIMEP   = FIRING INDICATED MEP
C       FIWK    = FIRING INDICATED WORK
C       IDATA   = BINARY VOLTAGE DATA
C       IFILE   = FILENAME OF PRESSURE DATA
C       PMEP    = PUMPING MEP
C       R       = CRANK THROW (IN.)
C       RL      = CONNECTING ROD LENGTH (IN.)
C       SDIMEP  = STANDARD DEVIATION OF FIRING INDICATED MEP
C       SDPMEP  = STANDARD DEVIATION OF PUMPING MEP
C       SDTMEP  = STANDARD DEVIATION OF THERMODYNAMIC MEP
C       TMEP    = THERMODYNAMIC MEP
C
C       SET IFIRST = 1 SO RESULT FILE WILL BE CREATED
C       SET IFIRST = 2 TO APPEND EXISTING FILE
C
C ******************************************************************************
        DIMENSION IFILE(10),AFILE(10),DFILE(10),MFILE(10)
        DIMENSION FILE(10),IDATE(10),KDATE(10)
        DIMENSION BFUEL(3),IHEADR(40),IDATA(720),RFILE(10)
        DIMENSION VOLT(720),TESTFILE(20),FIMEP(30),PMEP(30),TMEP(30)
        DOUBLE PRECISION RUN,RUNNO
        COMMON /A/ CO2,MCO2,CO2B,AFC,AFO,XMF,Y
        COMMON /PDATA/ PRES1(720),PRES(720)
        REAL MCO2,NPRES,NTEMP,NOZZLE
        REAL LHV,MTEMP,MTRFR,MPRES,ISMEP,NOX
C
        N = 0
        CALB = 91.274
        BORE = 3.250
        R = 2.250
        RL = 10.0
        CR = 8.0
C
        WRITE(10,400)
400     FORMAT(1X,"FILENAME OF DATA:",Z)
        READ(11,300)FILE(1)
300     FORMAT(S18)
```

```
      CALL OPEN(0,FILE(1),IER)
      IF(IER.NE.1)TYPE" FILE OPEN ERROR CHAN 0",IER
      READ(0)NUM,PREF,JCYCLE,IOUT,IFIRST
      READ(0,510)TESTFILE(1)
      READ (0,510) RFILE(1)
510   FORMAT(S18)
      CALL OPEN(3,TESTFILE,1,IER)
      READ(3,500)BFUEL(1)
500   FORMAT(S8)
      READ(3)LHV,AFS,Y,X,SG,CR,RPM,MPRES,MTEMP,OTEMP,
     &WTEMP,XPRES,NOZZLE
      CALL FGTIM(IHR,IMIN,ISEC)
      CALL DATE(KDATE,IER)
C
C ****** READ AND WRITE HEADER INFORMATION *****
C
      WRITE(IOUT,410)KDATE(1),KDATE(2),KDATE(3),IHR,IMIN,ISEC
410   FORMAT(/////,100X,"DATE  :",I2,"/",I2,"/",I2,/,100X,
     &"TIME  :",I2,":",I2,":",I2,/////)
      WRITE(IOUT,411)
411   FORMAT(//" FUEL CHARACTERISITICS :")
      WRITE(IOUT,412)BFUEL(1),LHV,AFS,Y,X,SG
412   FORMAT(/5X,"BASE FUEL ",11X,S8,/,5X,"LOWER HEATING VALUE",2X,
     &F6.0,/,5X,"STOICHIOMETRIC A/F ",2X,F6.3,/,5X,"FUEL MOLECULE ",
     &7X,"CH("F5.3,")O(",F5.3,")",/,5X,"SPECFIC GRAVITY",6X,
     &F5.3,/)
      WRITE(IOUT,413)
413   FORMAT(1X," ENGINE CONDITIONS")
      WRITE(IOUT,414)CR,RPM,MPRES,XPRES,MTEMP,OTEMP,WTEMP
414   FORMAT(/,5X,"COMPRESSION RATIO ",14X,F4.1,/5X,"ENGINE
     & SPEED,RPM ",16X,F5.0,/,5X,"INTAKE MANIFOLD PRESSURE,KPA
     & ",4X,F6.2,/,5X,"EXHAUST PRESSURE, KPA ",11X,F5.2,/,5X,
     &"MIXTURE TEMP., DEG.F "12X,F4.0,/,5X,"OIL TEMP., DEG. F
     & "15X,F4.0,/,5X,"COOLANT TEMP., DEG. F",12X,F4.0,/)
C
C ***** WRITE OUT HEADER *****
C
      WRITE(IOUT,420)
      WRITE(IOUT,421)
420   FORMAT("1",///,3X,"RUN NO",5X,"DATAFILE",5X,"PHI",6X,"EGR",
     &6X,"IMEP",4X,"% DEV.",6X,"PMEP",3X,"% DEV.",5X,"TMEP",3X,"% DEV.")
421   FORMAT(27X,"OXY",7X,"%",7X,"KPA",17X,"KPA",15X,"KPA"/)
C
      IF(IFIRST.EQ.2)GO TO 5
      CALL OPEN(4,RFILE,2,IER)
      IF(IER.NE.1)TYPE "FILE OPEN ERROR - CHAN 4",IER
      WRITE(4,411)
      WRITE(4,412)BFUEL(1),LHV,AFS,Y,X,SG
      WRITE(4,413)
      WRITE(4,414)CR,RPM,MPRES,XPRES,MTEMP,OTEMP,WTEMP
      WRITE(4,420)
      WRITE(4,421)
      GO TO 6
5     CONTINUE
      CALL APPEND(4,RFILE,2,IER)
      IF(IER.NE.1)TYPE "FILE APPEND ERROR - CHAN 4",IER
6     CONTINUE
C
C ***** CALCULATE VOLUME *****
C
      VOLD=BORE**2*0.7854*R*2
      VOLC=VOLD/(CR-1.)
      VOLMAX=VOLD+VOLC
      DO 120 I=1,720
      J=I-1
      CA = FLOAT(J)
      CA=CA*0.01745
      SINA=SIN(CA)
      COSA=COS(CA)
      AP=(BORE**2)*0.7854
```

```
        SIN2A=SINA**2
        RL2=(R/RL)**2
        QNT=(1.-RL2*SIN2A)**0.5
        VOL=AP*(R*(1.-COSA)+RL*(1.-QNT))
        VOLT(I)=(VOL+VOLC)*0.00001638
  120   CONTINUE
C
C **** READ ENGINE DATA FILE & CALCULATE AIR/FUEL RATIO *****
C
15      CONTINUE
        READ(0,520)RUN,IFILE(1),AFILE(1),DFILE(1),MFILE(1)
520     FORMAT(F10.0,S12,S12,S12,S12)
16      READ(3)RUNNO,BPRES,BTEMP,NPRES,NTEMP,FUEL,SPKT,BKFR,MTRFR
        IF(RUNNO.LE.10.0D0)GO TO 35
        READ(3)HC,NOX,CO2,CO,O2,MCO2,XTEMP
        IF(RUNNO.NE.RUN)GO TO 16
C
        XHC = HC/10000.0
        XNO = NOX/10000.0
        XN = 100./(3.*XHC+CO+CO2)
        H2O = (50.0*Y/XN-4.*XHC)/(CO/(3.8*CO2)+1.0)
        XMF = 12.01+1.008*Y+16.0*X
        A = (3.*XHC-CO/2.+1.5*H2O)*XN/100.0
        B = CO2+CO/2.+H2O/2.+XNO/2.+O2
        C = (B*XN/100.)-X/2.
        AFO = 4.76*28.97/XMF*C
        PHIO = AFO/AFS
C
        CO2B = 400.0
        CALL EGR(XEGR)
C
        CALL FOPEN (1,IFILE)
        READ BINARY (1) IHEADR,ICYCLE
        WRITE(10,425)IHEADR(1),ICYCLE
425     FORMAT(5X,S60,5X,I2," CYCLES RECORDED",//)
C
C ***** SCALE PRESSURE DATA ******
C
        DO 200 J=1,JCYCLE
         DO 100 I=1,720
         READ BINARY(1)IDATA(I)
         FACTOR = (CALB/3276.7)*6.895
         PRES(I) = FLOAT(IDATA(I))
         PRES(I) = (PRES(I)-310.)*FACTOR
100     CONTINUE
        PRESC = PRES(180)-PREF
         DO 110 I=1,720
         PRES(I) = PRES(I)-PRESC
110     CONTINUE
C
C **** SHIFT PRESSURE DATA BY THE AMOUNT IDEG
C
        CALL PHASE (2)
C
C ***** CALCULATE WORK *****
C
        WK12T=0.0
        DO 130 I=1,179
        WK12=(PRES(I)+PRES(I+1))*(VOLT(I+1)-VOLT(I))/2.0
        WK12T=WK12+WK12T
130     CONTINUE
        WK23T=0.0
        DO 140 I=180,359
        WK23=(PRES(I)+PRES(I+1))*(VOLT(I+1)-VOLT(I))/2.0
        WK23T=WK23+WK23T
140     CONTINUE
        WK34T=0.0
        DO 150 I=360,539
        WK34=(PRES(I)+PRES(I+1))*(VOLT(I+1)-VOLT(I))/2.
        WK34T=WK34+WK34T
```

```
150     CONTINUE
        WK41T=0.0
        DO 160 I=540,719
        WK41=(PRES(I)+PRES(I+1))*(VOLT(I+1)-VOLT(I))/2.
        WK41T=WK41+WK41T
160     CONTINUE
        DEM = VOLD*0.00001638
C
C ***** CALCULATIONS FOR FIRING DATA
C
        FIWK = WK34T+WK23T
        PWK = WK41T+WK12T
        FIMEP(J) = FIWK/DEM
        PMEP(J) = PWK/DEM
        TMEP(J) = (FIWK+PWK)/DEM
C
200     CONTINUE
        REWIND 1
        CALL FCLOSE (1)
C
C ***** FIND THE AVERAGE AND STANDARD DEVIATION
C
        SUM = 0.0
        SUM1 = 0.0
        SUM2 = 0.0
        SIMEP = 0.0
        SPMEP = 0.0
        STMEP = 0.0
        DO 210 I=1,JCYCLE
        SIMEP = FIMEP(I)+SIMEP
        SPMEP = PMEP(I)+SPMEP
        STMEP = TMEP(I)+STMEP
210     CONTINUE
        AIMEP = SIMEP/JCYCLE
        APMEP = SPMEP/JCYCLE
        ATMEP = STMEP/JCYCLE
        DO 220 I=1,JCYCLE
        SUM = ((FIMEP(I)-AIMEP)**2)+SUM
        SUM1 = ((PMEP(I)-APMEP)**2)+SUM1
        SUM2 = ((TMEP(I)-ATMEP)**2)+SUM2
220     CONTINUE
        NCYCLE = JCYCLE-1
        SDIMEP = (SUM/NCYCLE)**0.5
        SDPMEP = (SUM1/NCYCLE)**0.5
        SDTMEP = (SUM2/NCYCLE)**0.5
C
C ***** CALCULATE % STANDARD DEVIATION *****
C
        SDIMEP = (SDIMEP/AIMEP)*100.0
        SDPMEP = (SDPMEP/(-1.0*APMEP))*100.0
        SDTMEP = (SDTMEP/ATMEP)*100.0
C
C ***** WRITE OUT RESULTS *****
C
        WRITE(IOUT,430)RUNNO,IFILE(1),PHIO,XEGR,AIMEP,SDIMEP,APMEP,
     &SDPMEP,ATMEP,SDTMEP
430     FORMAT(1X,F10.0,1X,S11,3X,F5.3,2X,F6.2,5X,F6.1,2X,F6.2,5X,F6.1,
     &2X,F6.2,5X,F6.1,2X,F6.2,/)
C
        WRITE(4,430)RUNNO,IFILE(1),PHIO,XEGR,AIMEP,SDIMEP,
     &APMEP,SDPMEP,ATMEP,SDTMEP
C
        N=N+1
        IF(N.EQ.NUM)GO TO 25
        GO TO 15
25      CONTINUE
        REWIND 0
        REWIND 3
        REWIND 4
        CALL CLOSE(0,IER)
```

```
      IF(IER.NE.1)TYPE"FILE CLOSE ERROR CHAN 1",IER
      CALL CLOSE(3,IER)
      IF(IER.NE.1)TYPE"FILE CLOSE ERROR CHAN 3",IER
      CALL CLOSE(4,IER)
      IF(IER.NE.1)TYPE "FILE CLOSE ERROR CHAN 4",IER
      STOP
35    CONTINUE
      CALL RESET
      CALL CLOSE(0,IER)
      CALL CLOSE(3,IER)
      TYPE " RUN NUMBER NOT FOUND"
      STOP
      END
```

```
C ***** ENGPLOT.FR ****************************************************
C
C THIS PROGRAM IS DESIGNED TO READ THE DATAFILE OF ENGINE DATA
C AND CALCULATE THE AMOUNT OF AVIALABLE EXHAUST ENGERY TO POSSIBLE
C DRIVE AN EXHAUST TURBINE.  THE DATAFILE HAS THE SAME FORMAT AS THE
C DATAFILE USED IN THE PROGRAM CFRCALC.
C
C
C AUTHOR:       K.R. SCHMID
C               MECHANICAL ENGINEERING DEPARTMENT
C               UNIVERSITY OF MISSOURI - ROLLA
C               ROLLA, MO 65401
C
C
C REVISION HISTORY:
C
C               04/15/79 - ORGINAL CREATED
C               12/10/79 - REVISED FOR LEAN SUPERCHARGE STUDY
C               11/14/80 - ENGERY.FR CREATED FROM CFRCALC.FR
C               07/12/81 - SUBROUTINE EGR ADDED
C               09/19/81 - MODIFIED TO PLOT DATA
C
C
C
C  LOADING INFORMATION:
C
C       RLDR ENGPLOT EGR GRID SYMBOL VECTR.LB FORT.LB
C
C  NOMENCLATURE:
C
C       AFLOW = MASS OF AIR FLOW,LB/MIN
C       AFS =   STOICHIOMERTIC A/F
C       BFUEL = BASE FUEL NAME, 8 CHARACTERS
C       BPRES = BAROMETRIC PRESSURE, IN.HG.
C       BRFR =  BEAM FORCE WHEN FIRING,LB
C       BTEMP = BAROMETRIC TEMPERATURE,F
C       CEFF =  COMPRESSOR EFFICIENCY (%)
C       CIP =   COMPRESSOR INLET PRESSURE (PSIA)
C       CO =    CARBON MONOXIDE,%
C       CO2 =   CARBON DIOXIDE,%
C       COP =   COMPRESSOR OUTLET PRESSURE (PSIA)
C       CPE =   EXHAUST SPECFIC HEAT
C       CPI =   INTAKE SPECFIC HEAT
C       CR =    COMPRESSION RATIO
C       FUFL =  MASS FUEL FLOW, LB/MIN
C       HC =    HYDROCARONS, PPM (PROPANE)
C       ITEMP = COMPRESSOR INLET TEMPERATURE DEG. R
C       KE =    EXHAUST SPECIFIC HEAT RATIO
C       KI =    INTAKE SPECIFIC HEAT RATIO
C       LHV =   LOWER HEATING VALUE OF FUEL, BTU/LBM
C       MASS =  MASS FLOW THROUGH THE COMPRESSOR AND TURBINE
C       MCO2 =  INTAKE MANIFOLD CO2, %
C       MPRES = INTAKE MANIFOLD PRESSURE, KPA
C       MTEMP = INTAKE MANIFOLD TEMPERATURE, DEG F
C       MTRFR = MOTORING BEAM FORCE, LB
C       NOX =   OXIDES OF NITROGEN, PPM
C       NOZZLE= NOZZLE NUMBER USED FOR TEST
C       NPRES = CRITICAL FLOW NOZZLE PRESSURE, PSIG
C       NTEMP = CRITICAL NOZZLE TEMPERATURE, DEG F
C       O2 =    OXYGEN, %
C       OTEMP = OIL TEMPERATURE, DEG F
C       PC =    KILOWATTS NEEDED TO DRIVE COMPRESSOR
C       PHIC =  CARBON BASED A/F EQUIVALENCE RATIO
C       PHIO =  OXYGEN BASED A/F EQUIVALENC RATIO
C       PHIX =  EXPERIMENTAL A/F EQUIVALENCE RATIO
C       PT50 =  KILOWATTS DEVELOPED BY EXHAUST TURBINE @ 50% EFF.
C       PT75 =  KILOWATTS DEVELOPED BY EXHAUST TURBINE @ 75% EFF.
C       PT85 =  KILOWATTS DEVELOPED BY EXHAUST TURBINE @ 85% EFF.
C       RPM =   ENGINE SPPED, RPM
```

```
C       RUNNO = RUN NUMBER, 8 DIGIT NUMBER, 1ST 6 DIGITS = MO/DAY/YEAR
C               LAST 2 DIGITS = RUN FOR DAY
C       SG =    SPECIFIC GRAVITY OF FUEL, FM/ML
C       SPKT =  SPARK TIMING, DEG BTDC, ENTER DATA IN WHOLE DEG. IDENTIFY
C               MBT BY ADDING DECIMAL > 0.1, EXAMPLE: 31.5 INDICATES MBT
C               SPARK TIMING OF 31 DEG. 20. =   NON MBT SPARK TIMING OF 20
C               DEGREES.
C       TIP =   TURBINE INLET PRESSURE (PSIG)
C       WTEMP = COOLANT TEMPERATURE, DEG. F
C       XTEMP = EXHAUST TEMPERATURE, DEG F
C       XPRES = EXHAUST PRESSURE, KPA
C       X =     MOLAR O/C RATIO OF FUEL
C       Y =     MOLAR H/C RATIO OF FUEL
C
C FORMAT FOR DATA ENTRY INTO FILE SCD-:
C
C       BFUEL
C
C       LHV,AFS,Y,X,SG,CR,RPM,MPRES,MTEMP,OTEMP,WTEMP,XPRES,NOZZLE
C       RUNNO,BPRES,BTEMP,NPRES,NTEMP,FUFL,SPKT,BKFR,MTRFR
C       HC,NOX,CO2,CO,O2,MCO2,XTEMP
C       RUNNO,BPRES,PTEMP,NPRES,NTEMP,FUFL,SPKT,BKFR,MTRFR
C       HC,NOX,CO2,CO,O2,MCO2,XTEMP
C       0.,0.,0.,0.,0.,0.,0.,0.,0.
C
C       (ZEROS ARE PLACED AT END OF FILE AS END OF FILE INDICATORS)
C
C **********************************************************************
        DIMENSION BFUEL(3),FNAME(6),RNAME(6),IDATE(10),KDATE(3)
        DOUBLE PRECISION RUNNO
        COMMON /A/ CO2,MCO2,CO2B,AFC,AFO,XMF,Y
        REAL IKW,ISCO,ISHC,ISFC,ISNO,LHV,MTEMP,MTRFR,NOX,MPRES,MCO2
        REAL NPRES,NTEMP,NOZZLE,KE,KI,MASS,ITEMP
C
        CPE = 0.27
        CPI = 0.24
        KE = 1.343
        KI = 1.40
        ITEMP = 585.0
        MORE = 0
C
5       CONTINUE
        WRITE(10,400)
400     FORMAT(1X,"<33><14>")
        WRITE(10,401)
401     FORMAT(/,5X,"INPUT ENGINE DATA FILENAME:",Z)
        READ(11,300)FNAME(1)
300     FORMAT(S10)
        WRITE(10,411)
411     FORMAT(/,5X,"COMPRESSOR OUTLET PRESSURE (PSIA) :",Z)
        ACCEPT COP
        WRITE(10,412)
412     FORMAT(/,5X,"COMPRESSOR EFFICIENCY (%)         :",Z)
        ACCEPT CEFF
        WRITE(10,413)
413     FORMAT(/,5X,"TURBINE INLET PRESSURE (PSIG)     :",Z)
        ACCEPT TIP
        WRITE(10,420)
420     FORMAT(/,5X,"SPARK TIMING (1-5% POWER LOSS;0-MBT SPARK
     & TIMING) ",Z)
        ACCEPT TIMING
        WRITE(10,421)
421     FORMAT(/,5X,"EGR RATE (0,5,10 %) = ?",Z)
        ACCEPT RATE
C
C
        CALL OPEN(16,FNAME,1,IER)
        IF(IER.NE.1)TYPE"FILE OPEN ERROR CHAN 16",IER
        CALL OPEN(15,"TEMP01",3,IER)
        IF(IER.NE.1)TYPE "FILE OPEN ERROR CHAN 15",IER
```

```
C
      READ(16,500)BFUEL(1)
500   FORMAT(58)
      READ(16)LHV,AFS,Y,X,SG,CR,RPM,MPRES,MTEMP,OTEMP,WTEMP,
     &XPRES,NOZZLE
C
      NUM = 0
      CIP13 = 13.0
      CIP14 = 14.3
      CEFF = CEFF/100.0
C
30    CONTINUE
      NUM = NUM+1
      READ(16)RUNNO,BPRES,BTEMP,NPRES,NTEMP,FUFL,SPKT,BKFR,MTRFR
      IF (RUNNO.LT.10.0D0)GO TO 60
      READ(16)HC,NOX,CO2,CO,O2,MCO2,XTEMP
C
C ***** BAROMETRIC PRESSURE CORRECTION AND AIR FLOW CALCULATION *****
C
      C1=(9.08E-5)*(BTEMP-28.63)
      C2=1+(1.01E-4)*(BTEMP-32)
      CORR=(C1/C2)*BPRES
      ATM=(BPRES-CORR)*0.49076
      D = (NTEMP+460.0)**0.5
      IF(NOZZLE.EQ.2)GO TO 32
      AFLOW=0.2175*((ATM+NPRES)**1.0315)/D
      GO TO 33
32    AFLOW=0.468*((ATM+NPRES)**1.066)/D
33    CONTINUE
      AFMASS=AFLOW/FUFL
      PHIX=AFMASS/AFS
C
C ***** EXHAUST EMISSIONS AIR/FUEL CALCULATIONS
C
      XHC=HC/10000.0
      XNO=NOX/10000.
      XN=100./(3.*XHC+CO+CO2)
      H2O = (50.0*Y/XN-4.*XHC)/(CO/(3.8*CO2)+1.)
      XMF = 12.01+1.008*Y+16.*X
      A = (3.*XHC-CO/2.+1.5*H2O)*XN/100.
      AFC = (28.97/XMF)*(XN+A-(Y+X)/2.)
      PHIC = AFC/AFS
      B = CO2+CO/2.+H2O/2.+XNO/2.+O2
      C = (B*XN/100.)-X/2.
      AFO = 4.76*28.97/XMF*C
      PHIO = AFO/AFS
C
C ***** CALCULATION OF COMPRESSOR AND TURBINE POWER
C
      XTEMP = XTEMP+460.0
      MASS = (PHIO*AFS+1.0)*FUFL
      YC13 = ((COP/CIP13)**((KI-1.0)/KI))-1.0
      YC14 = ((COP/CIP14)**((KI-1.0)/KI))-1.0
      YT = 1.0-((14.3/(TIP+14.3))**((KE-1.0)/KE))
      PC13 = MASS*CPI*ITEMP*YC13*(1.0/CEFF)*(778.0/33000.0)*0.746
      PC14 = MASS*CPI*ITEMP*YC14*(1.0/CEFF)*(778.0/33000.0)*0.746
      PT = MASS*CPE*XTEMP*YT*(778.0/33000.0)*0.746
      PT50 = PT*0.50
      PT75 = PT*0.75
      PT85 = PT*0.85
C
C ***** MBT SPARK TIMING CHECK
C
      ISPK = SPKT
      SPKT1 = ISPK
      DIFF = SPKT-SPKT1
      IF(DIFF.LT.0.01)GO TO 35
      XMBT = SPKT1
35    RELMBT = SPKT1-XMBT
C
```

```
C ***** EGR CALCULATION
C
        CO2B = 400.0
        CALL EGR(XEGR)
C
C ***** STORE DATA IN FILE (CHAN 15)
C
        WRITE(15,501)RUNNO,PHIX,PHIO,PHIC,RELMBT,XEGR,MASS,PC13,PC14,
     &PT50,PT75,PT85
501     FORMAT(1X,12F10.6)
C
        GO TO 30
60      CONTINUE
        CALL CLOSE(16,IER)
C
        WRITE(10,480)
480     FORMAT(//,1X," ***** TURN ON PLOTTER ******",//)
        PAUSE
        REWIND 15
        CEFF = CEFF*100.
        WRITE(10,600)
600     FORMAT(1X,"<33>CI 40 75 ")
        CALL GRID(1.0,2.0,0.20,1,0.0,1.0,0.20,1,150,900,130,730,1,1)
C
C ***** LABEL AXIS
C
        CALL ANMDE(400,75)
        WRITE(10,610)
610     FORMAT(1X," AIR/FUEL EQUIVALENCE RATIO")
        WRITE(10,611)
611     FORMAT(1X,"<33>CJ 90 ")
        CALL ANMDE (70,350)
        WRITE(10,612)
612     FORMAT(1X," POWER - KW")
        WRITE(10,613)
613     FORMAT(1X,"<33>CJ 0 ")
C
        CALL ANMDE(280,685)
        WRITE(10,620)
620     FORMAT(1X,"TEST CONDITIONS:")
        SICOP = COP*6.895
        CALL ANMDE(280,660)
        WRITE(10,621)SICOP
621     FORMAT(1X,"COMP OUTLET PRESS =",F6.1," KPA")
        CALL ANMDE(280,635)
        WRITE(10,622)CEFF
622     FORMAT(1X,"COMP EFF. = ",F4.1," %")
        CALL ANMDE (280,610)
        IF(TIMING.EQ.0)WRITE(10,623)
        IF(TIMING.EQ.1)WRITE(10,624)
623     FORMAT(1X,"MBT SPARK TIMING")
624     FORMAT(1X,"5 % POWER LOSS")
        CALL ANMDE(280,585)
        WRITE(10,625)RATE
625     FORMAT(1X,"EGR = ",F4.1,"%")
        CALL ANMDE (625,685)
        WRITE(10,626)
626     FORMAT(1X,"EXHAUST TURBINE EFF")
C
        DO 100 I=1,3
        GOTO (65,66,67) I
65      ISYM = 660
        IPERCENT=50
        GO TO 70
66      ISYM = 635
        IPERCENT=75
        GO TO 70
67      ISYM = 610
        IPERCENT=85
70      CONTINUE
```

```
      CALL MVABS(675,ISYM)
      CALL SYMBOL(I)
      ISYM = ISYM-5
      CALL ANMDE(705,ISYM)
      WRITE(10,630)IPERCENT
630   FORMAT(1X,I2," % ")
100   CONTINUE
      CALL ANMDE(625,580)
      WRITE(10,635)
635   FORMAT(1X,"COMP INLET PRESS")
      CALL MVABS(675,560)
      CALL SYMBOL(1)
      CALL ANMDE(705,555)
      WRITE(10,636)
636   FORMAT(1X,"89.6 KPA")
      CALL MVABS(675,535)
      CALL SYMBOL(2)
      CALL ANMDE(705,530)
      WRITE(10,637)
637   FORMAT(1X,"98.6 KPA")
C
C **** PLOT DATA
C
      NUM = NUM-1
      DO 110 I=1,NUM
      READ(15,501)RUNNO,PHIX,PHIO,PHIC,RELMBT,XEGR,MASS,PC13,PC14,
     &PT50,PT75,PT85
C
C ***** CHECK SPARK TIMING
C
      IF(TIMING.EQ.0)GO TO 40
      IF(RELMBT.NE.0)GO TO 41
      GO TO 110
40    IF(RELMBT.EQ.0.0)GO TO 41
      GO TO 110
41    CONTINUE
C
C ***** CHECK EGR RATE
C
      IF(RATE.EQ.0)GO TO 80
      IF(RATE.EQ.5)GO TO 81
      IF(XEGR.GE.7.0.AND.XEGR.LE.11.0)GO TO 85
      GO TO 110
80    IF(XEGR.EQ.0)GO TO 85
      GO TO 110
81    IF(XEGR.GE.3.0.AND.XEGR.LE.6.50)GO TO 85
      GO TO 110
85    CONTINUE
C
C ***** DETERMINE Y-DATA POINT FOR PLOTTING
C
      IF(IDATA.EQ.1)YPOINT=PT50
      IF(IDATA.EQ.2)YPOINT=PT75
      IF(IDATA.EQ.3)YPOINT=PT85
C
      CALL DPORT(150,900,130,730,1.0,2.0,0.0,1.0)
      CALL MOVEA(PHIO,PT50)
      CALL SYMBOL(1)
      CALL MOVEA(PHIO,PT75)
      CALL SYMBOL(2)
      CALL MOVEA(PHIO,PT85)
      CALL SYMBOL(3)
      CALL MOVEA(PHIO,PC13)
      CALL SYMBOL(1)
      CALL MOVEA(PHIO,PC14)
      CALL SYMBOL(2)
110   CONTINUE
C
      CALL ANMDE(0,0)
      REWIND 15
```

```
      CALL CLOSE(15,IER)
      IF(IER.NE.1)TYPE"FILE CLOSE ERROR CHAN 15",IER
      CALL DFILW("TEMP01",IER)
      IF(IER.NE.1)TYPE"FILE DELETE ERROR CHAN 15",IER
      WRITE(10,440)
440   FORMAT(1X,"<33>CN")
      ACCEPT FAKE
      WRITE(10,450)
450   FORMAT(/,1X," REPEAT PROGRAM ? (0-NO;1-YES)",Z)
      ACCEPT NCON
      IF(NCON.EQ.0)GO TO 90
      GO TO 5
90    CONTINUE
      STOP
      END
```

```
C ***** HEATREL.FR ************************************************************
C
C THIS PROGRAM IS DESIGNED TO DETERMINE AND WRITE OUT
C NUMERICAL RESULTS FOR AN APPROXIMATION OF THE HEAT RELEASE FOR A SPARK
C IGNITION ENGINE FROM PRESSURE (VOLTAGE DATA) VS. CRANK ANGLE DATA
C OBTAINED FROM THE ENGINE LAB AND STORED ON DISK OR FLOPPY. THE
C PROGRAM WAS DEVELOPED FROM A CONCEPT GIVEN IN SAE PAPER NO. 780967.
C
C
C AUTHOR:       K.R. SCHMID
C               MECHANICAL ENGINEERING DEPARTMENT
C               UNIVERSITY OF MISSOURI-ROLLA
C               ROLLA,MISSOURI 65401
C
C REVISION HISTORY
C
C               8/1/80 ORGINAL CREATED
C               9/13/80 REVISED FOR MULTIPLY RUNS
C               7/12/81 SUBROUTINE EGR ADDED
C
C
C  LOADING INFORMATION
C
C       RLDR HEATREL EGR PHASE FORT.LB 12/C
C
C DEFINTIONS:
C
C       IFILE   = FILENAME
C       IDATA   = BINARY VOLTAGE DATA
C       PRES    = CALIBRATED PRESSURE DATA
C       CALB    = CALIBRATION FACTOR (PSI/VOLT)
C       BORE    = ENGINE BORE (IN.)
C       R       = ENGINE CRANK THROW (IN.)
C       RL      = CONNECTING ROD LENGTH (IN.)
C       CR      = COMPRESSION RATIO
C       CSLOPE  = SLOPE OF COMPRESSION LINE (LOG-LOG PLOT)
C       DSLOPE  = SLOPE AT DATA POINT
C       ESLOPE  = SLOPE OF EXPANSION LINE
C       IGN     = SPARK TIMING
C       IGN1    = 20 DEGREES BEFORE SPARK TIMING
C       EVO     = EXHAUST VALVE OPENING
C       EVO1    = 20 DEGREES BEFORE EXHAUST VALVE OPEN
C       CPOINT  = EXTRAPOLATION OF COMPRESSION LINE TO ORDINATE AXIS
C       DPOINT  = DATA POINT
C       EPOINT  = EXTRAPOLATION OF EXPANSION LINE TO ORDINATE AXIS
C       COMB    = COMBUSTION DURATION
C       MFB     = MASS FRACTION BURNED
C       START   = START OF COMBUSTION
C       FINISH  = END OF COMBUSTION
C
C *****************************************************************************
        DIMENSION RFILE(10),IHEADR(40),IDATA(720),TESTFILE(20)
        DIMENSION IFILE(10),AFILE(10),DFILE(10),MFILE(10)
        DIMENSION VOLT(720),RATE(720),XMFB(720)
        DIMENSION IDATE(10),KDATE(3),BFUEL(3),FILE(20)
        DOUBLE PRECISION RUN,RUNNO
        COMMON /A/ CO2,MCO2,CO2B,AFC,AFO,XMF,Y
        COMMON /PDATA/ PRES1(720),PRES(720)
        REAL MCO2,NPRES,NTEMP,NOZZLE,LHV,MTEMP,MTRFR,MPRES,NOX
        INTEGER EVO,EVO1,SPARK,START,FINISH,COMB
C
        CALB = 91.274
        BORE = 3.250
        R = 2.250
        RL = 10.0
        CR = 8.0
        EVO = 500
        EVO1 = 480
        MCURVE = 0
```

```
      N = 0
C
      WRITE(10,400)
400   FORMAT(1X,"FILENAME OF DATA:",Z)
      READ(11,300)FILE(1)
300   FORMAT(S18)
      ACCEPT"OUTPUT DEVICE CODE(10-CONSOLE;12-PRINTER)",IOUT
      CALL OPEN(0,FILE(1),IER)
      IF(IER.NE.1)TYPE"FILE OPEN ERROR CHAN 0",IER
      READ(0)NUM,PREF
      READ(0,510)TESTFILE(1)
      READ(0,510)RFILE(1)
510   FORMAT(S18)
      CALL OPEN(3,TESTFILE,1,IER)
      IF(IER.NE.1)TYPE"FILE OPEN ERROR - CHAN 3",IER
      CALL OPEN(4,RFILE,2,IER)
      IF(IER.NE.1)TYPE"FILE OPEN ERROR - CHAN 4",IER
      READ(3,500)BFUEL(1)
500   FORMAT(S8)
      READ(3)LHV,AFS,Y,X,SG,CR,RPM,MPRES,MTEMP,OTEMP,
     &WTEMP,XPRES,NOZZLE
      CALL FGTIM(IHR,IMIN,ISEC)
      CALL DATE(KDATE,IER)
      IF(IER.NE.1)TYPE" ERROR IN CALLING THE DATE"
C
C ***** READ AND WRITE HEADER INFORMATION *******
C
      IF(IOUT.EQ.10)GO TO 6
      WRITE(IOUT,700)
700   FORMAT(1X,"<33><46><153><62><123>")
6     WRITE(IOUT,401)KDATE(1),KDATE(2),KDATE(3),IHR,IMIN,ISEC
401   FORMAT(/////,100X,"DATE :",I2,"/",I2,"/",I2,/,100X,
     &"TIME :",I2,":",I2,":",I2,/////)
      WRITE(IOUT,402)
402   FORMAT(//," FUEL CHARACTERISITICS :")
      WRITE(IOUT,403)BFUEL(1),LHV,AFS,Y,X,SG
403   FORMAT(/5X,"BASE FUEL ",11X,S8,/,5X,"LOWER HEATING VALUE",2X,
     &F6.0,/,5X,"STOICHIOMETRIC A/F ",2X,F6.3,/,5X,"FUEL MOLECULE ",
     &7X,"CH(",F5.3,")O(",F5.3,")",/,5X,"SPECFIC GRAVITY",6X,
     &F5.3,/)
      WRITE(IOUT)" ENGINE TEST CONDITIONS "
      WRITE(IOUT,404)CR,RPM,MPRES,XPRES,MTEMP,OTEMP,WTEMP
404   FORMAT(/,5X,"COMPRESSION RATIO ",14X,F4.1,/5X,"ENGINE
     & SPEED,RPM ",16X,F5.0,/,5X,"INTAKE MANIFOLD PRESSURE,KPA
     & ",4X,F6.2,/,5X,"EXHAUST PRESSURE, KPA ",11X,F5.2,/,5X,
     &"MIXTURE TEMP., DEG.F ",12X,F4.0,/,5X,"OIL TEMP., DEG. F "
     &,15X,F4.0,/,5X,"COOLANT TEMP., DEG. F",12X,F4.0,/)
      WRITE(IOUT,408)
      WRITE(IOUT,405)
      WRITE(IOUT,406)
      WRITE(IOUT,407)
405   FORMAT(4X,"RUN NO",4X,"PHI",5X,"EGR",4X,"EXHAUST",3X,
     &"COMP",4X,"EXP",5X,"RESIDUAL",3X,"TRAPPED",3X,"TRAPPED",5X,"HEAT",
     &5X,"SPARK",5X,"COMB",5X,"COMB",5X,"COMB")
406   FORMAT(14X,"OXY",6X,"%",5X,"PRESSURE",2X,"SLOPE",3X,"SLOPE",3X,
     &"MASS",7X,"MASS",6X,"FUEL",6X,"RELEASED",3X,"TIMING",4X,"START"
     &,4X,"FINISH",2X,"DURATION")
407   FORMAT(31X,"KPA",21X,"FRACTION",3X,"GRAMS",5X,"GRAMS",8X,"KJ",/)
408   FORMAT("1",///,60X," *** RESULTS ***",///)
C
C
C **** OUTPUT FILE HEADER TO RESULT FILE
C
      WRITE(4,402)
      WRITE(4,403)BFUEL(1),LHV,AFS,Y,X,SG
      WRITE(4)"ENGINE TEST CONDITIONS"
      WRITE(4,404)CR,RPM,MPRES,XPRES,MTEMP,OTEMP,WTEMP
      WRITE(4,408)
      WRITE(4,405)
      WRITE(4,406)
```

```
      WRITE(4,407)
C
C **** OPEN TEMPORARY STORAGE FILES
C
      CALL OPEN(16,"TEMP01",3,IER)
      IF(IER.NE.1)TYPE"FILE OPEN ERROR CHAN 16",IER
C
C ***** CALCULATE VOLUME *****
C
      VOLD = BORE**2.0*0.7854*R*2.0
      VOLC = VOLD/(CR-1.0)
      VOLMAX = VOLD+VOLC
      DO 100 I=1,720
      J=I-1
      CA = FLOAT(J)
      CA = CA*0.01745
      SINA = SIN(CA)
      COSA = COS(CA)
      AP = (BORE**2)*0.7854
      SIN2A = SINA**2
      RL2 = (R/RL)**2
      QNT = (1.0-RL2*SIN2A)**0.5
      VOL = AP*(R*(1.0-COSA)+RL*(1.0-QNT))
      VOLT(I) = ((VOL+VOLC)/VOLMAX)*100.
      TEMP = VOLT(I)
      VOLT(I) = ALOG10(TEMP)
100   CONTINUE
      LHV = LHV*1.054
C
C ***** READ ENGINE DATA FILE & CALCULATE AIR/FUEL RATIO ******
C
15    CONTINUE
C
      MFB25 = EVO
      MFB50 = EVO
      MFB75 = EVO
      START = EVO
      FINISH = EVO
      COMB = EVO
      SUM = 0.0
C
      READ(0,520)RUN,IFILE(1),AFILE(1),DFILE(1),MFILE(1)
520   FORMAT(F10.0,S12,S12,S12,S12)
16    READ(3)RUNNO,BPRES,BTEMP,NPRES,NTEMP,FUFL,SPRK,BKR,MTRFR
      IF(RUNNO.LE.10.0D0)GO TO 35
      READ(3)HC,NOX,CO2,CO,O2,MCO2,XTEMP
      IGN = IFIX(SPRK)
      IF(RUN.NE.RUNNO)GO TO 16
C
      XHC = HC/10000.0
      XNO = NOX/10000.0
      XN = 100.0/(3.0*XHC+CO+CO2)
      H2O = (50.0*Y/XN-4.0*XHC)/(CO/(3.8*CO2)+1.0)
      XMF = 12.01+1.008*Y+16.01*X
      A = (3.0*XHC-CO/2.0+1.5*H2O)*XN/100.0
      B = CO2+CO/2.0+H2O/2.0+XNO/2.+O2
      C = (B*XN/100.)-X/2.0
      AFO = 4.76*28.97/XMF*C
      PHIO = AFO/AFS
      CO2B = 400.0
      CALL EGR(XEGR)
C
C ***** READ AND WRITE FILE HEADER ****
C
      CALL FOPEN(1,AFILE)
      READ BINARY (1) IHEADR,ICYCLE
      WRITE(10,410)IHEADR(1),ICYCLE
410   FORMAT(5X,S60,5X,I2," CYCLES RECORED",/)
C
      FACTOR = (CALB/3276.7)*6.895
```

```
      DO 110 I=1,720
      READ BINARY (1) IDATA(I)
      PRES(I) = FLOAT(IDATA(I))
      PRES(I) = (PRES(I)-310.)*FACTOR
110   CONTINUE
      PRESC = PRES(180)-PREF
      DO 120 I=1,720
      TEMP = PRES(I)-PRESC
      PRES(I) = ALOG10(TEMP)
120   CONTINUE
C
C **** SHIFT PRESSURE DATA BY THE AMOUNT IDEG
C
      IDEG = 2
      CALL PHASE(IDEG)
C
      CALL FCLOSE(1)
C
C ***** CALCULATE APPROXIMATE HEAT RELEASE CURVE ****
C
      SPARK = IGN
      IGN = 360-IGN
      IGN1 = IGN-20
      XMFB(IGN1) = 0.0
      XMFB(IGN1+1) = 0.0
      CSLOPE = (PRES(IGN1)-PRES(IGN))/(VOLT(IGN1)-VOLT(IGN))
      ESLOPE = (PRES(EVO1)-PRES(EVO))/(VOLT(EVO1)-VOLT(EVO))
      CPOINT = -(CSLOPE)*(VOLT(IGN)-1.0)+PRES(IGN)
      EPOINT = -(ESLOPE)*(VOLT(EVO)-1.0)+PRES(EVO)
      DIFF = EPOINT-CPOINT
C
      DO 130 K=580,720
      SUM= SUM + PRES(K)
130   CONTINUE
      AVEEXH = SUM/141.0
      VOLS = ((AVEEXH-EPOINT)/ESLOPE)+1.0
      VOLS = ((10.0**VOLS)*VOLMAX)/100.0
      RES = VOLC/VOLS
      AVEEXH = 10.0**AVEEXH
      TRAPF = (FUFL*2.0)*453.6/RPM
      THEAT = TRAPF*LHV
      TRAPM = (TRAPF*(1.0+AFO))/(1.0+RES)
C
      DO 135 I=IGN1,EVO
      DSLOPE = CSLOPE*(1.0-XMFB(I-1))+ESLOPE*(XMFB(I-1))
      DPOINT = -(DSLOPE)*(VOLT(I)-1.0)+PRES(I)
      XMFB(I) = (DPOINT-CPOINT)/(EPOINT-CPOINT)
C
C **** DETERMINE HEAT RELEASE RATE ****
C
      RATE(I) = XMFB(I)-XMFB(I-1)
C
C **** DETERMINE SELECTED POINTS AND FLAG *****
C
      IF(XMFB(I).LE.0.0005)XMFB(I)=0.0000
      IF(XMFB(I).GE.0.9995)XMFB(I) = 1.0000
      IF(XMFB(I).LE.0.020.AND.XMFB(I).GE.0.005)START=I-360
      IF(XMFB(I).LE.0.920.AND.XMFB(I).GE.0.890)FINISH=I-360
      IF(XMFB(I).LE.0.275.AND.XMFB(I).GE.0.225)MFB25 = I
      IF(XMFB(I).LE.0.525.AND.XMFB(I).GE.0.475)MFB50 = I
      IF(XMFB(I).LE.0.775.AND.XMFB(I).GE.0.725)MFB75 = I
135   CONTINUE
      COMB = FINISH-START
      IGN = IGN-360
      CA25 = FLOAT(MFB25)
      CA50 = FLOAT(MFB50)
      CA75 = FLOAT(MFB75)
C
C ***** OUTPUT NUMERICAL RESULTS *****
C
```

```
      WRITE(IOUT,423)RUNNO,PHIO,XEGR,AVEEXH,CSLOPE,ESLOPE,RES,TRAPM,
     &TRAPF,THEAT,IGN,START,FINISH,COMB
      WRITE(4,423)RUNNO,PHIO,XEGR,AVEEXH,CSLOPE,ESLOPE,RES,TRAPM,
     &TRAPF,THEAT,IGN,START,FINISH,COMB
C
423   FORMAT(2X,F10.0,1X,F6.3,1X,F6.2,3X,F6.1,4X,F5.2,3X,F5.2,3X,
     &F6.3,5X,F7.4,3X,F7.4,3X,F7.3,5X,I3,6X,I3,6X,I3,6X,I3,/)
C
      WRITE BINARY(16)RUNNO,PHIO,XEGR,CA25,CA50,CA75,RATE(MFB25),
     &RATE(MFB50),RATE(MFB75)
      N = N+1
      IF(N.EQ.NUM)GO TO 25
      GO TO 15
35    TYPE"RUNNO NOT FOUND"
25    CONTINUE
      REWIND 16
      WRITE(IOUT,429)
      WRITE(IOUT,430)
      WRITE(IOUT,431)
      WRITE(IOUT,432)
      WRITE(4,429)
      WRITE(4,430)
      WRITE(4,431)
      WRITE(4,432)
C
      DO 140 I=1,NUM
      READ BINARY(16)RUNNO,PHIO,XEGR,CA25,CA50,CA75,RATE25,RATE50,
     &RATE75
      WRITE(IOUT,433)RUNNO,PHIO,XEGR,CA25,RATE25,CA50,RATE50,
     &CA75,RATE75
      WRITE(4,433)RUNNO,PHIO,XEGR,CA25,RATE25,CA50,RATE50,
     &CA75,RATE75
140   CONTINUE
C
429   FORMAT("1",///,40X," *** MASS FRACTION BURN RATE ***",///)
430   FORMAT(3X,"RUN NO.",5X,"PHI",5X,"EGR",4X,"---- 25% MFB ----",
     &5X,"---- 50% MFB ----",5X,"---- 75% MFB ----")
431   FORMAT(15X,"OXY",6X,"%",5X,"CRANK",4X,"MFB RATE",5X,
     &"CRANK",5X,"MFB RATE",5X,"CRANK",4X,"MFB RATE")
432   FORMAT(30X,"ANGLE",5X,"1/DEG",7X,"ANGLE",5X,"1/DEG",
     &8X,"ANGLE",4X,"1/DEG",/)
433   FORMAT(1X,F10.0,2X,F6.3,1X,F6.2,5X,F4.0,3X,F8.5,7X,F4.0,
     &4X,F8.5,7X,F4.0,3X,F8.5,/)
      IF(IOUT.EQ.10)GO TO 7
      WRITE(IOUT,701)
701   FORMAT(1X,"<33><46><153><60><123>")
C
7     CALL RESET
      CALL DFILW("TEMP01",IER)
      IF(IER.NE.1)TYPE"FILE ERROR (DELETE)"
      STOP
      END
```

```
C ***** LPVPLOT.FR ************************************************
C
C THIS PROGRAM IS DESIGNED TO PLOT LOG-PRESSURE VS.LOG-VOLUME
C DATA FROM A FILE CONTAINING VOLTS (PRESSURE) VS CRANK ANGLE DATA.
C
C AUTHOR:       R. T. JOHNSON
C               MECHANICAL ENGINEERING DEPARTMENT
C               UNIVERSITY OF MO - ROLLA
C               ROLLA, MO 65401
C               (314) 341 4661
C
C               K.R. SCHMID
C               MECHANICAL ENGINEERING DEPARTMENT
C               UNIVERSITY OF MISSOURI - ROLLA
C               ROLLA, MISSOURI 65401
C
C REVISION HISTORY:
C
C               10/13/79 - CREATED ORIGINAL
C               10/15/79 - UPDATE ORIGINAL
C                7/12/80 - UPDATE WITH SUBROUTINE PHASE
C                8/13/80 - UPDATED WITH SUBROUTINE GRID
C
C
C LOADING INFORMATION
C
C       RLDR LPVPLOT PHASE GRID VECTR.LB FORT.LB
C
C DEFINITIONS:
C
C       BORE    = ENGINE BORE(IN.)
C       CALB    = CALIBRATION FACTOR(PSI/VOLT)
C       CR      = COMPRESSION RATIO
C       IDATA   = BINARY VOLTAGE DATA
C       IFILE   = FILENAME OF PRESSURE DATA
C       PRES    = CALIBRATED PRESSURE DATA
C       R       = ENGINE CRANK THROW (IN.)
C       RL      = CONNECTING ROD LENGTH
C
C *****************************************************************
        DIMENSION IFILE(10),IHEADR(40),IDATA(720),VOLT(720)
        COMMON /PDATA/ PRES1(720),PRES(720)
C
        CALB = 91.274
        BORE = 3.250
        R = 2.250
        RL = 10.0
        CR = 8.0
        MCURVE = 0
C
10      CONTINUE
        WRITE(10,400)
400     FORMAT(1X,"(33)(14)")
        WRITE(10,401)
401     FORMAT(1X," INPUT FILE :",Z)
        READ(11,301) IFILE(1)
301     FORMAT (S18)
        WRITE(10,402)
402     FORMAT(/,1X," ABSOLUTE REFERENCE PRESSURE (KPA) : ",Z)
        READ(11,302) PREF
302     FORMAT(F6.2)
        WRITE(10,403)
403     FORMAT(/,1X," PRESSURE SHIFT (DEGREES) :",Z)
        READ(11,303)JDEG
303     FORMAT(I1)
        CALL FOPEN(0,IFILE)
        READ BINARY (0) IHEADR,ICYCLE
C
C ***** WRITE FILE HEADER AND DESCRIPTIVE HEADER *****
```

```
C
      WRITE(10,404) IHEADR(1),ICYCLE
404   FORMAT(//,40X,S78,//,40X,I2," CYCLES RECORDED")
      WRITE(10,405)
405   FORMAT(//,1X,"NUMBER OF CYCLES TO PLOT = ? ",Z)
      ACCEPT JCYCLE
      WRITE(10,410)
410   FORMAT(//,1X," ****** TURN ON PLOTTER ***** ",/)
      PAUSE
      IF(MCURVE.EQ.1)GO TO 11
C
C ***** CALCULATE VOLUME *****
C
      VOLD = BORE**2.0*0.7854*R*2
      VOLC = VOLD/(CR-1.0)
      VOLMAX = VOLD+VOLC
      DO 100 I=1,720
      J=I-1
      CA = FLOAT(I)
      CA = CA*0.01745
      SINA = SIN(CA)
      COSA = COS(CA)
      AP = (BORE**2)*0.7845
      SIN2A = SINA**2
      RL2 = (R/RL)**2
      QNT = (1.-RL2*SIN2A)**0.5
      VOL = AP*(R*(1.-COSA)+RL*(1.-QNT))
      VOLT(I) = ((VOLC+VOL)/VOLMAX)*100.0
      TEMP = VOLT(I)
      VOLT(I) = ALOG10(TEMP)
100   CONTINUE
C
C ***** DRAW GRID *****
C
      WRITE(10,600)
600   FORMAT(1X,"(33)CI 40 75 ")
      CALL GRID(1.0,2.0,0.2,1,1.0,4.0,1.0,1,150,900,130,730,1,1)
C
      CALL ANMDE(580,670)
      WRITE(10,610)IFILE(1)
610   FORMAT(1X,"INPUTFILE: ",S18)
      CALL ANMDE(580,640)
      WRITE(10,611)PREF
611   FORMAT(1X,"MANIFOLD PRESS. (KPA) ",F8.2)
      CALL ANMDE(430,75)
      WRITE(10,612)
612   FORMAT(1X,"LOG10 - % OF MAX. VOL. ")
      WRITE(10,613)
613   FORMAT(1X,"(33)CJ 90 ")
      CALL ANMDE(50,300)
      WRITE(10,614)
614   FORMAT(1X,"LOG10 - PRESSURE (KPA)")
      WRITE(10,615)
615   FORMAT(1X,"(33)CJ 0")
C
C ***** PLOT PRESSURE VS. VOLUME DATA *****
C
11    CONTINUE
      CALL DPORT(150,900,130,730,1.,2.,1.,4.0)
      FACTOR = (CALB/3276.7)*6.895
      DO 200 J=1,JCYCLE
      DO 210 I=1,720
      READ BINARY(0) IDATA(I)
      PRES(I) = FLOAT(IDATA(I))
      PRES(I) = (PRES(I)-310.)*FACTOR
210   CONTINUE
      PRESC = PRES(180)-PREF
      DO 220 I=1,720
      TEMP = PRES(I)-PRESC
      PRES(I) = ALOG10(TEMP)
```

```
220     CONTINUE
        CALL PHASE(JDEG)
C
        VOLT2=VOLT(1)
        PRES2=PRES(1)
        CALL MOVEA(VOLT2,PRES2)
        DO 225 I=2,720
        VOLTX=VOLT(I)
        PRESY=PRES(I)
        CALL DRAWA(VOLTX,PRESY)
225     CONTINUE
        CALL MVABS(150,130)
200     CONTINUE
        CALL FCLOSE(0)
        CALL MVABS(0,0)
        WRITE(10,601)
601     FORMAT(1X,"(33) CN")
        CALL ANMDE(0,0)
        ACCEPT FAKE
C ***** STOP TO TURN OFF PLOTTER *****
C ***** HIT RETURN KEY TO COMPLETE PROGRAM *****
        WRITE(10,430)
430     FORMAT(/,1X," PLOT A SECOND CURVE ? (NO-0,YES-1)",Z)
        READ(11,330)MCURVE
330     FORMAT(I1)
        IF(MCURVE.EQ.1)GO TO 10
        WRITE(10,435)
435     FORMAT(/,1X," REPEAT PROGRAM ? (NO-0,YES-1)",Z)
        READ(11,335)NCON
335     FORMAT(I1)
        IF(NCON.EQ.1)GO TO 10
        STOP
        END
```

```
C ***** MEPS.FR ***************************************************
C
C THIS PROGRAM IS DESIGNED TO CALCULATE VARIOUS INDICATED
C MEAN EFFECTIVE PRESSURES FROM THE PRESSURE - CRANK ANGLE
C DATA GENERATED FROM PRESFILE OR PRESAVE.  THE DEFINITIONS
C FOR THE TERMS WERE BASED UPON S.A.E PAPER NO. 7500026.
C
C AUTHOR:         R. T. JOHNSON
C                 MECHANICAL ENGINEERING DEPARTMENT
C                 UNIVERSITY OF MISSOURI - ROLLA
C                 ROLLA, MO 65401
C                 (314) 341 4661
C
C                 K.R. SCHMID
C                 MECHANICAL ENGINEERING DEPARTMENT
C                 UNIVERSITY OF MISSOURI - ROLLA
C                 ROLLA, MISSOURI 65401
C
C REVISION HISTORY:
C
C                 7/14/80 - CREATED ORIGINAL
C                 7/25/80 - REVISED FOR MULTIPLE RUNS
C                 7/13/81 - REVISED TO STORE RESULTS IN DATAFILE
C
C LOADING INFORMATION:
C
C        RLDR MEPS SHIFT FORT.LB 11/C
C
C DEFINITIONS:
C
C        IFILE   = FILENAME
C        IDATA   = BINARY VOLTAGE DATA
C        PRESS   = CALIBRATED PRESSURE DATA
C        CALB    = CALIBRATION FACTOR (PSI/VOLT)
C        BORE    = ENGINE BORE (IN.)
C        R       = ENGINE CRANK THROW (IN.)
C        RL      = CONNECTING ROD LENGTH (IN.)
C        CR      = COMPRESSION RATIO
C        BSMEP   = BRAKE MEP (SCALE)
C        ISMEP   = INDICATED MEP (SCALE)
C        FIWK    = FIRING INDICATED WORK
C        PWK     = FIRING PUMPING WORK
C        FIMEP   = FIRING INDICATED MEP
C        PMEP    = FIRING PUMPING MEP
C        FMEP    = FIRING FRICTIONAL MEP
C        SMMEP   = MOTOR MEP (SCALE)
C        XIWK    = MOTORING INDICATED WORK
C        XPWK    = MOTORING PUMPING WORK
C        XIMEP   = MOTORING INDICATED MEP
C        XPMEP   = MOTORING PUMPING MEP
C        XFMEP   = MOTORING FRICIONAL MEP
C
C        SET IFIRST = 1 TO CREAT A RESULT FILE
C        SET IFIRST = 2 TO APPEND A EXISTING RESULT FILE
C
C ******************************************************************
      DIMENSION RFILE(10),FILE(10),IDATE(10),KDATE(10)
      DIMENSION IFILE(10),AFILE(10),DFILE(10),MFILE(10)
      DIMENSION BFUEL(3),IHEADR(40),MHEADR(40),IDATA(720,2)
      DIMENSION VOLT(720),TESTFILE(20)
      DOUBLE PRECISION RUNNO,RUN
      COMMON /PDATA/ PRES1(720,2),PRES(720,2)
      REAL MCO2,NPRES,NTEMP,NOZZLE
      REAL LHV,MTEMP,MTRFR,MPRES,ISMEP,NOX
C
      N = 0
      CALB = 91.274
      BORE = 3.250
      R = 2.250
```

```
      RL = 10.0
      CR = 8.0
C
      WRITE(10,400)
400   FORMAT(1X,"FILENAME OF DATA:",Z)
      READ(11,300)FILE(1)
300   FORMAT(S18)
      CALL OPEN(0,FILE(1),IER)
      IF(IER.NE.1)TYPE" FILE OPEN ERROR CHAN 0",IER
      READ(0)NUM,PREF,IFIRST
      READ(0,510)TESTFILE(1)
      READ(0,510)RFILE(1)
510   FORMAT(S18)
      CALL OPEN(3,TESTFILE,1,IER)
      READ(3,500)BFUEL(1)
500   FORMAT(S8)
      READ(3)LHV,AFS,Y,X,SG,CR,RPM,MPRES,MTEMP,OTEMP,
     &WTEMP,XPRES,NUZZLE
      CALL FGTIM(IHR,IMIN,ISEC)
      CALL DATE(KDATE,IER)
C
C ***** READ AND WRITE HEADER INFORMATION *****
C
      WRITE(12,410)KDATE(1),KDATE(2),KDATE(3),IHR,IMIN,ISEC
410   FORMAT(/////,100X,"DATE :",I2,"/",I2,"/",I2,/,100X,
     &"TIME :",I2,":",I2,":",I2,/////)
      WRITE(12,411)
411   FORMAT(//" FUEL CHARACTERISITICS :")
      WRITE(12,412)BFUEL(1),LHV,AFS,Y,X,SG
412   FORMAT(/5X,"BASE FUEL ",11X,S8,/,5X,"LOWER HEATING VALUE",2X,
     &F6.0,/,5X,"STOICHIOMETRIC A/F ",2X,F6.3,/,5X,"FUEL MOLECULE ",
     &7X,"CH(",F5.3,")O(",F5.3,")",/,5X,"SPECFIC GRAVITY",6X,
     &F5.3,/)
      WRITE(12)" ENGINE TEST CONDITIONS"
      WRITE(12,413)CR,RPM,MPRES,XPRES,MTEMP,OTEMP,WTEMP
413   FORMAT(/,5X,"COMPRESSION RATIO ",14X,F4.1,/5X,"ENGINE
     & SPEED,RPM ",16X,F5.0,/,5X,"INTAKE MANIFOLD PRESSURE,KPA
     & ",4X,F6.2,/,5X,"EXHAUST PRESSURE, KPA ",11X,F5.2,/,5X,
     &"MIXTURE TEMP., DEG.F "12X,F4.0,/,5X,"OIL TEMP., DEG. F
     & "15X,F4.0,/,5X,"COOLANT TEMP., DEG. F",12X,F4.0,/)
      WRITE(12,420)
      WRITE(12,421)
      WRITE(12,422)
420   FORMAT("1",2X,"RUN NO",5X,"PHI",17X,"SCALE",28X,
     &"FIRING",20X,"MOTORING")
421   FORMAT(21X,"BRAKE",3X,"MOTOR",4X,"MMEP",5X,"IMEP",5X,"IMEP",5X,
     &"PMEP",5X,"FMEP",5X,"IMEP",5X,"PMEP",5X,"FMEP")
422   FORMAT(21X,"FORCE",3X,"FORCE",4X,"KPA",6X,"KPA",6X,"KPA",6X,
     &"KPA",6X,"KPA",6X,"KPA",6X,"KPA",6X,"KPA",/)
C
C *** WRITE HEADER INFORMATION TO THE RESULT FILE ***
C
      IF(IFIRST.EQ.2)GO TO 5
      CALL OPEN(4,RFILE,2,IER)
      IF(IER.NE.1)TYPE" FILE OPEN ERROR - CHAN 4",IER
      WRITE(4,410)KDATE(1),KDATE(2),KDATE(3),IHR,IMIN,ISEC
      WRITE(4,411)
      WRITE(4,412)BFUEL(1),LHV,AFS,Y,X,SG
      WRITE(4)" ENGINE TEST CONDITIONS"
      WRITE(4,413)CR,RPM,MPRES,XPRES,MTEMP,OTEMP,WTEMP
      WRITE(4,420)
      WRITE(4,421)
      WRITE(4,422)
      GO TO 6
5     CONTINUE
      CALL APPEND(4,RFILE,2,IER)
      IF(IER.NE.1)TYPE "FILE APPEND ERROR - CHAN 4",IER
C
6     CONTINUE
C ***** CALCULATE VOLUME *****
```

```
C
      VOLD=BORE**2*0.7854*R*2
      VOLC=VOLD/(CR-1.)
      VOLMAX=VOLD+VOLC
      DO 120 I=1,720
      J=I-1
      CA = FLOAT(J)
      CA=CA*0.01745
      SINA=SIN(CA)
      COSA=COS(CA)
      AP=(BORE**2)*0.7854
      SIN2A=SINA**2
      RL2=(R/RL)**2
      QNT=(1.-RL2*SIN2A)**0.5
      VOL=AP*(R*(1.-COSA)+RL*(1.-QNT))
      VOLT(I)=(VOL+VOLC)*0.00001638
 120  CONTINUE
C
C ***** READ ENGINE DATA FILE & CALCULATE AIR/FUEL RATIO *****
C
15    CONTINUE
      READ(0,520) RUN,IFILE(1),AFILE(1),DFILE(1),MFILE(1)
520   FORMAT(F10.0,S12,S12,S12,S12)
16    READ(3)RUNNO,BPRES,BTEMP,NPRES,NTEMP,FUFL,SPKT,BKFR,MTRFR
      IF(RUNNO.LE.10.0D0)GO TO 35
      READ(3)HC,NOX,CO2,CO,O2,MCO2,XTEMP
      IF(RUNNO.NE.RUN)GO TO 16
C
      XHC = HC/10000.0
      XNO = NOX/10000.0
      XN = 100./(3.*XHC+CO+CO2)
      H2O = (50.0*Y/XN-4.*XHC)/(CO/(3.8*CO2)+1.0)
      XMF = 12.01+1.008*Y+16.0*X
      A = (3.*XHC-CO/2.+1.5*H2O)*XN/100.0
      B = CO2+CO/2.+H2O/2.+XNO/2.+O2
      C = (B*XN/100.)-X/2.
      AFO = 4.76*28.97/XMF*C
      PHIO = AFO/AFS
C
C ***** READ AND WRITE ENGINE PRESSURE FILE HEADER *****
C
      CALL FOPEN(1,AFILE)
      CALL FOPEN(2,MFILE)
C
      READ BINARY (1) IHEADR,ICYCLE
      READ BINARY (2) MHEADR,MCYCLE
C
      WRITE(10,425)IHEADR(1),ICYCLE
425   FORMAT(5X,S60,5X,I2," CYCLES RECORDED",/)
C
C ***** SCALE PRESSURE DATA ******
C
      DO 115 J=1,2
      DO 100 I=1,720
      READ BINARY(J)IDATA(I,J)
      FACTOR = (CALB/3276.7)*6.895
      PRES(I,J) = FLOAT(IDATA(I,J))
      PRES(I,J) = (PRES(I,J)-310.)*FACTOR
100   CONTINUE
      PRESC = PRES(180,J)-PREF
      DO 110 I=1,720
      PRES(I,J) = PRES(I,J)-PRESC
110   CONTINUE
115   CONTINUE
      CALL SHIFT(2)
      CALL FCLOSE(1)
      CALL FCLOSE(2)
C
C ***** CALCULATE WORK *****
C
```

```
      DO 125 J = 1,2
       WK12T=0.0
      DO 130 I=1,179
      WK12=(PRES(I,J)+PRES((I+1),J))*(VOLT(I+1)-VOLT(I))/2.0
       WK12T=WK12+WK12T
130   CONTINUE
       WK23T=0.0
      DO 140 I=180,359
      WK23=(PRES(I,J)+PRES((I+1),J))*(VOLT(I+1)-VOLT(I))/2.0
       WK23T=WK23+WK23T
140   CONTINUE
       WK34T=0.0
      DO 150 I=360,539
      WK34=(PRES(I,J)+PRES((I+1),J))*(VOLT(I+1)-VOLT(I))/2.
       WK34T=WK34+WK34T
150   CONTINUE
       WK41T=0.0
      DO 160 I=540,719
      WK41=(PRES(I,J)+PRES((I+1),J))*(VOLT(I+1)-VOLT(I))/2.
       WK41T=WK41+WK41T
160   CONTINUE
       DEM = VOLD*0.00001638
       IF(J.EQ.2)GO TO 10
C
C ***** CALCULATIONS FOR FIRING DATA
C
       BSMEP = BKFR*27.89
       ISMEP = (BKFR+MTRFR)*27.89
       FIWK = WK34T+WK23T
       PWK = WK41T+WK12T
       FIMEP = FIWK/DEM
       PMEP = PWK/DEM
       FMEP = -BSMEP+FIMEP+PMEP
C
C ***** CALCULATIONS FOR MOTORING DATA *****
C
10     CONTINUE
       SMMEP = MTRFR*27.89
       XIWK = WK34T+WK23T
       XPWK = WK41T+WK12T
       XIMEP = XIWK/DEM
       XPMEP = XPWK/DEM
       XFMEP = SMMEP+XIMEP+XPMEP
C
125    CONTINUE
C
C ***** WRITE OUT RESULTS *****
C
       WRITE(12,430)RUNNO,PHIO,BKFR,MTRFR,SMMEP,ISMEP,FIMEP,PMEP
     &,FMEP,XIMEP,XPMEP,XFMEP
       WRITE(4,430)RUNNO,PHIO,BKFR,MTRFR,SMMEP,ISMEP,FIMEP,PMEP
     &,FMEP,XIMEP,XPMEP,XFMEP
430    FORMAT(1X,F10.0,2X,F5.2,3X,F5.2,3X,F5.2,3X,F6.2,3X,F6.2,3X,
     &F6.2,3X,F6.2,3X,F6.2,3X,F6.2,3X,F6.2,3X,F6.2,/)
C
       N=N+1
       IF(N.EQ.NUM)GO TO 25
       GO TO 15
25     CONTINUE
       REWIND 0
       REWIND 3
       REWIND 4
       CALL RESET
       STOP
35     CONTINUE
       REWIND 0
       REWIND 3
       REWIND 4
       CALL RESET
       TYPE" RUN NUMBER NOT FOUND"
```

```
STOP
END
```

```
C ***** MFBPLOT.FR ***********************************************
C
C THIS PROGRAM IS DESIGNED TO DETERMINE AND PLOT THE
C APPROXIMATION OF THE MASS FRACTION CURVE FOR A
C SPARK IGNITION ENGINE FROM A FILE CONTAINING
C VOLTS(PRESSURE) VS. CRANK ANGLE DATA. DEVELOPED
C FROM CONCEPT GIVEN IN S.A.E. PAPER NO. 780967.
C
C AUTHOR:         K.R. SCHMID
C                 MECHANICAL ENGINEERING DEPARTMENT
C                 UNIVERSITY OF MISSOURI-ROLLA
C                 ROLLA,MISSOURI 65401
C
C REVISION HISTORY
C
C                 08/1/80 ORGINAL CREATED
C                 11/22/80 PLOTTING ADDED
C                 07/12/81 SUBROUTINE EGR ADDED
C
C
C LOADING INFORMATION:
C
C       RLDR MFBPLOT GRID EGR PHASE VECTR.LB FORT.LB
C
C DEFINTIONS:
C
C       BORE    = ENGINE BORE (IN.I
C       CALB    = CALIBRATION FACTOR (PSI/VOLT)
C       COMB    = COMBUSTION DURATION
C       CPOINT  = EXTRAPOLATION OF COMPRESSION LINE TO ORDINATE AXIS
C       CSLOPE  = SLOPE OF COMPRESSION LINE (LOG-LOG PLOT)
C       CR      = COMPRESSION RATIO
C       DPOINT  = DATA POINT
C       DSLOPE  = SLOPE AT DATA POINT (LOG-LOG PLOT)
C       EPOINT  = EXTRAPOLATION OF EXPANSION LINE TO ORDINATE AXIS
C       ESLOPE  = SLOPE OF EXPANSION LINE (LOG-LOG PLOT)
C       EVO     = EXHAUST VALVE OPEN
C       FINISH  = END OF COMBUSTION PROCESS
C       IDATA   = BINARY VOLTAGE DATA
C       IGN     = SPARK TIMING
C       IFILE   = FILENAME OF PRESSURE DATA
C       MFB     = MASS FRACTION BURNED
C       PRES    = CALIBRATED PRESSURE
C       R       = ENGINE CRANK THROW (IN.)
C       RL      = CONNECTING ROD LENGTH (IN.)
C       START   = START OF COMBUSTION
C
C ****************************************************************
        DIMENSION IFILE(10),IHEADR(40),IDATA(720),TESTFILE(20)
        DIMENSION VOLT(720),RATE(720),XMFB(720)
        DIMENSION IDATE(10),KDATE(3),BFUEL(3),FILE(20)
        DOUBLE PRECISION RUN,RUNNO
        COMMON /A/ CO2,MCO2,CO2B,AFC,AFO,XMF,Y
        COMMON /PDATA/ PRES1(720),PRES(720)
        REAL MCO2,NPRES,NTEMP,NOZZLE,LHV,MTEMP,MTRFR,MPRES,NOX
        INTEGER EVO,EVO1,SPARK,START,FINISH,COMB
C
        CALB = 91.274
        BORE = 3.250
        R = 2.250
        RL = 10.0
        CR = 8.0
        EVO = 500
        EVO1 = 480
        MCURVE = 0
        N = 0
C
10      CONTINUE
        WRITE(10,400)
```

```
400     FORMAT(1X,"<33><14>")
        WRITE(10,401)
401     FORMAT(/,1X,"FILENAME OF DATA:",Z)
        READ(11,301)FILE(1)
301     FORMAT(S18)
        CALL OPEN(0,FILE(1),IER)
        IF(IER.NE.1)TYPE"FILE OPEN ERROR CHAN 0",IER
        WRITE(10,402)
402     FORMAT(/,1X,"RUN NUMBER OF DATA:",Z)
        ACCEPT RUN
        WRITE(10,403)
403     FORMAT(/,1X,"PRESSURE DATA FILENAME:",Z)
        READ(11,303)IFILE(1)
303     FORMAT(S18)
        WRITE(10,404)
404     FORMAT(/,1X,"REFERENCE PRESSURE (KPA):",Z)
        ACCEPT PREF
        READ(0,500)BFUEL(1)
500     FORMAT(S8)
        READ(0)LHV,AFS,Y,X,SG,CR,RPM,MPRES,MTEMP,OTEMP,
     &WTEMP,XPRES,NOZZLE
C
C ***** CALCULATE VOLUME *****
C
        VOLD = BORE**2.0*0.7854*R*2.0
        VOLC = VOLD/(CR-1.0)
        VOLMAX = VOLD+VOLC
        DO 100 I=1,720
        J=I-1
        CA = FLOAT(J)
        CA = CA*0.01745
        SINA = SIN(CA)
        COSA = COS(CA)
        AP = (BORE**2)*0.7854
        SIN2A = SINA**2
        RL2 = (R/RL)**2
        QNT = (1.0-RL2*SIN2A)**0.5
        VOL = AP*(R*(1.0-COSA)+RL*(1.0-QNT))
        VOLT(I) = ((VOL+VOLC)/VOLMAX)*100.
        TEMP = VOLT(I)
        VOLT(I) = ALOG10(TEMP)
100     CONTINUE
        LHV = LHV*1.054
C
C ***** READ ENGINE DATA FILE & CALCULATE AIR/FUEL RATIO ******
C
C
        MFB25 = EVO
        MFB50 = EVO
        MFB75 = EVO
        START = EVO
        FINISH = EVO
        COMB = EVO
        SUM = 0.0
C
16      CONTINUE
        READ(0)RUNNO,BPRES,BTEMP,NPRES,NTEMP,FUEL,SPRK,BKR,MTRFR
        IF(RUNNO.LE.10.0D0)GO TO 30
        READ(0)HC,NOX,CO2,CO,O2,MCO2,XTEMP
        IF(RUN.NE.RUNNO)GO TO 16
        IGN = IFIX(SPRK)
C
        XHC = HC/10000.0
        XNO = NOX/10000.0
        XN = 100.0/(3.0*XHC+CO+CO2)
        H2O = (50.0*Y/XN-4.0*XHC)/(CO/(3.8*CO2)+1.0)
        XMF = 12.01+1.008*Y+16.01*X
        A = (3.0*XHC-CO/2.0+1.5*H2O)*XN/100.0
        B = CO2+CO/2.0+H2O/2.0+XNO/2.+O2
        C = (B*XN/100.)-X/2.0
```

```
      AFO = 4.76*28.97/XMF*C
      PHIO = AFO/AFS
C
      CO2B = 400.0
      CALL EGR(XEGR)
C
C ***** READ AND WRITE FILE HEADER ****
C
      CALL FOPEN(1,IFILE)
      READ BINARY (1) IHEADR,ICYCLE
      WRITE(10,410)IHEADR(1),ICYCLE
410   FORMAT(/,5X,S60,//,5X,I2," CYCLES RECORED",/)
C
C
      FACTOR = (CALB/3276.7)*6.895
      DO 110 I=1,720
      READ BINARY (1) IDATA(I)
      PRES(I) = FLOAT(IDATA(I))
      PRES(I) = (PRES(I)-310.)*FACTOR
110   CONTINUE
      PRESC = PRES(180)-PREF
      DO 120 I=1,720
      TEMP = PRES(I)-PRESC
      PRES(I) = ALOG10(TEMP)
120   CONTINUE
C
C **** SHIFT PRESSURE DATA BY THE AMOUNT IDEG
C
      IDEG =2
      CALL PHASE(IDEG)
      CALL FCLOSE(1)
      CALL RESET
C
C ***** CALCULATE APPROXIMATE HEAT RELEASE CURVE ****
C
      SPARK = IGN
      IGN = 360-IGN
      IGN1 = IGN-20
      XMFB(IGN1) = 0.0
      XMFB(IGN1+1) = 0.0
      CSLOPE = (PRES(IGN1)-PRES(IGN))/(VOLT(IGN1)-VOLT(IGN))
      ESLOPE = (PRES(EVO1)-PRES(EVO))/(VOLT(EVO1)-VOLT(EVO))
      CPOINT = -(CSLOPE)*(VOLT(IGN)-1.0)+PRES(IGN)
      EPOINT = -(ESLOPE)*(VOLT(EVO)-1.0)+PRES(EVO)
      DIFF = EPOINT-CPOINT
C
      DO 130 K=580,720
      SUM= SUM + PRES(K)
130   CONTINUE
      AVEEXH = SUM/141.0
      VOLS = ((AVEEXH-EPOINT)/ESLOPE)+1.0
      VOLS = ((10.0**VOLS)*VOLMAX)/100.0
      RES = VOLC/VOLS
      AVEEXH = 10.0**AVEEXH
      TRAPF = (FUFL*2.0)*453.6/RPM
      THEAT = TRAPF*LHV
      TRAPM = (TRAPF*(1.0+AFO))/(1.0+RES)
C
      DO 135 I=IGN1,EVO
      DSLOPE = CSLOPE*(1.0-XMFB(I-1))+ESLOPE*(XMFB(I-1))
      DPOINT = -(DSLOPE)*(VOLT(I)-1.0)+PRES(I)
      XMFB(I) = (DPOINT-CPOINT)/(EPOINT-CPOINT)
C
C ***** DETERMINE HEAT RELEASE RATE ****
C
      RATE(I) = XMFB(I)-XMFB(I-1)
C
C ***** DETERMINE SELECTED POINTS AND FLAG *****
C
      IF(XMFB(I).LE.0.0005)XMFB(I)=0.0000
```

```
      IF(XMFB(I).GE.0.9995)XMFB(I) = 1.0000
      IF(RATE(I).LE.0.0005)RATE(I)=0.0000
135   CONTINUE
      J = - SPARK
C
      WRITE(10,411)
411   FORMAT(/,1X," ***** TURN ON PLOTTER ***** ")
      PAUSE
C
C ***** PLOT MASS FRACTION BURNED RESULTS *****
C
      WRITE(10,600)
600   FORMAT(1X,"(33)CI 40 75")
      CALL GRID(-60.0,140.0,20.0,1,0.0,1.0,.20,1,140,860,130,730,1,1)
      YNUM = 0.0
      DO 140 IY = 130,730,120
      I2Y = IY-5
      CALL ANMDE(880,I2Y)
      WRITE(10,610)YNUM
610   FORMAT(1X,F5.3)
      YNUM = YNUM+0.01
140   CONTINUE
C
C ***** LABEL AXIS ****
C
      CALL ANMDE(380,90)
      WRITE(10,620)
620   FORMAT(1X,"CRANK ANGLE DEGREES")
      WRITE(10,621)
621   FORMAT(1X,"(33)CJ 90 ")
      CALL ANMDE(60,300)
      WRITE(10,622)
622   FORMAT(1X,"MASS FRACTION BURNED")
      CALL ANMDE(960,300)
      WRITE(10,623)
623   FORMAT(1X,"MASS BURNED RATE -1/DEG")
      WRITE(10,624)
624   FORMAT(1X,"(33)CJ 0 ")
      CALL ANMDE(175,700)
      WRITE(10,630)IFILE(1)
630   FORMAT(1X,"DATAFILE:",S18)
      CALL ANMDE(175,675)
      WRITE(10,631)XEGR
631   FORMAT(1X,"EGR RATE =",F4.1,"%")
      CALL ANMDE(175,650)
      WRITE(10,632)PHIO
632   FORMAT(1X,"EQ. AIR/FUEL = ",F5.3)
      CALL ANMDE(175,625)
      WRITE(10,633)SPARK
633   FORMAT(1X,"SPARK TIMING",I3)
C
C **** PLOT DATA *****
C
      CALL DPORT(140,860,130,730,-60.0,140.0,0.0,1.0)
      CA = FLOAT(J)
      YDATA = XMFB(IGN)
      CALL MOVEA(CA,YDATA)
      DO 210 I = IGN,EVO
      YDATA = XMFB(I)
      CALL DRAWA(CA,YDATA)
      CA = CA+1
210   CONTINUE
C
C ***** PLOT MASS BURNED RATE *****
C
      CALL DPORT(140,860,130,730,-60.0,140.0,0.0,0.05)
      CA = FLOAT(J)
      YDATA = RATE(IGN)
      CALL MOVEA(CA,YDATA)
      DO 220 I=IGN,EVO
```

```
      YDATA = RATE(I)
      CALL DRAWA(CA,YDATA)
      CA = CA+1.
220   CONTINUE
      CALL MVABS(0,0)
      WRITE(10,601)
601   FORMAT(1X,"<33>CN ")
      CALL ANMDE(0,0)
      ACCEPT FAKE
      WRITE(10,430)
430   FORMAT(/,1X," REPEAT PROGRAM ? (NO-0;YES-1):",Z)
      ACCEPT NCON
      IF(NCON.EQ.0)STOP
      GO TO 10
30    CONTINUE
      REWIND 0
      CALL CLOSE(0,IER)
      IF(IER.NE.1)TYPE "FILE CLOSE ERROR CHAN 0",IER
      TYPE " "
      TYPE " RUN NUMBER NOT FOUND "
      TYPE " "
      WRITE(10,430)
      ACCEPT NCON
      IF(NCON.EQ.0)STOP
      GO TO 10
      END
```

```
C ***** PRESAVE.FR ***********************************************
C
C THIS PROGRAM IS DESIGNED TO CALCULATE THE AVERAGE
C AND STANDARD DEVIATION FOR THE PRESSURE DATA OBTAINED
C FROM THE PROGRAM PRESFILE.  THE PROGRAM IS STRUCTURED
C SO THAT SEVERAL PRESSURE - CRANK ANGLE DATA FILES
C CAN BE PROCESSED.
C
C  AUTHOR:       R. T. JOHNSON
C                MECHANICAL ENGINEERING DEPARTMENT
C                UNIVERSITY OF MISSOURI - ROLLA
C                ROLLA, MISSOURI 65401
C
C                K.R. SCHMID
C                MECHANICAL ENGINEERING DEPARTMENT
C                UNIVERSITY OF MISSOURI - ROLLA
C                ROLLA, MISSOURI 65401
C
C  REVISION HISTORY:
C
C        12/2/79 CREATED ORIGINAL
C        8/20/80 ORGINAL UPDATED FOR MULTIPLY RUNS
C
C
C  LOADING INFORMATION:
C
C        RLDR PRESAVE FORT.LB
C
C
C  TESTFILE FORMAT:
C
C        NUM,PREF
C        DATA FILENAME
C        AVE. DATA FILENAME
C        DEV. DATA FILENAME
C
C ****************************************************************
        DIMENSION TESTFILE(10)
        DIMENSION IFILE(10),OFILE1(10),OFILE2(10),PRESAV(720),
     &PRESVAR(720),IHEADRI(40),IHEADRO(40),IHEADRD(40)
C
        WRITE(10,400)
400     FORMAT(1X," FILENAME OF DATA :",Z)
        READ(11,300)TESTFILE(1)
300     FORMAT(S18)
        CALL OPEN(3,TESTFILE(1),IER)
        IF(IER.NE.1)TYPE" FILE OPEN ERROR CHAN 3 "
        READ(3)NUM,PREF
        N = 0
C
10      CONTINUE
        READ(3,500)IFILE(1)
        READ(3,500)OFILE1(1)
        READ(3,500)OFILE2(1)
        PREF=PREF*5.207
500     FORMAT(S18)
C
C ***** OPEN DATA AND RESULT FILES *****
C
        CALL OPEN (0,IFILE,1,IER)
        IF (IER.NE.1) TYPE "FILE OPEN ERROR CHAN 0 ",IER
        CALL OPEN (1,OFILE1,3,IER)
        IF (IER.NE.1) TYPE "FILE OPEN ERROR CHAN 1 ",IER
        CALL OPEN (2,OFILE2,3,IER)
        IF (IER.NE.1) TYPE "FILE OPEN ERROR CHAN 2 ",IER
        READ BINARY (0) IHEADRI,ICYCLE
        WRITE(10,425) IHEADRI(1),ICYCLE
425     FORMAT(1X,//,1X,S78,//1X,"NO. OF CYCLES = ",I2)
        WRITE BINARY (1) IHEADRI,ICYCLE
```

```
      WRITE BINARY (2) IHEADRI, ICYCLE
C
C ***** CALCULATE AVERAGE CYCLE *****
C
      ACYCLE=FLOAT(ICYCLE)
      ACYCLE1=ACYCLE-1.
      DO 100 I=1,720
      READ BINARY (0) IDAT
      DAT=FLOAT(IDAT)
      PRESAV(I)=DAT
100   CONTINUE
      PRESC=PRESAV(180)-PREF
      DO 110 I=1,720
      PRESAV(I)=PRESAV(I)-PRESC-PREF
110   CONTINUE
      TYPE "END OF FIRST CYCLE AVERAGE"
      ICYCLE1=ICYCLE-1
      DO 120 I=1,ICYCLE1
      DO 120 J=1,720
      READ BINARY (0) IDAT
      DAT=FLOAT(IDAT)
      DAT1=DAT-PRESC-PREF
      PRESAV(J)=PRESAV(J)+DAT1
120   CONTINUE
      DO 130 I=1,720
      PRESAV(I)=PRESAV(I)/ACYCLE
      TEMP=PRESAV(I)
      ITEMP=IFIX(TEMP)
      WRITE BINARY (1) ITEMP
130   CONTINUE
      TYPE "END OF AVERAGE FILE WRITE, BEGIN DEVIATION"
C
C ***** CALCULATE DEVIATION ******
C
      REWIND 0
      REWIND 1
      READ BINARY (0) IHEADRI,ICYCLE
      READ BINARY (1) IHEADRO,ICYCLE
      DO 140 I=1,720
      READ BINARY (1) ITEMP
      TEMP=FLOAT(ITEMP)
      PRESAV(I)=TEMP
      READ BINARY (0) IDAT
      DAT=FLOAT(IDAT)
      DAT=DAT-PRESC-PREF
      PRESVAR(I)=(DAT-PRESAV(I))**2
140   CONTINUE
C  END OF FIRST VARIANCE CALCULATION
      DO 150 I=1,ICYCLE1
      DO 150 J=1,720
      READ BINARY (0) IDAT
      DAT=FLOAT(IDAT)
      DAT=DAT-PRESC-PREF
      DIF2=(DAT-PRESAV(J))**2
      PRESVAR(J)=PRESVAR(J)+DIF2
150   CONTINUE
      DO 160 I=1,720
      PRESVAR(I)=((PRESVAR(I))/ACYCLE1)**0.5
      TEMP1=(PRESVAR(I)/(PRESAV(I)+PREF))*32768.
      IPRESV=IFIX(TEMP1)
      WRITE BINARY (2) IPRESV
160   CONTINUE
C
      REWIND 0
      REWIND 1
      REWIND 2
      CALL CLOSE(0,IER)
      CALL CLOSE(1,IER)
      CALL CLOSE(2,IER)
      N=N+1
```

```
      IF(N.EQ.NUM)GO TO 25
      GO TO 10
25    CONTINUE
      REWIND 3
      CALL CLOSE(3,IER)
      IF(IER.NE.1)TYPE" FILE CLOSE ERROR CHAN 3"
      STOP
      END
```

```
C ***** PRESFILE.FR ******************************************
C
C THIS PROGRAMN IS DESIGNED TO ACQUIRE "ICYCLE" (1-30)
C CYCLES OF PRESSURE - CRANK ANGLE DATA.
C DATA IS TAKEN AT ONE CRANK ANGLE DEGREE INCREMENTS.
C
C AUTHOR:          R.T. JOHNSON
C                  MECHANICAL ENGINEERING DEPARTMENT
C                  UNIVERSITY OF MISSOURI - ROLLA
C                  ROLLA, MISSOURI 65401
C                  (314) 341 4661
C
C DEFINITIONS:
C
C       IDATA = DATA ARRAY
C       3200 = TRIGGER THRESHOLD (BINARY)
C       ICYCLE = NUMBER OF CYCLES
C       IHEADR = DESCRIPTIVE INFORMATION FOR FILE
C
C LOADING INFORMATION:
C
C       RLDR PRESFILE GETCYCLE.RB FORT.LB 2/K
C
C ************************************************************
      DIMENSION IDATA(720,30), IFILE(10),IHEADR(40)
      CALL DSTRT(IER)
      IF (IER .NE. 1) GOTO 10
  5   WRITE(10,400)
400   FORMAT(1X,"FILENAME : ",Z)
      READ(11,300) IFILE(1)
300   FORMAT(S30)
      CALL CFILW(IFILE,2,IER)
      IF (IER .EQ. 1) GO TO 20
      WRITE(10,410) IFILE(1)
410   FORMAT(1X,"FILE ALREADY EXISTS : ",S20)
      GO TO 5
 20   CALL FOPEN(0,IFILE)
      WRITE(10,415)
415   FORMAT(1X,"DESCRIPTIVE DATA : ",Z)
      READ(11,315) IHEADR(1)
315   FORMAT(S78)
      WRITE(10,420)
420   FORMAT(1X,"NUMBER OF CYCLES (1-30) = ",Z)
      READ(11,320) ICYCLE
320   FORMAT (I2)
      WRITE BINARY (0) IHEADR,ICYCLE
      ICNT = ICYCLE*720
C
      CALL GETCY(IDATA(1,1),3200,ICNT)
      TYPE "DATA TAKEN - BEGINNING WRITE TO FILE"
      DO 100 I=1,ICYCLE
       DO 100 J=1,720
100    WRITE BINARY(0) IDATA(J,I)
      CALL FCLOS(0)
      GO TO 11
10    TYPE "DSTRT ERROR"
11    CONTINUE
      STOP
      END
```

```
C ***** PRESREAD.FR ***********************************************
C
C THIS PROGRAM IS DESIGNED TO OUTPUT THE CONTENTS OF A PRESSURE-
C CRANK ANGLE DATAFILE TO EITHER THE CONSOLE OR LINE PRINTER.
C
C  AUTHOR:        R.T. JOHNSON
C                 MECHANICAL ENGINEERING DEPARTMENT
C                 UNIVERSITY OF MISSOURI - ROLLA
C                 ROLLA, MISSOURI 65401
C                 (314) 341 4661
C
C                 K.R. SCHMID
C                 UNIVERSITY OF MISSOURI - ROLLA
C                 ROLLA, MISSOURI 65401
C
C
C REVISION HISTORY:
C
C  REV  DATE            COMMENTS
C
C  ---  ----            --------
C
C  01   9/17/79         INITIAL REVISION
C  02   10/28/79        REVISED TO INCLUDE MULTIPLE FILES WITH HEADERS
C  03   11/4/79         REVISED TO SEPARATE CYCLES
C  04   01/3/80         REVISED TO INCLUDE LINE NUMBER
C
C
C *****************************************************************
        DIMENSION IFILE(10),ICHAN(10),PVOLT(10),IHEADR(40)
        WRITE (10,400)
400     FORMAT (1X,10X,"INPUTFILE : ",Z)
        READ (11,300) IFILE(1)
300     FORMAT (S18)
        CALL FOPEN (0,IFILE)
        WRITE (10,410)
410     FORMAT(1X,/,10X,"OUTPUTFILE (10-CONSOLE, 12-PRINTER) : ",Z)
        ACCEPT IOUT
        IF (IOUT.EQ.10.OR.IOUT.EQ.12)GO TO 6
        GO TO 5
6       CONTINUE
        READ BINARY (0) IHEADR,ICYCLE
        WRITE (10,420) IHEADR(1),ICYCLE
420     FORMAT (/,10X,S60,//,10X,I2," CYCLES RECORDED")
        WRITE(10,430)
430     FORMAT(/,10X,"NUMBER OF CYCLES TO BE OUTPUT : ",Z)
        READ(11,330) ICYCLE1
330     FORMAT(I2)
        IF(IOUT.EQ.10) GO TO 7
        WRITE(12,440)IFILE(1)
440     FORMAT(10X,S18,/)
        WRITE(12,450)IHEADR(1)
450     FORMAT(10X,S78,/)
7       CONTINUE
        NUM=1
        DO 100 K=1,ICYCLE1
        WRITE (IOUT,460) NUM
460     FORMAT (/,30X," CYCLE  ",I2,/)
        NUM=NUM+1
        DO 101 I=1,72
         DO 102 J=1,10
         READ BINARY (0) ICHAN(J)
         PVOLT(J)=FLOAT(ICHAN(J))
         PVOLT(J)=PVOLT(J)/3276.7
102      CONTINUE
        WRITE(IOUT,470)(PVOLT(J),J=1,10),I
470     FORMAT(1X,10(2X,F5.2),4X,I2)
101     CONTINUE
100     CONTINUE
        CALL FCLOS(0)
```

```
        STOP
5       TYPE " ERROR FOR OUTPUT DEVICE CODE "
        CALL FCLOSE(0)
        STOP
        END
```

```
C ***** PVPLOT.FR ***********************************************
C
C THIS PROGRAM IS DESIGNED TO PLOT PRESSURE VS. VOLUME
C DATA FROM A FILE CONTAINING VOLTS (PRESSURE) - CRANK
C ANGLE DATA.
C
C AUTHOR:        R. T. JOHNSON
C                MECHANICAL ENGINEERING DEPARTMENT
C                UNIVERSITY OF MO - ROLLA
C                ROLLA, MO 65401
C                (314) 341 4661
C
C                K.R. SCHMID
C                MECHANICAL ENGINEERING DEPARTMENT
C                UNIVERSITY OF MISSOURI - ROLLA
C                ROLLA, MISSOURI 65401
C
C REVISION HISTORY:
C
C                10/13/79 - CREATED ORIGINAL
C                10/15/79 - UPDATE ORIGINAL
C                 7/12/80 - UPDATE WITH SUBROUTINE PHASE
C                 8/13/80 - UPDATED WITH SUBROUTINE GRID
C
C
C LOADING INFORMATION
C
C       RLDR PVPLOT PHASE GRID VECTR.LB FORT.LB
C
C DEFINITIONS:
C
C       BORE    = ENGINE BORE (IN.)
C       CALB    = CALIBRATION FACTOR (PSI.IN)
C       CR      = COMPRESSION RATIO
C       IDATA   = BINARY VOLTAGE DATA
C       IFILE   = FILENAME OF PRESSURE DATA
C       PRES    = CALIBRATED PRESSURE DATA
C       R       = ENGINE CRANK THROW (IN.)
C       RL      = CONNECTING ROD LENGTH (IN.)
C
C ******************************************************************
        DIMENSION IFILE(10),IHEADR(40),IDATA(720),VOLT(720)
        COMMON /PDATA/ PRES1(720),PRES(720)
C
        MCURVE = 0
        CALB = 91.274
        BORE = 3.250
        R = 2.250
        RL = 10.0
        CR = 8.0
C
10      CONTINUE
        WRITE(10,400)
400     FORMAT(1X,"(33)(14)")
        WRITE(10,401)
401     FORMAT(1X," INPUT FILE :",Z)
        READ(11,301) IFILE(1)
301     FORMAT (S18)
        WRITE(10,402)
402     FORMAT(/,1X," ABSOLUTE REFERENCE PRESSURE (KPA) : ",Z)
        READ(11,302) PREF
302     FORMAT(F6.2)
        WRITE(10,403)
403     FORMAT(/,1X," PRESSURE SHIFT (DEGREES) :",Z)
        READ(11,303)JDEG
303     FORMAT(I1)
        CALL FOPEN(0,IFILE)
        READ BINARY (0) IHEADR,ICYCLE
C
```

```
C ***** WRITE FILE HEADER AND DESCRIPTIVE HEADER *****
C
      WRITE(10,404) IHEADR(1),ICYCLE
404   FORMAT(//,40X,S78,//,40X,I2," CYCLES RECORDED")
      WRITE(10,405)
405   FORMAT(//,1X,"NUMBER OF CYCLES TO PLOT = ? ",Z)
      ACCEPT JCYCLE
      WRITE(10,410)
410   FORMAT(//,1X," ****** TURN ON PLOTTER ***** ",/)
      PAUSE
      IF(MCURVE.EQ.1)GO TO 11
C
C ***** CALCULATE VOLUME *****
C
      VOLD = BORE**2.0*0.7854*R*2
      VOLC = VOLD/(CR-1.0)
      DO 100 I=1,720
      J=I-1
      CA = FLOAT(I)
      CA = CA*0.01745
      SINA = SIN(CA)
      COSA = COS(CA)
      AP = (BORE**2)*0.7845
      SIN2A = SINA**2
      RL2 = (R/RL)**2
      QNT = (1.-RL2*SIN2A)**0.5
      VOL = AP*(R*(1.-COSA)+RL*(1.-QNT))
      VOLT(I) = (VOL+VOLC)*16.387
100   CONTINUE
C
C ***** DRAW GRID *****
C
      WRITE(10,600)
600   FORMAT(1X,"<33>CI 40 75 ")
      CALL GRID(0.0,1000.0,200.0,1,0.0,5000.0,1000.0,1,150,
     &900,130,730,1,1)
C
      CALL ANMDE(580,670)
      WRITE(10,610)IFILE(1)
610   FORMAT(1X,"INPUTFILE: ",S18)
      CALL ANMDE(580,640)
      WRITE(10,611)PREF
611   FORMAT(1X,"MANIFOLD PRESS. (KPA) ",F8.2)
      CALL ANMDE(430,75)
      WRITE(10,612)
612   FORMAT(1X,"VOLUME - CU. CM. ")
      WRITE(10,613)
613   FORMAT(1X,"<33>CJ 90 ")
      CALL ANMDE(50,275)
      WRITE(10,614)
614   FORMAT(1X,"PRESSURE (KPA)")
      WRITE(10,615)
615   FORMAT(1X,"<33>CJ 0")
C
C ***** PLOT PRESSURE VS. VOLUME DATA *****
C
11    CONTINUE
      CALL DPORT(150,900,130,730,0.0,1000.0,0.0,5000.0)
      FACTOR = (CALB/3276.7)*6.895
      DO 200 J=1,JCYCLE
      DO 210 I=1,720
      READ BINARY(0) IDATA(I)
      PRES(I) = FLOAT(IDATA(I))
      PRES(I) = (PRES(I)-310.)*FACTOR
210   CONTINUE
      PRESC = PRES(180)-PREF
      DO 220 I=1,720
      PRES(I) = PRES(I)-PRESC
220   CONTINUE
      CALL PHASE(JDEG)
```

```
C
      VOLT2=VOLT(1)
      PRES2=PRES(1)
      CALL MOVEA(VOLT2,PRES2)
      DO 225 I=2,720
      VOLTX=VOLT(I)
      PRESY=PRES(I)
      CALL DRAWA(VOLTX,PRESY)
225   CONTINUE
      CALL MVABS(150,130)
200   CONTINUE
      CALL FCLOSE(0)
      CALL MVABS(0,0)
      WRITE(10,601)
601   FORMAT(1X,"<33> CN")
      CALL ANMDE(0,0)
      ACCEPT FAKE
C ***** STOP TO TURN OFF PLOTTER *****
C ***** HIT RETURN KEY TO COMPLETE PROGRAM *****
      WRITE(10,430)
430   FORMAT(/,1X," PLOT A SECOND CURVE ? (NO-0,YES-1)",Z)
      READ(11,330)MCURVE
330   FORMAT(I1)
      IF(MCURVE.EQ.1)GO TO 10
      WRITE(10,435)
435   FORMAT(/,1X," REPEAT PROGRAM ? (NO - 0,YES-1 )",Z)
      READ(11,335)NCON
335   FORMAT(I1)
      IF(NCON.EQ.1)GO TO 10
      STOP
      END
```

```
      SUBROUTINE EGR(EGRCAL)
C ******************************************************************
C
C     EXHAUST GAS RECIRCULATION CALCULATION BASED UPON EXHAUST
C     GAS EMISSIONS AND INTAKE MANIFOLD CARBON DIOXIDE.
C
C
C              K.R. SCHMID
C              MECHANICAL ENGINEERING DEPARTMENT
C              UNIVERSITY OF MISSOURI - ROLLA
C              ROLLA, MO 65401
C
C
C REVISION HISTORY:
C
C               7/12/81 - CREATED ORIGINAL
C NOMENCLATURE:
C
C     AFA =   AIR/FUEL AVERAGE BASED ON EMISSIONS
C     AFC =   CARBON BASED AIR/FUEL
C     AFO =   OXYGEN BASED AIR/FUEL
C     CO2 =   CARBON DIOXIDE,%
C     CO2B =  BACKGROUND CO2 IN AIR, PPM
C     MCO2 =  INTAKE MANIFOLD CO2, %
C     Y =     MOLAR H/C RATIO OF FUEL
C
C
C *********************************************************************
      COMMON /A/ CO2,MCO2,CO2B,AFC,AFO,XMF,Y
      REAL MCO2,ICO2
C
      IF(MCO2.LE.0.000)GO TO 35
      ECO2 = (CO2-CO2B*0.0001)/100.
      ICO2 = (MCO2-CO2B*0.0001)/100.
      EGR1 = ICO2/ECO2
      AFA = (AFC+AFO)/2.
      XMFA = 1.+AFA*XMF/28.96
15    XNE = (XMFA*EGR1)/(1.-EGR1)
      XME = XMFA-1.+Y/4.
      XA = XNE/XME
C
      EGR = (ICO2/ECO2)*(1.+Y/2*ECO2)/(1.+Y/2*ICO2+ICO2/XA)
      DIF = EGR1-EGR
      ADIF = ABS(DIF)
      EGR1 = EGR
      EGR = EGR*100.
      IF(ADIF.GT.0.0001) GO TO 15
      GO TO 25
25    CONTINUE
      EGRCAL = EGR
      RETURN
35    CONTINUE
      EGRCAL = 0.0000
      RETURN
      END
```

```
; GETCYCLE
;
; CODE FOR PRESSURE-CRANLANGLE DATA ACQUISITION
; FROM MECHANICAL ENGINEERNG ENGINE LAB.
;
        .TITL GETCY

        .ENT GETCY, DSTRT
        .EXTN .UIEX, .IXMT, .REC
        .EXTD .CPYL, .FRET

        .NREL

ADSLOT=0
DISLOT=4
DAC=40           ; DEVICE CODE FOR DGDAC,
CP=1B0           ; CLEAR PENDING FLAG


; AI
;
; ROUTINE TO ACCESS THE A/D CONVERTOR
;
; CALL AI(ICHAN,IDATA,IER)
;
; WHERE:
;
; ICHAN IS THE INTERGER CHANNEL YOUR WISH TO ACCESS (0-31)
; IDATA IS AN INTEGER IN THE RANGE OF -32768 TO +32768.
; IER IS THE RETURNED ERROR CODE, 1 SYSTEM OK.
;
AI:     STA 3 AIRTN      ; SAVE RETURN

; READ CONTROLLER STATUS
        DIA 0 DAC
        STA 0 OLDSTAT    ; SAVE IT

; SELECT AND START A/D CHANNEL
AISTRT: LDA 1 ADRCNTX    ; GET ADDRESS/CONTEXT WORD FOR A/D
        NIOS DAC         ; SET CONTROLLER BUSY
        DOA 1 DAC        ; SELECT A/D CONVERTER
        LDA 0 MXPIO
        DOB 0 DAC        ; SELECT PIO AND MUX BUS FOR A/D
        SUB 0 0          ; GET CHANNEL # 0
        LDA 1 MUXNO      ; GET MUX NUMBER
        ADD 1 0          ; ADD TO CHANNEL NO
        DIA 2 DAC        ; GET PRESTART STATUS
        DOCS 0 DAC       ; SELECT CHANNEL AND START CONVERSION
        DIA 0 DAC        ; GET MODULE STATUS
        LDA 1 CMODE      ; GET CM BIT
        AND# 0 1 SZR     ; SKIP IF MODULE MODE
        JMP AISTRT       ; SLIPPED OUT OF MODULE MODE
        MOVZL 0 0 SZC    ; SKIP IF BUSY
        JMP AIOK         ; AI STARTED OK
        MOVZL 0 0 SNC    ; SKIP IF DONE
        JMP AISTRT       ; NOT BUSY OR DONE

AIOK:   SKPDN DAC        ; WAIT FOR DONE
        JMP .-1

        JSR DACIN        ; CHECK REASON FOR DONE
        JMP AIOK         ; JUST A CHASSIS IRPT, IGNORE IT

        STA 1 IDATA      ; SAVE DATA

; RETURN TO CALLER AFTER RESTORING ORIG STATUS
        LDA 0 OLDSTAT
        LDA 1 C37
        AND 1 0          ; MASK OFF ALL BUT CM AND ADDR BITS
        DOA 0 DAC        ; RESTORE OLD STATUS
```

```
        LDA 0 IDATA      ; GET DATA
        JMP @AIRTN       ; AND RETURN

IDATA:  0
AIRTN:  0
ADRCNTX:         ADSLOT
OLDSTAT:         0
MXPIO:  1B1              ; MUX BUS BIT FOR SPEC CONV INSTRUCTION
MUXNO:  0B11
CMODE:  1B11
C37:    37
.MSG:   .+1
MSG:    0
ADINP:  0                ; ANALOG INPUT DATA
D4000:  4000.            ; OFFSET FOR CONTROLLER MODE INTERUPT ADDRESS

; CONTROLLER MODE INTERUPT - ERROR


; DSTRT
;
; THIS ROUTINE MUST BE CALLED TO IDEF DEVICE FOR RDOS BEFORE ANY OTHER
; DGDACPAC ROUTINES ARE CALLED.
;
; CALL DSTRT(IER)
;
; WHERE IER = 1 IF ALL WENT OK
;           = 3+SYSTEM ERROR CODE IF NOT OK

        1
DSTRT:  JSR @.CPYL       ; GET ARG LIST
        LDA 0 DVCDE      ; IDENTIFY DEVICE TO RDOS
        .SYSTM
        .DEBL
        JMP SYSER

        LDA 1 .DCT
        .SYSTM
        .IDEF
        JMP SYSER

        LDA 0 C77
        .SYSTM
        .DEBL            ; ENABLE CPU INSTR
        JMP .+1

; THE FOLLOWING SETS THE INTERUPT MASK BITS
        LDA 1 CMODE
        DOA 1 DAC        ; SELECT CM MODE
        SUB 0 0
        DOB 0 DAC        ; SPECIFY MODULE SUBMASK
        LDA 0 CMASK
        DOC 0 DAC        ; SPECIFY CONTROLLER SUBMASK

; RETURN WITH ERROR CODE = 1 (OK)
        SUBZL 0 0
        STA 0 @-167 3    ; RETURN CODE = 1
        JMP @.FRET       ; RETURN

SYSER:  LDA 0 C3
        ADD 0 2
        STA 2 @-167 3
        JMP @.FRET       ; RETURN WITH ERROR CODE IN IER

CMASK:  13B7+1B10        ; OTMP,Y-AD,Y-BY,Y-TM
C3:     3
C77:    77
DVCDE:  DAC
.DCT:   .+1
```

```
        0               ; DAC DCT
        1B5
        .+1
        JSR DACIN
        JMP .+1
        .UIEX

; DGDAC 'DONE' CHECK ROUTINE
; CALL TO CHECK REASON FOR 'DONE' SET
;
; JSR DACIN
; (CHASSIS IRPT)
; (A/D IRPT) (DATA IN AC1)

DACIN:  DIAP 0 DAC      ; IDENTIFY SUBSYSTEM INTERUPT
        DIA 1 DAC       ; FIRST DIA IS OLD STATUS
        LDA 2 CMDINT
        AND# 2 1 SZR    ; SKIP IF NOT CHASSIS INTERUPT
        JMP CMISV       ; GO SERVICE CHASSIS

        LDA 1 ADRC1
        DOA 1 DAC       ; SELECT A/D AND CP
        DIBC 1 DAC      ; GET DATA AND CLEAR A/D

        LDA 2 C37
        AND 2 0         ; MASK OFF ALL BUT CM AND ADDR BITS
        DOA 0 DAC       ; RESTORE ORIG STATUS

DACSM:  JMP 1 3         ; RETURN, CALL+2 WITH DATA IN AC1

; ACTIVE DONE IS ONLY ALLOWABLE CONTROLLER IRPT
; JUST RESTART BUSY AND DISMISS INTERUPT
CMISV:  NIOS DAC
        JMP 0 3         ; RETURN CALL+1

C2:     2
CMDINT: 1B11
ADRC1:  CP+ADSLOT       ; SELECT A/D AND SET CLEAR PENDING FLAG


; DI
;
; CALL DI(IDATA)

; FUNCTION: TRANSFER 16-BIT DIGITAL INPUT WORD TO IDATA

; DUE TO PECULIARITY OF 4291 DIGITAL INPUT MODULE, THE WORD
; WHICH IS TRANSFERED TO IDATA IS THE STATE OF THE DIGITAL INPUT
; LINES AT THE TIME OF THE PREVIOUS CALL TO DI. THE 'S' PULSE
; ACTUALLY CAUSES THE DATA TO BE LATCHED IN THE INPUT BUFFER REGISTER.
; CONSEQUENTLY, YOU WILL NEED TO CALL DI ONCE BEFORE THE DATA
; IS REALLY VALID.

DI:     DIA 1 DAC       ; GET OLD STATUS
        NIOS DAC        ; BUSY CONTROLLER
        LDA 0 ADRC3
        DOA 0 DAC       ; SELECT DI AND MODULE MODE
        DIBS 0 DAC      ; GET DATA AND LATCH IN NEW DATA FOR NEXT TIME
        MOV 0 2         ; RETURN WITH DATA IN AC2
        LDA 0 C37
        AND 1 0
        DOA 0 DAC       ; RESTORE OLD STATUS
        MOV 2 0         ; RETURN WITH DATA IN AC0 TOO
        JMP 0 3         ; RETURN

ADRC3:  DISLOT          ; DI SLOT

; GETCY

; ROUTINE TO WAIT FOR TRIGGER PULSE, THEN GET (RAPIDLY)
```

```
; KNT SAMPLES AND STUFF THEM INTO IARAY
;
; CALL GETCY(IARAY(1),ITHRSH,KNT)
;
; WHERE:
;
;    IARAY IS DATA ARRAY DIMENSIONED 'KNT'
;    KNT IS NUMBER OF SAMPLES TO TAKE
;    ITHRSH IS A/D THRESHOLD AT WHICH SAMPLING BEGINS
;
;  GETCY WAITS FOR BIT TRANSITION ON DI LINE 0, THEN
;     IF A/D CHANNEL ZERO IS BELOW THRESHOLD, SAMPLES
;     AND STORES KNT SAMPLES IN SYNCRONISM WITH TIMING
;     MARK ON DI BIT 1.  GETCY IS DESIGNED TO BE USED
;     WITH ENGINE PERFORMANCE SYSTEM.
        3               ; 3 ARG
GETCY:  JSR @.CPYL      ; GET ADDRESS OF ARRAY
        LDA 0 -167 3    ; GET ARRAY ADDRESS
        STA 0 .ARAY     ; SAVE IT
        LDA 0 @-166 3   ; GET THRESHOLD
        STA 0 THRSH     ; SAVE IT
        LDA 0 @-165 3   ; GET # OF SAMPLES TO TAKE
        STA 0 KNT       ; INIT COUNTER
        INTDS           ; TURN OFF THE LIGHTNING, IGOR

; GETCY GETS KNT SAMPLES STARTING WITH AN INDEX MARK ON DI BIT 0
; SAMPLES ARE TAKEN WHEN BIT1 MAKES 1-0 TRANSITION

WFTM:   JSR @.DI        ; GET DIGTAL INPUT
        MOVZL 0 0 SZC   ; SKIP IF TIMING MARK
        JMP .-2         ; WAIT FOR IT

GETSMPL:        JSR @.AI        ; GET SAMPLE

        LDA 1 THRSH     ; GET THESHHOLD
        SUBZL# 1 0 SNC  ; SKIP IF BELOW THRESHOLD
        JMP WFTM        ; WAIT FOR ANOTHER TIMING MARK

SVSMP:  STA 0 @.ARAY    ; SAVE IT
        ISZ .ARAY
        DSZ KNT         ; DONE?
        JMP GETNX       ; NOPE
        INTEN           ; YUP, LET EM RIP
        JMP @.FRET      ; RETURN

GETNX:  JSR @.DI
        MOVZL 0 0
        MOVZL 0 0 SNC   ; WAIT FOR A 1 TIME MARK
        JMP GETNX

        JSR @.DI
        MOVZL 0 0
        MOVZL 0 0 SZC   ; WAIT FOR A 1-0 TRANS
        JMP .-3

        JSR @.AI        ; GET SAMPLE
        JMP SVSMP       ; SAVE SAMPLE

.AI:    AI
.DI:    DI
THRSH:  0
.ARAY:  0
KNT:    0

        .END
```

```
      SUBROUTINE GRID(XSTART,XSCALE,XINC,NXTIC,YSTART,YSCALE,YINC,
     &NYTIC,IX1,IX2,IY1,IY2,KNUM,KTOP)
C *******************************************************************
C
C THIS PROGRAM IS DESIGNED TO DRAW THE GRID
C FOR PLOTTING OF DATA . THE PROGRAM WILL
C DRAW THE AXIS AND LABEL WITH NUMBERS THE TICK
C MARKS.
C
C
C AUTHOR:        K.R. SCHMID
C                MECHANICAL ENGINERING DEPARTMENT
C                UNIVERSITY OF MISSOURI - ROLLA
C                ROLLA,MISSOURI 65401
C
C REVISION HISTORY:
C
C                8/14/80 - ORGINAL CREATED
C
C DEFINITIONS:
C
C      IXDIV   = X-AXIS SPACING OF NUMBERS IN SCREEN COORDINATES
C      IXTIC   = X-AXIS SPACING OF TICK MARKS
C      XSTART  = X-AXIS STARTING COORDINATE
C      XSCALE  = X-AXIS FULL SCALE COORDINATE
C      XINC    = X-AXIS NUMERICAL INCREMENT
C      NXTIC   = X-AXIS NUMBER OF TICK MARKS BETWEEN NUMERIALS
C
C      IYDIV   = Y-AXIS SPACING OF NUMBERS IN SCREEN COORDINATES
C      IYTIC   = Y-AXIS SPACING OF TICK MARKS
C      YSTART  = Y-AXIS STARTING COORDINATE
C      YSCALE  = Y-AXIS FULL SCALE COORDINATE
C      YINC    = Y-AXIS NUMERICAL INCREMENT
C      NYTIC   = Y-AXIS NUMBER OF TICK MARKS BETWEEN NUMERIALS
C
C      IX1     = X-AXIS LOWER LEFT SCREEN COORDINATE
C      IX2     = X-AXIS UPPER RIGHT SCREEN COORDINATE
C      IY1     = Y-AXIS LOWER LEFT SCREEN COORDINATE
C      IY2     = Y=AXIS UPPER RIGHT SCREEN COORDINATE
C      KTOP     = DRAW GRID TOP LINE (1-YES)
C      KNUM     = WRITE X-AXIS NUMERICALS (1-YES)
C
C *******************************************************************
C
C ***** CALCULATE CONSTANTS *****
C
      IXDIV =(IX2-IX1)/((XSCALE-XSTART)/XINC)
      IYDIV = (IY2-IY1)/((YSCALE-YSTART)/YINC)
      IXTIC = IXDIV/(NXTIC+1)
      IYTIC = IYDIV/(NYTIC+1)
      IT1X = IX1+5
      IT2X = IX2-5
      IT1Y = IY1+5
      IT2Y = IY2-5
      JY1 = IY1+IYTIC
      JY2 = IY2-IYTIC
      JX1 = IX1+IXTIC
      JX2 = IX2-IXTIC
      KY1 = IY1-20
      KX1 = IX1-70
C
C ***** DRAW GRID LINES *****
C
      CALL TKINI(10,11)
      CALL MVABS(IX1,IY1)
      CALL DWABS(IX2,IY1)
      CALL DWABS(IX2,IY2)
      IF(KTOP.EQ.0)CALL MVABS(IX1,IY2)
      IF(KTOP.EQ.1)CALL DWABS(IX1,IY2)
```

```
      CALL DWABS(IX1,IY1)
      DO 100 IY = JY1,JY2,IYTIC
      CALL MVABS(IX1,IY)
      CALL DWABS(IT1X,IY)
100   CONTINUE
      DO 110 IX = JX1,JX2,IXTIC
      CALL MVABS(IX,IY2)
      CALL DWABS(IX,IT2Y)
110   CONTINUE
      DO 120 IX = JX1,JX2,IXTIC
      CALL MVABS(IX,IY1)
      CALL DWABS(IX,IT1Y)
120   CONTINUE
      DO 130 IY = JY1,JY2,IYTIC
      CALL MVABS(IX2,IY)
      CALL DWABS(IT2X,IY)
130   CONTINUE
C
C ***** LABEL AXIS *****
C
      XNUM = XSTART
      IF(KNUM.EQ.0)GO TO 151
      DO 150 IX=IX1,IX2,IXDIV
      I2X=IX-35
      CALL ANMDE(I2X,KY1)
      WRITE(10,610)XNUM
610   FORMAT(1X,F6.1)
      XNUM= XINC+XNUM
150   CONTINUE
151   CONTINUE
      YNUM=YSTART
      DO 160 IY=IY1,JY2,IYDIV
      I2Y = IY-5
      CALL ANMDE(KX1,I2Y)
      WRITE(10,610)YNUM
      YNUM=YNUM+YINC
160   CONTINUE
      RETURN
      END
```

```
      SUBROUTINE PHASE(IDEG)
C ************************************************************************
C
C THIS PROGRAM IS DESIGNED TO SHIFT  PRESSURE DATA.
C THE AMOUNT OF THE DATA SHIFT IS DEFINED BY THE TERM
C IDEG.
C
C AUTHOR:        K.R. SCHMID
C                MECHANICAL ENGINEERING DEPARTMENT
C                UNIVERSITY OF MISSOURI-ROLLA
C                ROLLA,MISSOURI 65401
C
C REVISION HISTORY:
C
C                07/10/80 - ORGINAL CREATED
C
C
C ************************************************************************
      COMMON /PDATA/ PRES1(720),PRES(720)
C
      DO 100 J=1,IDEG
      K = IDEG-J
      PRES1(J) = PRES(720-K)
100   CONTINUE
      K1 = 720-IDEG
      DO 110 J=1,K1
      PRES1(J+IDEG) = PRES(J)
110   CONTINUE
      DO 120 I=1,720
      PRES(I) = PRES1(I)
120   CONTINUE
      RETURN
      END
```

```
      SURROUTINE SHIFT(IDEG)
C ****************************************************************
C
C THIS PROGRAM IS DESIGNED TO SHIFT THE PRESSURE DATA.
C THE AMOUNT OF THE DATA SHIFT IS DEFINED BY THE TERM
C IDEG.
C
C AUTHOR:        K.R. SCHMID
C                MECHANICAL ENGINEERING DEPARTMENT
C                UNIVERSITY OF MISSOURI - ROLLA
C                ROLLA,MISSOURI 65401
C
C REVISION HISTORY:
C
C                07/10/80 - ORGINAL CREATED
C
C ****************************************************************
      COMMON /PDATA/ PRES1(720,2),PRES(720,2)
C
      DO 100 KK = 1,2
      DO 110 J=1,IDEG
      K = IDEG-J
      PRES1(J) = PRES(720-K)
110   CONTINUE
      K1 = 720-IDEG
      DO 120 J=1,K1
      PRES1(J+IDEG) = PRES(J)
120   CONTINUE
      DO 130 I=1,720
      PRES(I) = PRES1(I)
130   CONTINUE
100   CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SYMBOL(ISYM)
C ******************************************************************
C
C THIS PROGRAM IS DESIGNED TO DRAW SYMBOLS FOR
C PLOTTING DATA POINTS.
C
C AUTHOR:        K.R. SCHMID
C                MECHANICAL ENGINEERING DEPARTMENT
C                UNIVERSITY OF MISSOURI-ROLLA
C                ROLLA,MISSOURI 65401
C
C REVISION HISTORY:
C
C                07/17/80 - ORGINAL CREATED
C
C SYMBOLS :
C
C                CIRCLE = 1
C                BOX =    2
C                TRI1 =   3
C                TRI2 =   4
C
C ******************************************************************
      IF(ISYM.EQ.1)GO TO 10
      IF(ISYM.EQ.2)GO TO 20
      IF(ISYM.EQ.3)GO TO 30
      IF(ISYM.EQ.4)GO TO 40
C
C ***** CIRCLE ******
C
10    CONTINUE
      CALL DWREL(1,0)
      CALL DWREL(0,-1)
      CALL DWREL(-1,0)
      CALL DWREL(0,1)
      CALL MVREL(3,7)
      CALL DWREL(4,-4)
      CALL DWREL(0,-6)
      CALL DWREL(-4,-4)
      CALL DWREL(-6,0)
      CALL DWREL(-4,4)
      CALL DWREL(0,6)
      CALL DWREL(4,4)
      CALL DWREL(6,0)
      RETURN
C
C ***** BOX *****
C
20    CONTINUE
      CALL DWREL(1,0)
      CALL DWREL(0,-1)
      CALL DWREL(-1,0)
      CALL DWREL(0,1)
      CALL MVREL(-7,7)
      CALL DWREL(14,0)
      CALL DWREL(0,-14)
      CALL DWREL(-14,0)
      CALL DWREL(0,14)
      RETURN
C
C ***** TRIANGLE POINTING UPWARD ******
C
30    CONTINUE
      CALL DWREL(1,0)
      CALL DWREL(0,-1)
      CALL DWREL(-1,0)
      CALL DWREL(0,1)
      CALL MVREL(0,9)
      CALL DWREL(-7,-14)
```

```
      CALL DWREL(14,0)
      CALL DWREL(-7,14)
      RETURN
C
C ***** TRIANGLE POINTING DOWNWARD ******
C
40    CONTINUE
      CALL DWREL(1,0)
      CALL DWREL(0,-1)
      CALL DWREL(-1,0)
      CALL DWREL(0,1)
      CALL MVREL(0,-10)
      CALL DWREL(-7,14)
      CALL DWREL(14,0)
      CALL DWREL(-7,-14)
      RETURN
      END
```

```
      SUBROUTINE TITLE(IDATA,IROTATE,X,Y)
C *******************************************************************
C
C THIS PROGRAM IS DESIGNED TO TITLE THE AXIS OF SEVERAL
C PLOTTING PROGRAMS.
C
C AUTHOR:        K.R. SCHMID
C                UNIVERSITY OF MISSOURI - ROLLA
C                MECHANICAL ENGINEERING DEPARTMENT
C                ROLLA, MISSOURI 65401
C
C DEFINITIONS:
C
C       IPOWER = DESIGNATES THE POWER BASE
C       IDATA = DATA CHANNEL TO BE PLOTTED
C       IROTATE = DETERMINES IF THE LETTERING IS TO ROTATED
C                 90 DEGREES (1-YES;0-NO).
C
C REVISION HISTORY:
C
C                07/07/80 - ORGINAL CREATED
C
C *******************************************************************
      COMMON IPOWER
      IF(IROTATE .EQ.1)WRITE(10,600)
      CALL ANMDE(X,Y)
      IF(IPOWER.EQ.0)GO TO 19
C
      IF(IDATA.EQ.1)WRITE(10,101)
      IF(IDATA.EQ.2)WRITE(10,102)
      IF(IDATA.EQ.3)WRITE(10,103)
      IF(IDATA.EQ.4)WRITE(10,104)
      IF(IDATA.EQ.5)WRITE(10,105)
      IF(IDATA.EQ.6)WRITE(10,106)
      IF(IDATA.EQ.7)WRITE(10,107)
      IF(IDATA.EQ.8)WRITE(10,108)
      GO TO 20
C
19    CONTINUE
      IF(IDATA.EQ.1)WRITE(10,201)
      IF(IDATA.EQ.2)WRITE(10,202)
      IF(IDATA.EQ.3)WRITE(10,203)
      IF(IDATA.EQ.4)WRITE(10,204)
      IF(IDATA.EQ.5)WRITE(10,205)
      IF(IDATA.EQ.6)WRITE(10,206)
      IF(IDATA.EQ.7)WRITE(10,107)
      IF(IDATA.EQ.8)WRITE(10,108)
C
20    CONTINUE
      IF(IROTATE.EQ.1)WRITE(10,610)
      RETURN
600   FORMAT(1X,"<33>CJ 90 ")
610   FORMAT(1X,"<33>CJ 0 ")
101   FORMAT(1X," INDICATED SPECFIC HC - UG/J")
102   FORMAT(1X," INDICATED SPECFIC CO - UG/J")
103   FORMAT(1X," INDICATED SPECFIC NO  - UG/J")
104   FORMAT(1X," INDICATED POWER - KW")
105   FORMAT(1X," AIR/FUEL EQUIVALENCE RATIO ")
106   FORMAT(1X," INDICATED EFFICIENCY - %")
107   FORMAT(1X," SPARK TIMING - DEGREES")
108   FORMAT(1X," EXHAUST TEMP. - F")
201   FORMAT(1X," BRAKE SPECFIC HC - UG/J")
202   FORMAT(1X," BRAKE SPECFIC CO - UG/J")
203   FORMAT(1X," BRAKE SPECFIC NO  - UG/J")
204   FORMAT(1X," BRAKE POWER - KW")
205   FORMAT(1X," AIR/FUEL EQUIVALENCE RATIO ")
206   FORMAT(1X," BRAKE EFFICIENCY - %")
      END
```